Recent Achievements at the ~MeV-scale in the MicroBooNE Experiment

Will Foreman (IIT)
on behalf of the MicroBooNE Collaboration

Fermilab Wine and Cheese

December 15, 2023

A brief visual tour of energy scales…

A brief visual tour of energy scales...

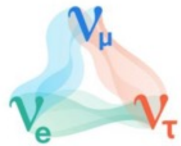
blip

E ~ O(0.1-1 MeV)

Topological features at the ~MeV scale!

Neutrino Physics Refresher

Flavor eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

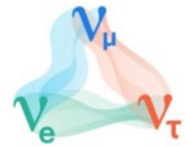
Mixing matrix

$$U_{\mathrm{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
θ = mixing angle

Neutrino Physics Refresher

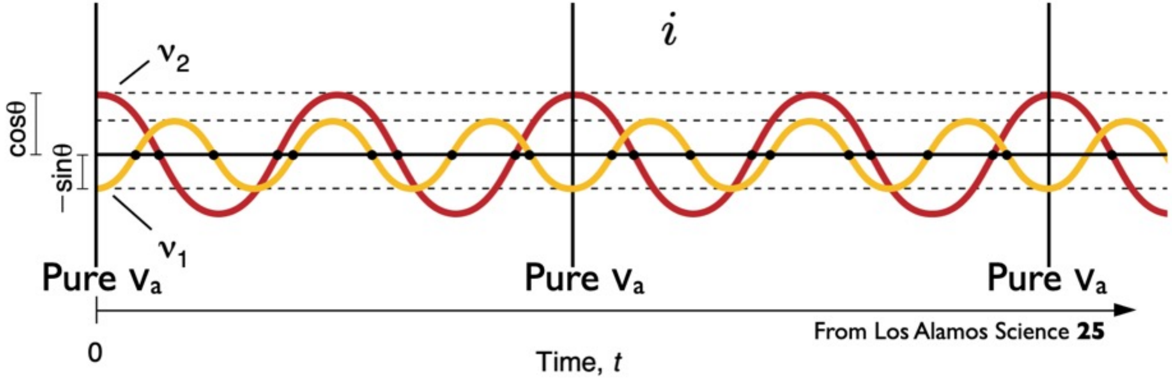
Flavor eigenstates | Mass eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing matrix

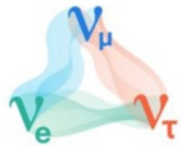
$$\Psi_{\nu_a}(x,t) = f(x,t) \sum_i U_{ai} e^{-i(m_i t/2E)}$$



$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2\left[1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)}\right]$$

Neutrino Physics Refresher

Flavor eigenstates



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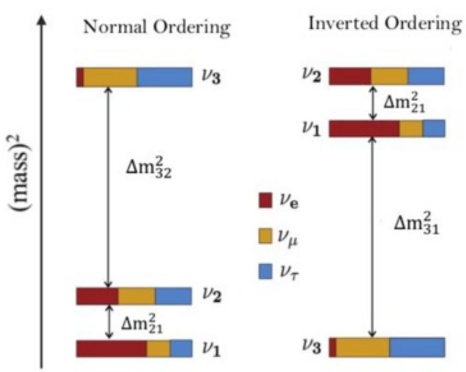
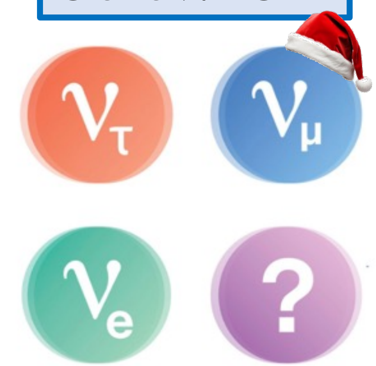
Mass state ordering?



Charge-parity violation?

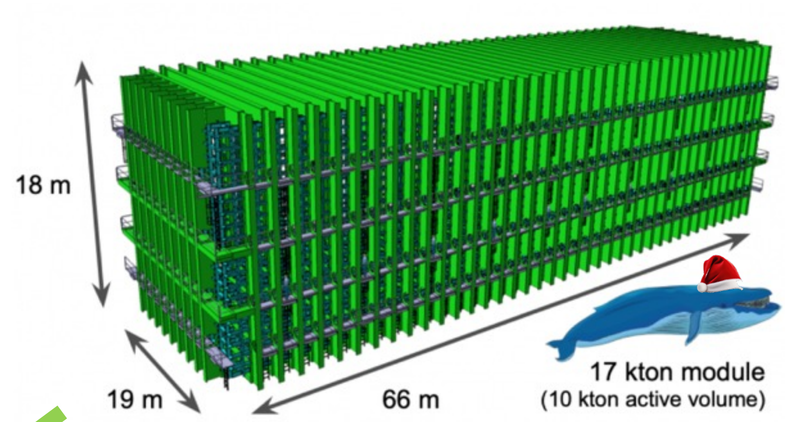
δ_{CP} ?

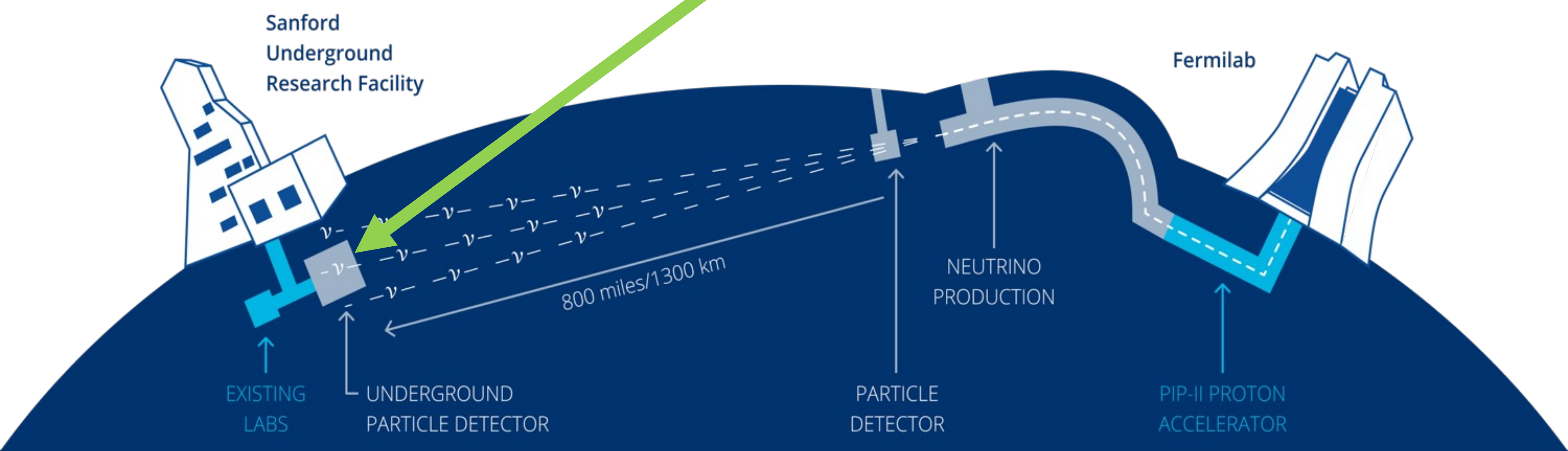
Sterile ν / BSM?



Deep Underground Neutrino Experiment (DUNE)

- neutrino oscillations
- BSM searches
- astrophysical neutrinos



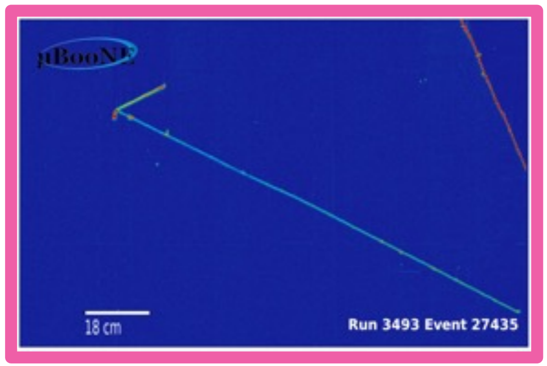


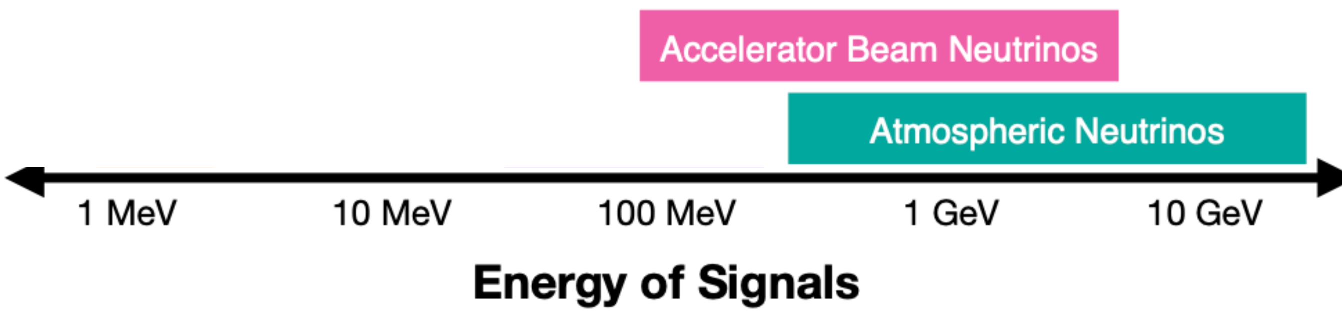
Deep Underground Neutrino Experiment (DUNE)

- neutrino oscillations
- BSM searches
- astrophysical neutrinos

Measure δ_{CP} , improve precision on θ_{13}, and determine sign on Δm^2_{13} (mass ordering)

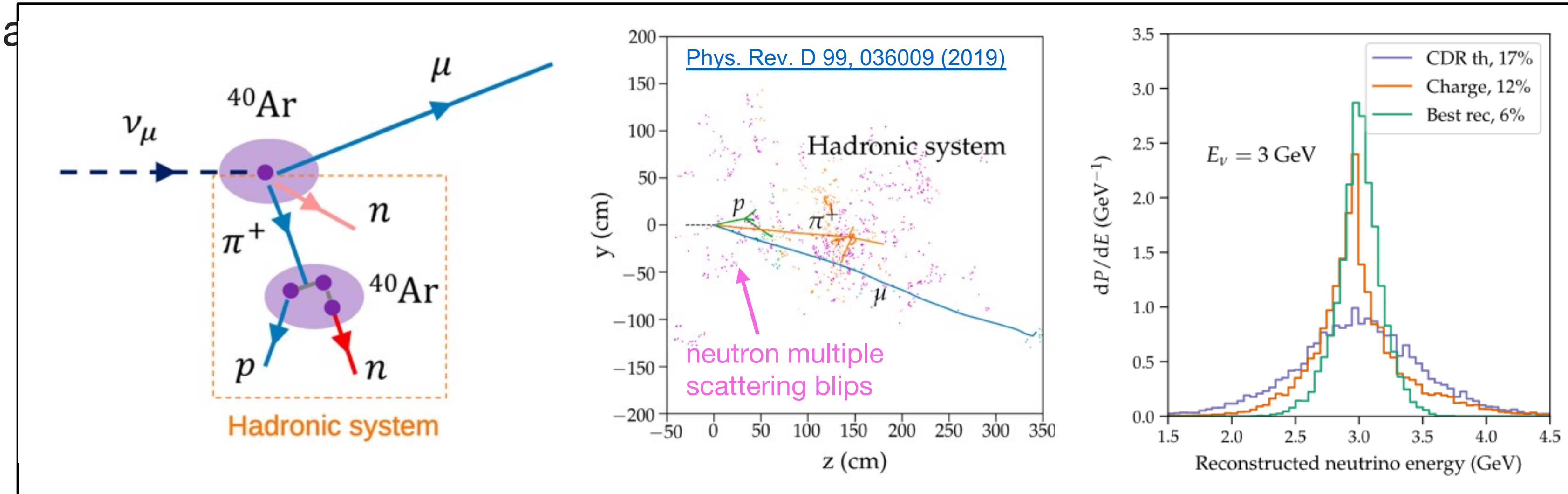
Primary energy range:
~100s of MeV to ~10 GeV

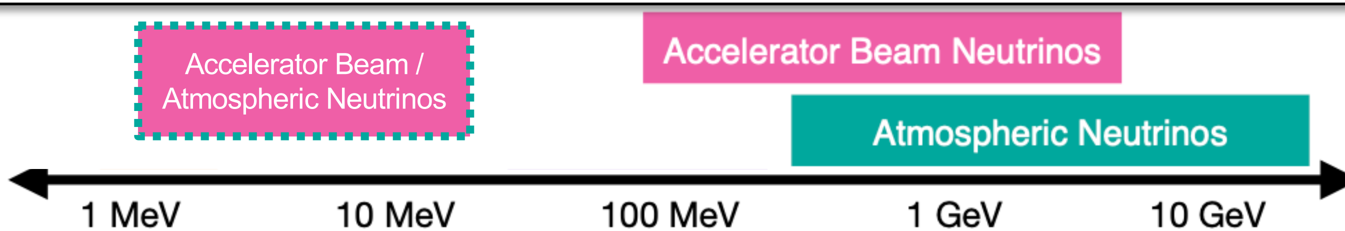




Deep Underground Neutrino Experiment (DUNE)

- neutrino oscillations → **Measure δ_{CP} , improve precision on θ_{13}, and determine sign on Δm^2_{13} (mass ordering)**
- BSM searches
- a





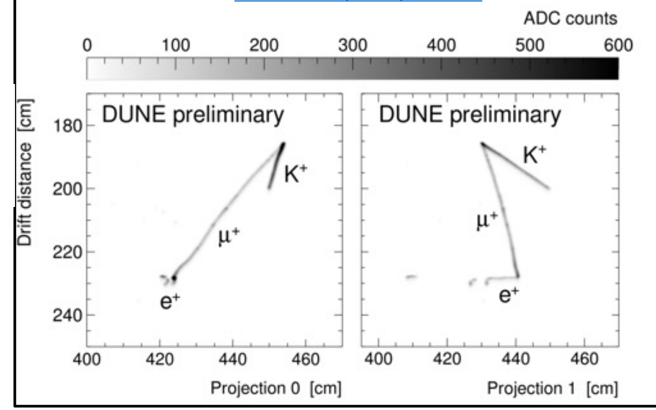
Deep Underground Neutrino Experiment (DUNE)

- neutrino oscillations
- BSM searches
- astrophysical neutrinos

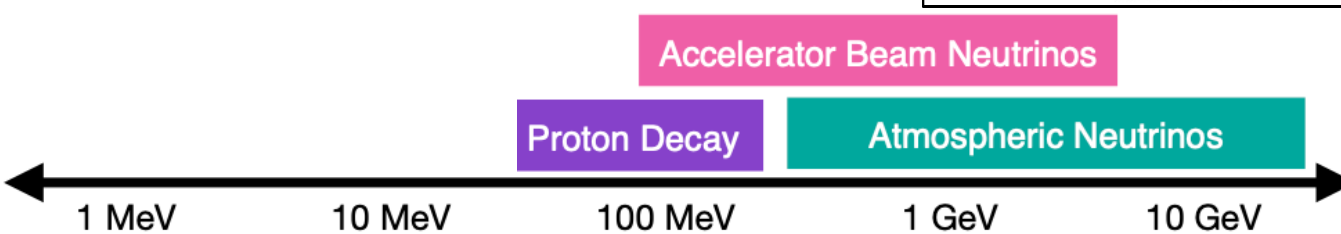
Proton decay, neutron-antineutron oscillations, heavy sterile ν, dark ν...

Proton decay (p→νK⁺)

[Journal of Physics: Conference Series 718 (2016) 062032]



Primary energy range:
~10s of MeV to ~100 MeV



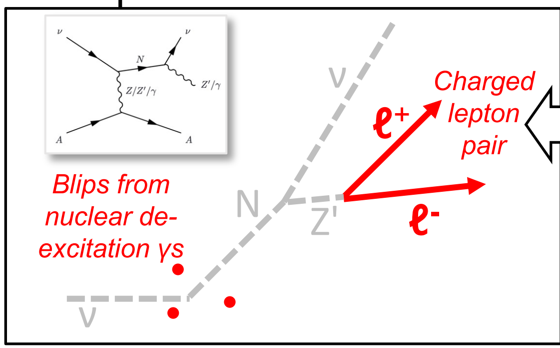
Energy of Signals

Deep Underground Neutrino Experiment (DUNE)

- neutrino oscillations
- BSM searches
- astrophysical neutrinos

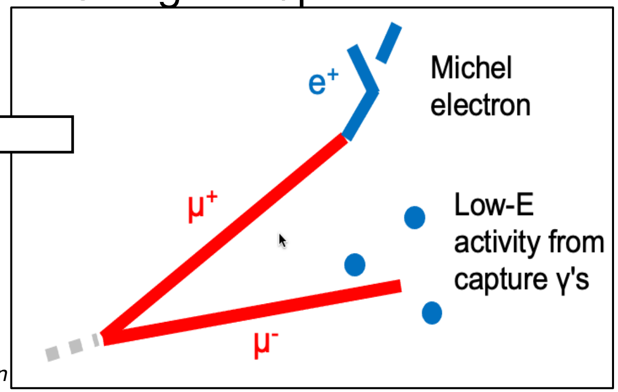
Proton decay, neutron-antineutron oscillations, heavy sterile ν, dark ν...

Up-scattered dark ν

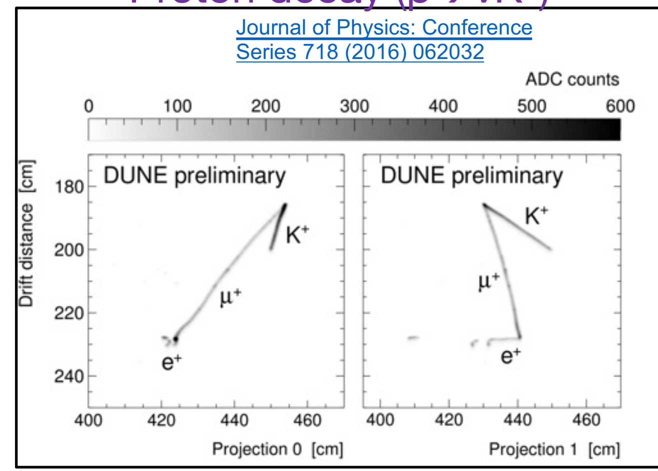


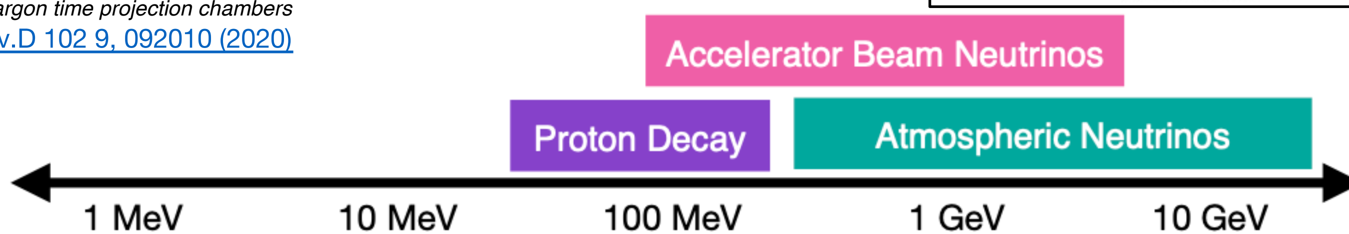
Benefits of MeV-scale reconstruction capabilities in large liquid argon time projection chambers
Phys.Rev.D 102 9, 092010 (2020)

Charge & π/μ discrimination



Proton decay (p→νK+)





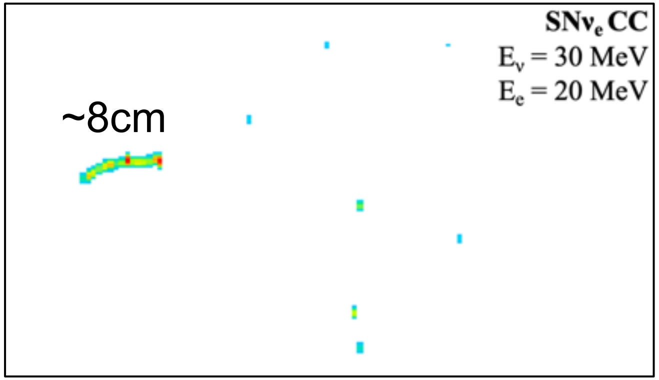
Energy of Signals

Deep Underground Neutrino Experiment (DUNE)

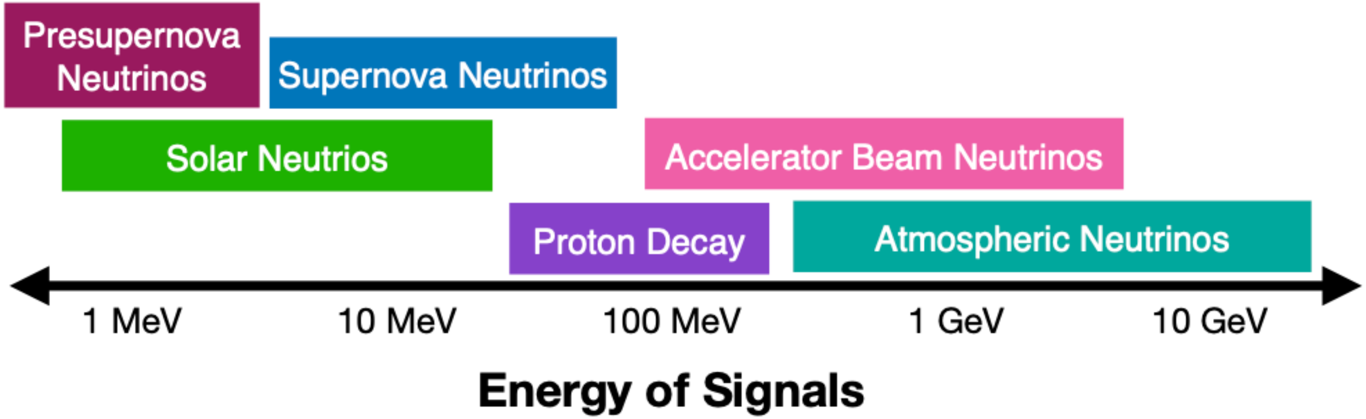
- neutrino oscillations
- BSM searches
- astrophysical neutrinos

Detect ν from sun and supernova bursts

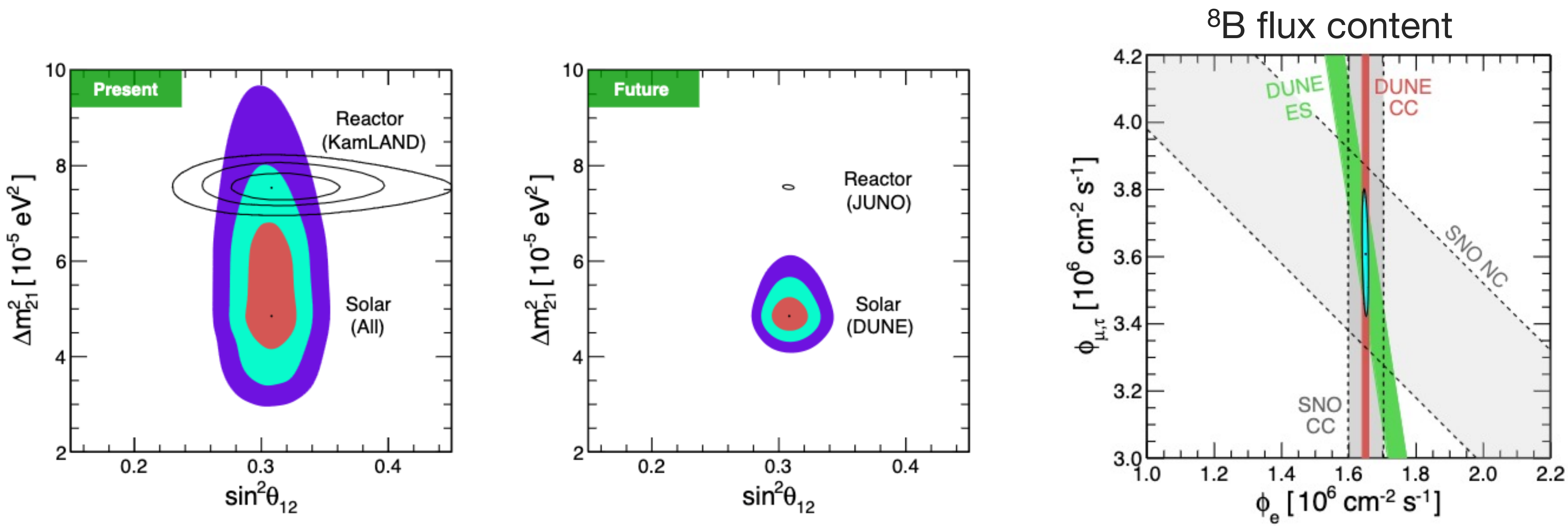
Primary energy range:
~1 MeV to ~10s of MeV



Simulated 20 MeV electron



Solar neutrinos in DUNE

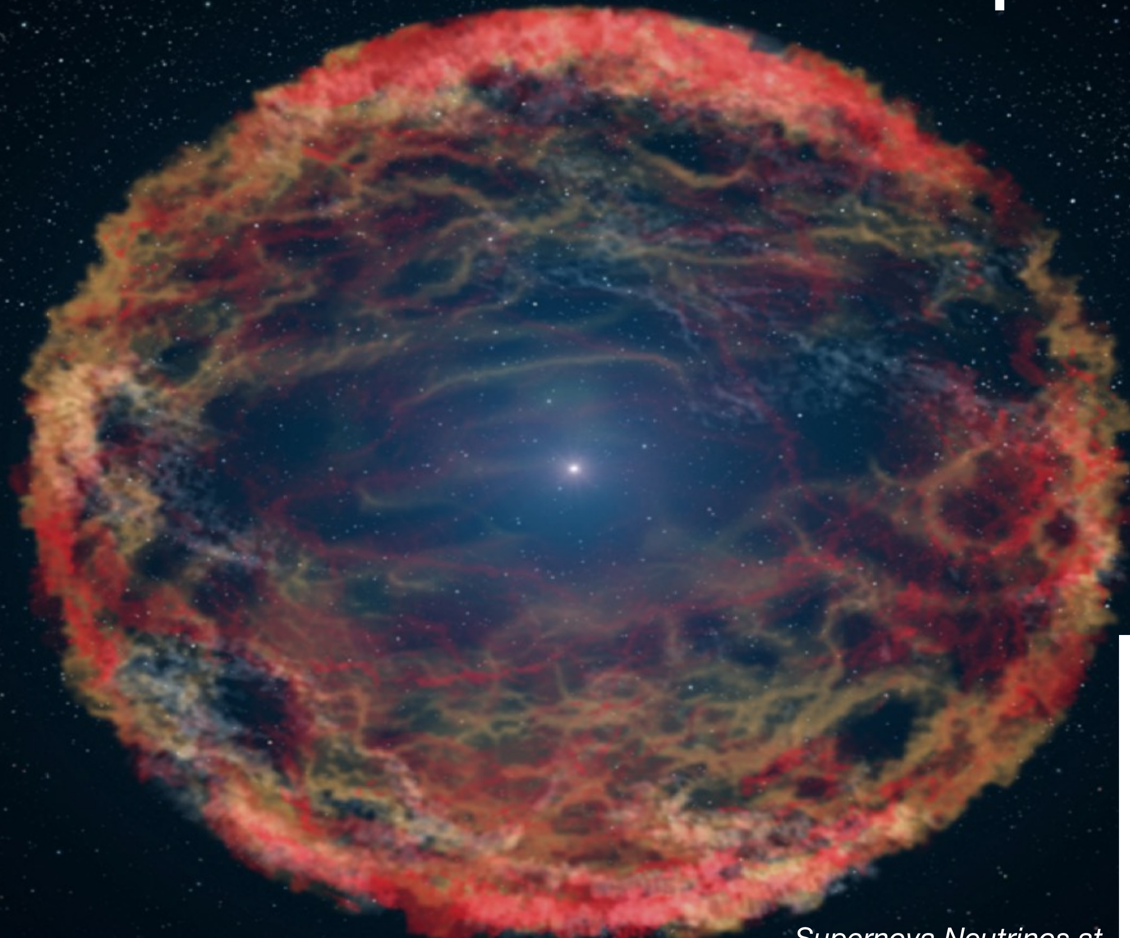


DUNE as the Next-Generation Solar Neutrino Experiment

Phys. Rev. Lett. 123, 131803

DUNE could see > 10^5 signal events (E>5 MeV) over its lifetime, enabling world-leading measurements of θ_{12}, $\Delta m_{12}{}^2$, and solar neutrino fluxes

Supernova neutrinos in DUNE

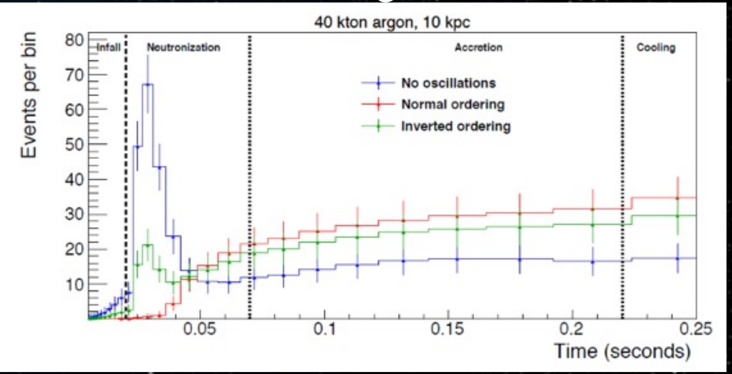


A galactic supernova should happen every ~10-50 years.

Neutrino signal = unique probe into astrophysics at core of explosion

This would be a ground-breaking achievement for the DUNE detector!

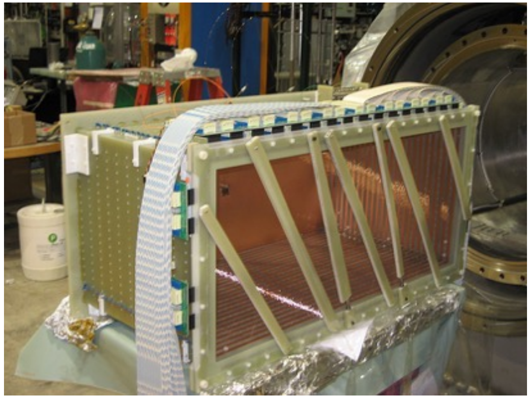
Mass ordering determination

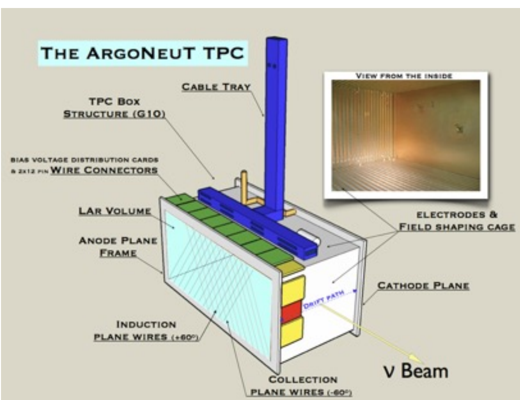


Supernova Neutrinos at the DUNE Experiment
[2020 J. Phys: Conf Ser 1342]

Past MeV-Scale Demonstrations in LArTPCs

ArgoNeuT



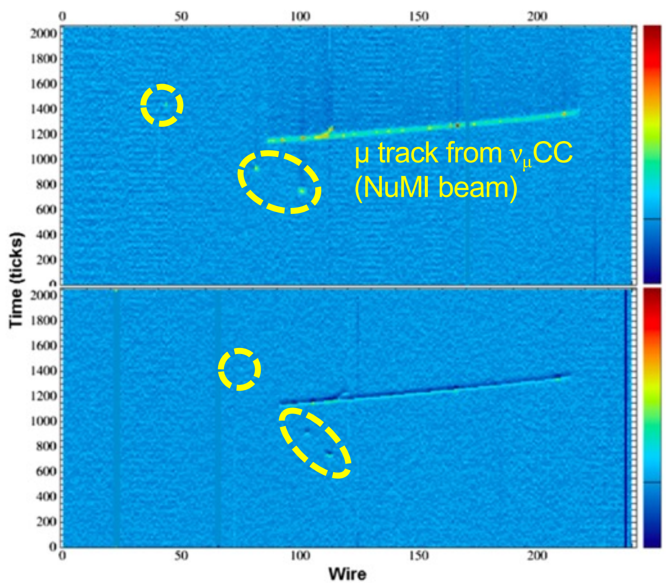


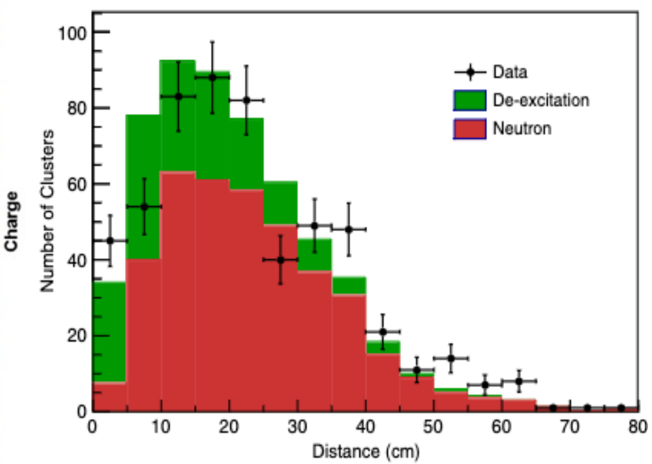
Demonstration of MeV-scale physics in liquid argon time projection chambers using ArgoNeuT

R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] E. Church,[6] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] A. Ferrari,[8] R. S. Fitzpatrick,[9] B. Fleming,[2] A. Hackenburg,[2] G. Horton-Smith,[4] C. James,[1] K. Lang,[10] M. Lantz,[11] I. Lepetic,[12,*] B. R. Littlejohn,[12,†] X. Luo,[2] R. Mehdiyev,[10] B. Page,[5] O. Palamara,[1] B. Rebel,[1] P. R. Sala,[13] G. Scanavini,[2] A. Schukraft,[1] G. Smirnov,[8] M. Soderberg,[14] J. Spitz,[9] A. M. Szelc,[15] M. Weber,[7] W. Wu,[1] T. Yang,[1] and G. P. Zeller[1]

(ArgoNeuT Collaboration)

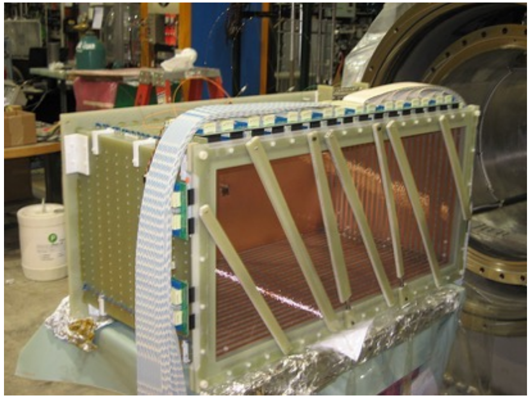
[Phys. Rev. D 99, 012002 (2019)](#)

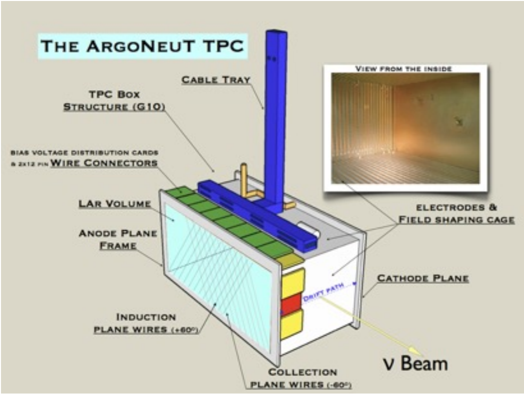




Past MeV-Scale Demonstrations in LArTPCs

ArgoNeuT



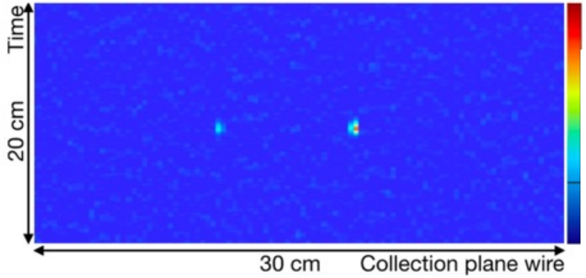


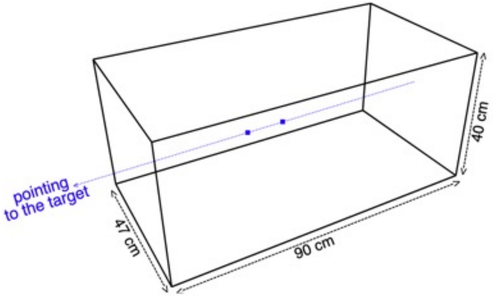
Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab

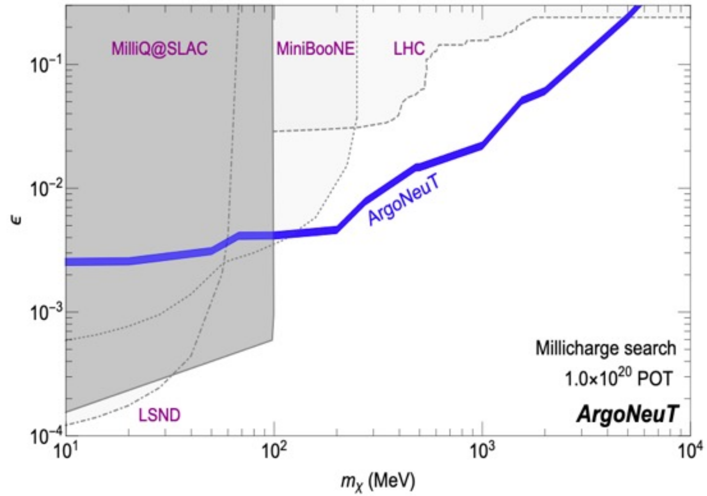
R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] D. Edmunds,[5] R. S. Fitzpatrick,[6] B. Fleming,[7] R. Harnik,[1] C. James,[1] I. Lepetic,[8,*] B. R. Littlejohn,[8] Z. Liu,[9] X. Luo,[10] O. Palamara,[1,†] G. Scanavini,[7] M. Soderberg,[11] J. Spitz,[6] A. M. Szelc,[12] W. Wu,[1] and T. Yang[1]

(ArgoNeuT Collaboration)

Phys Rev Lett. 124, 131801 (2020)







Remaining Challenges

- Successful demonstrations in smaller LArTPCs... but can we do the same in large ones?
  - Lowering thresholds
  - Precise energy reconstruction
  - Controlling low-energy backgrounds

→ ***Critical for maximizing DUNE's physics potential***

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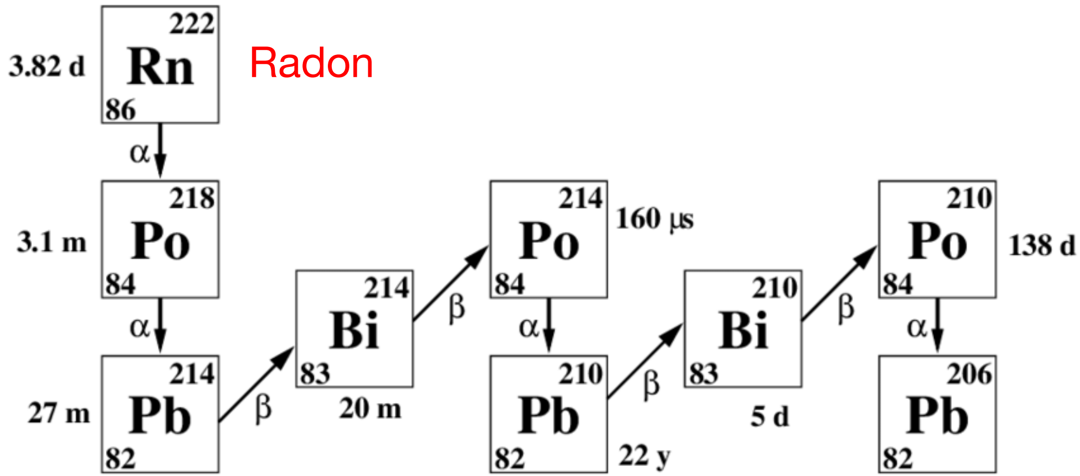
Critical for maximizing DUNE's physics potential



Remaining Challenges

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  but can we do the same in large ones?
  - Lowering thresholds
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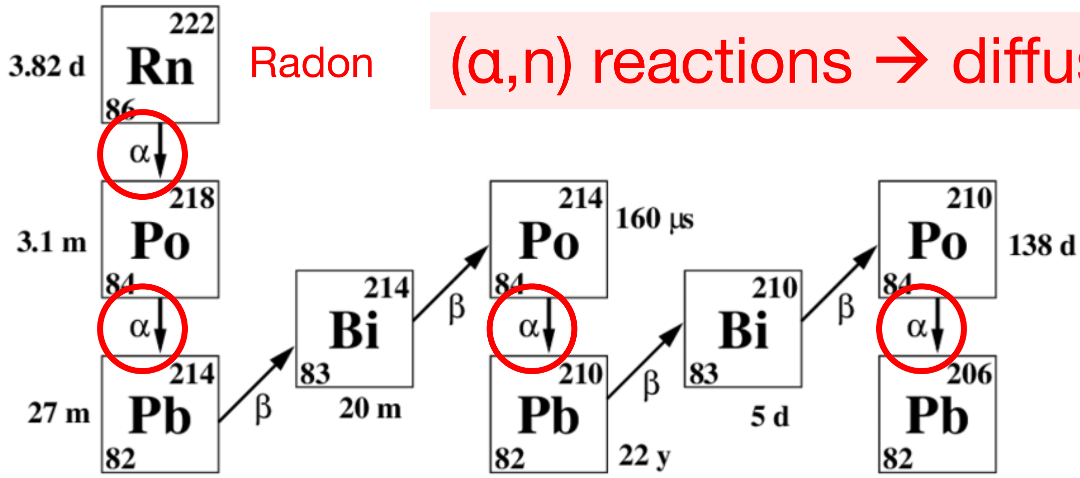
  - Controlling low-energy backgrounds

Critical for maximizing DUNE's physics potential

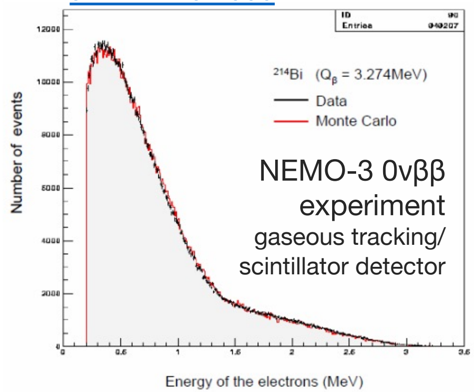
(α,n) reactions → diffuse neutrons

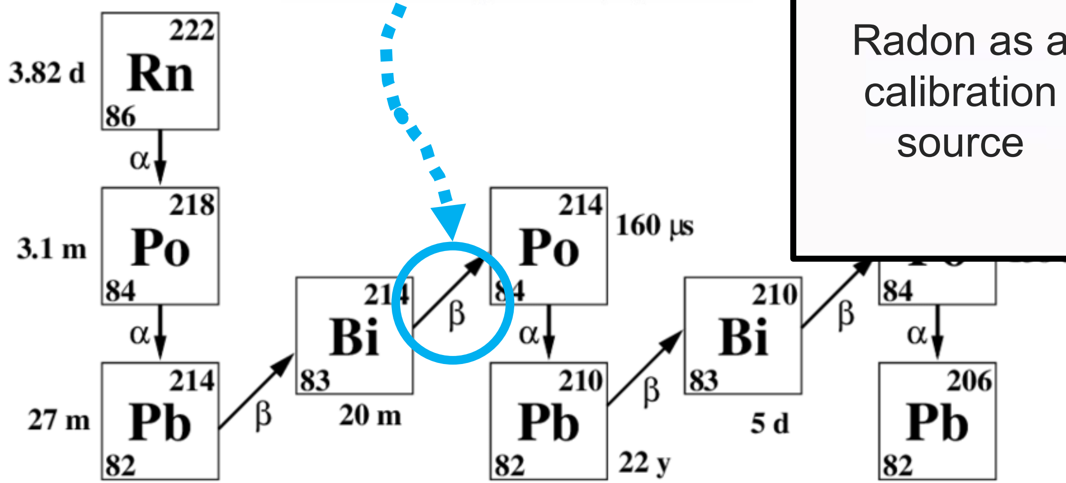


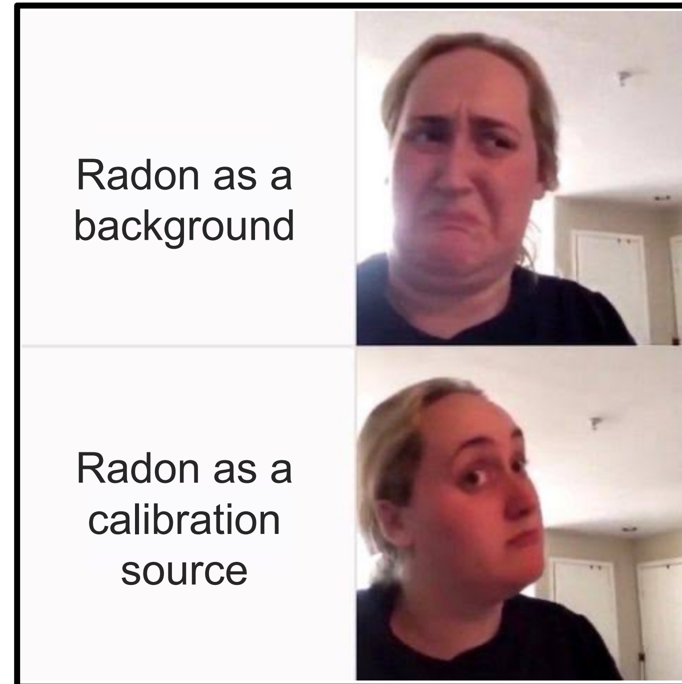
Remaining ~~Challenges~~ *Opportunities?*

Short ^{214}Po half-life makes it taggable (delayed coincidence w/ ^{214}Bi β decay)

arXiv:1210.7666







Radon in dark matter experiments

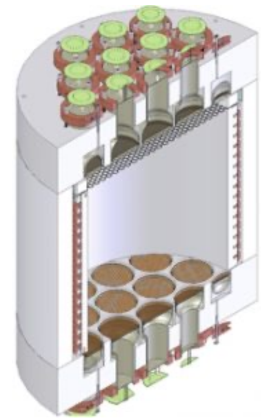
- Existing methods of radio-purification in LAr:
  - rigorous material screening
  - outgassing campaigns
  - specialized systems for filtering Rn from gaseous argon

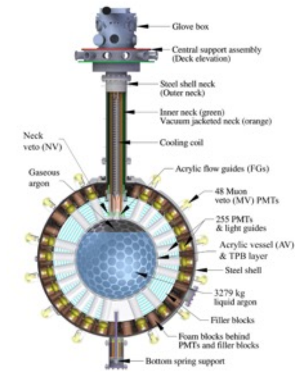
- DUNE aims to achieve < 1 mBq/kg to accomplish the goals laid out in previous slides

- *How will we accomplish this?*
  - Filtration in the gaseous phase will be more challenging at large scale

^{222}Rn Levels

[1]DarkSide-50: ~2.1 μBq/kg
[2]DEAP-3600: < 0.2 μBq/kg





[1] Phys Rev D 98, 102006 (2018)
[2] Phys Rev D 100, 022004 (2019)

Bq = decays per second

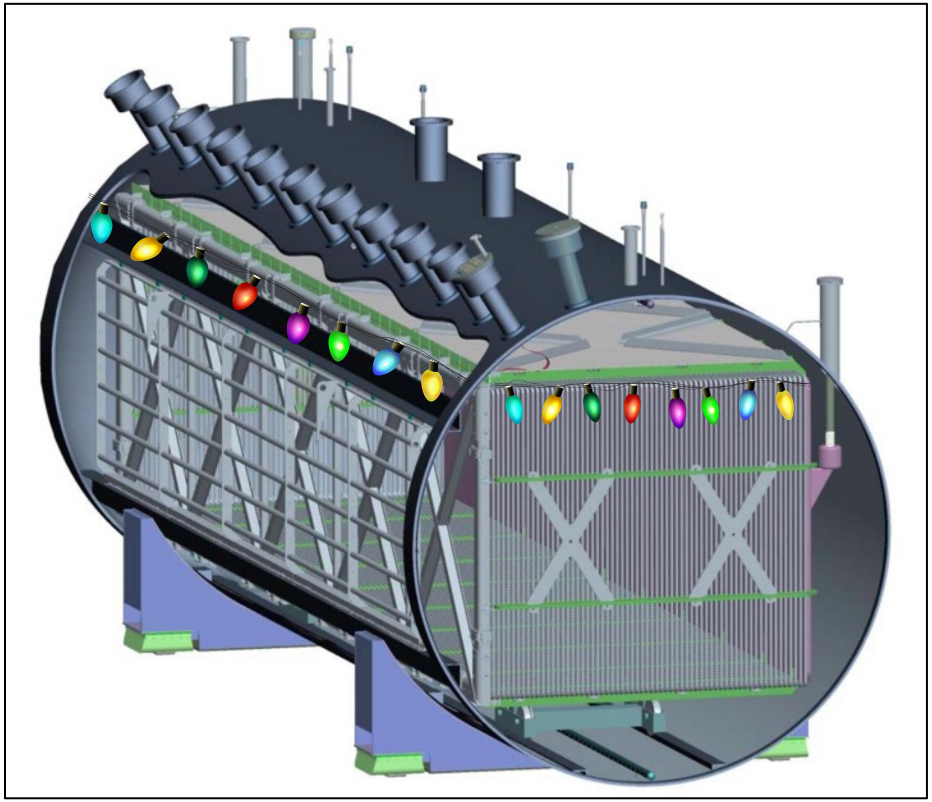
What does MicroBooNE have to say on this?

I will now present some recent results from MicroBooNE's MeV-scale program that addresses challenges related to:

- Reconstruction at the MeV-scale in large LArTPCs
- Radon mitigation
- MeV and *sub*-MeV calorimetry

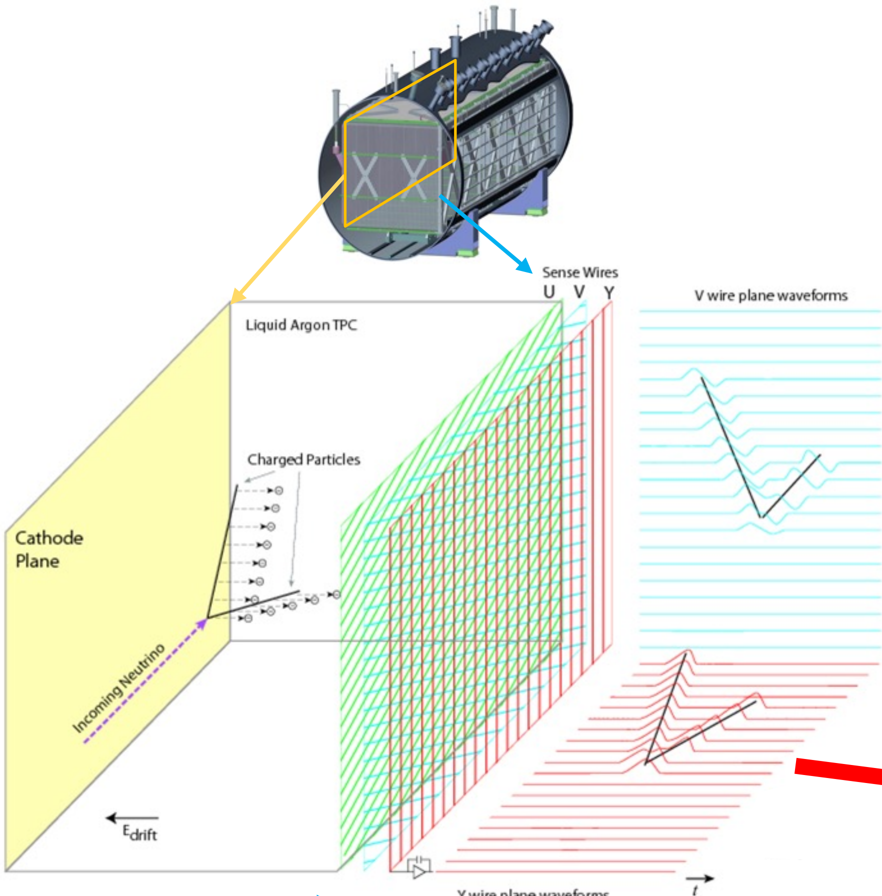
The MicroBooNE Detector

2017 JINST 12 P02017



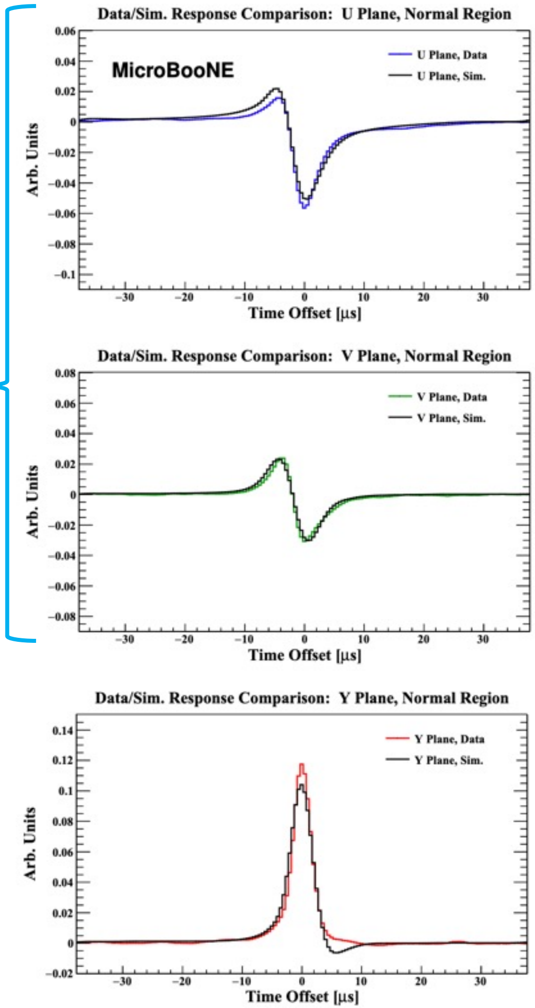
~10m × 2.5m × 2.3m

Signal readout and processing



Drift ~ 2.3 ms

JINST 13 P07007 (2018)



Signal readout and processing

Raw wire signals

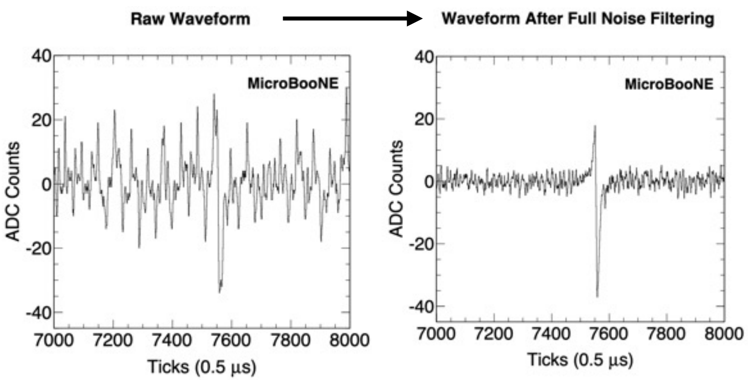
↓

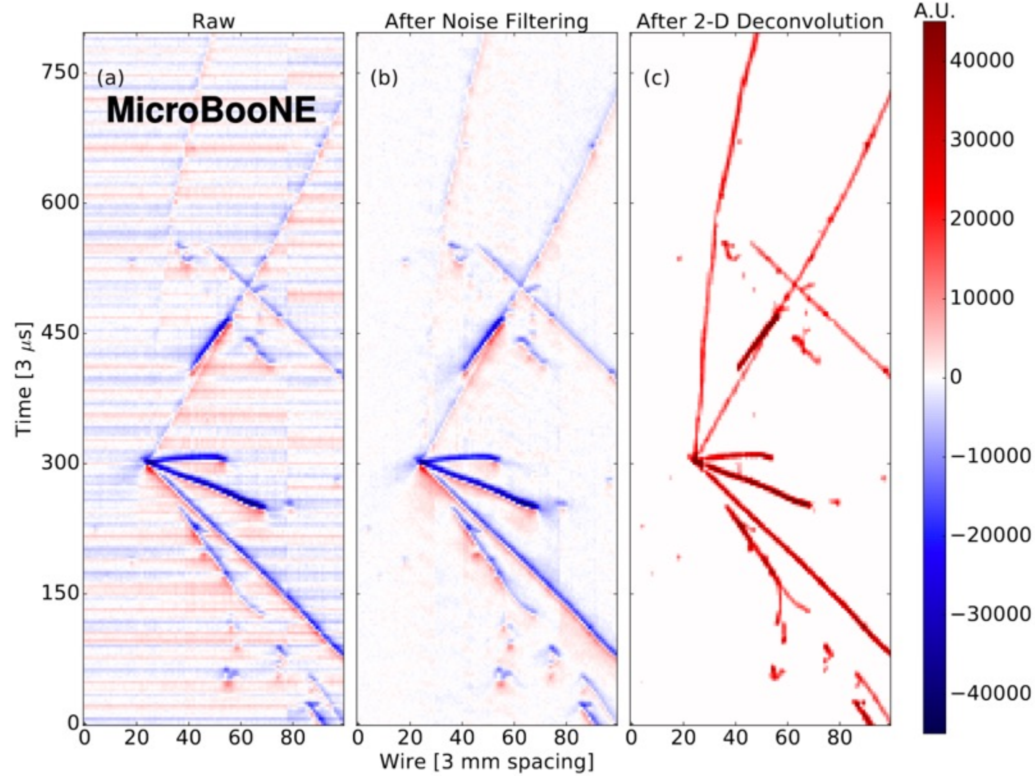
WireCell toolkit

- Noise filter
- De-convolution
- ROI-finding

Filtered signal ROIs

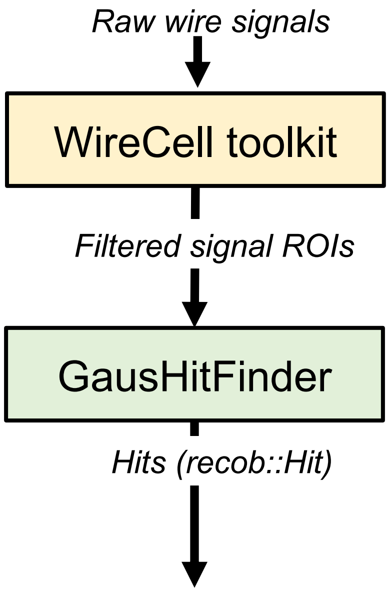
↓





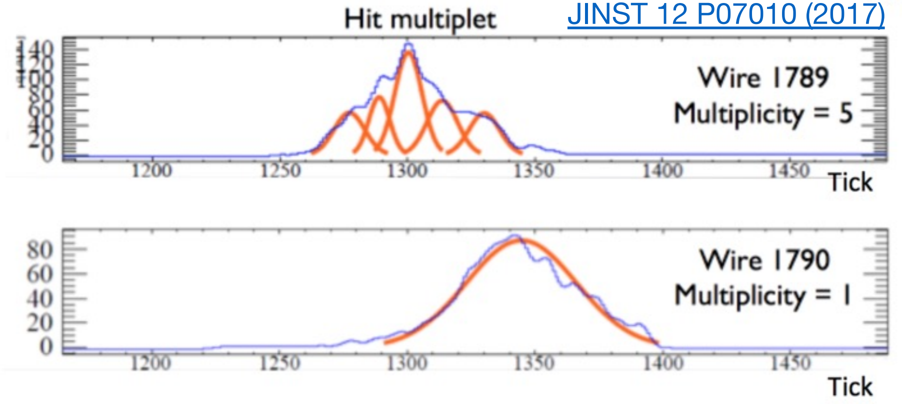
JINST 13 P07007 (2018)

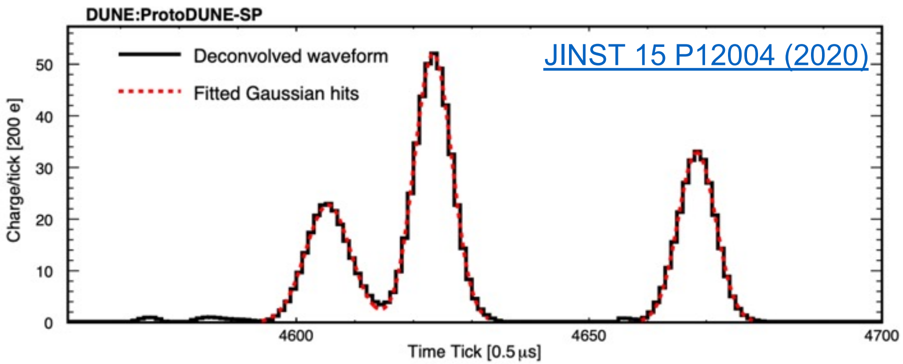
Signal readout and processing



- Search each ROI for ADC above threshold
- Fit pulses to Gaussians

JINST 12 P07010 (2017)





JINST 15 P12004 (2020)

Signal readout and processing

Raw wire signals

↓

WireCell toolkit

Filtered signal ROIs

↓

GausHitFinder

Hits (recob::Hit)

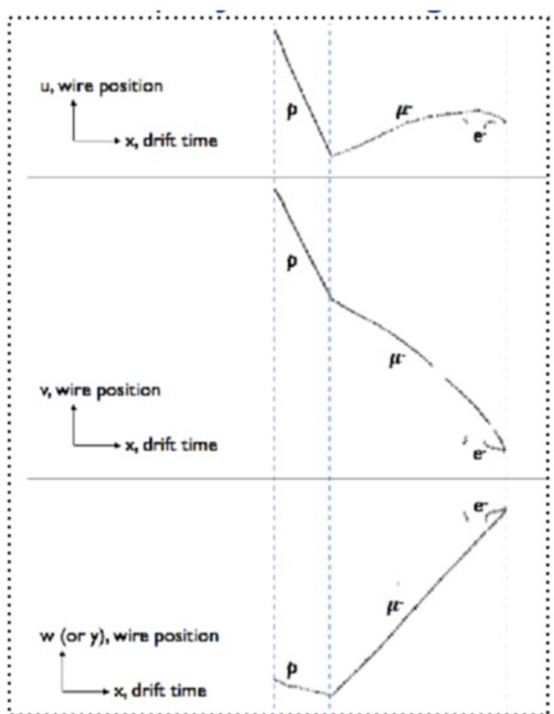
↓

Pandora 3D track reconstruction

Tracks (recob::Tracks)

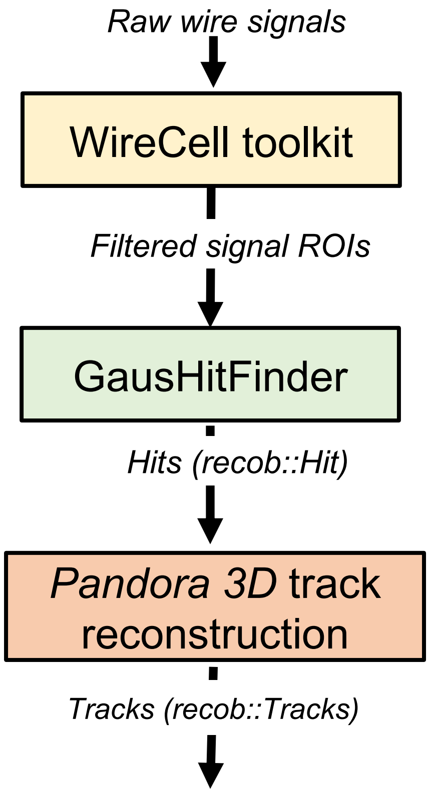
↓

Clusters of hits from different wireplanes are matched in time to form 3D images

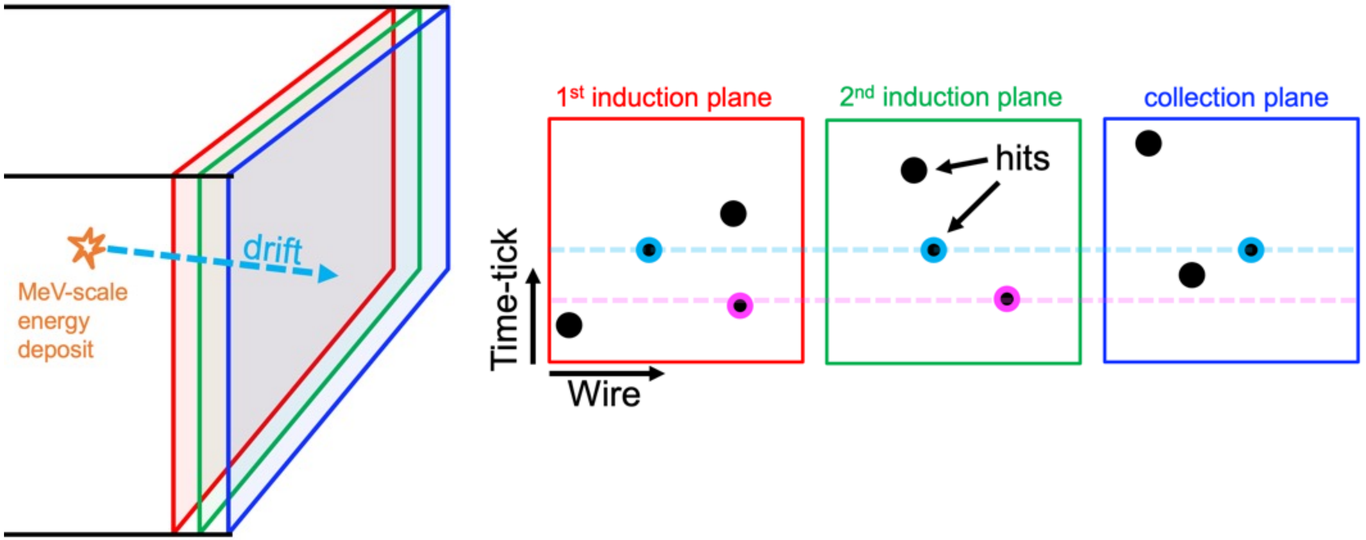


Long/extended patterns = less ambiguous matching

Signal readout and processing



For individual hits or small clusters of hits from MeV-scale depositions, avoiding false matches becomes a challenge!



Signal readout and processing

Raw wire signals

↓

WireCell toolkit

Filtered signal ROIs

↓

GausHitFinder

Hits (recob::Hit)

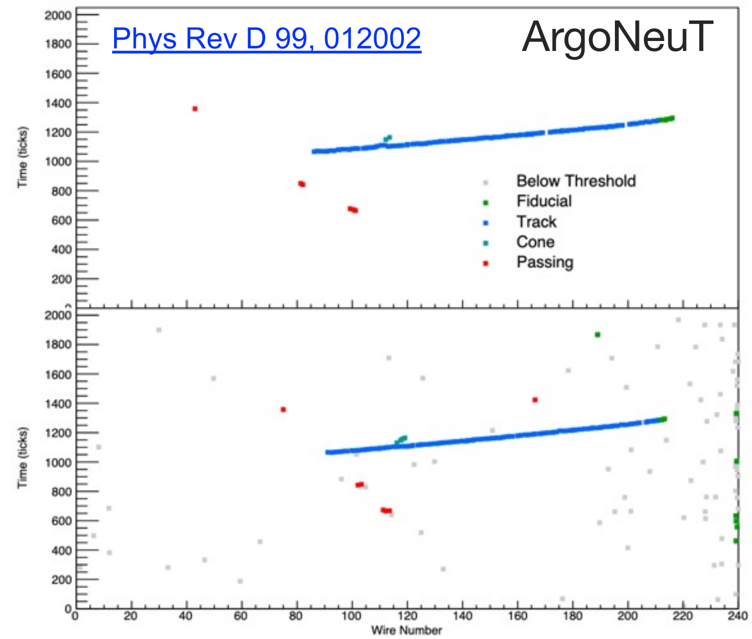
↓

Pandora 3D **track reconstruction**

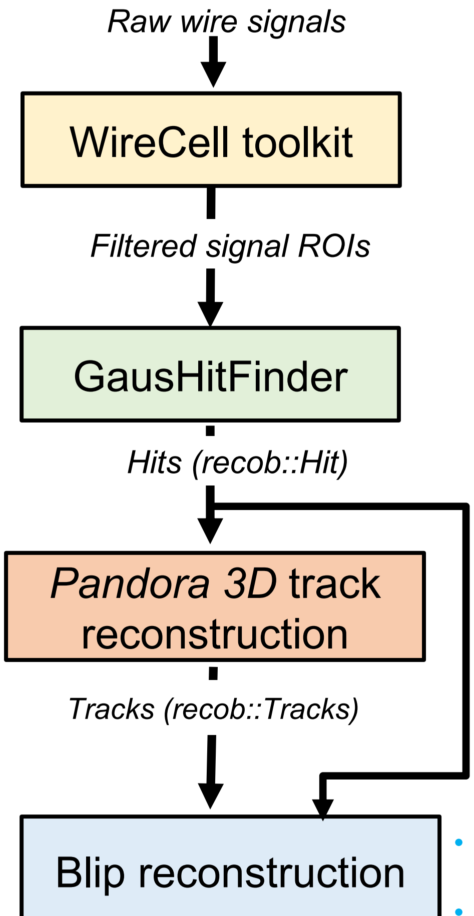
Tracks (recob::Tracks)

↓

For individual hits or small clusters of hits from MeV-scale depositions, avoiding false matches becomes a challenge!



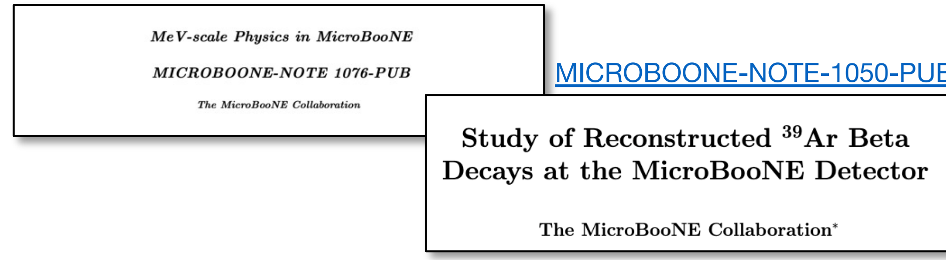
Signal readout and processing



- Take non-tracked hits, perform plane matching
- Reconstructs 3D blips

MICROBOONE-NOTE-1076-PUB (2020)

MICROBOONE-NOTE-1050-PUB (2018)



MeV-scale Physics in MicroBooNE

MICROBOONE-NOTE 1076-PUB

The MicroBooNE Collaboration

Study of Reconstructed ^{39}Ar Beta Decays at the MicroBooNE Detector

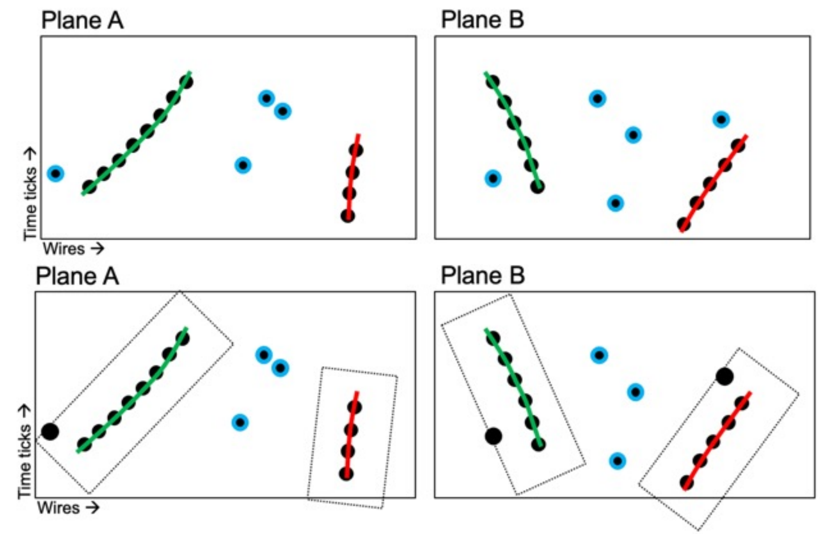
The MicroBooNE Collaboration*

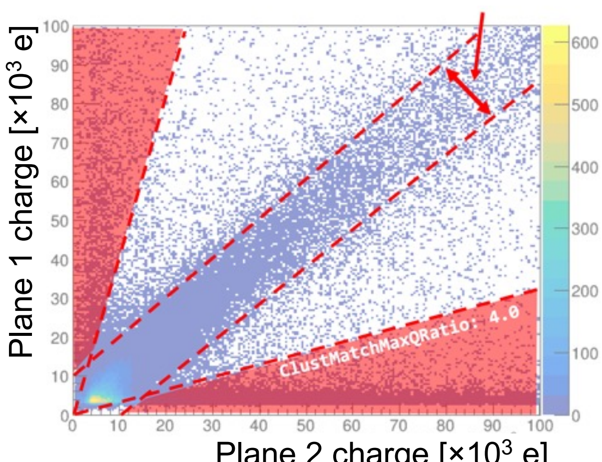
MeV-scale reconstruction in MicroBooNE

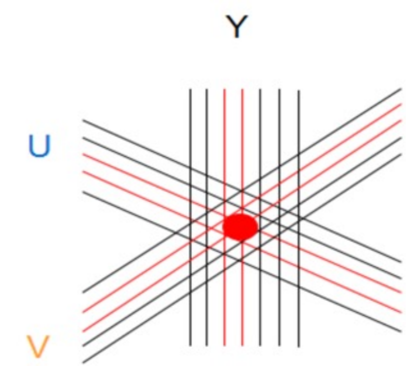
- Techniques pioneered in ArgoNeuT have been further developed in MicroBooNE
- Dedicated algorithm class has since been written encompassing these tools → *flexible integration into other reco & analysis workflows*
  - *Millicharged particle searches*
  - *ν NC1p selection background mitigation*
  - *Neutron tagging*
  - *Radiogenic calibrations*

Blip reconstruction in a nut-shell

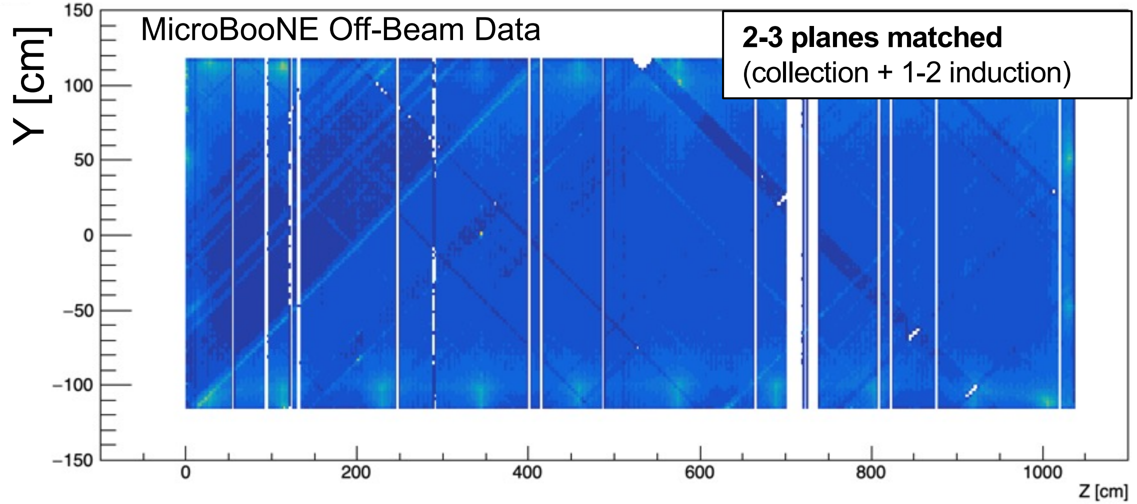
1. **Isolated hits identification**
   Hits *within* tracks > configurable length are vetoed; optional 2D masking in regions surrounding long tracks
2. **Hit clustering per plane**
   Hit width ('RMS') defines proximity threshold for clustering in wire-time space
3. **Cluster plane-matching**
4. **Geometric requirement**
   Wires must cross!
5. **Relative charge comparison**

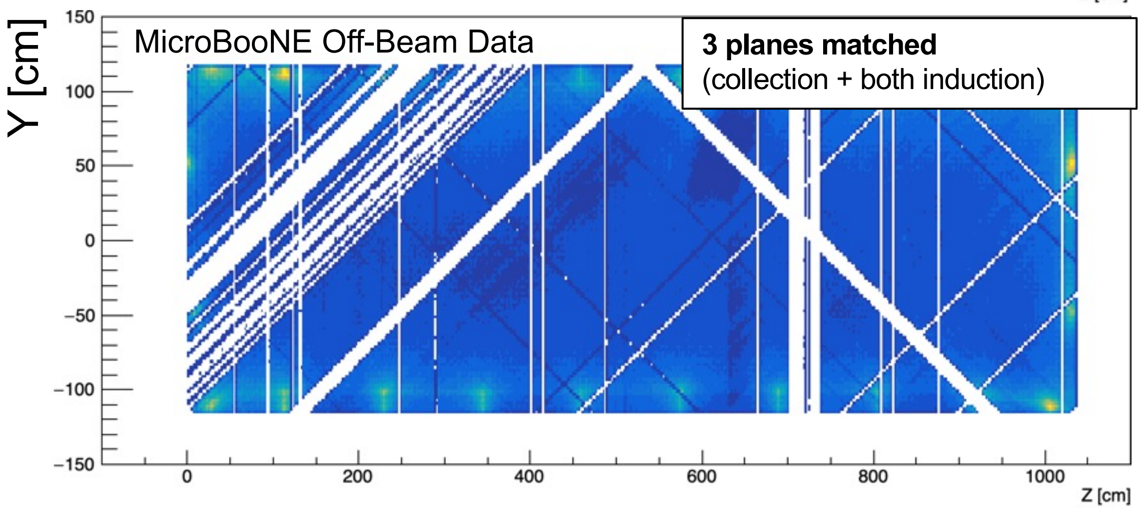


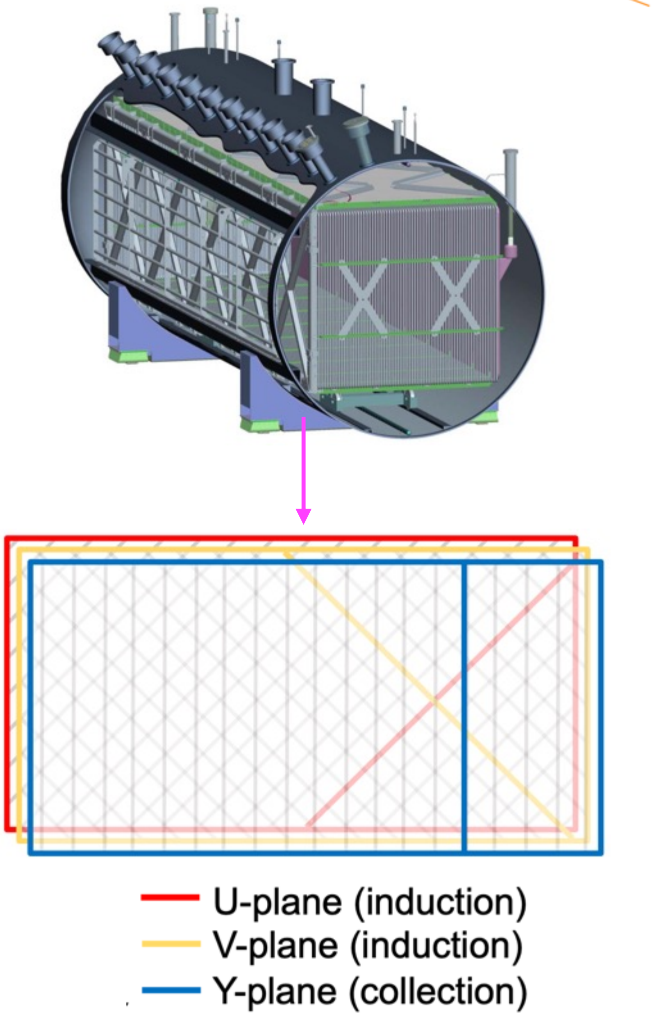




Ambient blips in MicroBooNE data

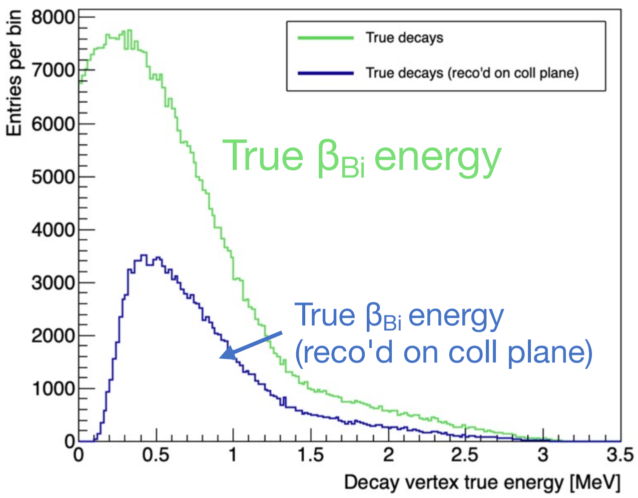


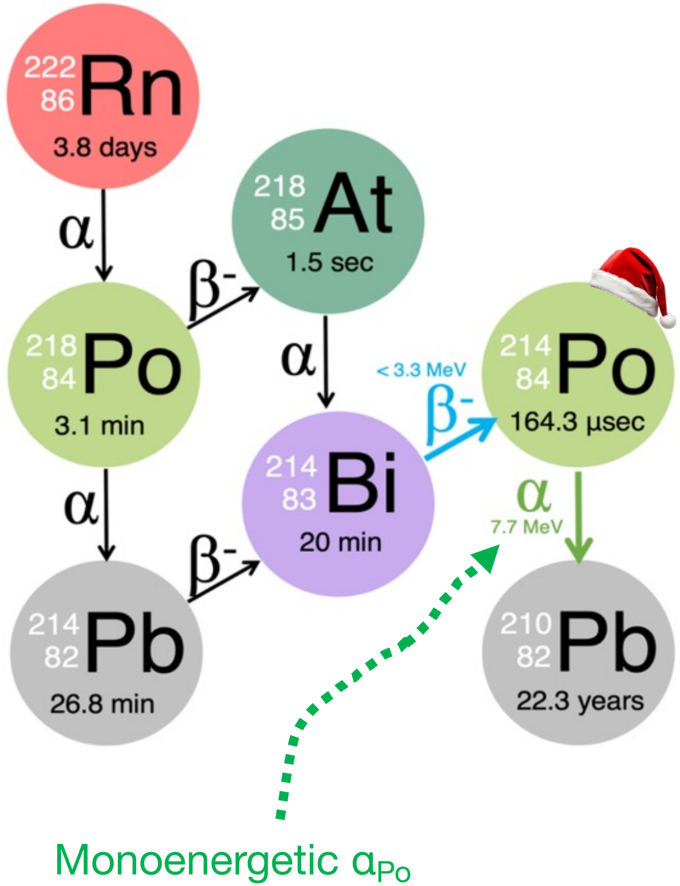




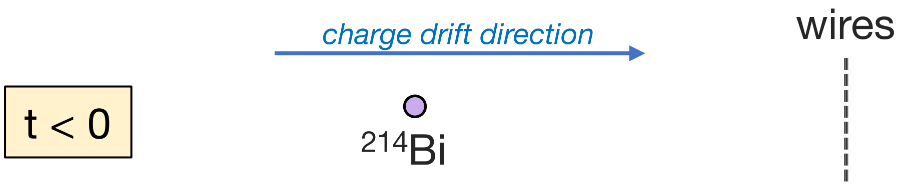
Radon studies in MicroBooNE

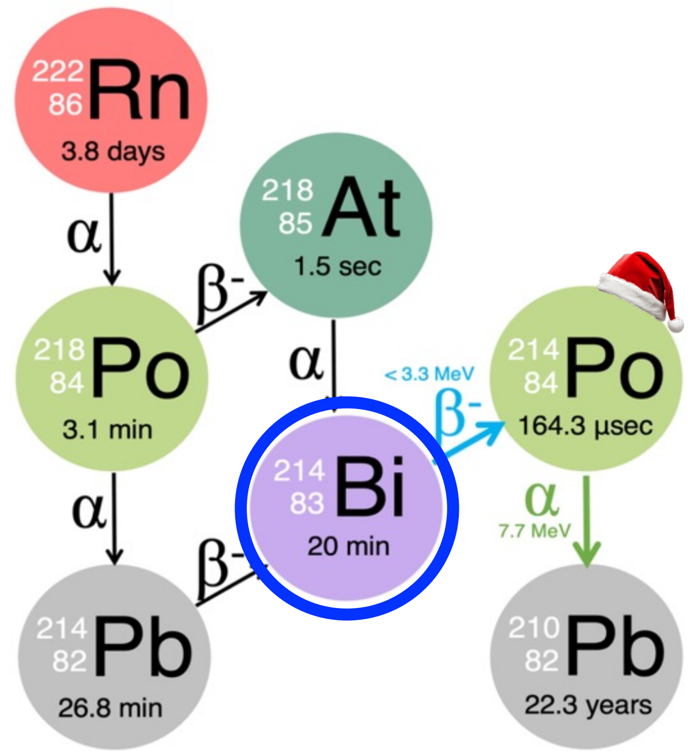
- *During its **2021 R&D run**, MicroBooNE explored radon's calibration potential by doping Rn into the active volume of LAr*
  - **222-Rn has a 3.8 day half-life**
    → *mixes throughout active volume*
  - **214-Po has a short 164μs half-life**
    → can tag the associated 214-Bi β



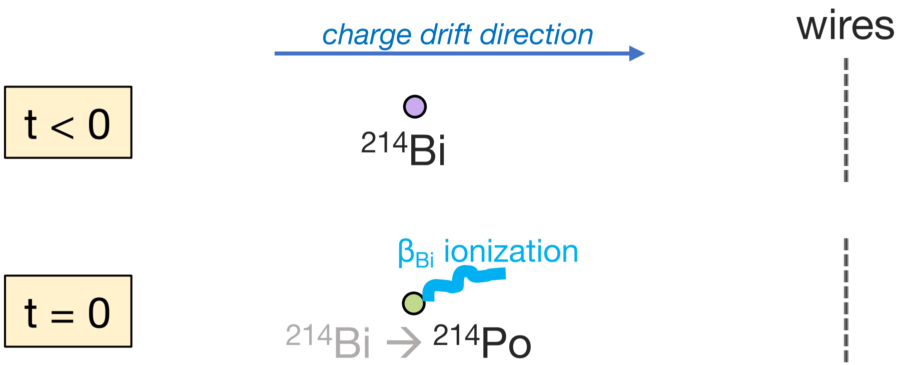


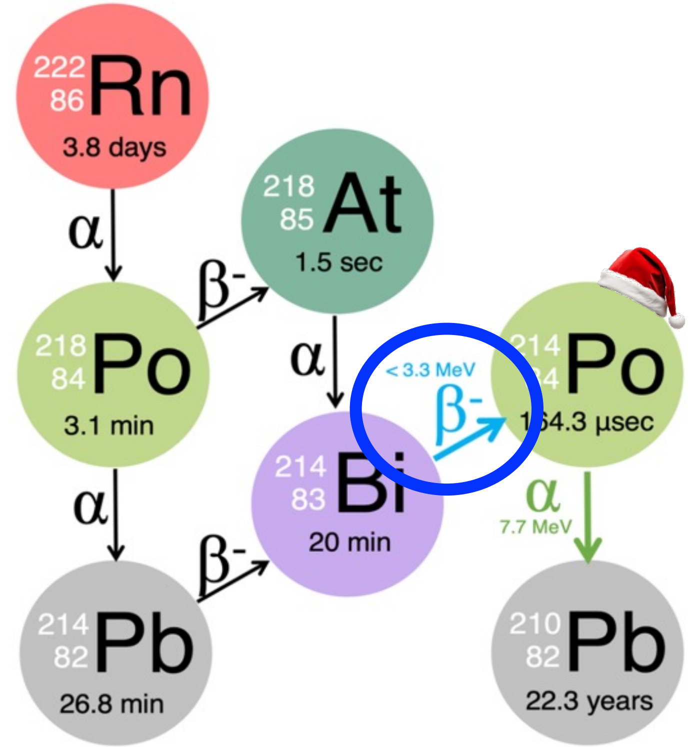
$^{214}Bi \rightarrow ^{214}Po$ Decay Tagging



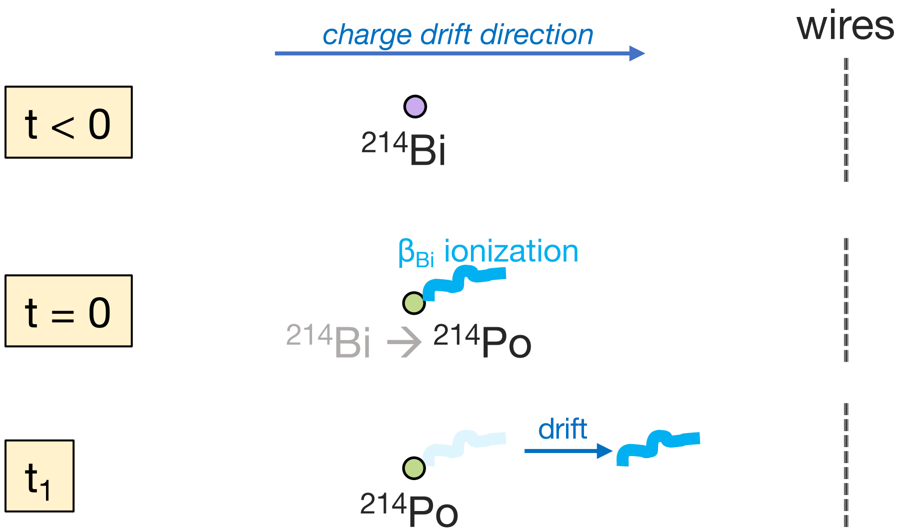


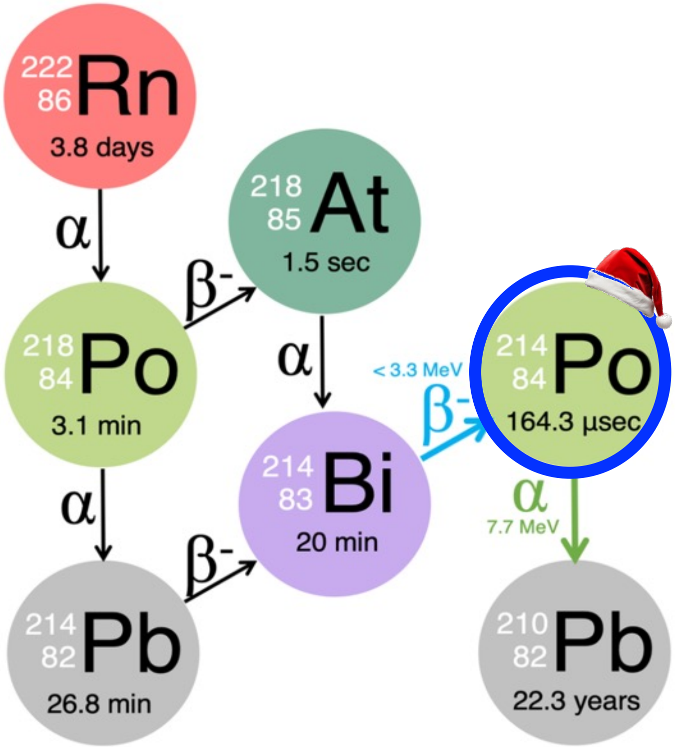
$^{214}Bi \rightarrow ^{214}Po$ Decay Tagging



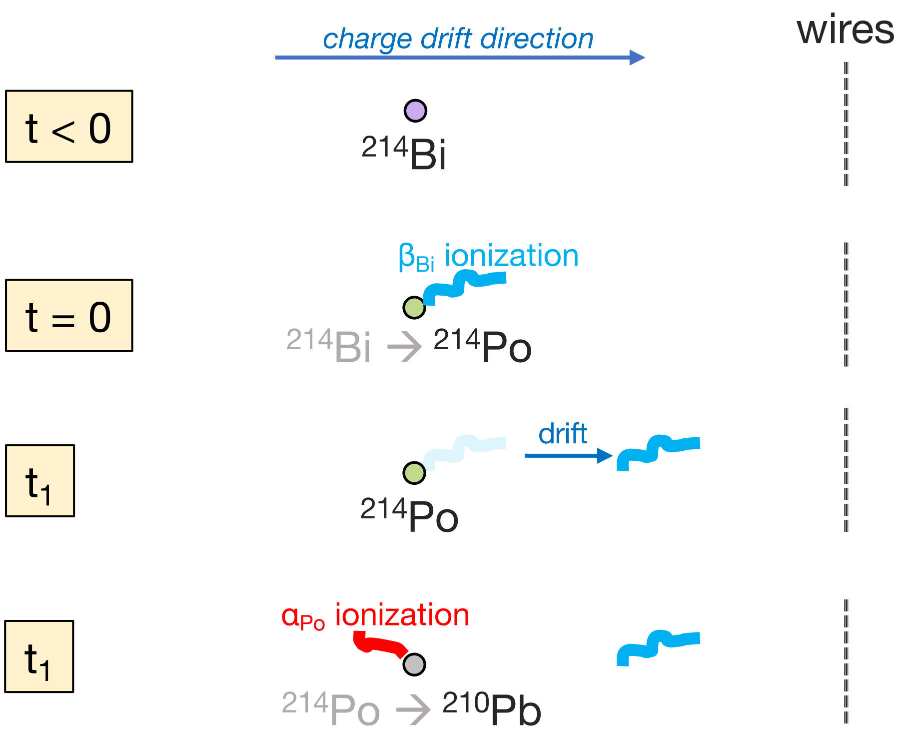


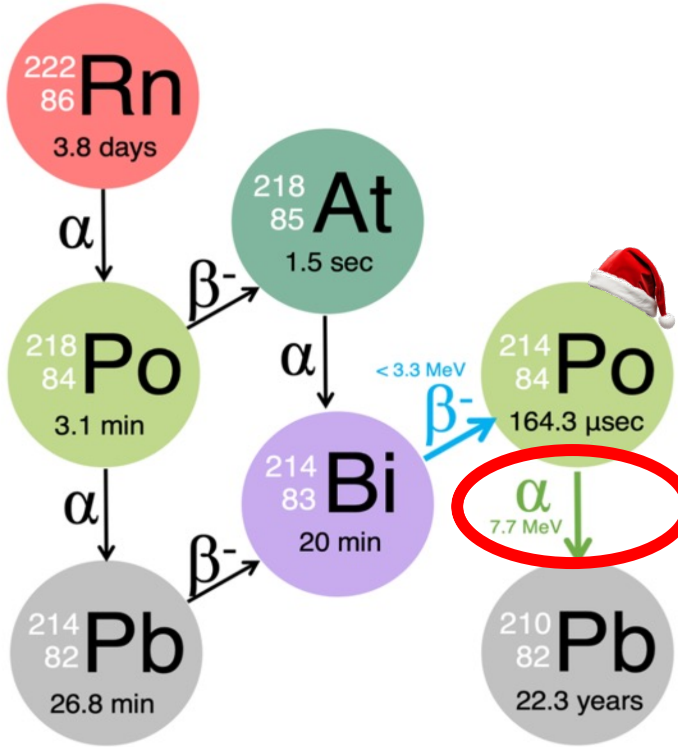
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



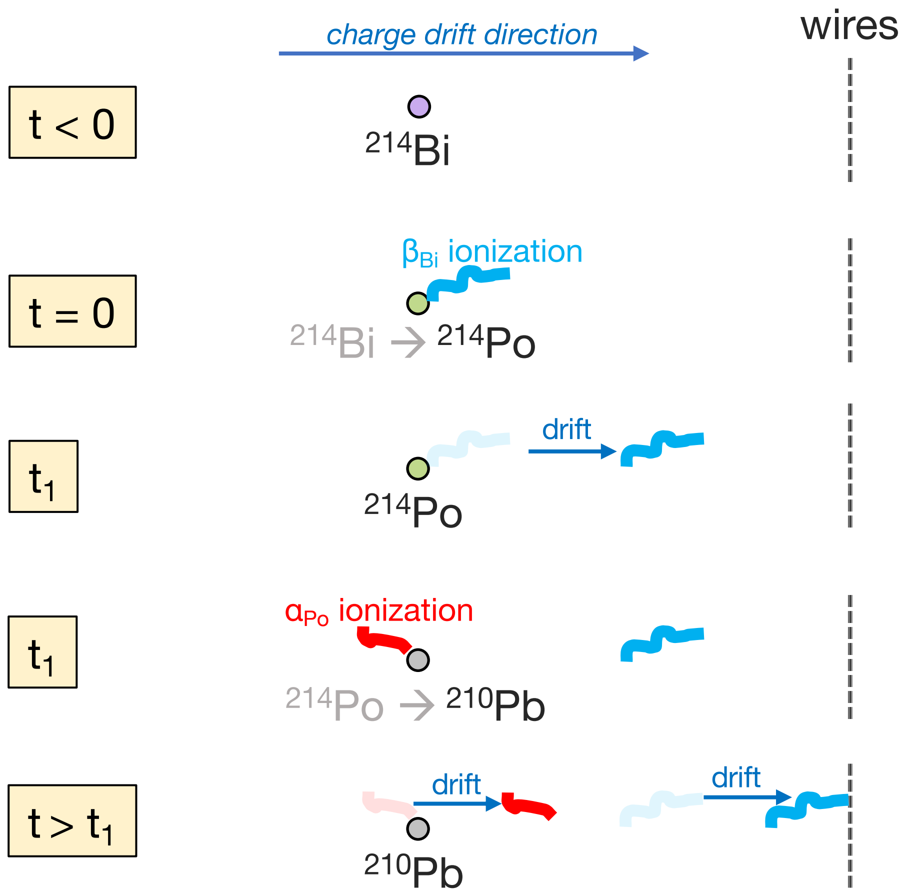


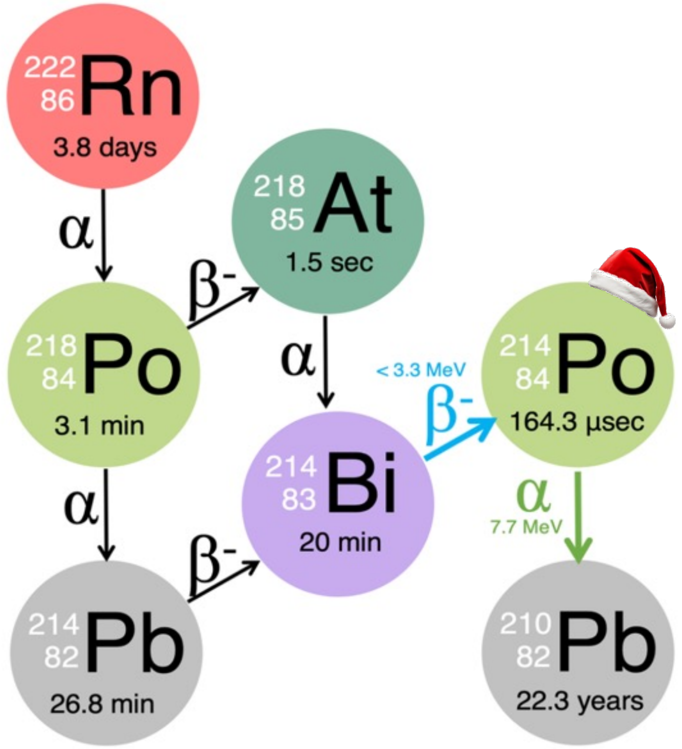
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



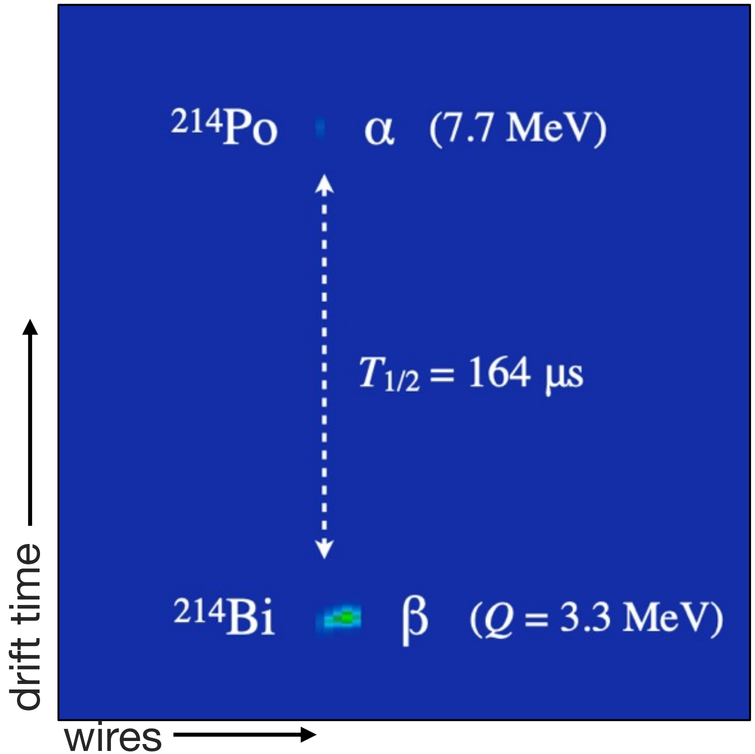


^{214}Bi → ^{214}Po Decay Tagging

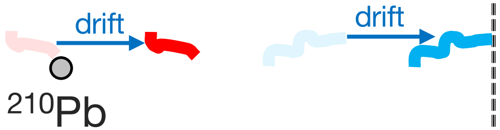


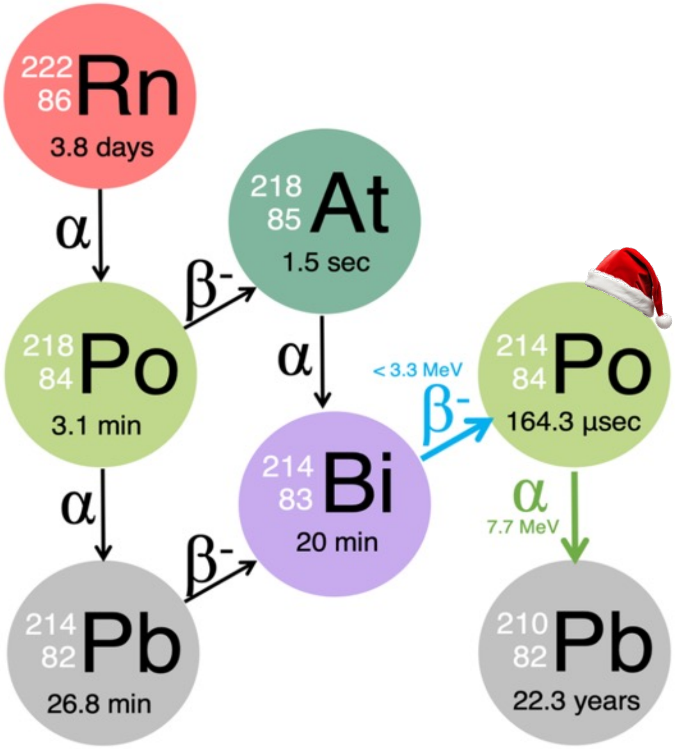


$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging

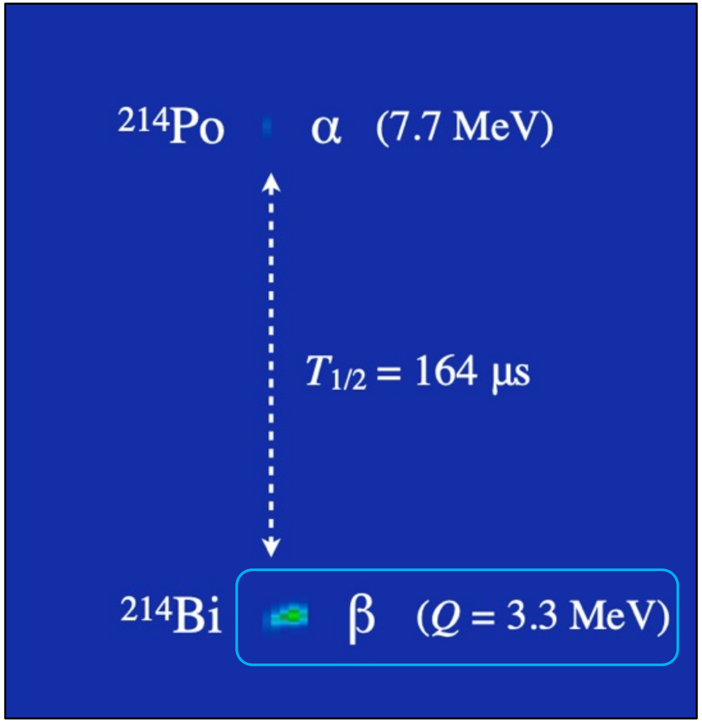


t > t1





$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



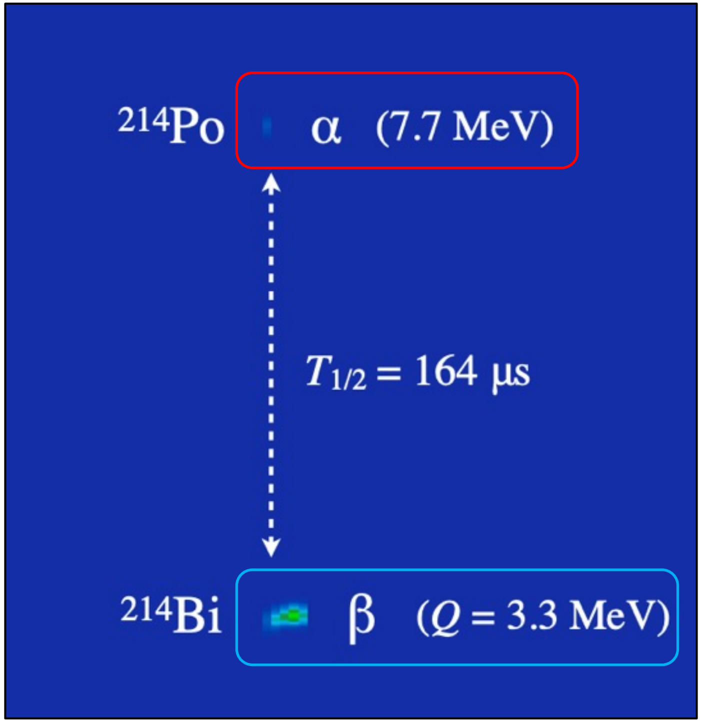
Regular ol' electron

dE/dx ~ 2 MeV/cm

Mean ~ 15,000 e^-

up to ~80,000 e^-

^{214}Bi → ^{214}Po Decay Tagging



Heavily ionizing alpha

dE/dx ~ O(100) MeV/cm

In ionization clouds *this* dense, extreme "charge quenching" occurs

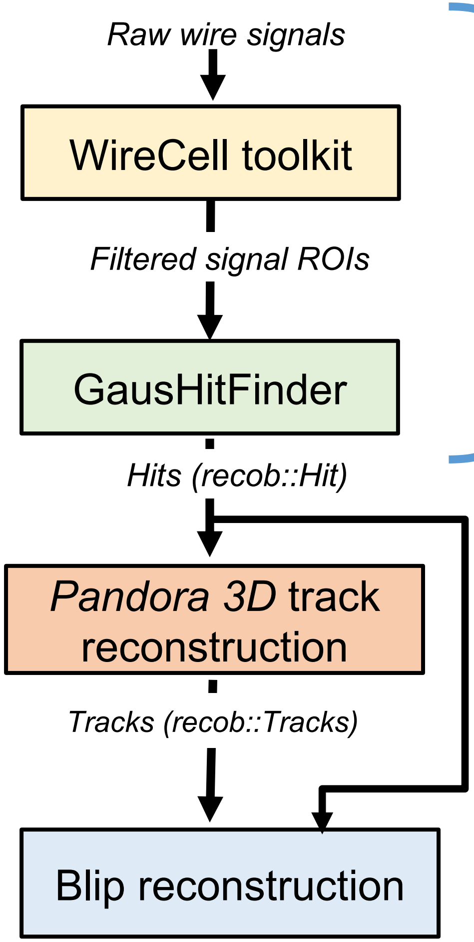
(e^- -Ar^+ recombination + collisional effects)

→ *Signal is fainter, < ~4000 e^-*

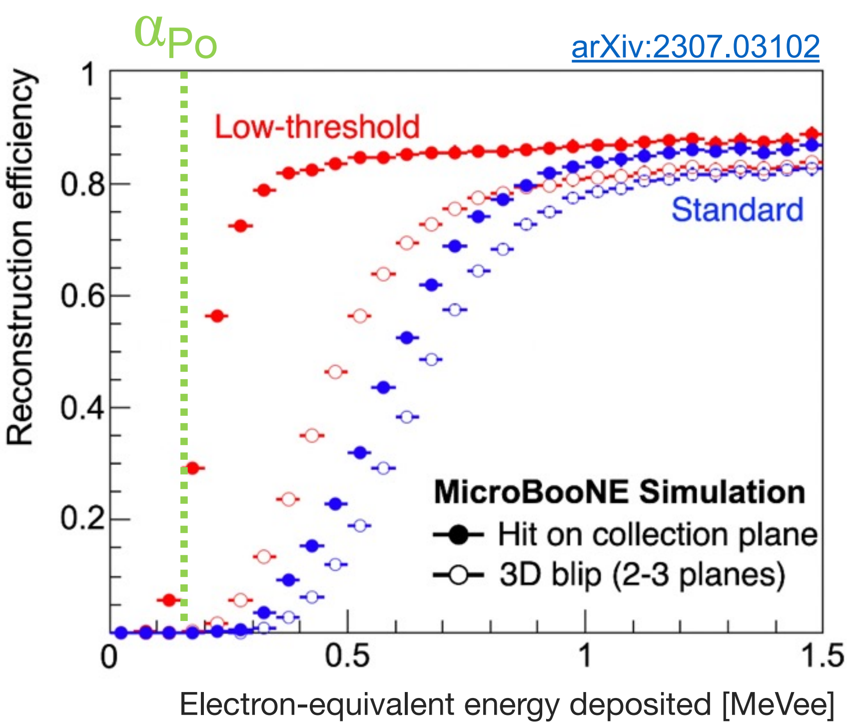
This **7.7 MeV α** ends up only depositing as much charge as a ***~150-200 keV electron!***

('Electron-equivalent energy' = MeVee, KeVee)

Lowering the energy thresholds



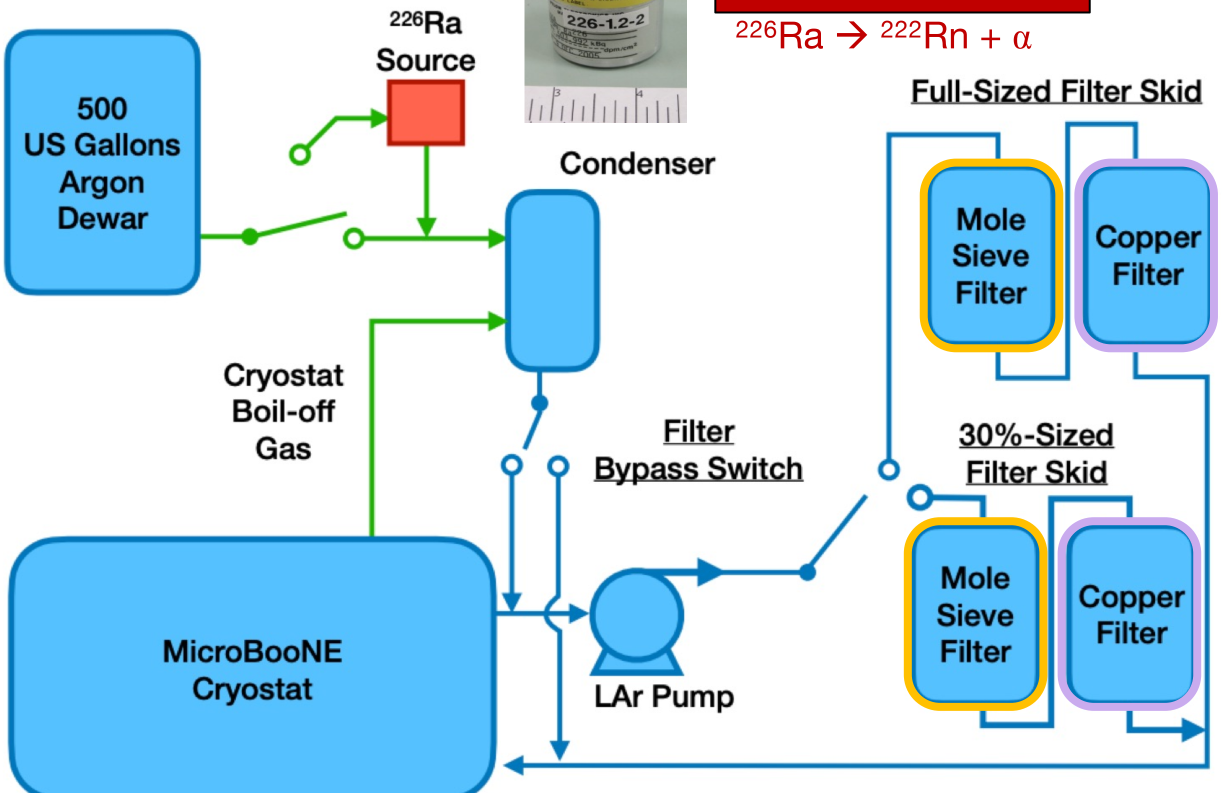
For this analysis, settings in the signal processing and hit-finding were tweaked to *improve* our energy sensitivity, **especially on the collection plane.**



Doping radon into MicroBooNE

500 kBq radium source attached to input Ar gas line

$^{226}Ra \rightarrow {}^{222}Rn + \alpha$



Filters aim to remove electronegative contaminants

4Å molecular sieve
1.6-2.6 mm beads
removes water

Copper filter
Cu-0226 S
removes O_2

Doping radon into MicroBooNE

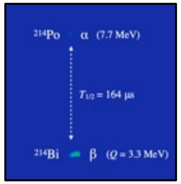
Design by Mike Zuckerbrot

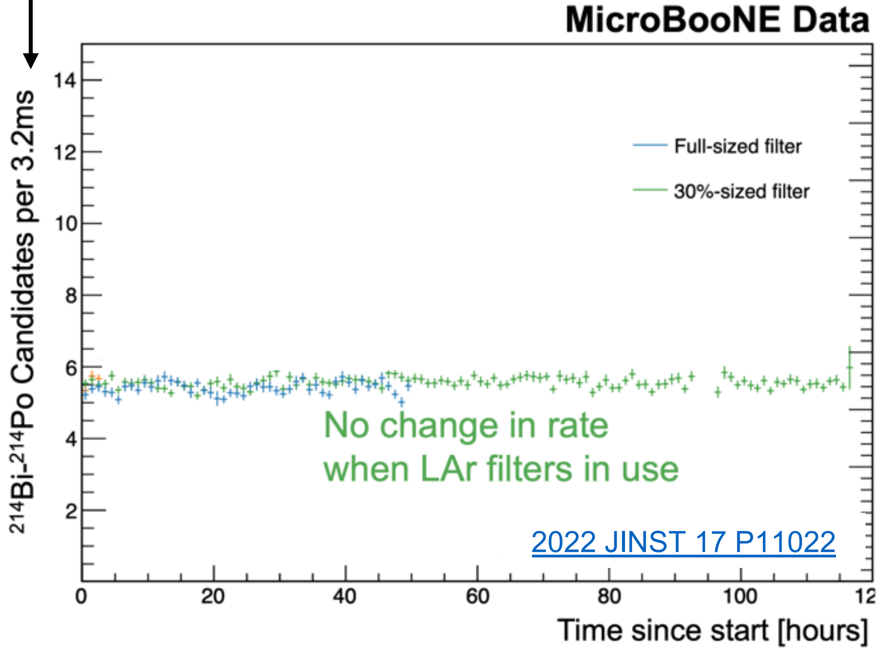
The original pipe will be cut, a conflat tee will be pressure fit, the source will be added, the tee will be sealed, the system will vacuum pumped, leak checked, and then operated

J. Zennamo, Fermilab

9

Bi-Po candidate rate: full filters

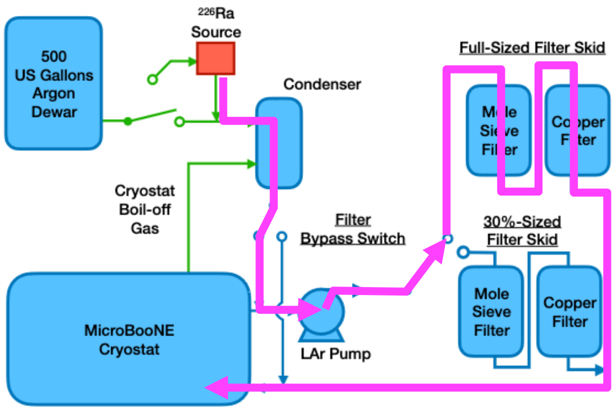
Rate () on collection plane only



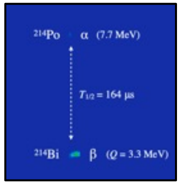
No change in rate when LAr filters in use

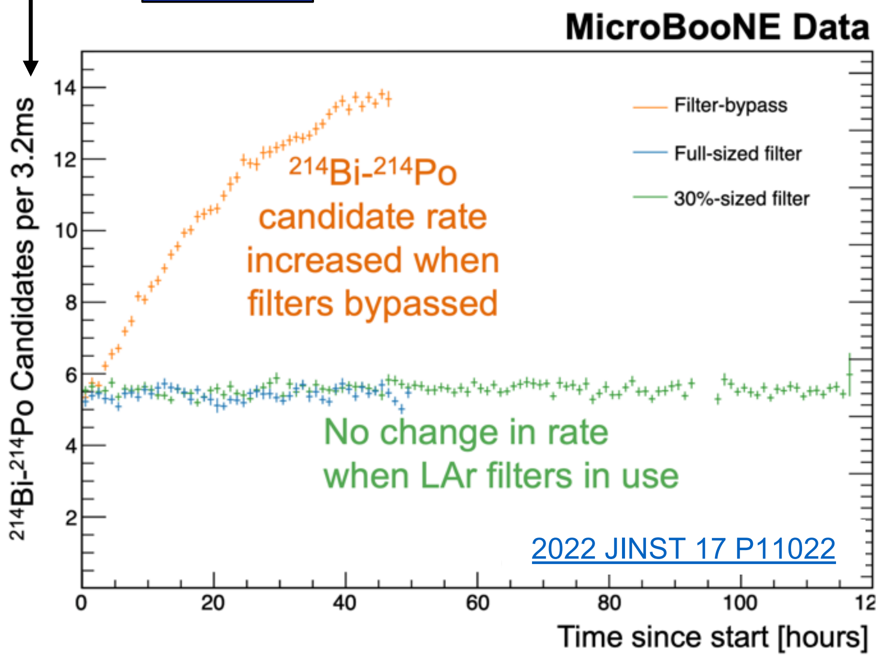
[2022 JINST 17 P11022]

Usual filter configuration

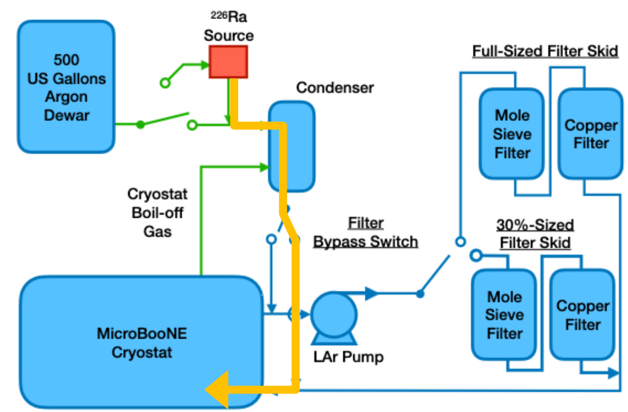


Bi-Po candidate rate: *filter bypass*

Rate () on collection plane only



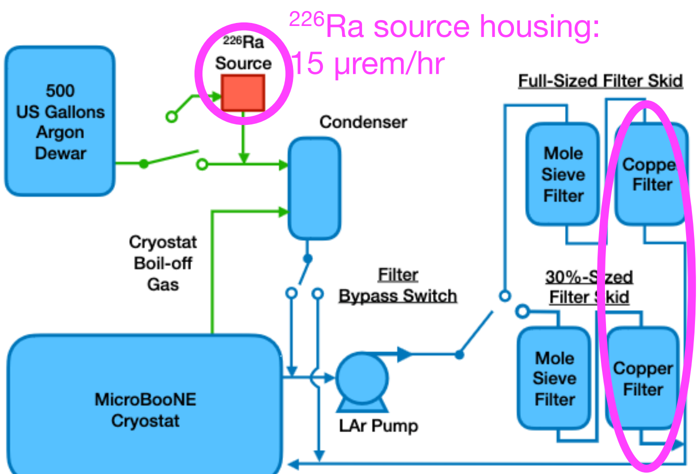
"Filter bypass"

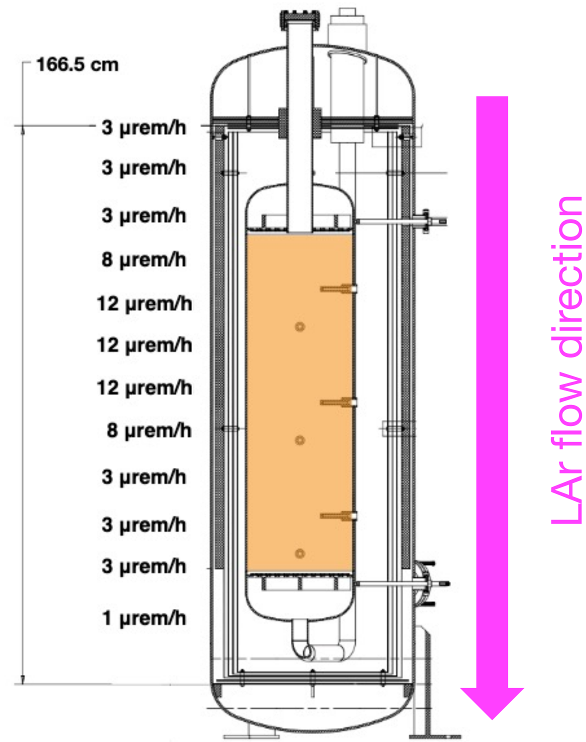


> 99.9997% of Rn removed by 77L filter

Radiological survey

Confirmed accumulation of radon in copper filter





Implications

JINST 17 P11022 (2022)

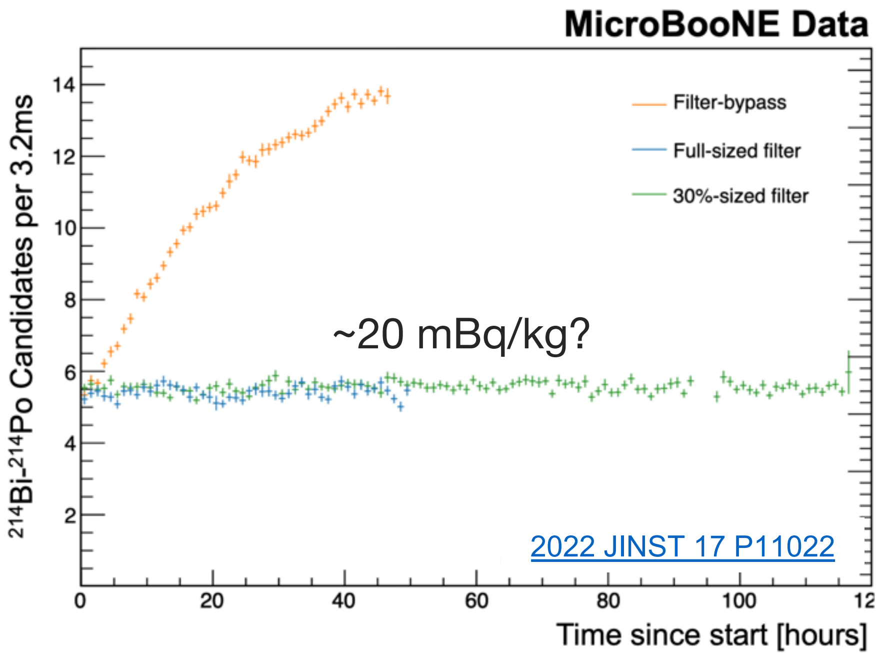
PREPARED FOR SUBMISSION TO JINST

Observation of Radon Mitigation in MicroBooNE by a Liquid Argon Filtration System

MicroBooNE Collaboration

- This result was surprising!
  - Our single-phase liquid filtration – designed to remove *electronegative impurities* – seems to also remove radon
- Promising indications for DUNE

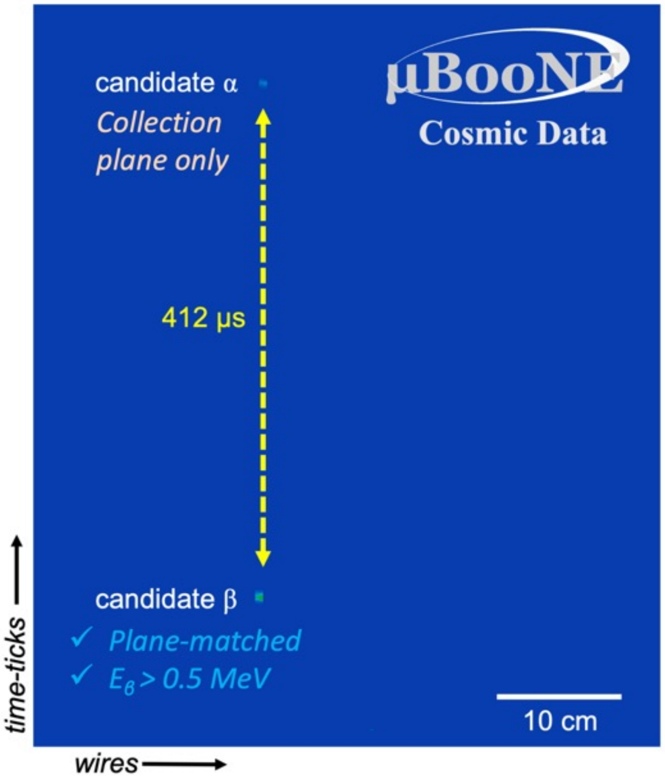
Remaining questions...



- **What *is* the ambient Rn rate?**
- Background rate from previous study would be equivalent to ~20 mBq/kg
- Higher purity selection is needed to resolve this

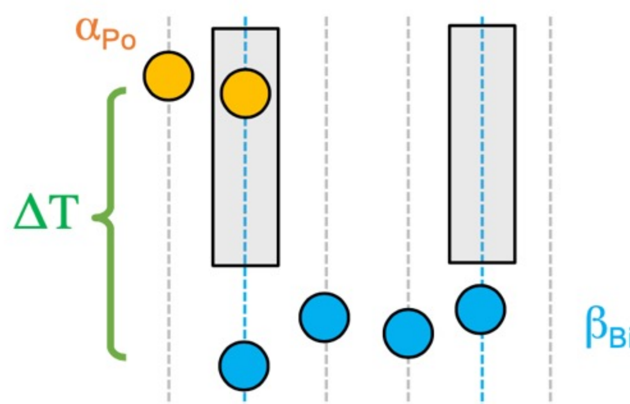
Taking a closer look at the radon datasets...

arXiv:2307.03102



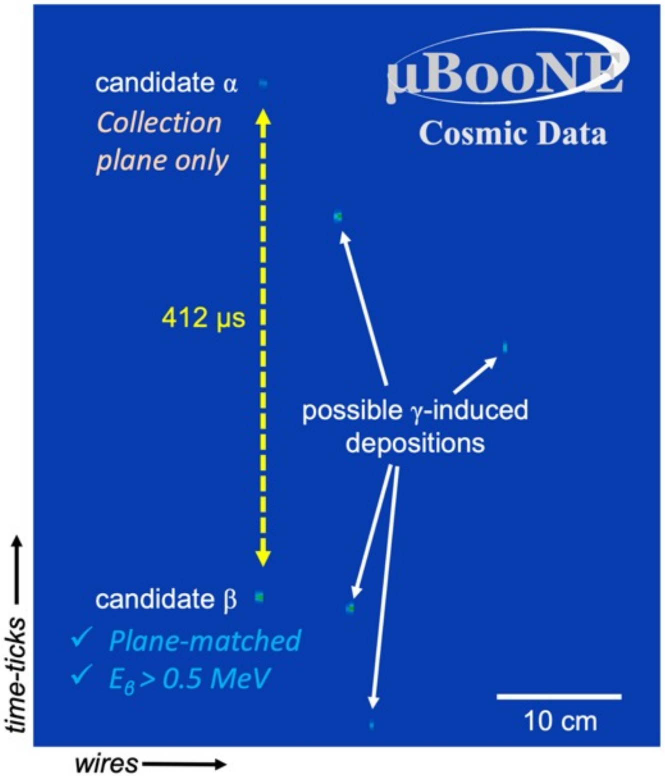
Follow-up study was performed with improved signal selection:

- Require plane-matched β
- Fiducialization cuts
- Energy cut of $E_\beta > 0.5$ MeV
- Additional cuts on α blip size



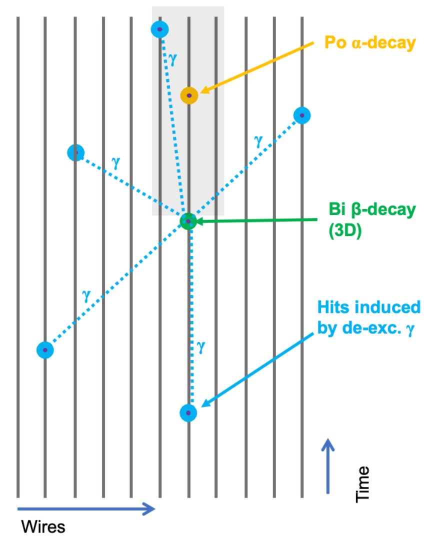
Taking a closer look at the radon datasets...

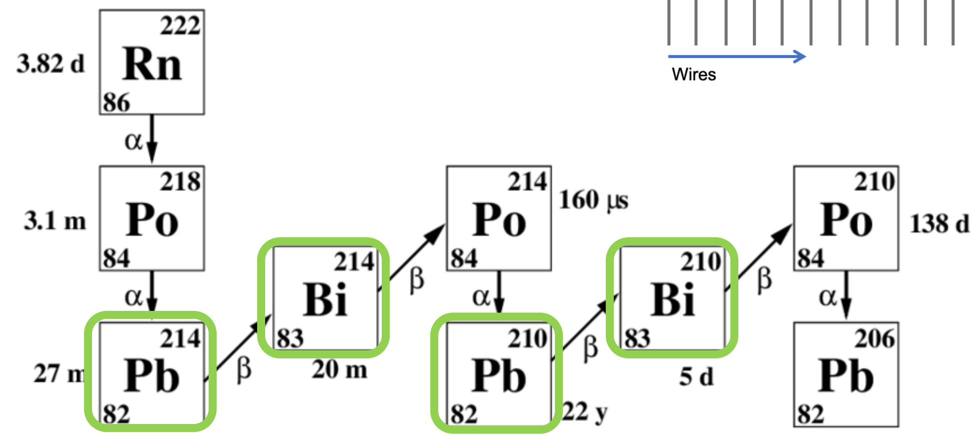
arXiv:2307.03102



$$^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po} + \beta + N\gamma$$

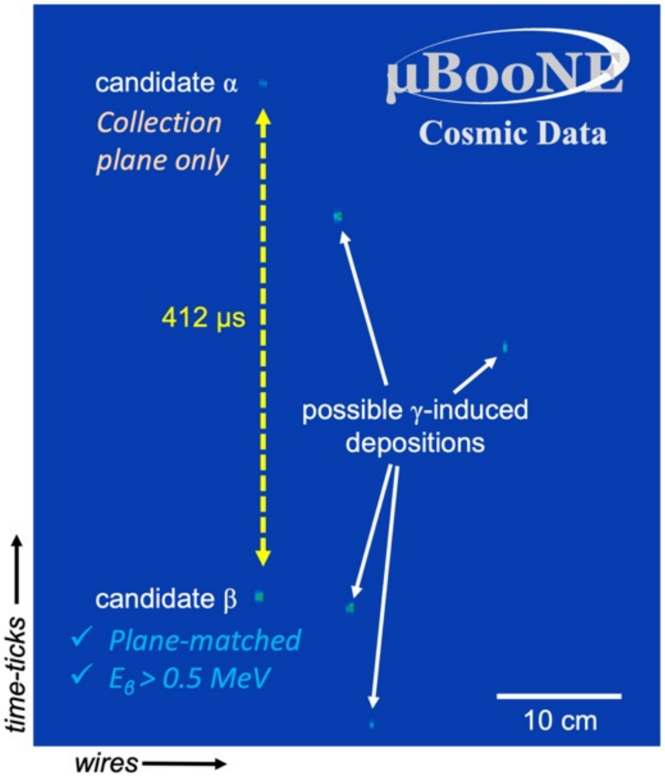
BiPo signal can be faked by other beta-emitting isotope decays

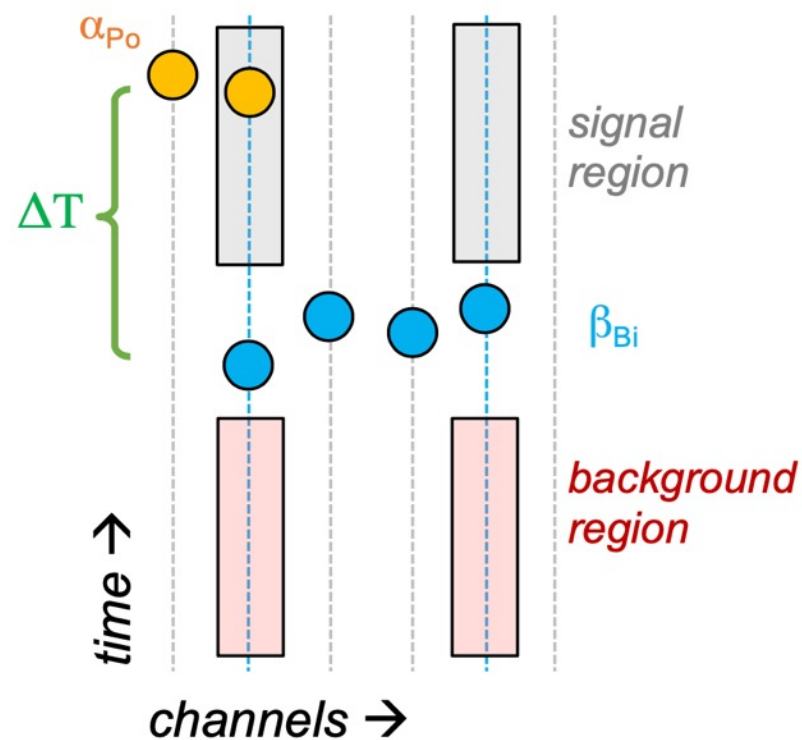




Taking a closer look at the radon datasets...

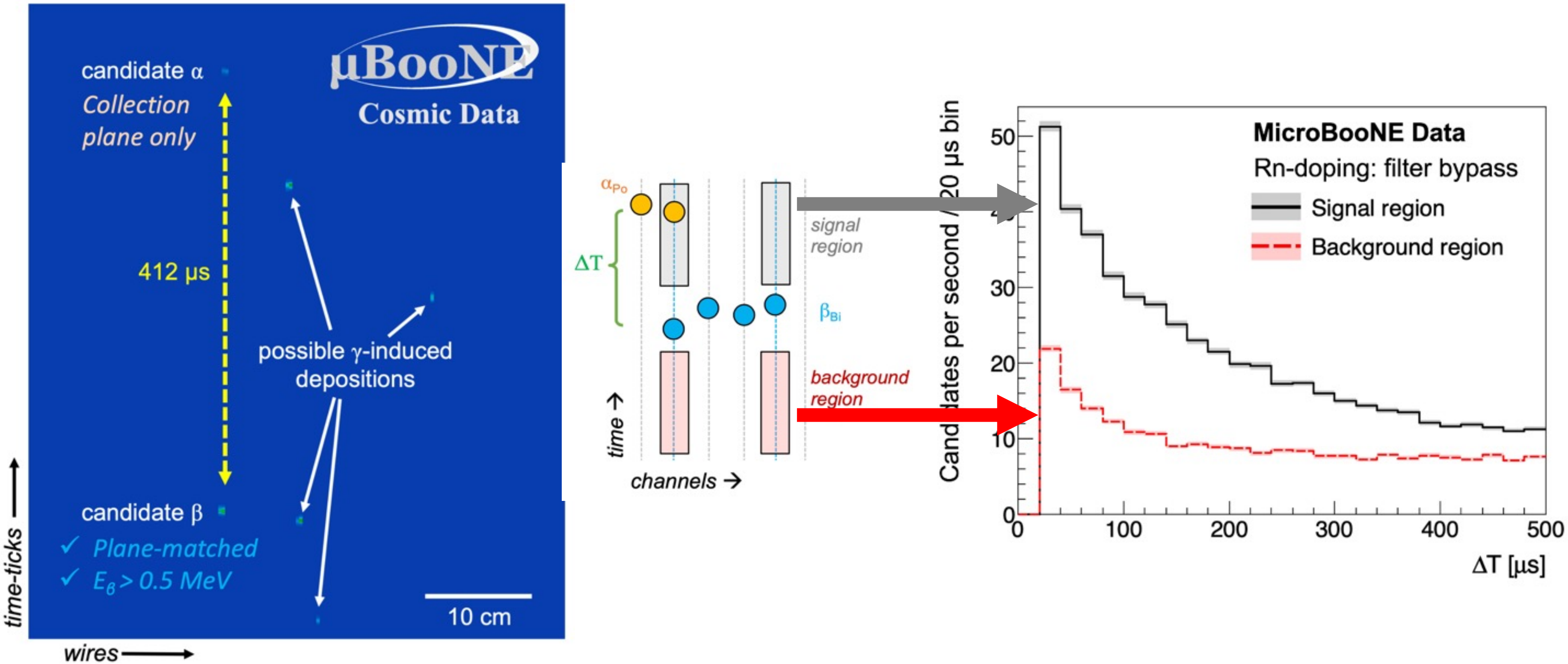
arXiv:2307.03102





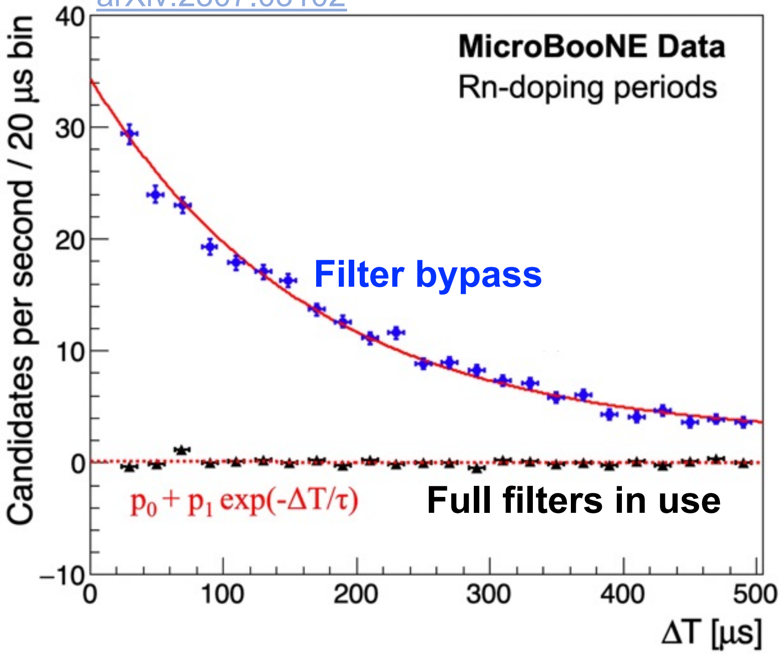
Taking a closer look at the radon datasets...

arXiv:2307.03102



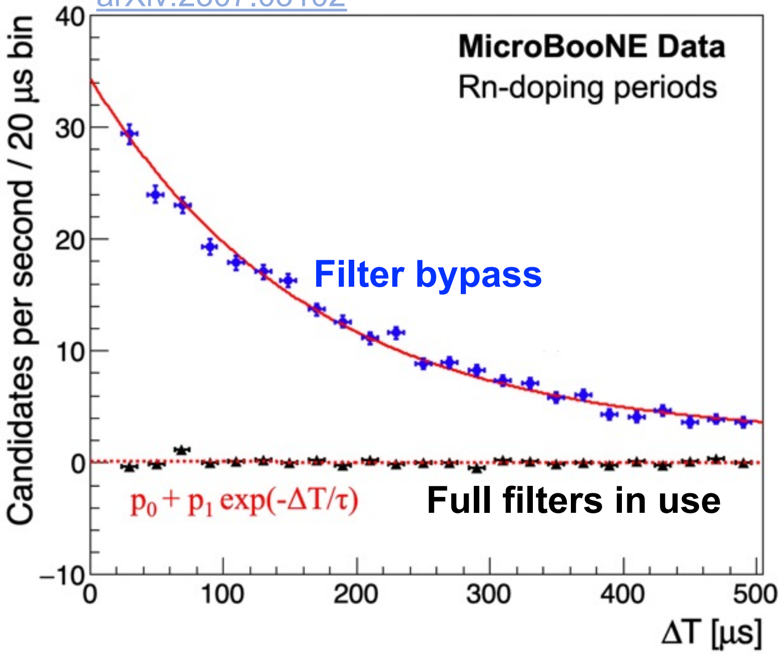
Background subtraction and ΔT template fitting

arXiv:2307.03102

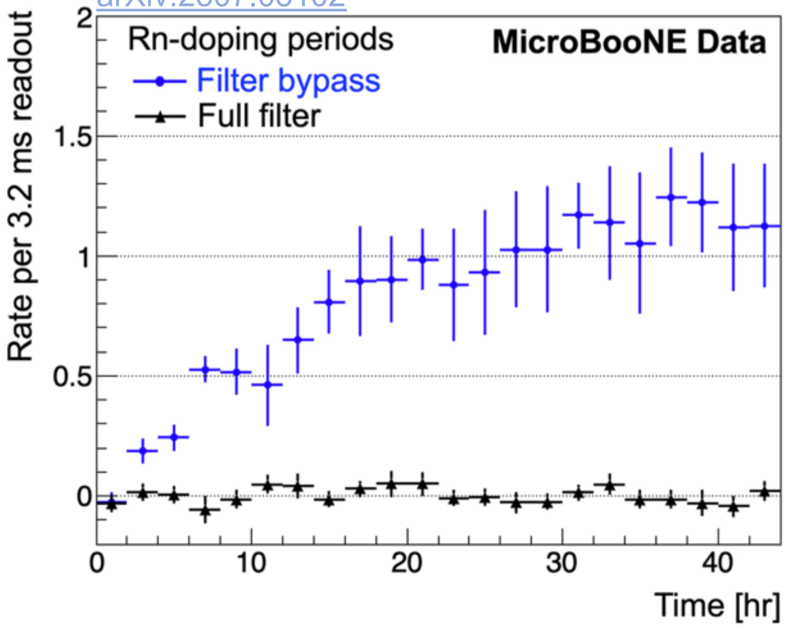


Background subtraction and ΔT template fitting

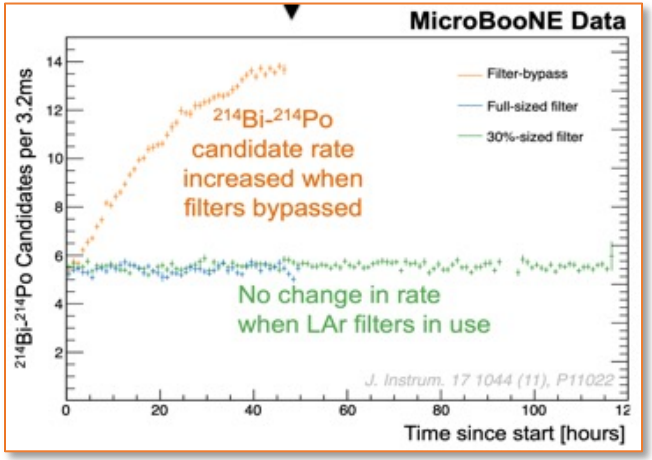
[arXiv:2307.03102]



[arXiv:2307.03102]

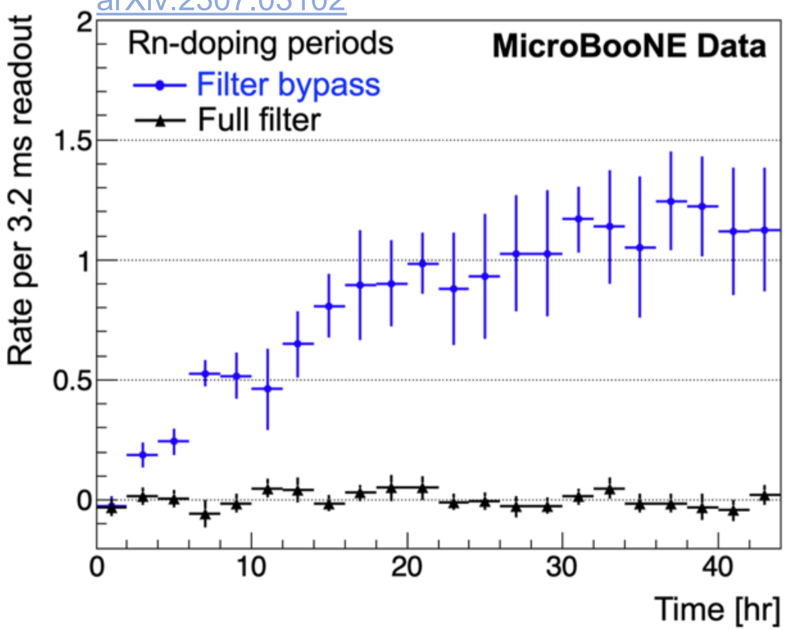


Results on radon-doped data



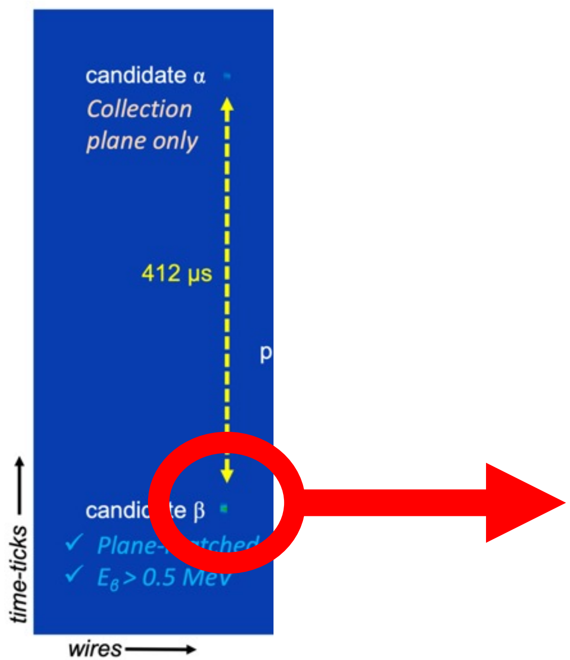
Previous study's background rate (~5.5 candidates/evd) has been successfully removed

arXiv:2307.03102

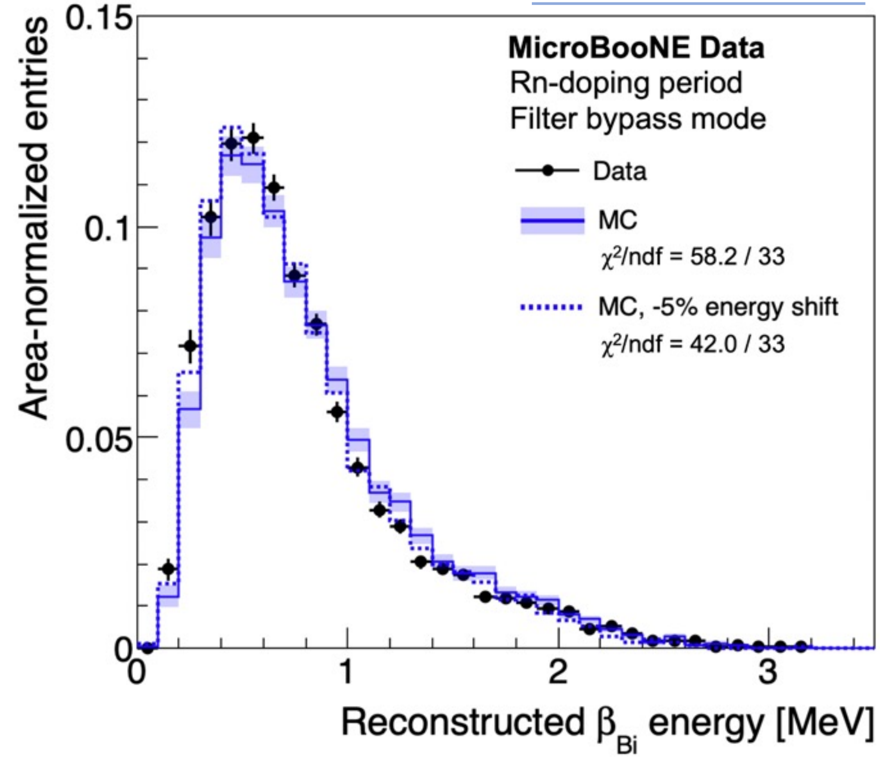


Calorimetric validation: β_{Bi}

Same BG subtraction applied to β *energy spectrum*



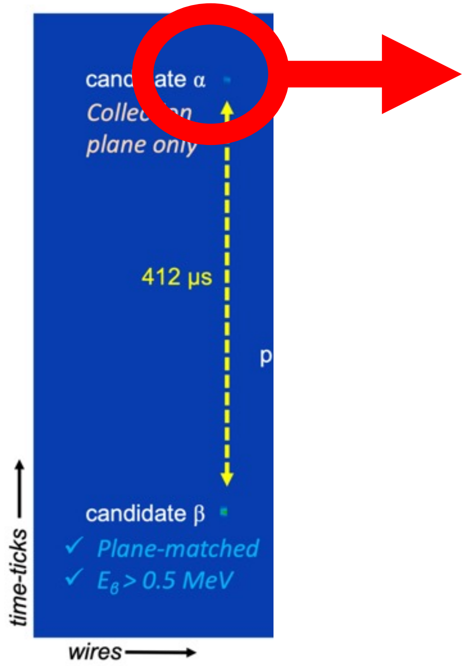
arXiv:2307.03102

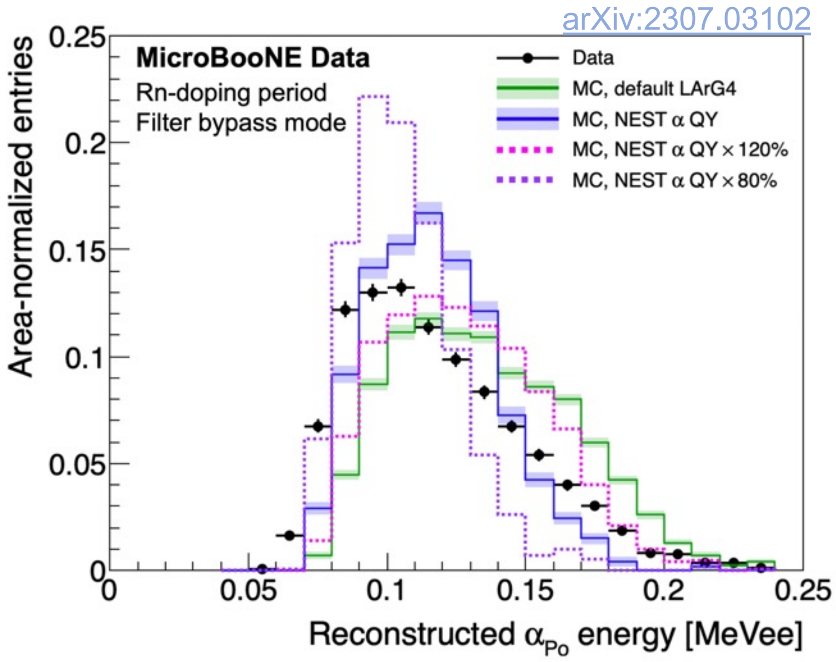


Calorimetric validation: α_{Po}

... and same for the α_{Po} energy spectrum

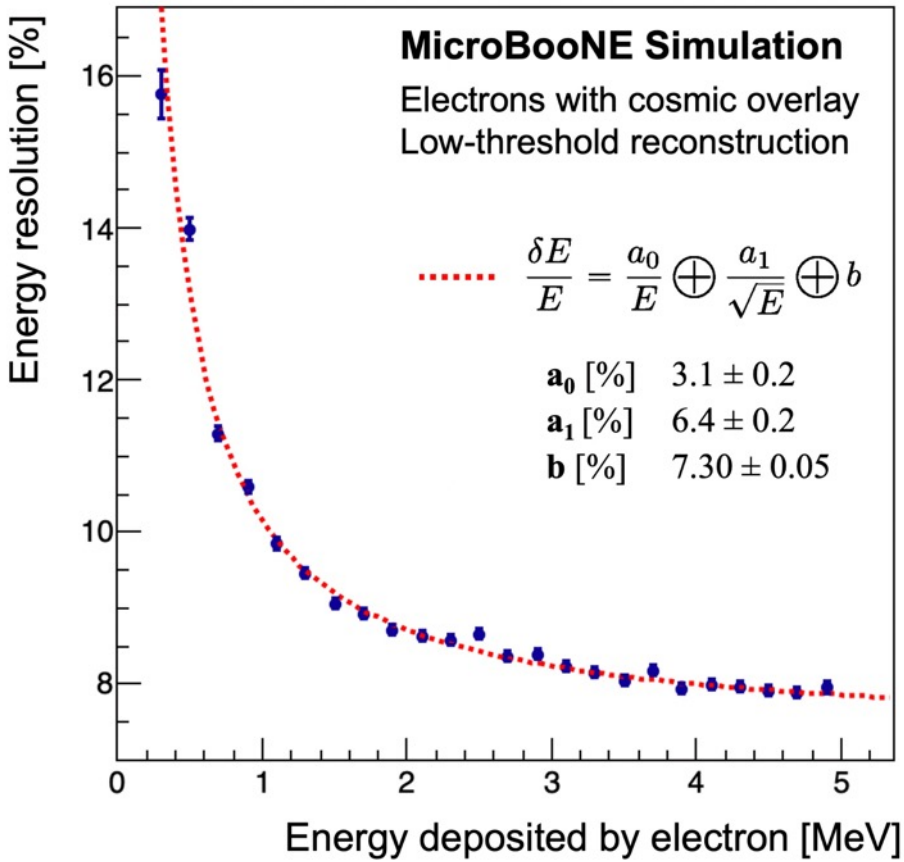
(large uncertainties in charge yield/quenching)





MC energy resolution

arXiv:2307.03102



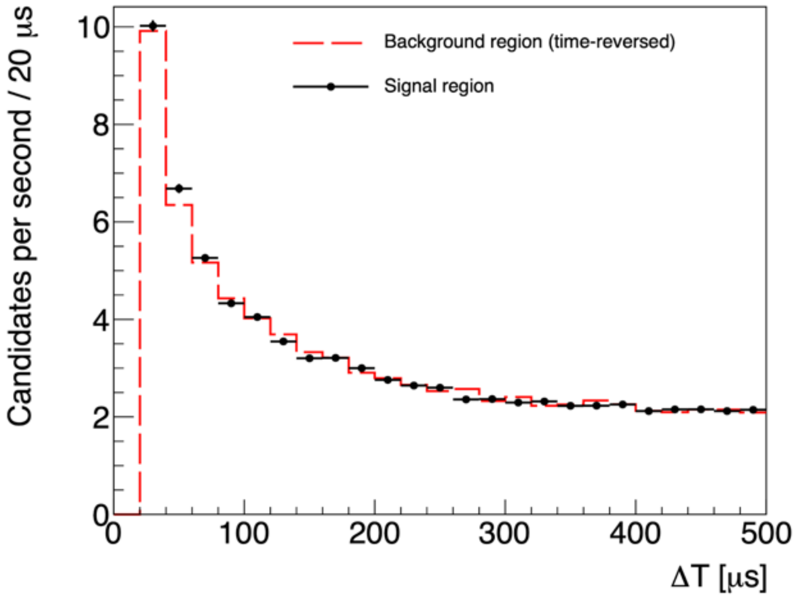
MC electron resolution:

- 10% at 1 MeV
- 8% at 5 MeV

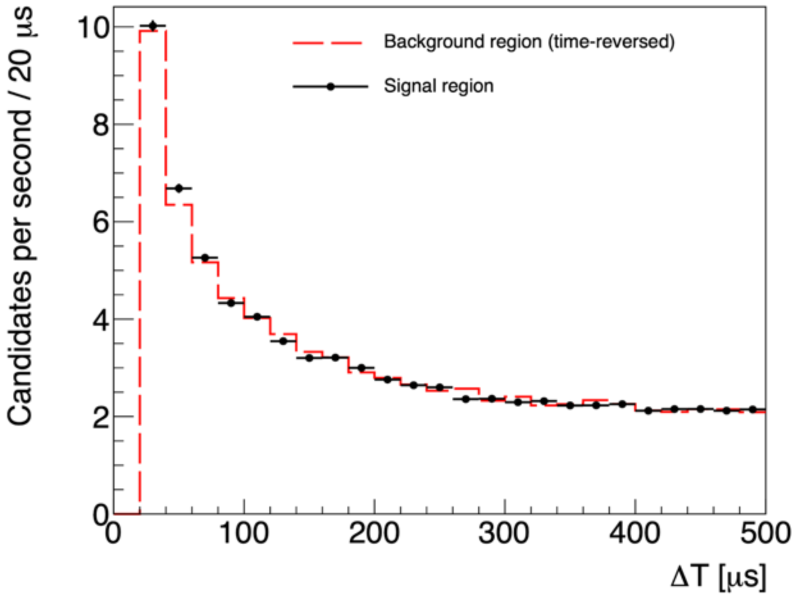
DUNE requirements for:

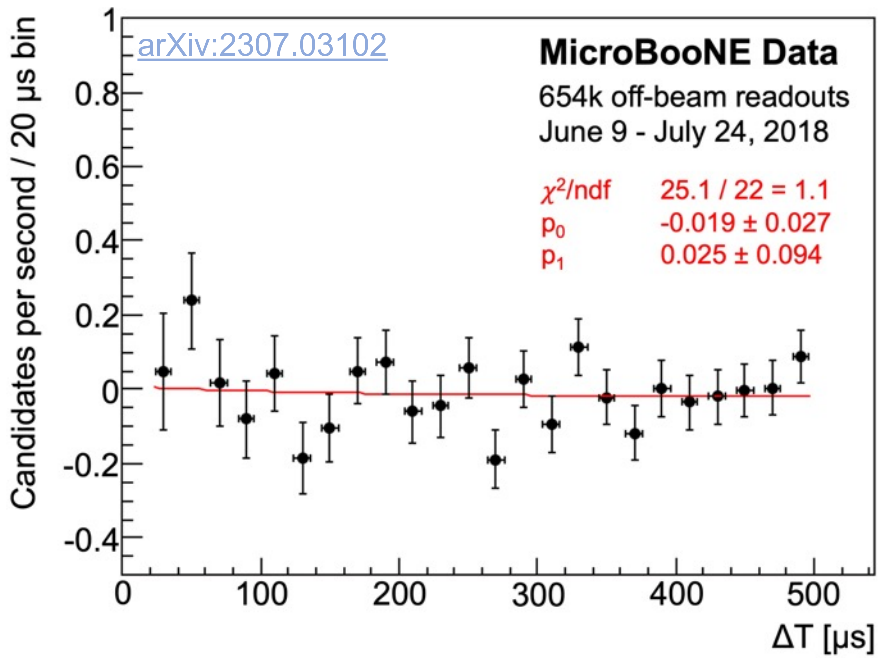
- SNe ν: ~10-20%
  Euro. Phys. J. 81, 423 (2021)
- Solar ν: ~7% for > 5 MeV
  Phys. Rev. Lett. 123, 131803 (2019)

Results from standard data-taking conditions

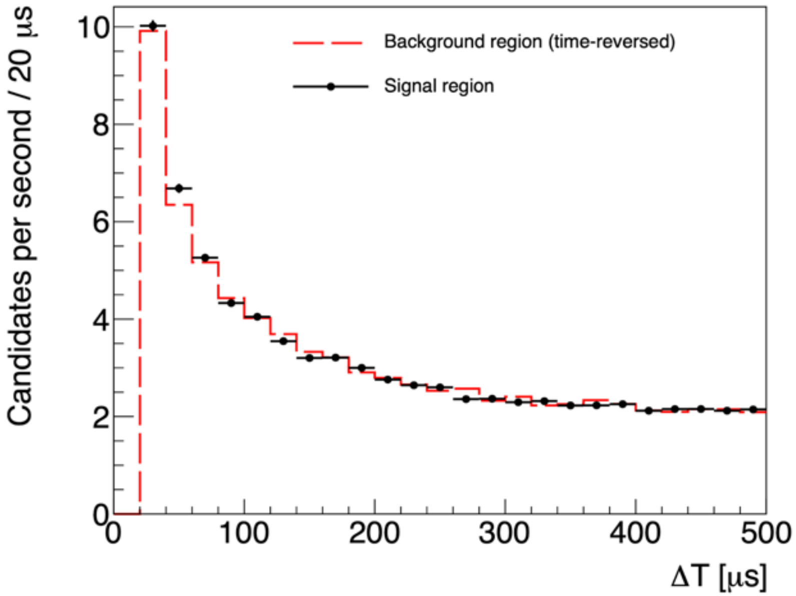


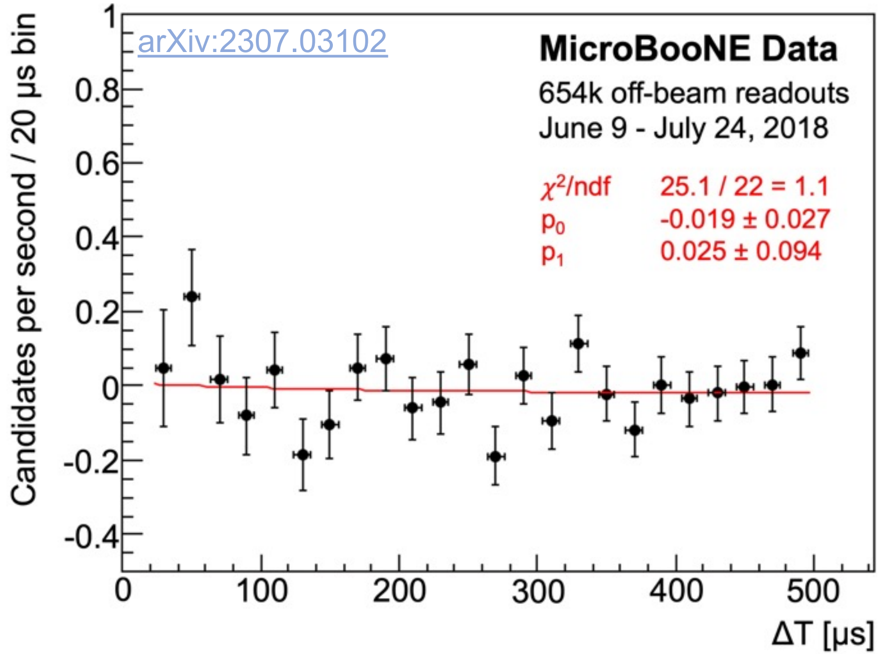
Results from standard data-taking conditions





Results from standard data-taking conditions





DUNE Rn target:
< 1 mBq/kg

n = (0.7 ± 2.5 (stat) ± 1.4** (syst))$\times 10^{-3}$ decays/readout

R* = 0.04 ± 0.15 (stat) ± 0.09 (syst) mBq/kg
= 0.04 ± 0.17 mBq/kg
< 0.38 mBq/kg at 95% CL

Implications

arXiv:2307.03102 (2023) – under review by PRD

Measurement of ambient radon daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector

P. Abratenko,[35] O. Alterkait,[35] D. Andrade Aldana,[15] L. Arellano,[20] J. Asaadi,[34] A. Ashkenazi,[32]
S. Balasubramanian,[12] B. Baller,[12] G. Barr,[25] D. Barrow,[25] J. Barrow,[21,32] V. Basque,[12] O. Benevides Rodrigues,[15]

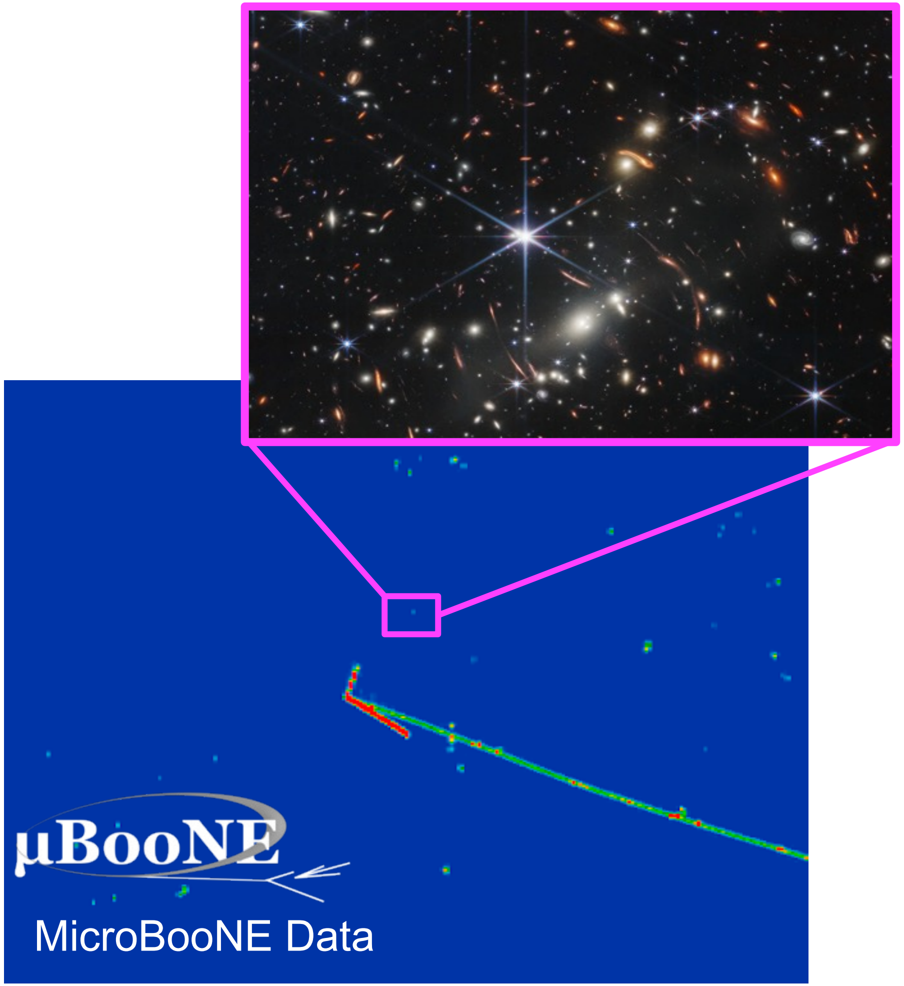
- **Combined with 'radon mitigation' result, this is a resounding indication that single-phase LArTPC liquid filtration can achieve high radon radiopurity**
  - Comfortably within DUNE's requirements
- Existing readout / reconstruction sufficient for DUNE to achieve baseline goals
  - Of course, this may be a little harder in DUNE due to its larger size...

Conclusions

- MeV-scale reconstruction is the 'next frontier' in ν LArTPC physics
- MicroBooNE has used its well-understood detector to demonstrate these capabilities
  - Novel measurements for a large LArTPC
  - Results help bridge the gap between dark matter and νLArTPC worlds

Thank you!

and thanks to the Fermilab ***New Initiatives*** program for funding the radon-doping R&D!



Backup

Advantage of mm-scale tracking + calorimetry?

→ e/γ shower separation

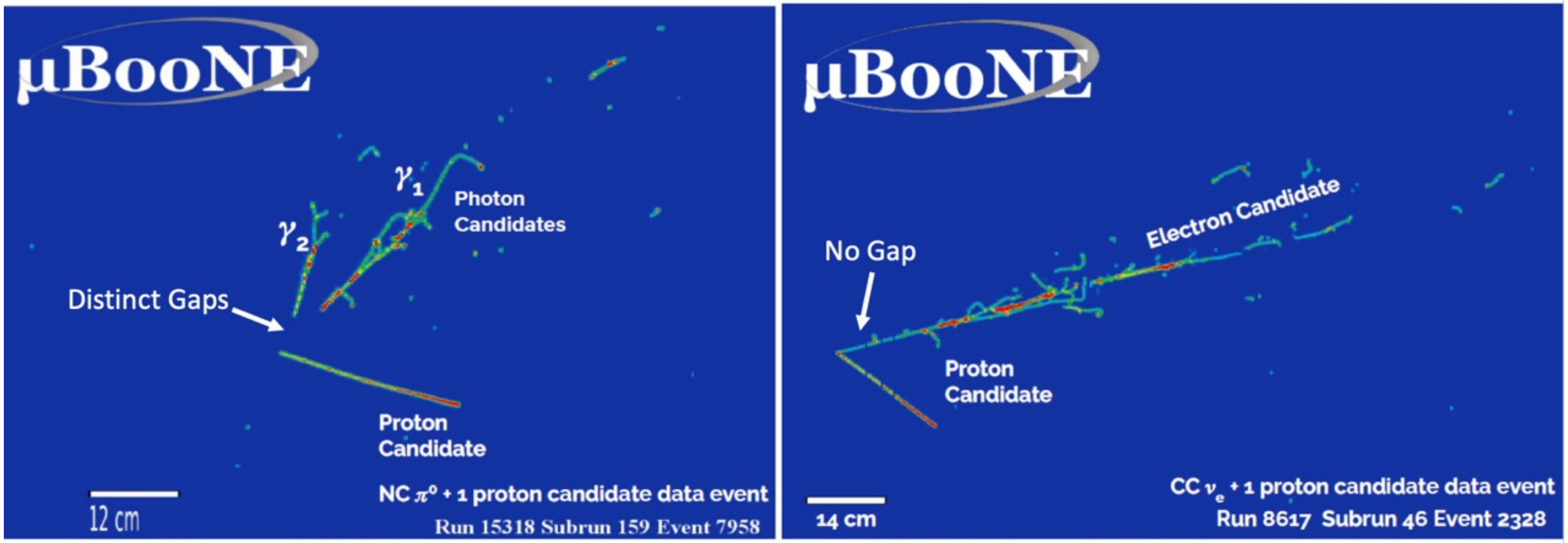
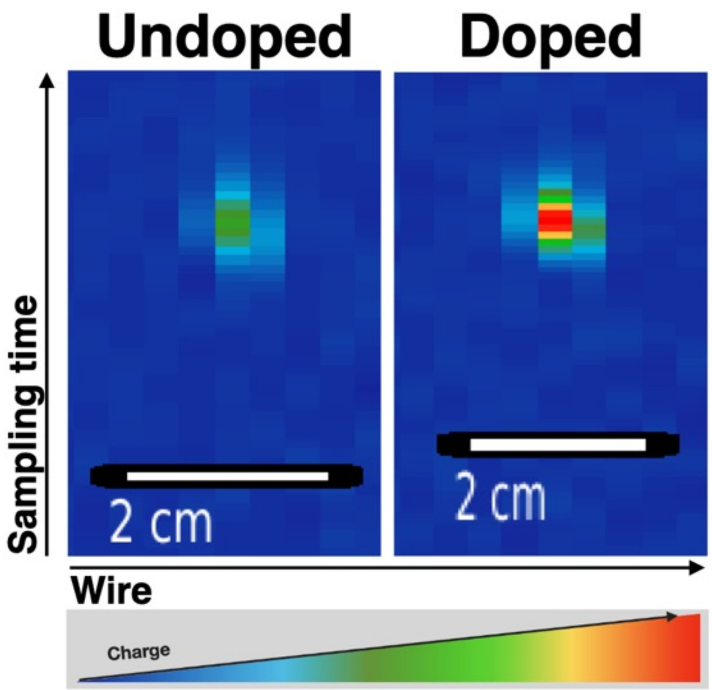
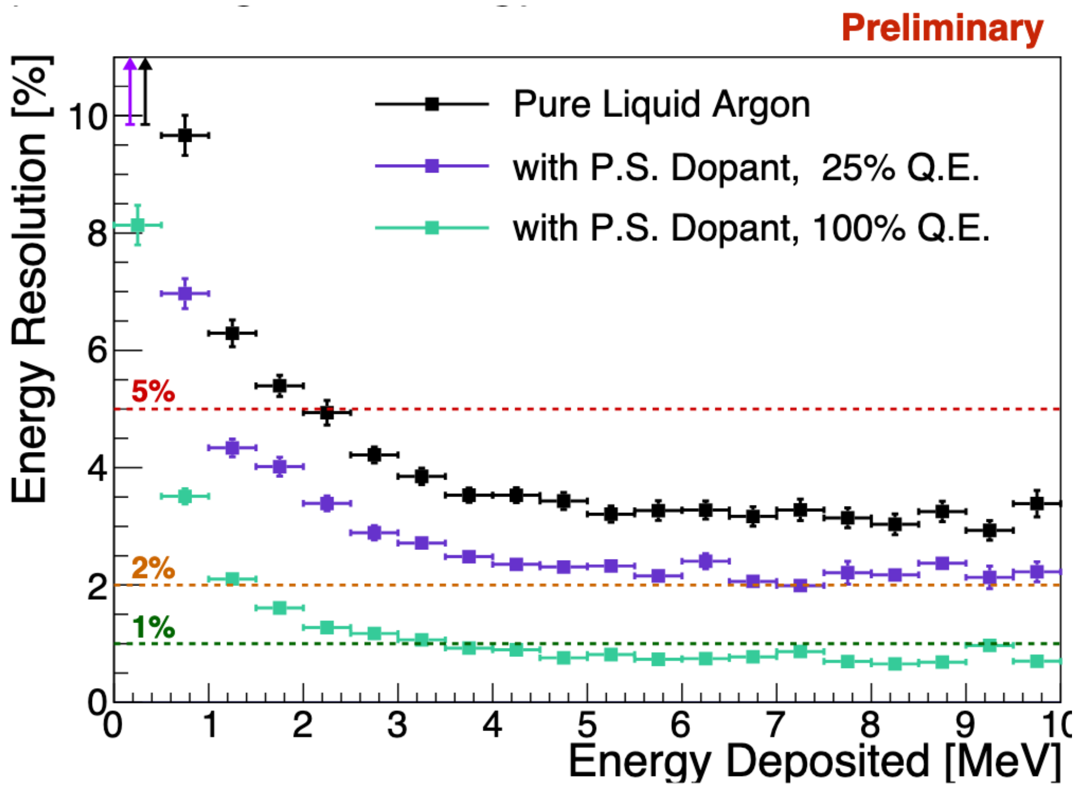


Photo-ionizing dopants





[Improving LArTPC Performance with Photo-Ionizing Dopants](), Joseph Zennamo

Solar neutrinos in DUNE

DUNE as the Next-Generation Solar Neutrino Experiment

Phys. Rev. Lett. 123, 131803

Δm_{12}^2 probed by day-night flux asymmetry

$$A_{D/N} = (D - N)/\tfrac{1}{2}(D + N)$$

Can break degeneracy between θ_{12} and $\phi(^8\mathrm{Bi})$ by measuring two interaction channels via crude angular cuts:

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^* \longrightarrow R_{\mathrm{Ar}} \propto \phi(^8\mathrm{B}) \times \sin^2\theta_{12}$$

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- \longrightarrow R_e \propto \phi(^8\mathrm{B}) \times \left(\sin^2\theta_{12} + \tfrac{1}{6}\cos^2\theta_{12}\right)$$

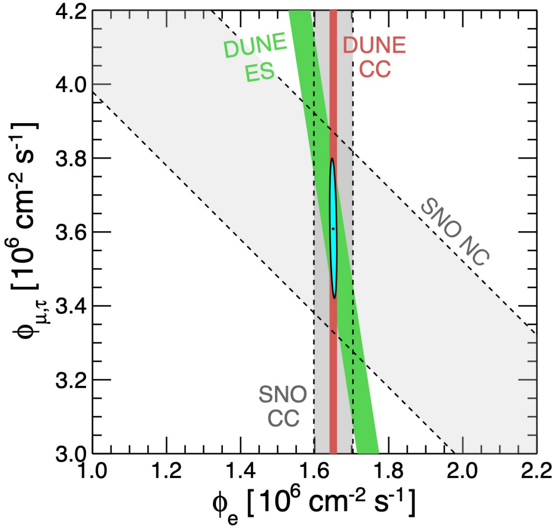


FIG. 3. Estimated precision of the ν_e and $\nu_{\mu,\tau}$ content of the ^{8}B flux, present (SNO [5, 53]) and future (DUNE), with the ellipse for DUNE alone. Based on a simplified analysis, with only statistical uncertainties (1σ) but assuming 2 d.o.f., and with SNO fluxes slightly rescaled to match their global-fit ^{8}B flux. Note small axis ranges. Full analysis in text.

Energy resolution improvements in LAr

[Phys. Rev. D 99, 036009 (2019)](#)

TABLE I. Detection thresholds according to the DUNE CDR document [5]. The values given correspond to the kinetic energy of each particle.

	p	$\pi^\pm$	γ	μ	e	others
Thresholds (MeV)	50	100	30	30	30	50

(1) *CDR thresholds*: Any particle created below the thresholds listed in Table I is lost.
(2) *Total charge calorimetry*: Thresholds are set to zero and no information about the hadronic system other than the total ionization charge is used.
(3) *Detailed event reconstruction*: Thresholds are low and recombination corrections are applied to each particle in the event individually.

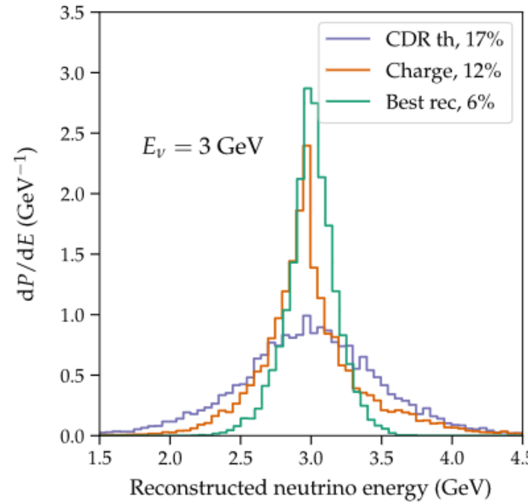


FIG. 14. Simulations of reconstructed neutrino energies for $E_\nu = 3$ GeV true energy in the CC $\nu_e + {}^{40}$Ar scattering process. The histograms correspond to three different sets of assumptions, as described in the text.

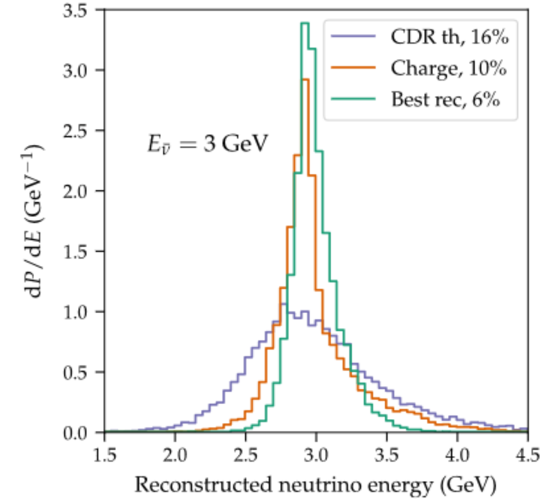
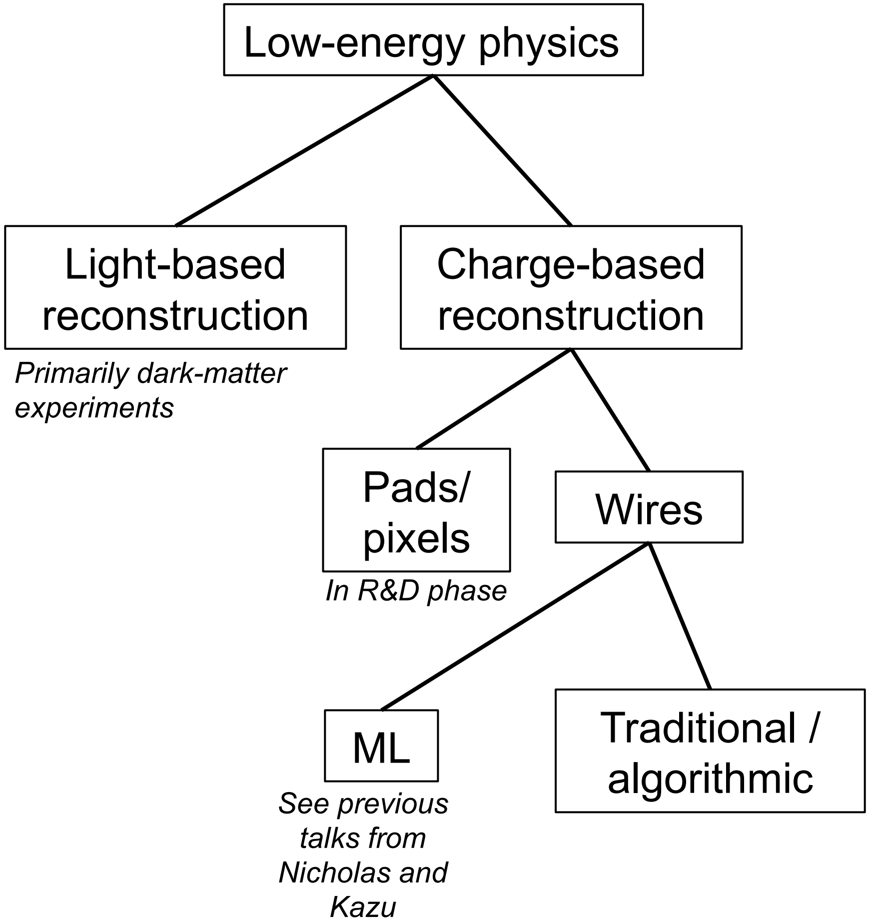


FIG. 15. Same as Fig. 14, but for $\bar{\nu}_e + {}^{40}$Ar scattering.

Understanding the energy resolution of liquid argon neutrino detectors

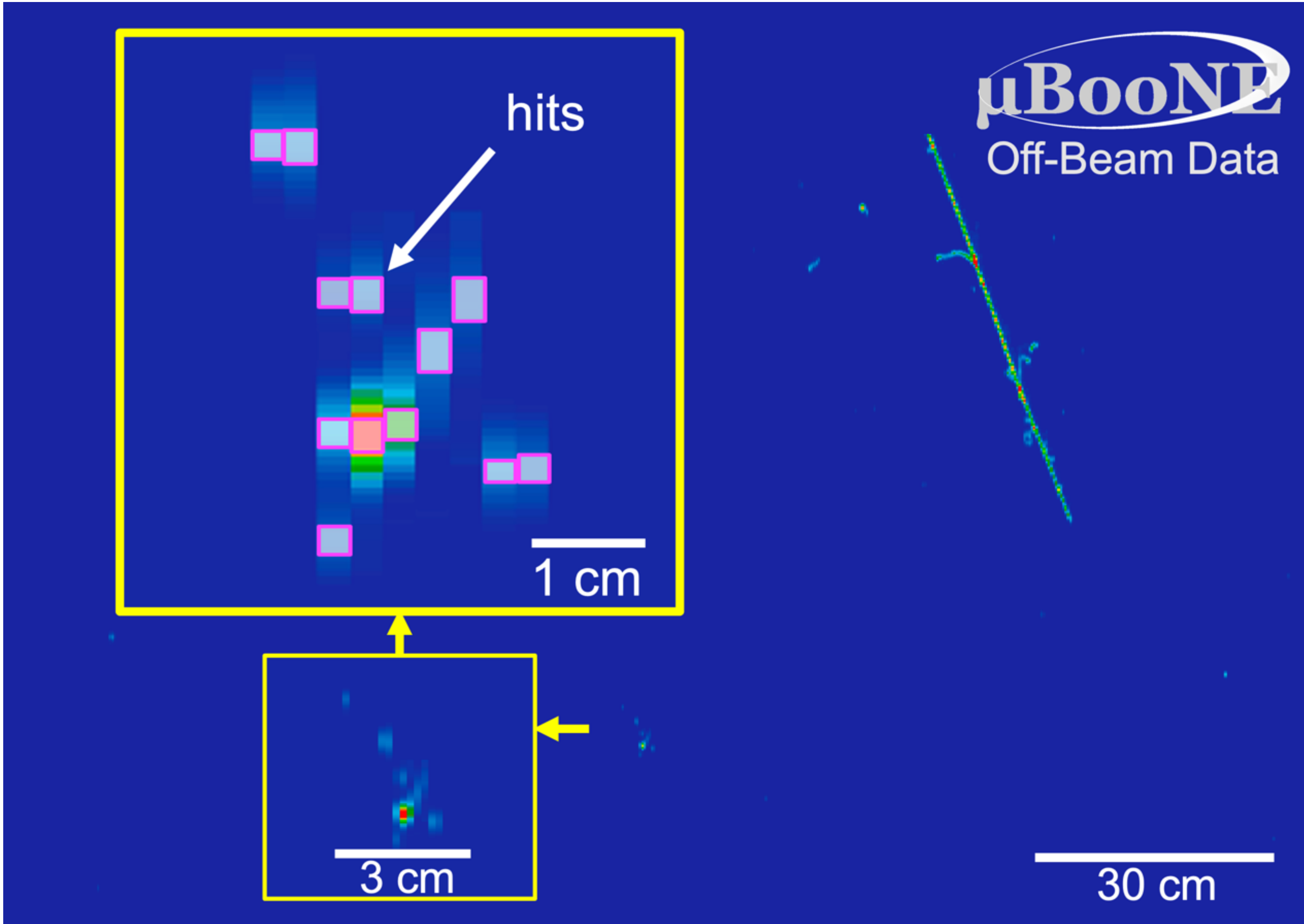
Alexander Friedland* and Shirley Weishi Li†
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA

(Received 13 December 2018; published 13 February 2019)

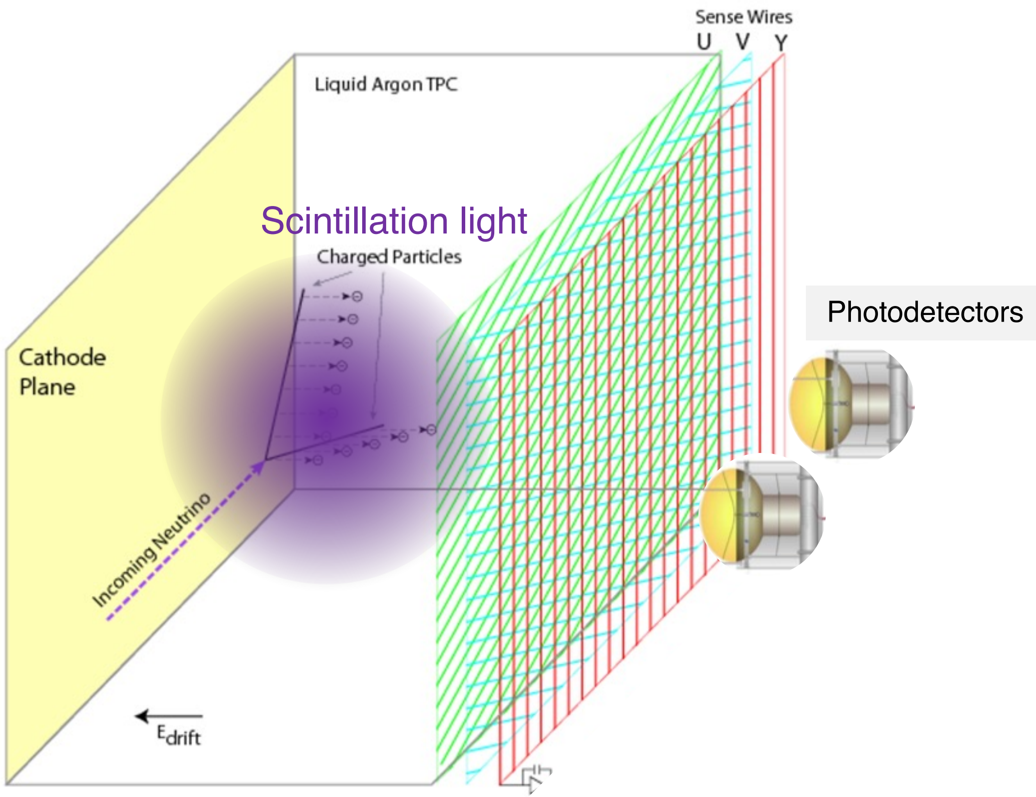


Traditional reconstruction

- Wire signals are noise-filtered and processed with deconvolution algorithms
- ADC thresholded hit-finding via Gaussian fits to pulses
- Advantages:
  - Software infrastructure in place in LArSoft & demonstrated with published results
  - Based on 'first-principles', no need to train a network
- Disadvantages:
  - Lowering thresholds is challenging
  - Limited by noise floor


hits
1 cm
3 cm
µBooNE
Off-Beam Data
30 cm

Yes, it's time for *that* diagram...

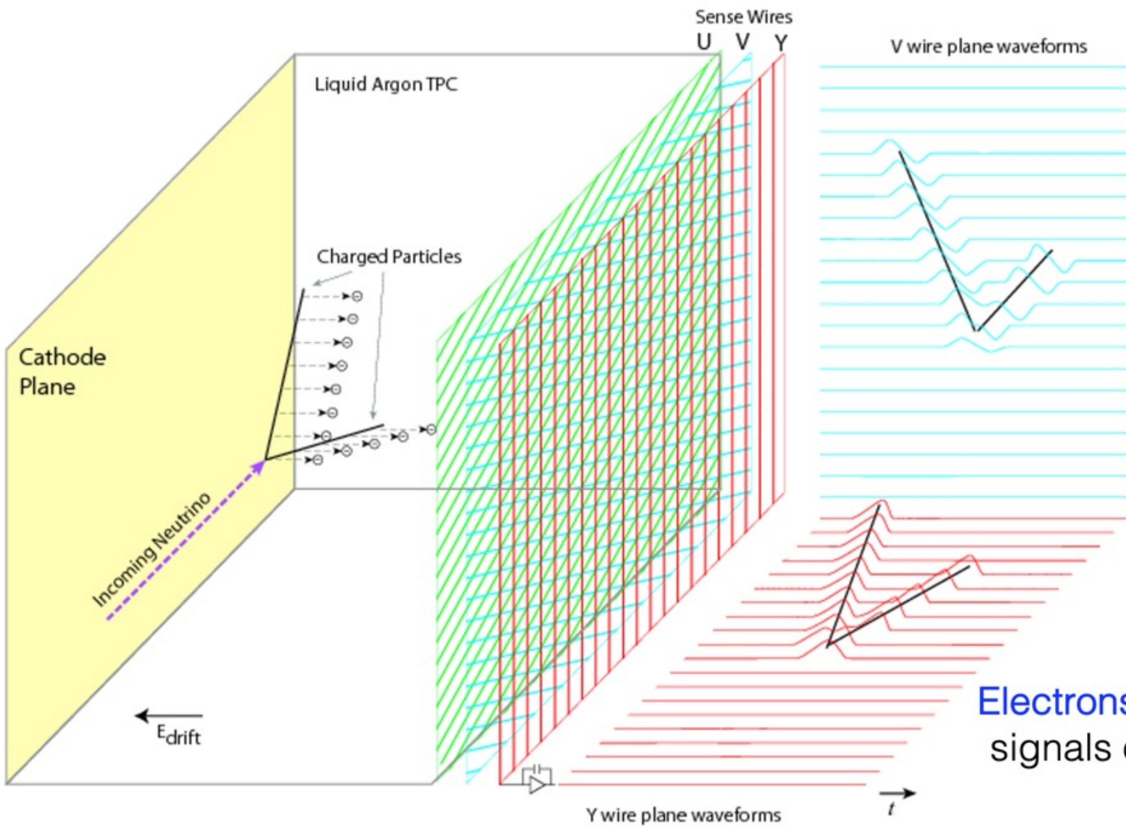


Liquid argon time projection chamber (LArTPC)

✓ **Scalable**

✓ **Prolific scintillator**

Yes, it's time for *that* diagram...



Electrons induce signals on wires

Liquid argon time projection chamber (LArTPC)

- ✓ **Scalable**
- ✓ **Prolific scintillator**
- ✓ **Millimeter-scale 3D images**
- ✓ **Calorimetry**

Ion mobility in LAr

Some fraction of isotopes are positive ions → drift toward cathode at very slow speeds

Phys Rev C 92, 045504

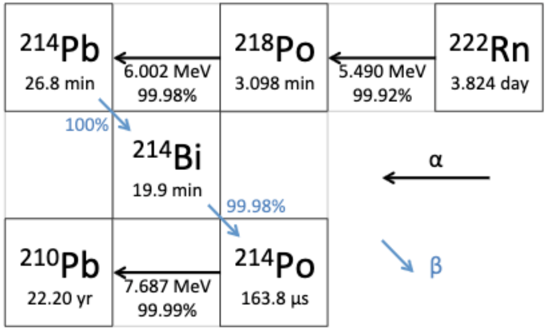
Results from LXe in EXO-200

$^{222}Rn \rightarrow {}^{218}Po^{+}$ $f_{\alpha} = 50.3 \pm 3.0\%)$

$v_d \sim 0.3\ cm^2 / (kV\ s)$

$^{214}Pb \rightarrow {}^{214}Bi^{+}$ $f_{\beta} = 76.5 \pm 5.7\%$

Implies that measured Bi→Po rate can't be directly translated to a ^{222}Rn rate, as some isotopes will have drifted and plated onto cathode



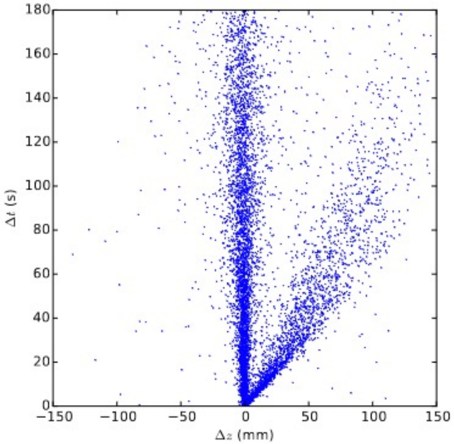


Figure 8. (Color online) Scatter plot of ^{218}Po drift distance versus time between the ^{222}Rn and ^{218}Po decays. Displacement (Δz) is defined as positive when movement is towards the cathode.

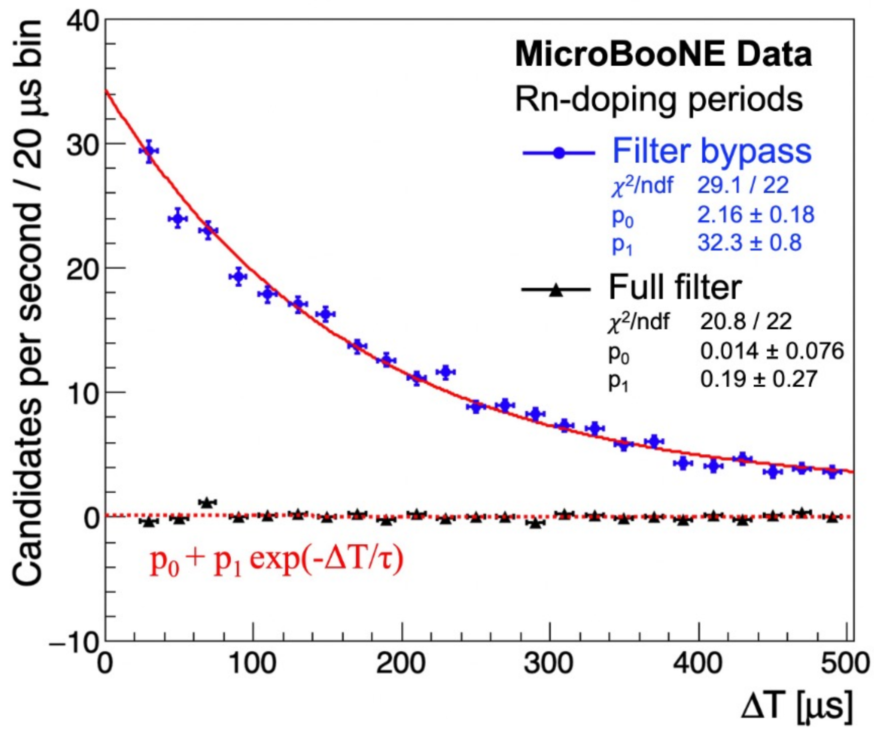
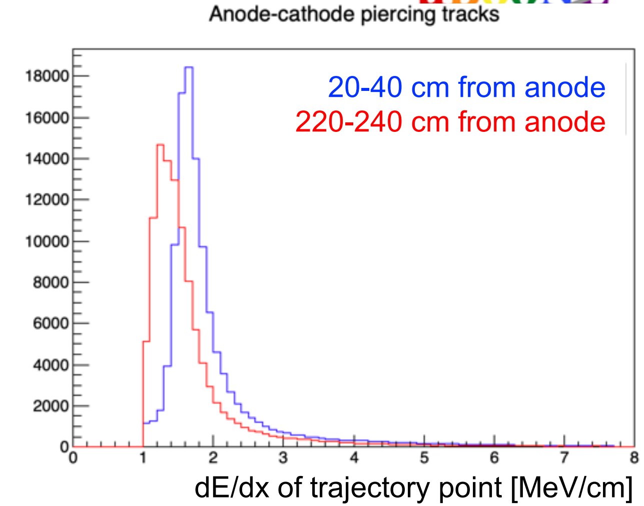
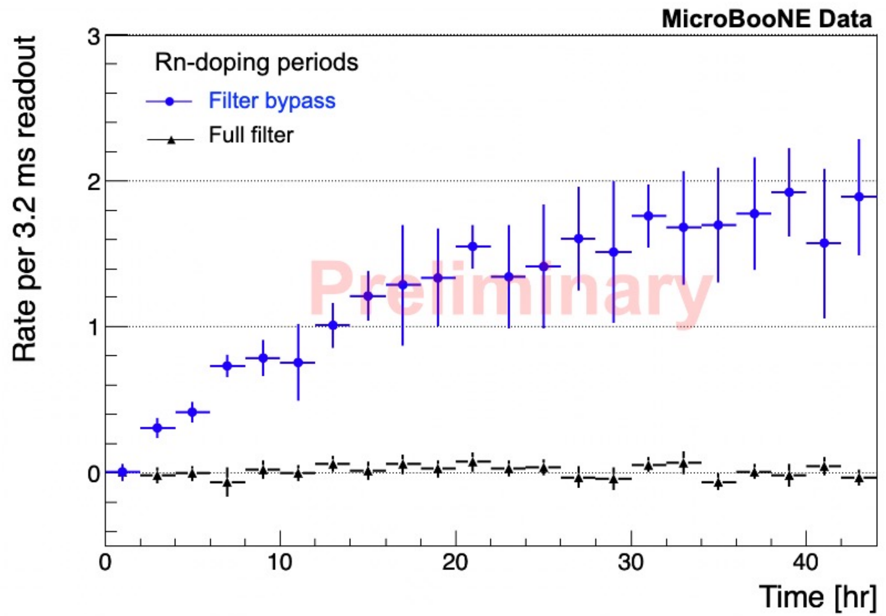


FIG. 9. The background-subtracted and fitted ΔT distributions for the Rn-doping data for a period when the filter was bypassed (blue) and the preceding period where the full filtration system was employed (black).

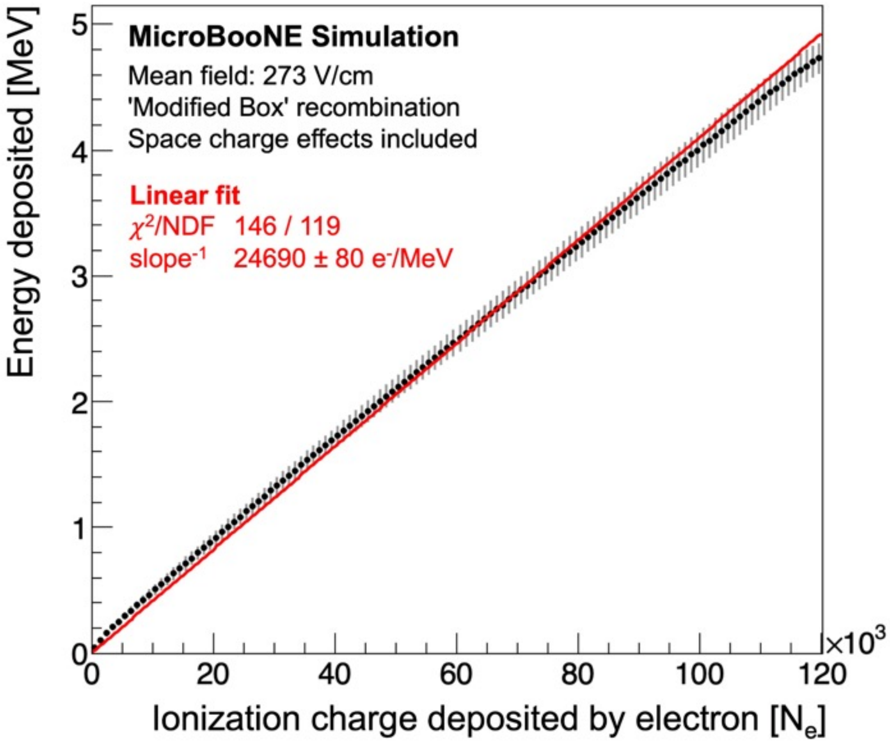
- Looked at ratio of dE/dx for segments of ACP tracks near and far from the wire planes
- Confirmed average ~8 ms lifetime (weighted by β candidates over time), consistent with previous estimate from scaling the Bi214 beta spectrum
  - Removes an 'unknown' in the energy scale puzzle





Time period [hrs]	Far/near dEdx ratio	Equivalent lifetime [ms]
0-5	1.01(2)	> 180
5-10	0.940(8)	29 +/- 12
10-15	0.902(8)	18 +/- 3
15-20	0.855(11)	12 +/- 2
20-25	0.828(12)	9.6 +/- 1.8
25-30	0.820(9)	9.2 +/- 0.5
30-35	0.776(6)	7.2 +/- 0.5
35-40	0.758(7)	6.6 +/- 0.6
40-45	0.735(7)	5.9 +/- 0.4

Charge vs energy for electrons

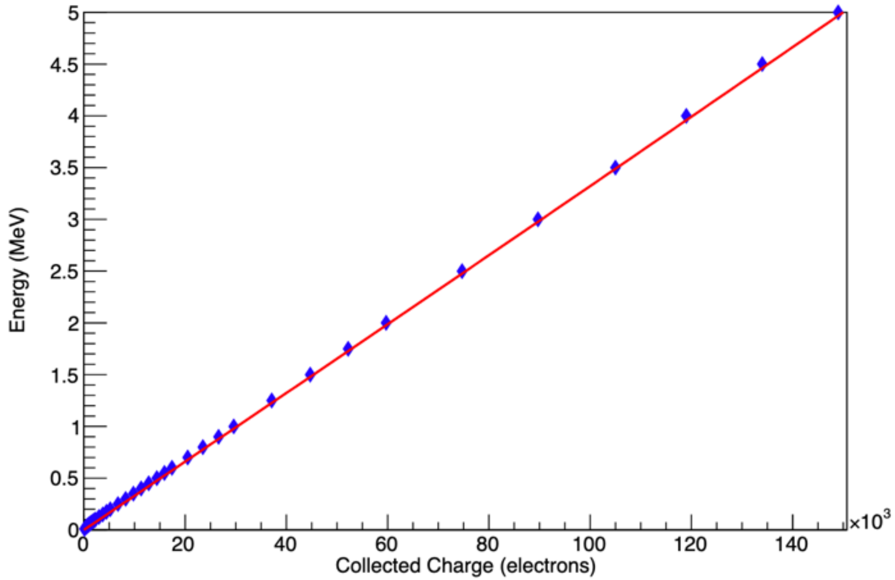


MicroBooNE (arXiv:1704.02927) and LArIAT (arXiv:1909.07920)

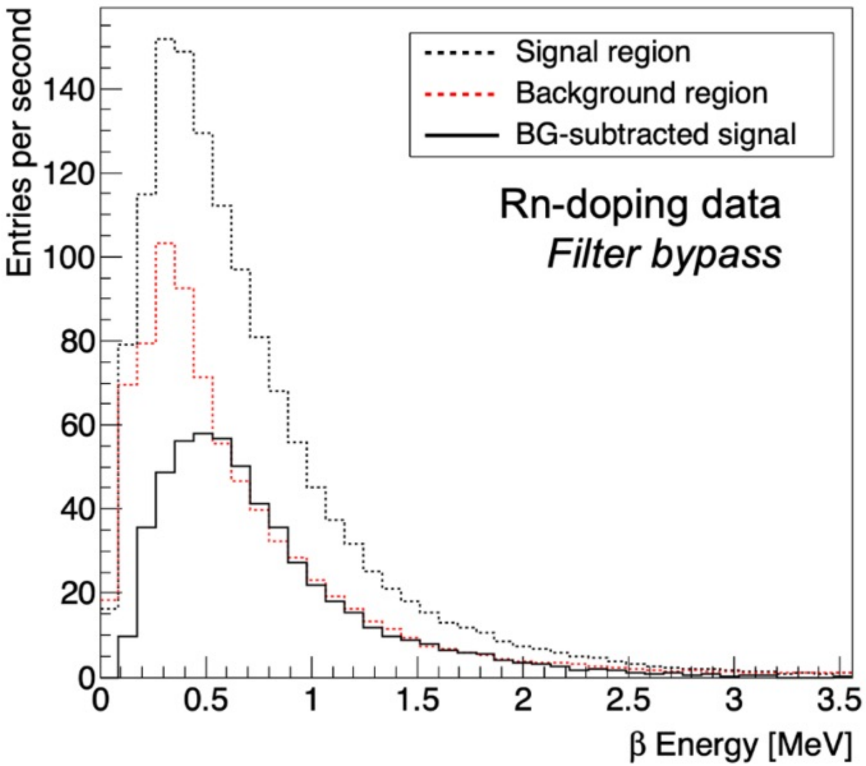
- Analyses of Michel electron showers
- For blips, assumed constant dE/dx (i.e., constant recombination)

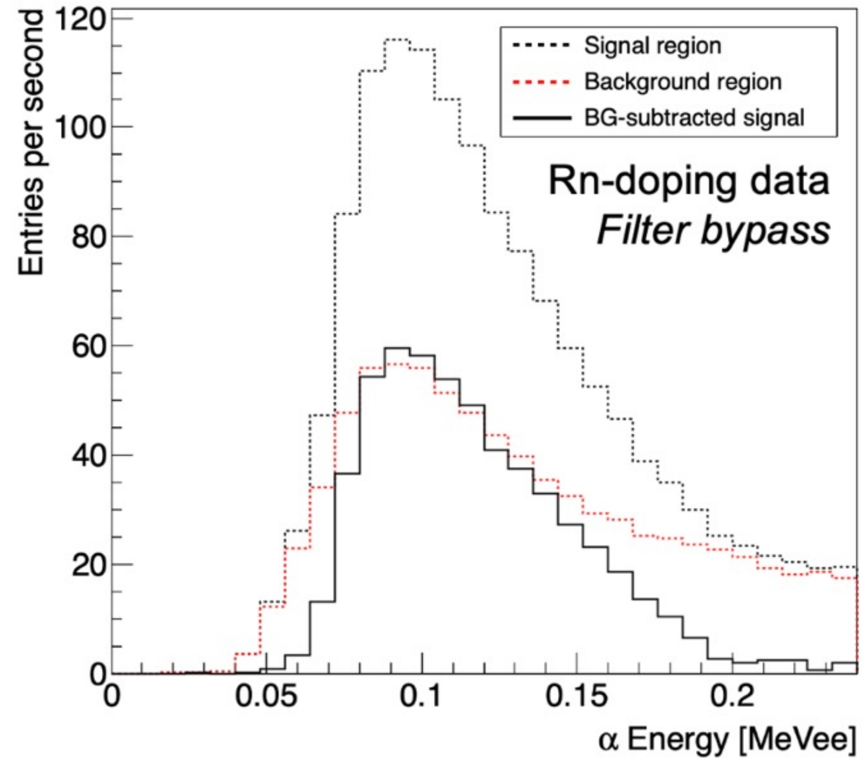
ArgoNeuT (arXiv:1810.06502)

- Nuclear de-excitation γ analysis
- Used NIST data on low-E electrons, together with recombination, to directly relate measured Q to energy

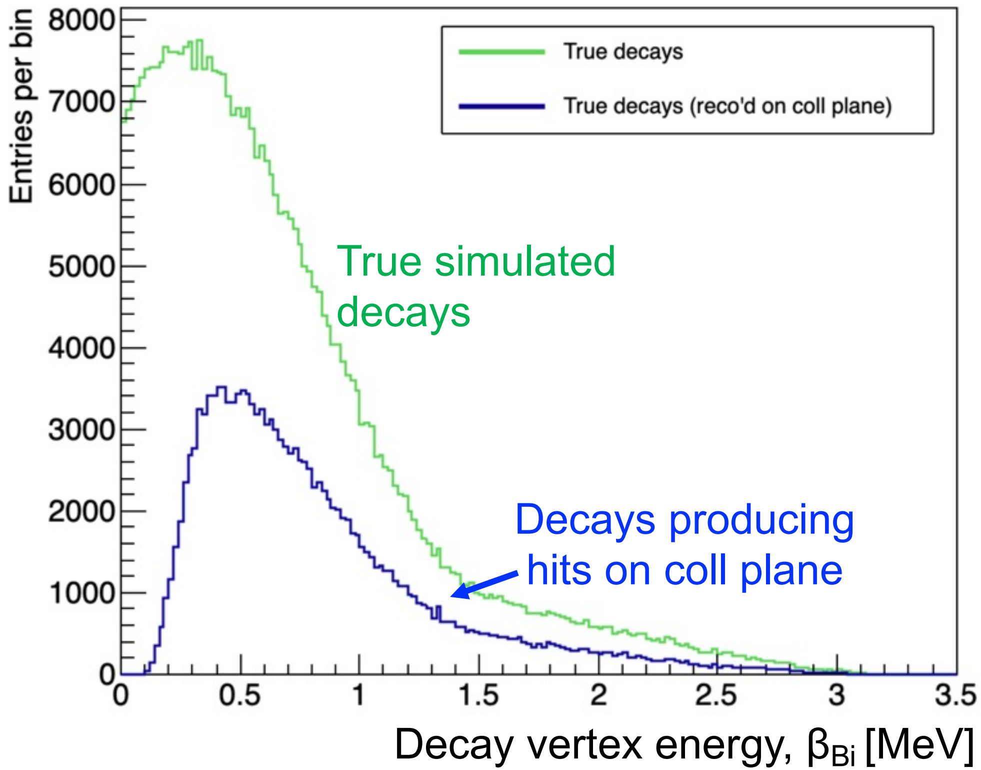


Energy spectra backgrounds





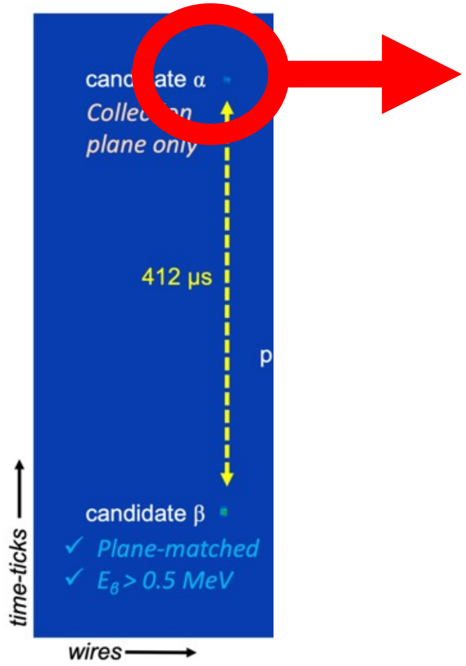
Simulated energy spectra



Calorimetric validation: α_{Po}

Using NEST-parameterized alpha charge-yield (QY) model

https://zenodo.org/record/7577399



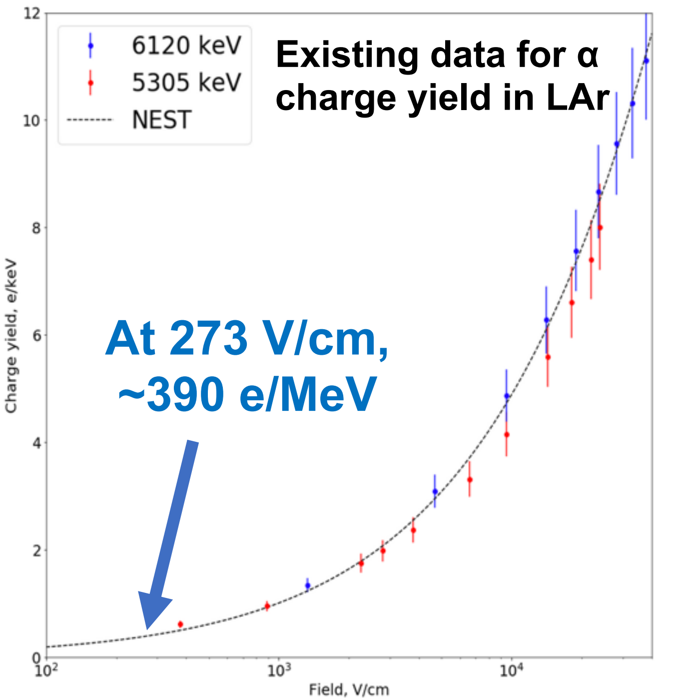
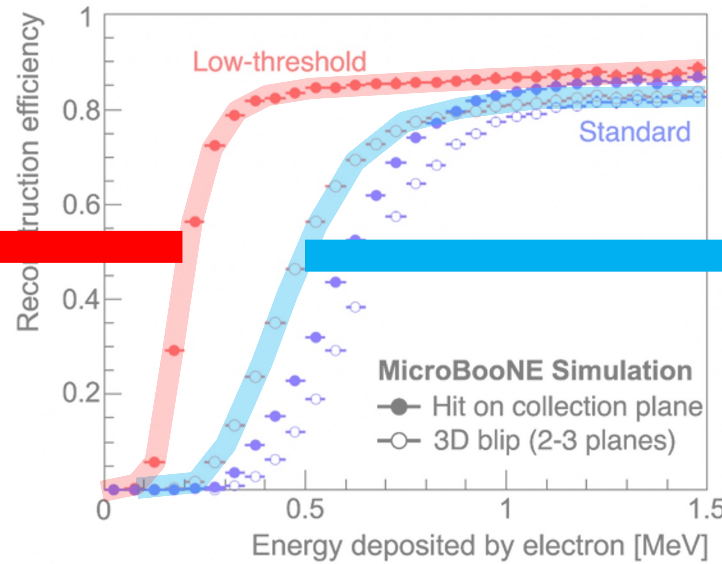
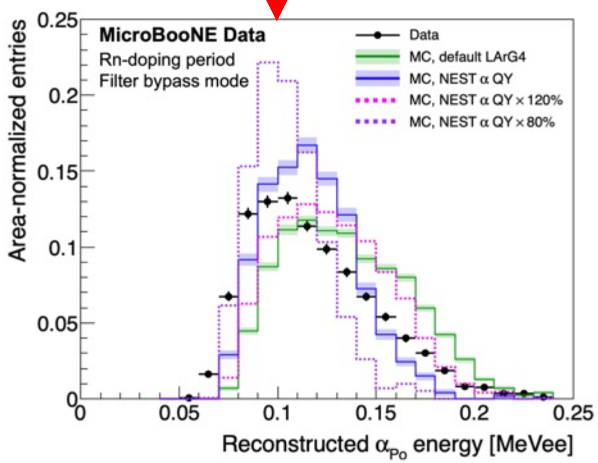
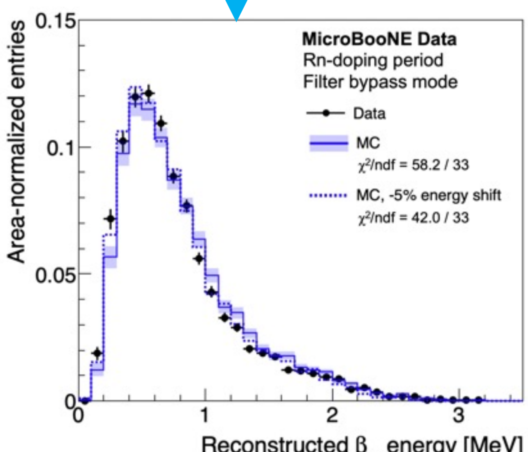


Figure 9: Charge yield model comparison with data from Po-210 and Cf-252





Heavily sculpted by hit-finding thresholds



Monte Carlo Efficiency

α QY: +/-20%

D_L: ± 1σ, D_T: ± 30%

All charge scaled +/-5%

'Birks' model, and enhanced recombination fluctuations

Systematic	Uncertainty
Alpha QY	± 43%
Electron diffusion	+26%, -17%
Energy scale	± 15%
Recombination modeling	± 1.9%
Total	+52%, -49%

Final efficiency for BiPo rate measurement:
$\varepsilon = (6 \pm 3)\ \%$

Contributions to efficiency

	Relative probability (NEST)	Relative probability (LArG4)
Volume remaining after 2D cosmic track-masking	~86%	same
Bi214 beta decays producing collection plane hits*	~51%	same
Bi214 blips plane-matched	~62%	same
Po214 alphas producing collection plane hits	~22%	~43%
Total	**~6%**	**~12%**

* Using ‘low-threshold’ reconstruction

CNN-based ROI finder in ArgoNeuT

JINST 17 (2022) P01018

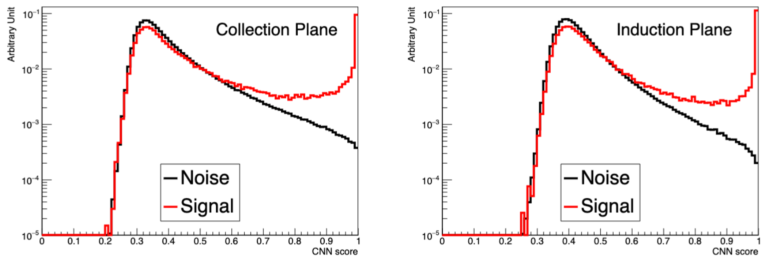
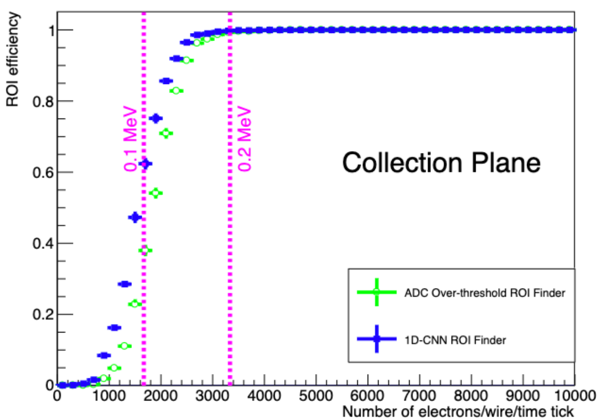


Figure 7. 1D-CNN scores for simulated noise and signal wavefoms in the induction plane (right) and the collection plane (left).



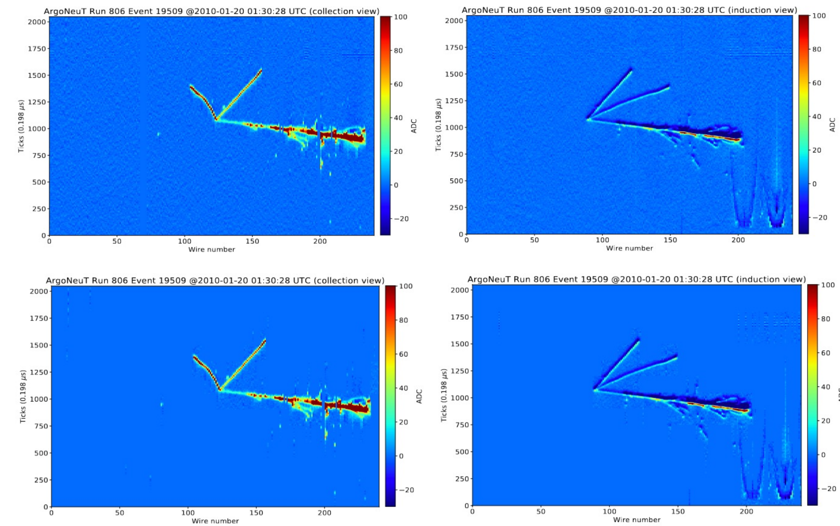


Figure 8. Event display after applying the 1D-CNN ROI finder for the event shown in Figure 1 and Figure 2.

BlipReco code structure

ubreco/BlipReco (3.3 MB total)

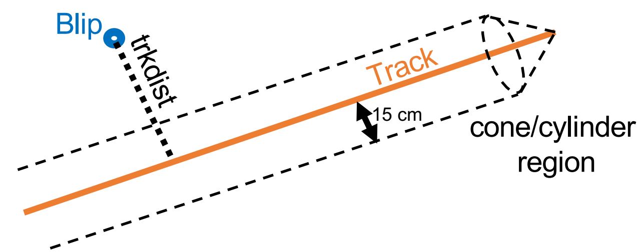
```
Alg
BlipAna_module.cc
blipreco_badchannels.txt
blipreco_configs.fcl
BlipRecoProducer_module.cc
CMakeLists.txt
job
ParticleDump_module.cc
TrackMasker_module.cc
Utils
```

Utils

```
BlipUtils.cc
BlipUtils.h
classes_def.xml
classes.h
CMakeLists.txt
DataTypes.h
```

DataTypes.h

```
struct Blip {

  int       ID              = -9;       // Blip ID / index
  bool      isValid         = false;    // Blip passes basic checks
  int       TPC             = -9;       // TPC
  int       NPlanes         = -9;       // Num. matched planes
  int       MaxWireSpan     = -9;       // Maximum span of wires on any plane cluster
  float     Charge          = -9;       // Charge on calorimetry plane
  float     Energy          = -999;     // Energy (const dE/dx, fcl-configurable)
  float     EnergyESTAR     = -999;     // Energy (ESTAR method from ArgoNeuT)
  float     Time            = -999;     // Drift time [ticks]
  float     ProxTrkDist     = -9;       // Distance to cloest track
  int       ProxTrkID       = -9;       // ID of closest track
  bool      inCylinder      = false;    // Is it in a cone/cylinder region?

  TVector3  Position;                   // 3D position TVector3
  float     SigmaYZ         = -9.;      // Uncertainty in YZ intersect [cm]
  float     dX              = -9;       // Equivalent length along drift direction [cm]
  float     dYZ             = -9;       // Approximate length scale in YZ space [cm]

  // Plane/cluster-specific information
  blip::HitClust clusters[kNplanes];

  // Truth-matched energy deposition
  blip::TrueBlip truth;

  // Prototype getter functions
  double X() { return Position.X(); }
  double Y() { return Position.Y(); }
  double Z() { return Position.Z(); }
```



"Blip" data object prototype (C++ struct)

- Encodes XYZ, charge, & energy of 3D blips
- Includes distance to nearest track & track cone-cylinder region flag
- Truth-matching information also encoded

DataTypes.h

```
// True energy depositions
struct TrueBlip {
  int       ID              = -9;       // unique blip ID
  int       TPC             = -9;       // TPC ID
  float     Time            = -999e9;   // time [us]
  float     Energy          = 0;        // energy dep [MeV]
  int       DepElectrons    = 0;        // deposited electrons
  int       NumElectrons    = 0;        // electrons reaching wires
  float     DriftTime       = -9;       // drift time [us]
  int       LeadG4ID        = -9;       // lead G4 track ID
  int       LeadG4Index     = -9;       // lead G4 track index
  int       LeadG4PDG       = -9;       // lead G4 PDG
  float     LeadCharge      = -9;       // lead G4 charge dep
  TVector3  Position;                   // XYZ position
```