# BSM Searches with LArTPCs

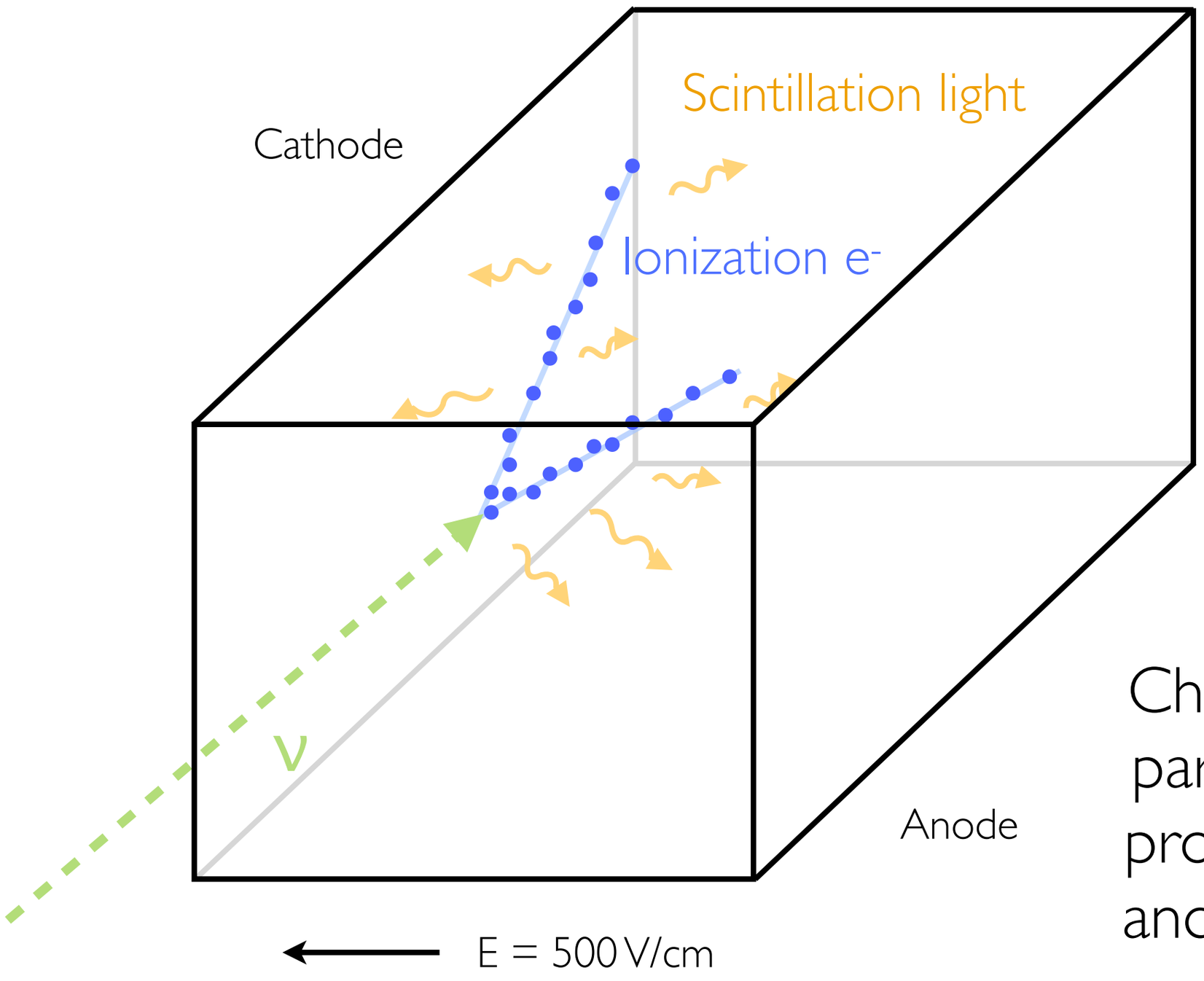
Yun-Tse Tsai (SLAC)

BSM UTA Workshop

April 12th 2019

SLAC NATIONAL ACCELERATOR LABORATORY

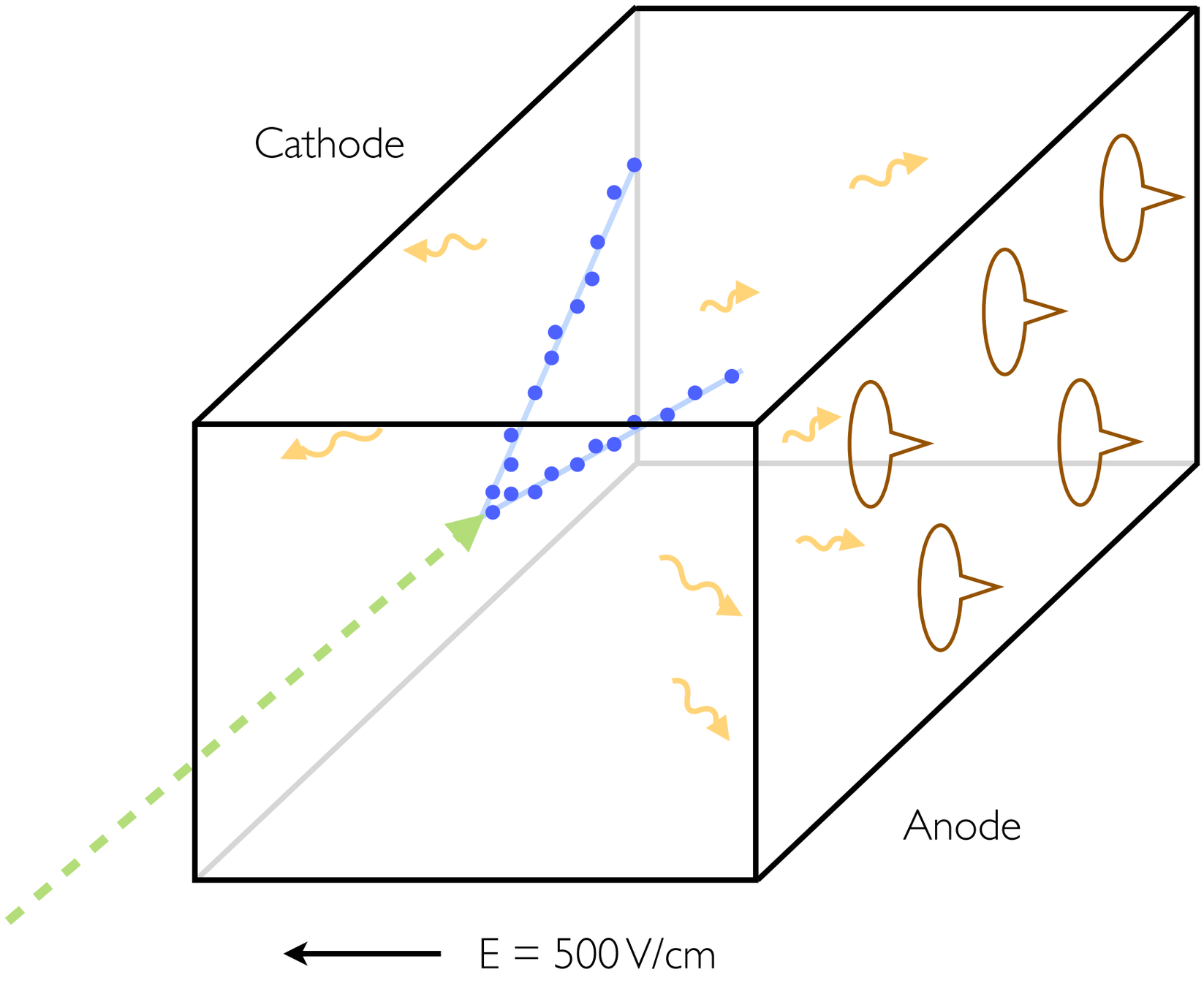
# LArTPC




Incoming neutrino interacting with LAr

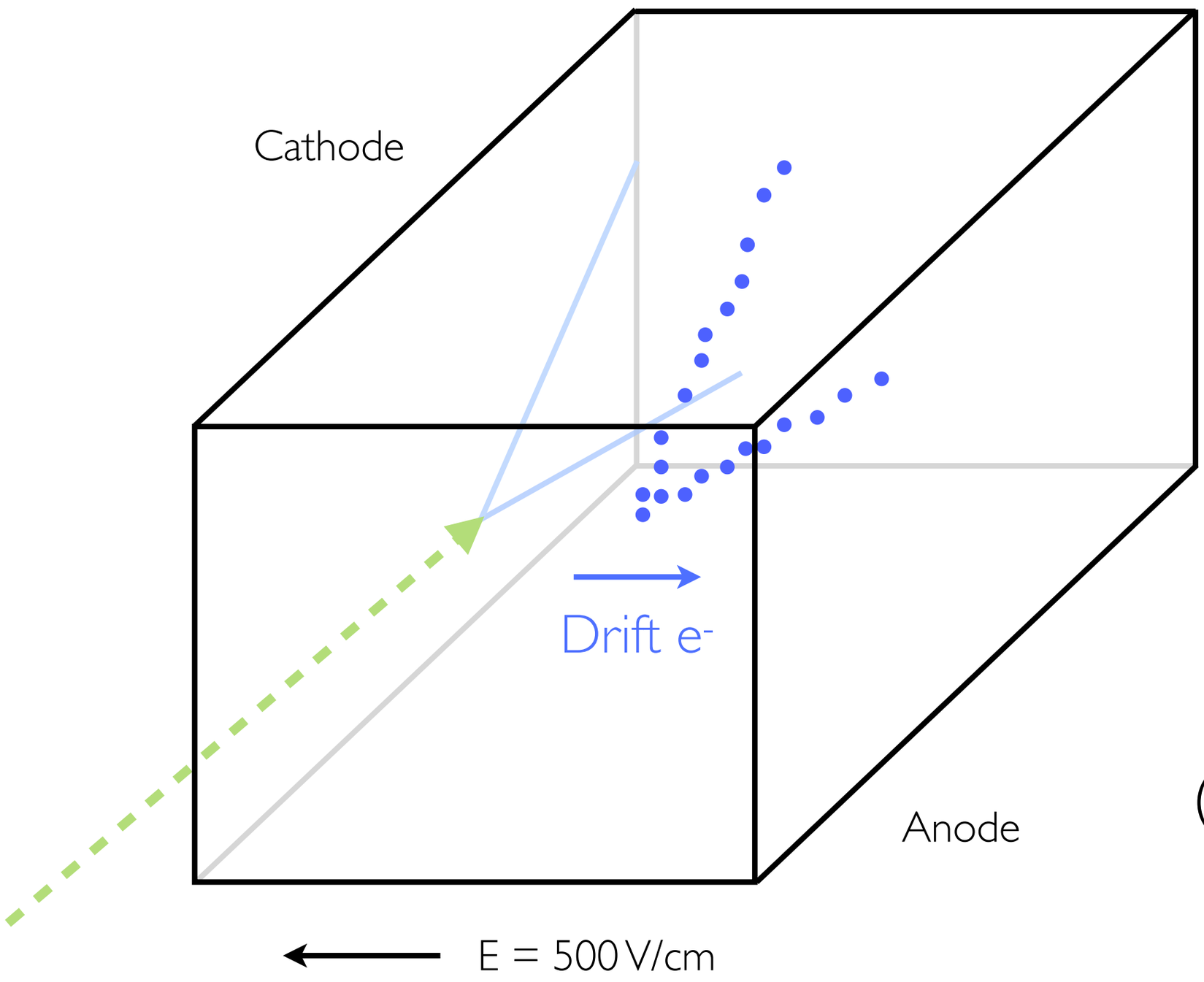
Charged secondary particles ionize LAr, producing electrons and scintillation light

# LArTPC



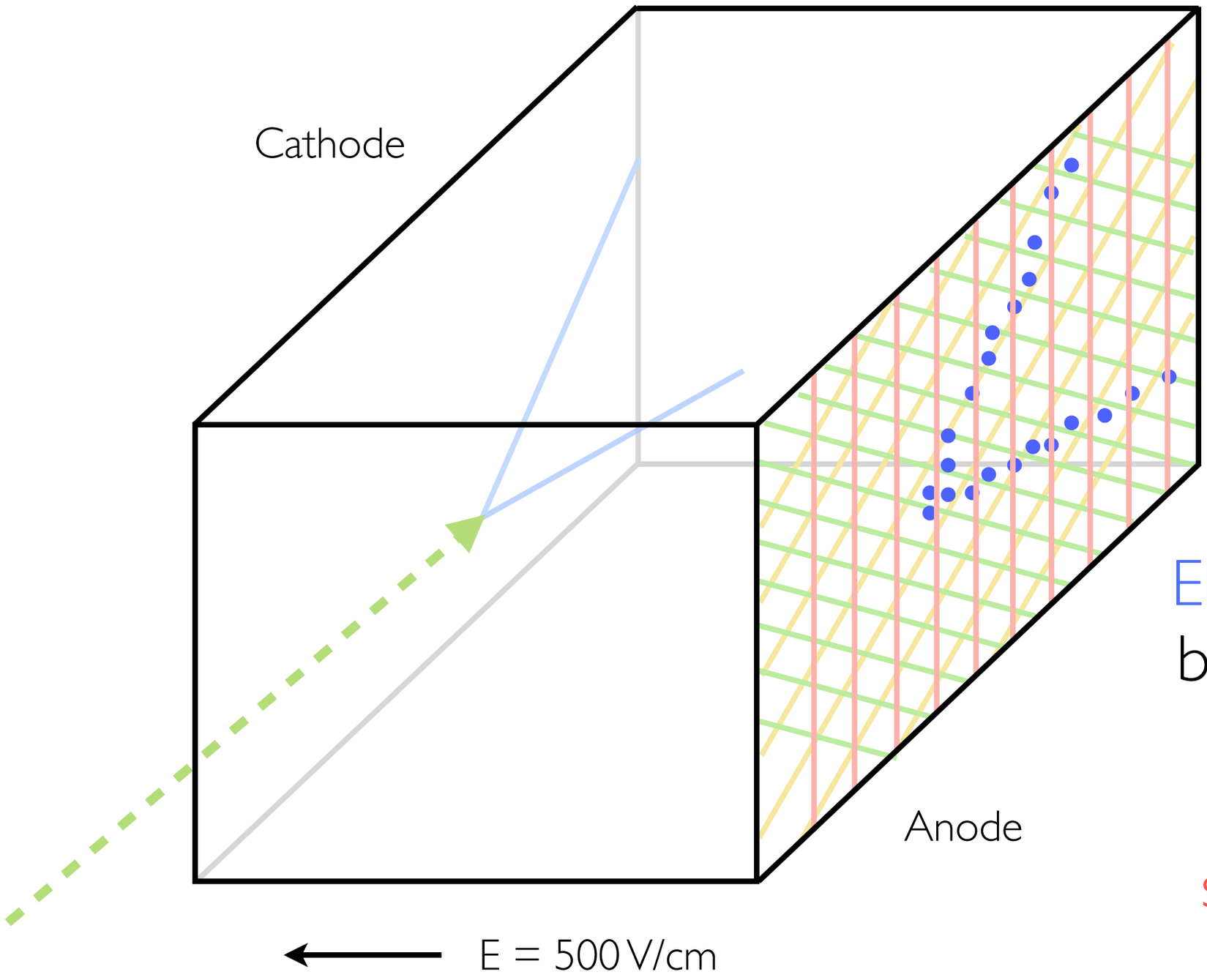

Light collected by PMT, determining event time $t_0$

# LArTPC




Electrons drift towards anode (drift time at ms scale)

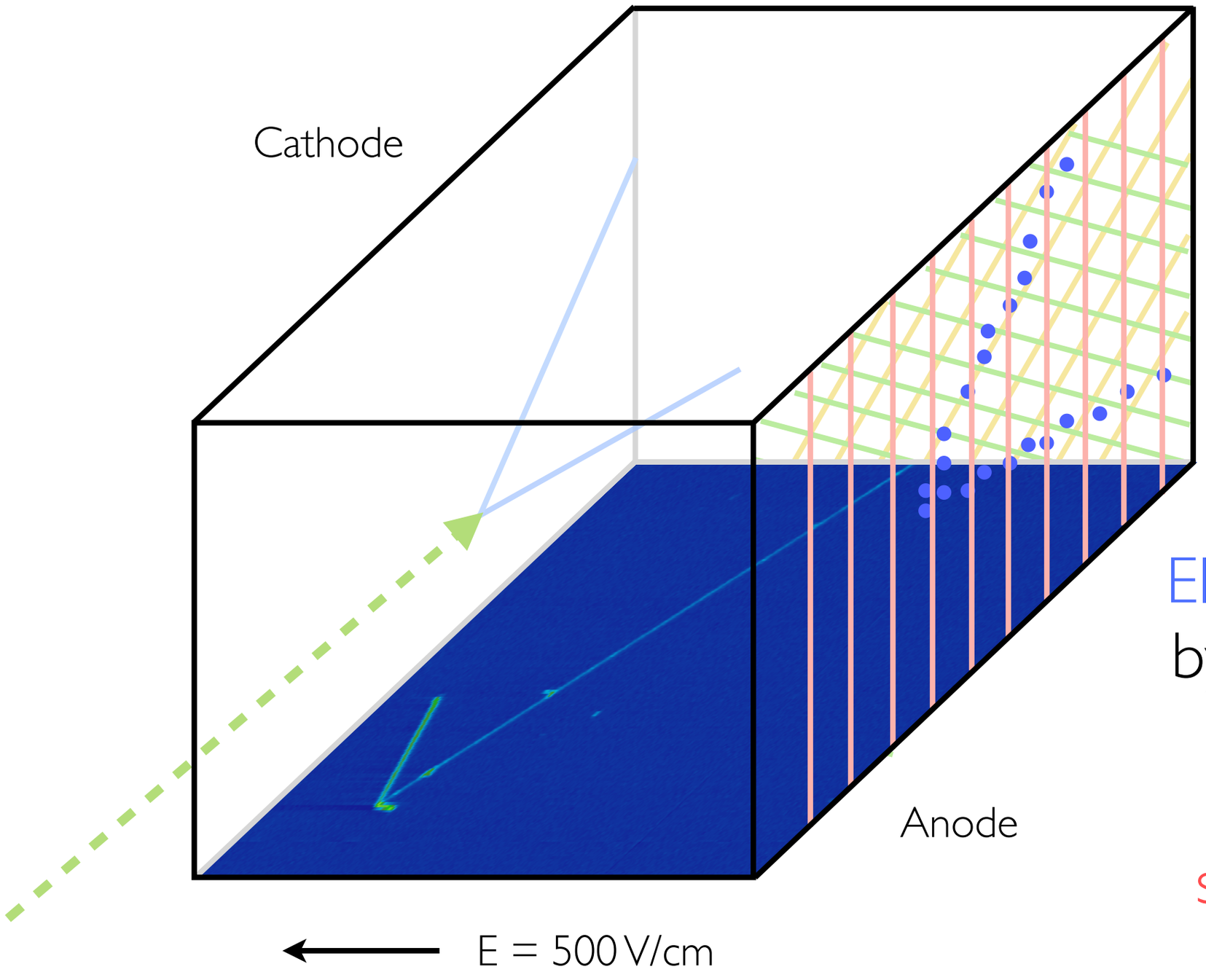
# LArTPC




2 induction planes
1 collection plane

Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

# LArTPC

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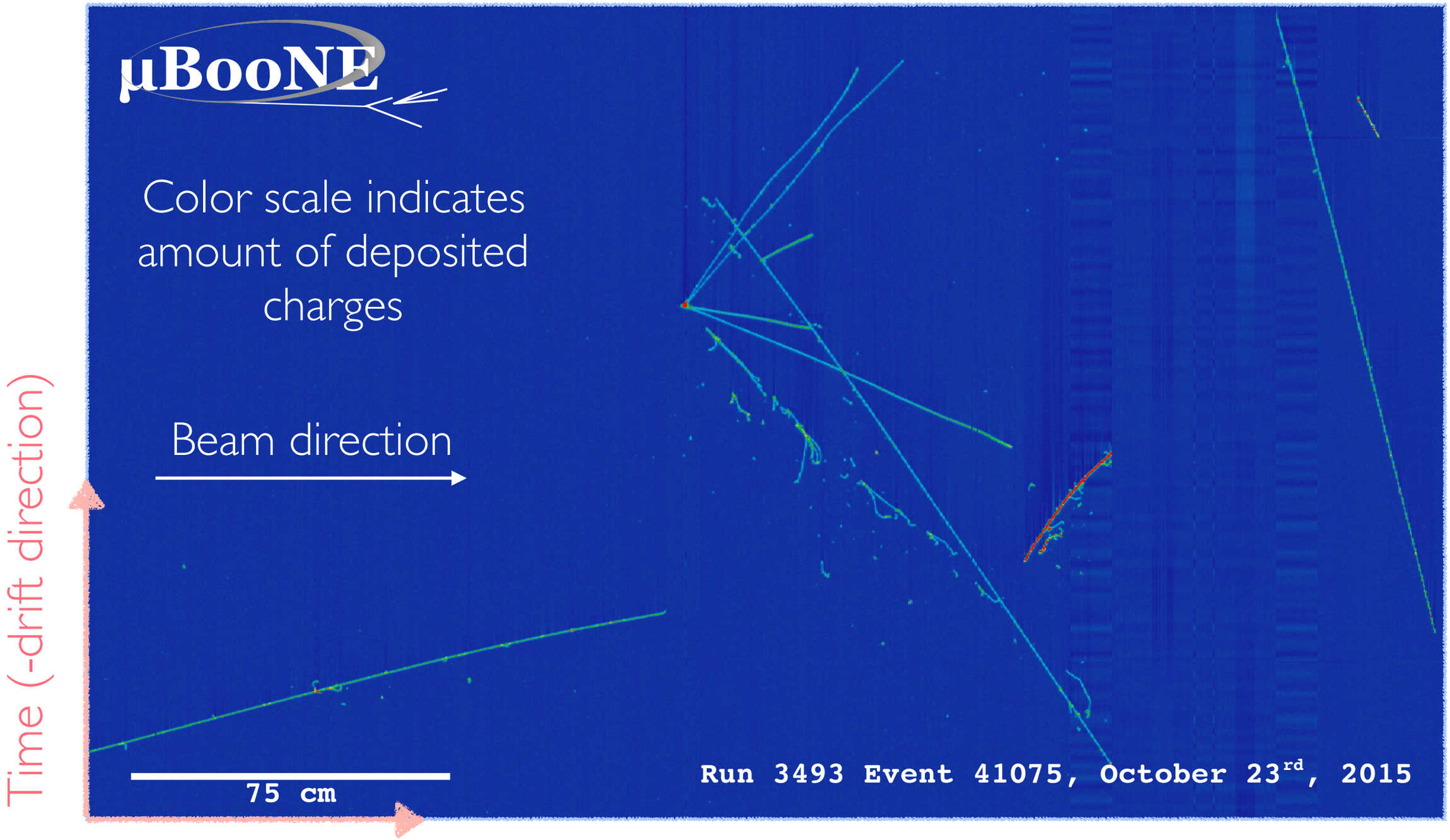
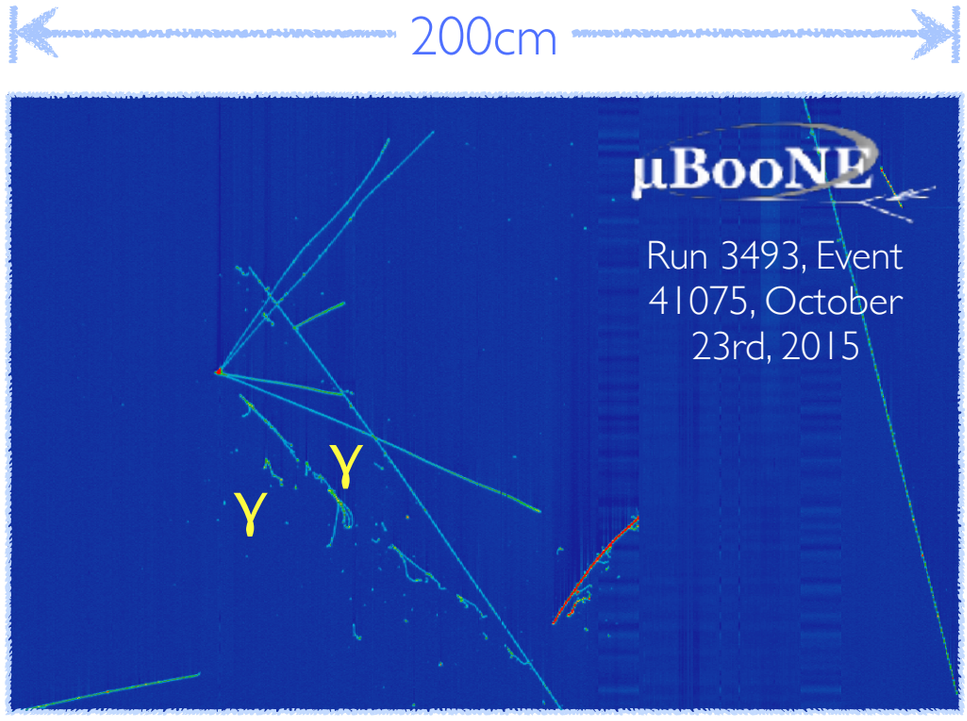
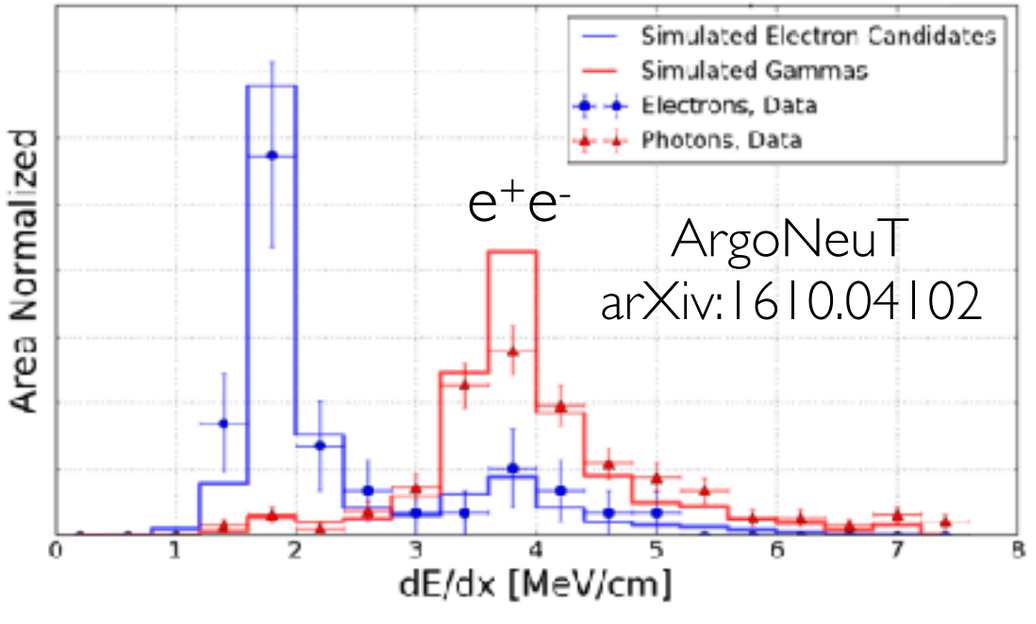

μBooNE
Color scale indicates amount of deposited charges
Beam direction
75 cm
Run 3493 Event 41075, October 23rd, 2015
Time (-drift direction)
Wire

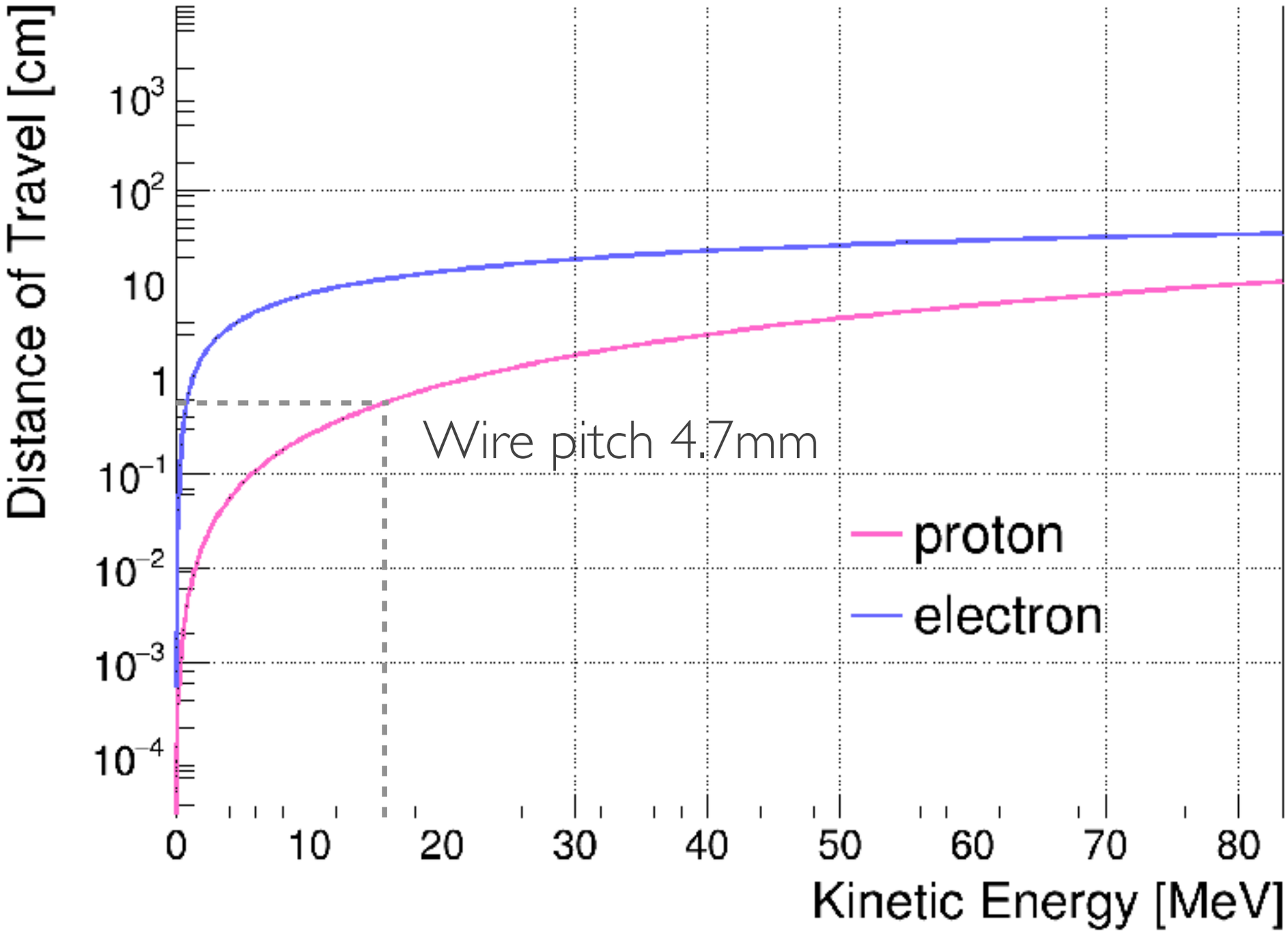
# Why LArTPC?

- Liquid-Argon Time-Projection Chamber
- LAr: large interaction rate
- Modular and scalable
- Millimeter resolution
- Calorimetric measurement
  - e/γ separation
- Supernova $\nu_e$ (E~10MeV)
- Low detection threshold
- Potential for new physics



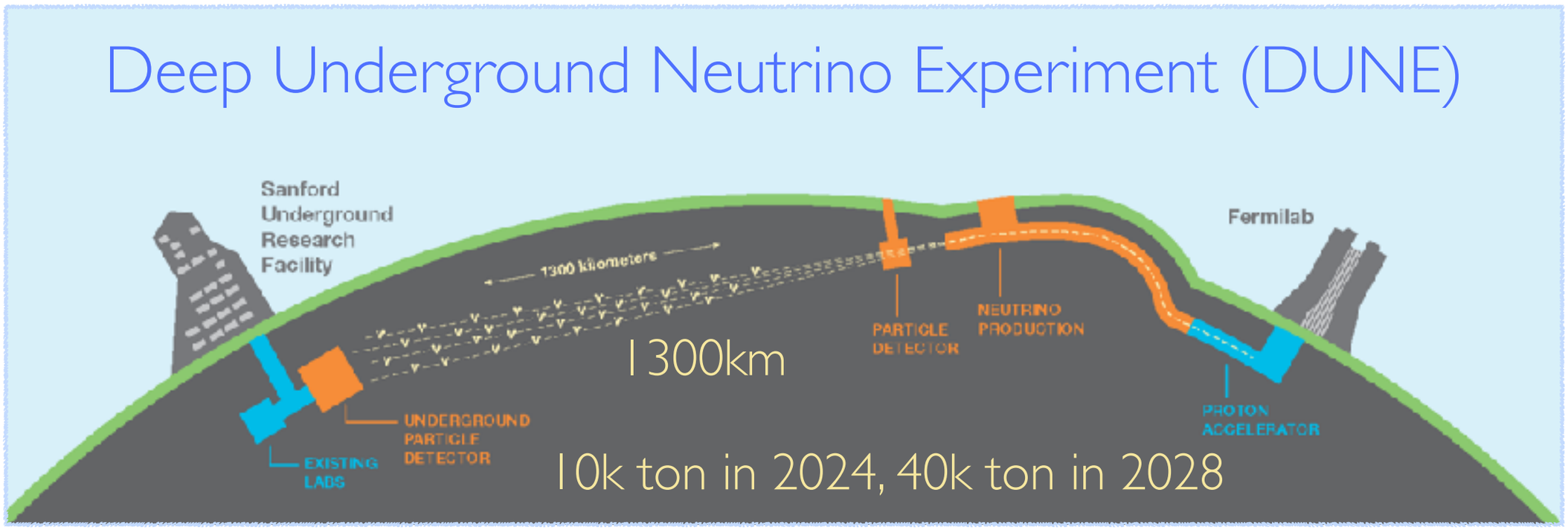



# Low Energy Threshold



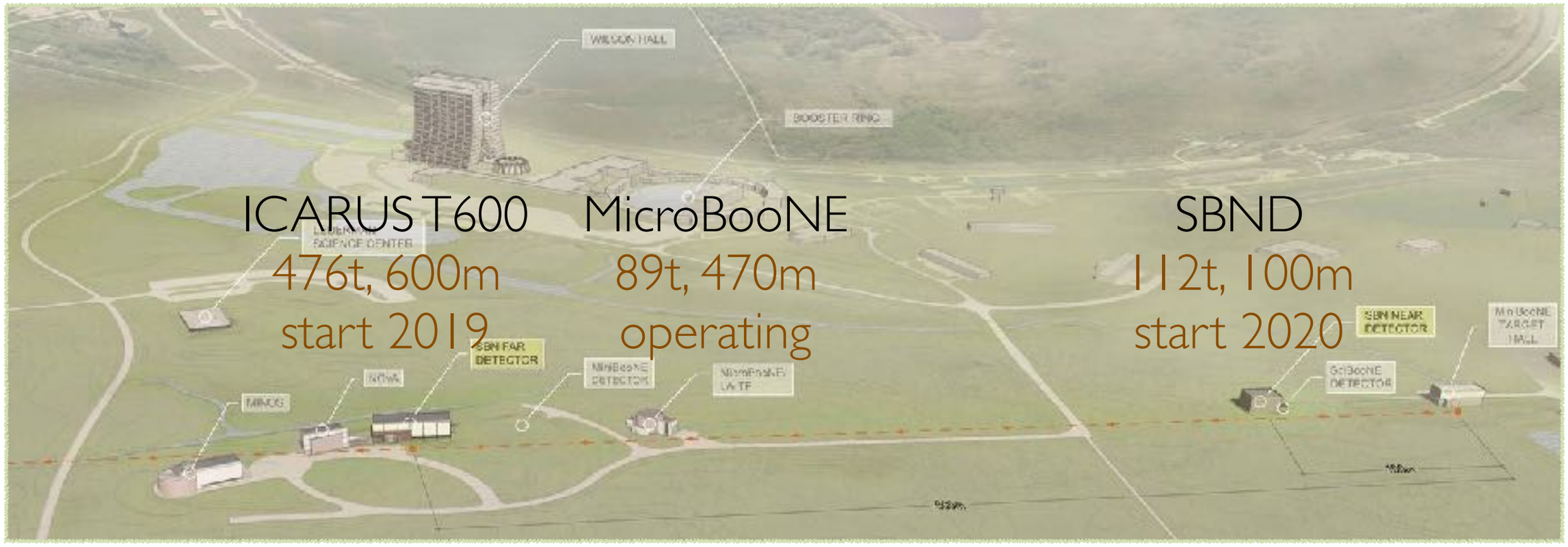
# Long Baseline Experiment

## Deep Underground Neutrino Experiment (DUNE)




- Aim to measure
  - CP violation in lepton sector
  - neutrino mass ordering
  - neutrinos from supernovae, proton decays, etc.
- $\nu_\mu$ from Fermilab accelerator, detected by LArTPC

# Short Baseline Program




ICARUS T600
476t, 600m
start 2019

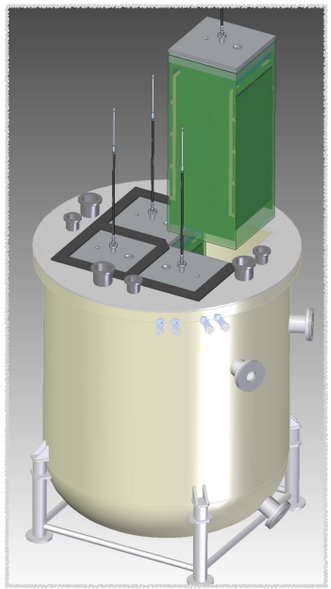
MicroBooNE
89t, 470m
operating

SBND
112t, 100m
start 2020

- Address LSND and MiniBooNE anomalies: sterile $\nu$?
- Measure $\nu$-Ar cross section
- BNB $\nu_\mu$ from Fermilab accelerator
- 3 LArTPC detectors in different baselines

# Available LArTPCs

prototype



- DUNE near detectors:
  - Characterize the neutrino flux
  - Measure **ν** cross sections

~500m,
O(100ton)

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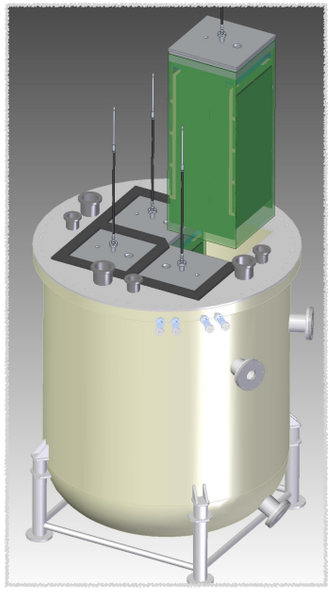

- DUNE near detectors:
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  - Search for new particles produced in the beam, e.g. heavy neutral lepton, dark sector and millicharged particles

Dark matter?

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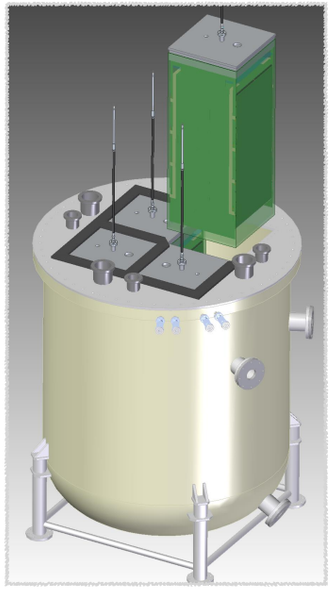

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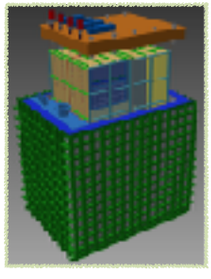
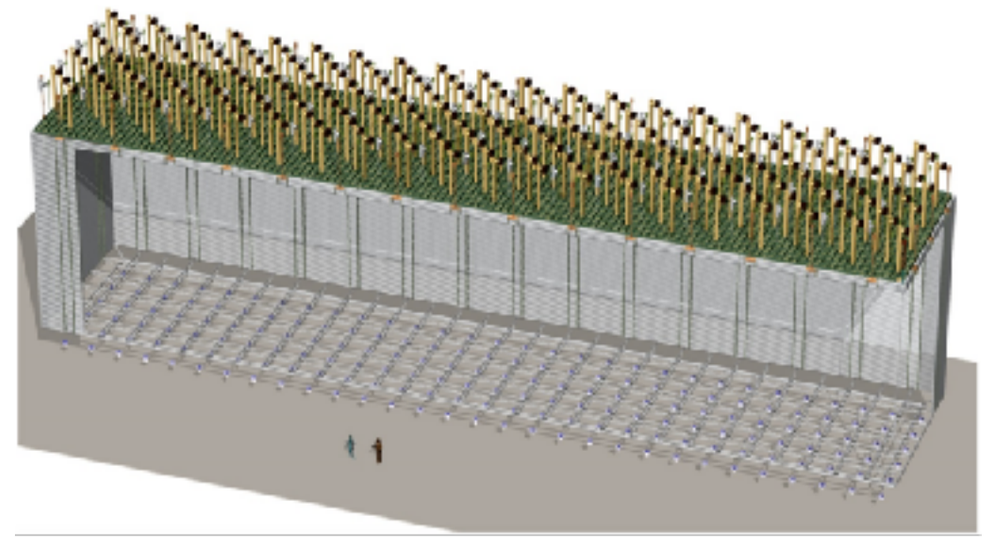


- Short baseline neutrino program:
  Search for sterile **ν**

~500m,
O(100ton)

# Available LArTPCs

- DUNE far detectors
  - CP violation
  - Mass ordering
  - Neutrino mixing parameters



>1000km, ~40k ton

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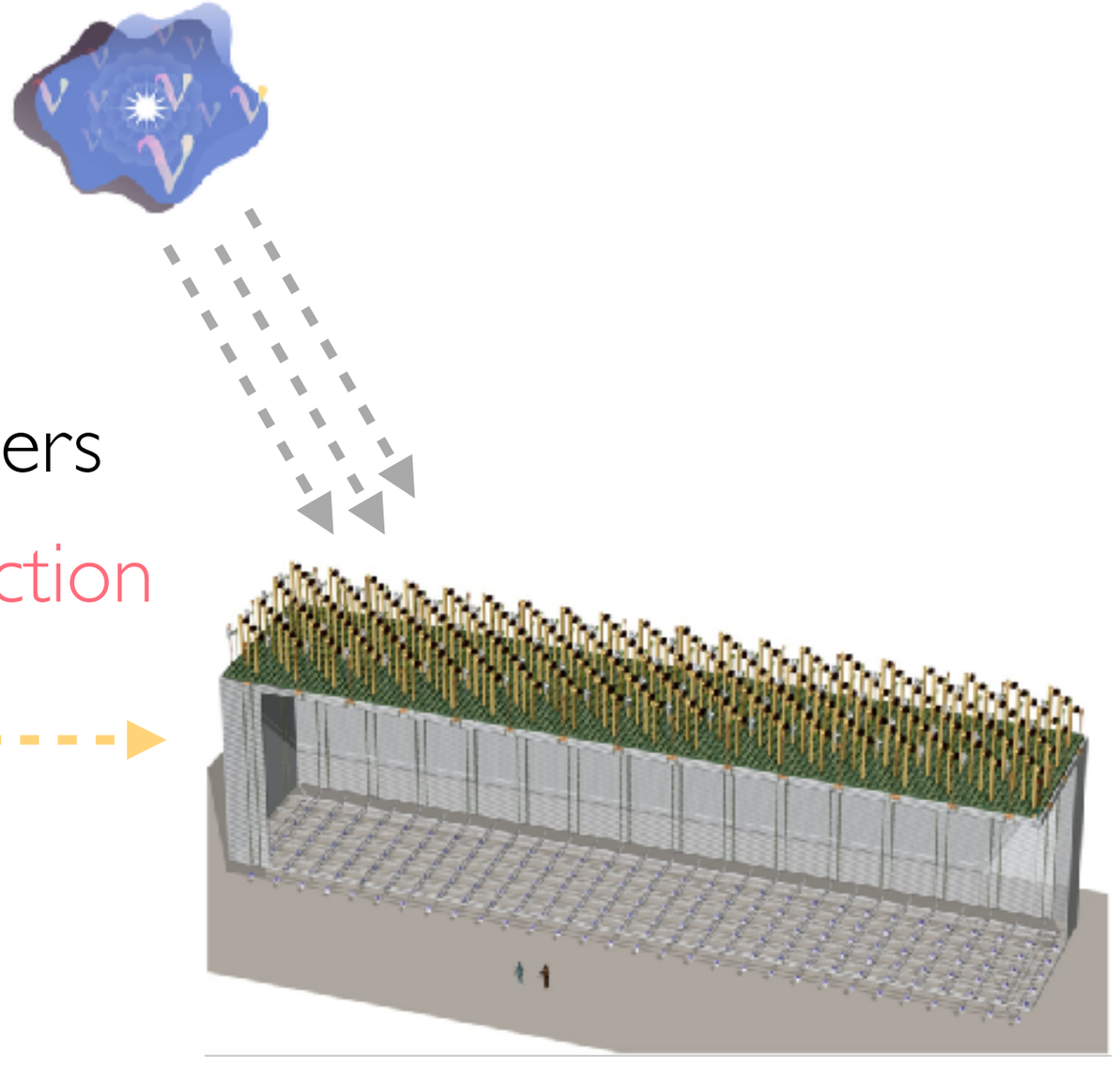

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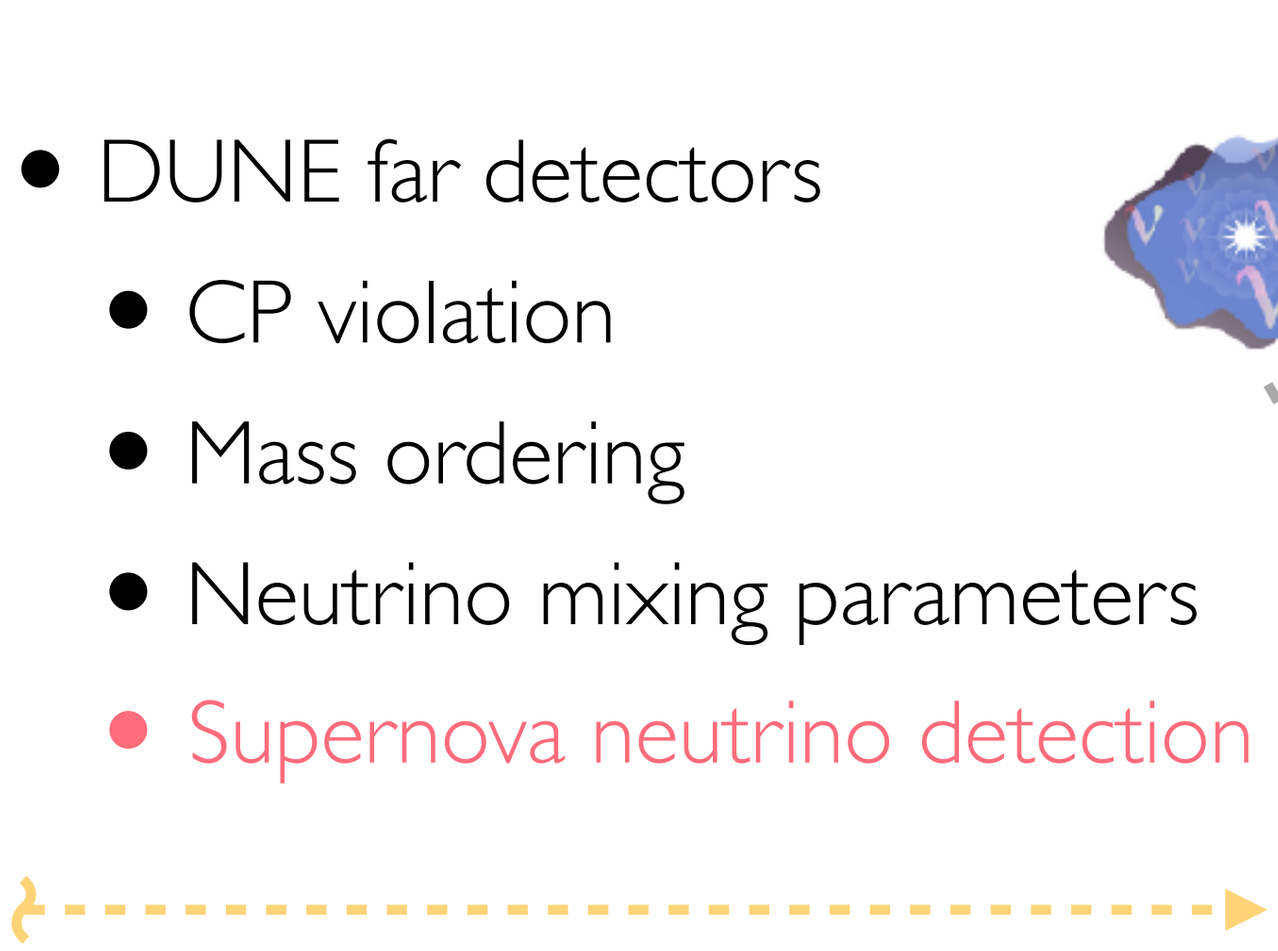
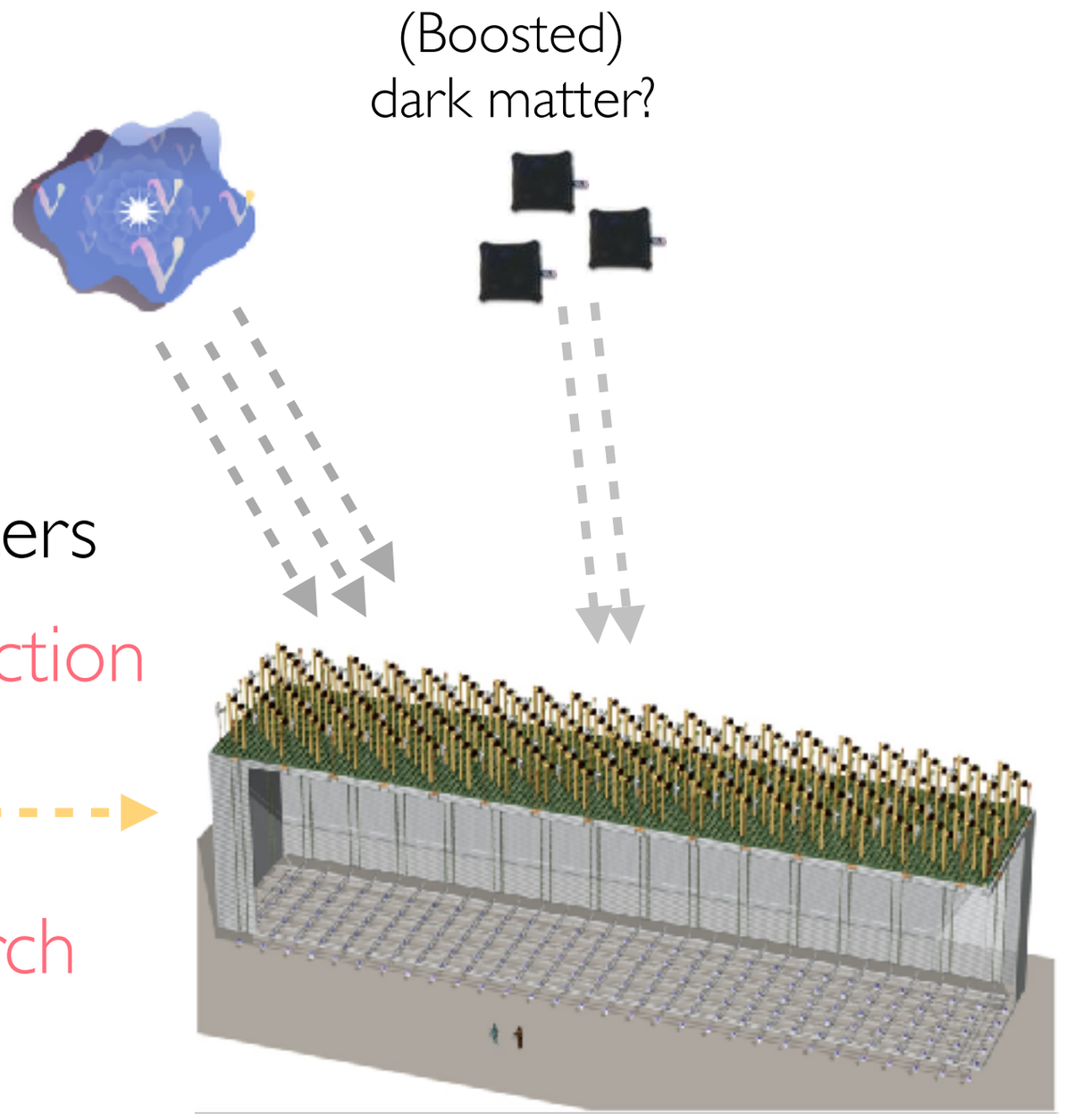


- Boosted dark matter search

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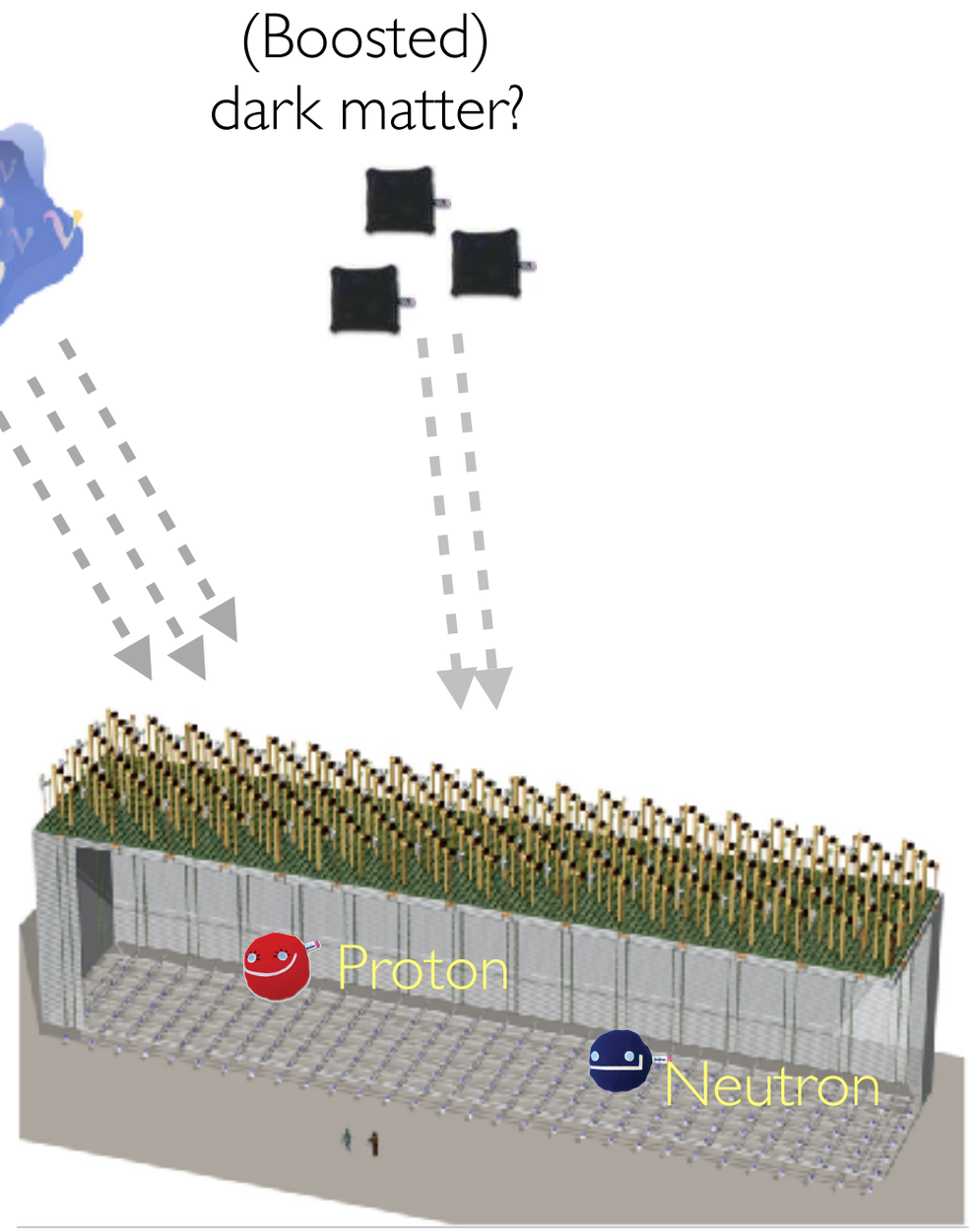


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# Available LArTPCs

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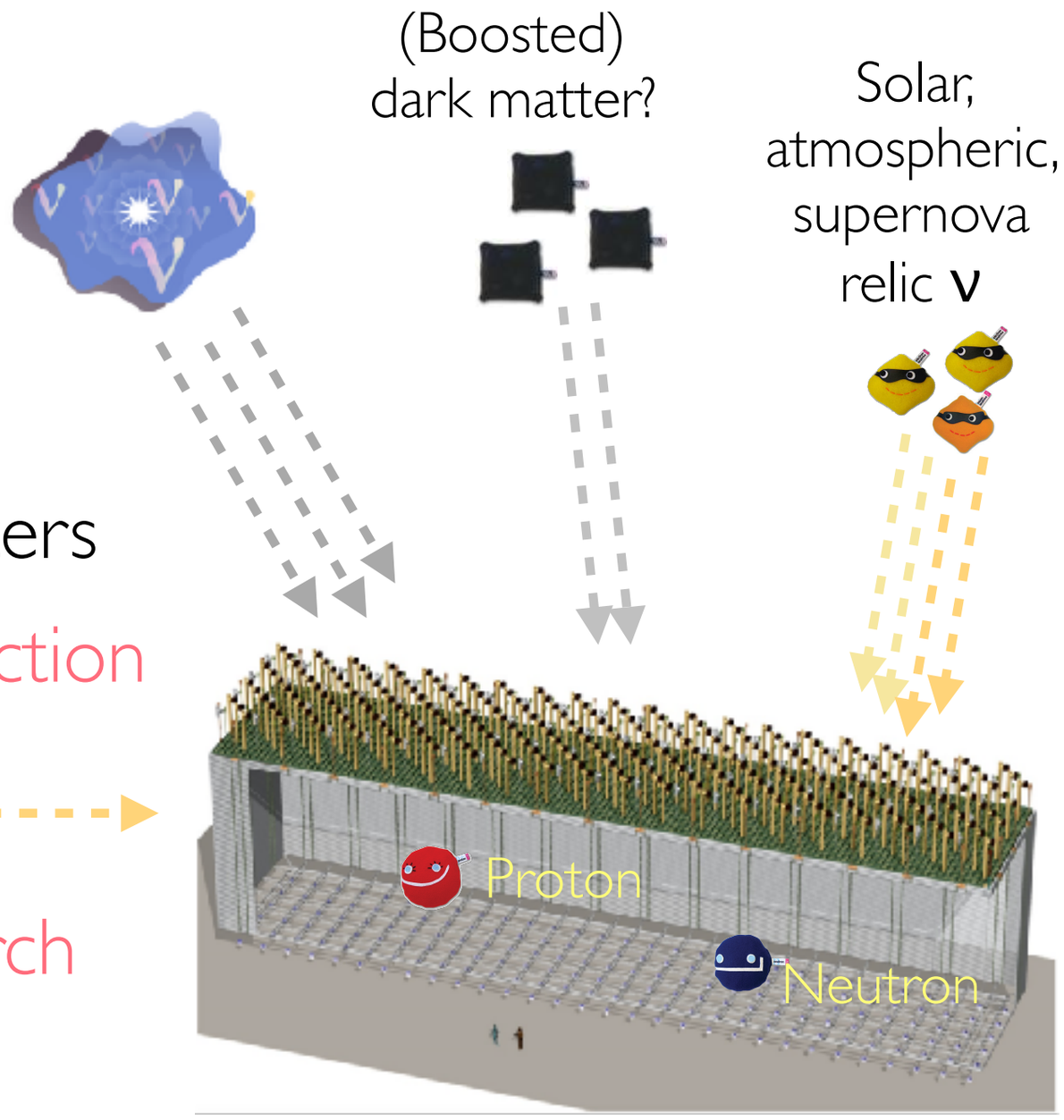
- Boosted dark matter search
- Nucleon decay search
- Astroparticle/rare process searches



# Unique Features of LArTPC

- 10 MeV-scale $\nu_e$ detection
  - Supernova neutrinos
- Low threshold on hadron/muon detection
  - $p \rightarrow K^+ \bar{\nu}$
  - Boosted dark matter
  - Dark sector particles
  - Single electron signature with O(10MeV)
- Millimeter resolution
  - Neutron-antineutron oscillation, $n+\bar{n} \rightarrow \pi^+\pi^-3\pi^0$
  - $\nu_\tau$ appearance

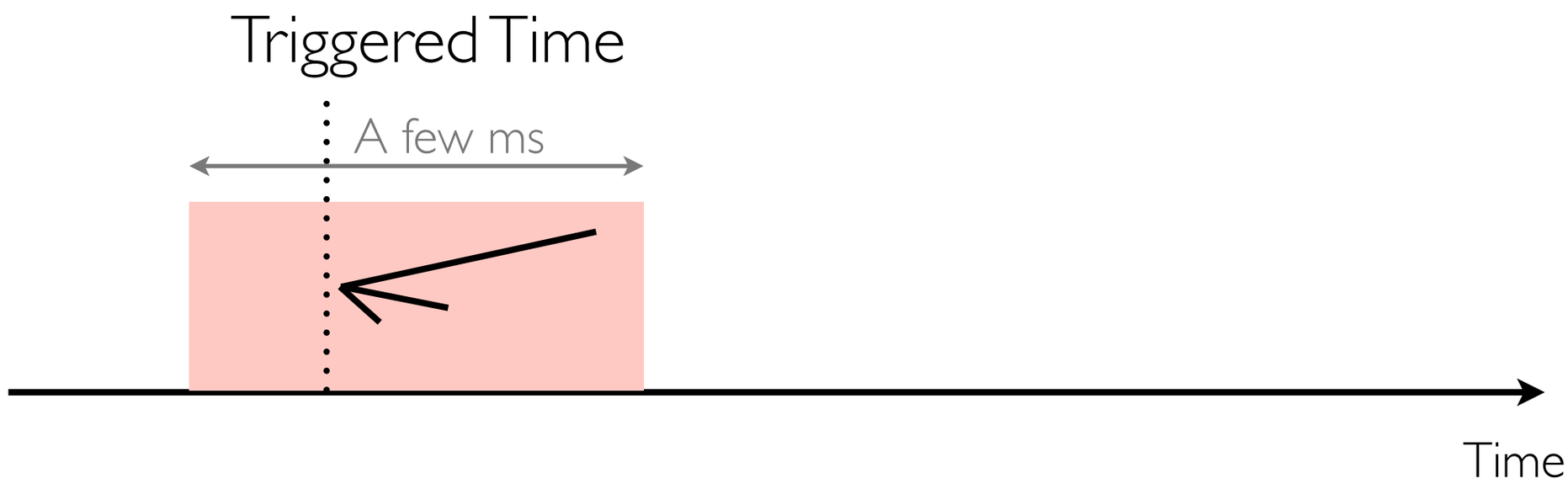
# LArTPC Near Detector

- Advantages
  - Relatively massive target
  - Active in the interaction vertices
  - Low threshold on hadron/muon detection
- Shortcomings
  - Timing: a slow detector
  - SM neutrino background ($\nu$-Ar interactions)
- Search for exotic particles
  - Through interactions with LAr
  - With low energy

# Experimental Apparatus for BSM Searches

# Data Acquisition

Record neutrino events induced by accelerator beam:
Know when neutrinos arrive in advance
Record the relevant chunk of data



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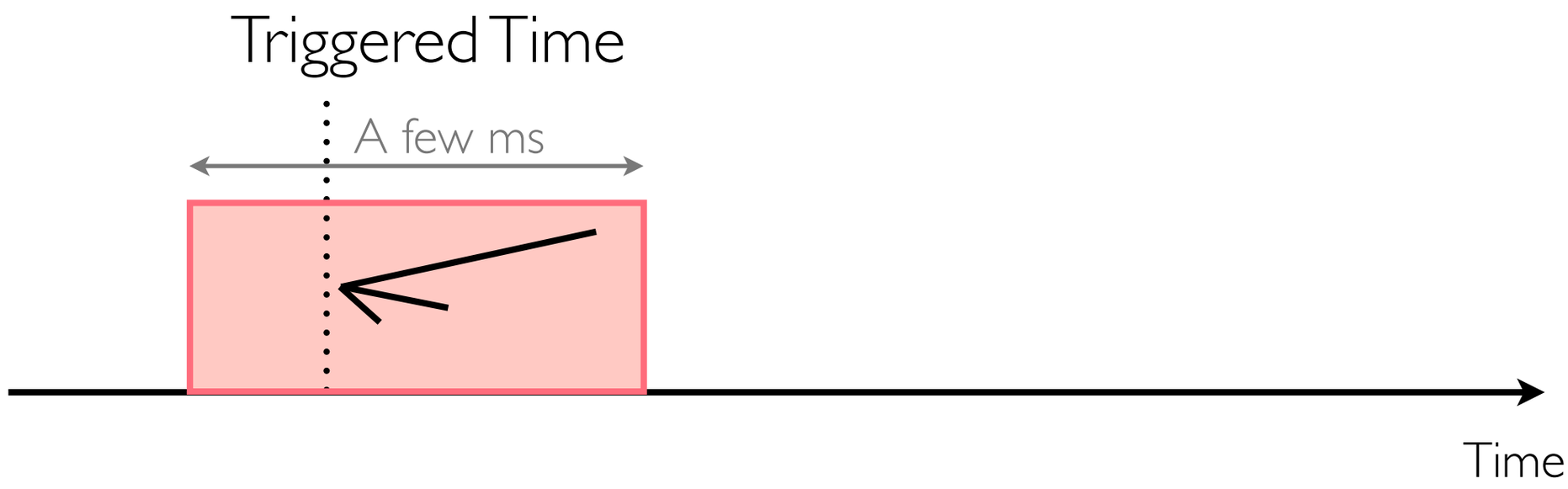

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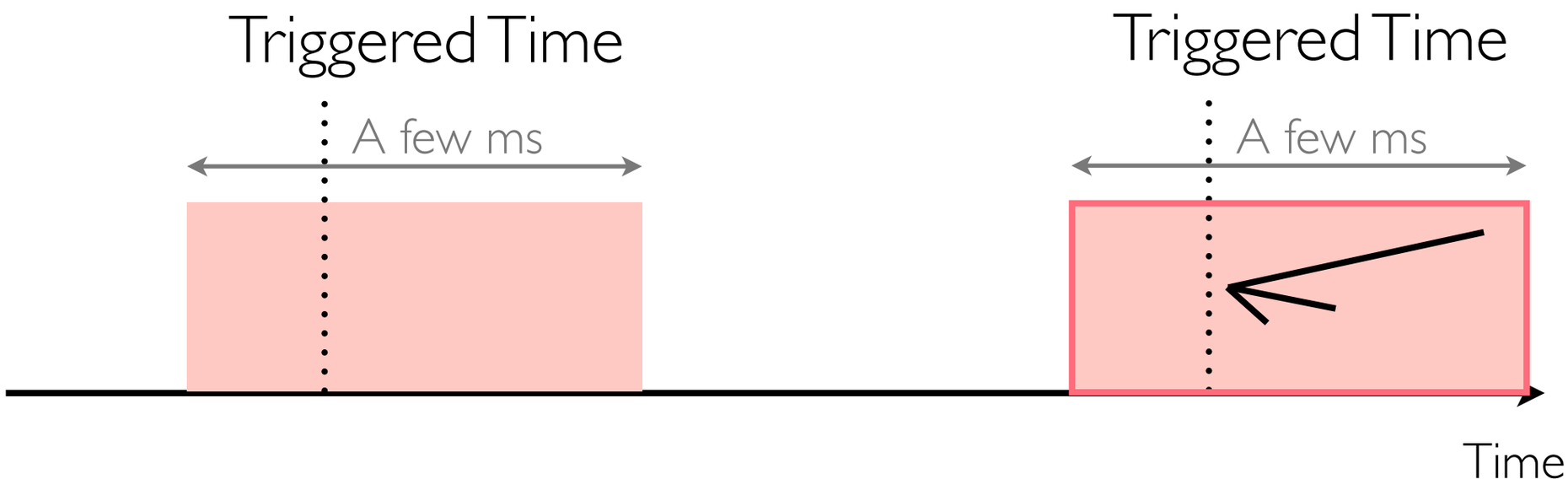

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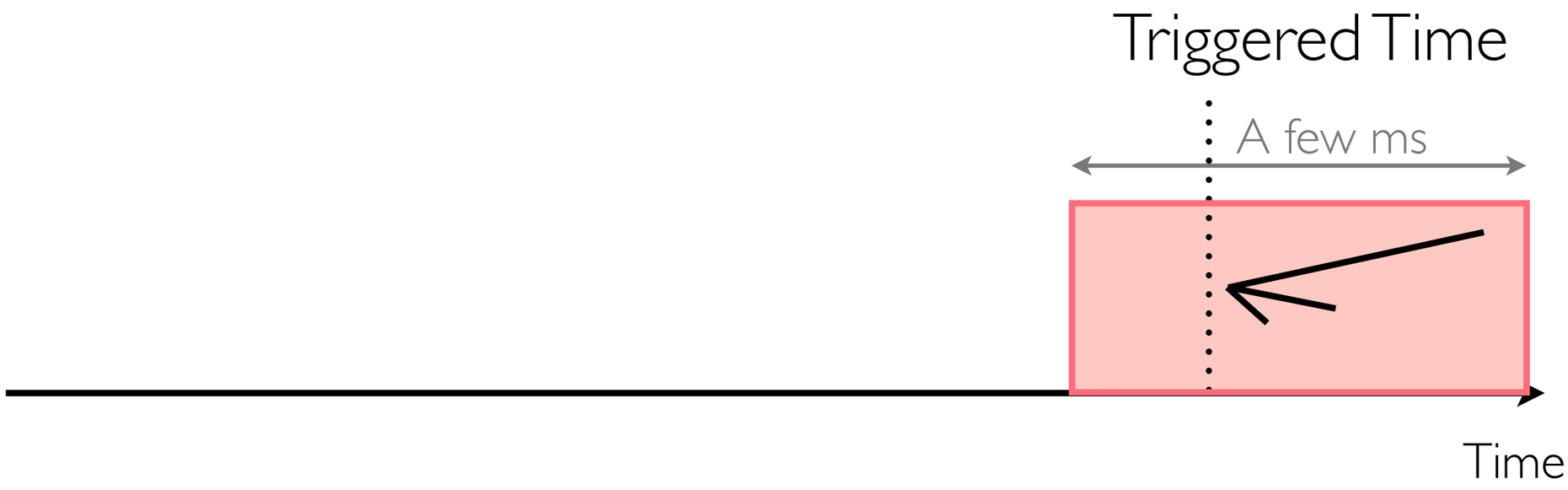
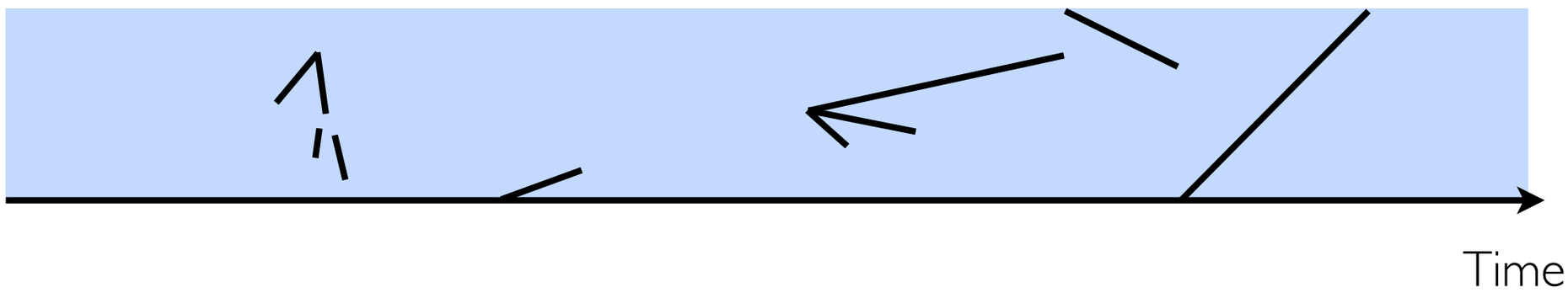


# Data Acquisition

Record physics events not induced by accelerator beam:
Do not know when interesting events occur in advance
Continuously read out data

Find interesting events in real time and record them



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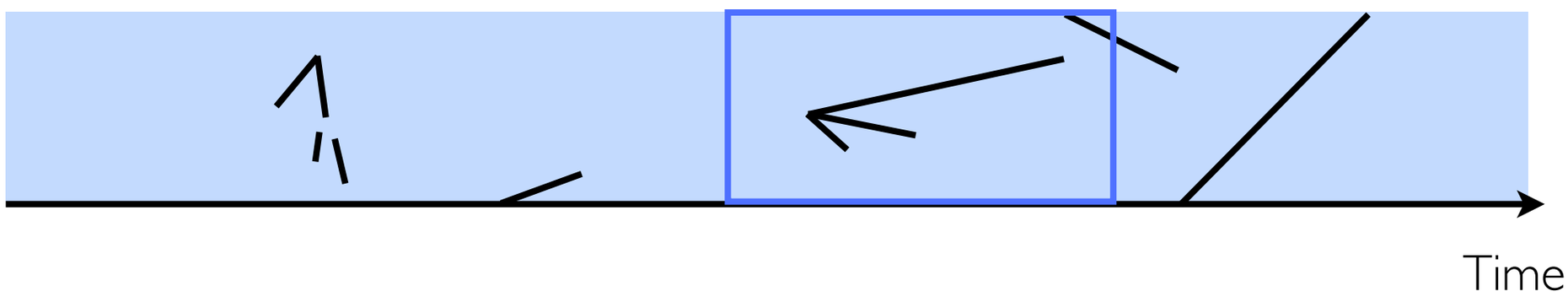

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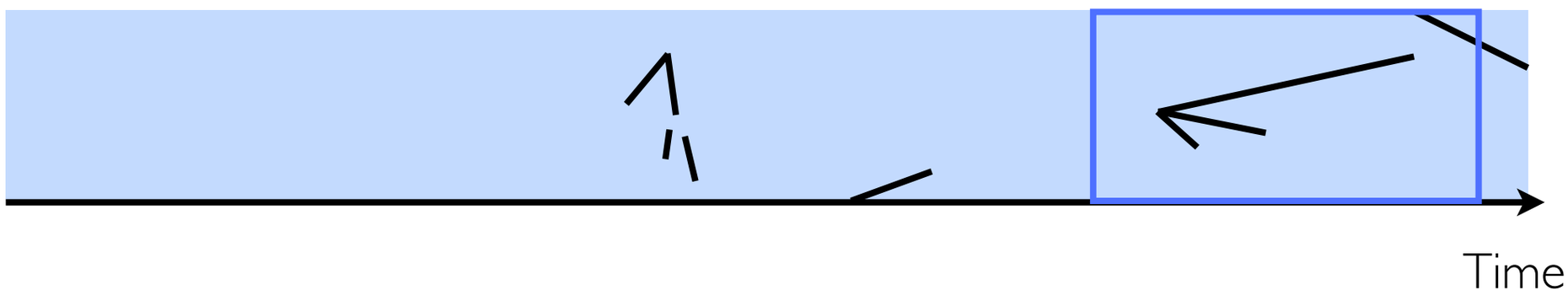

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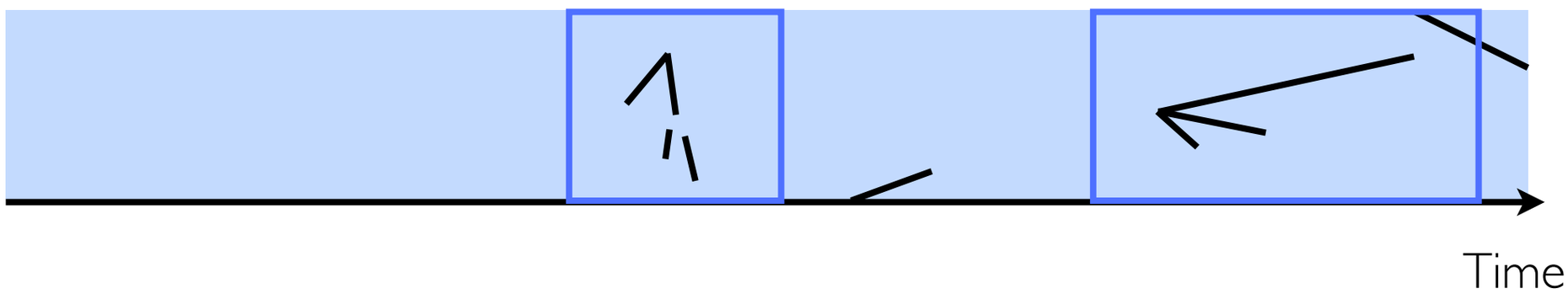


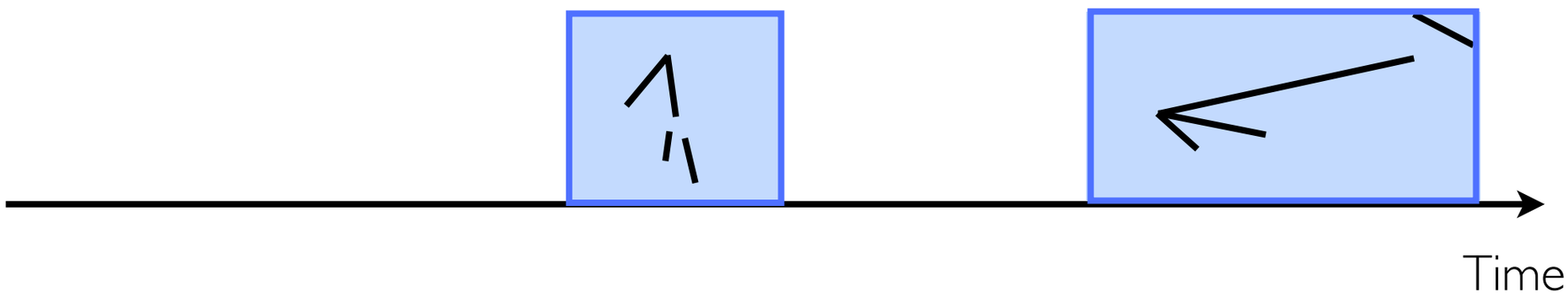
# Data Acquisition

High spatial resolution in LArTPC results in a huge volume of data

Main challenge on data acquisition

Drive the DUNE data acquisition design

Find interesting events in real time and record them

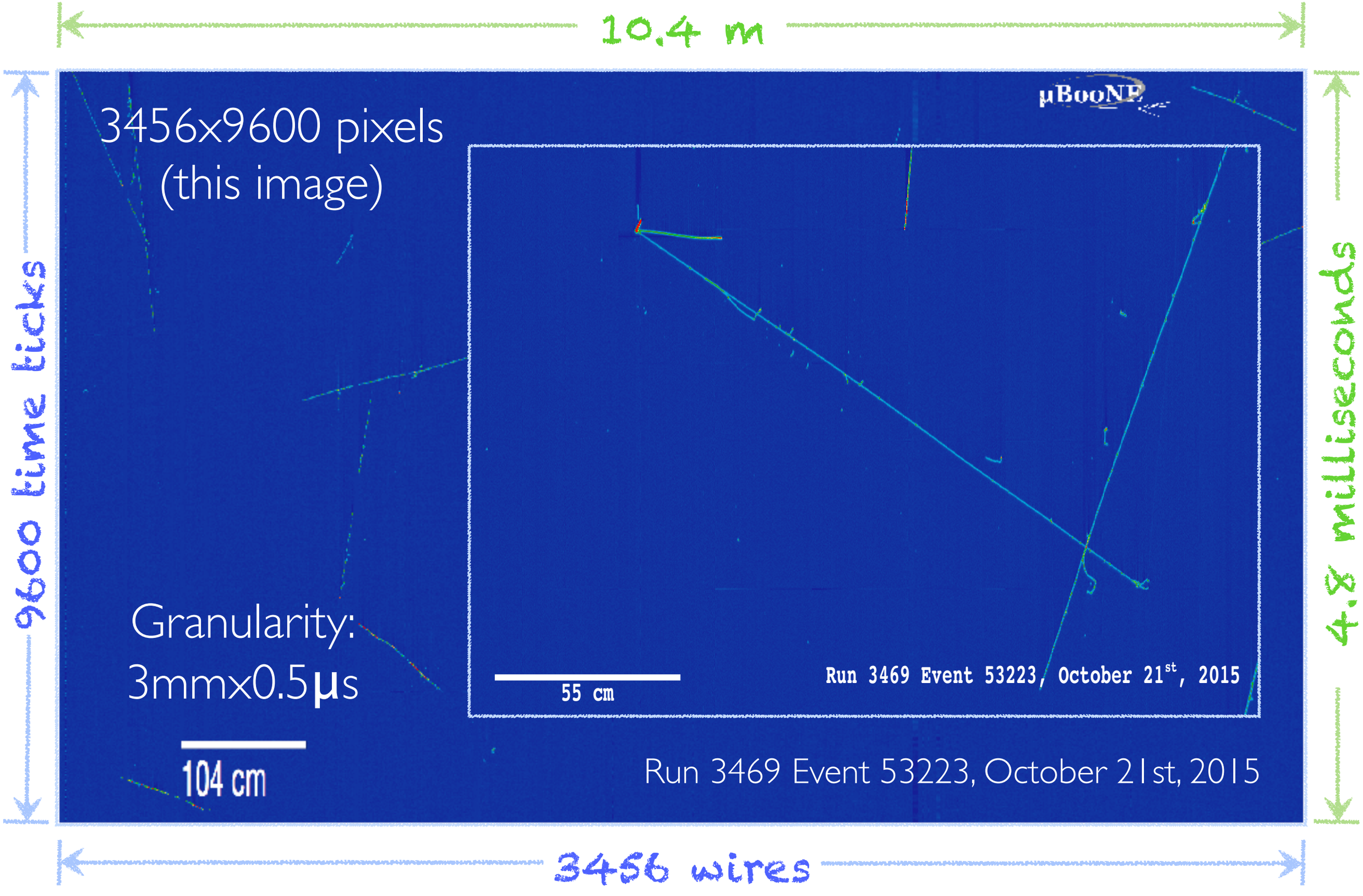


10.4 m


9600 time ticks

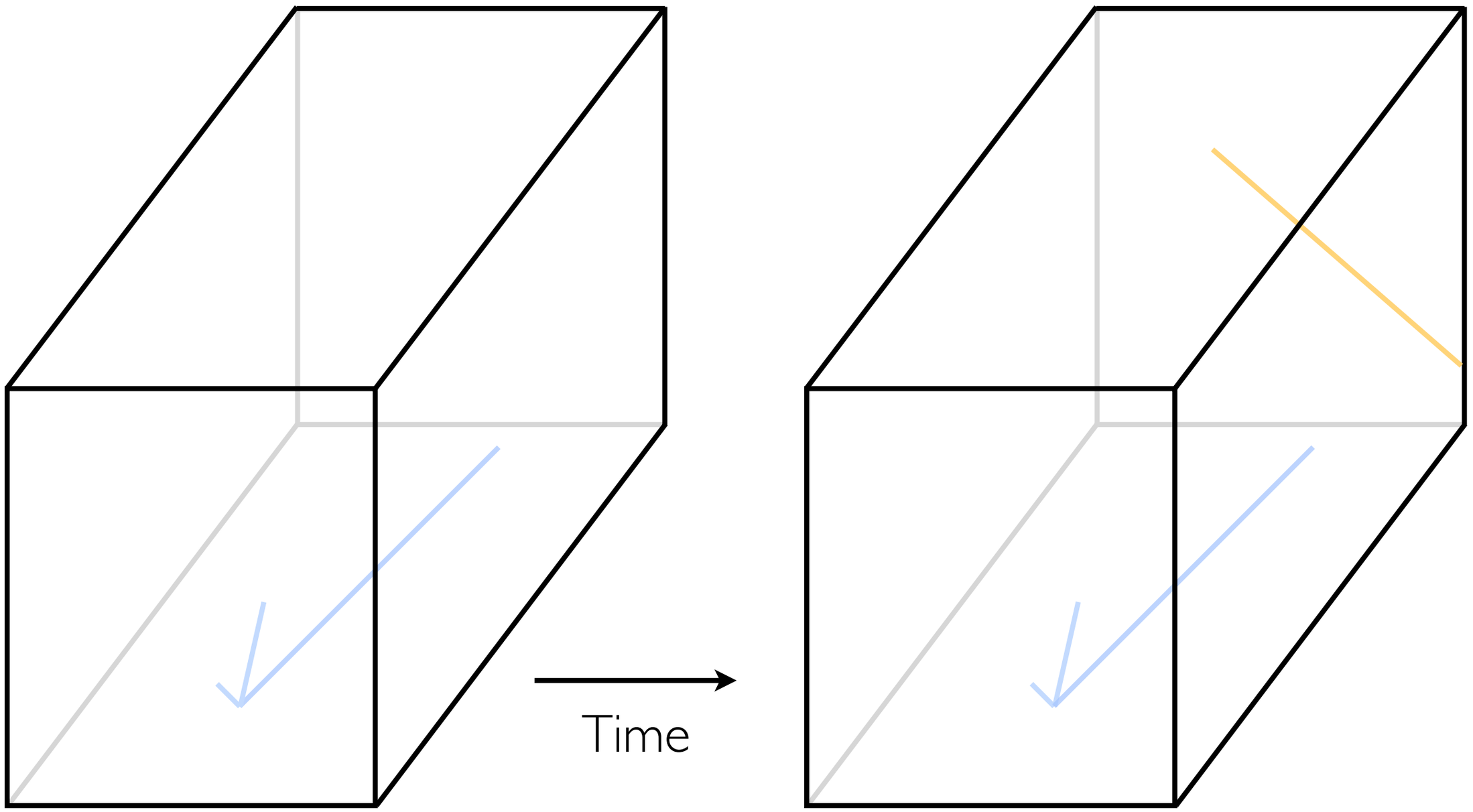
4.8 milliseconds

3456 wires


10.4 m
9600 time ticks
4.8 milliseconds
3456x9600 pixels
(this image)
μBooNE
Granularity:
3mmx0.5μs
104 cm
55 cm
Run 3469 Event 53223, October 21st, 2015
Run 3469 Event 53223, October 21st, 2015
3456 wires

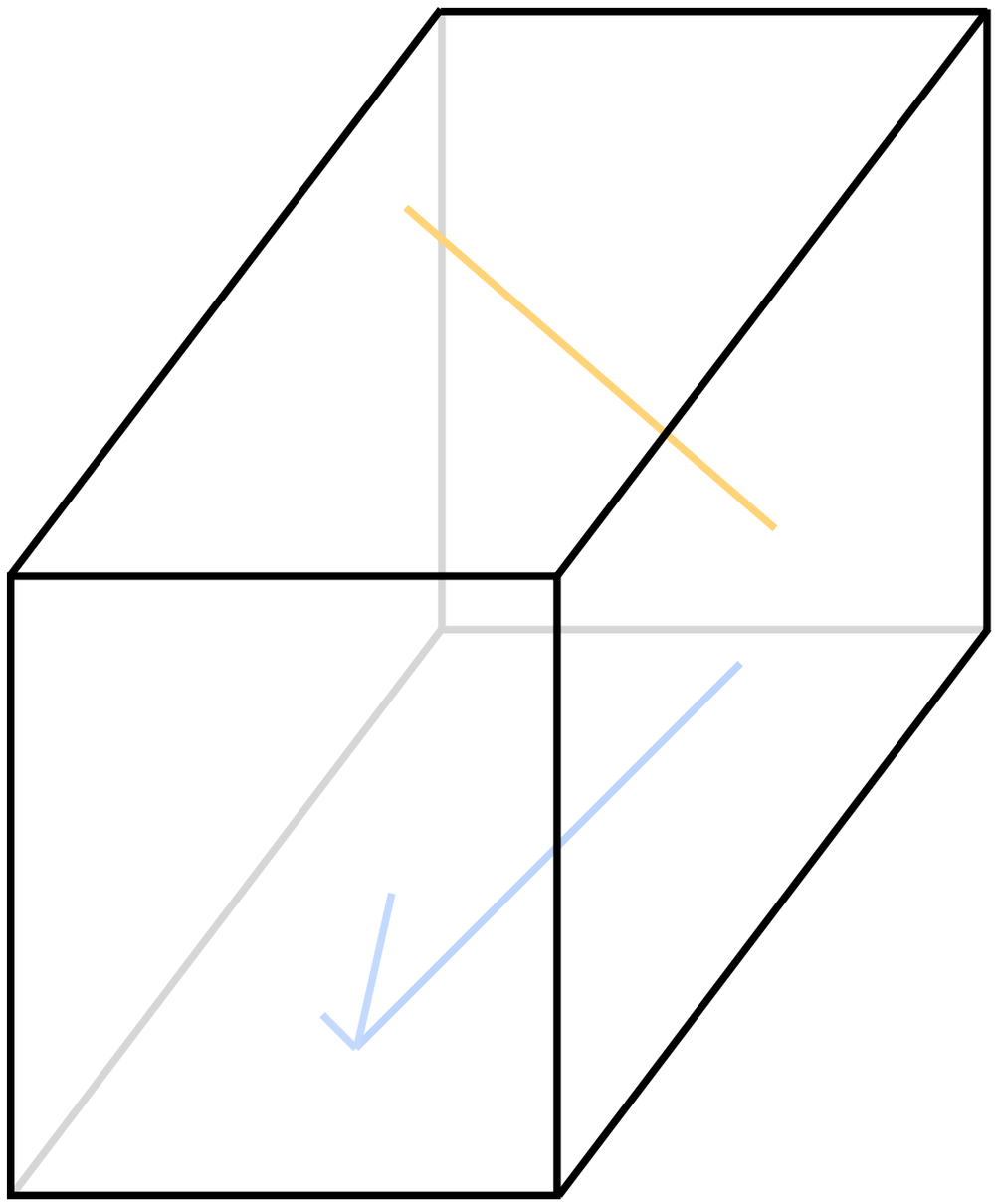
# Activity Correlation

Scenario 1

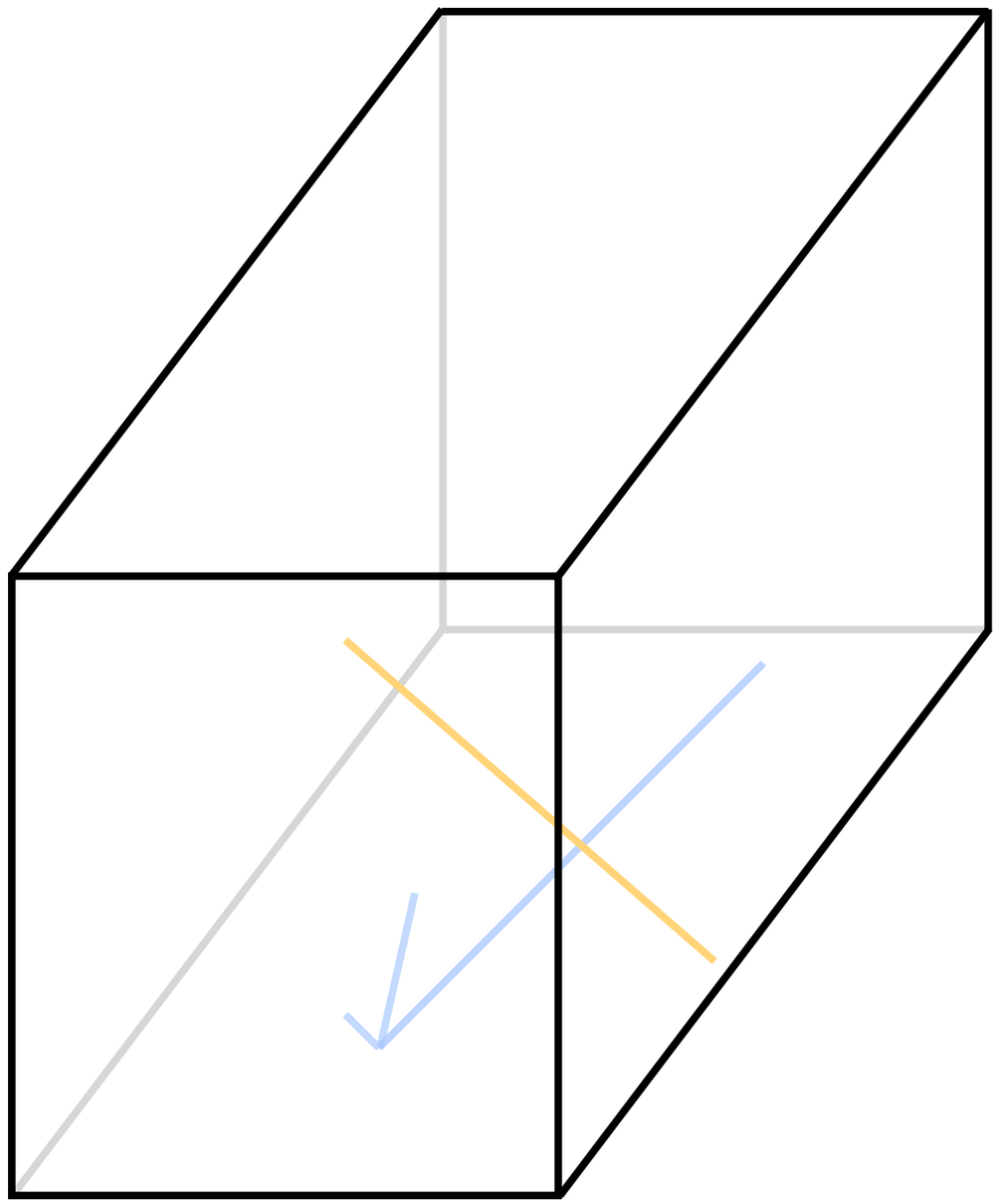


# Activity Correlation

Scenario 2



Scenario 3



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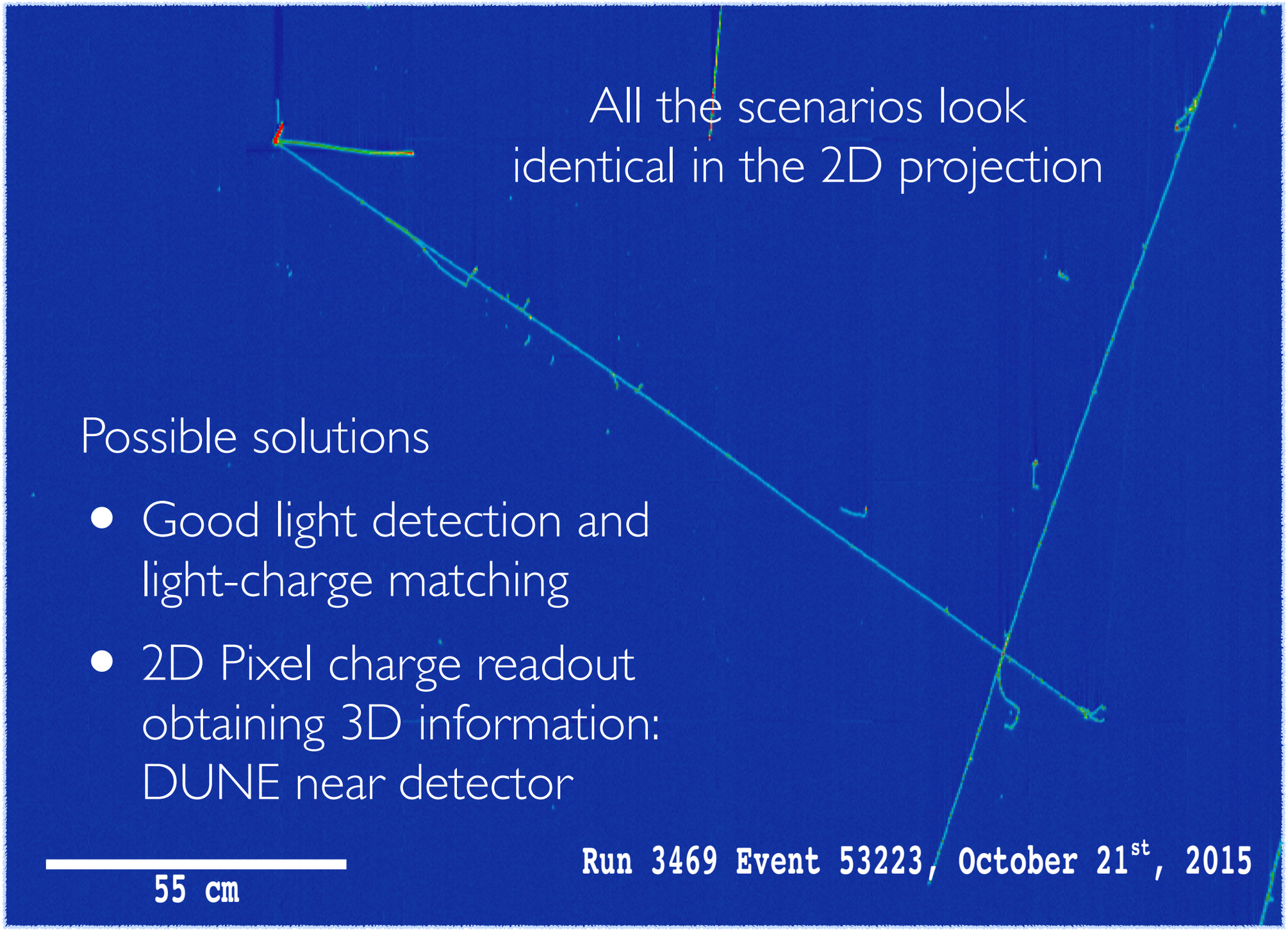

# Reconstruction Challenges

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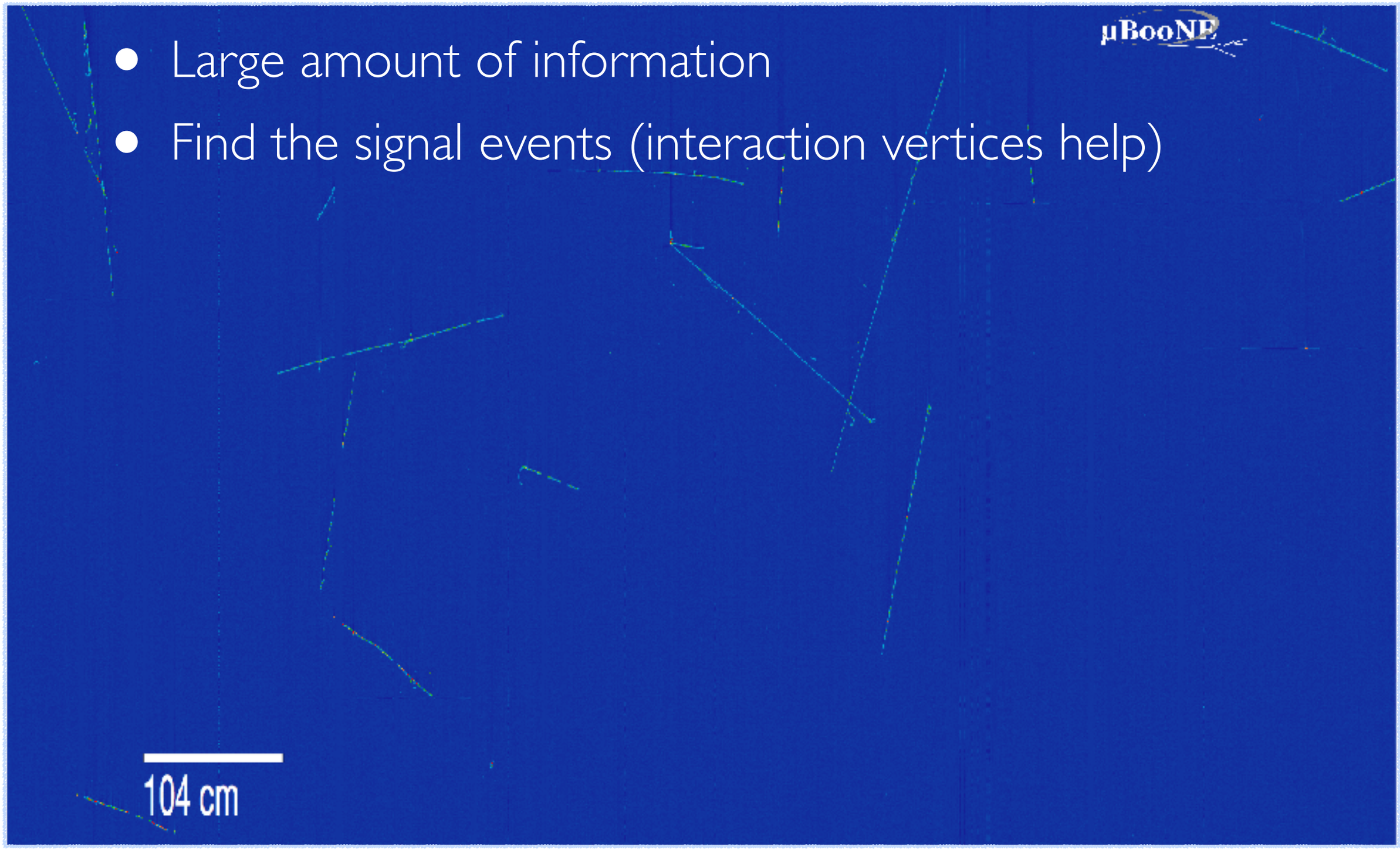
- Large amount of information
- Find the signal events (interaction vertices help)



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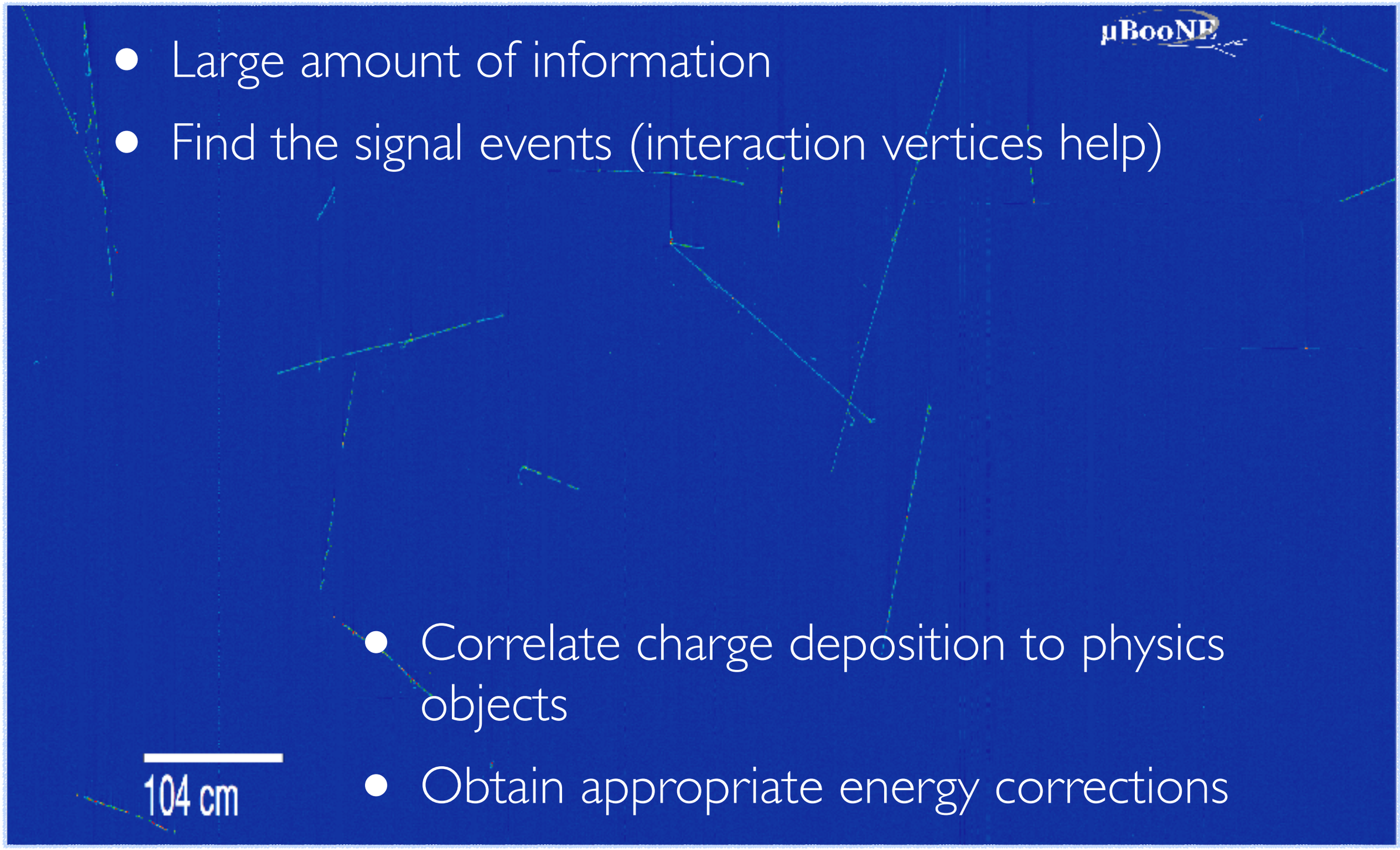
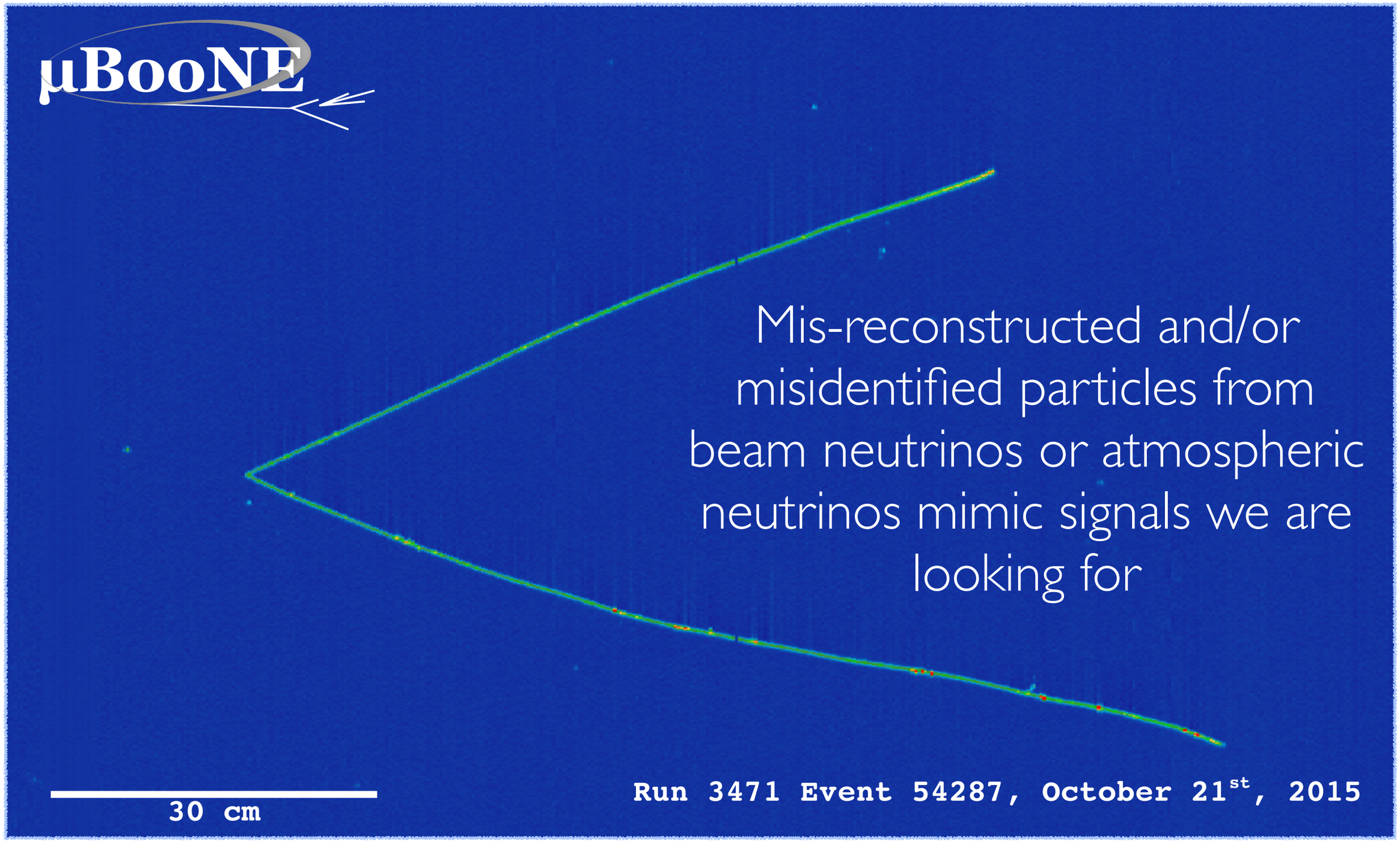



- Large amount of information
- Find the signal events (interaction vertices help)
- Correlate charge deposition to physics objects
- Obtain appropriate energy corrections

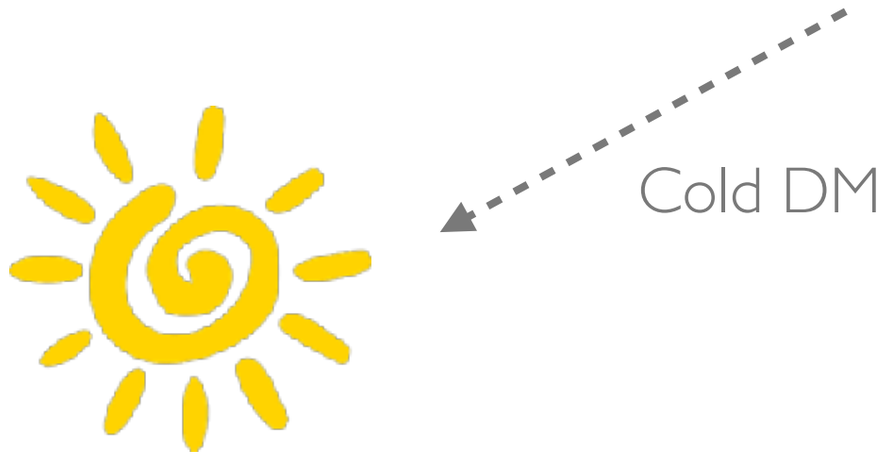
# Possible Background Source



# Search for Boosted Dark Matter at DUNE

Analysis Team: Josh Berger, Mark Convery, Yanou Cui, Matt Graham, Lina Necib, Gianluca Petrillo, Y.-T. Tsai, Yue Zhao

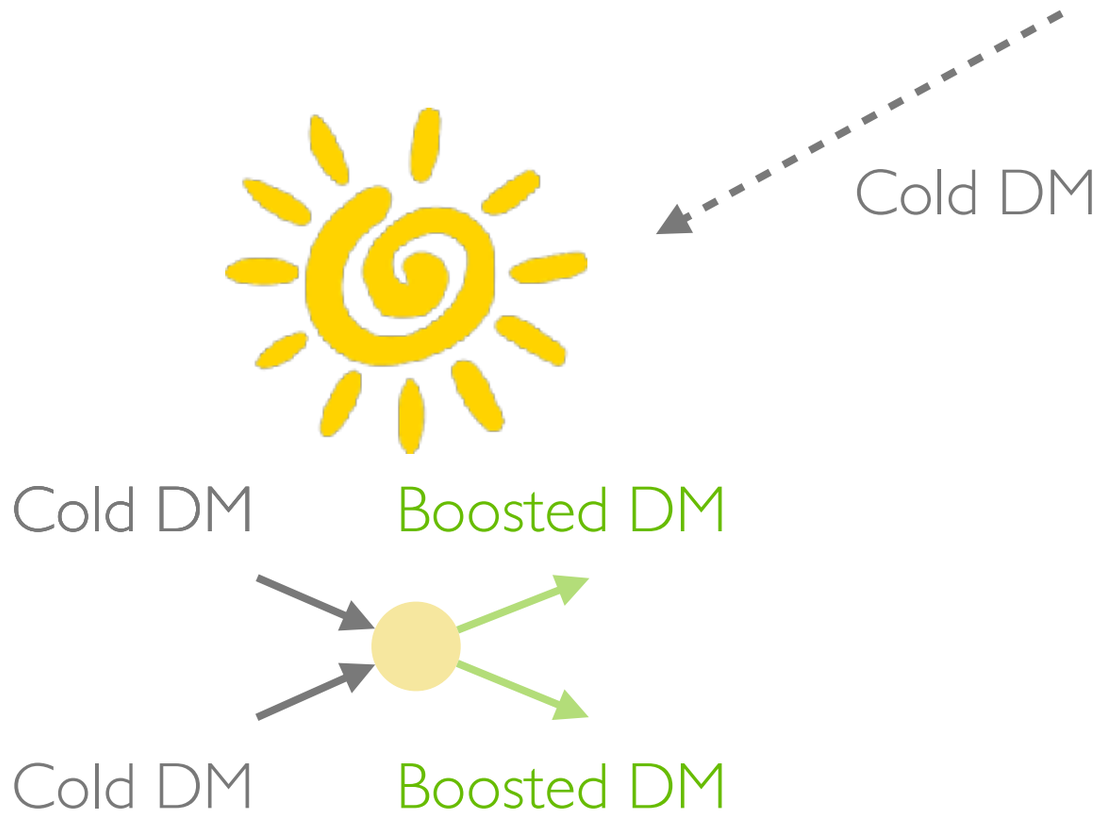
# Boosted Dark Matter




1. Cold dark matter captured by dark matter concentrated region, such as the Sun or Galaxy Center

Refs: Y. Cui's, J. Berger's Talks,
JCAP 1502 (2015) 005

# Boosted Dark Matter

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2. Produce lighter, boosted dark matter via annihilation or decay

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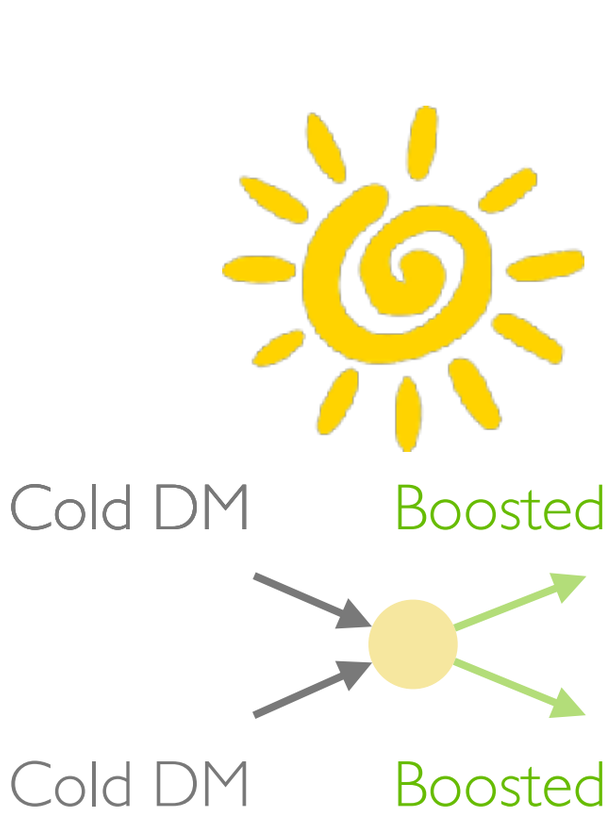


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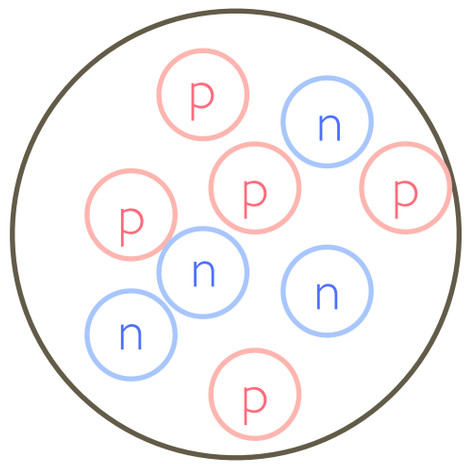
2. Produce lighter, boosted dark matter via annihilation or decay

3. Boosted dark matter interact with electrons or nucleons in detectors

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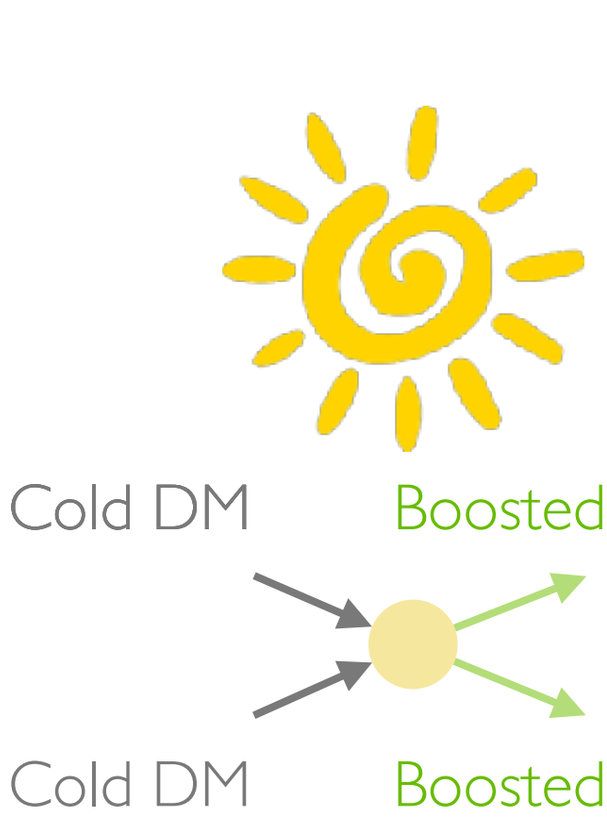


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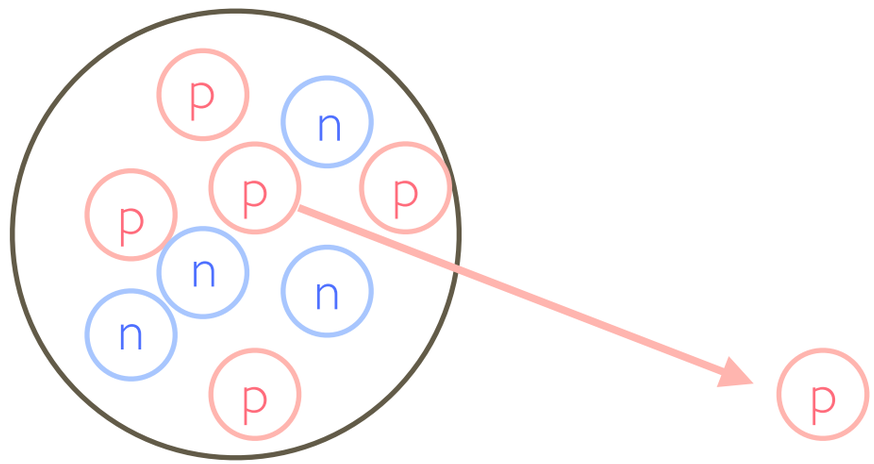
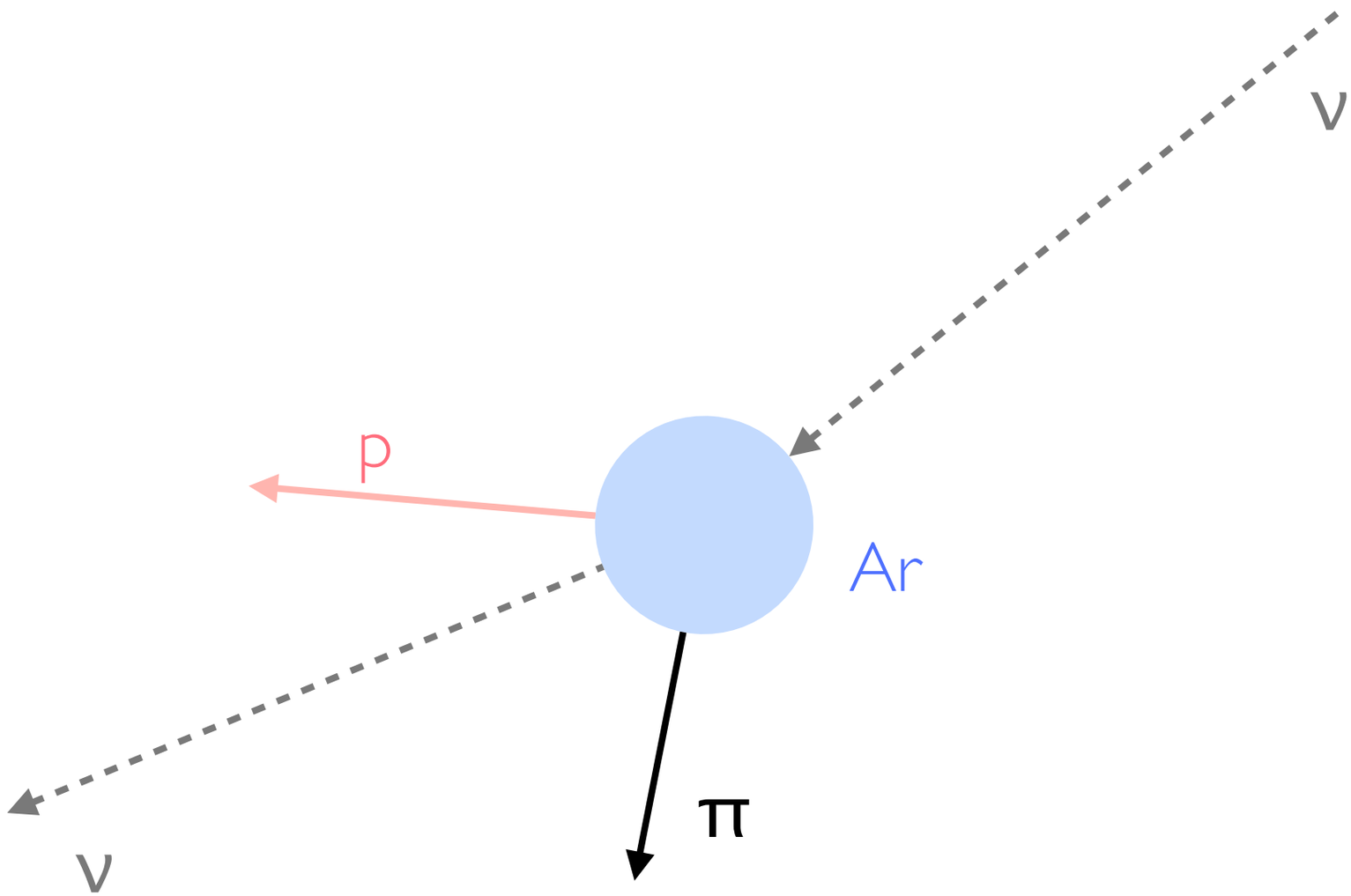



4. Look for scattered electrons or recoil protons

Refs: Y. Cui's, J. Berger's Talks, JCAP 1502 (2015) 005

# Main Background

Main background events:
neutral-current (NC)
atmospheric neutrinos



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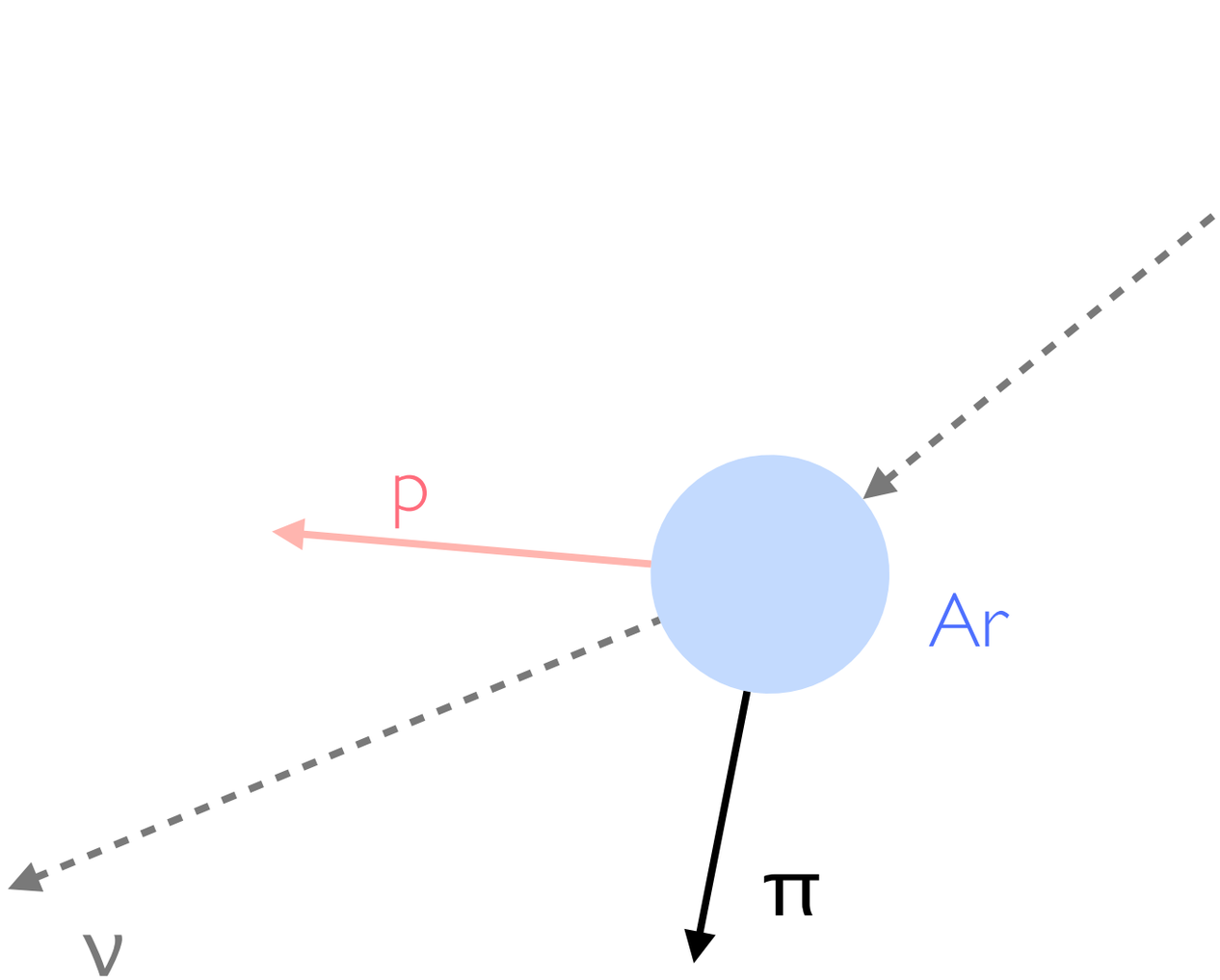
Main background events:
neutral-current (NC)
atmospheric neutrinos

Bartol maximum
flux: $\nu_e$, $\nu_\mu$, $\overline{\nu}_e$, $\overline{\nu}_\mu$

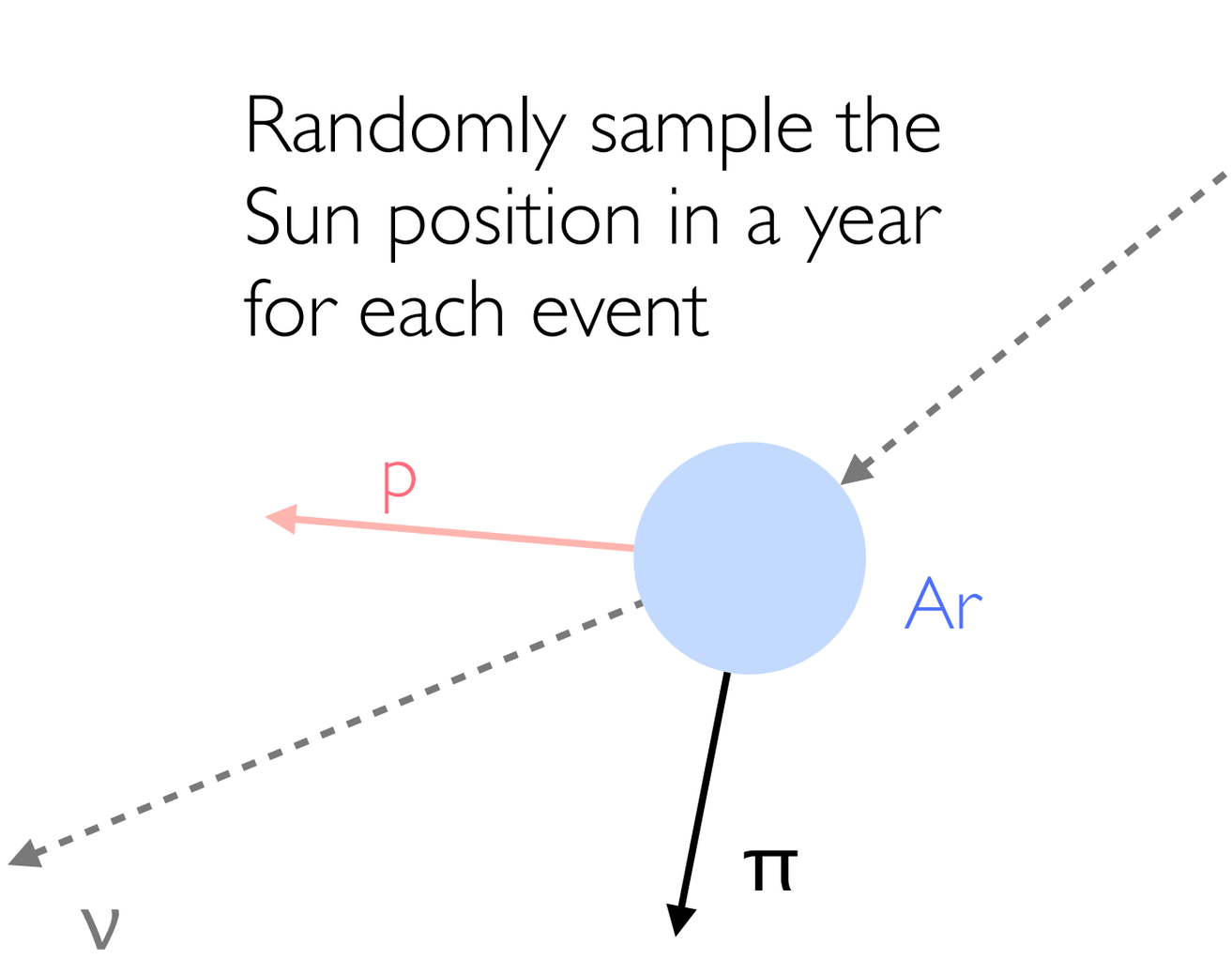


# Main Background

Main background events:
neutral-current (NC)
atmospheric neutrinos

Bartol maximum
flux: $\nu_e$, $\nu_\mu$, $\overline{\nu}_e$, $\overline{\nu}_\mu$

Randomly sample the
Sun position in a year
for each event



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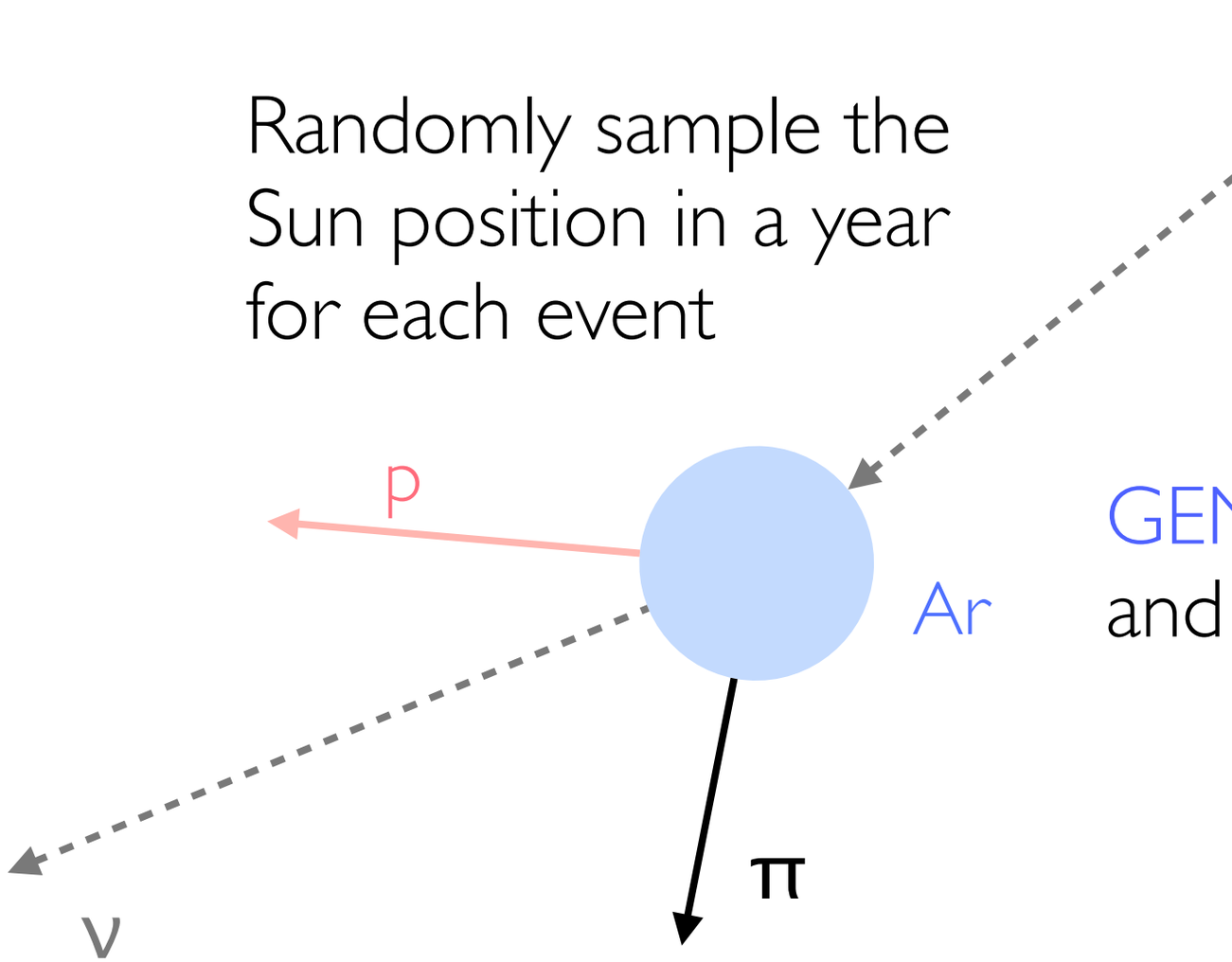


GENIE for neutrino-Ar
and final state interactions

# Main Background

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neutral-current (NC)
atmospheric neutrinos

Bartol maximum
flux: $\nu_e$, $\nu_\mu$, $\overline{\nu}_e$, $\overline{\nu}_\mu$

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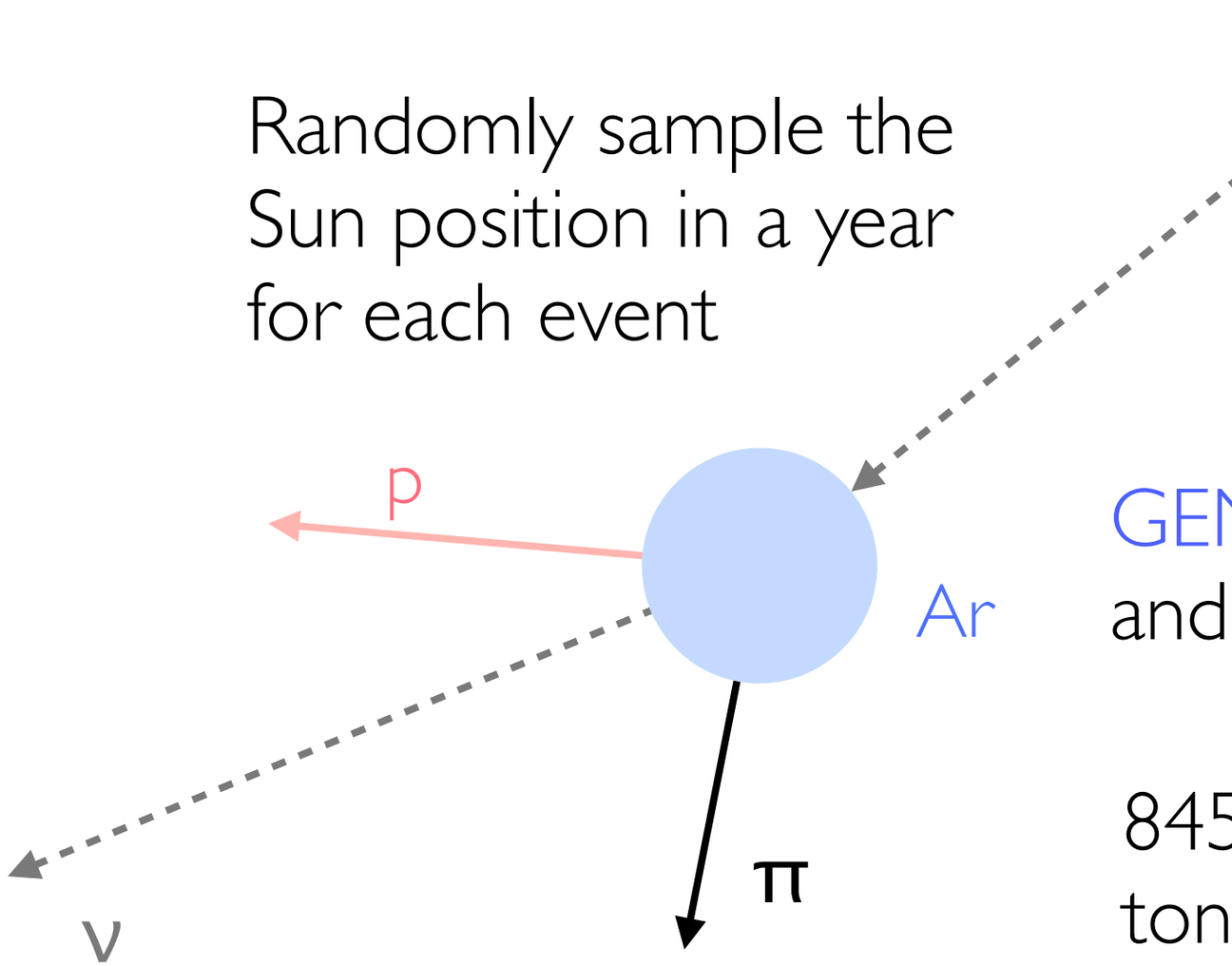
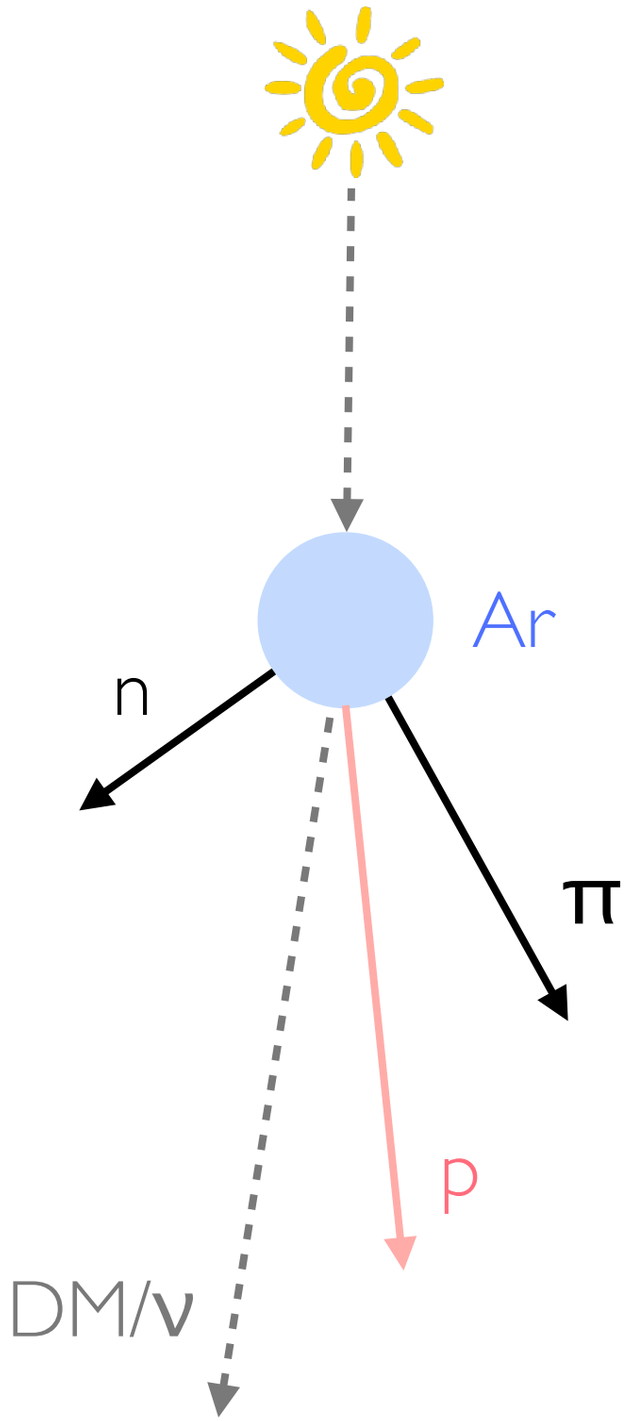


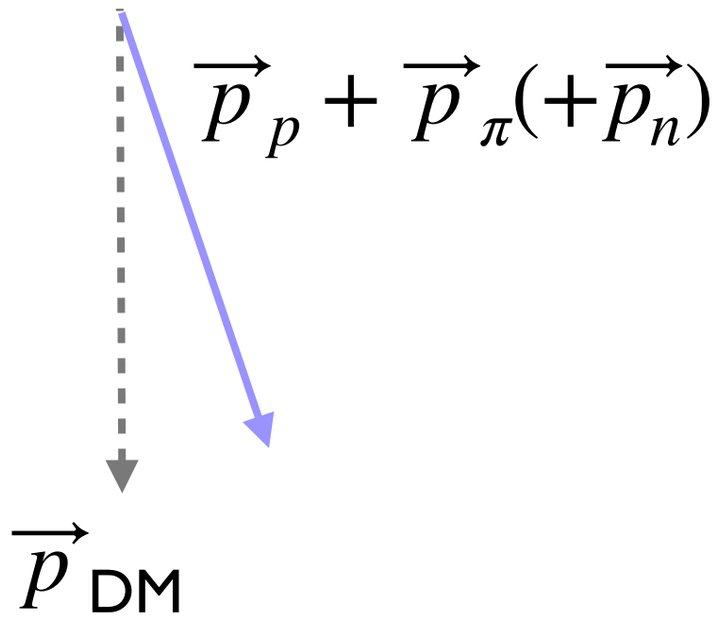

GENIE for neutrino-Ar
and final state interactions

845 NC events in 10k
ton LAr per year

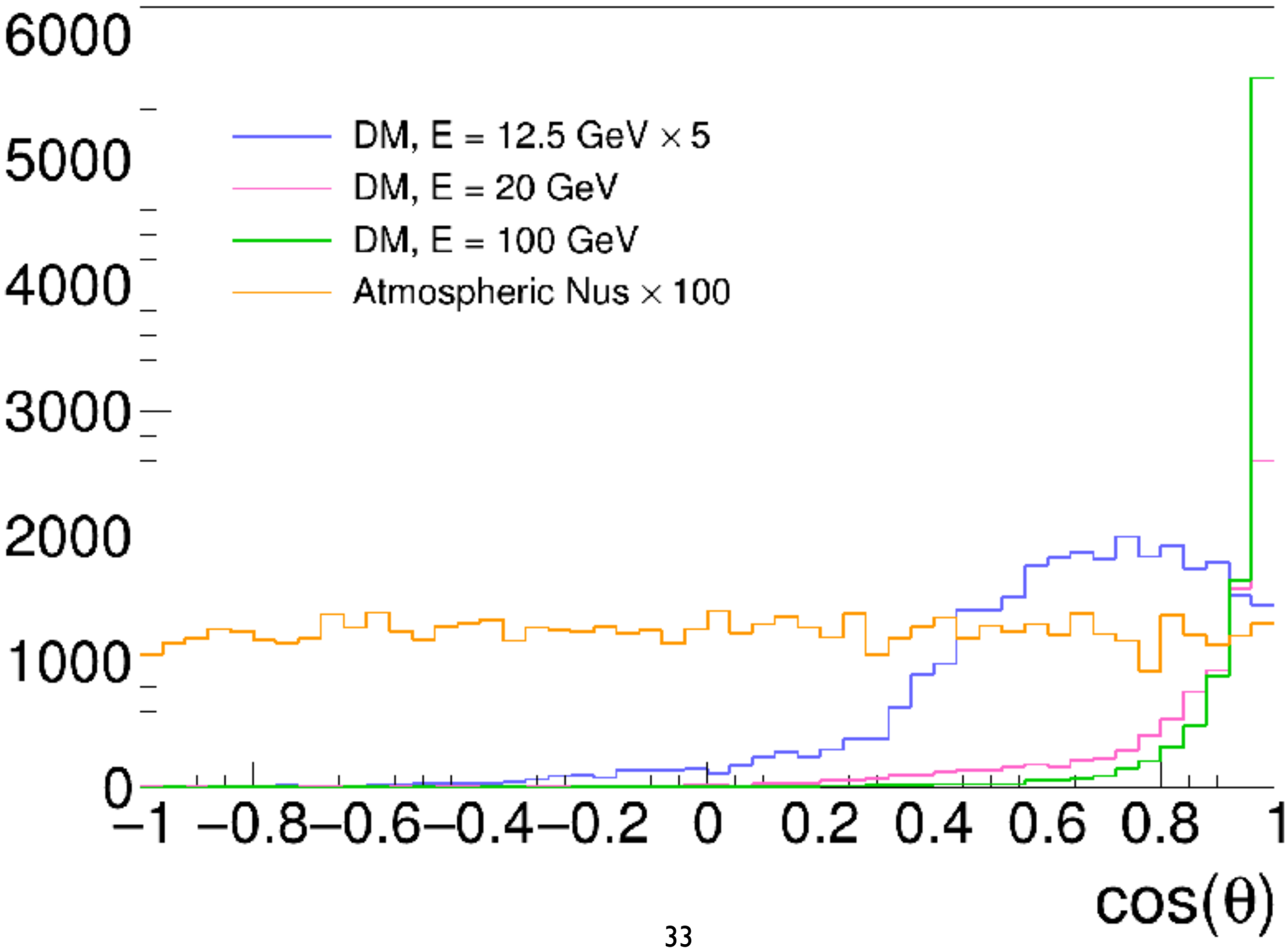
# Definition of Angle, θ




Angle between the Sun direction and the total momentum of all the visible particles in the final state



# Preliminary Selection



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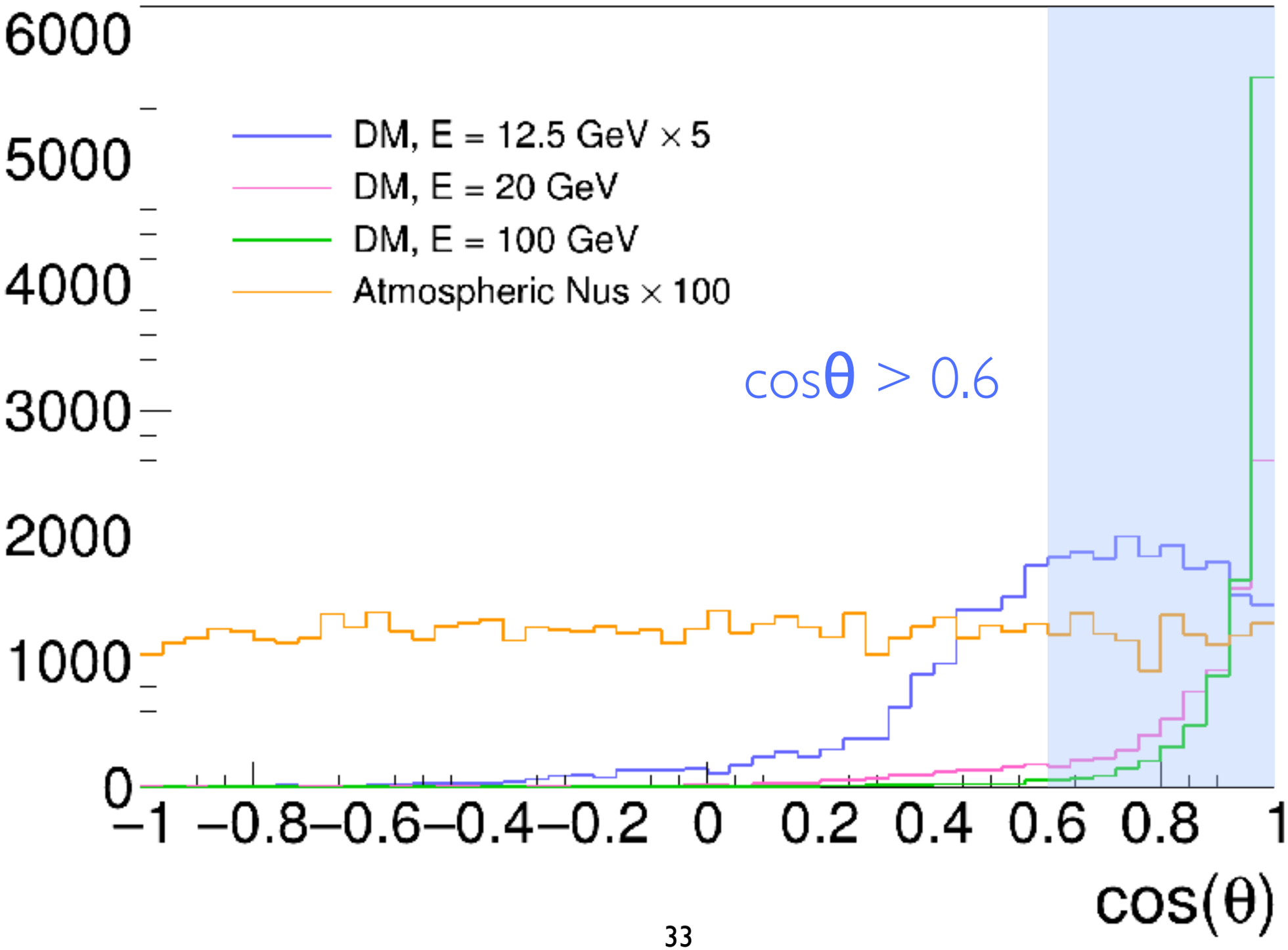
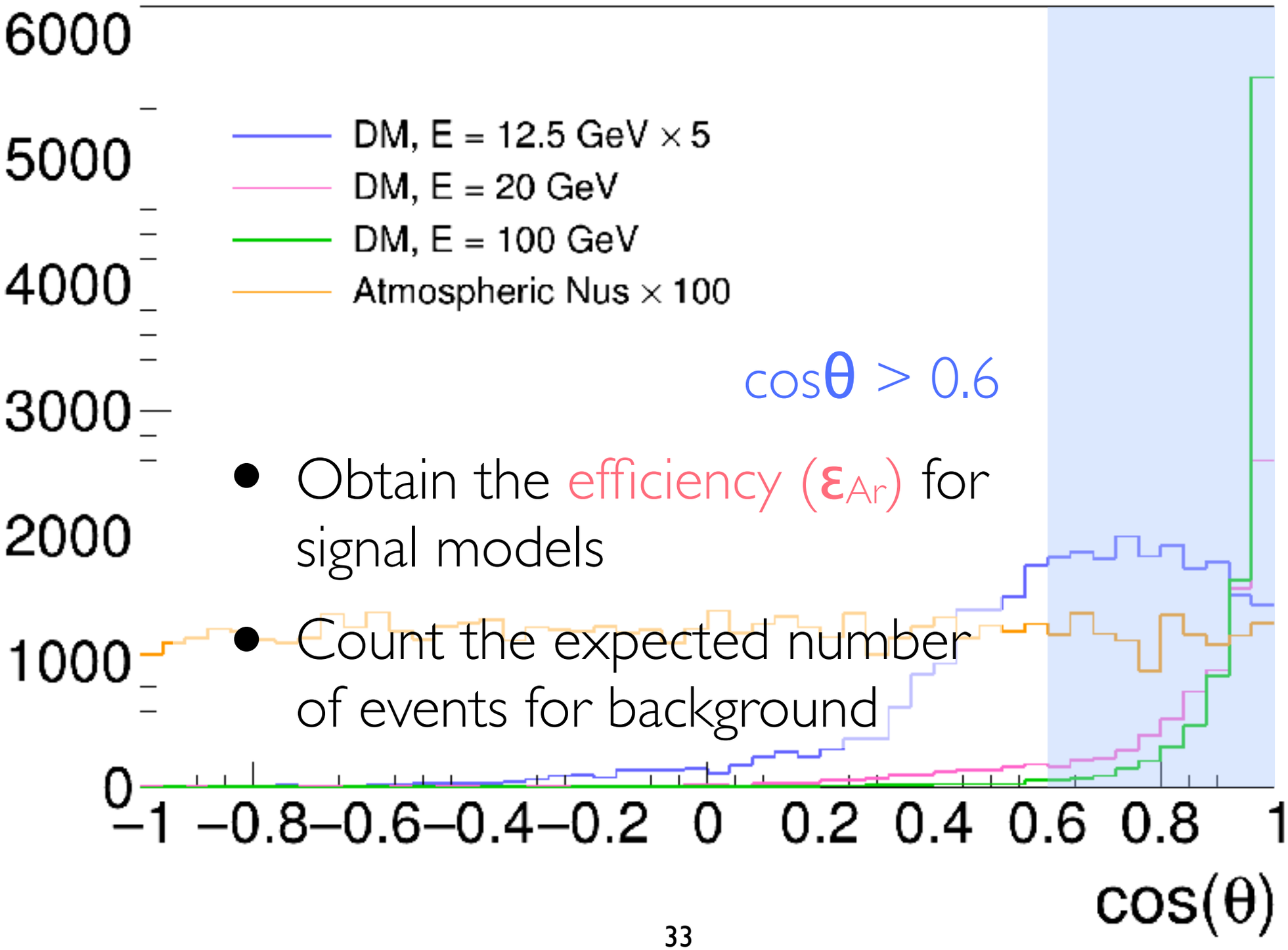


# Preliminary Selection

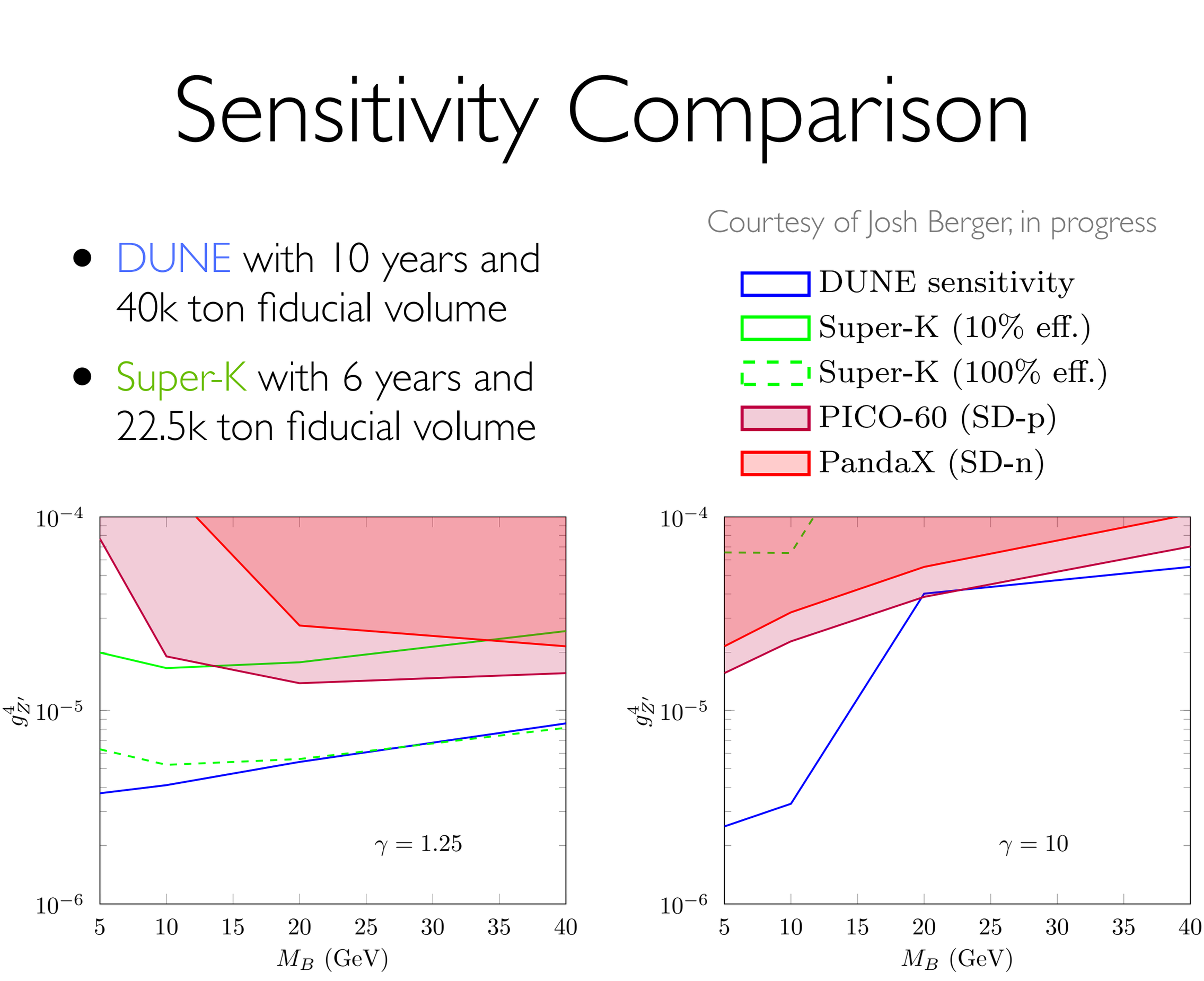



- Obtain the efficiency ($\varepsilon_{Ar}$) for signal models
- Count the expected number of events for background

# Sensitivity Comparison

- DUNE with 10 years and 40k ton fiducial volume
- Super-K with 6 years and 22.5k ton fiducial volume

Courtesy of Josh Berger, in progress




# Search for Heavy Neutral Lepton at MicroBooNE

Analysis Team: Owen Goodwin, Davide Porzio, Stefan Söldner-Rembold, Y.-T. Tsai

# Heavy Neutral Lepton

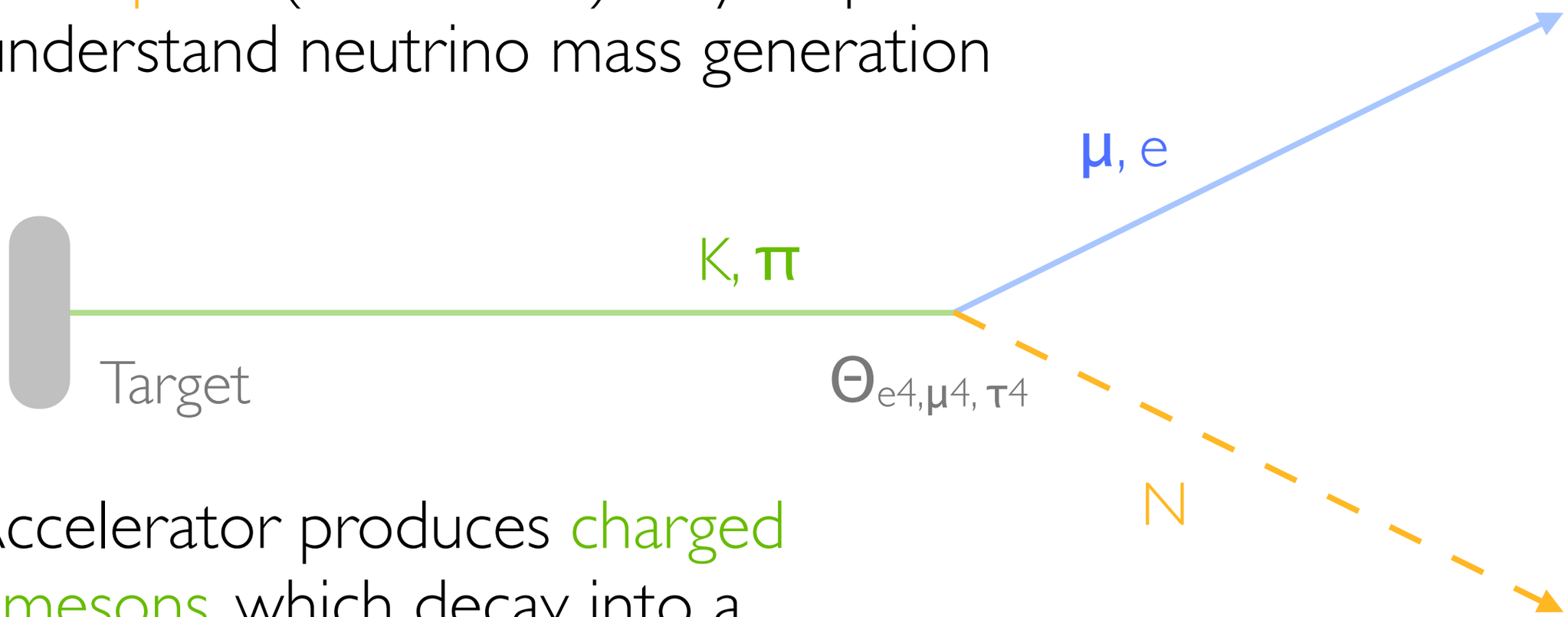
Search for MeV-scale heavy neutral lepton (HNL or N) may help understand neutrino mass generation

K, **π**

Target

# Heavy Neutral Lepton

Search for MeV-scale heavy neutral lepton (HNL or N) may help understand neutrino mass generation

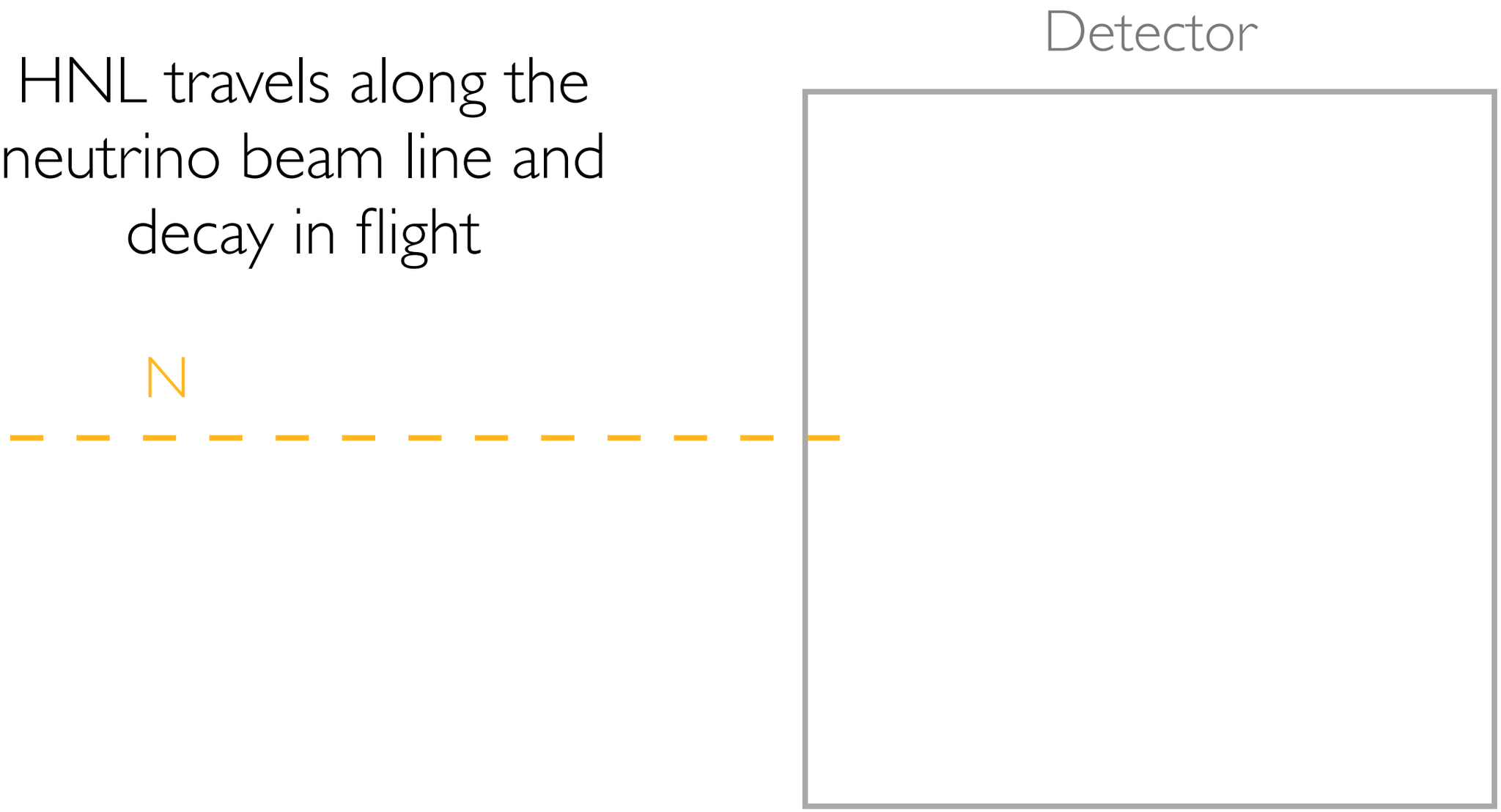



Accelerator produces charged mesons, which decay into a charged lepton and a HNL via a mixing angle, $\Theta_{e4, \mu4, \tau4}$, between the SM neutrino and the HNL

Consider Majorana particles
No helicity suppression

# HNL Detection

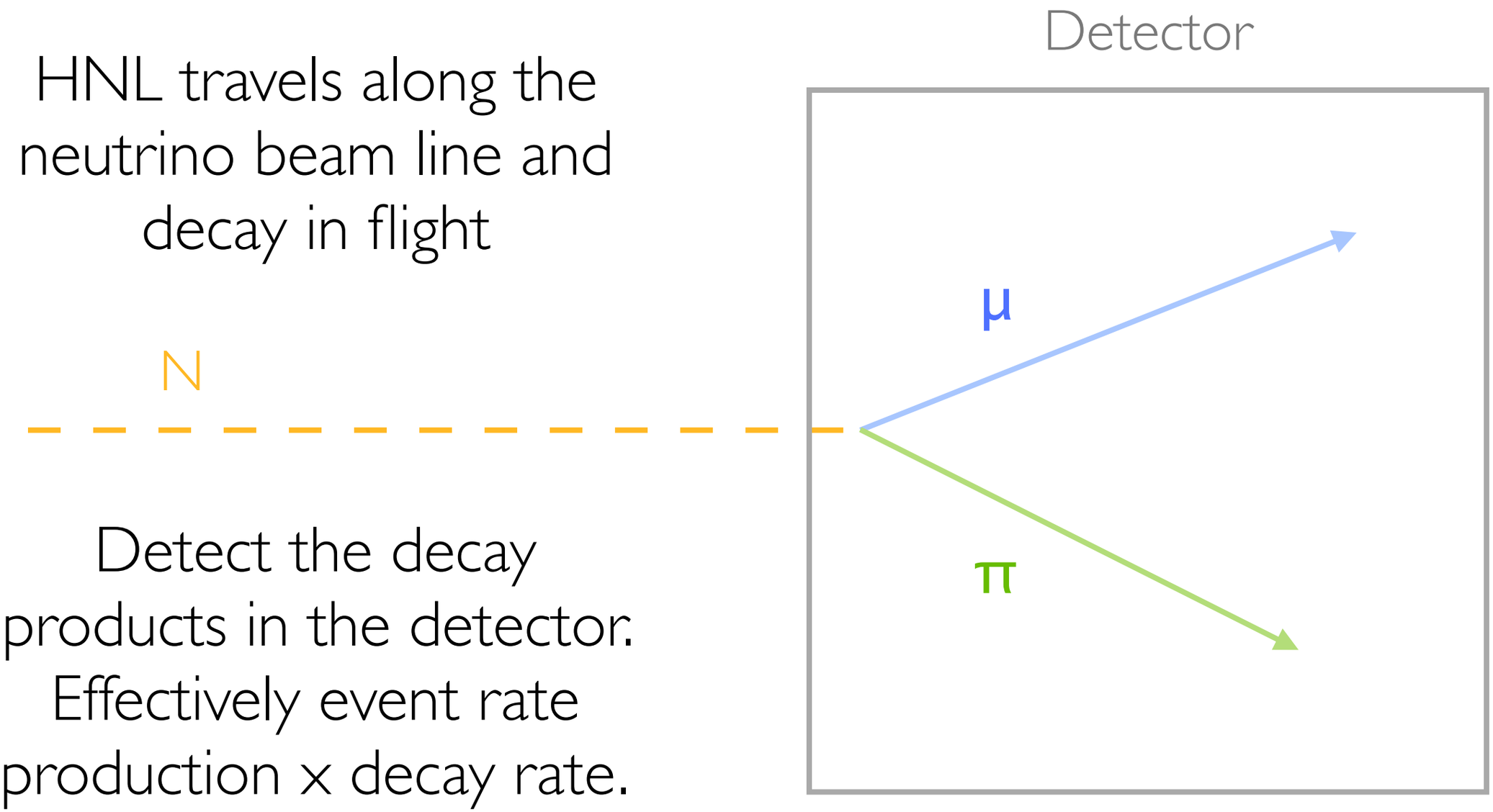
HNL travels along the neutrino beam line and decay in flight



# HNL Detection

HNL travels along the neutrino beam line and decay in flight

Detect the decay products in the detector. Effectively event rate production x decay rate. Measure the mixing angle $\Theta_{\mu 4, e4, \tau 4}$ with each $M_N$

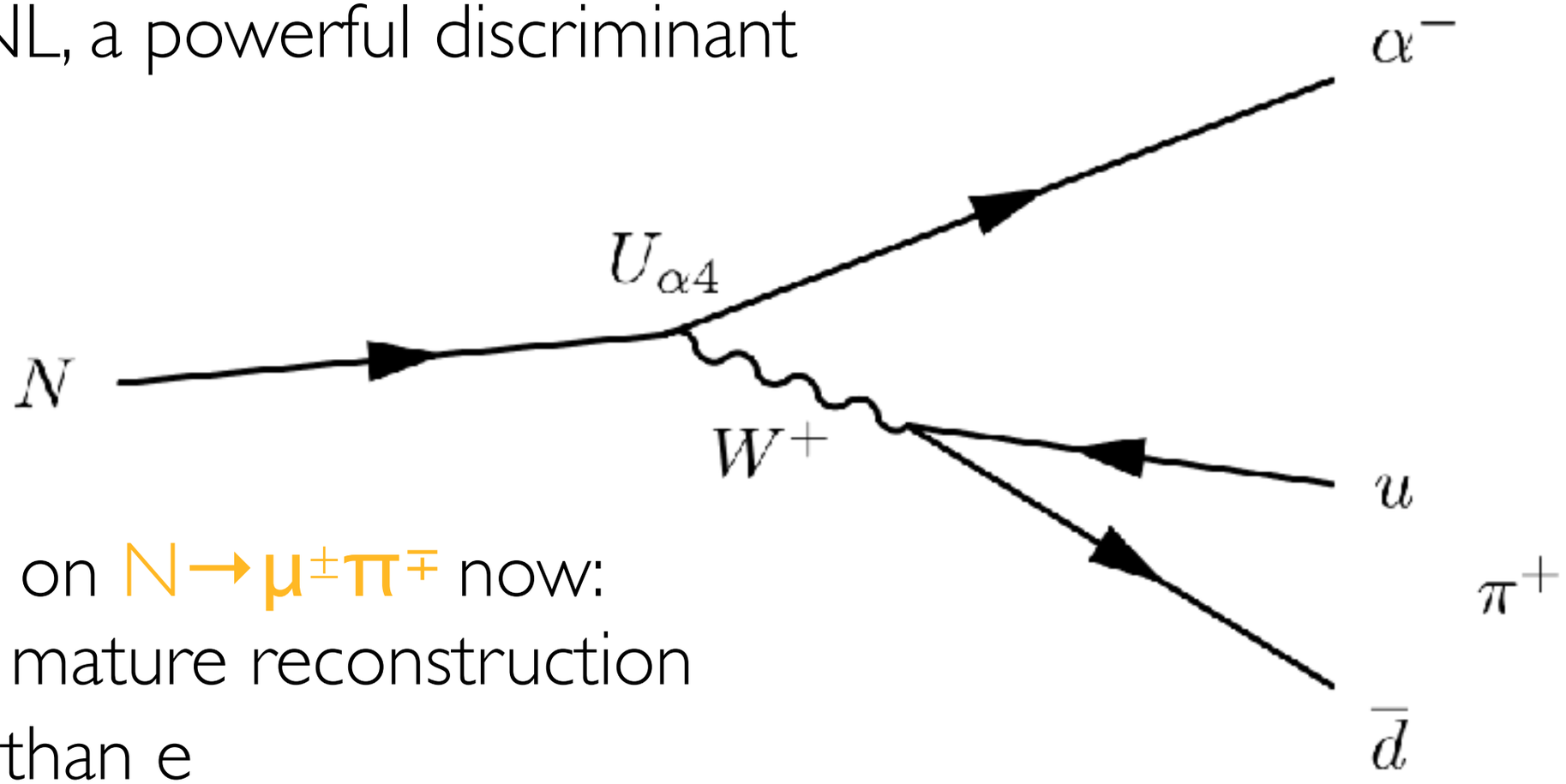



A decay channel

# 2-body Decay Signature

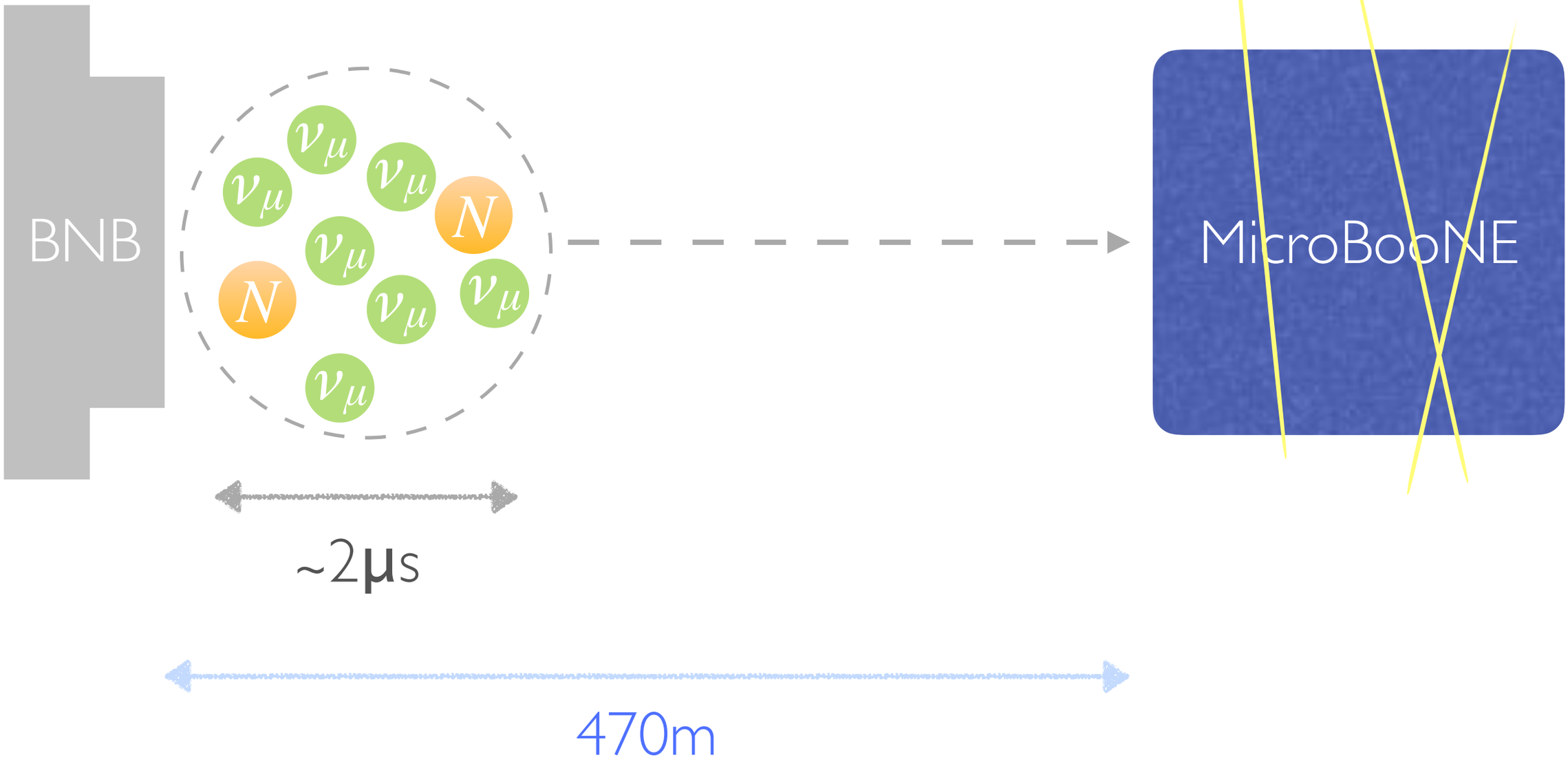
$N \to l^{\pm}\pi^{\mp}$

- Fully reconstructed final states
- Able to reconstruct the invariant mass of HNL, a powerful discriminant

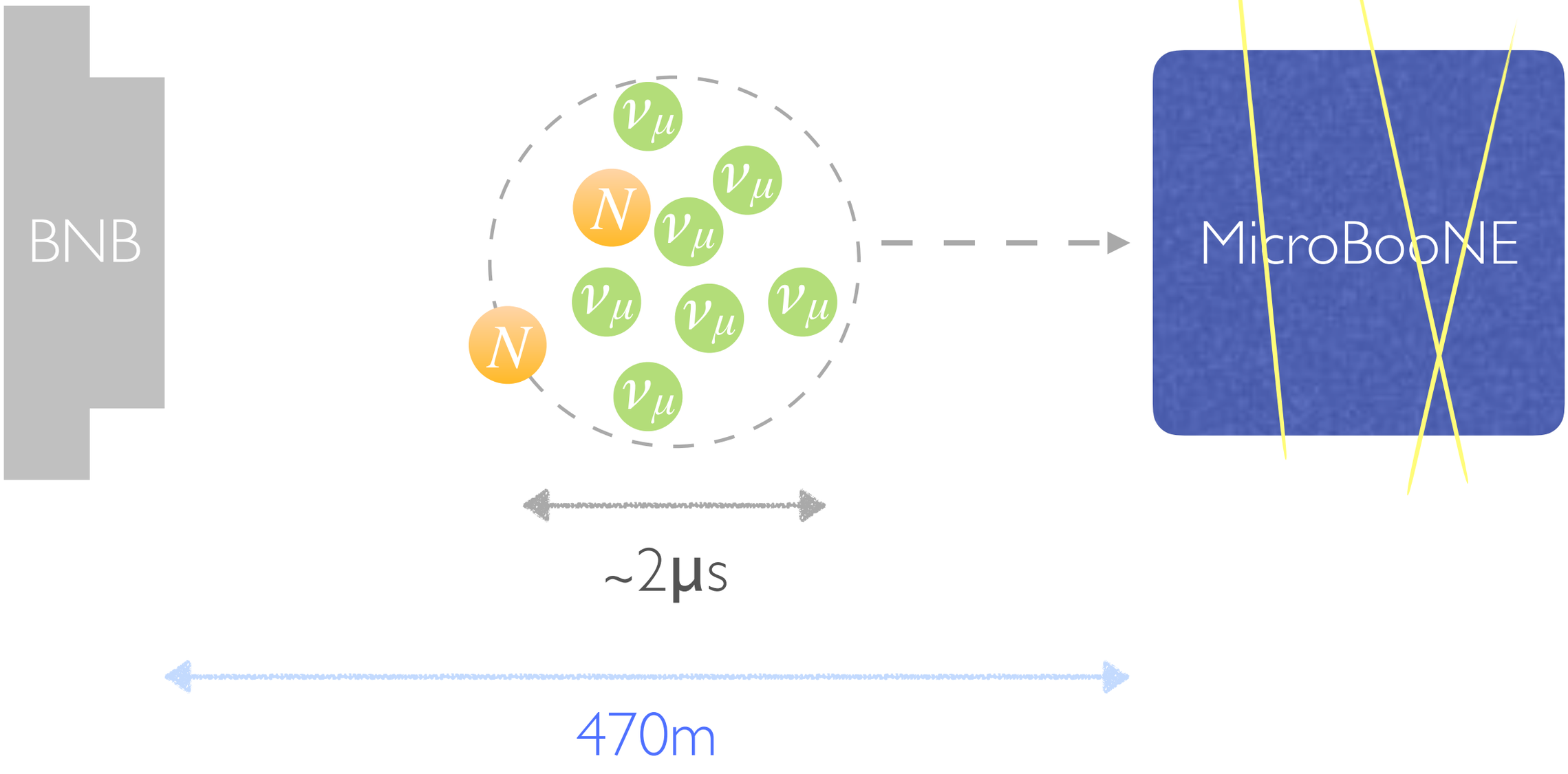



Focus on $N \to \mu^{\pm}\pi^{\mp}$ now:
more mature reconstruction
for **μ** than e

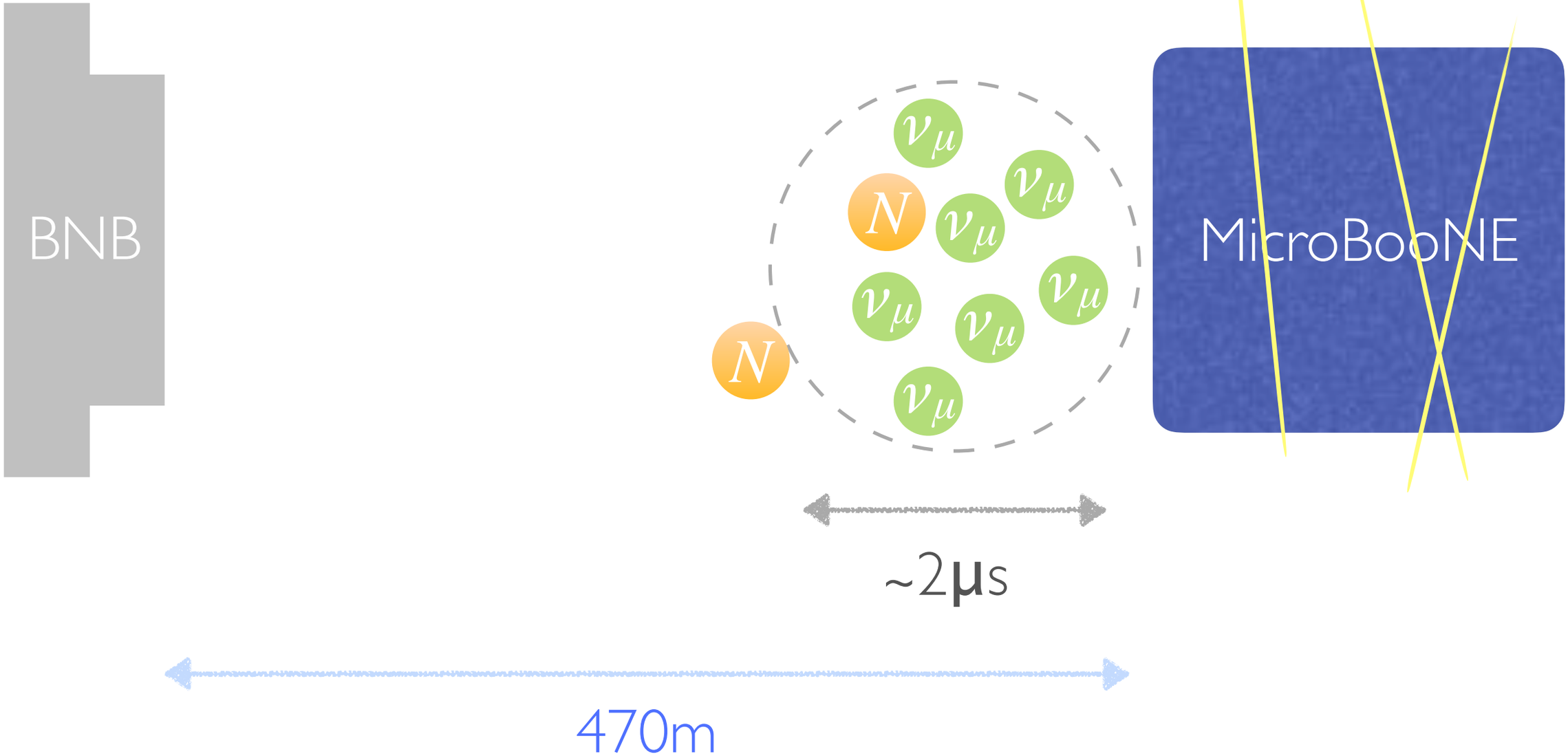
# Time of Flight



# Time of Flight



# Time of Flight



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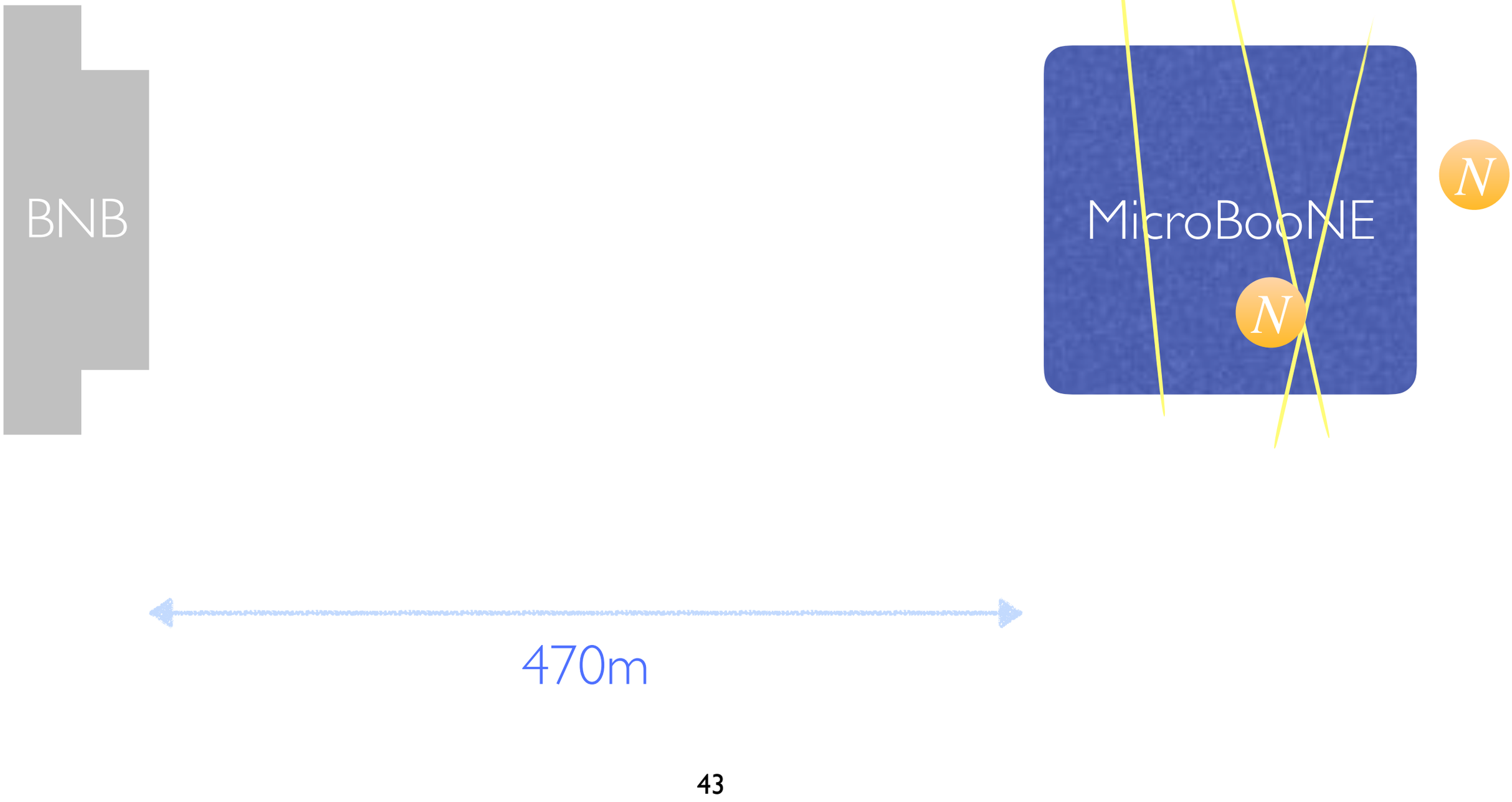
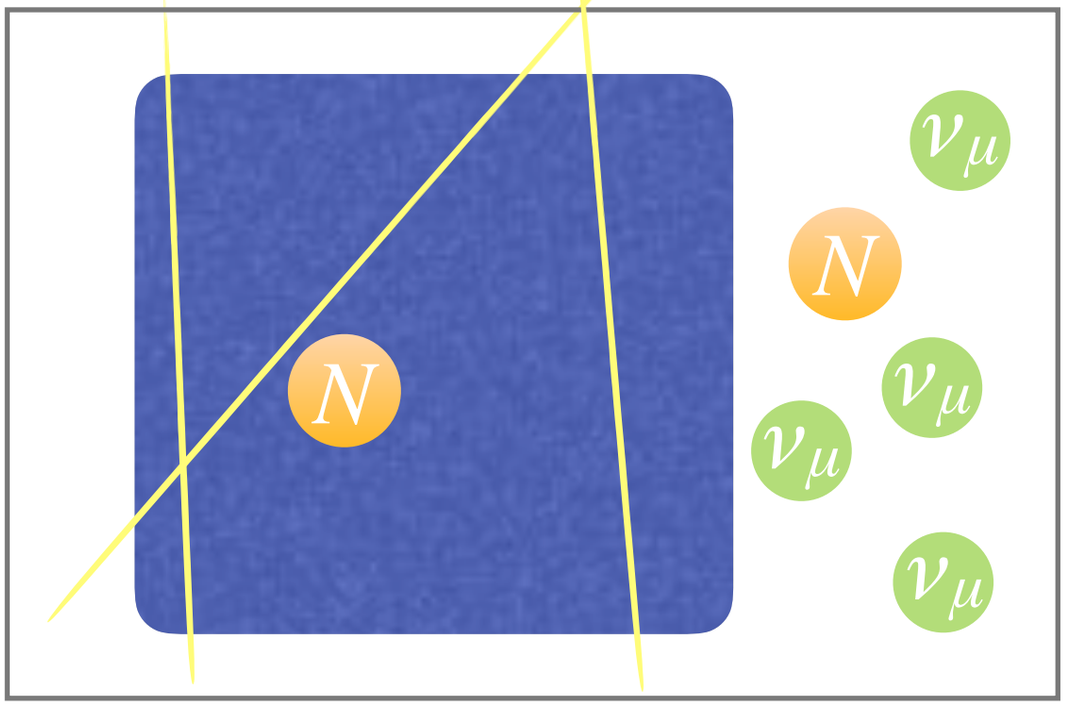
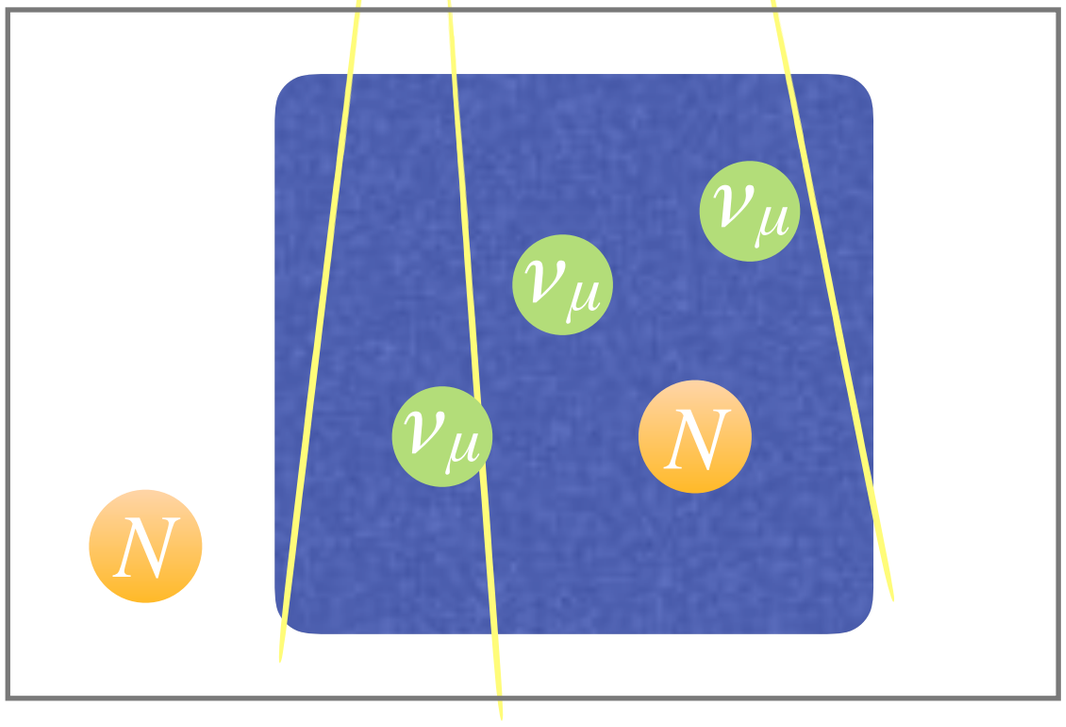


# Data-Driven Analysis

Triggered events

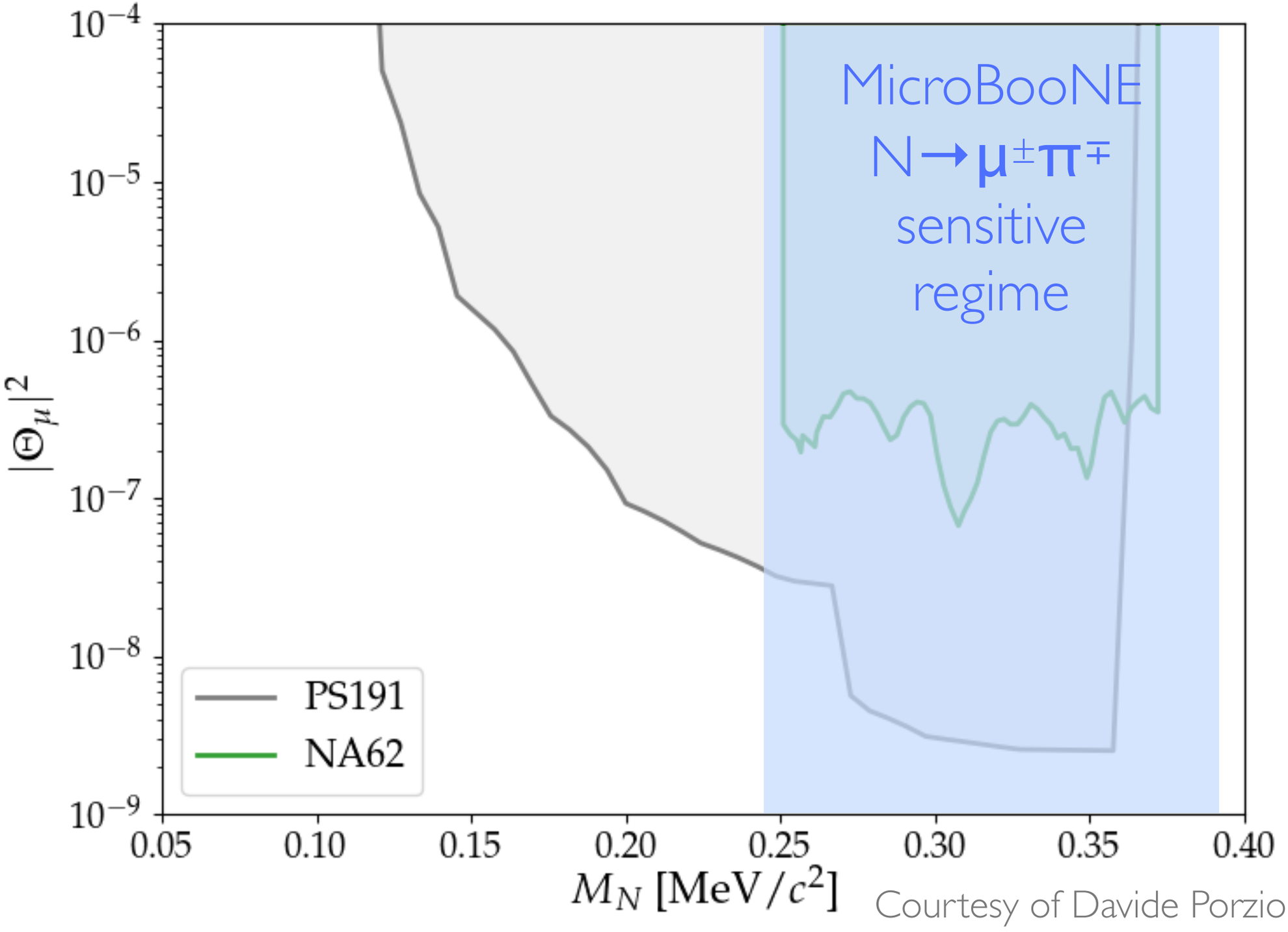



Vetoed events



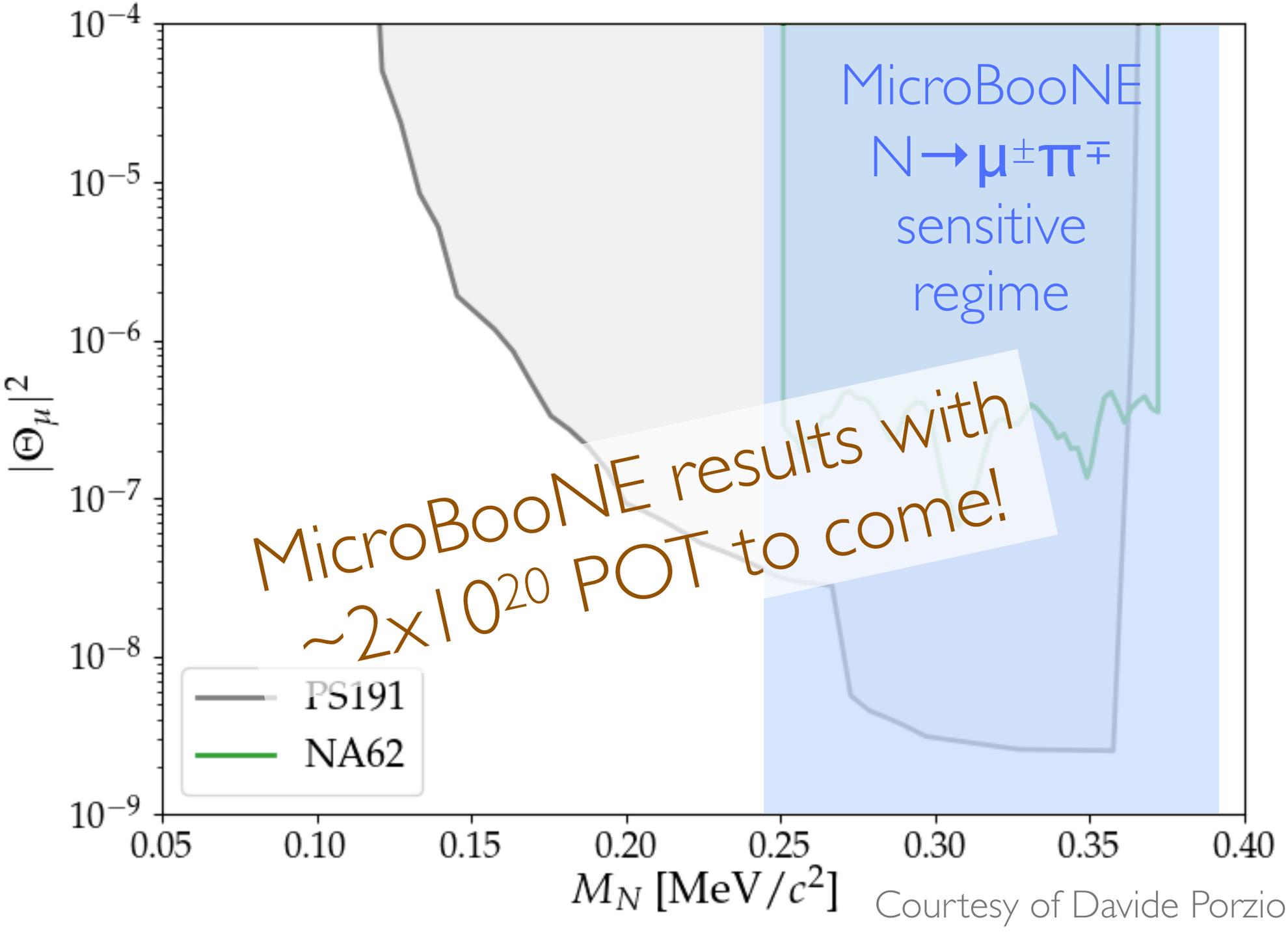

- Use the events triggered in late trigger window, but vetoed those triggered in the BNB trigger window
- ~10% HNL ($M_N$=370MeV/$c^2$), but no SM neutrino background
- Measure an excess of events in a data sample containing only cosmic rays

# Sensitivity

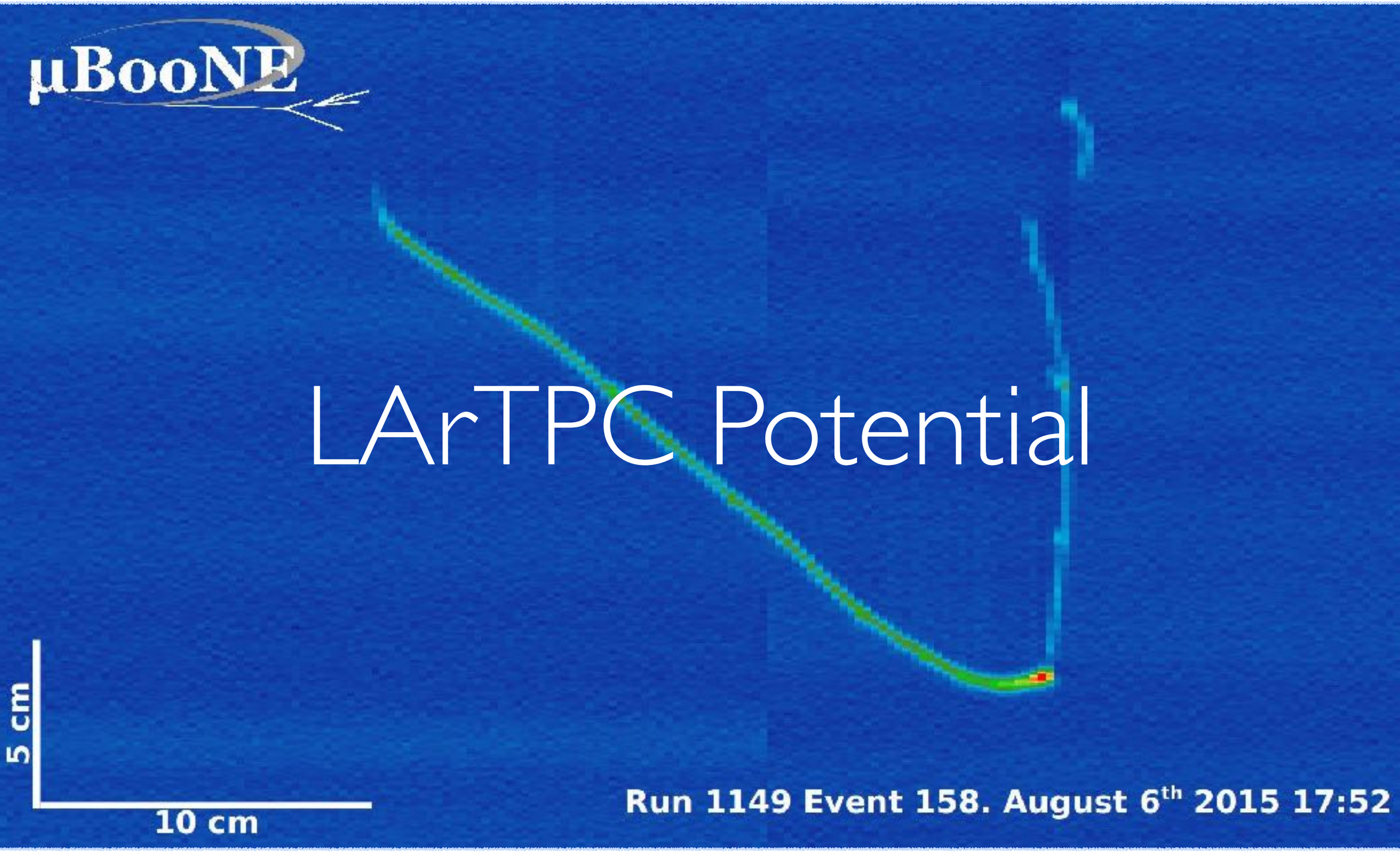



Courtesy of Davide Porzio

# Sensitivity

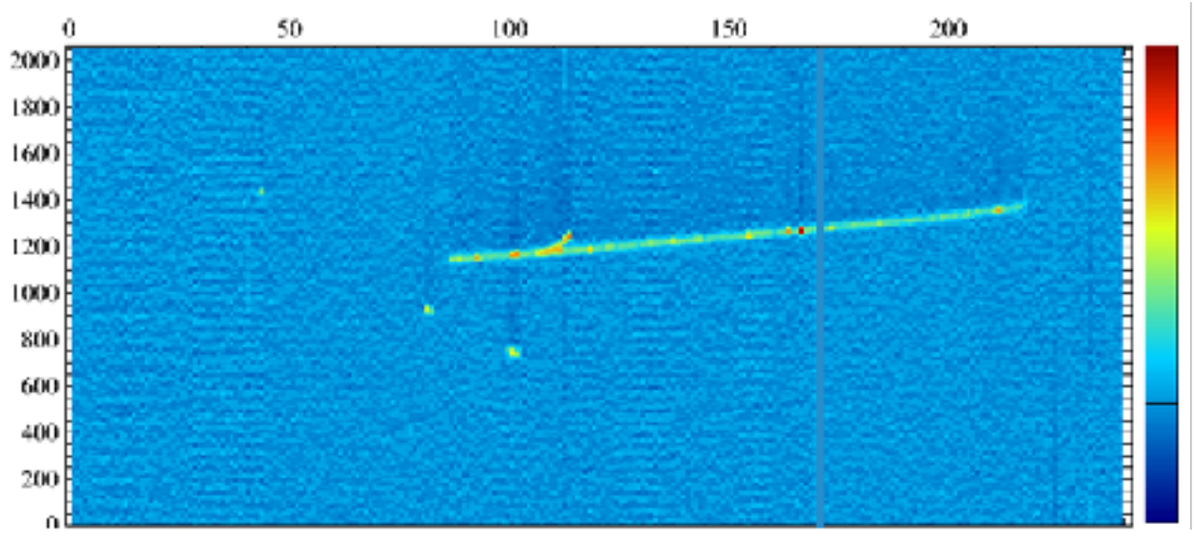


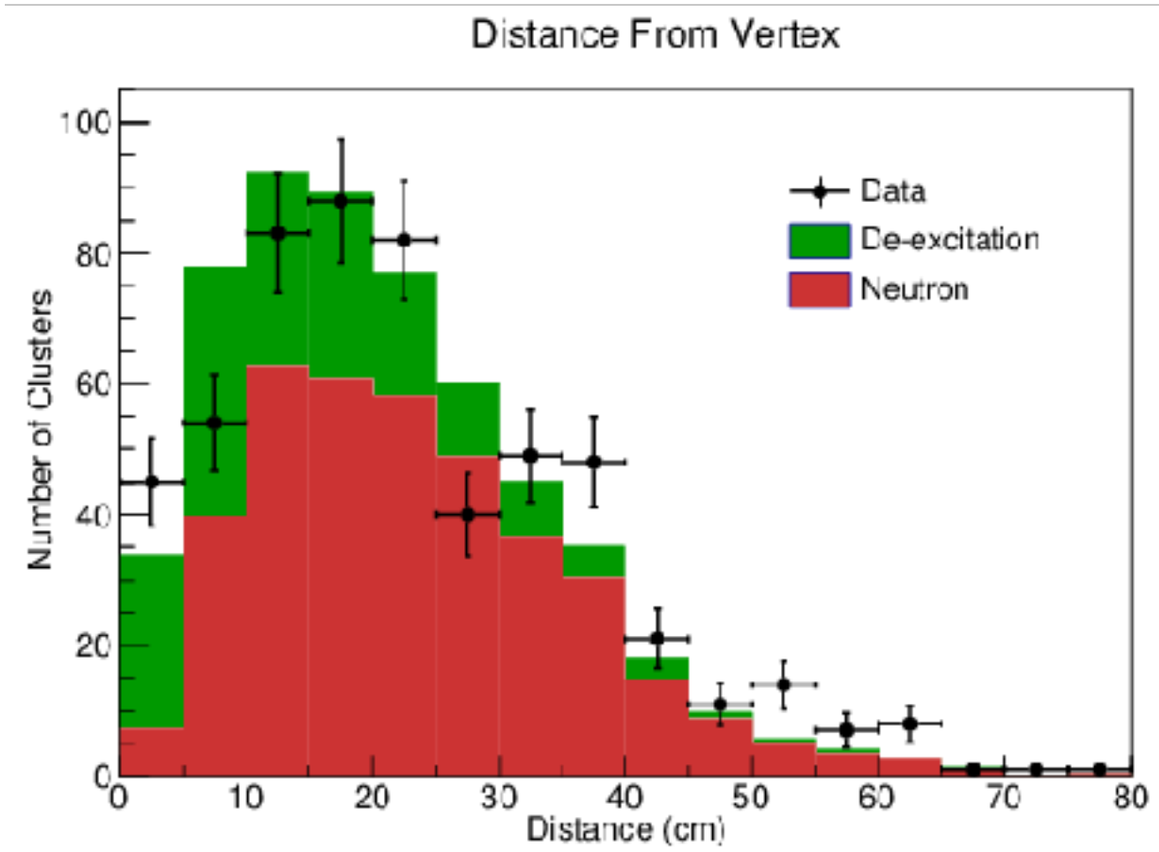

Courtesy of Davide Porzio


μBooNE
LArTPC Potential
5 cm
10 cm
Run 1149 Event 158. August 6th 2015 17:52

# Neutron Detection

- ArgoNeuT measured energy depositions from photons produced by
  - De-excitation of the interacted nucleus
  - Inelastic scattering of primary neutrons
- Open a window of studies of new physics scenarios
- Not able to separate the two sources yet
- arXiv: 1810.06502



# Summary

- LArTPCs: A promising technology of neutrino experiments being rapidly developed
- Unique features of LArTPCs allow sensitivity in unprobed parameter space and potential discovery
- Fruitful beyond Standard Model physics opportunities with
  - Far detectors (DUNE)
  - Near detectors (SBN and DUNE)

# Backup