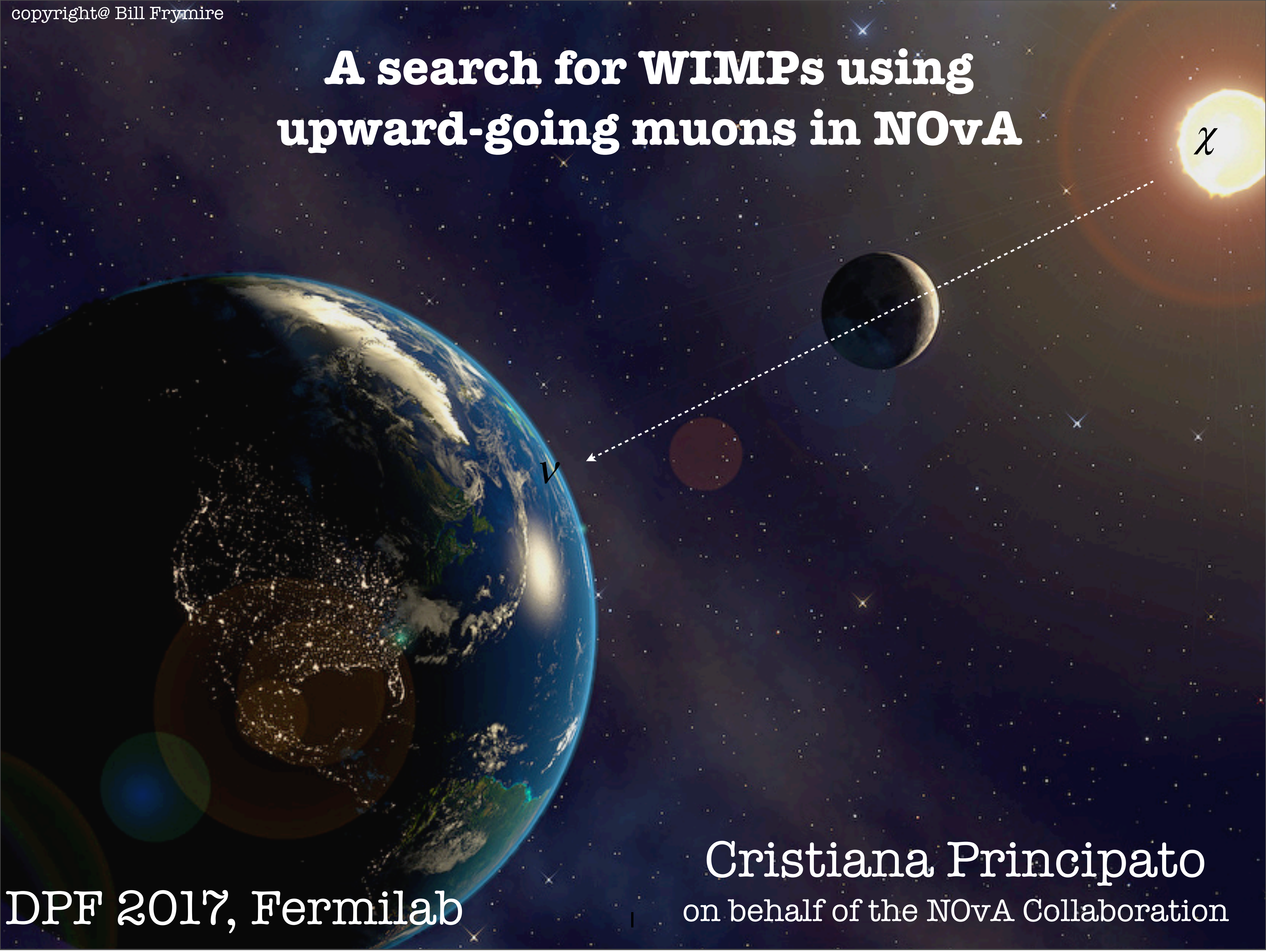
A search for WIMPs using upward-going muons in NOvA

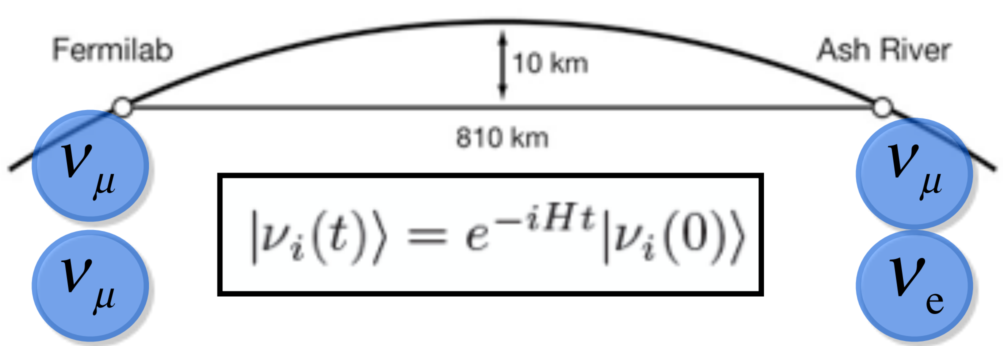


Cristiana Principato
on behalf of the NOvA Collaboration

DPF 2017, Fermilab

The NOvA Experiment

Main Goal: Study neutrino oscillations using the NuMI neutrino beam at Fermilab. NOvA looks for transition of muon-type neutrinos to electron-type neutrinos.



Determining the mixing parameters via oscillation probabilities measurements, done by counting or measuring the energy spectrum of each neutrino flavor

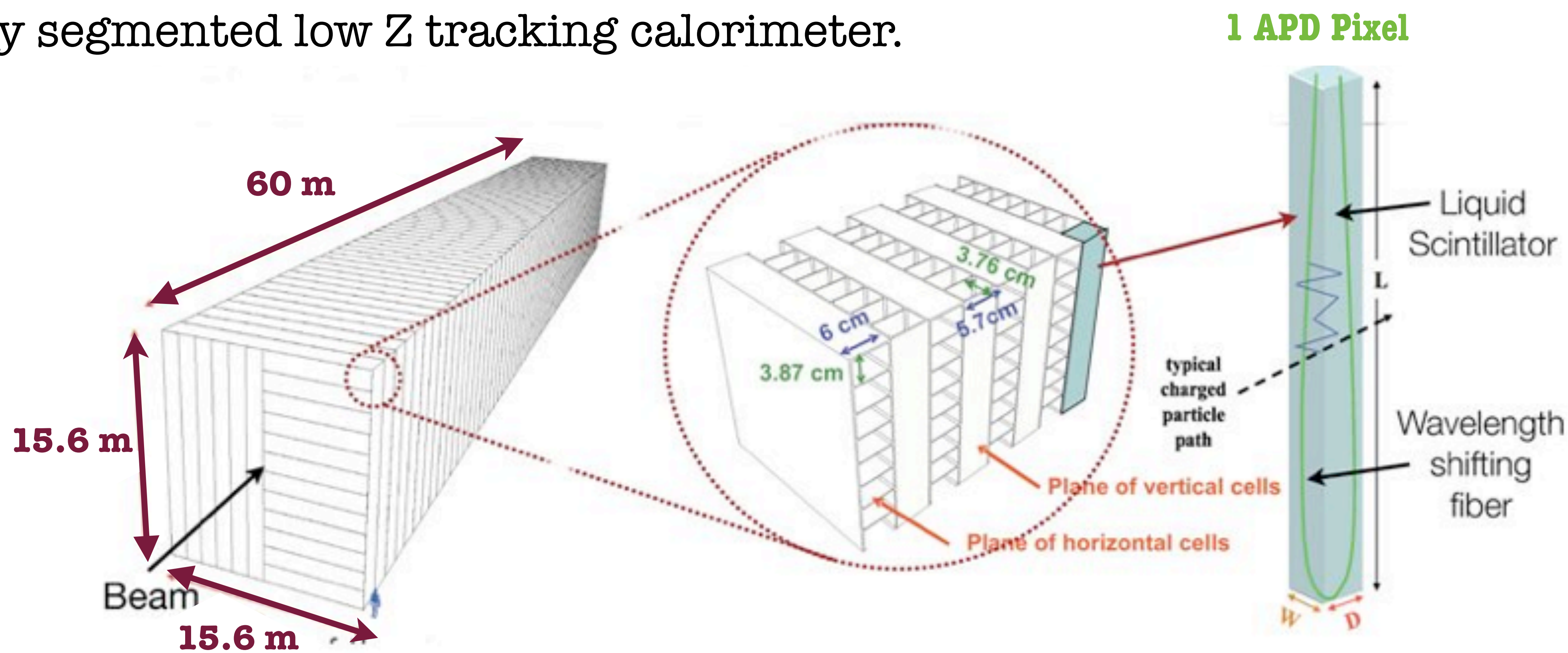
But even if this detector is optimize for ν_e appearance, its design is suitable for exotic searches

The Far Detector

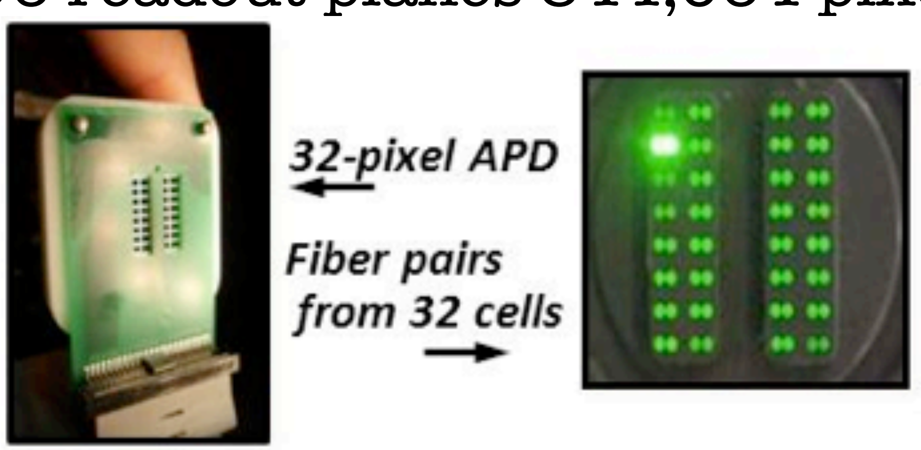
14 kTons of liquid scintillator on the surface of the Earth

Liquid-Scintillator detectors provide good energy resolution, particle identification and favorable background conditions

Highly segmented low Z tracking calorimeter.



896 readout planes 344,064 pixels



Technology:

-PVC cells filled with scintillator oil

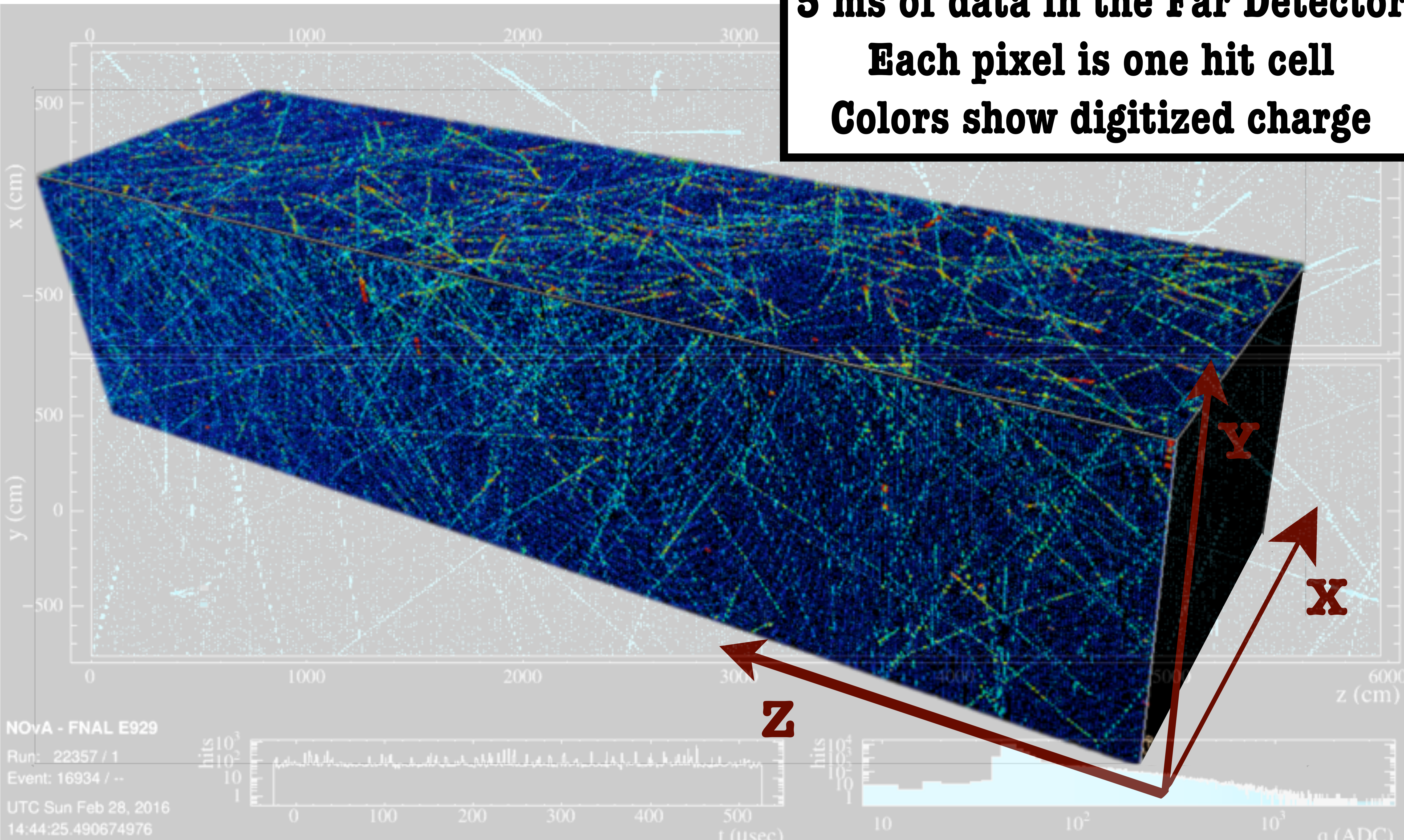
-Each cell contains a wavelength shifting fiber

- A module (32 cells) is read by one Avalanche Photodiode (APD)

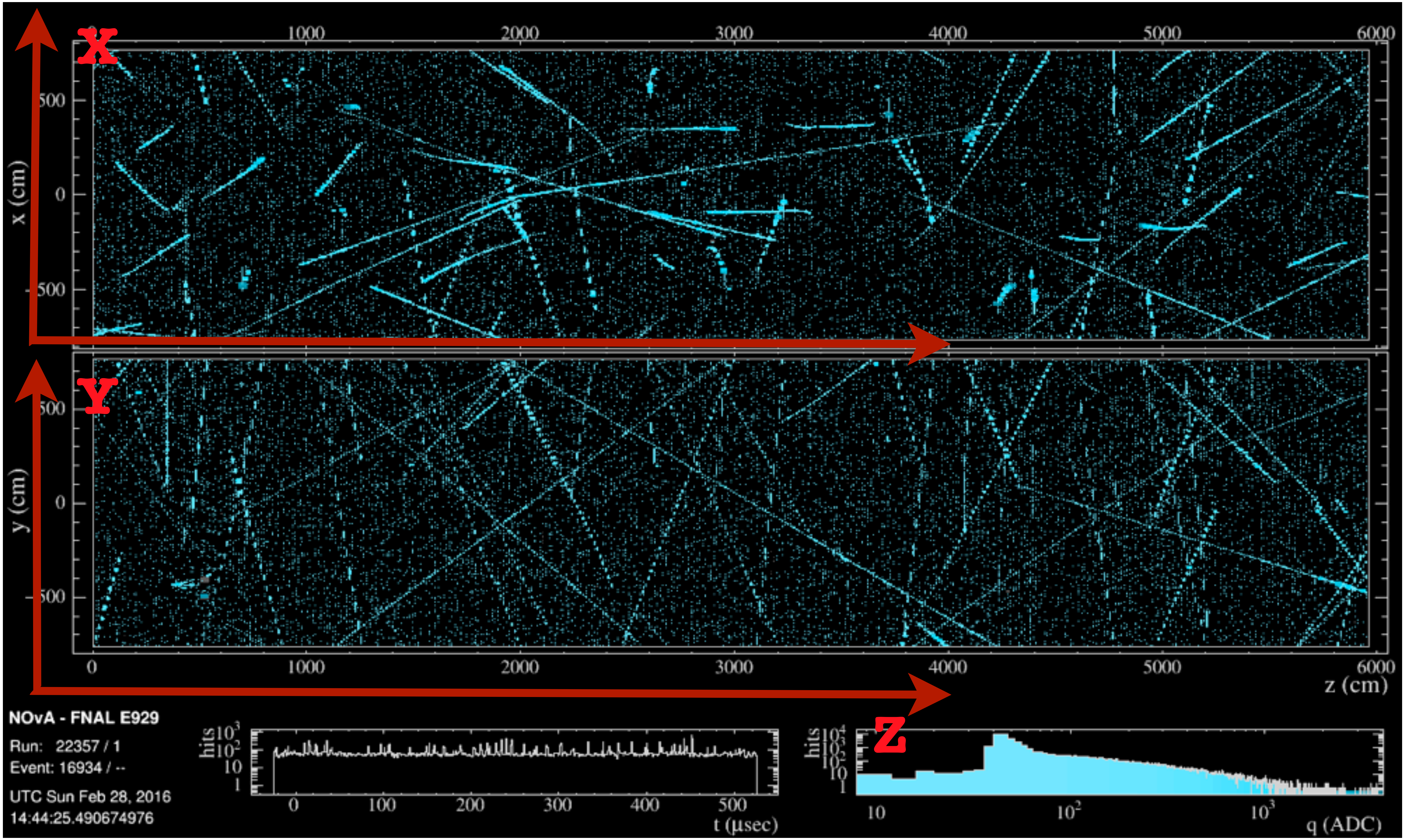
A MIP will produce around 25 PE at the far end of a cell

Real data events from NOvA

5 ms of data in the Far Detector
Each pixel is one hit cell
Colors show digitized charge



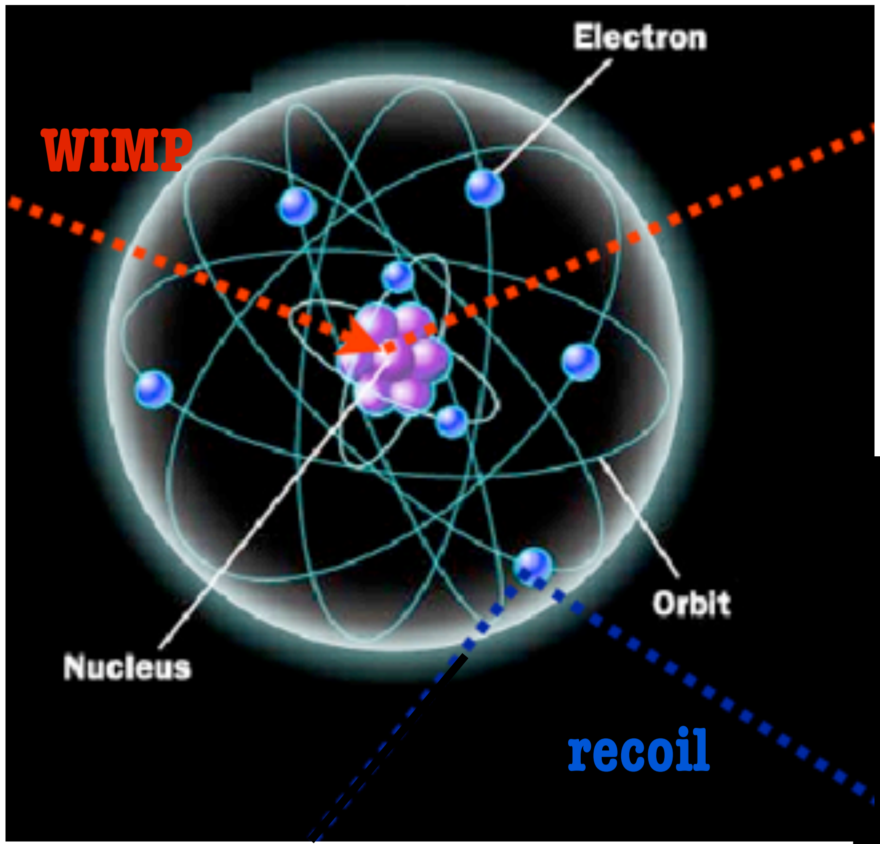
Real data events from NOvA



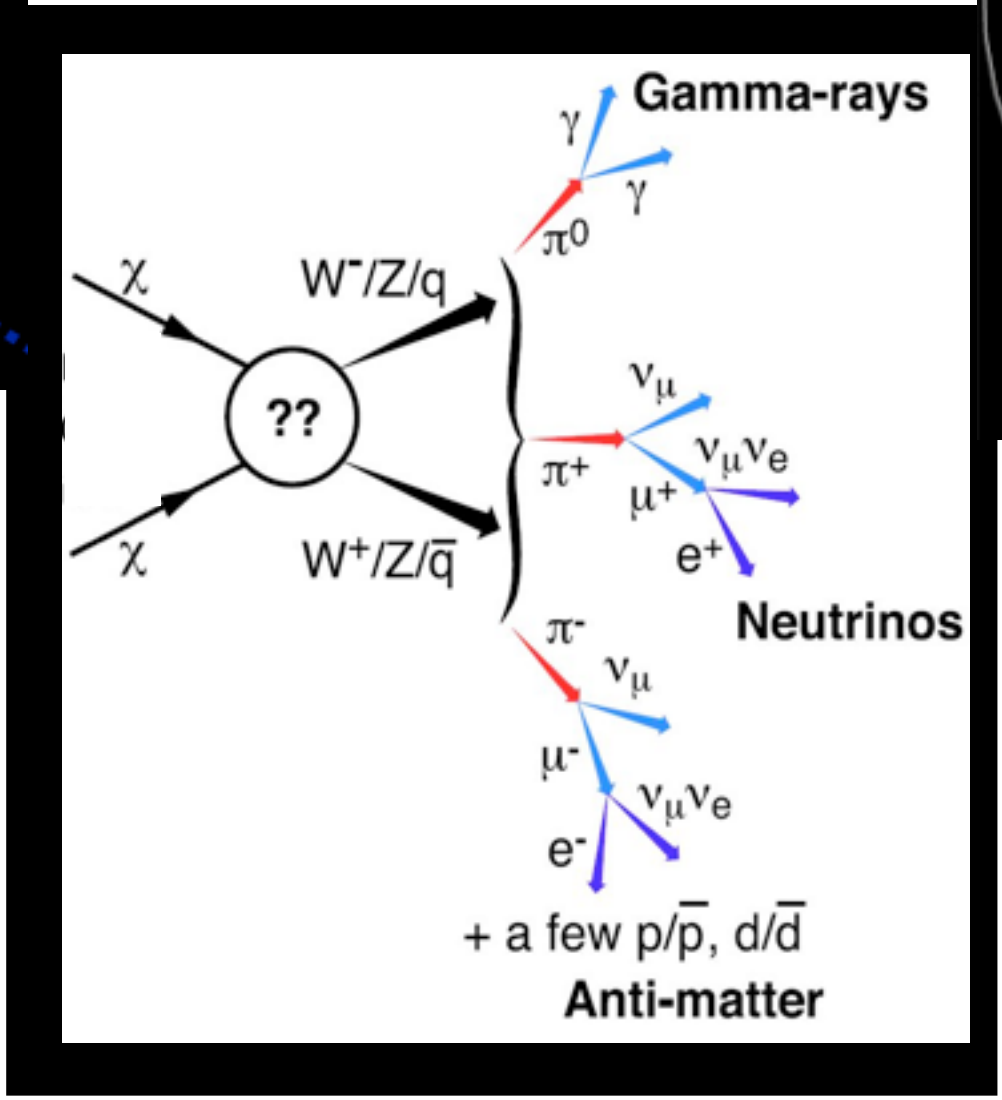
Same 5 ms of data in the event display

WIMPs Search

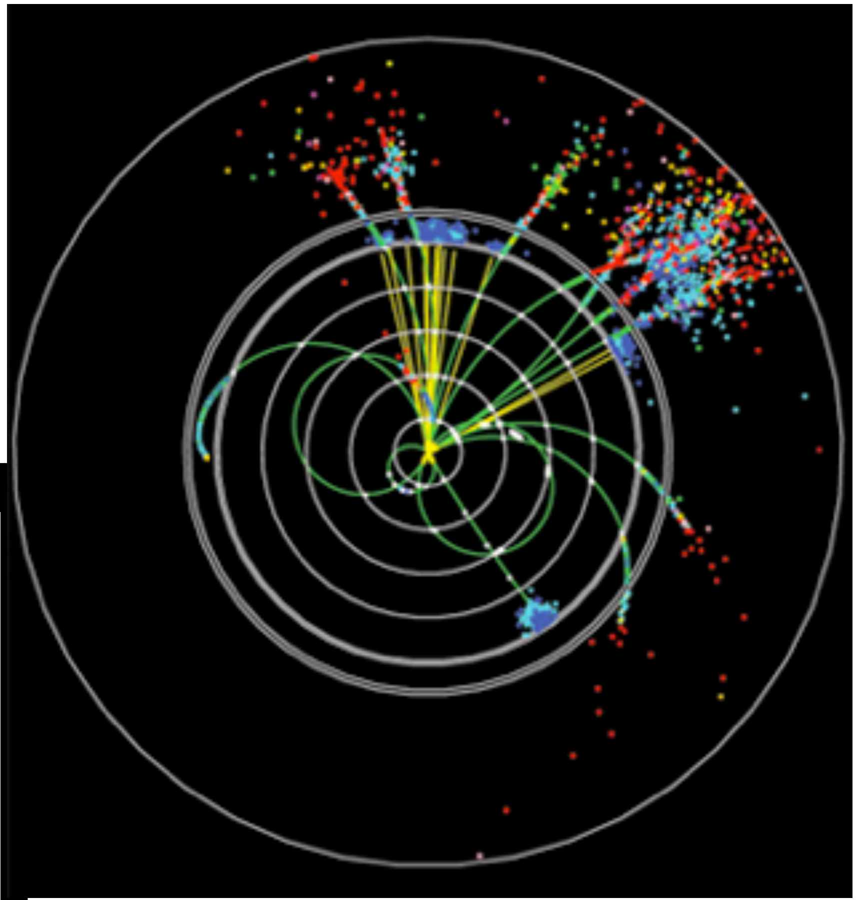
Direct Search



Indirect Search

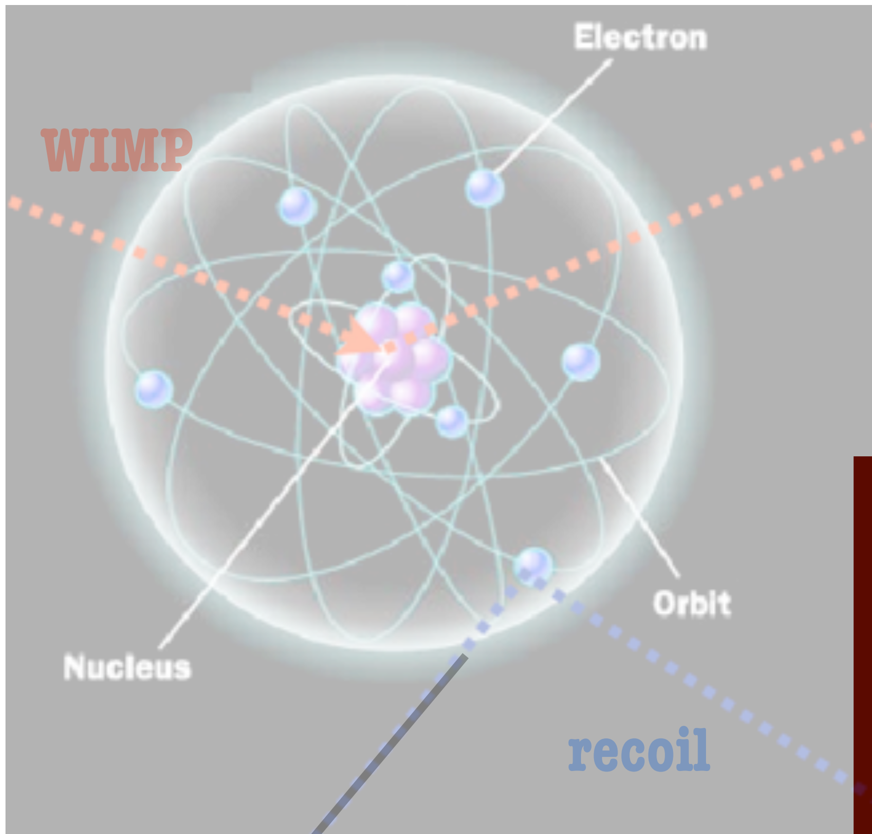


Production at Collider

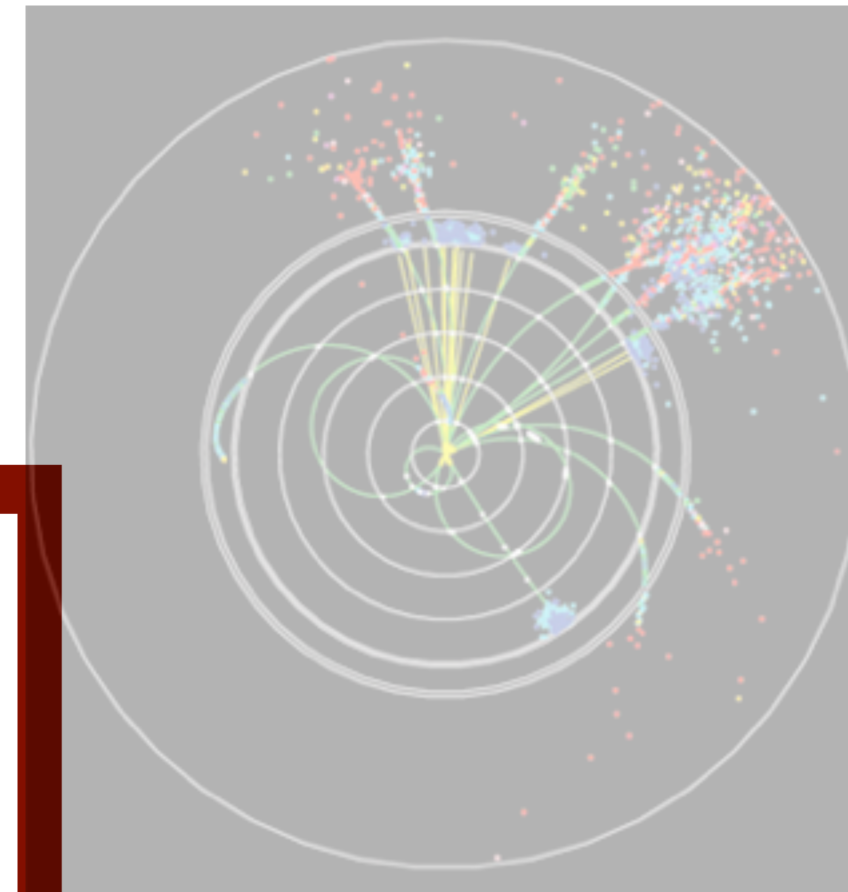


WIMPs Search

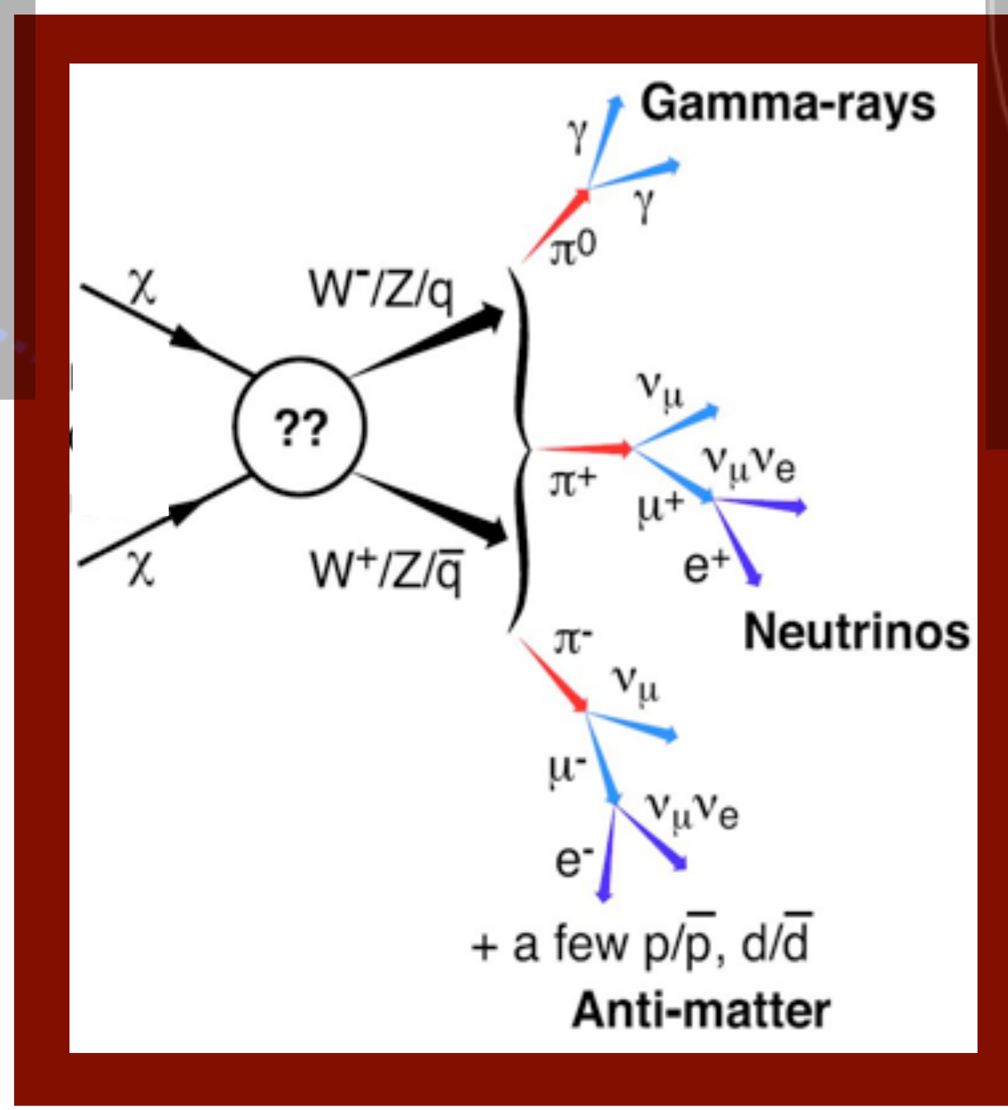
Direct Search



Production at Collider



Indirect Search

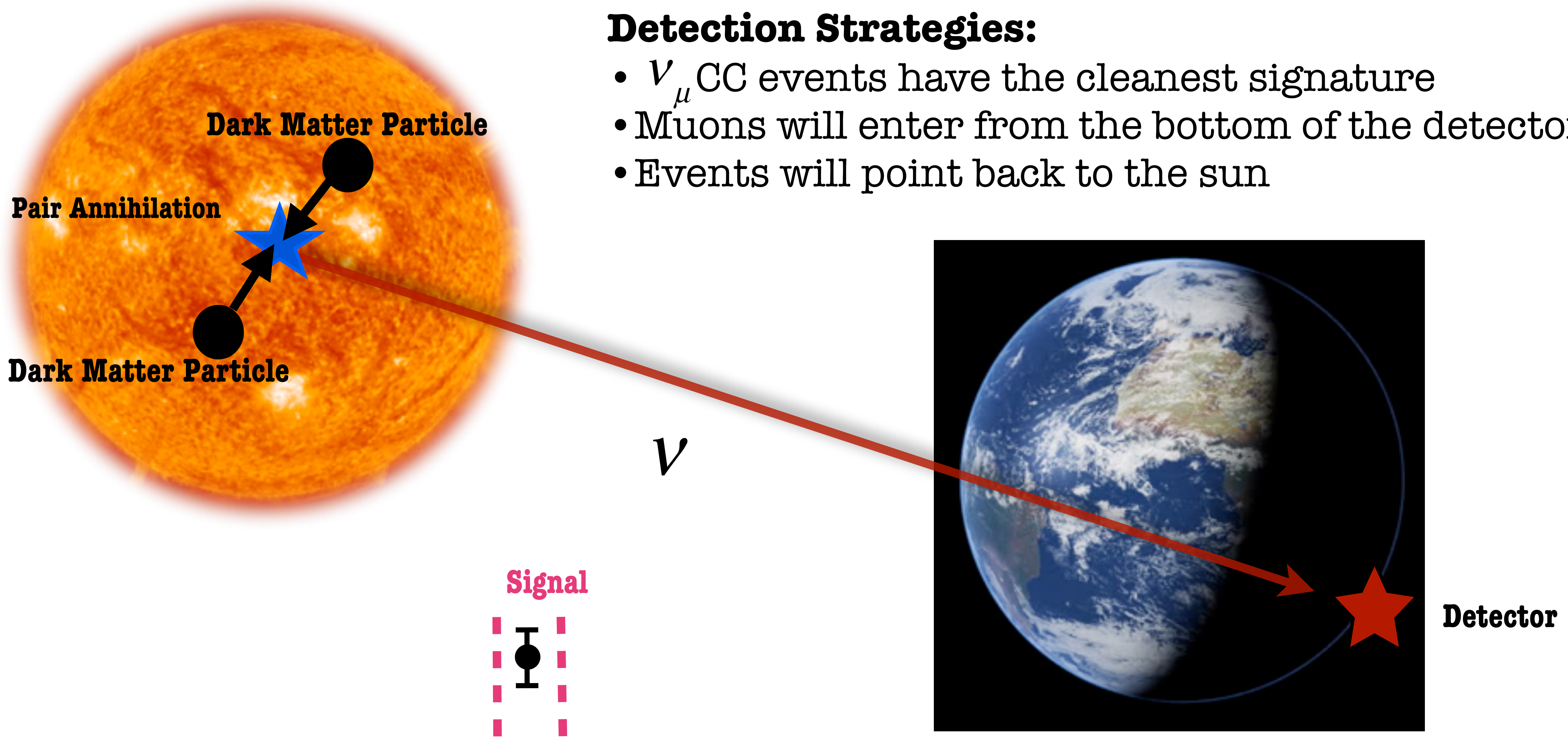


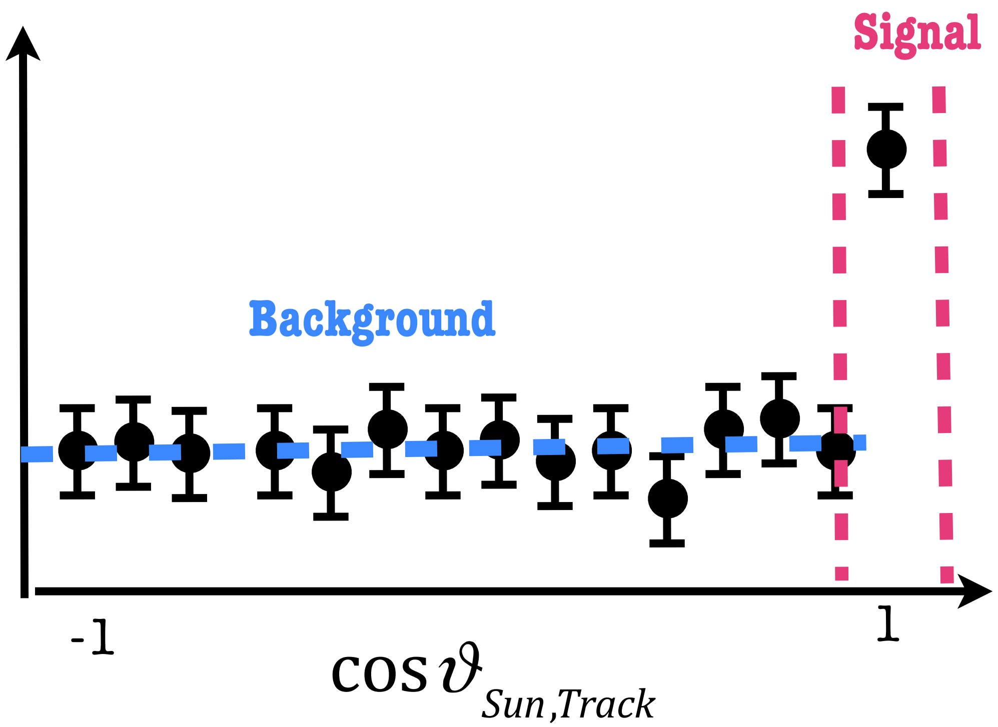
Indirect WIMPs Search

Neutrinos coming from the decay of annihilation products in a massive object, like the Sun

Detection Strategies:

- ν_μ CC events have the cleanest signature
- Muons will enter from the bottom of the detector
- Events will point back to the sun





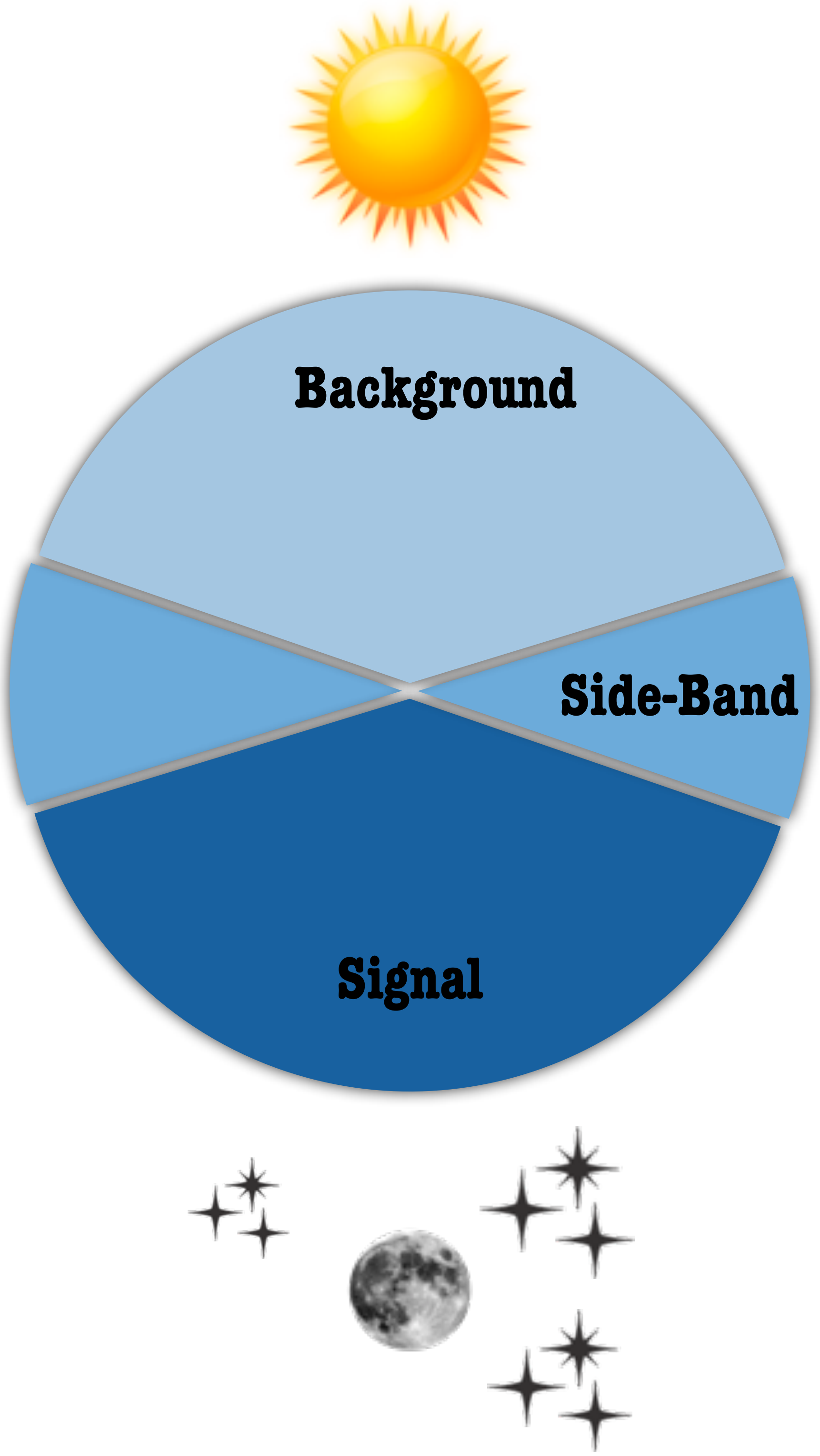
Signal events

An excess of upward-going muons events detected at night and pointing back to the sun

Tuesday, August 1, 17

Dataset

Triggers ran in a stable configuration since December 2014, at 1 Hz.
The work presented here covers 424 days from December 2014 to March 2016.



- **Day region**, background sample
- **Twilight region**, control sample
- **Night region**, signal sample (BLINDED)

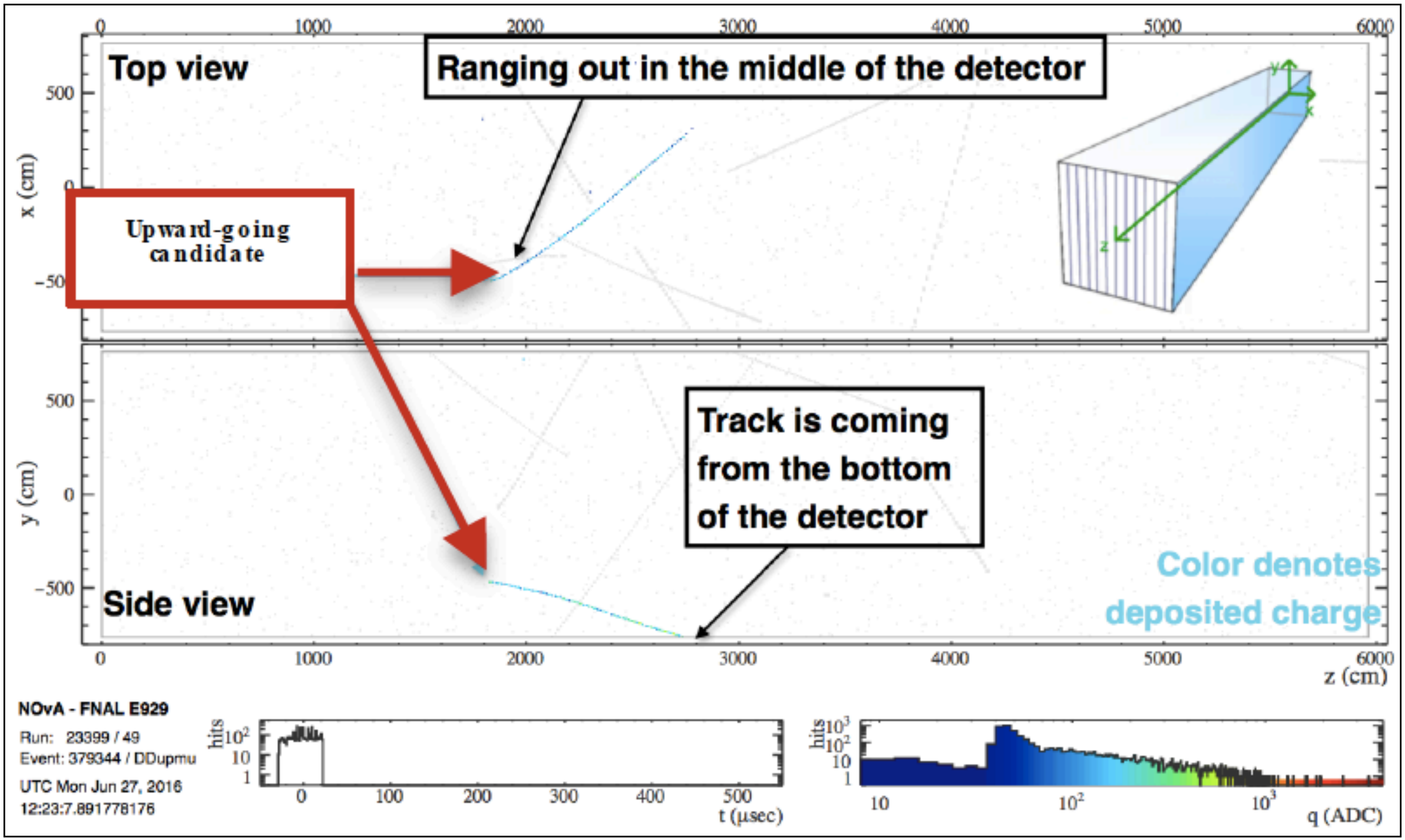
Reminder:
Signal events are upward-going muons, originated from the interaction of neutrinos below the detector, that traveled through the Earth and point back to the Sun

How to select a candidate

Selection:

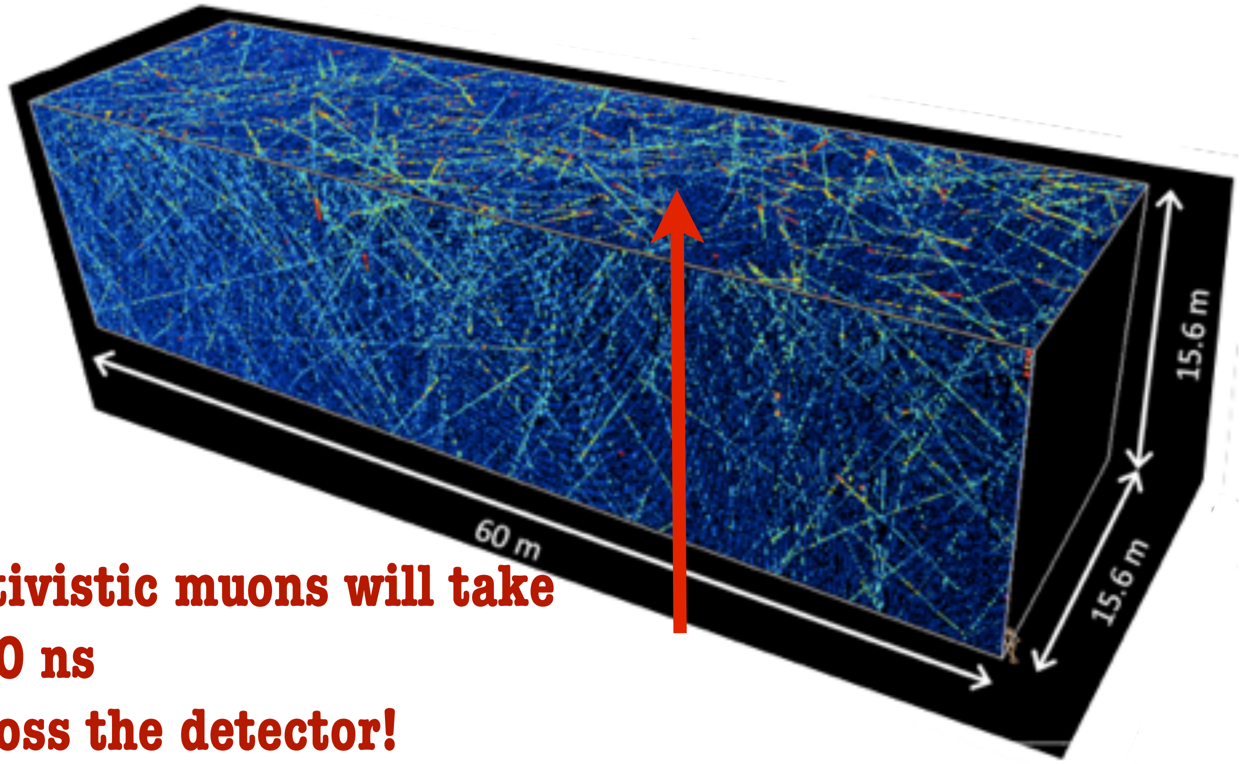
The detector's timing resolution allows directionality determination using a timing-based classifier

Timing is the main discriminant of this analysis



Timing Resolution

5 ms of data at the NOvA Far Detector where the cosmic ray muon rate is 150 kHz



Relativistic muons will take
t > 50 ns
to cross the detector!

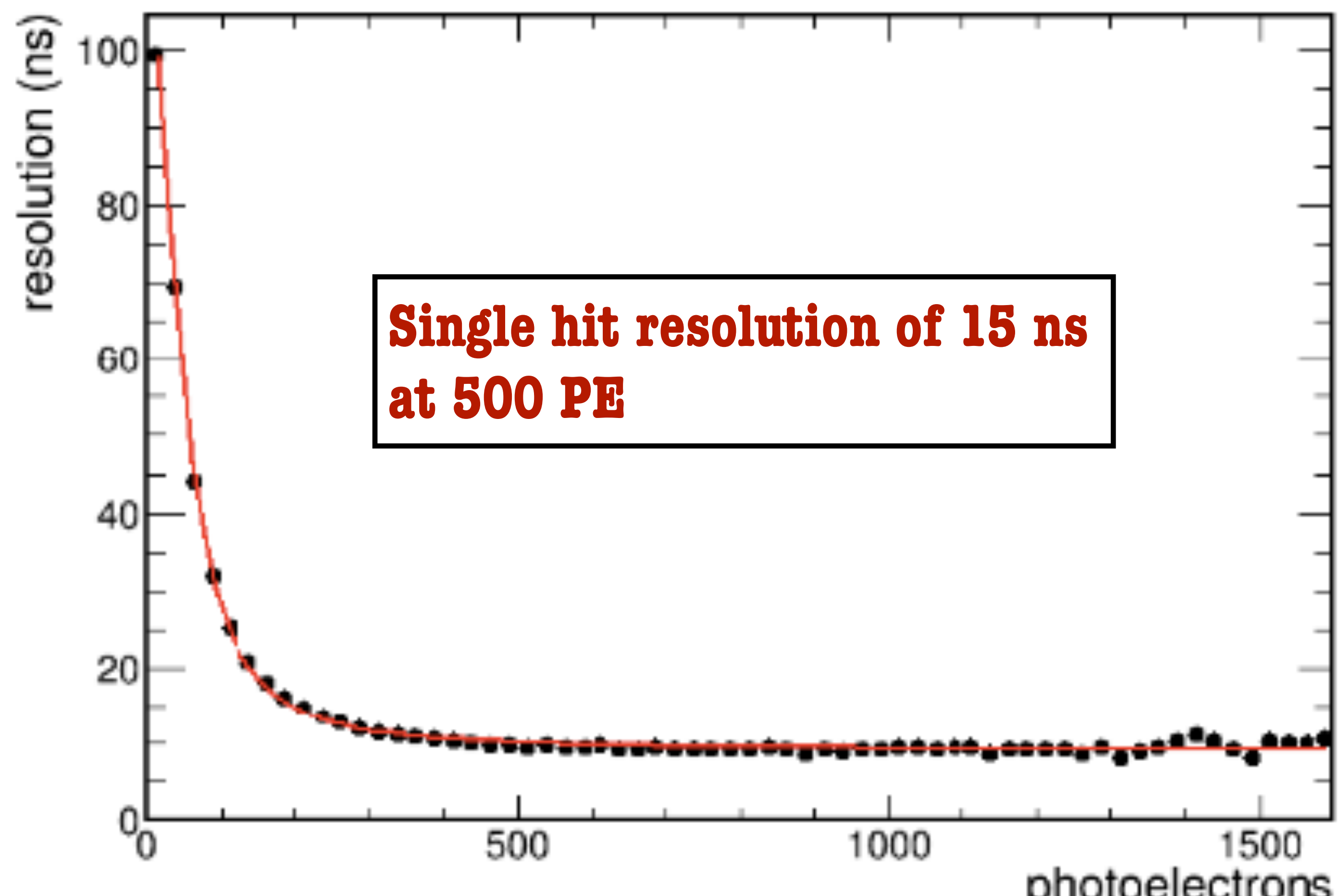
We have 10^{10} downward-going events per day and we are trying to observe 1 or 2 upward-going muons

In our analysis we use timing to discriminate signal from background, a good timing resolution is crucial for this search

Rejection power:

Trigger: From **10^{10}** events to 10^5

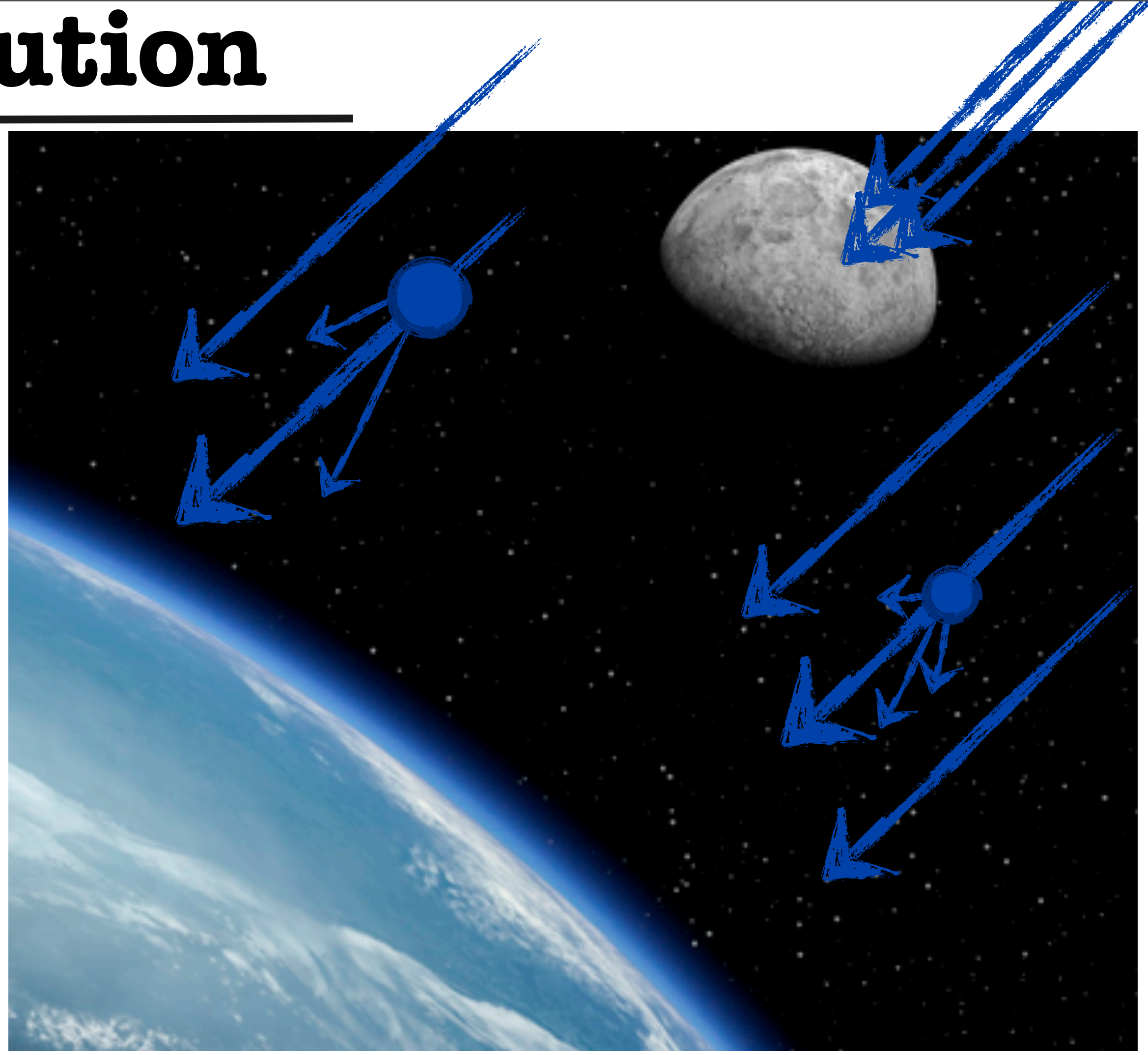
Offline: From 10^5 events to few



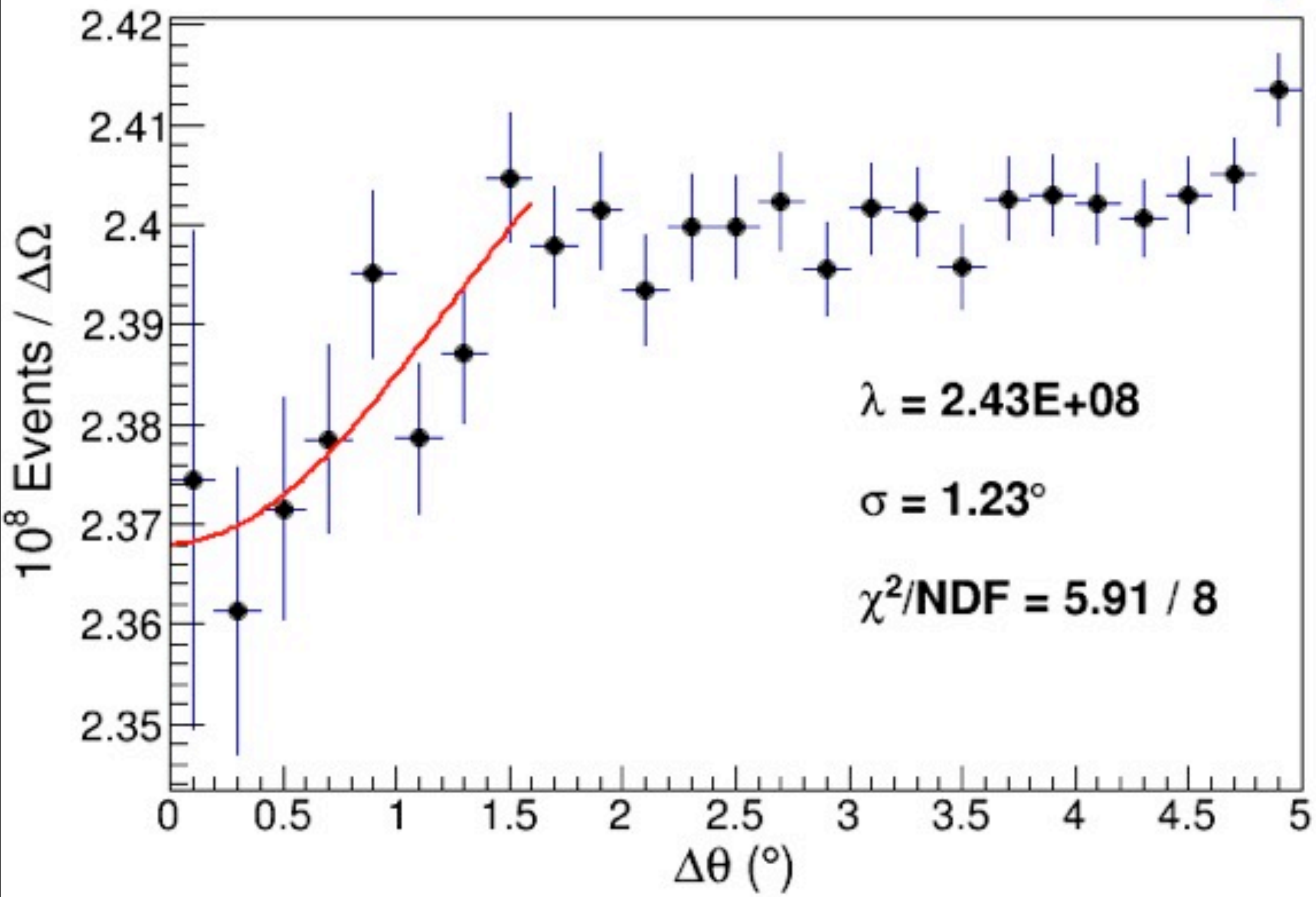
Pointing resolution

Since we want to detect an excess of neutrinos coming from the sun, good enough pointing resolution is needed.

Able to observe the shadow of the Moon in the downward-going cosmic ray muon sample.



NOvA Preliminary



Unfolding the angular size of the Moon to extract an upper limit on the angular resolution for pointing at celestial objects.

Pointing resolution is around 1 degree

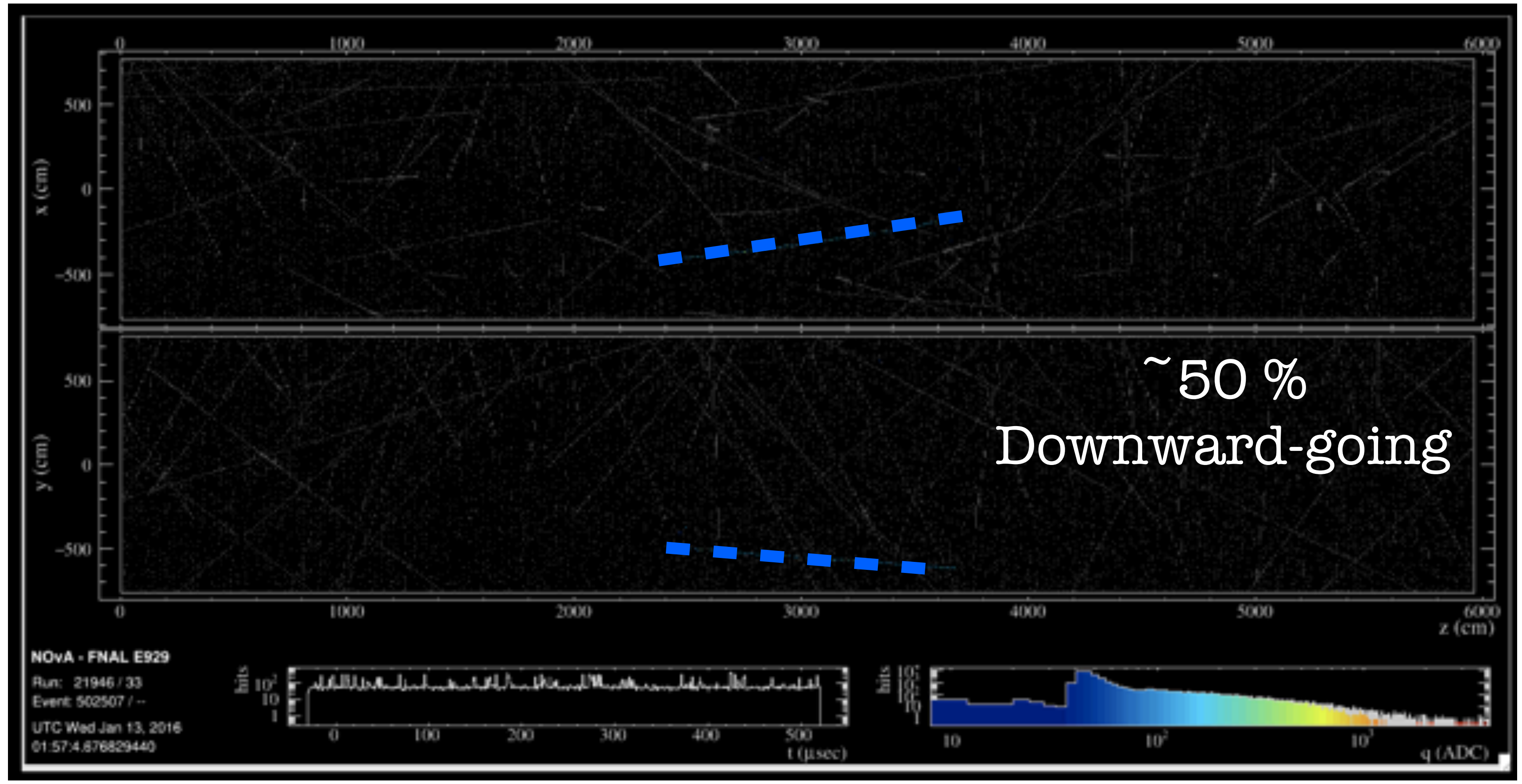
Triggers sanity check

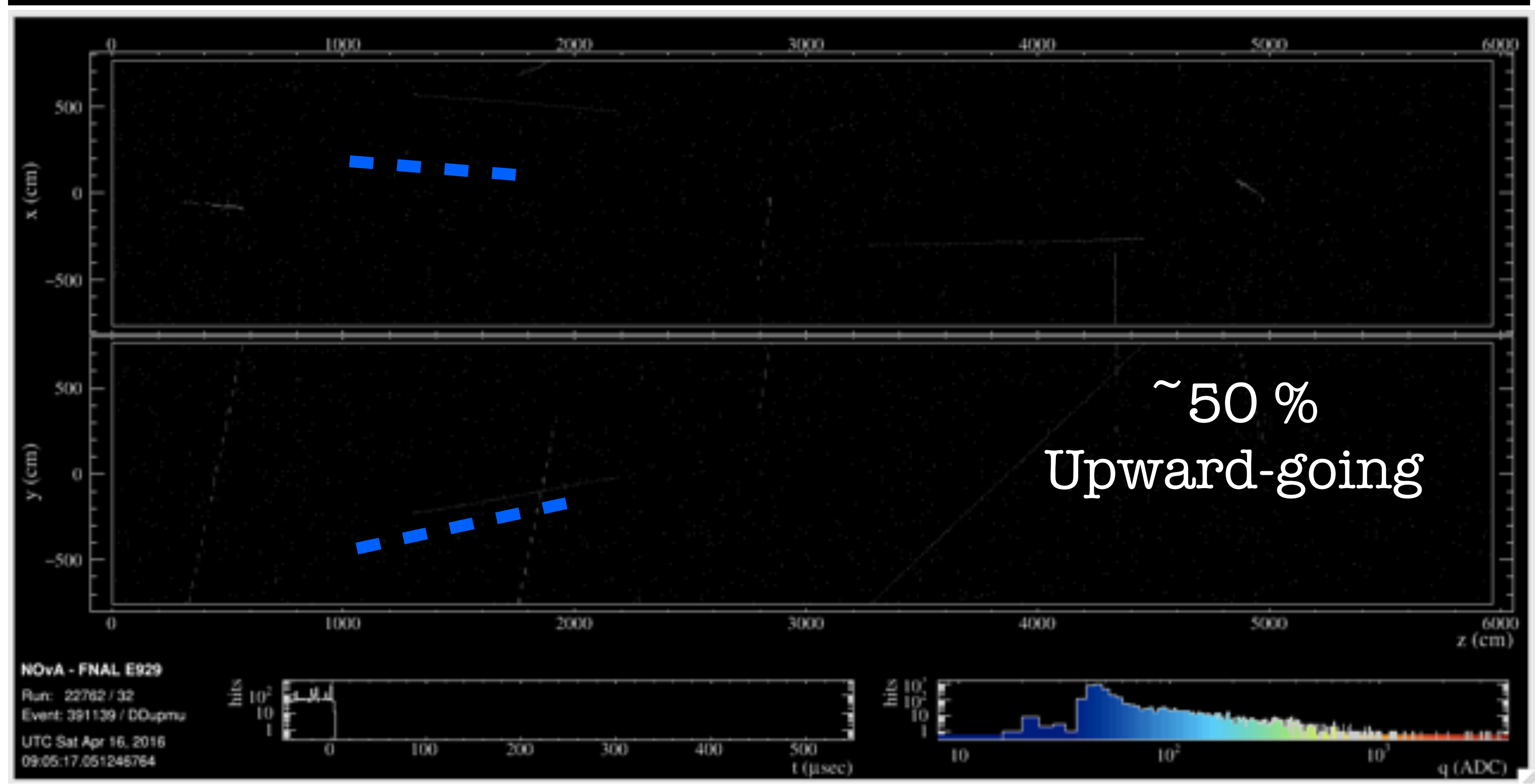
4 beam muon interaction events used in the oscillation analysis

Beam direction

ν_μ ν_μ ν_μ ν_μ

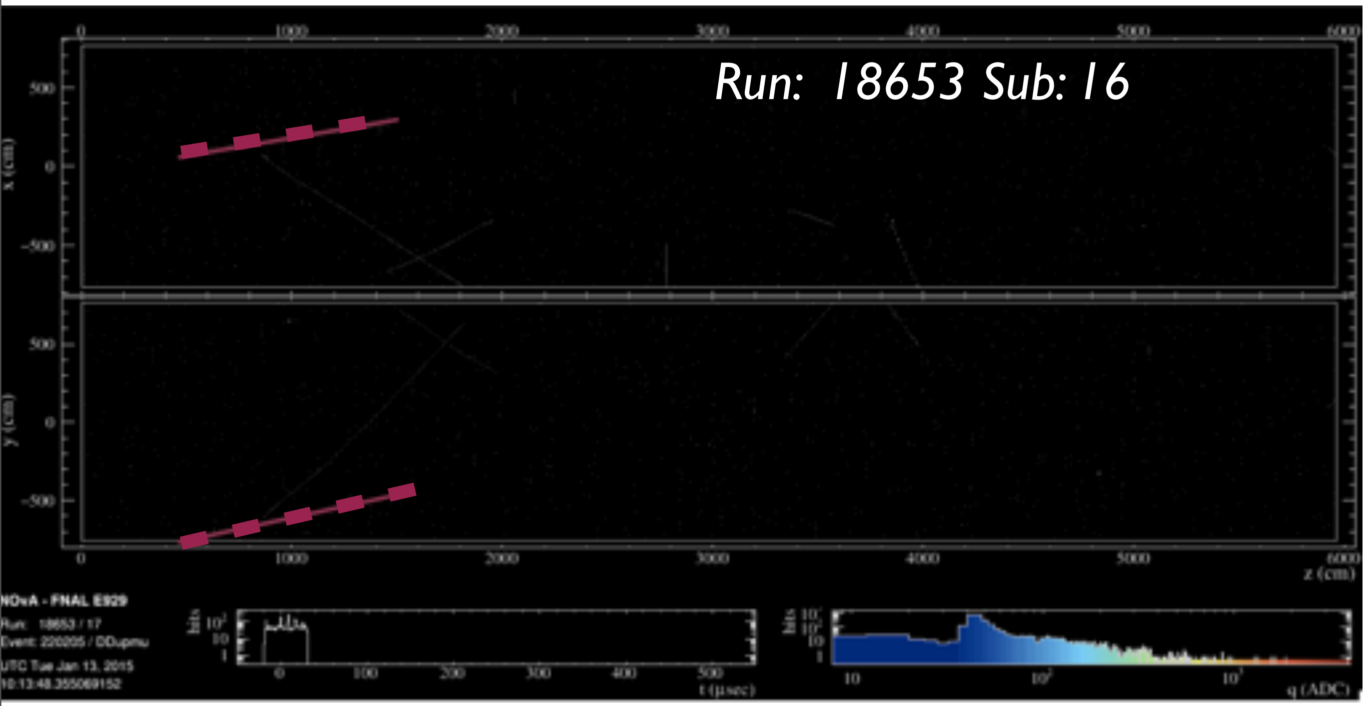
Did we trigger on these?

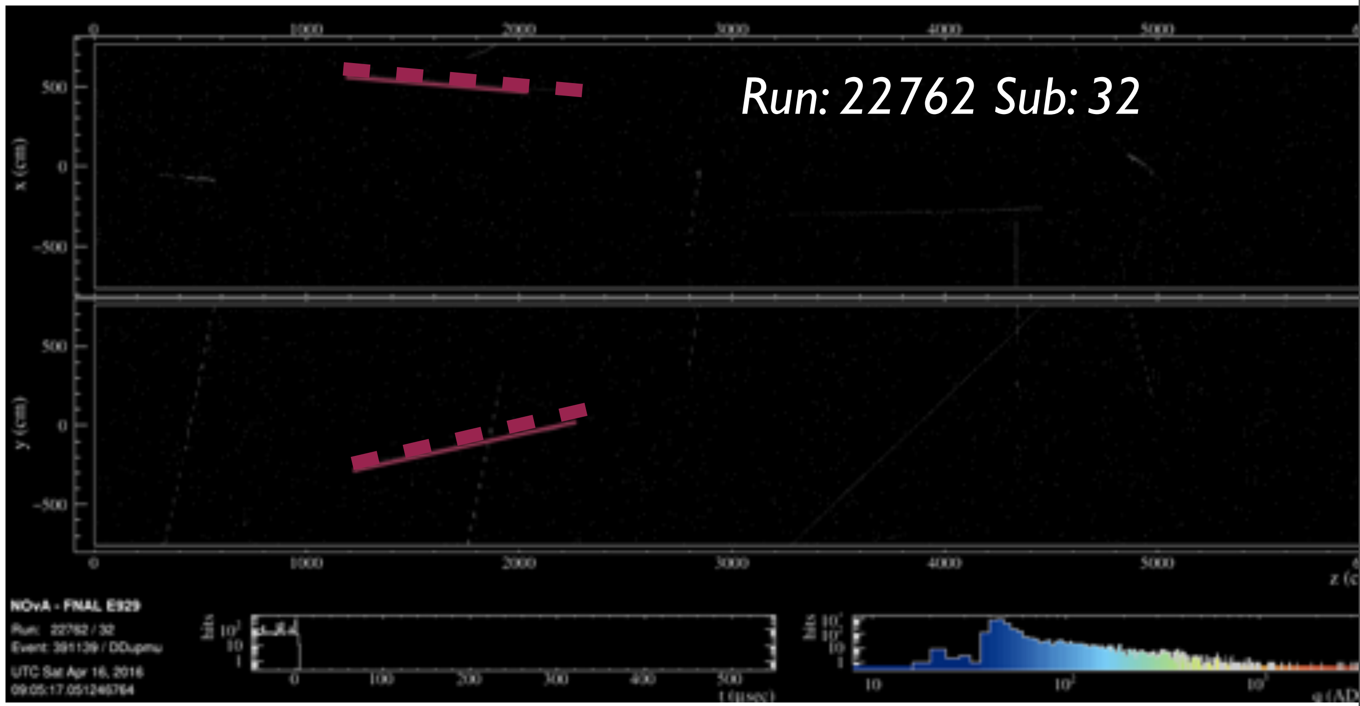




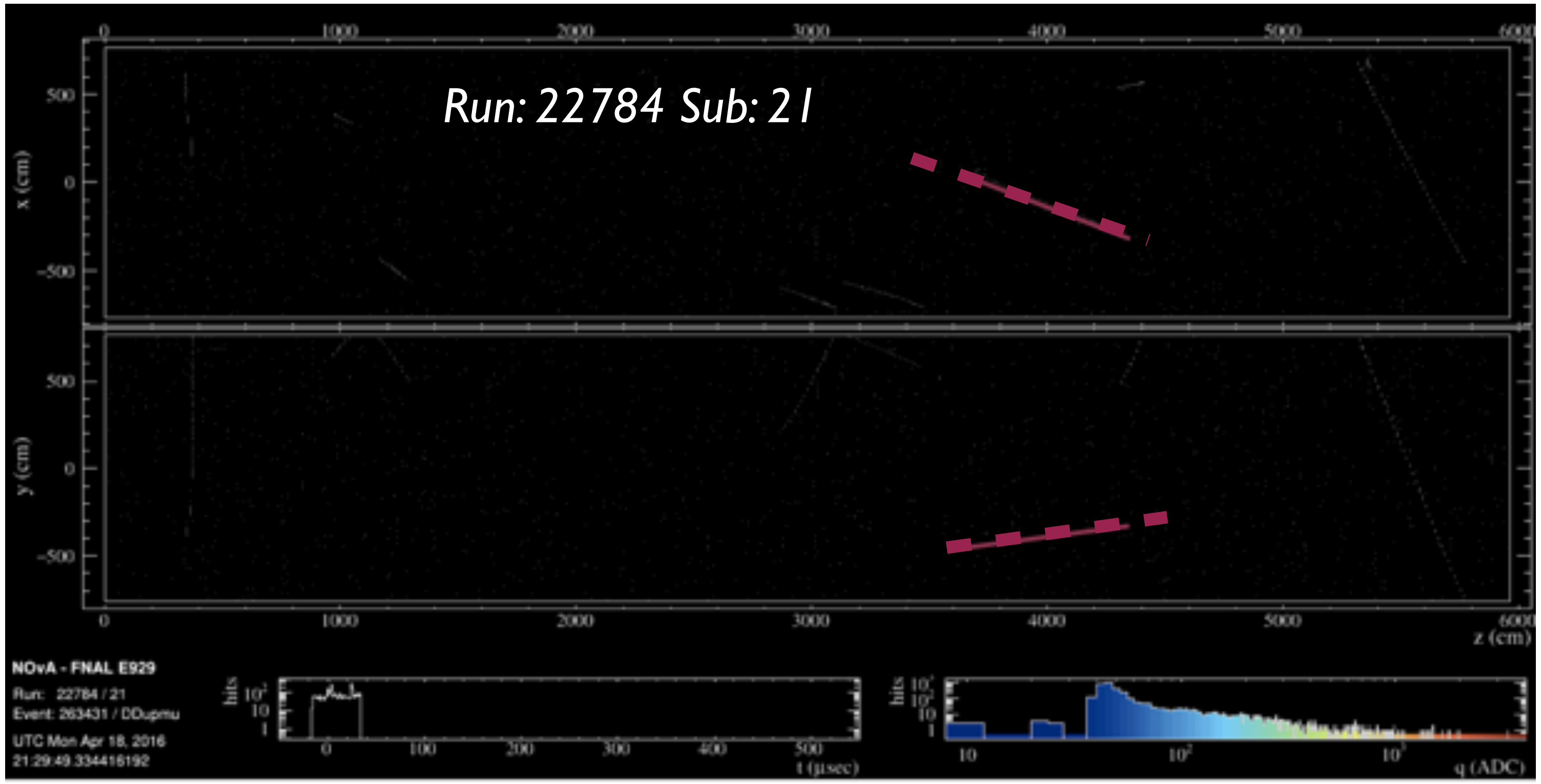
Trigger performance

We triggered on 3 out of 4 events





Beam direction



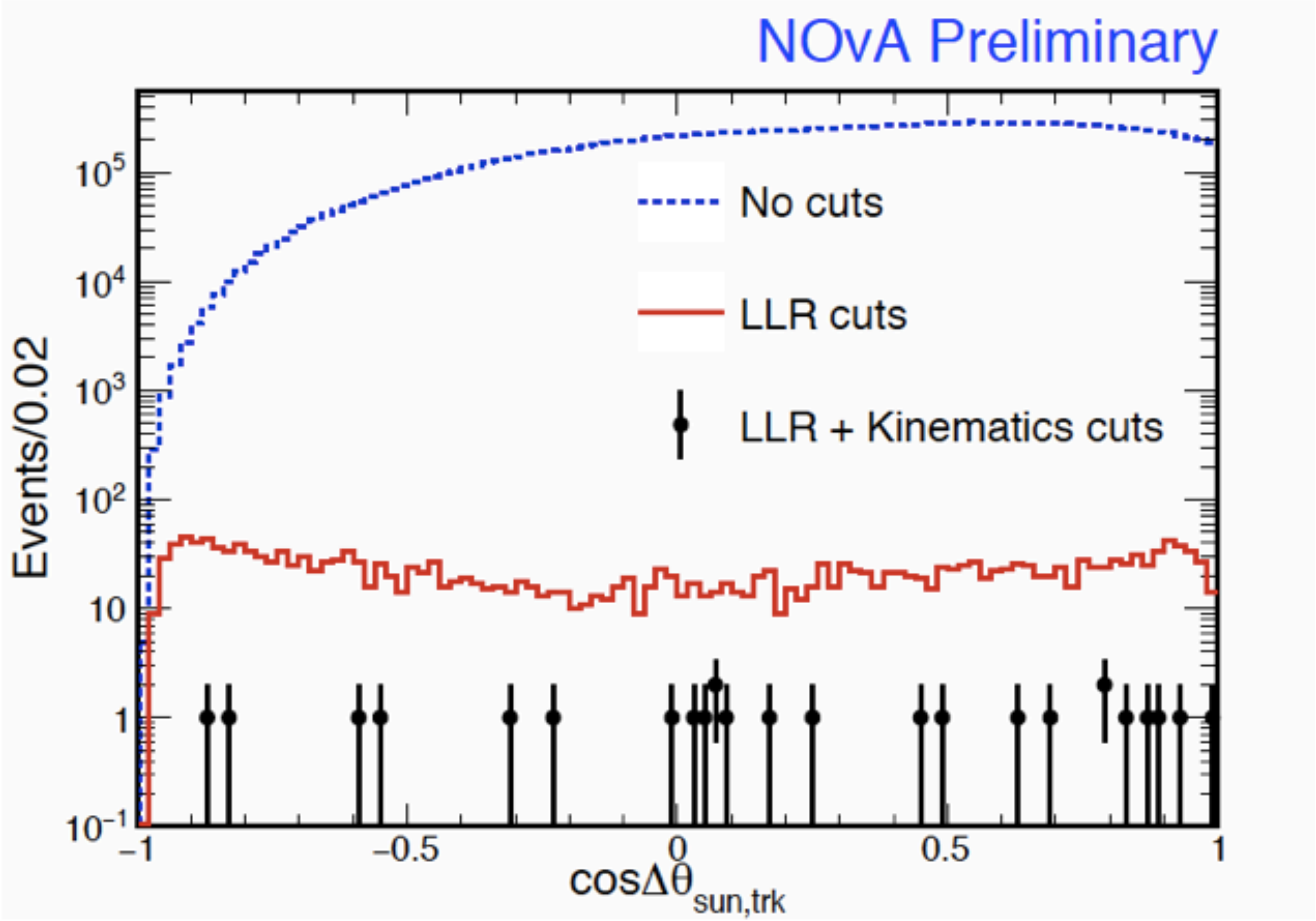
Test of the background prediction

The background sample is completely data-driven:

-Measure the number of events in the background
-Predict the number of events that we should observe in the side-band region (twilight)

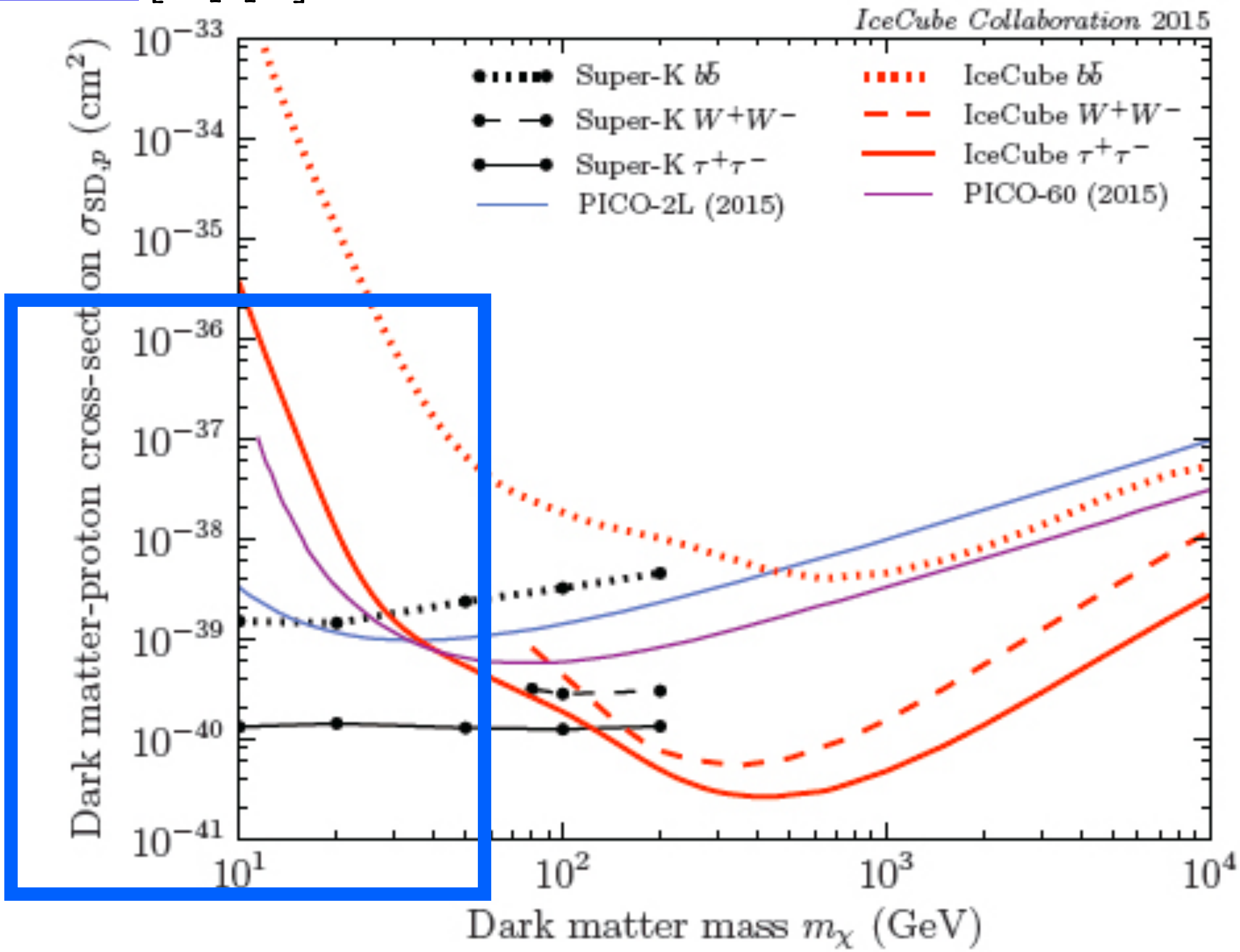
Results

- **33 events observed** in the background sample
- **24 events observed** in the twilight region (23 expected)



Current Limits on WIMPs flux

arXiv:1601.00653 [hep-ph]



For high-mass signal hypothesis, the IceCube experiment has the highest sensitivity
While for the lower mass, the Super Kamiokande experiment has the best sensitivity

NOvA experiment could be competitive for the low Dark Matter mass scenarios

What we have so far

- Worked to optimize the timing resolution to be able to use this powerful discriminant

- Studied the pointing resolution to measure our ability to point at celestial objects

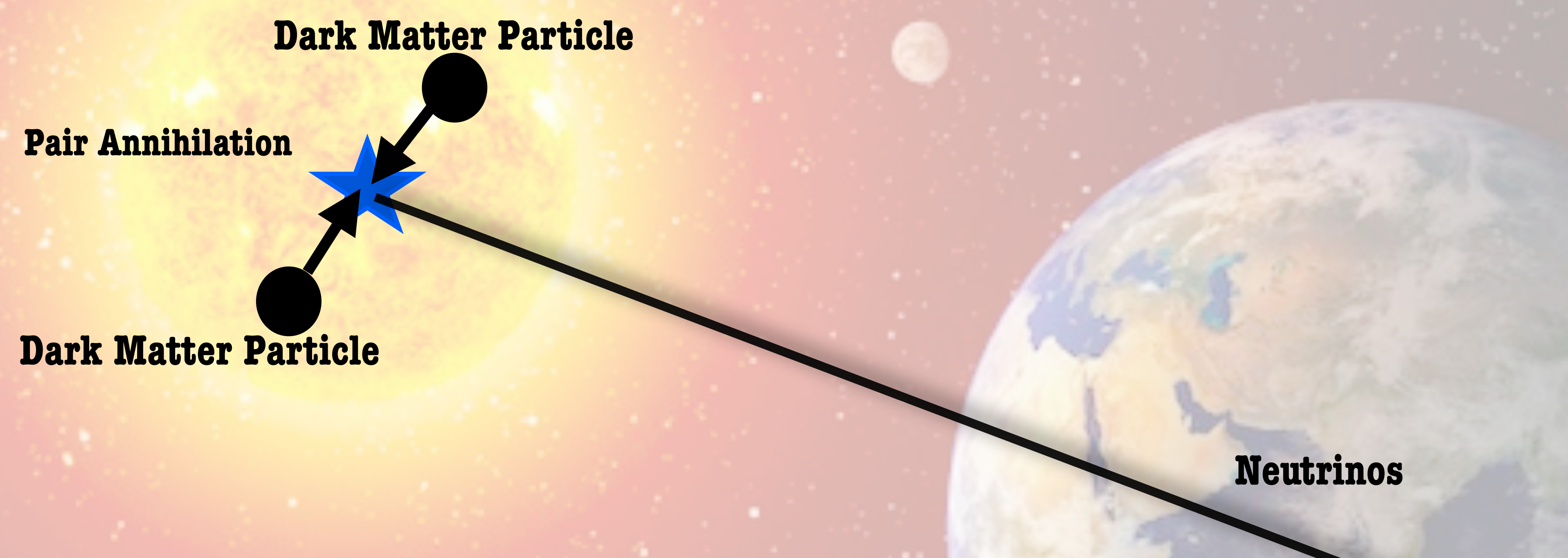
- Have a trigger running able to remove background by 5 orders of magnitude

- Have a data-driven background sample (day sample) that allows us to study the events.
This allows us to predict the background in the twilight sample

What's next

1) Work in progress to have a reliable MC model of upward-going muons interacting in the NOvA detector, and originated by interaction in the core of the sun.

2) Once we'll have the MC for the signal, we will be able to study the efficiency, acceptance and systematic,
and estimate the number of signal events we should see in our detector.



3) If no events are found that exceed our expected background, we can estimate an upper limit for WIMP production in the Sun.

$$\Phi(90\%C.L.) = \frac{N_{90}(n_{obs}, n_{BG}, F)}{\varepsilon \times A \times T}$$

Thank you for your attention

Backup

Preliminary trigger efficiency

Cut	Value	In	Out	Cut Flow
Length	> 5 m	512044	237795	
dx	> 5 cells	237795	174682	73%
dY	> 10 cells	174682	116749	66%
dZ	> 5 cells	116749	114475	98%
3D track	TRUE	114475	114475	100%
R2X	> 0.95	114475	103575	90%
R2Y	> 0.95	103575	101136	98%
Hits X	> 15	101136	98880	97%
Hits Y	> 15	98880	98621	~100%
Hits X and Y	> 60	98621	97329	97%
LLR	> 3	97329	86416	88%
Chi2	< 1.5	86416	76644	89%
Slope	0 < s < 2	76644	75544	98%
Passed/Good track		97329	75544	**77%**
Passed/In track		237795	75544	**31%**

efficiency = # of tracks that passed the trigger / # of good reco tracks

DDUpMu Sample

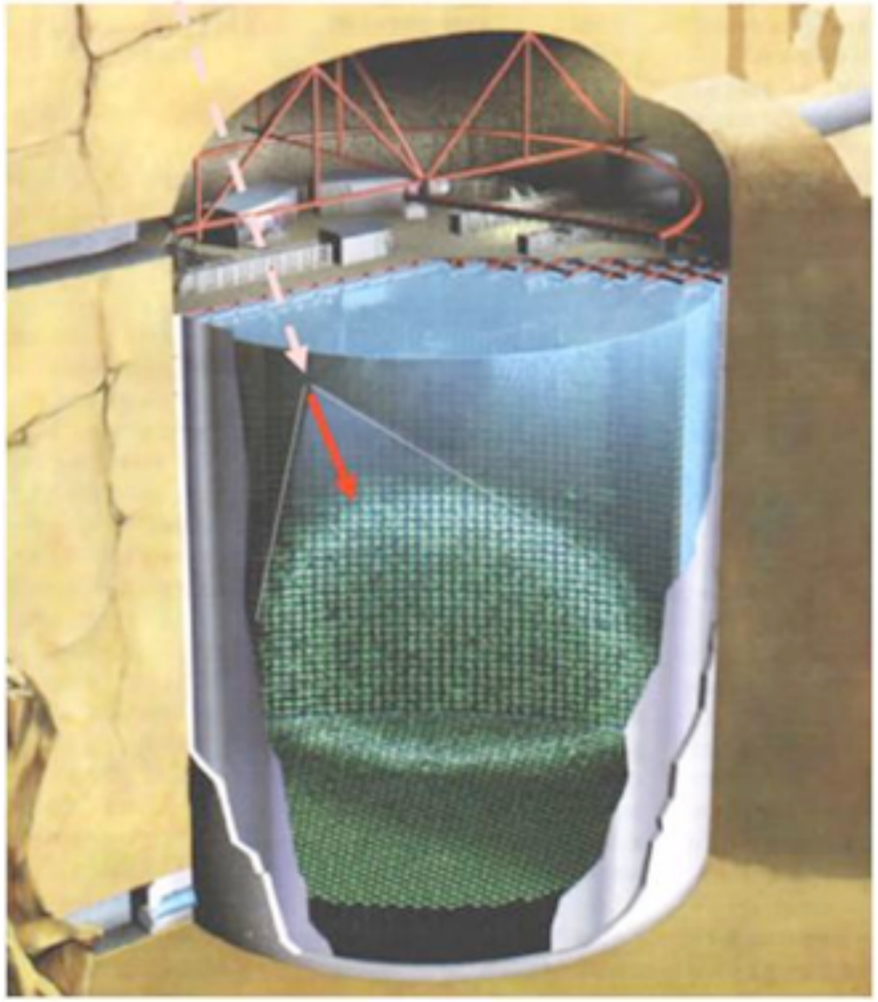
7 of the 78 events happened before our triggers were functioning.

→ Number of initial events **71 events**

DDupMu trigger cuts:

1)	Track length > 5m	=	**53 events**
2)	Number of X hits > 15 cells	=	**51 events**
3)	Number of Y hits > 15 cells	=	**50 events**
4)	Track linearity in X > 0.99	=	**24 events**
5)	Track linearity in Y > 0.99	=	**7 events**
6)	X length > 5 cells	=	**7 events**
7)	Y length > 10 cells	=	**7 events**
8)	Z length > 5 cells	=	**7 events**
9)	Upward-going	=	**4 events**

Super-K vs NOvA



Super Kamiokande

- Water Cerenkov Detector
- Readout:

ID 11,129 20inch PMT

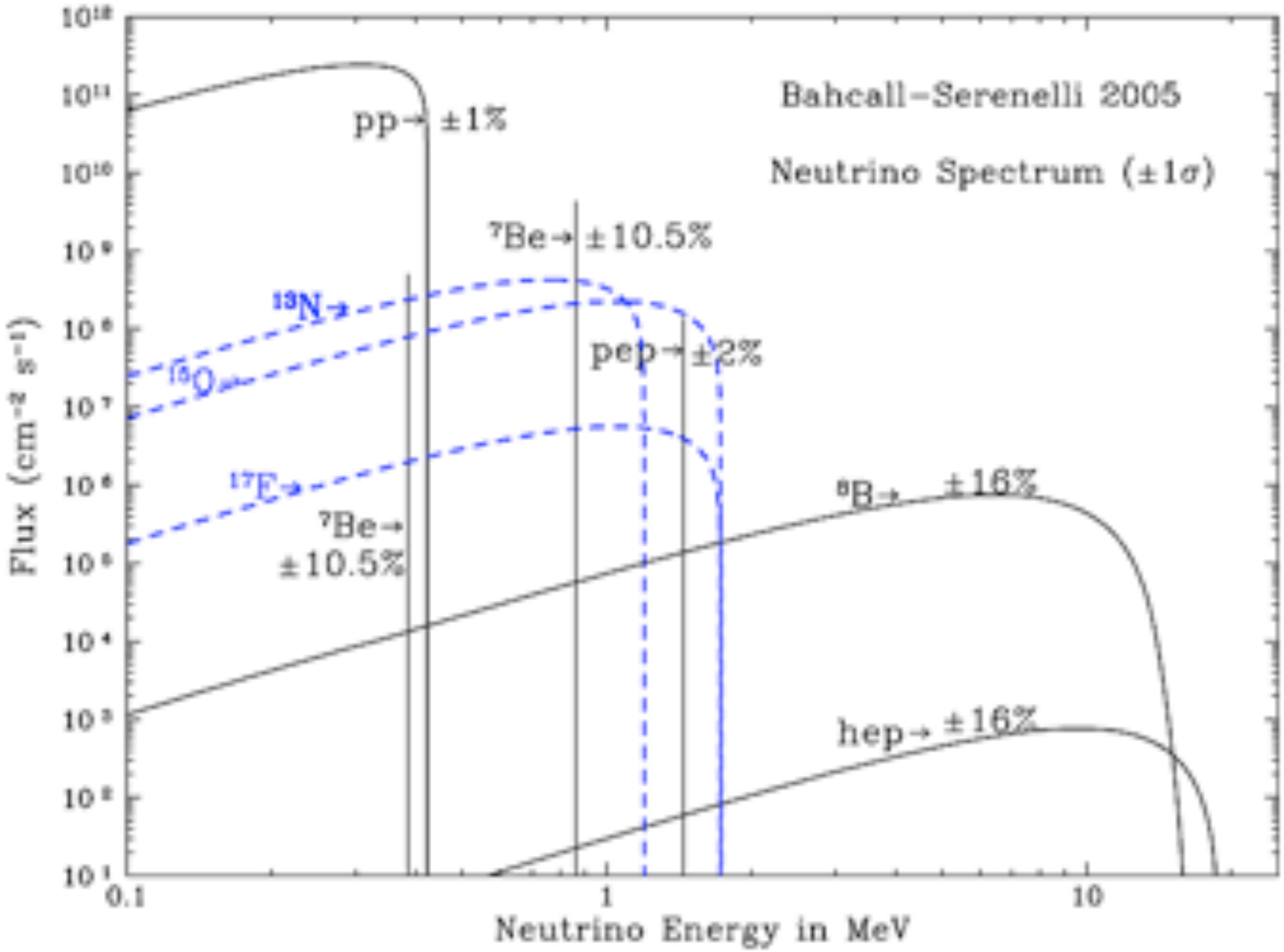
OD 1885   8inch PMT

- Fiducial Volume: 22 kton
- Energy threshold for muon: 160 MeV
- Unable to see protons
- Running since: 1996

NOvA

- Highly segmented liquid scintillator
- Readout: 344,064 pixels
- Fiducial Volume: 14 kton
- Energy threshold for muon: 10 MeV
- Able to see protons
- Running since: 2014

Neutrino from Sun



Energy too low to be detected by NOvA

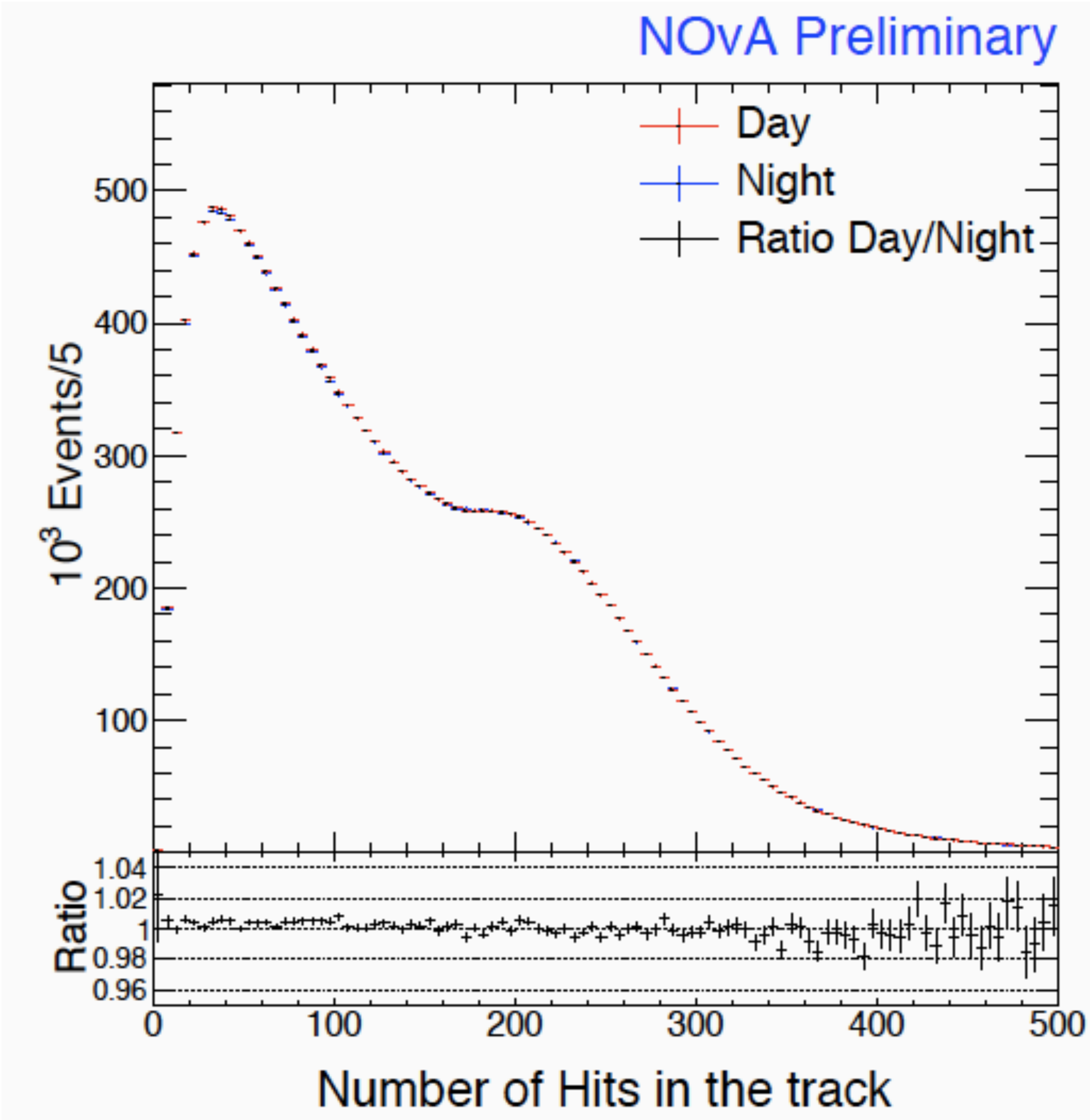
Background Studies

150 kHz of downward-going cosmic rays could look just like our signal if we apply a parity operation on our detector. **Great tool for background studies!**

1) Signal events will be during the night, Background events during the day. Does the detector perform the same?

2) What is the rejection power of our cut?

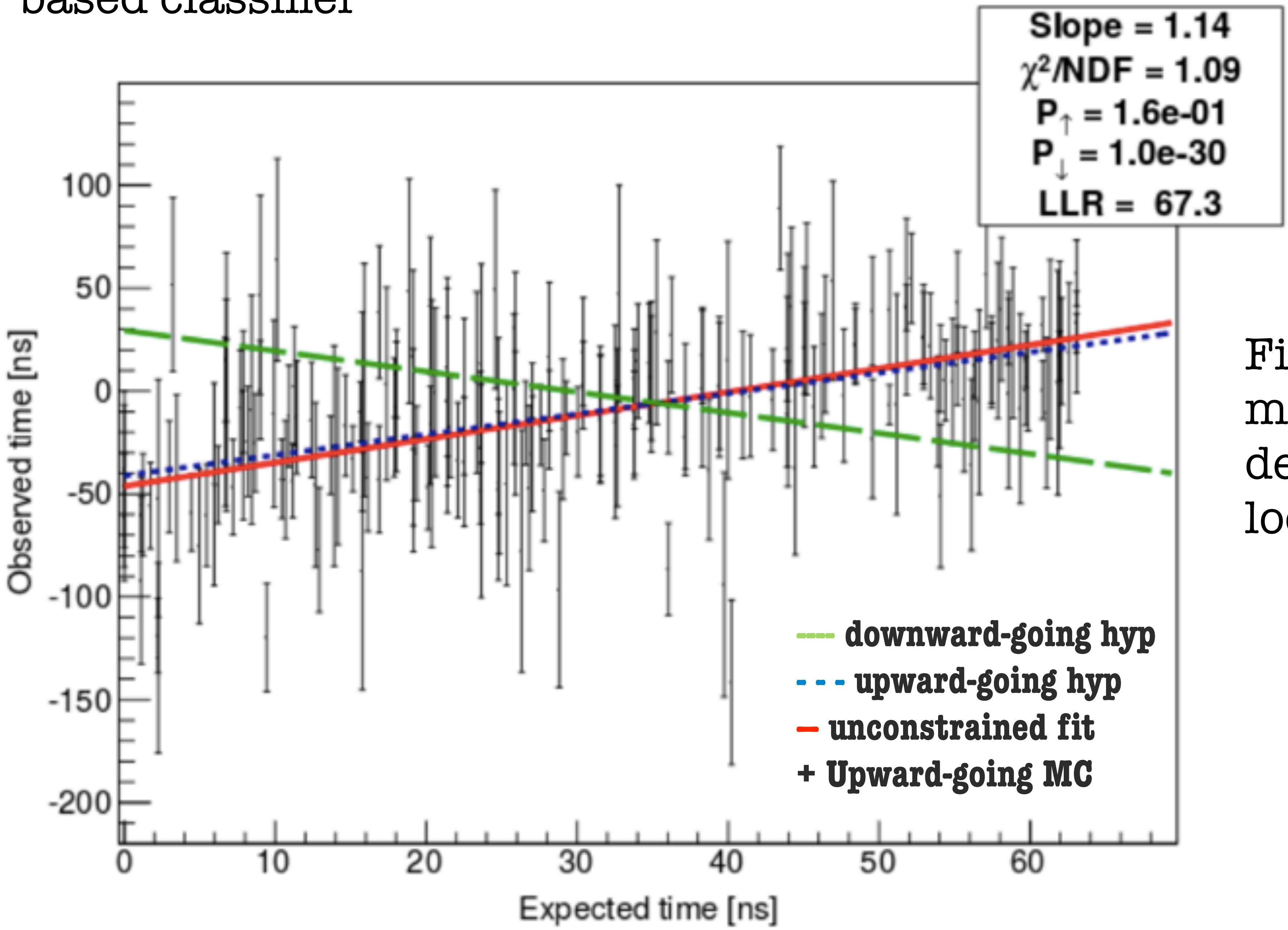
3) From efficiency studies of our cut on cosmic ray data samples, we estimated a 30% efficiency



Trigger

To select events of interest for non-beam search, data-driven trigger is required

Trigger selection:
The detector's timing resolution allows directionality determination using a timing-based classifier



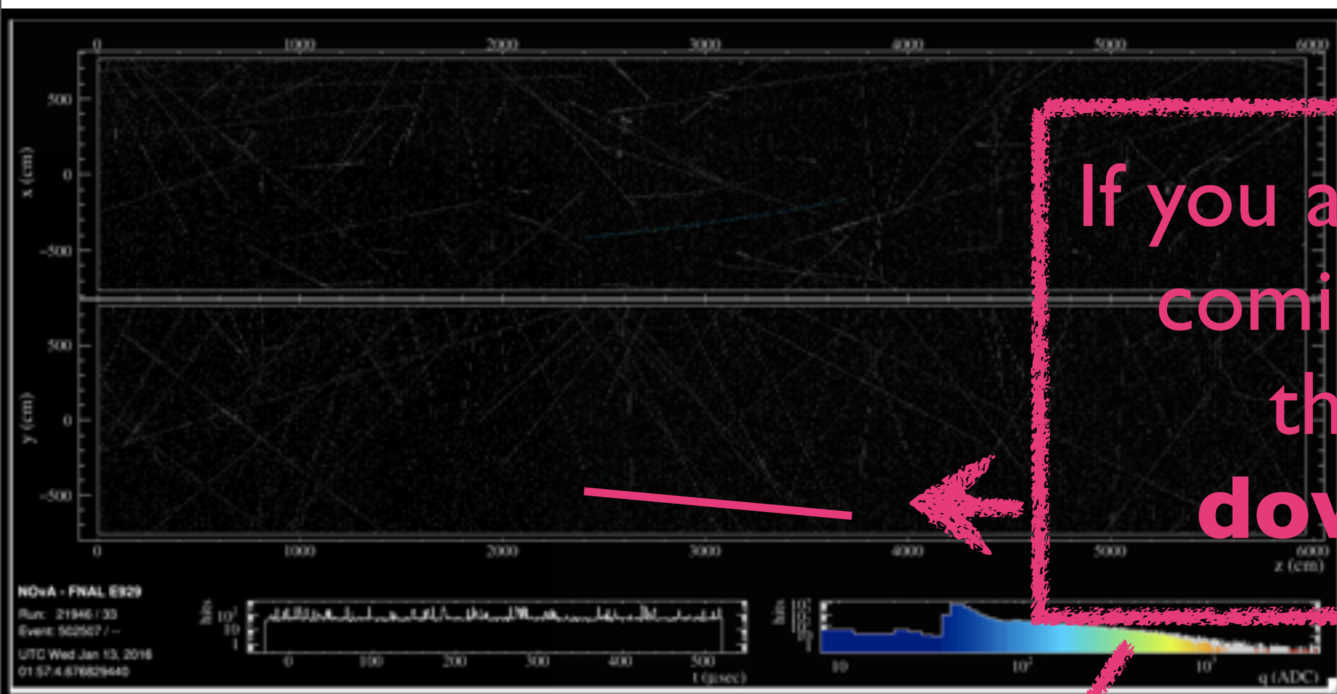
First we select a high-quality muon track and then determine directionality by looking at the slope

Trigger rate is approx 1 Hz, and it's able to reduce cosmic background by a factor of 10^5

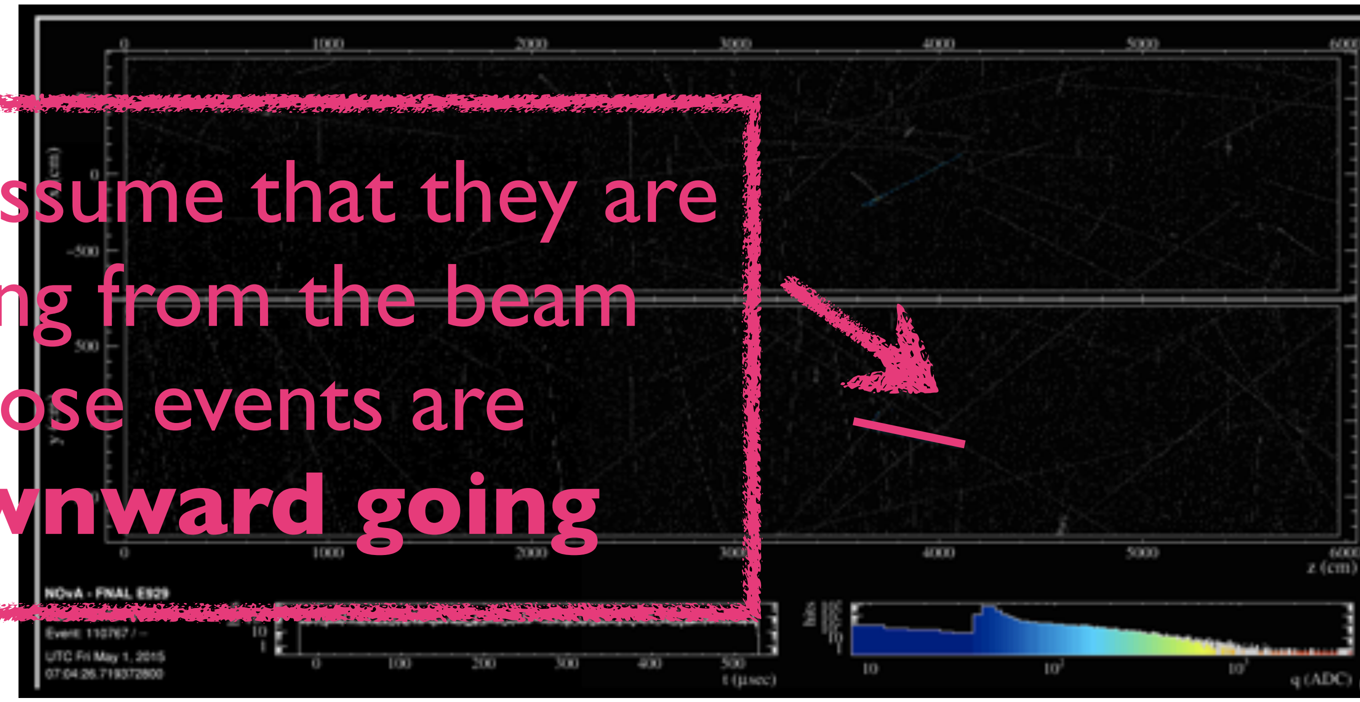
DDUpMu Sample

3 of these 4 events we didn't trigger on, are downward-going

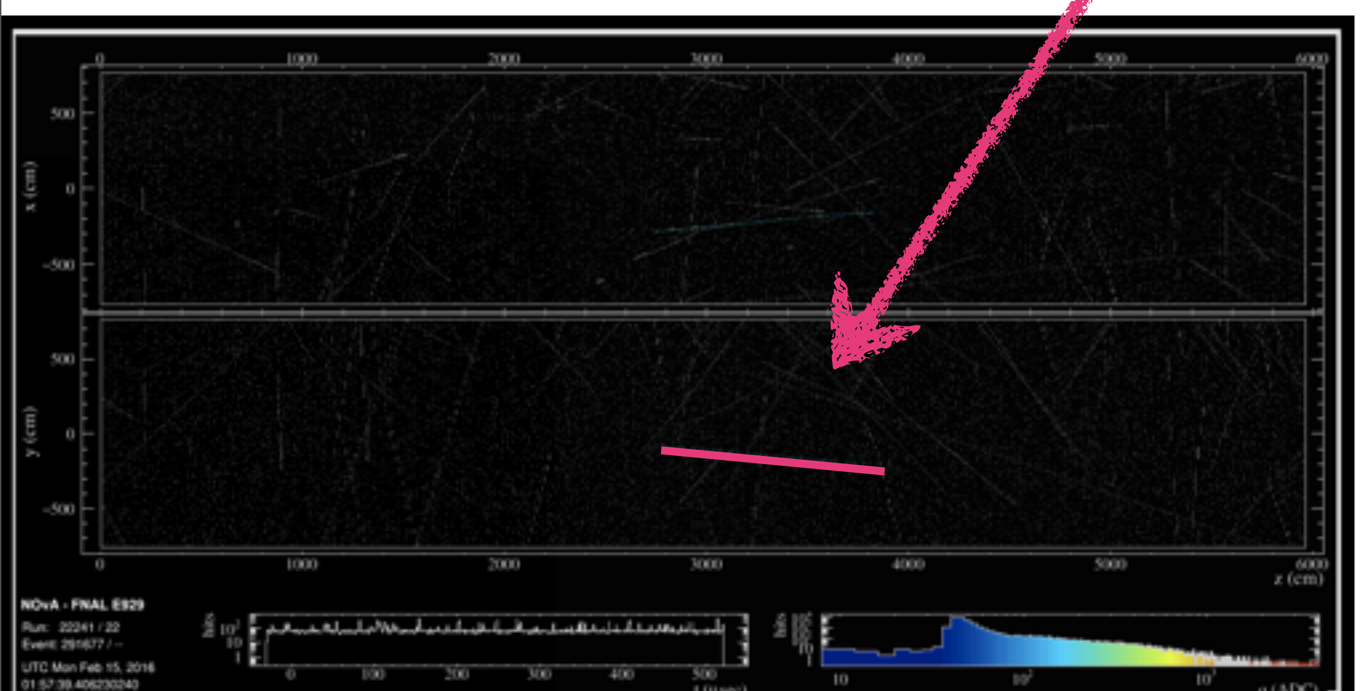
Run: 19476 Sub: 6



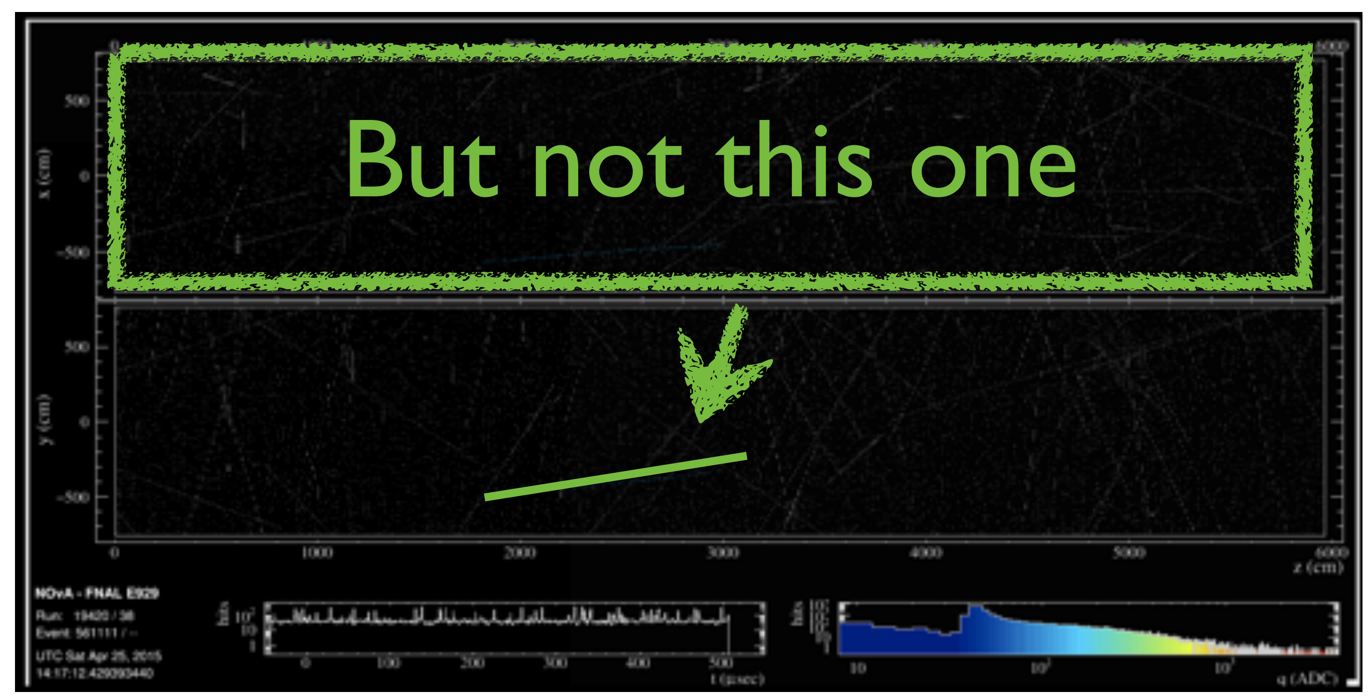
Run: 21946 Sub: 33



If you assume that they are coming from the beam those events are **downward going**



Run: 22241 Sub: 22



But not this one

Run: 19420 Sub: 38

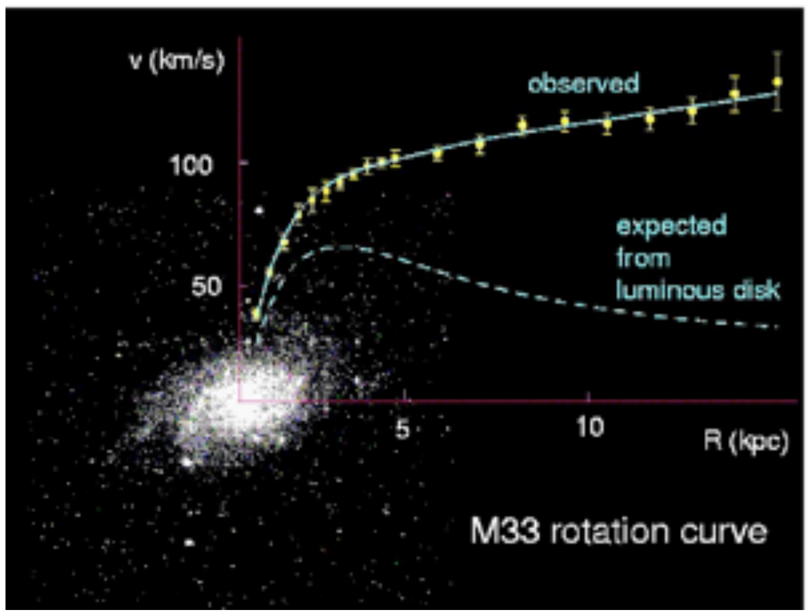
Cristiana Principato

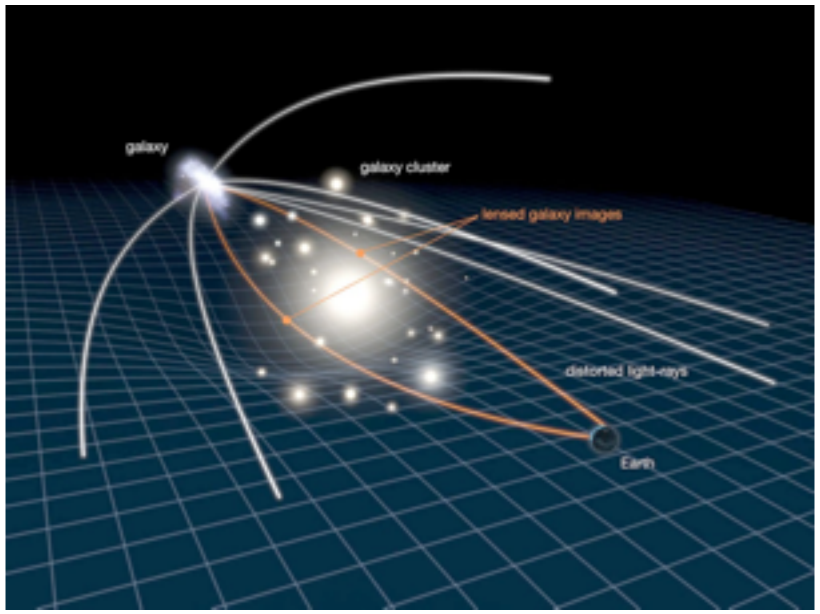
Weakly Interactive Massive Particles

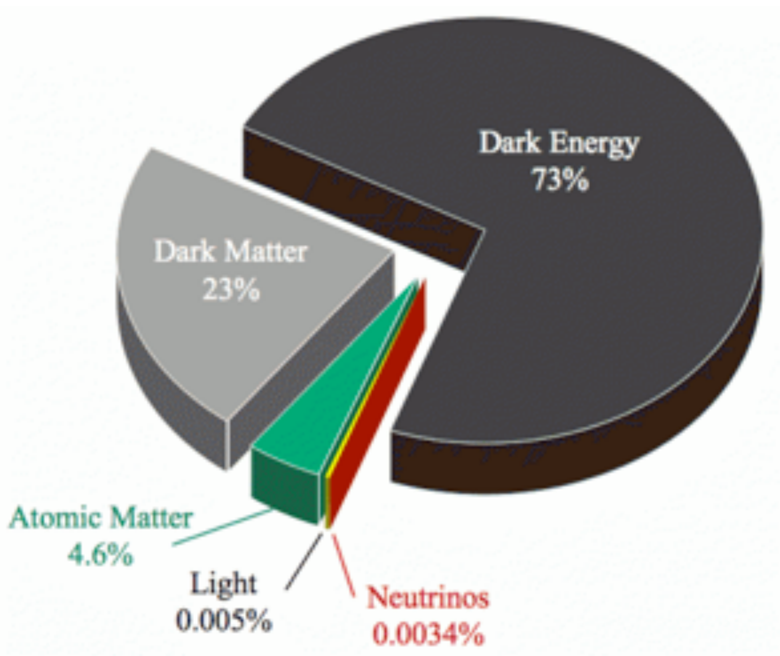
WIMPs: One potential non baryonic form of Dark Matter

Evidence for DM existence comes from cosmological observations.

Motion of the stars in galaxies, orbits of galaxies in galaxy clusters, temperature of the intracluster gas in galaxy clusters and gravitational lensing of distant galaxies







What we know about DM:

- **Massive** (gravitationally attractive & clustering)
- **Cold** (slow-moving)
- **Dark** (does not emit or absorb light)
- **Non/Weakly interacting** (Does have gravitational influence/ Interaction only through some weak force and gravity)

DDUpMu and DDContained triggers

Analysis strategy:

1) Start with artdaq files of these 78 ν_μ events

2) Apply offline the same cut that we have online

3) Check how many events pass our trigger cuts

4) Look for matches between ν_μ events and DDupmu/DDContained trigger events.