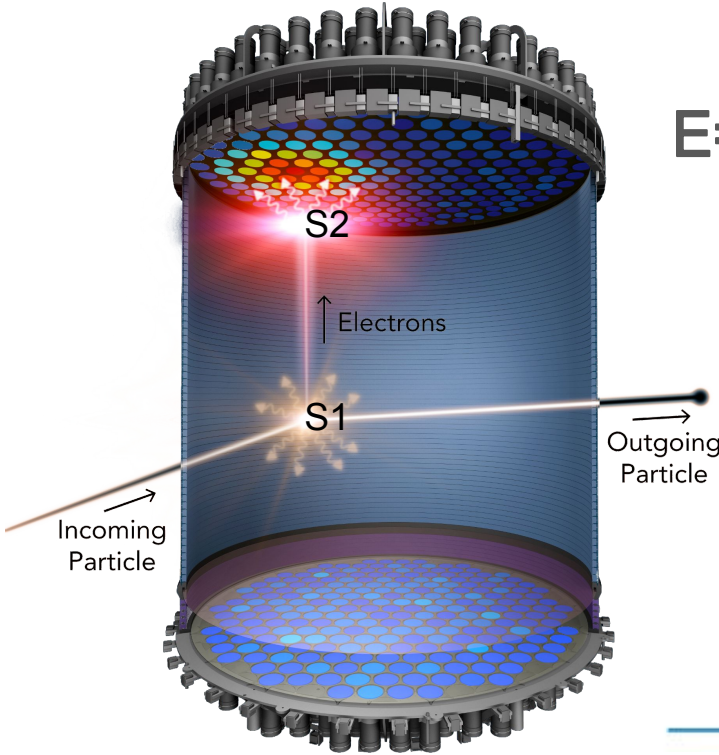
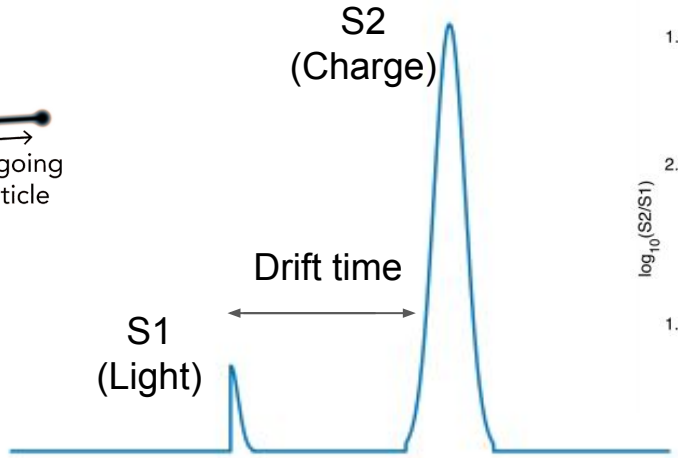
# Optimal Pair-finding for Flow Mapping in Liquid Xenon Time Projection Chambers

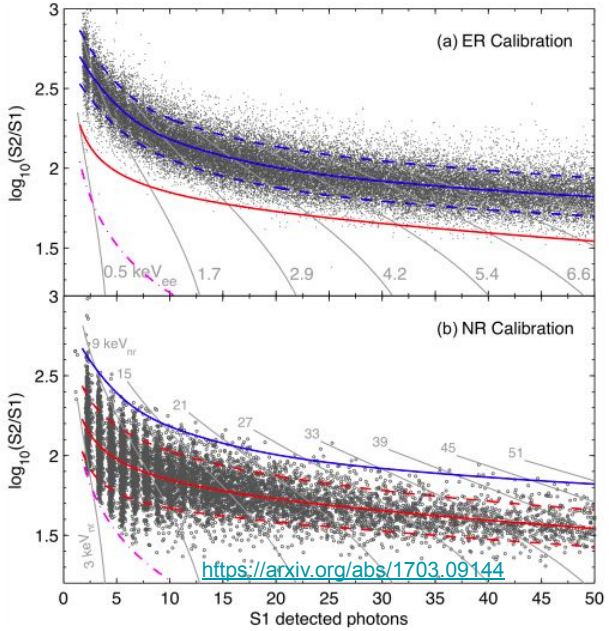
Jacob McLaughlin
For the LZ Collaboration

# LXe-TPC Signal Overview

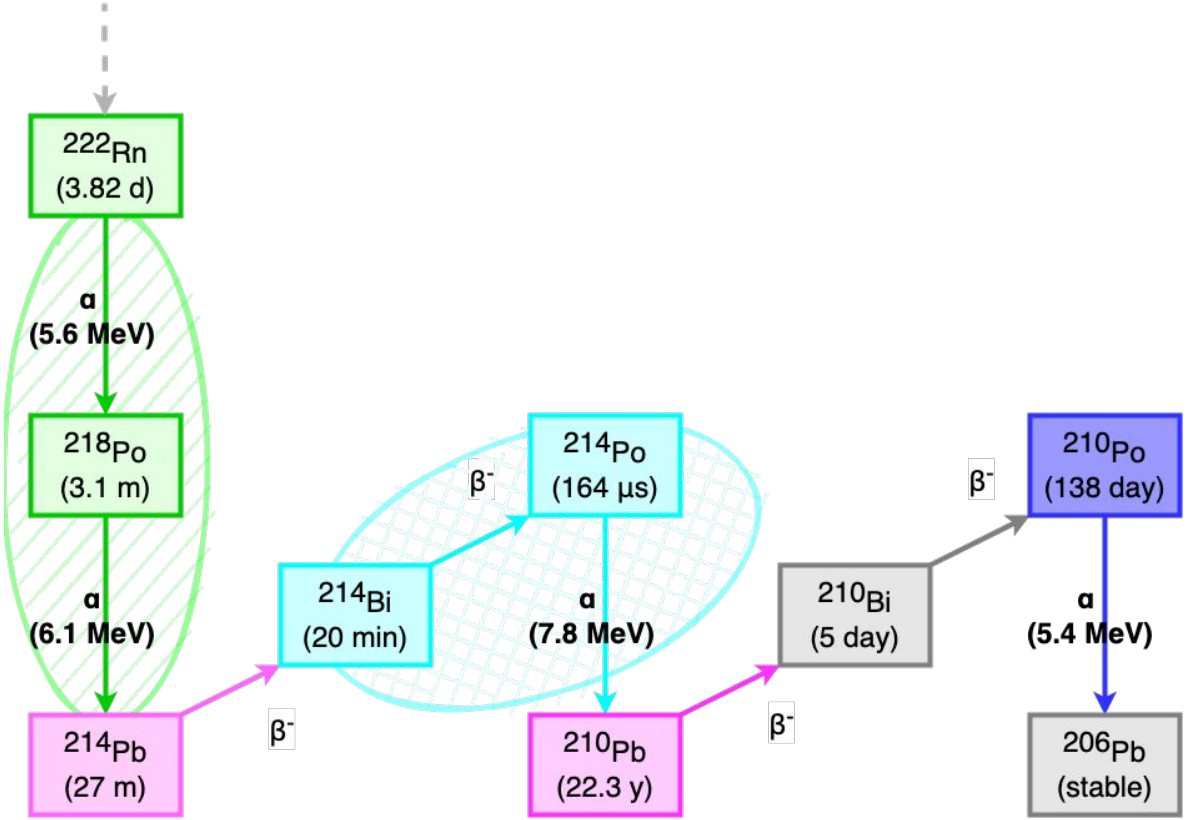



$$E=W*(S1/g1 + S2/g2)$$



# Radon Chain Overview



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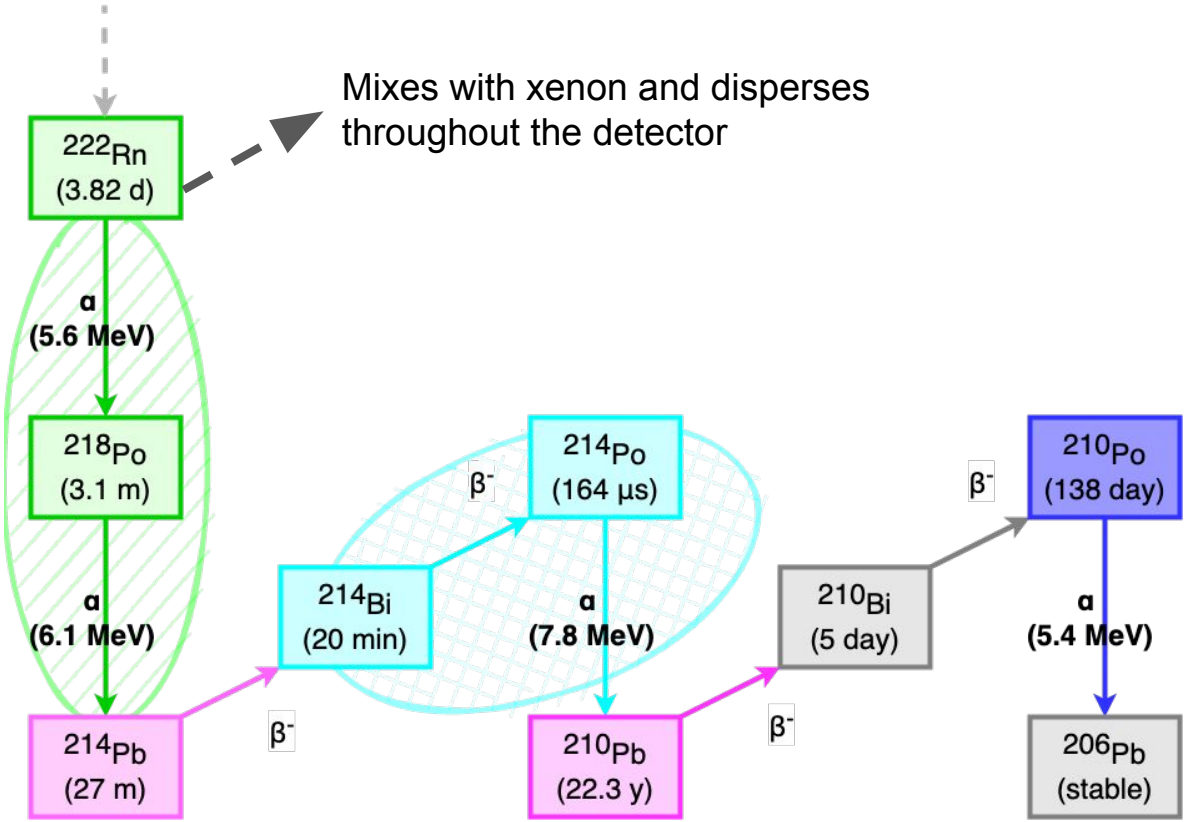
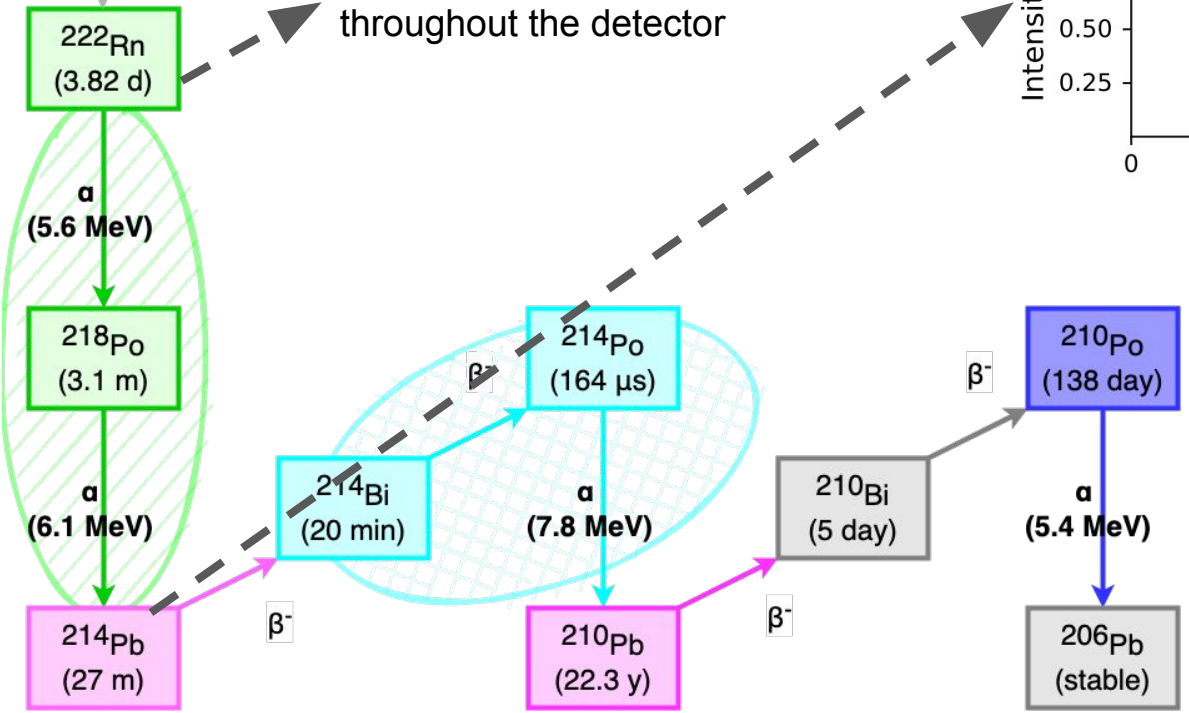
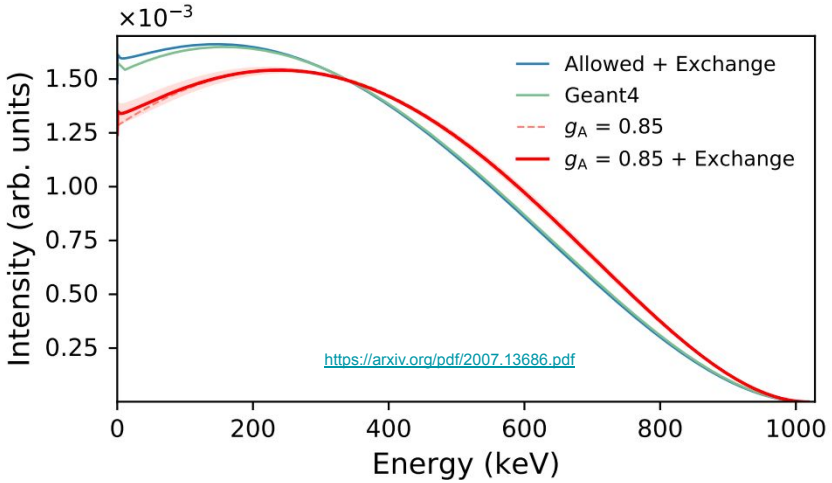


# Radon Chain Overview

Mixes with xenon and disperses throughout the detector



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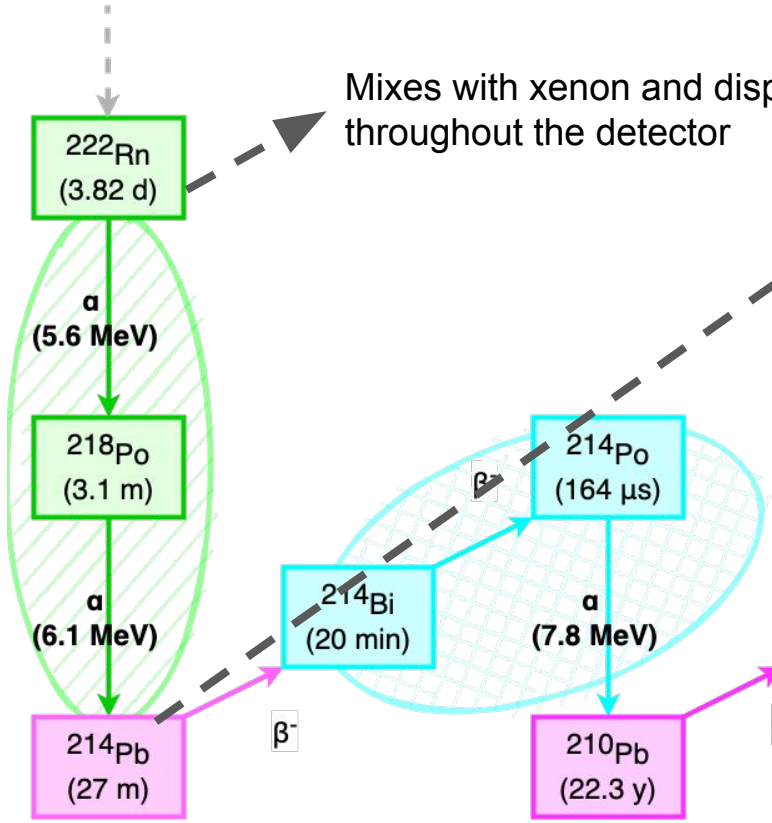
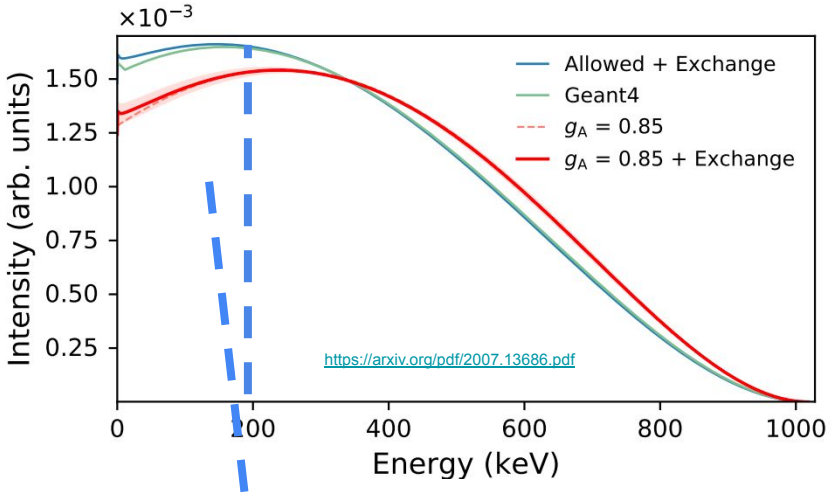
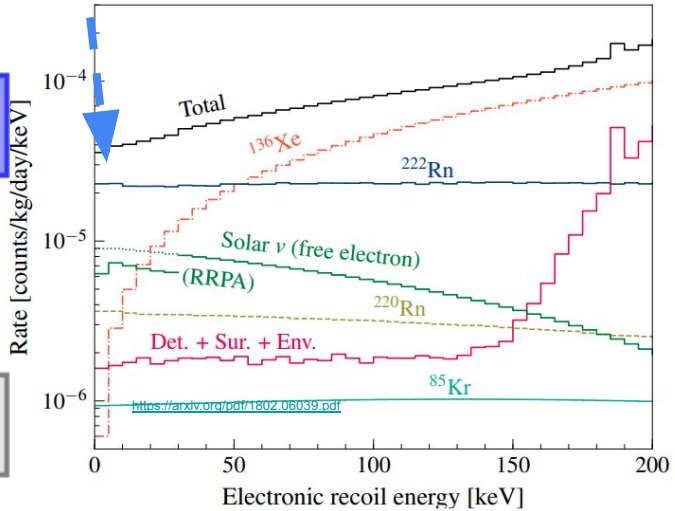
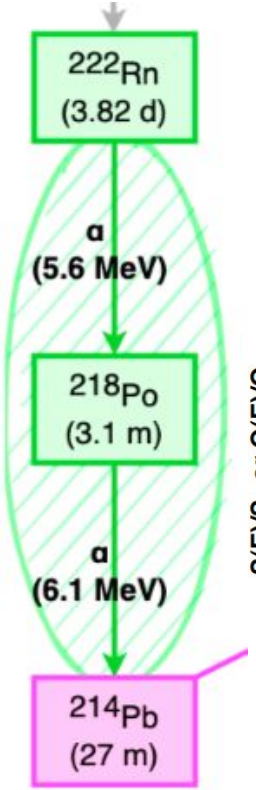


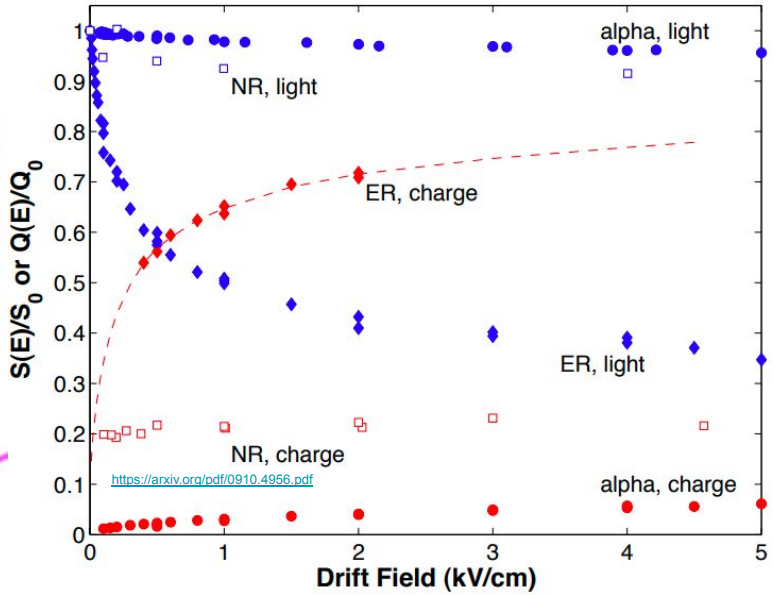



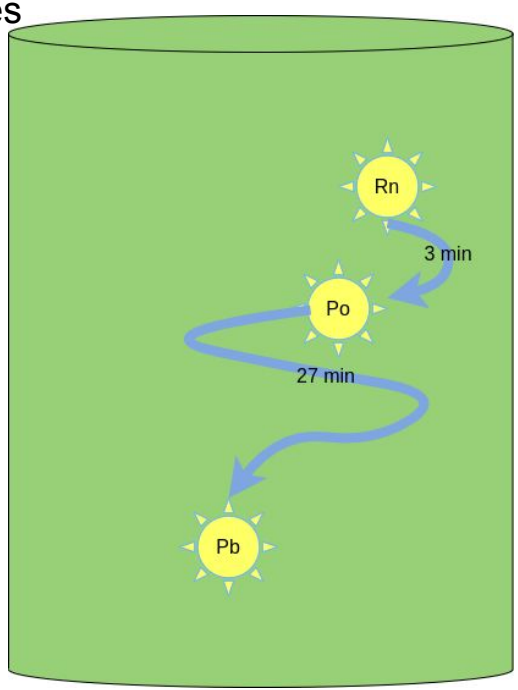



# A Pb-214 Signal: Spatial Correlation



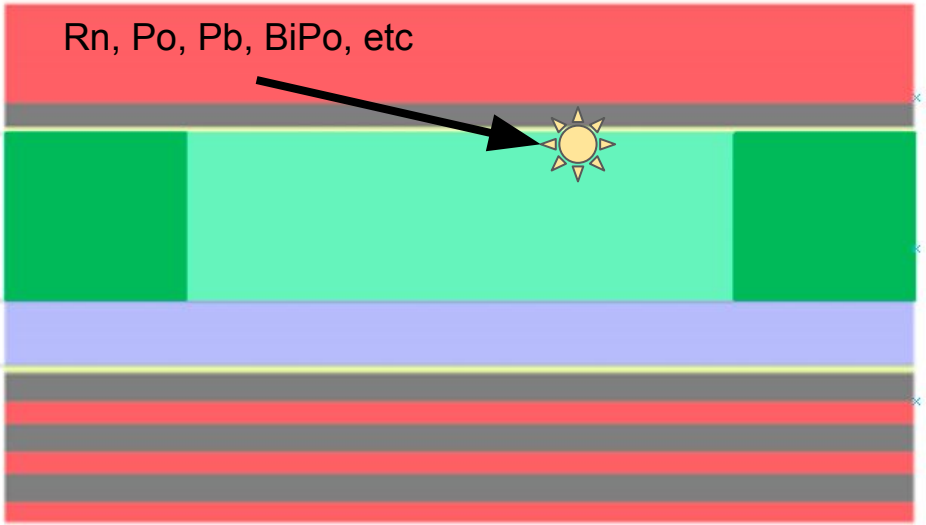

- Child decays and parent decays are spatially correlated
- Alpha tagging is easy
  - Uniquely large light yields; Large energy values

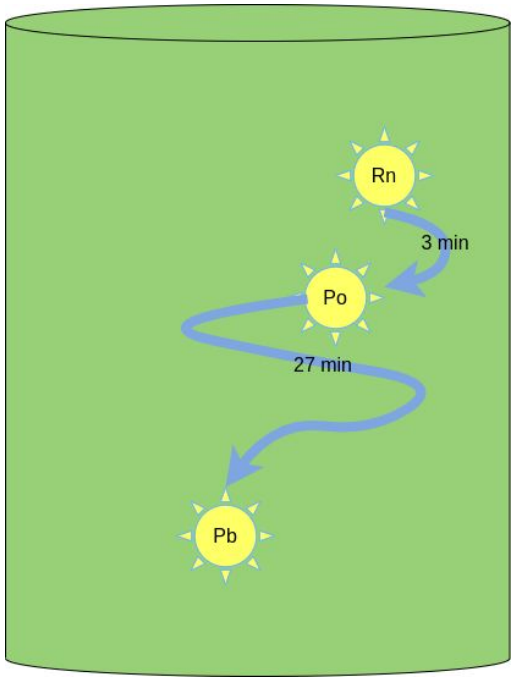


# Key to Spatial Tagging: Flow Mapping

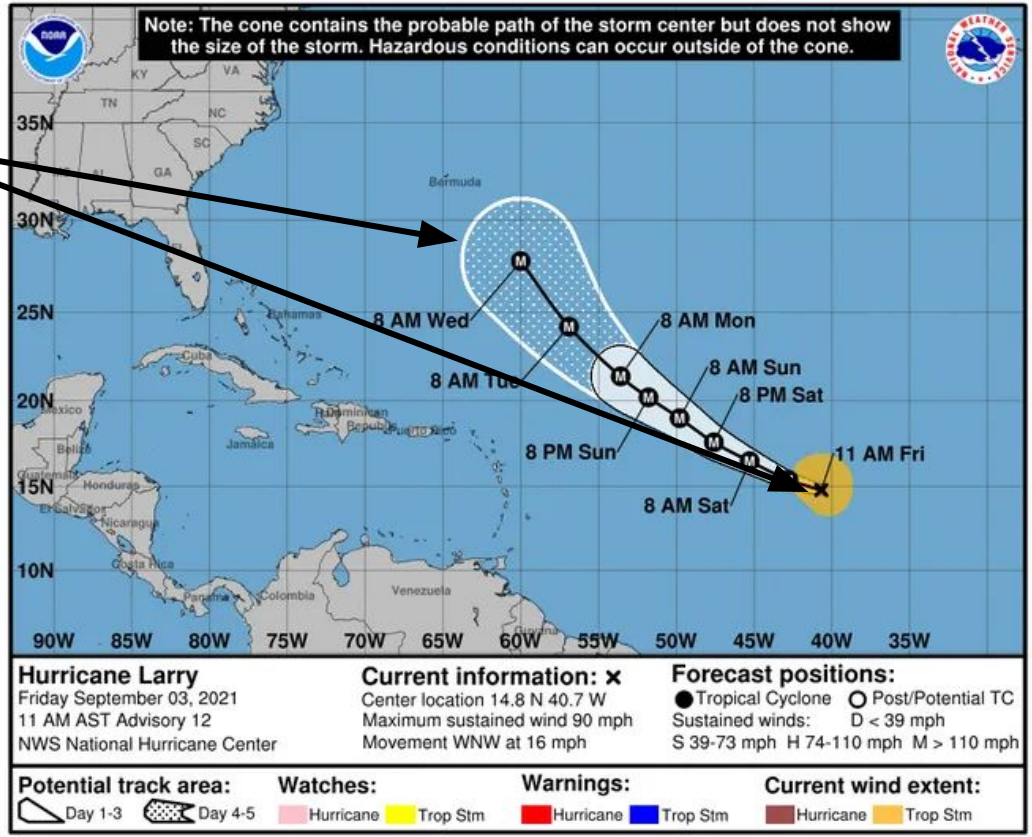
- High efficiency alpha tagging picks out Rn and Po events
- Rn and Po displacements offer a window into flow
  - Rn paired with Po that aren't its child will distort flow pictures
    - Essential to have robust pairing algorithm



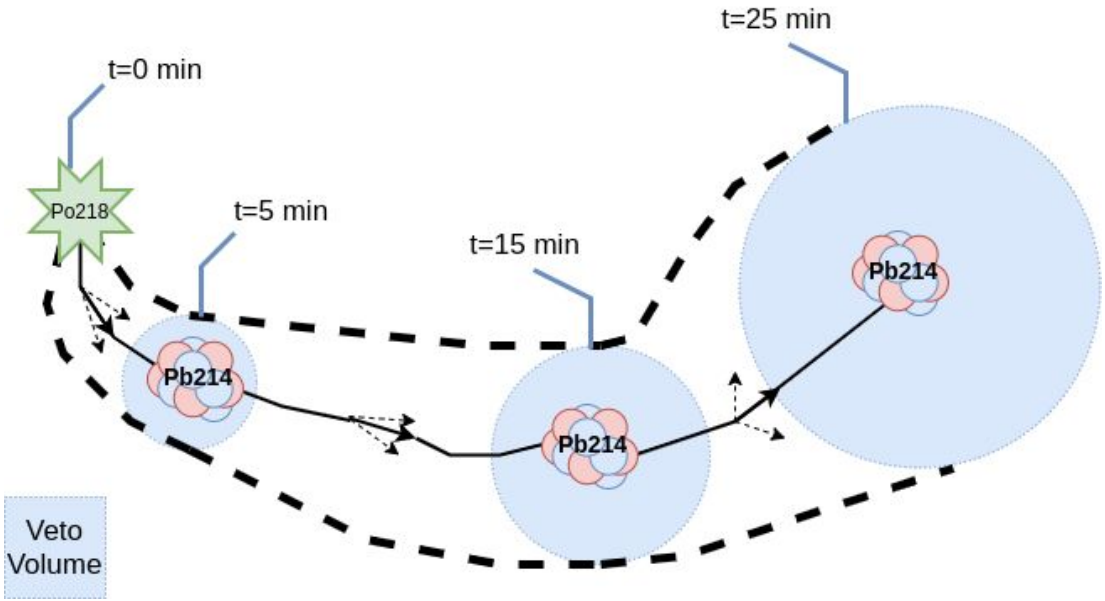
# Veto volumes are dictated by flow uncertainty

- Uncertainty in flow can result in substantial broadening of veto regions over time
- Greater flow uncertainty means larger the veto region
- Large veto regions means large loss of exposure



# How good does the LZ flowmap need to be?

- Suppose we have constant isotropic local flow uncertainty
  - Spherical time-dependent veto region centered on Pb expected location



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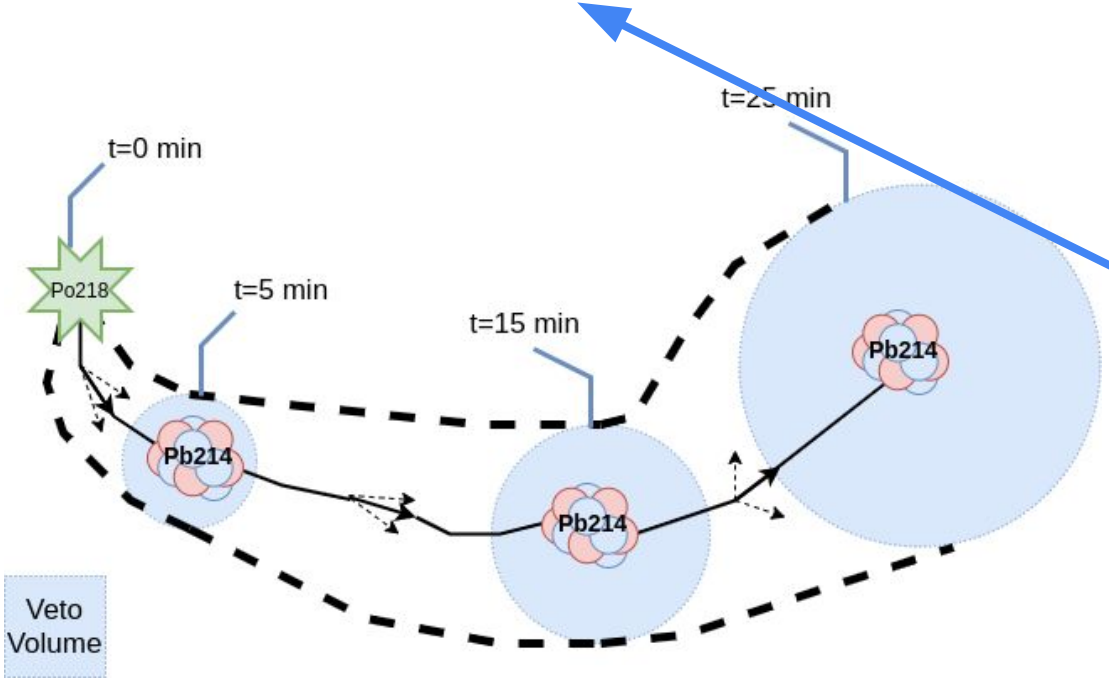
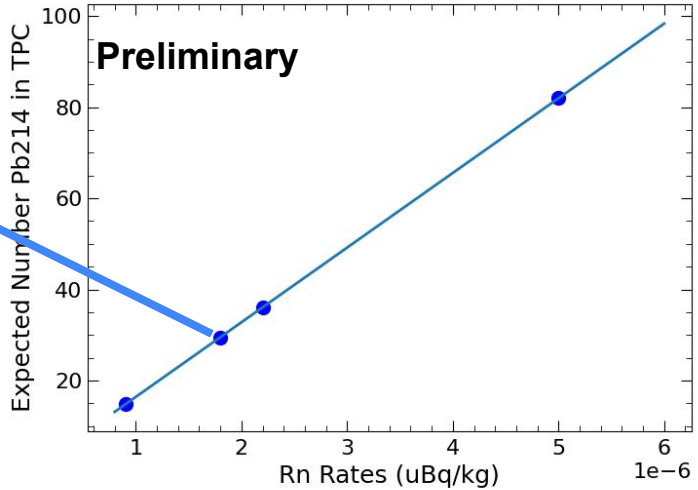
  - $\langle N_{Pb} \rangle$ = 29.5 Pb atoms/TPC volume



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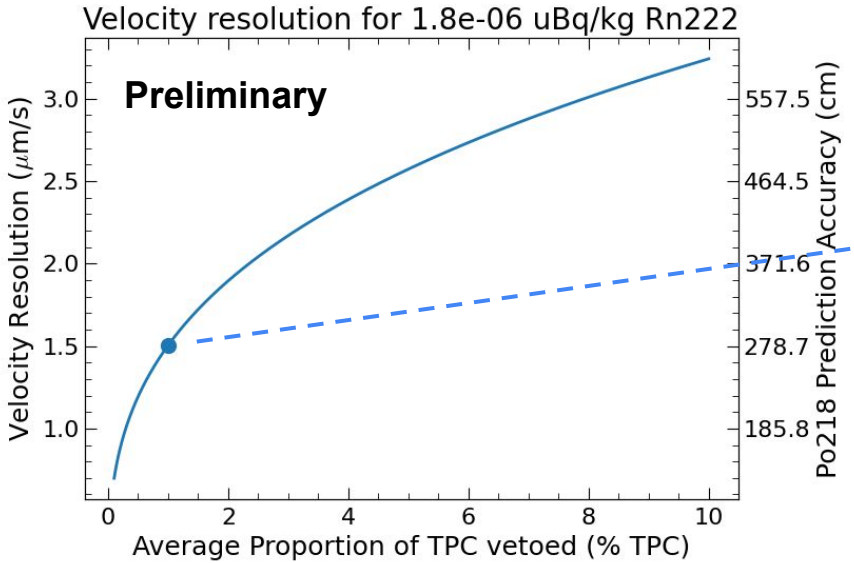
- Suppose we have constant isotropic local flow uncertainty
  - Spherical time-dependent veto region centered on Pb expected location
  - $\langle N_{Pb} \rangle$ = 29.5 Pb atoms/TPC volume
  - Maintain the veto for up to 3 $Pb_{214}$ half lives



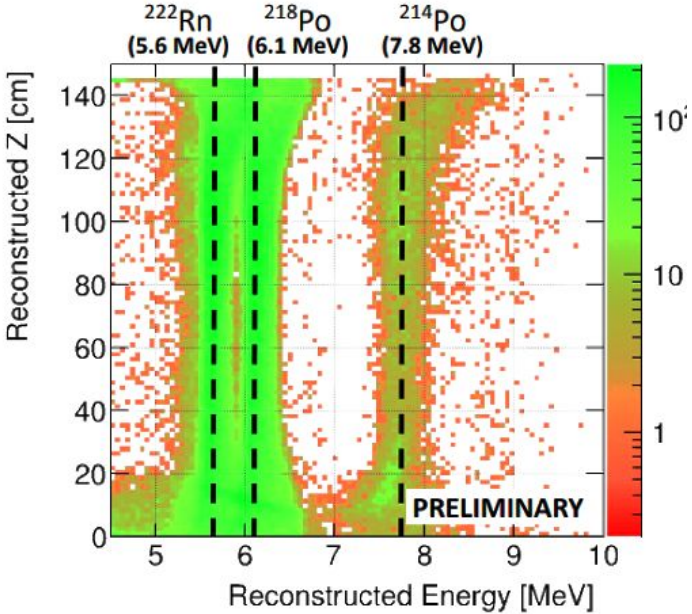

Preliminary

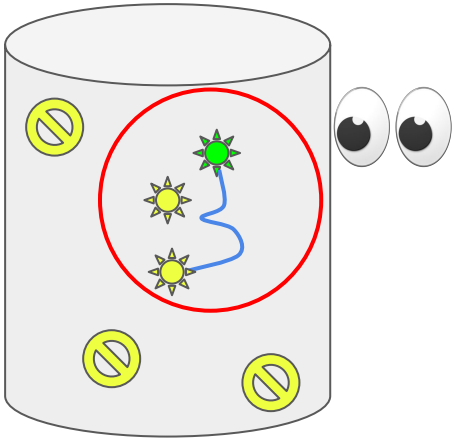
| Parameter | Value |
|---|---|
| $\Delta r_{Pb\ max}$ | 7.3 cm |
| $u_{\sigma}$ | 1.5 μm/s |
| $\Delta r_{Po\ max}$ | 0.28 cm |

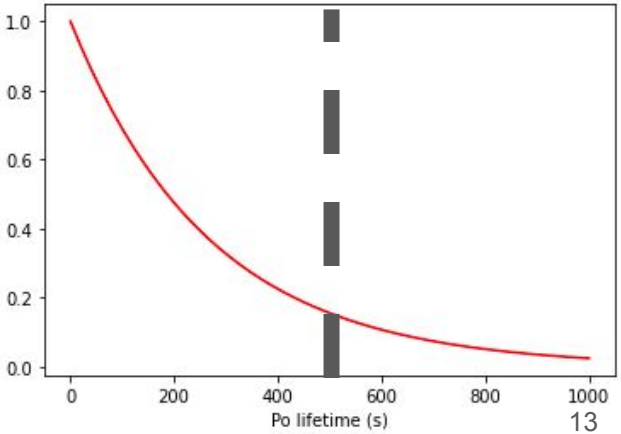
1.2e-3 cm/s from compressor (600 slpm flow)
8.3e-4 cm/s from compressor (400 slpm flow)

# What goes into a pair finding search?

- Parent-Child selection cuts criteria
- Acceptance volume for candidate child decays
- A time to look at the acceptance volume

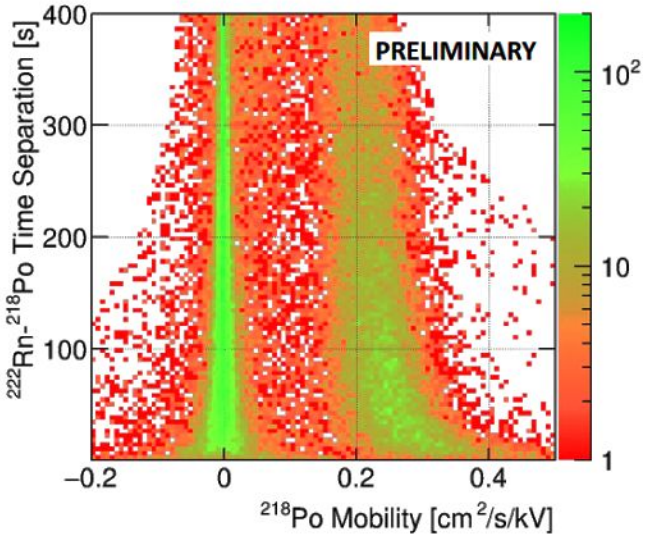


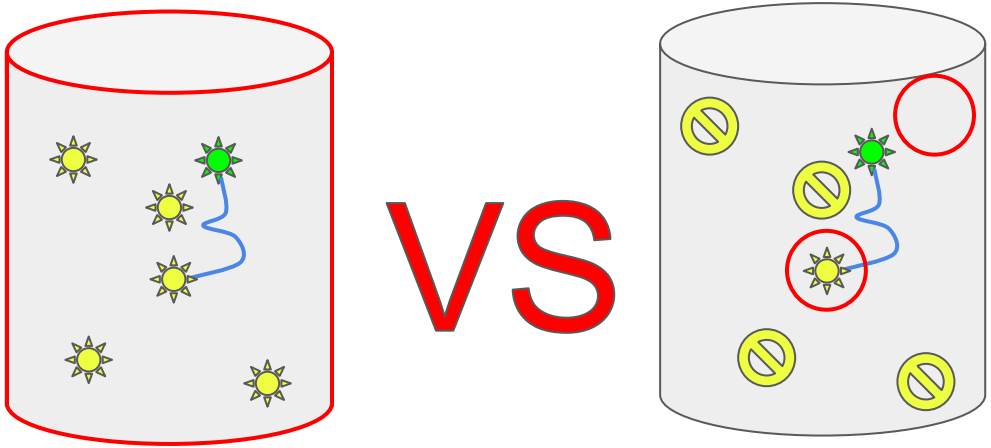





# Picking a Rn-Po search volume

- 2 distinct Z-velocity populations
  - Charged and uncharged Po
- Minimization of search volumes will minimize backgrounds
  - Some balance for true child selection efficiency



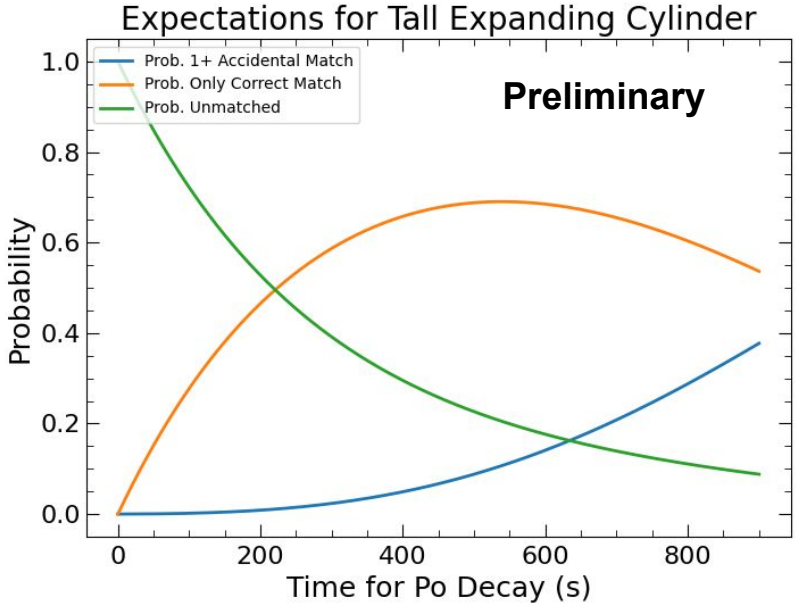



# Picking a search time

- Given a search volume and Rn rate:
  - <$N_{Accidental}$>: number of incorrect Po paired to an Rn
  - $P_{True\ Pair}$: Chance of matching an Rn to its child Po decay

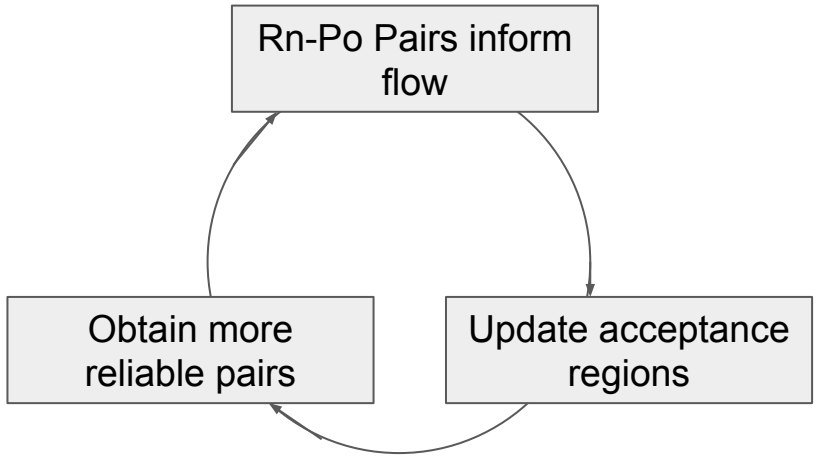
$$p_{\text{true pair}} = \epsilon_{\text{search vol.}} \epsilon_{\text{E select}} p_{\text{has decayed}}(t)$$
$$= \epsilon_{\text{search vol.}}(\vec{v}(x,y,z)) \epsilon_{\text{E select}} \int_0^{t_{\max}} \frac{1}{\tau} e^{-\frac{t}{\tau}} dt$$

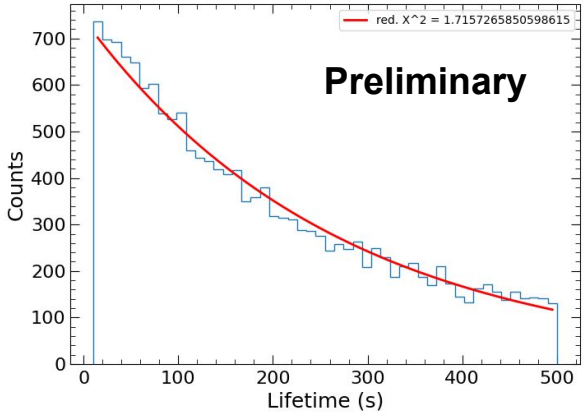
$$< N_{\text{Accidental}} > = \epsilon_{\text{E select}} \int_0^{t_{\max}} M_{\text{search}}(t) R dt$$
$$= \epsilon_{\text{E select}} \int_0^{t_{\max}} \rho V_{\text{search}}(t) R dt$$

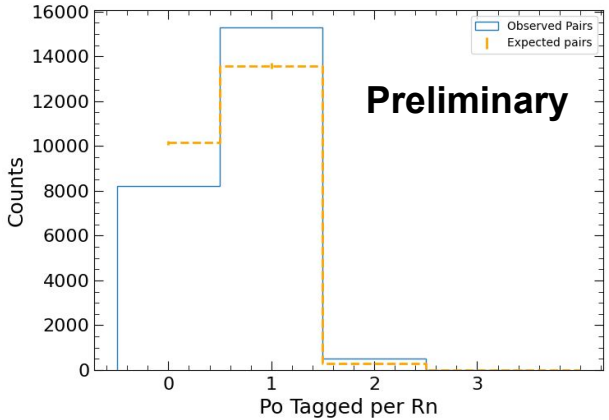


# Iterative Method to Improve Pair Finding

- Key details to keep track of
  - Accidental pair / True pairs
    - Lifetime fit
  - Pairs escaping your search
    - Can gauge efficiency in signal dominated searches

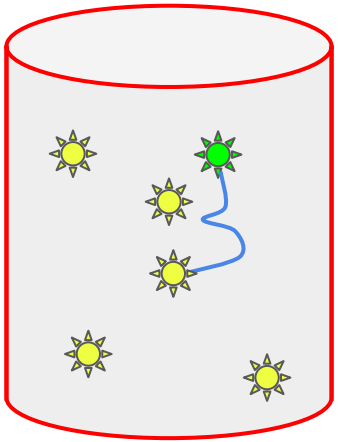


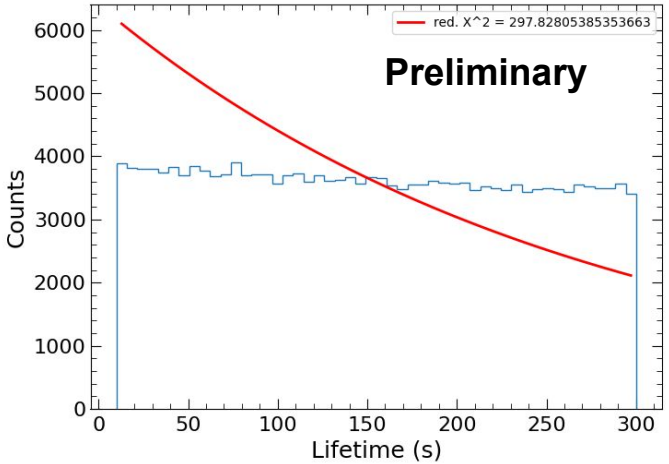



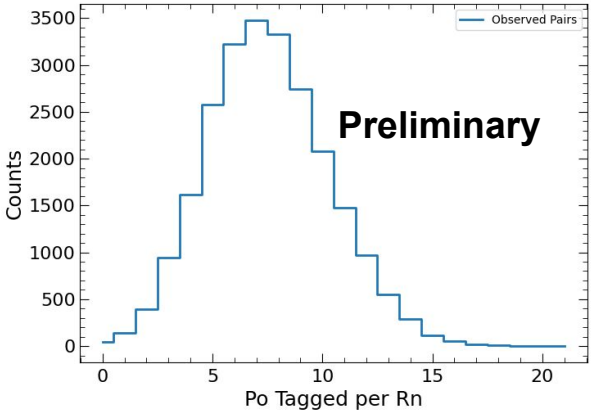



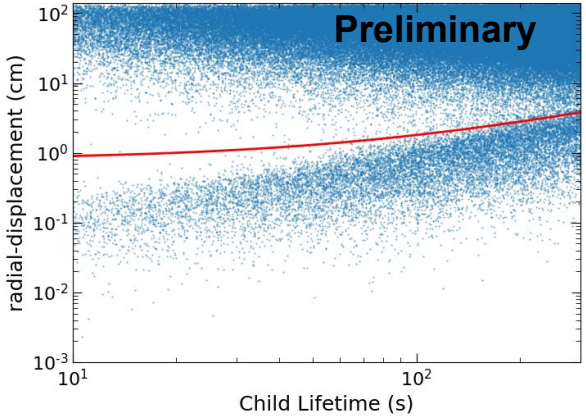
# Starting from Nothing: Full TPC Search Volume

- Rn is almost guaranteed to be paired with an accidental Po
- True pairs will:
  - Move with a characteristic speed
  - Tend to be at smaller radial displacements

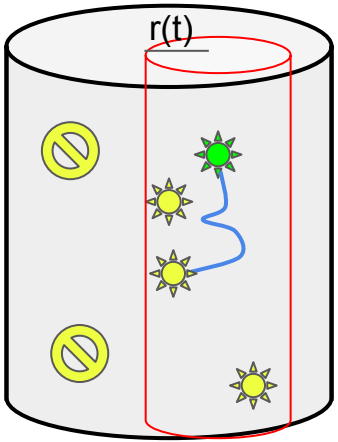


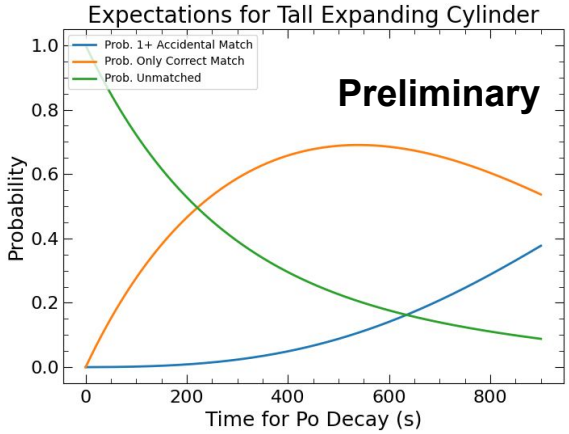


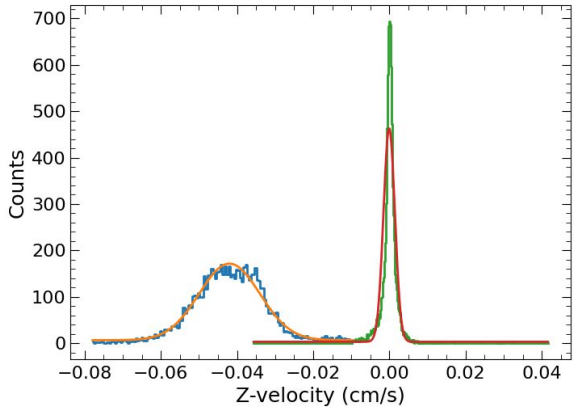



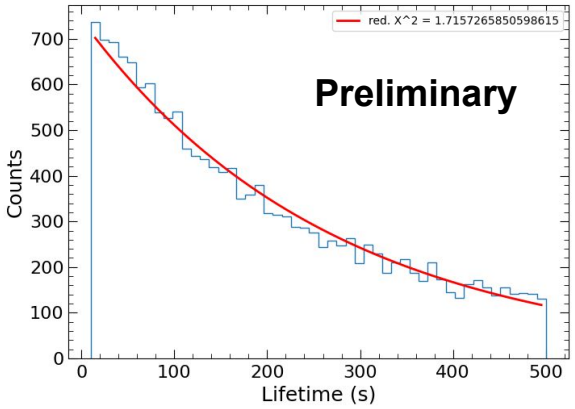



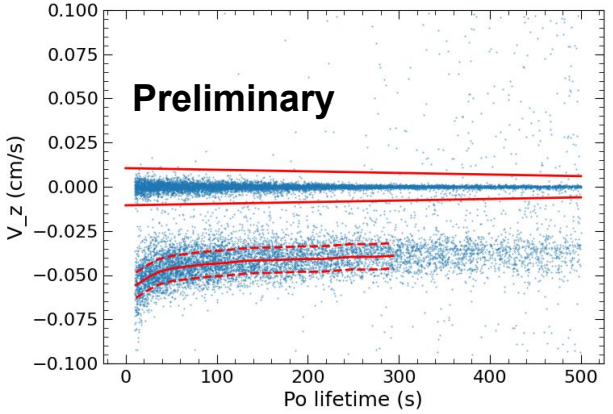
# Iteration 2: Tall Cylinders



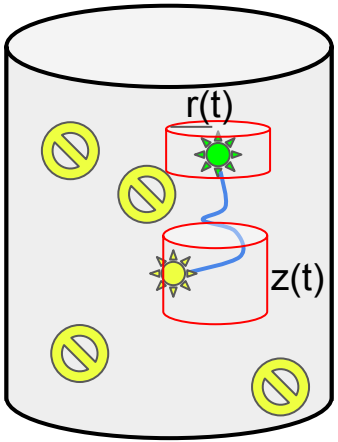



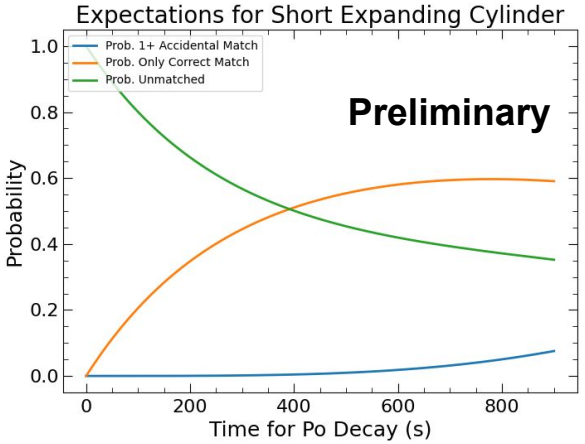



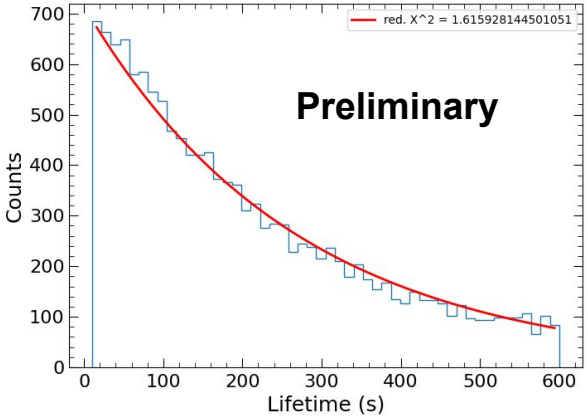



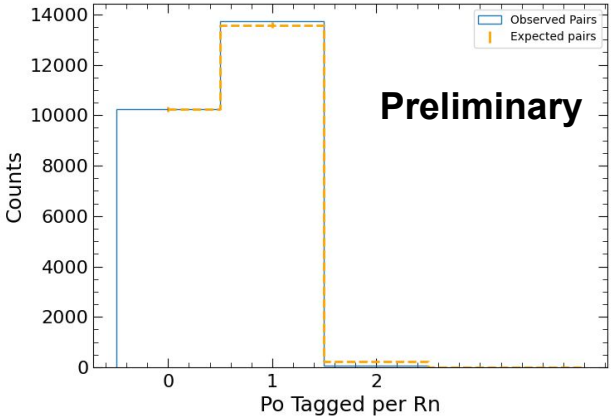
# Iteration 3: Short Cylinders

- $\varepsilon_{selection}$ : 0.93
  - Energy cut selection
- $\varepsilon_{catch}$: 0.71
  - cathode & wall plate-out
  - z-cut efficiency for charged daughters
  - ~5% fudge factor for planar displacement cut and charge fractions



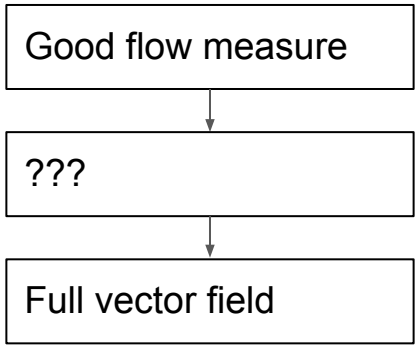



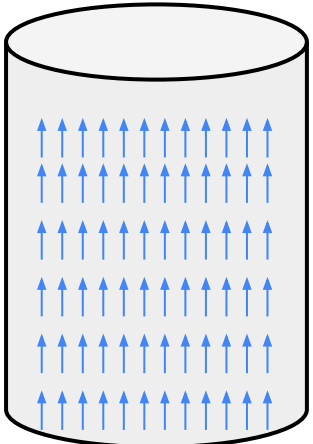



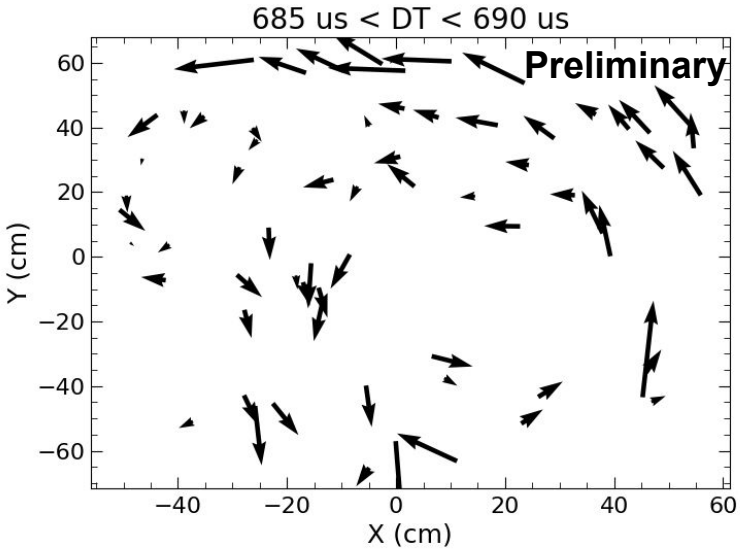



# Next Steps: Begin to Incorporate local flow

- Clear coherent circulation in slices of the detector
- Can model local flow in a variety of approaches
  - Interpolative models
    - Slow response to flow changes
  - Finite element simulations
    - Can be quickly checked against data
  - Data fit to underlying divergence free basis
  - Machine learning dimensionality reduction
  - Clustering/Classification of flow voxels

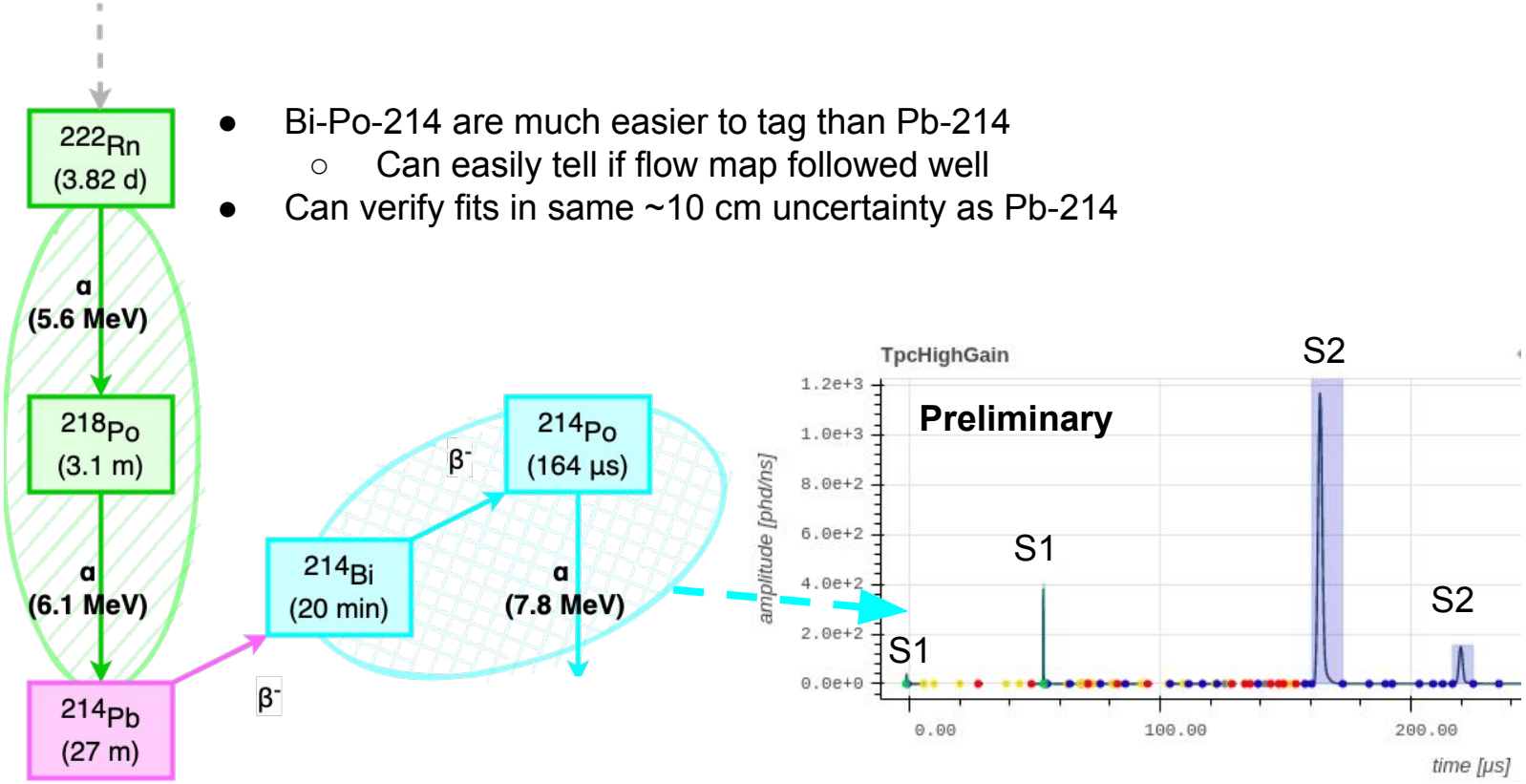




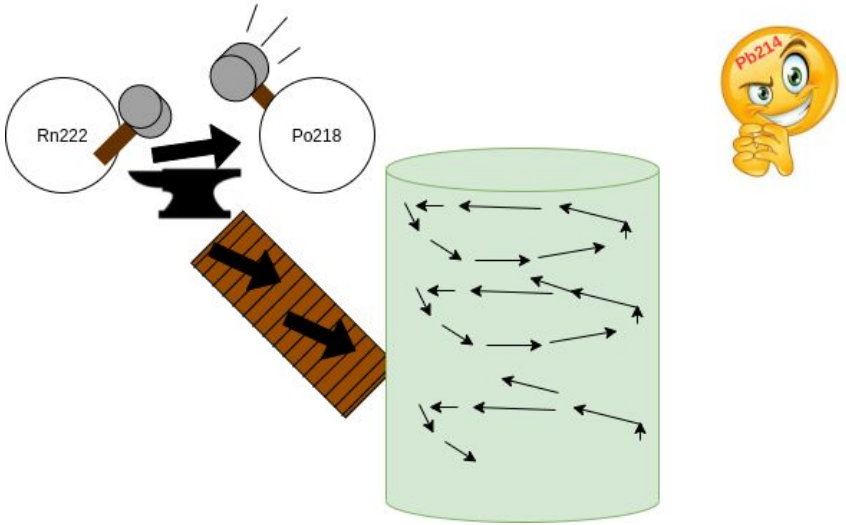
# Bi-Po as an ultimate check on flow maps

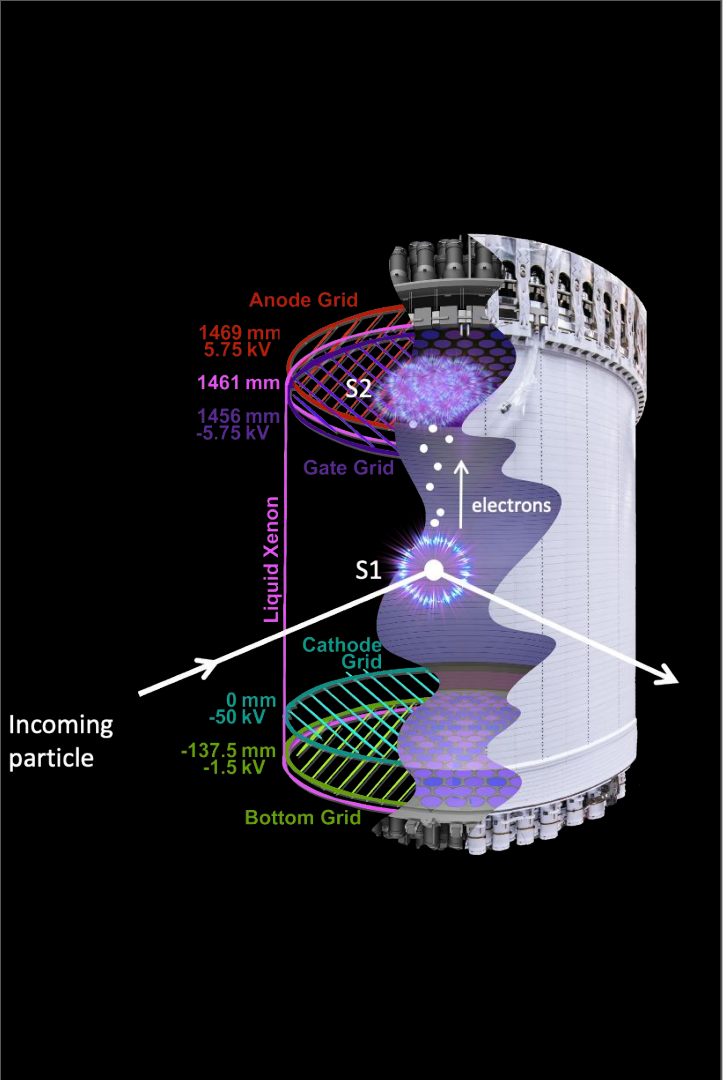
- Bi-Po-214 are much easier to tag than Pb-214
  - Can easily tell if flow map followed well
- Can verify fits in same ~10 cm uncertainty as Pb-214



# Conclusions and Next Steps

- True Rn-Po pairs can be found over 4+ half lives with minimal accidental pair contamination
- Efficiencies for Rn-Po pair finding are well constrained
- Coherent flow cells can be identified within the detector allowing for smooth flow fields to be extracted
- Flow fields can be vetted using Po218 - > BiPo214 tagging
- Successful flow fields can be used as input to spatial Pb214 veto



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# Backup Slides

# Handling Pb-214 Backgrounds: Event by Event

**Gamma tagging**

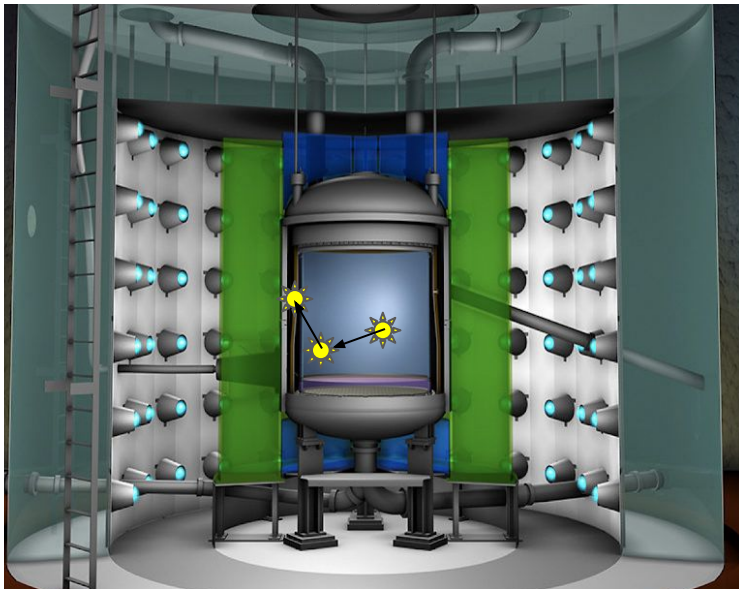
$^{214}_{82}Pb_{132}$

0+ — 0.0 — 27.06 m 7

Q⁺ 1018 keV 11

B- : 100.0 % 0--> $^{214}_{83}Bi_{131}$

| I% | Log ft | # | Jp | En [keV] |
|---|---|---|---|---|
| 0.015 | 6.26 | 10 | | 888.03 |
| 2.75 | 4.43 | 9 | 1+ | 838.994 |
| | | 8 | | 797.30 |
| 1.063 | 6.23 | 7 | (1-) | 533.672 |
| | | 6 | (2-) | 377.03 |
| 44.5 | 5.07 | 5 | 0-,1- | 351.9323 |
| 39.0 | 5.250 | 4 | 1- | 295.2236 |
| 0.075 | 8.04 | 3 | (2)- | 258.869 |
| | | 2 | (2-,3-) | 62.68 |
| | | 1 | 2- | 53.2260 |
| 12.7 | 6.26 | 0 | 1- | 0.0 |



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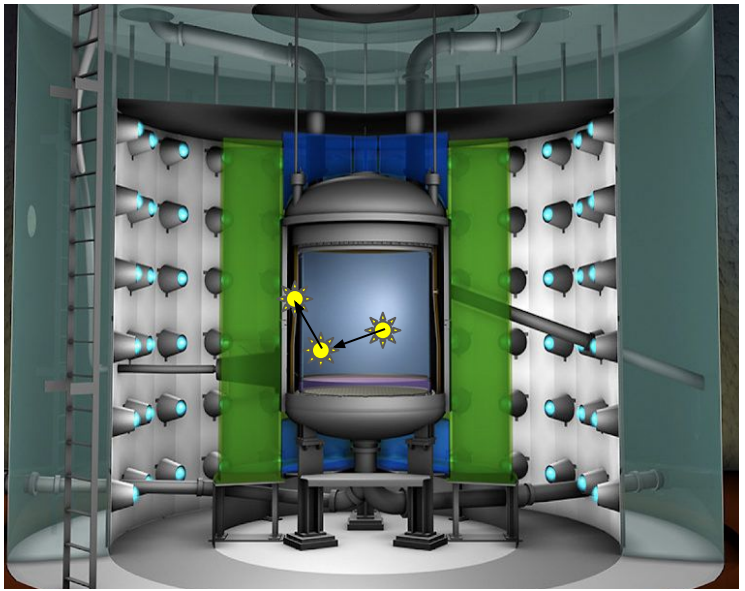
0+ 0.0 27.06 m 7

Q⁺ 1018 keV 11

B- : 100.0 % 0--> $^{214}_{83}Bi_{131}$

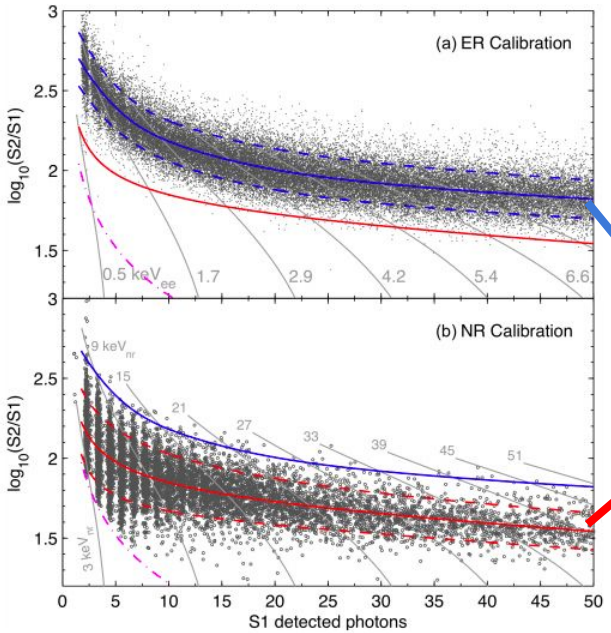
| I% | Log ft | # | Jp | En [keV] |
|---|---|---|---|---|
| 0.015 | 6.26 | 10 | | 888.03 |
| 2.75 | 4.43 | 9 | 1+ | 838.994 |
| | | 8 | | 797.30 |
| 1.063 | 6.23 | 7 | (1-) | 533.672 |
| | | 6 | (2-) | 377.03 |
| 44.5 | 5.07 | 5 | 0-,1- | 351.9323 |
| 39.0 | 5.250 | 4 | 1- | 295.2236 |
| 0.075 | 8.04 | 3 | (2)- | 258.869 |
| | | 2 | (2-,3-) | 62.68 |
| | | 1 | 2- | 53.2260 |
| 12.7 | 6.26 | 0 | 1- | 0.0 |

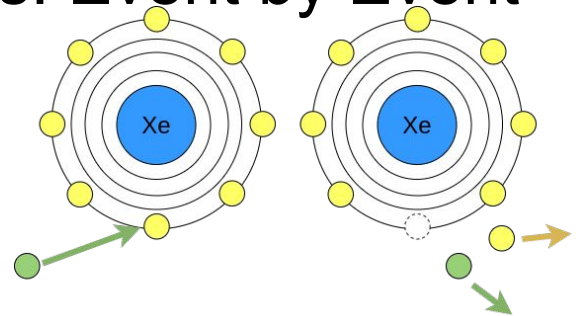
**Fails on at least 12.7% of decays**

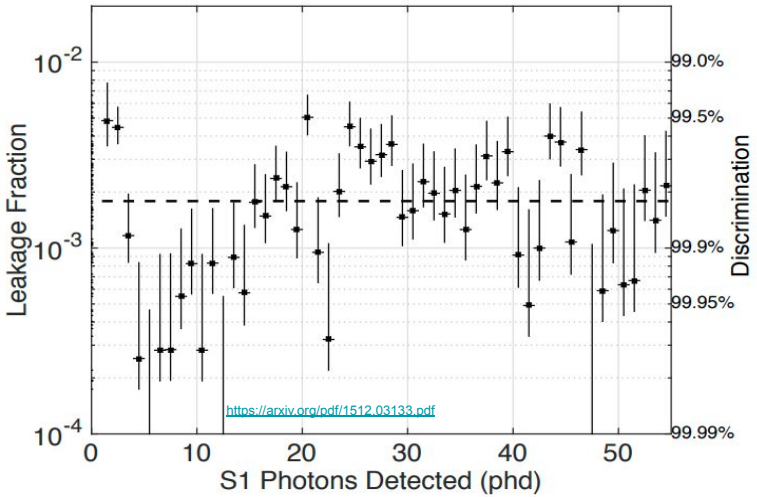


# Handling Pb-214 Backgrounds: Event by Event

**Particle Identification**

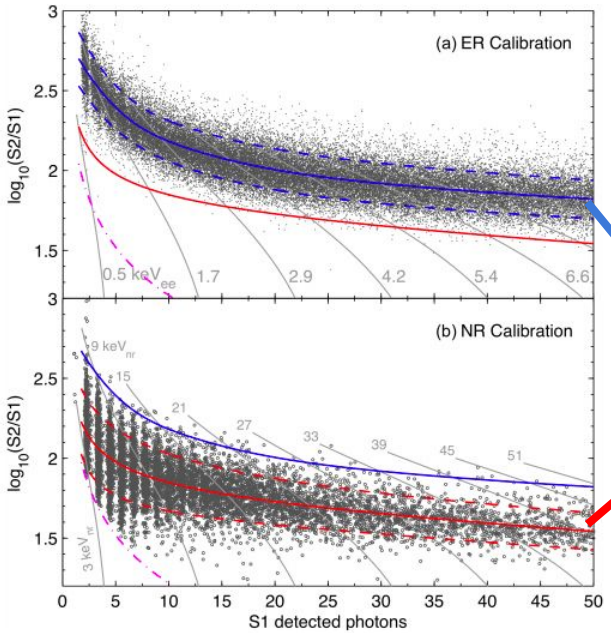


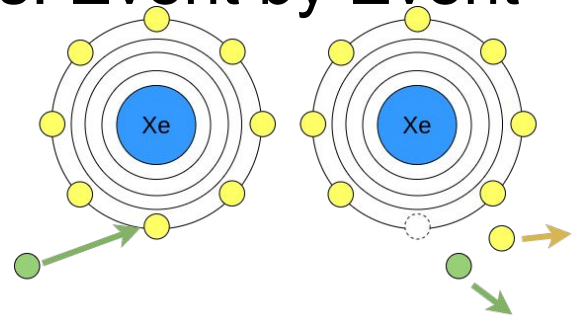



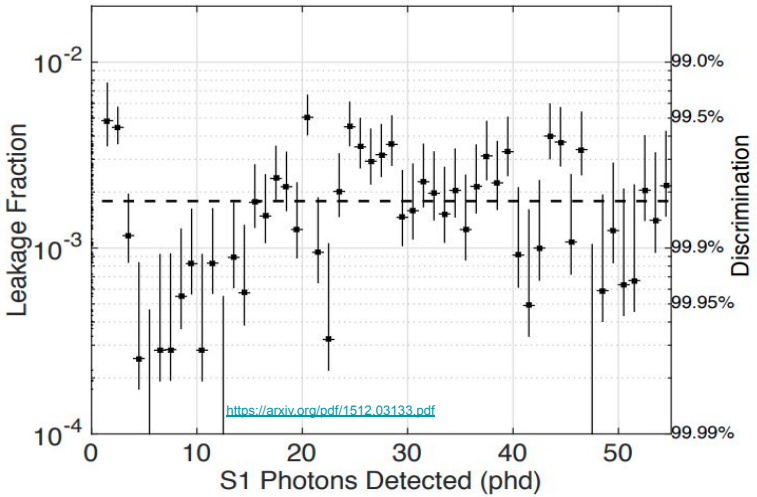



# Handling Pb-214 Backgrounds: Event by Event

**Particle Identification**

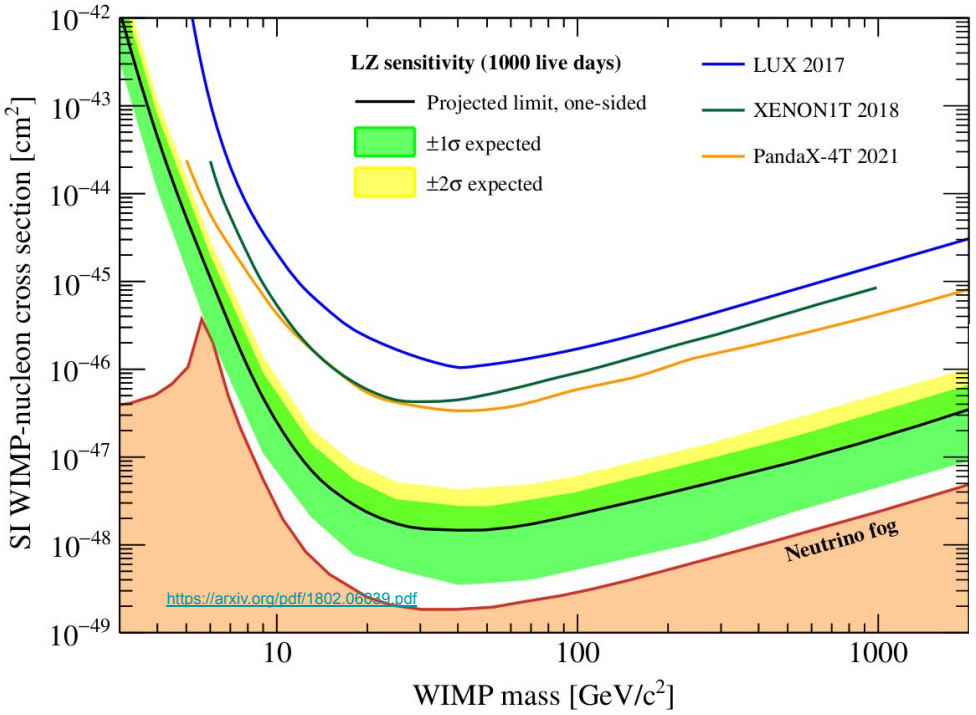


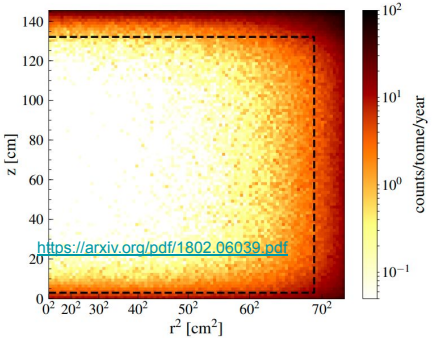

**Great but only helps for NR searches**

# LXe-TPC Major Advantages

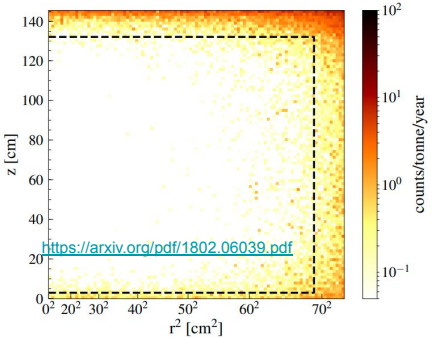



- External backgrounds well handled through fiducialization and veto systems
- Target mass scalability
- High Z target

Without Veto

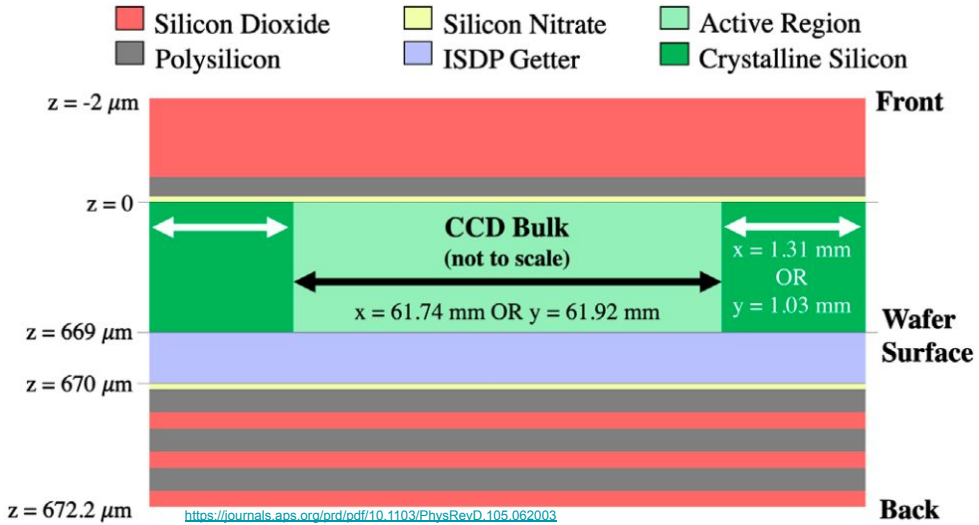



With Veto



# Solid State Analogue: Spatial Coincidence Tagging

- CCD searches have excellent position resolution (~15 um)
- Child isotopes are fixed in solid state detectors
- Limits set on Si-32 contamination and checks on Pb-210 rates




β-β from Si-32, P-32 search
△t = 13.7 days