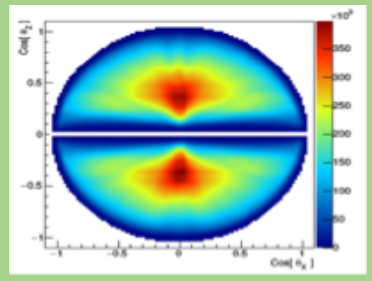
Muographic Analysis of the *NOvA-ND* Cosmic Data



Muography Session GI5.4

EGU General Assembly 2022

Vienna, Austria

Peter Filip

for NOvA Collaboration

Institute of Physics, Prague, Czech Academy of Sciences

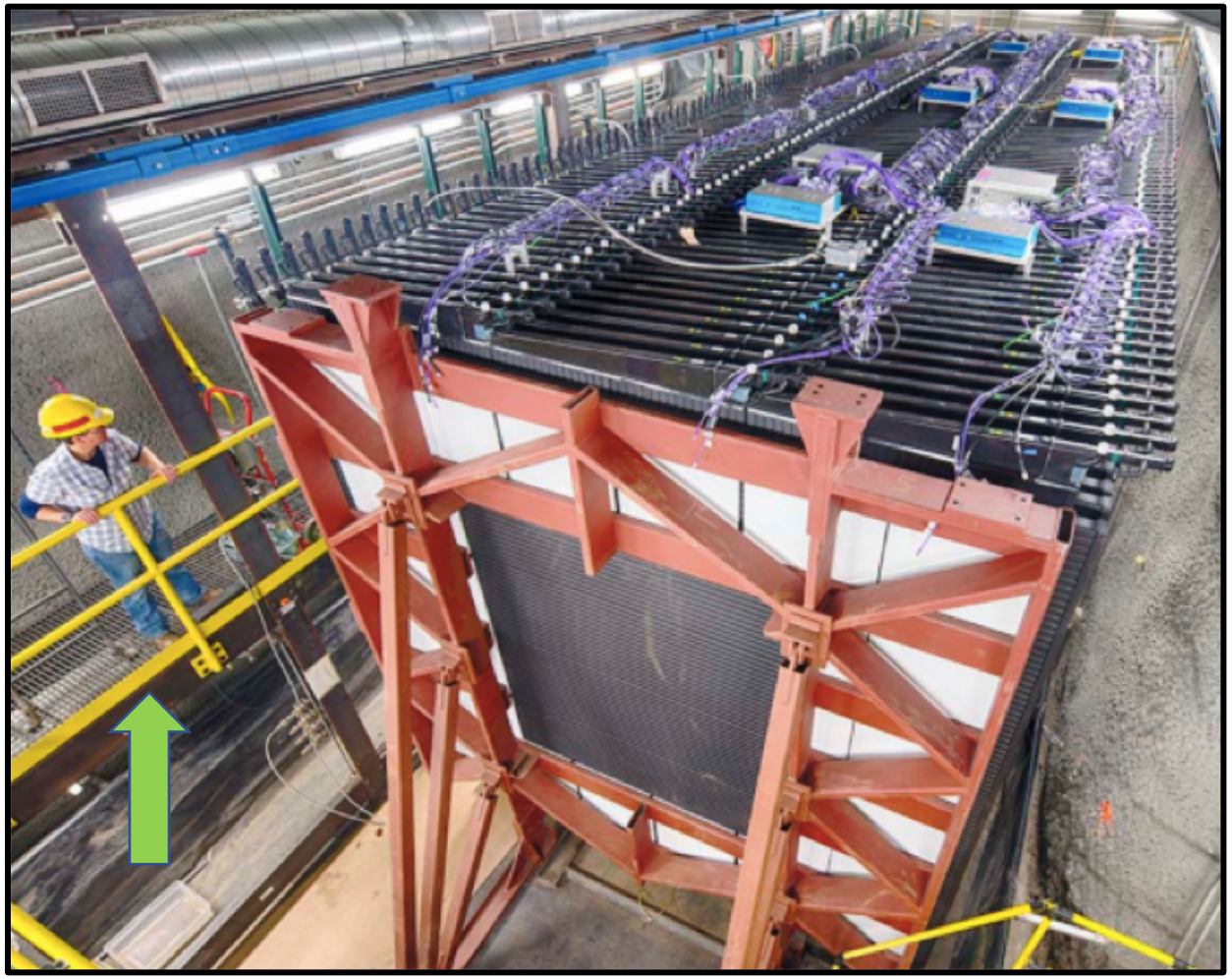
(26. of May, 2022)

NOvA Near Detector (ND) at Fermilab, near Chicago

300 Tons, 20192 channels, liquid. scintillator (130t)

100 meters underground

4m x 4m



16 meters long

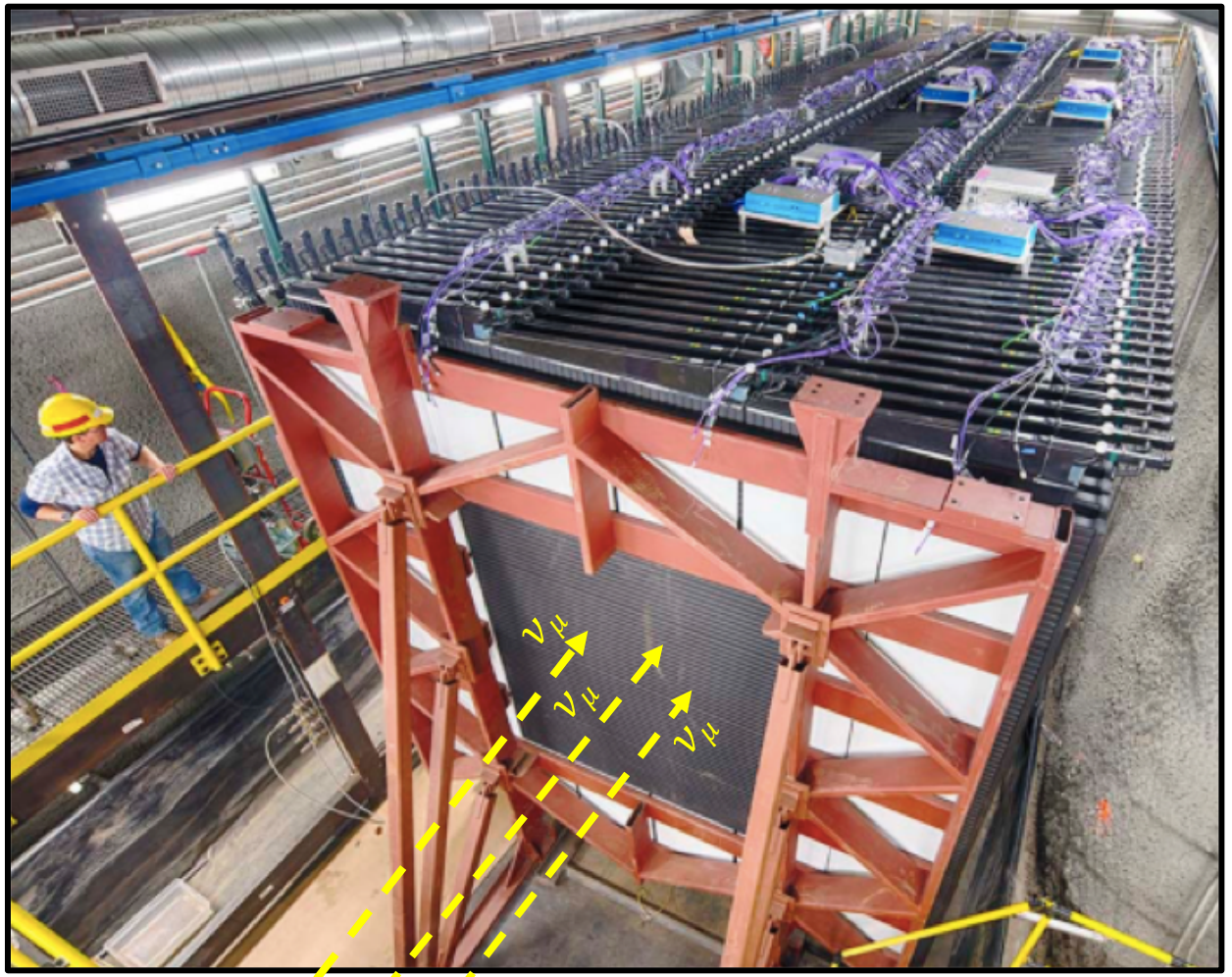
4m x 4m

NOvA Near Detector (ND) at Fermilab, near Chicago

300 Tons, 20192 channels, liquid. scintillator (130t)

100 meters underground

4m x 4m



16 meters long

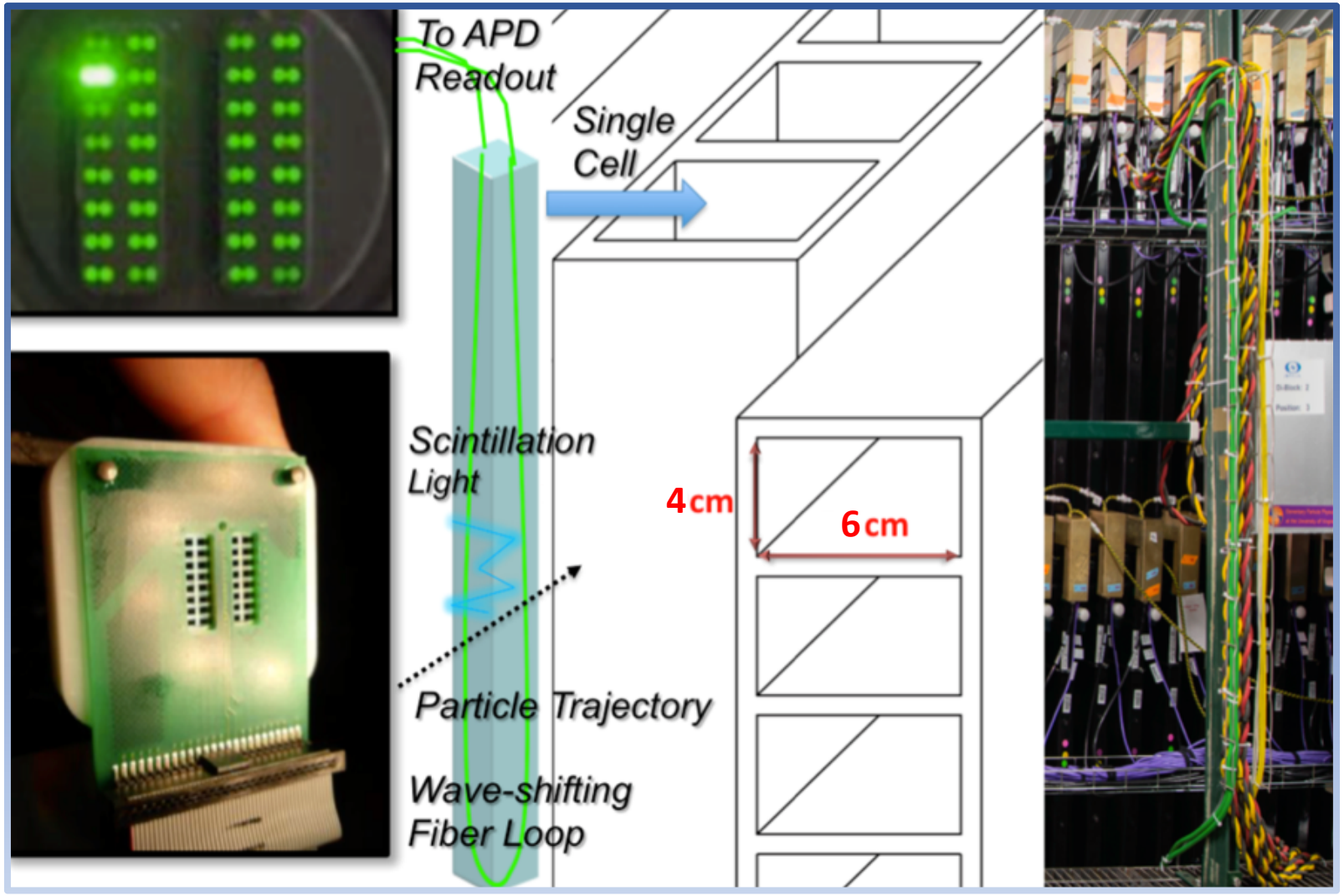
4m x 4m

Detector Technology

1 pixel
1 Fiber → 2 ends
32 Fibers → 1 APD

Avalanche PhotoDiodes

APDs cooled by Peltier Modules to **T = -15°C**



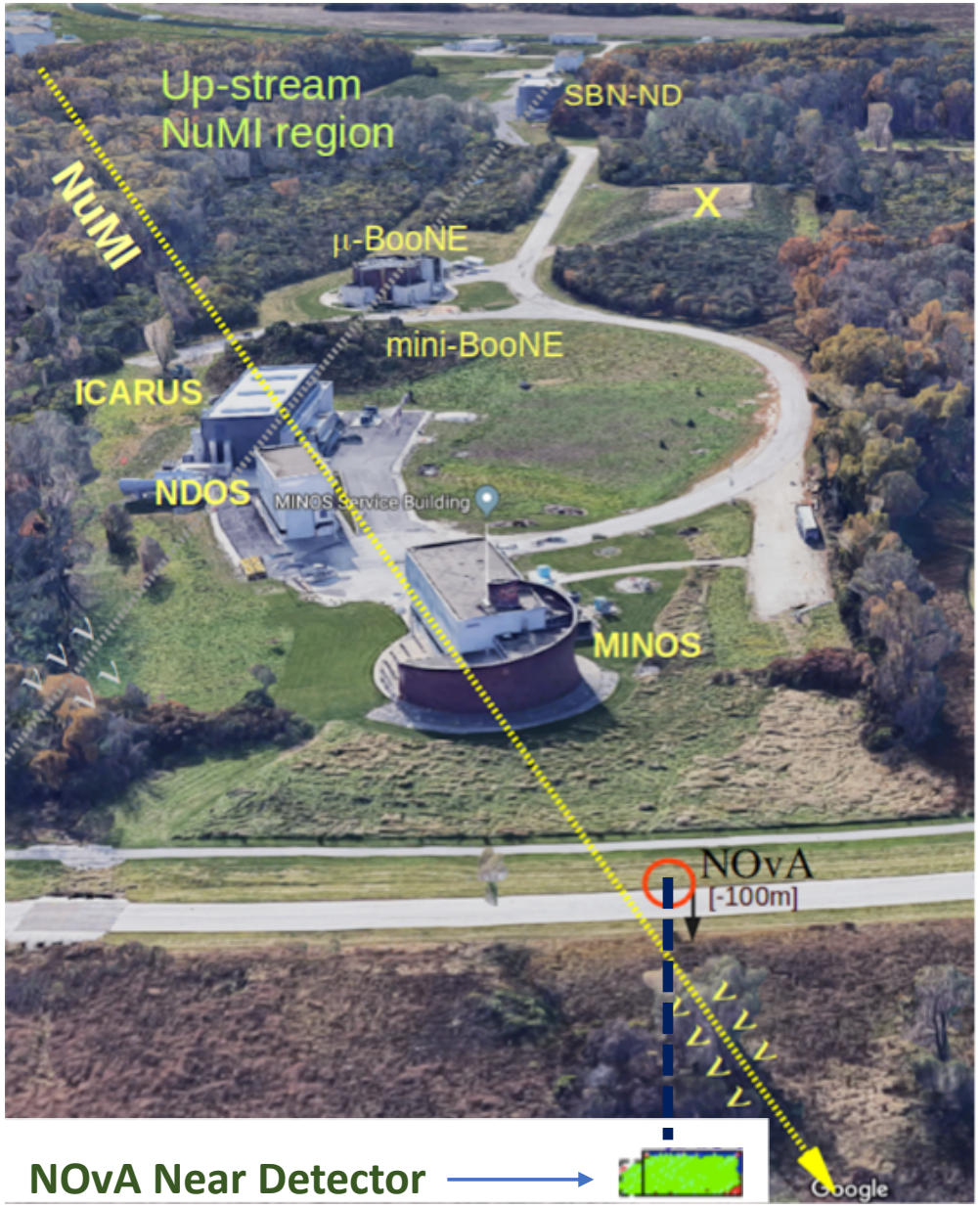
Front-End-Boards **GPS** *synchronized* (Far + Near detector)

≈ **30 minutes** of DATA stored in Memory (buffer PC Nodes) for Trigger decisions

45sec of continuous data can be saved to permanent storage upon "SN" Trigger

See: NOvA Technical Design Report, FERMILAB-DESIGN-2007-01

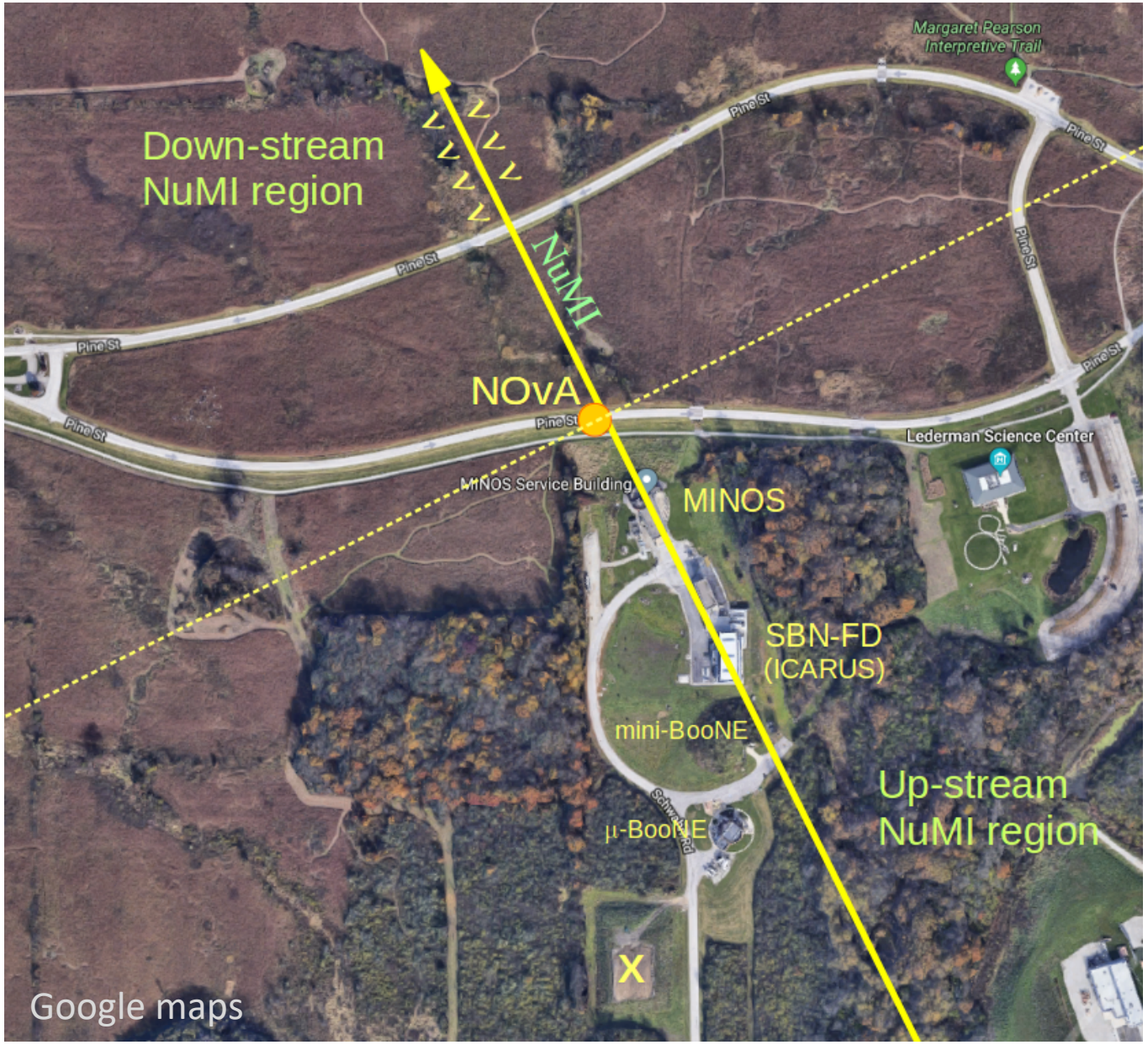
3D view (google maps)



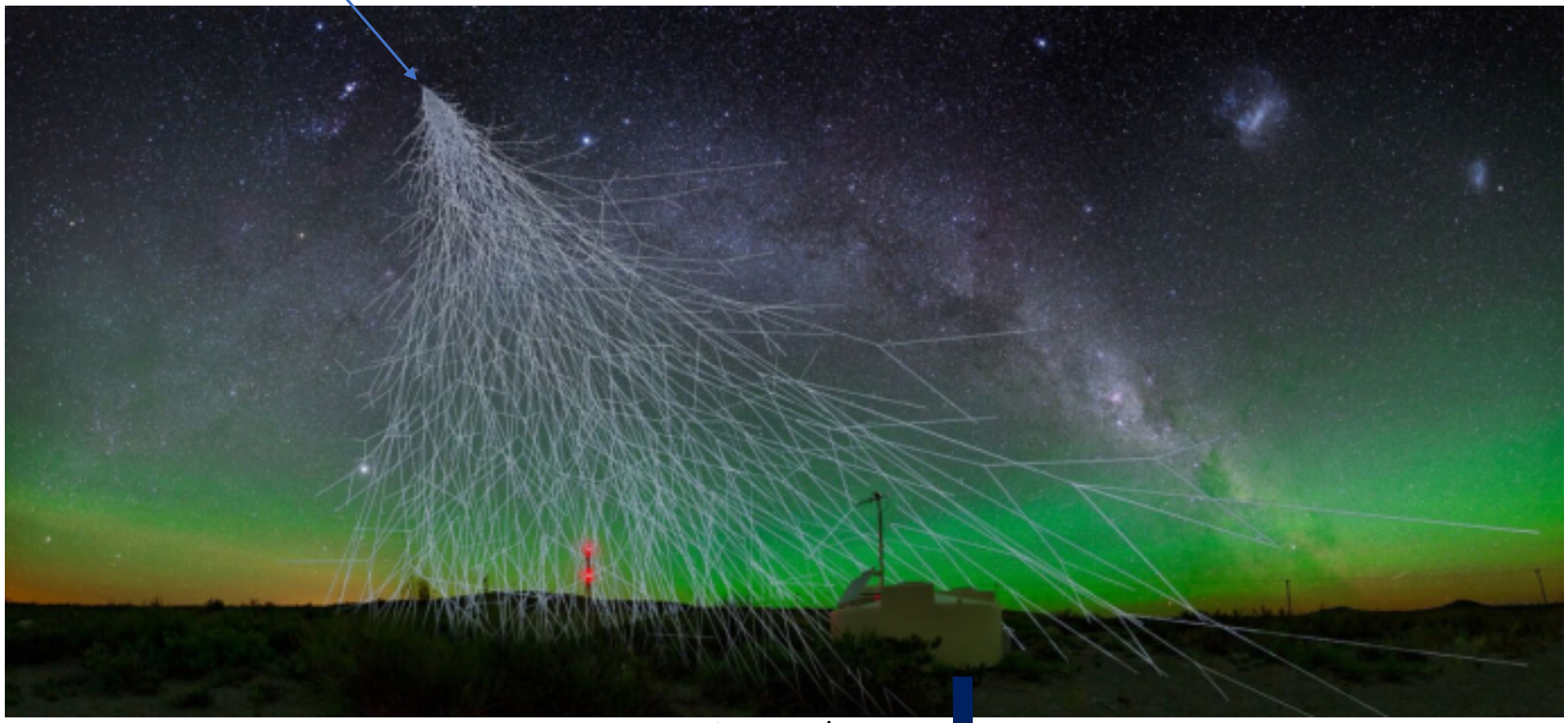
underground (-100m)

810km to Minnesotta

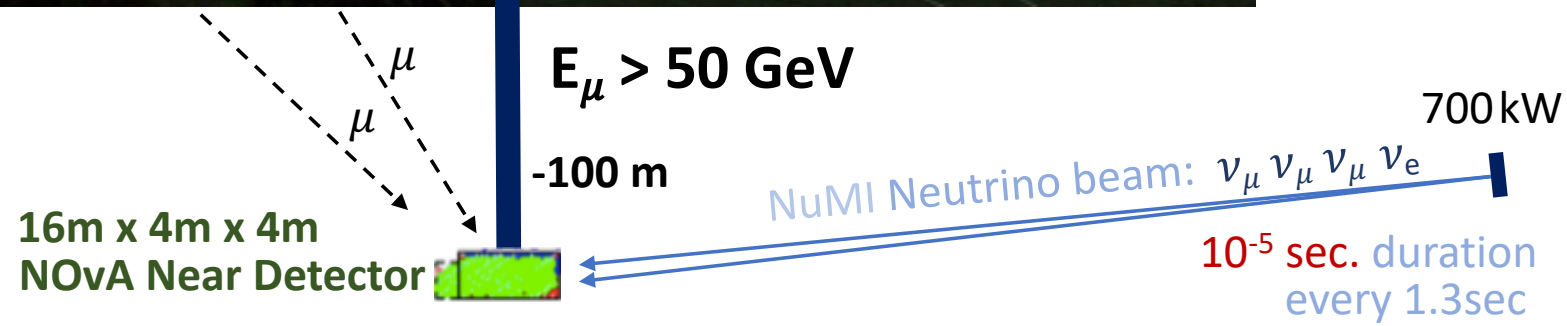
Fermilab Neutrino Area



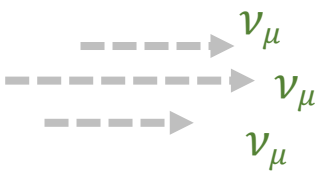
Cosmic Rays arriving to Underground Detector



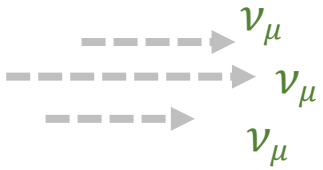
- Cosmic muons: 35 Hz Flux at NOvA-ND
  -> continuously recorded
- Zero dead time DAQ :
  -> 30 minutes in data memory buffer

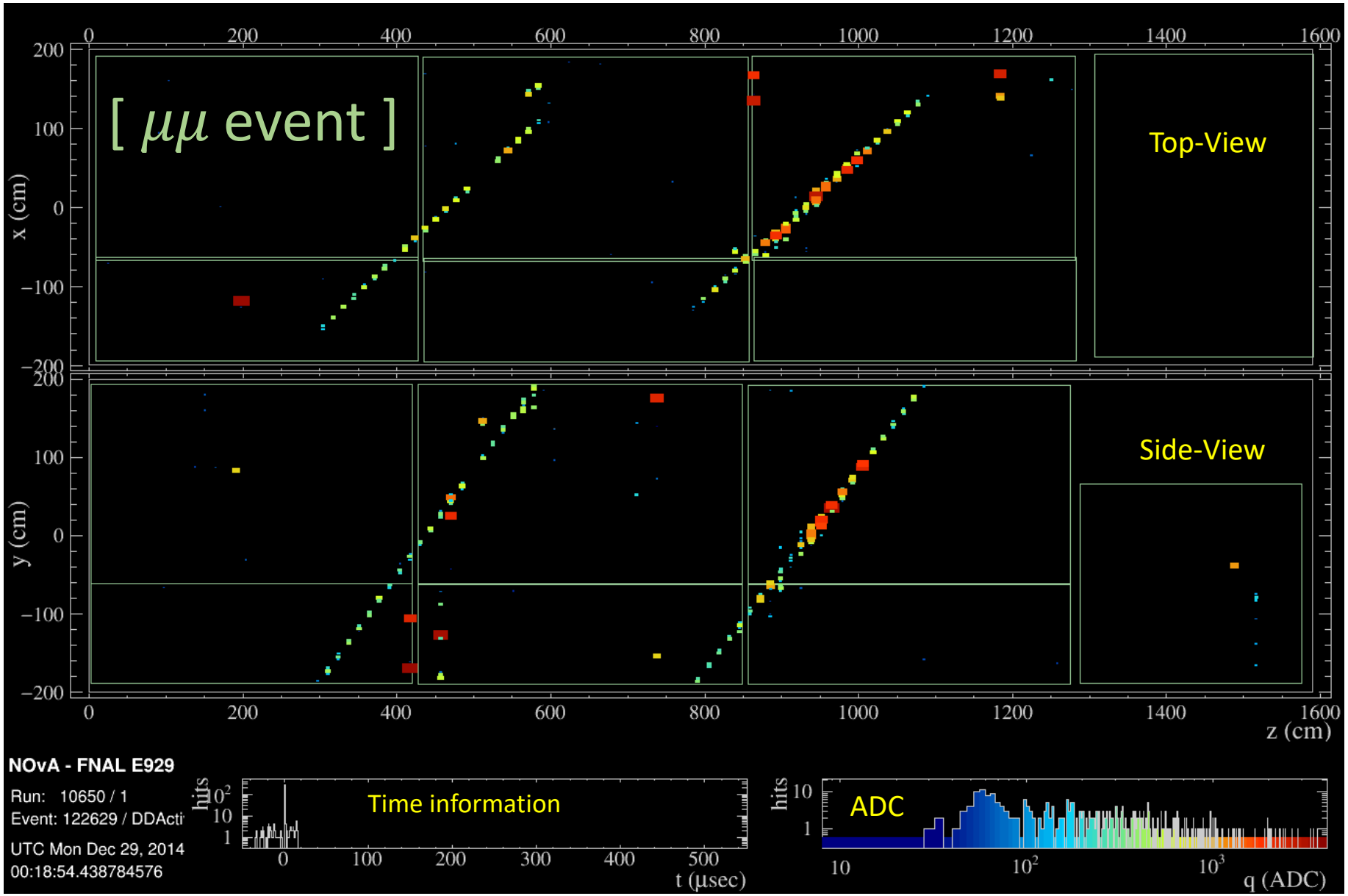


Cosmic Muon Tracks in NOvA-ND



NuMI Beam
direction
10 μsec only





0.17 Hz Rate

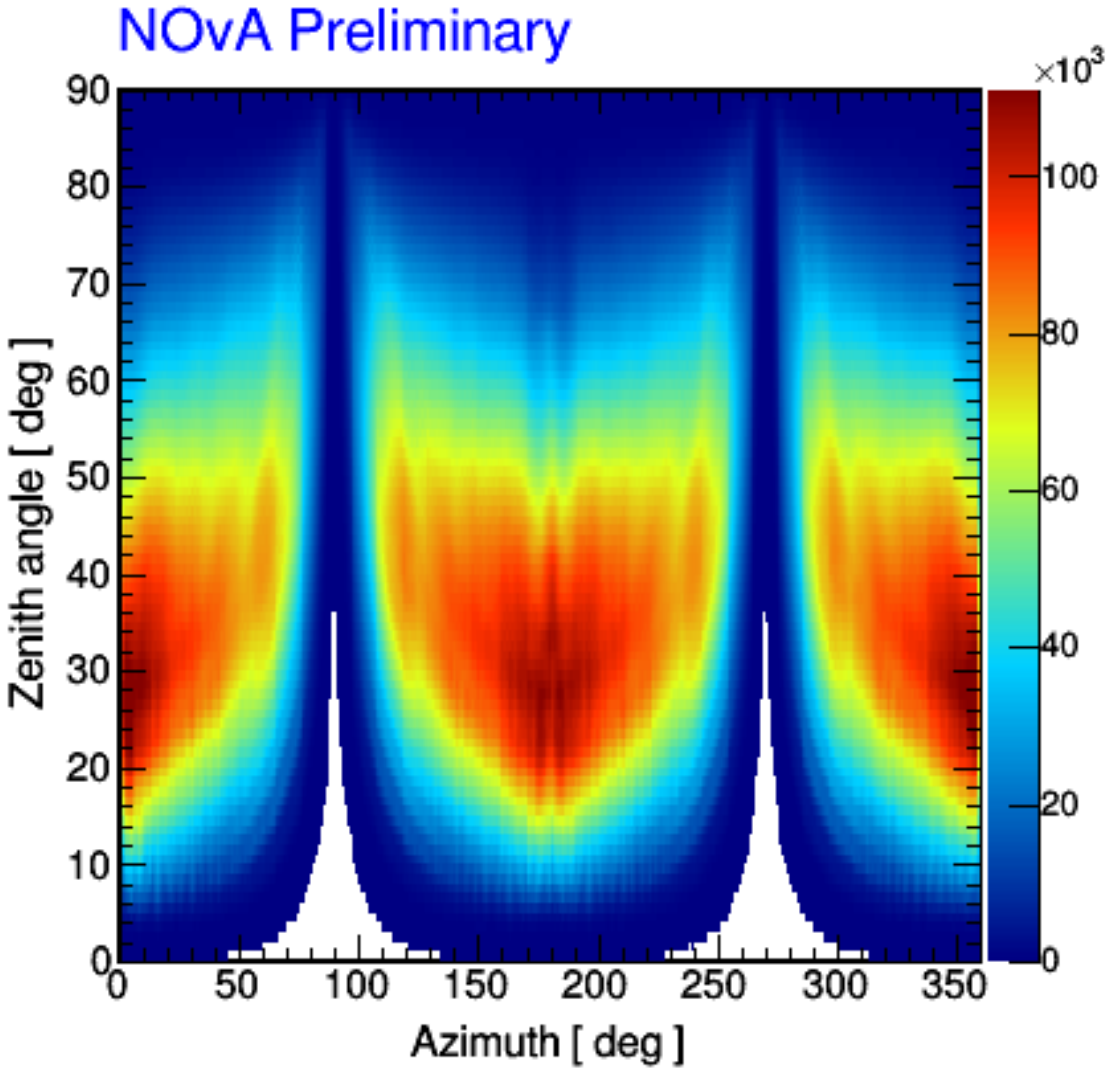
(multi-muons)

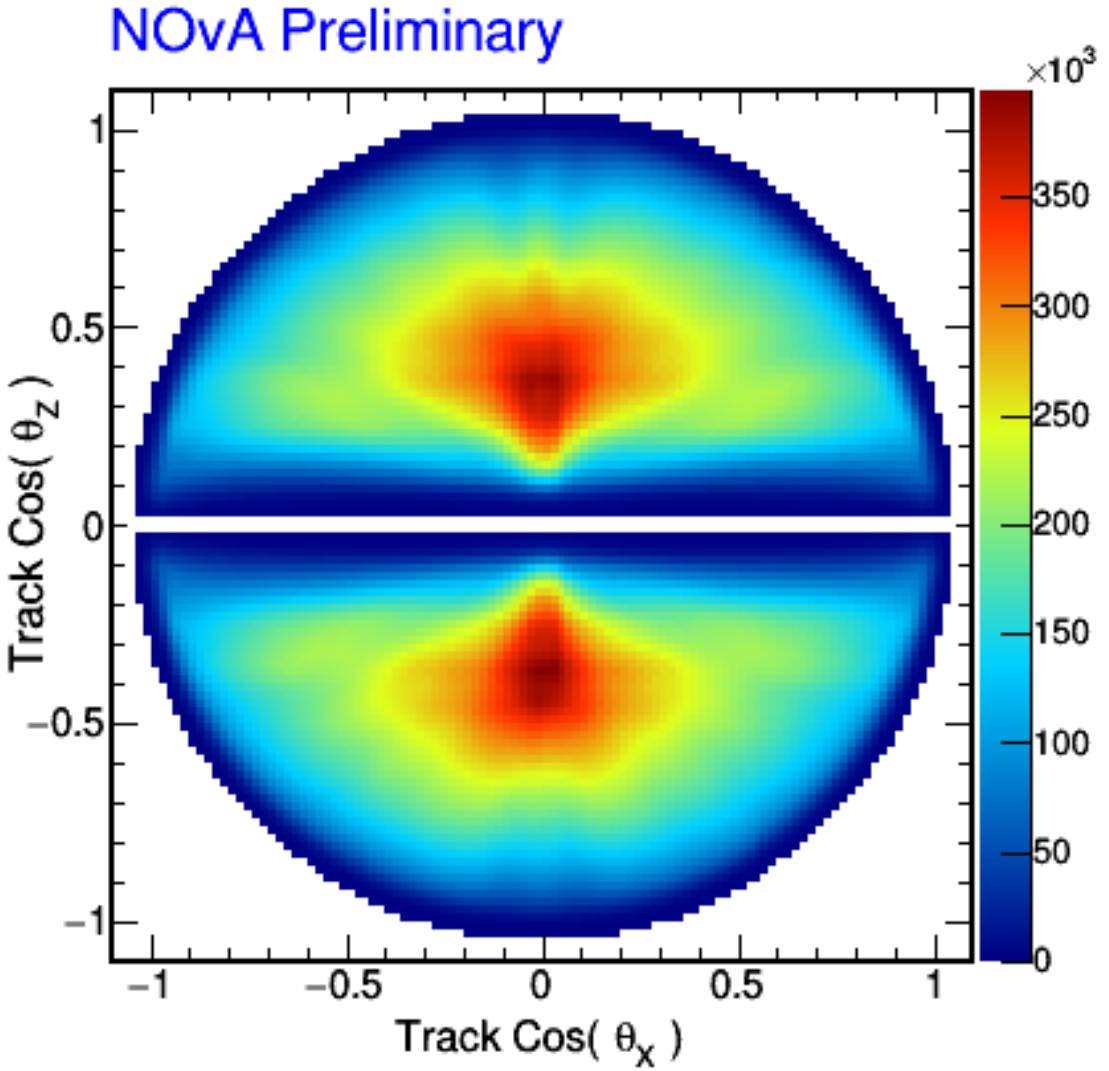
35 Hz total Cosmic Rate

ANGULAR DISTRIBUTION OF *RECONSTRUCTED* μ-TRACKS

NOvA Near Detector
→ ACCEPTANCE ←

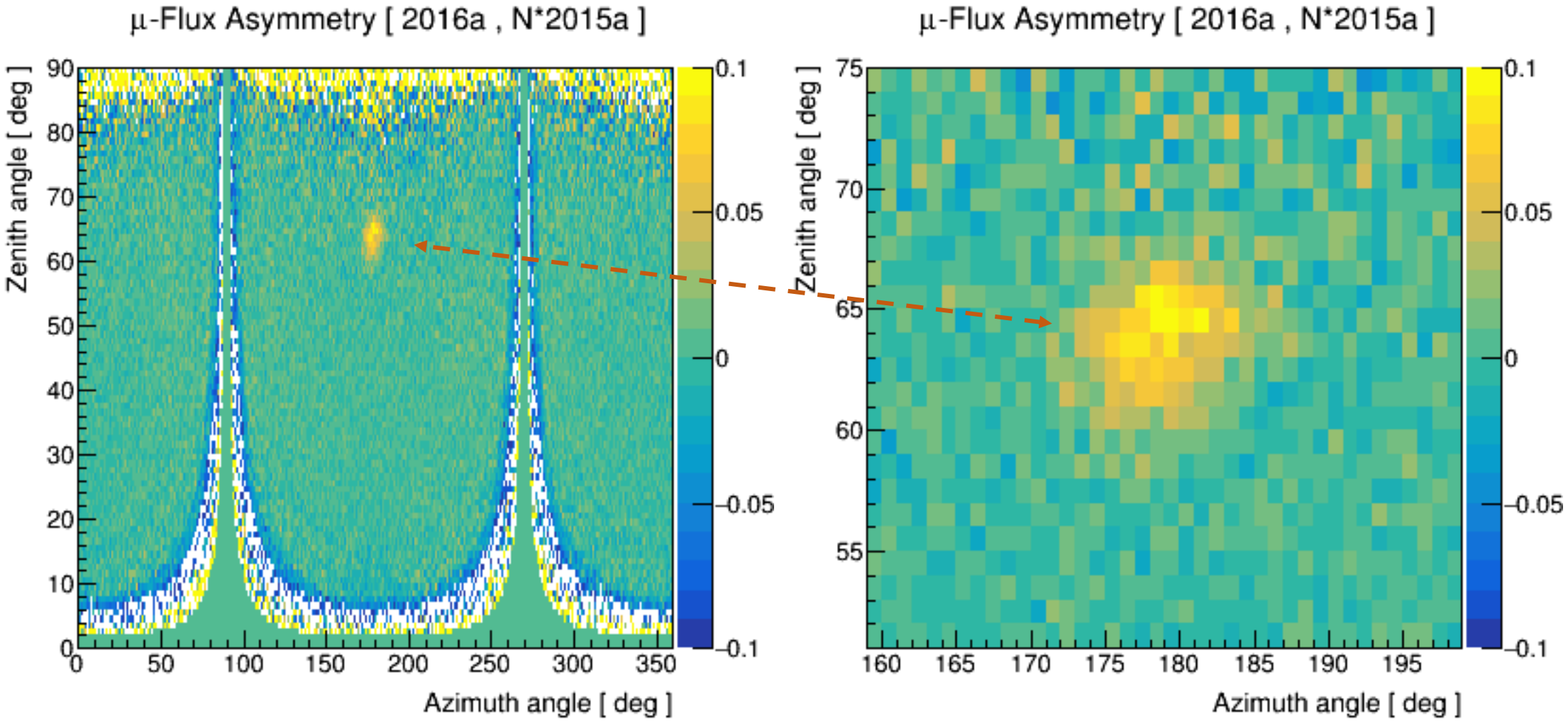
SYMMETRIES



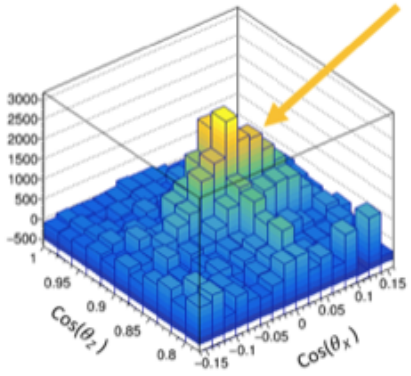


TIME variation: Excessive Cosmic Muons Flux

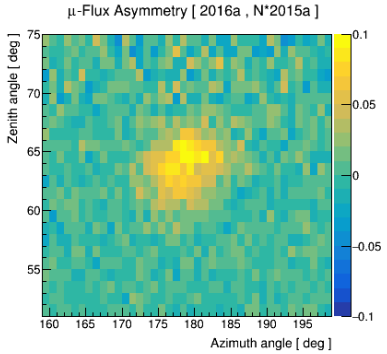
Bump = More Muons in Sep.-Dec. 2015 compared to 2016 data



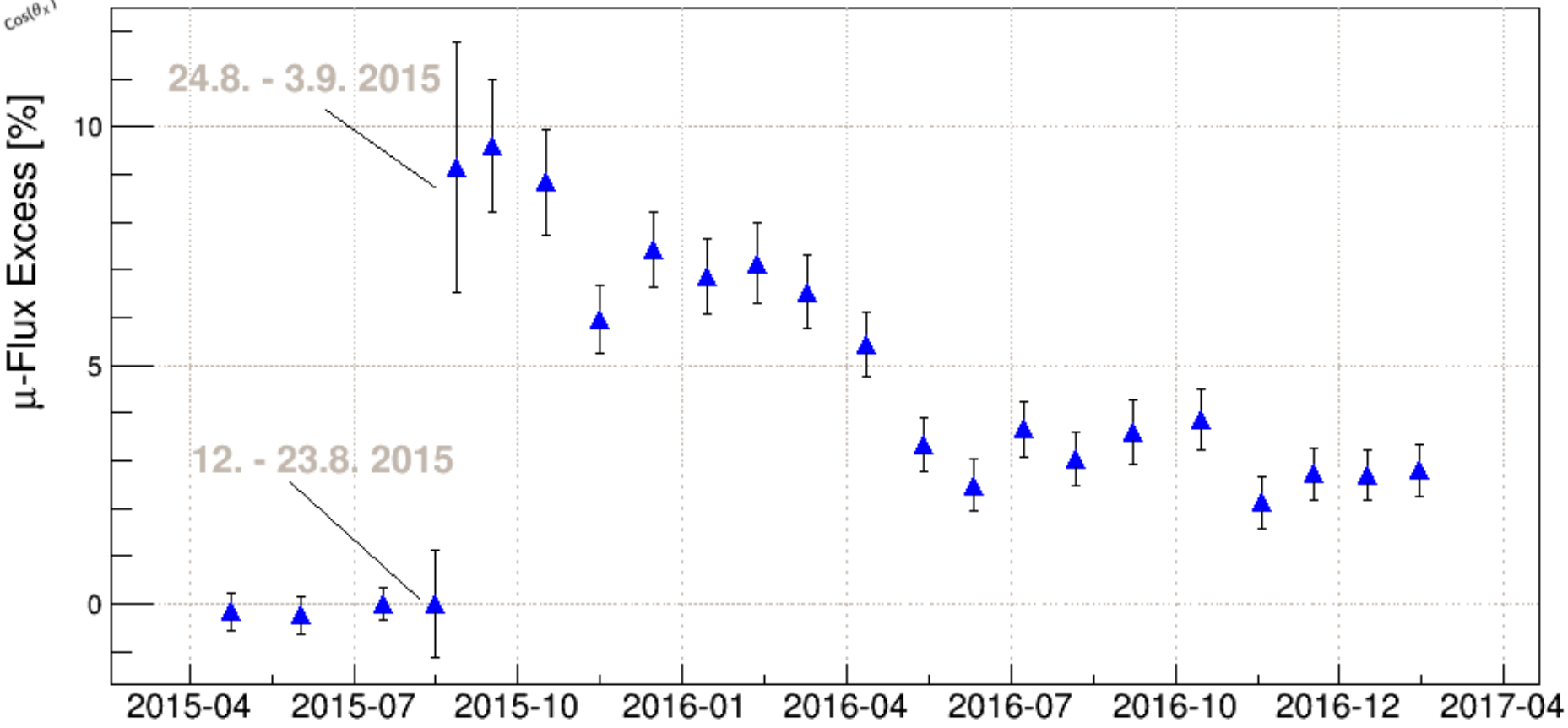
Time Evolution of the Excessive Muon Flux



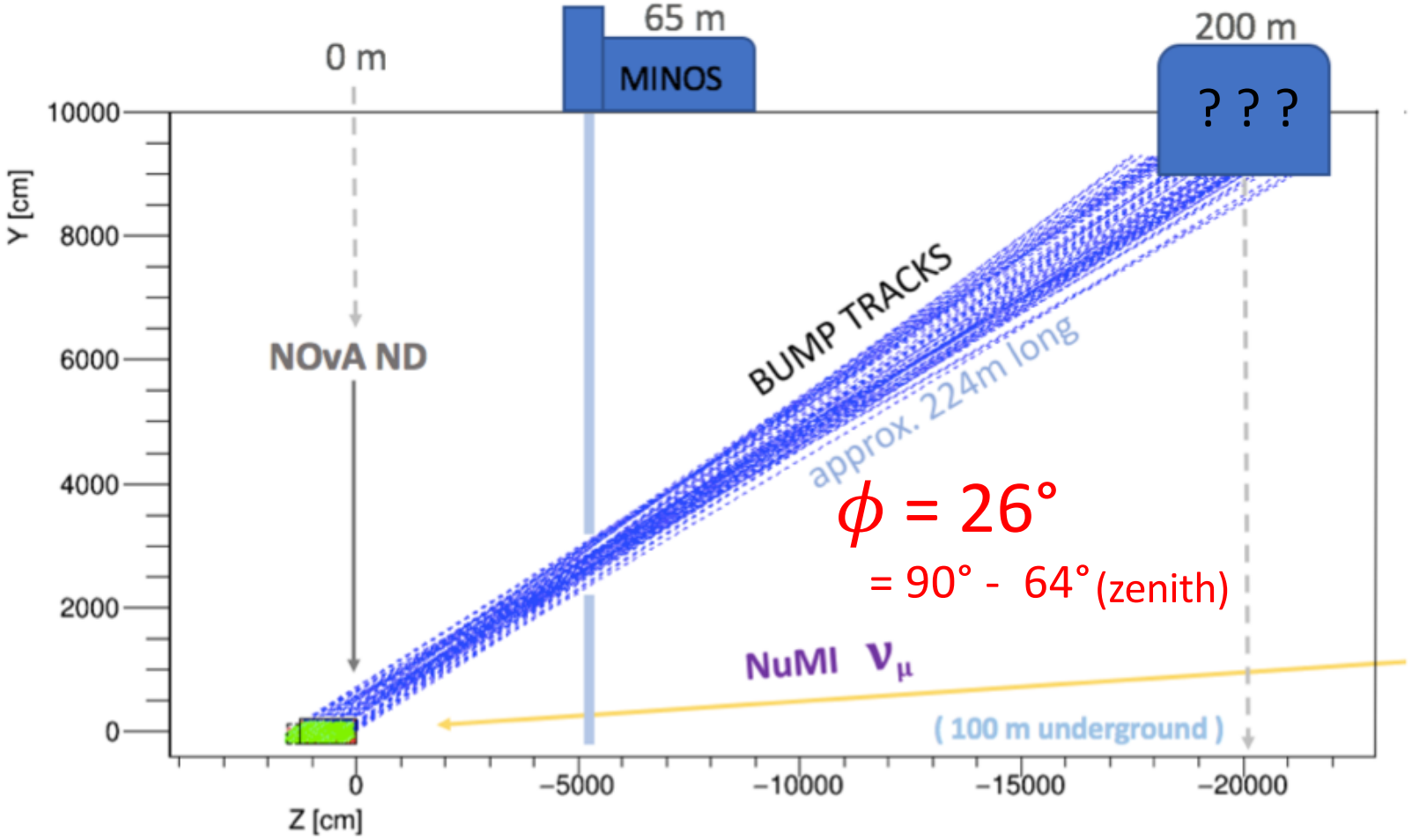
Excess **started** on 24.8.2015, and it was changing

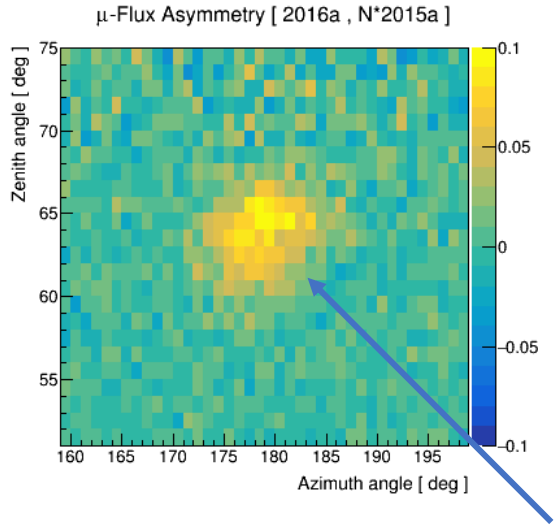


μ-Flux Excess (64±4° Zenith, and 179±9° Azimuth) in NOvA-ND, due to SBN-FD

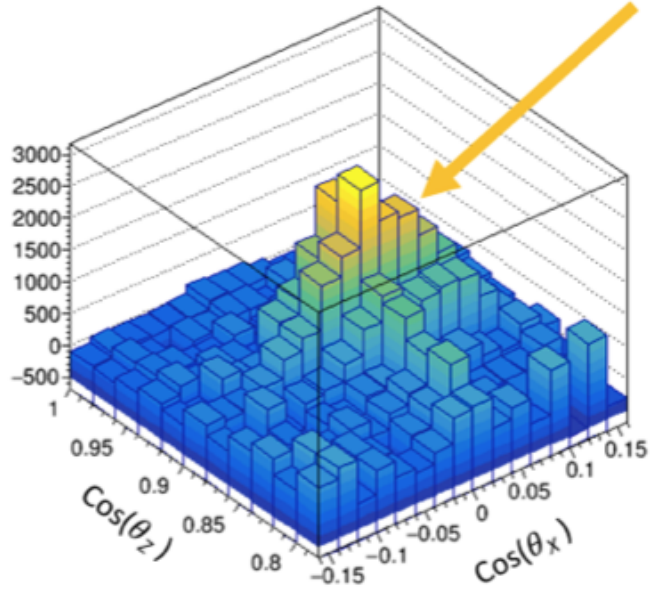


FINDING the **LOCATION of MUONS** on THE SURFACE



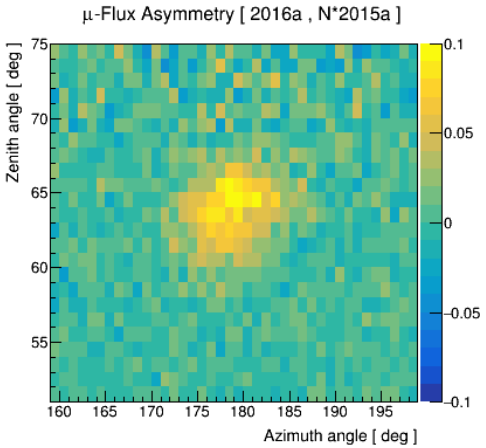


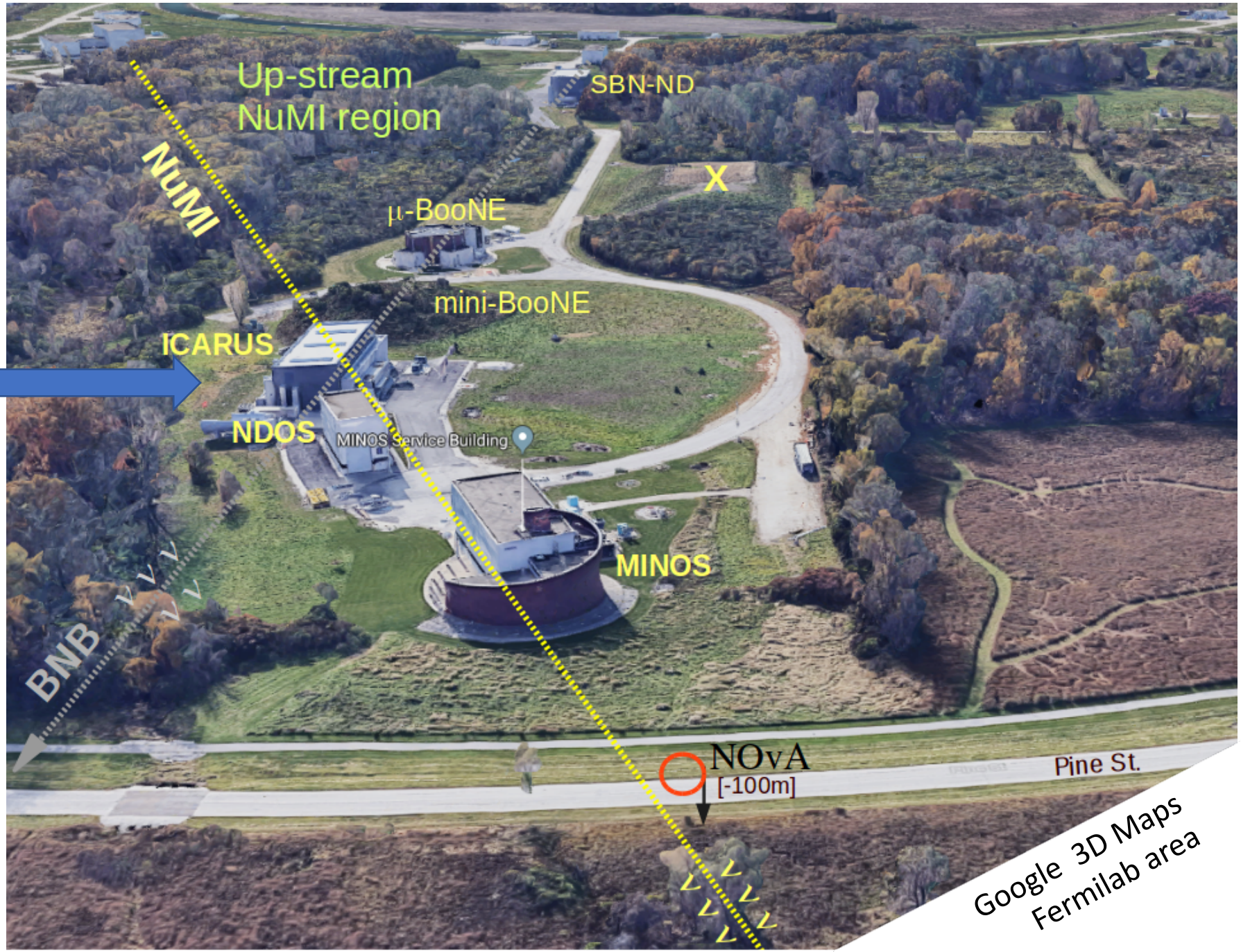
Excessive Muons



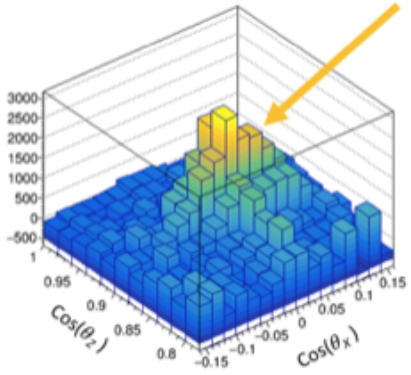
ICARUS

LESS ATTENUATION due to
the SOIL EXCAVATION
for the LAr ICARUS detector

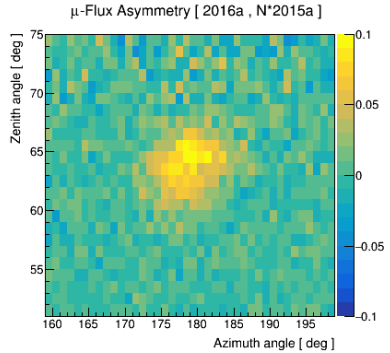




Time Evolution of the Excessive Muon Flux



Excess **started** on 24.8.2015, and it was changing



μ-Flux Excess (64±4° Zenith, and 179±9° Azimuth) in NOvA-ND, due to SBN-FD

μ-Flux Excess [%]

10
5
0

24.8. - 3.9. 2015

12. - 23.8. 2015

ICARUS Building Project Timeline

Excavation

Foundation Floor

Surface concrete and Backfill

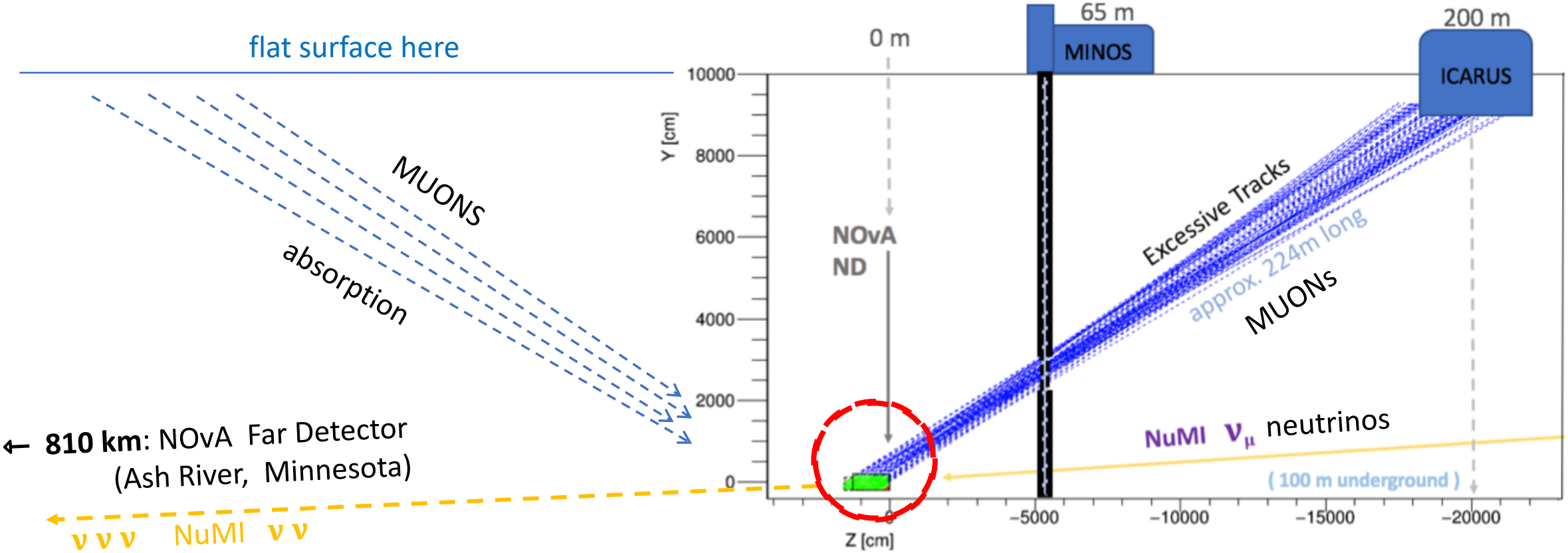
2015-04 2015-07 2015-10 2016-01 2016-04 2016-07 2016-10 2016-12 2017-04

ICARUS Excess: was found via Temporal Variation

+ also via: Angular Difference

⇒ Forward – Backward

μ-Flux SUBTRACTION



DIFFERENCIAL of the Muon Flux

muon-Flux:

DETECTOR Acceptance

$$F(\theta,\phi) = F_o \cdot G(\theta) \cdot K(\theta,\phi) \cdot A(\theta,\phi)$$

- F_o: μ-Flux — Time factor ACCUMULATION
- $G(\theta)$: $[\cos(\theta)]^k$ zenith dependence
- $K(\theta,\phi)$: absorption "KERNEL" GEOLOGY Buildings, Shafts, etc.
- $A(\theta,\phi)$: DETECTOR Acceptance

LEFT ⟷ RIGHT Subtraction

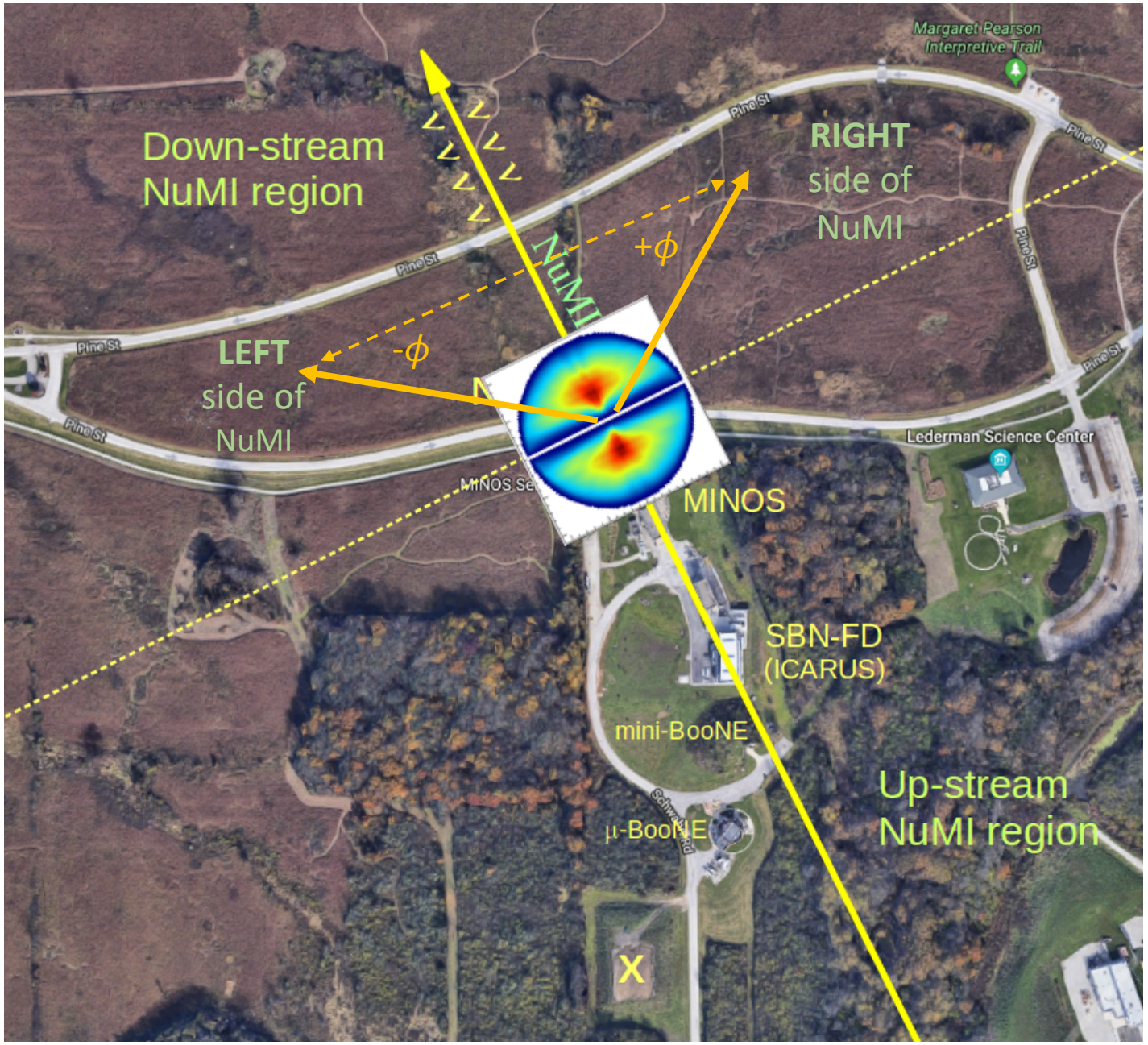
$$\frac{F(\theta,+\phi) - F(\theta,-\phi)}{F(\theta,+\phi) + F(\theta,-\phi)}$$

Acceptance CANCELS out: due to Symmetry of Detector

$$A(\theta,\alpha'+\phi) = A(\theta,\alpha'-\phi)$$

$[\alpha' = 0]$

Satellite 2D view (google maps)



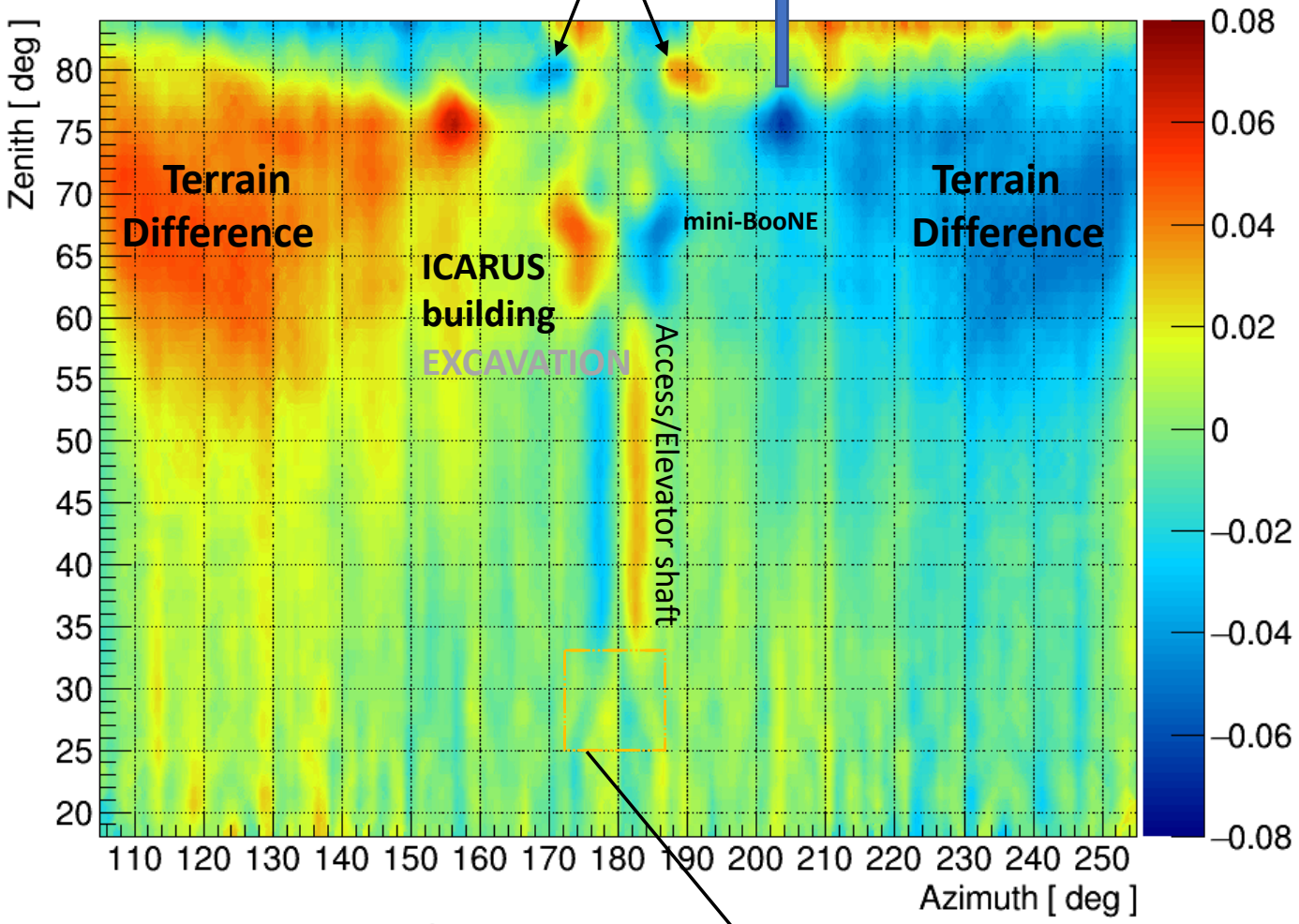
• *see Proceedings PoS* ICHEP2020 (2021) 800, by P.Filip

Left – Right: absorption difference of the Muon Flux

other μ2e-Exp. Hill
(Left → Right reflected)

[170°, 80°]

"X" – Hill = soil



u2e-Hill distance: 570m from NOvA
570m/100m = tan(80°)

NO sign of MINOS building
(it is Left-Right symmetric)

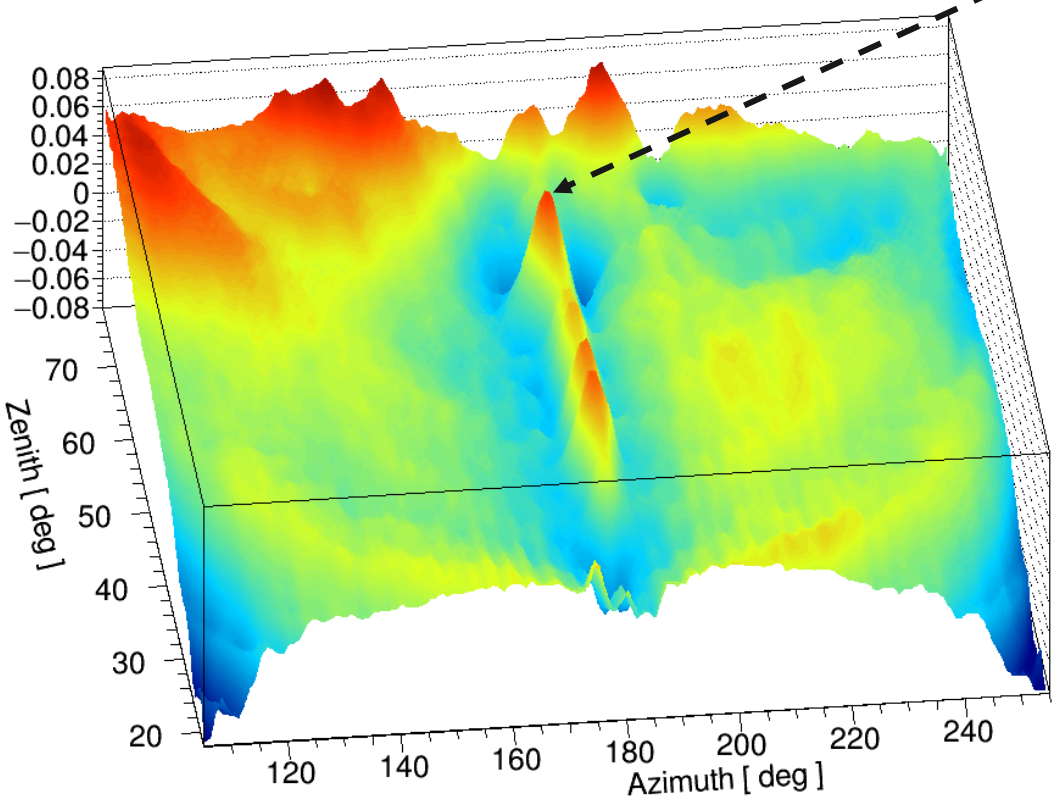
Muon – **Radiography** of NOvA-ND Cosmic Data (FNAL)

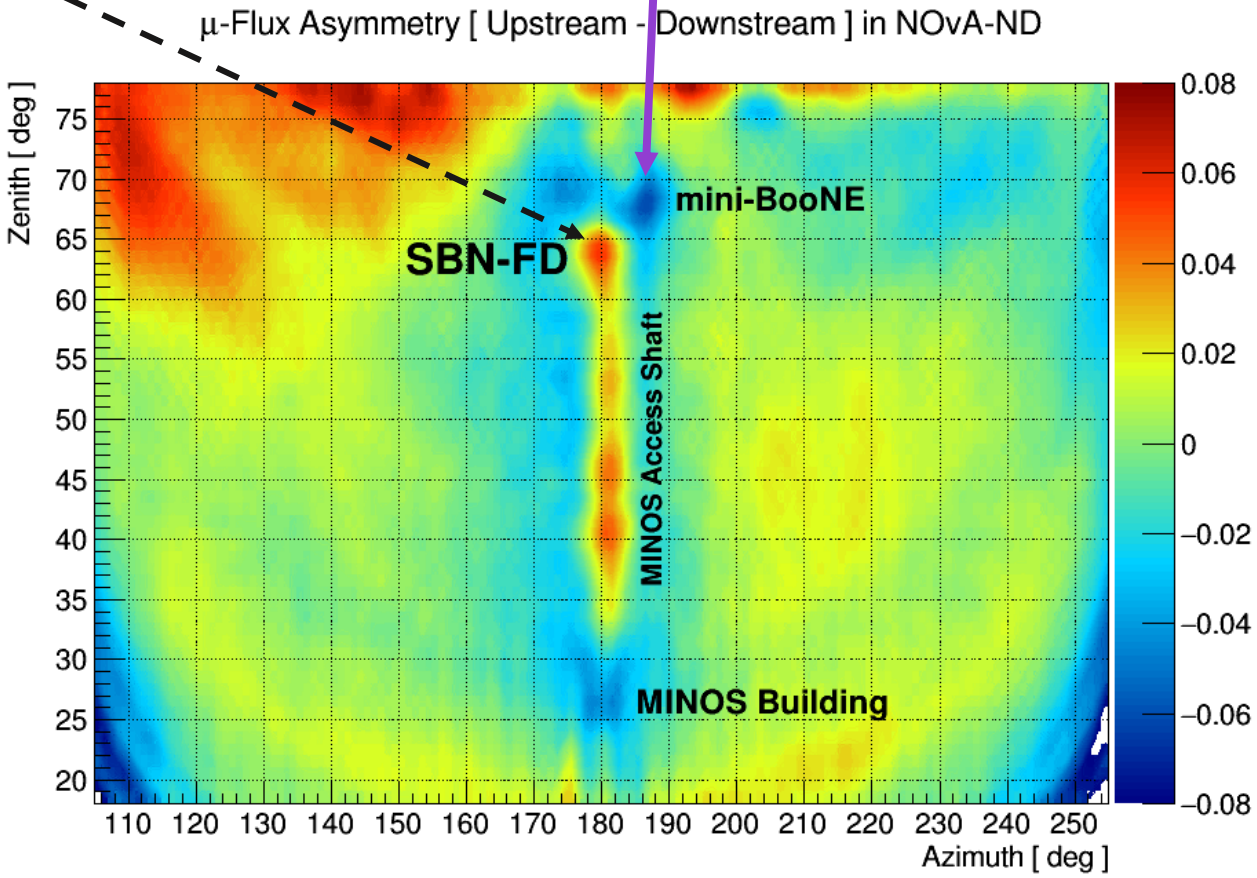
Upstream – Downstream

μ-Flux asymmetry

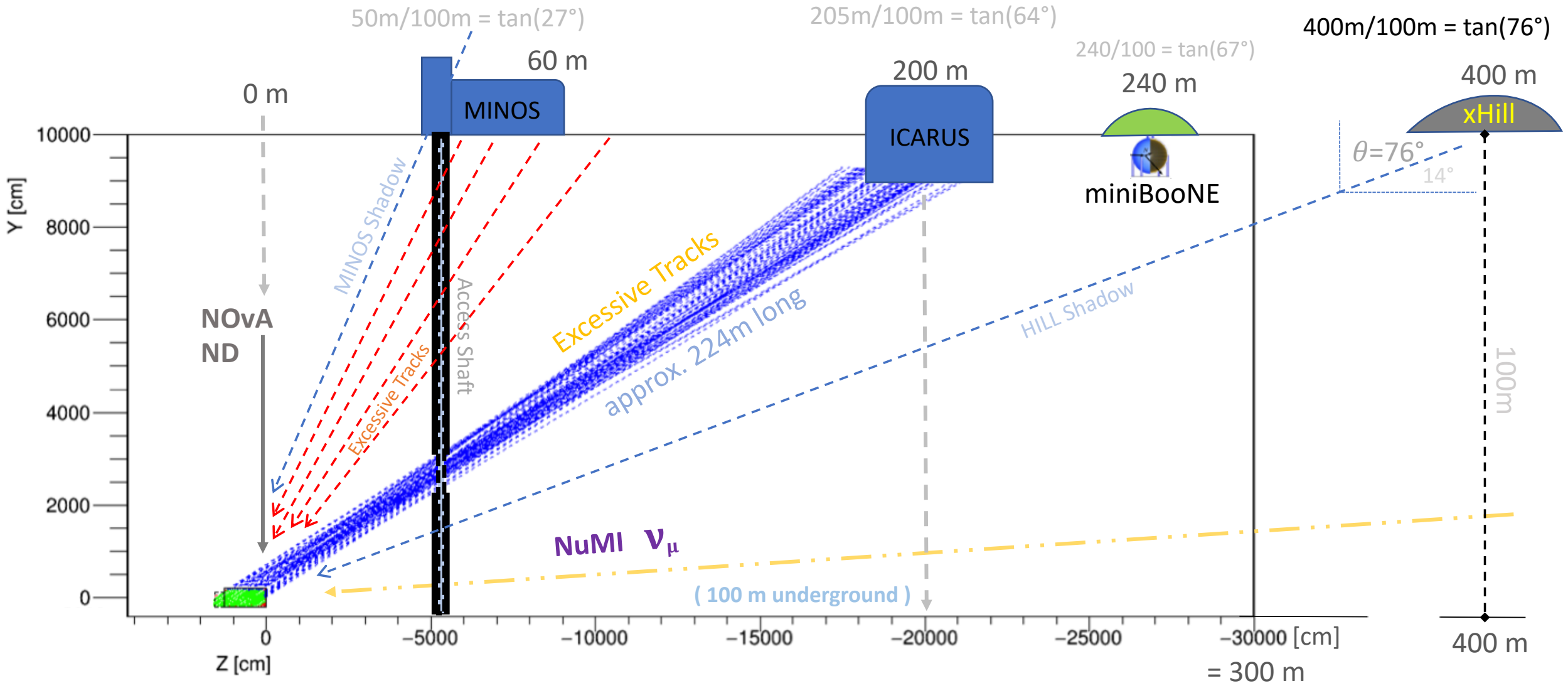
[179°, 26°]
ICARUS
excavation

mini-BooNE detector
Hill shadow [186°, 67°]



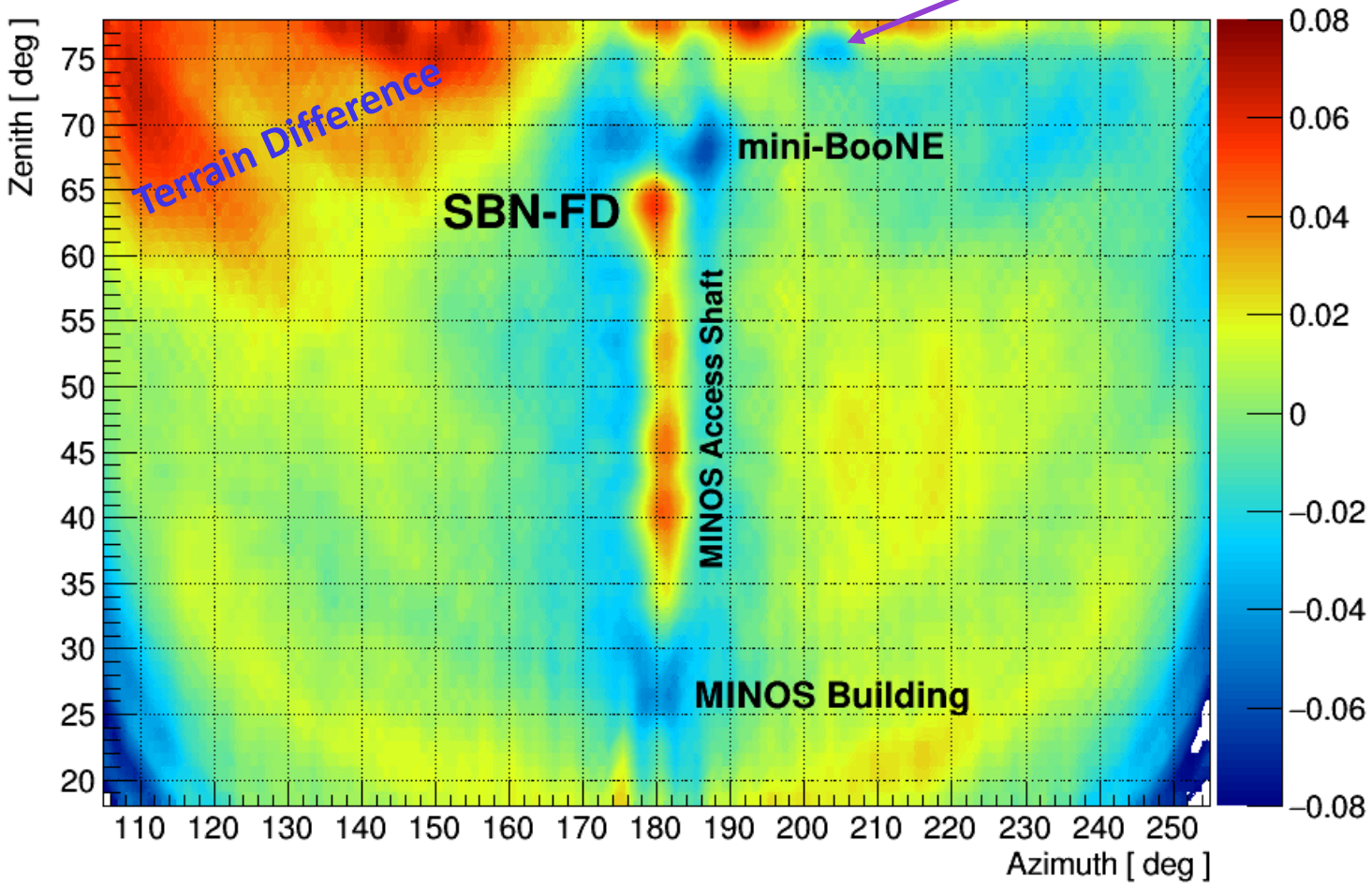


Positions of the Surface Buildings at Fermilab:



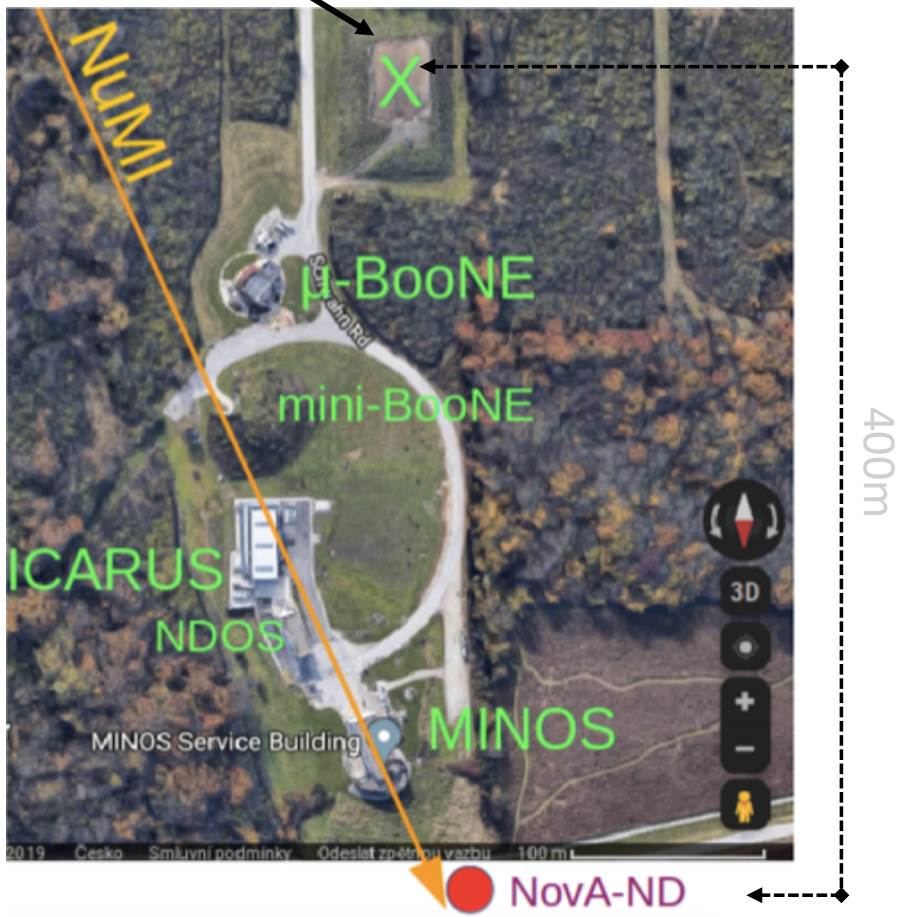
Muons Absorption Differences. NOvA-ND Data

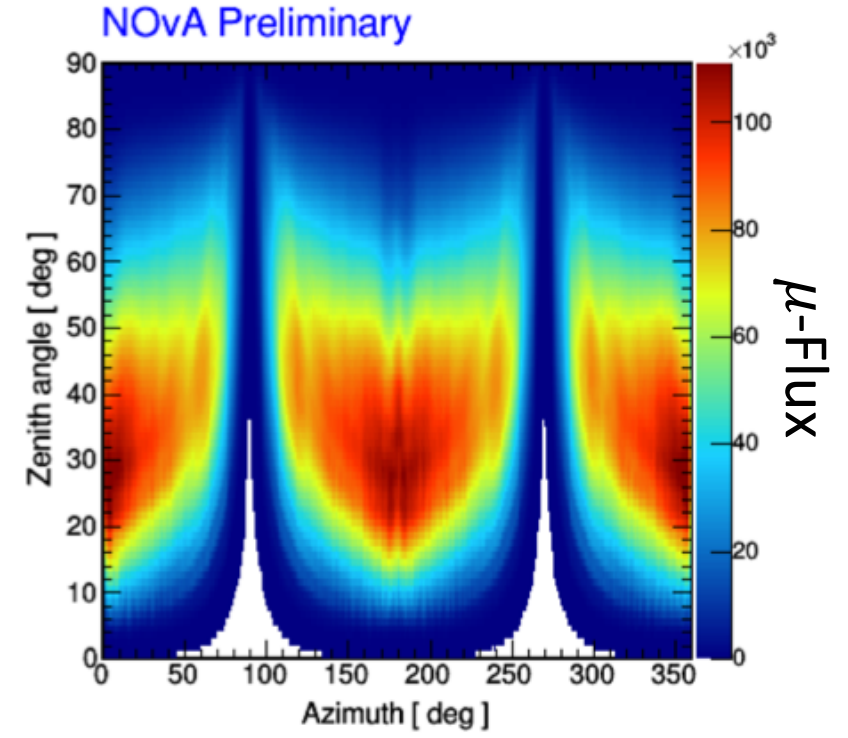
[Apr. 2015 + 18 months data] NOvA Near Detector
Cosmic Muon Flux
UPSTREAM - DOWNSTREAM μ-Flux subtraction

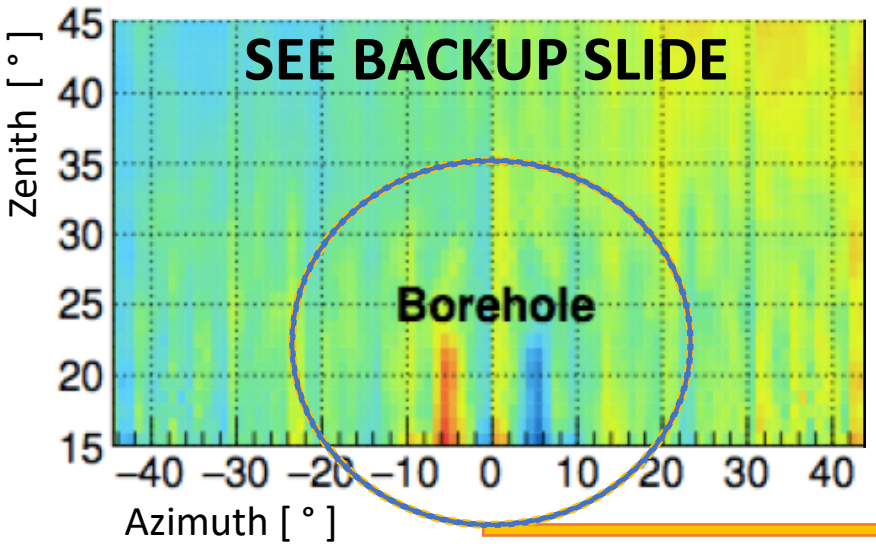


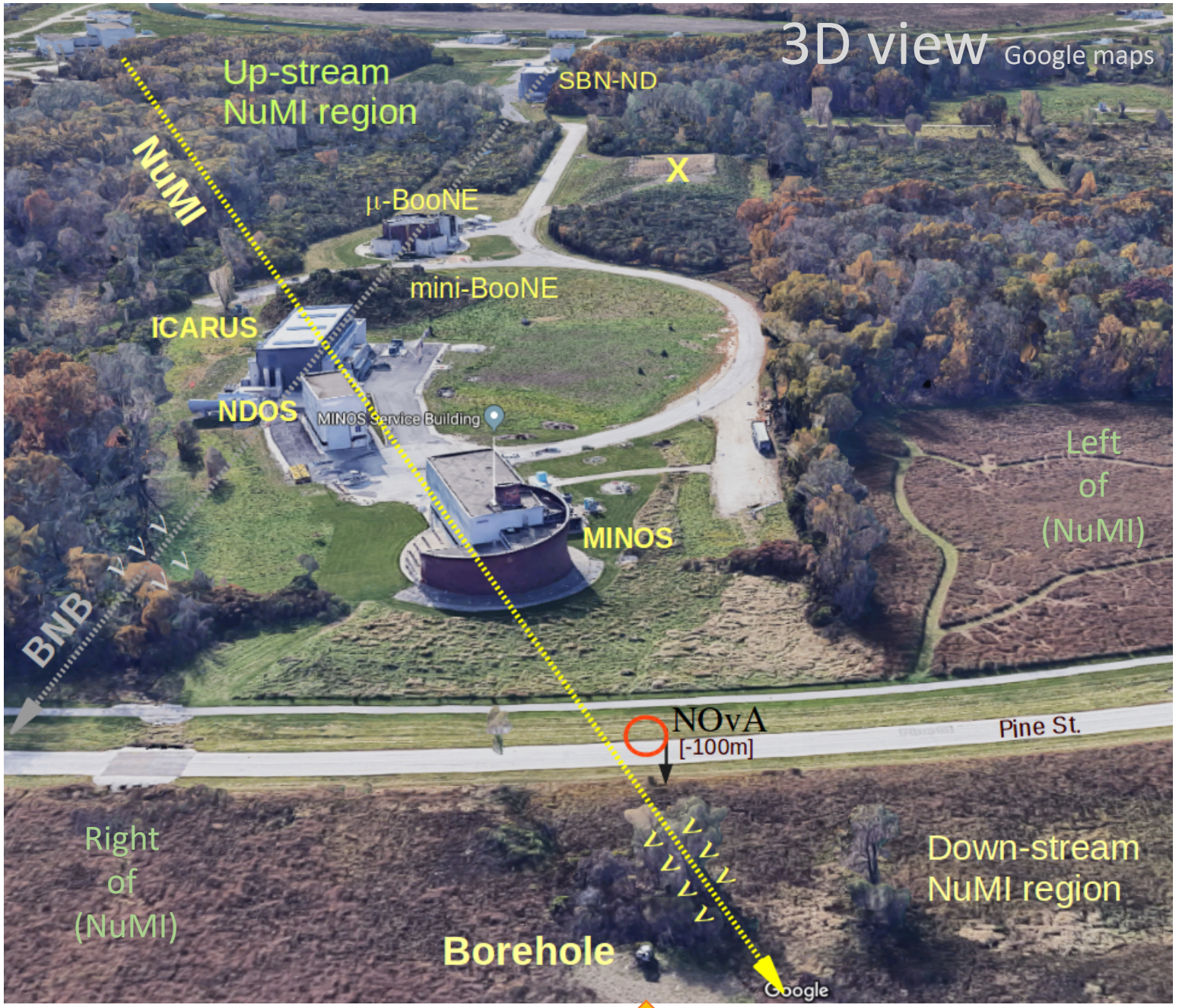
x-Hill: 400m South from NOvA ND

400m/100m = tan(76°)




NOvA Preliminary
Zenith angle [deg]
Azimuth [deg]
μ-Flux


SEE BACKUP SLIDE
Borehole
Zenith [°]
Azimuth [°]


3D view Google maps
Up-stream
NuMI region
NuMI
SBN-ND
X
μ-BooNE
mini-BooNE
ICARUS
NDOS
MINOS Service Building
MINOS
BNB
Left
of
(NuMI)
NOvA
[-100m]
Pine St.
Right
of
(NuMI)
Down-stream
NuMI region
Borehole
Google

CONCLUSIONS:

- For the SYMMETRIC detector ACCEPTANCE

  --> ***direct subtraction*** **of the angular μ-Flux is possible**

  see PoS ICHEP2020 (2021) 800

  --> **Radiographic images can be obtained straight from Data**

  (without Free-sky subtraction, and without Geant/MC simulation)

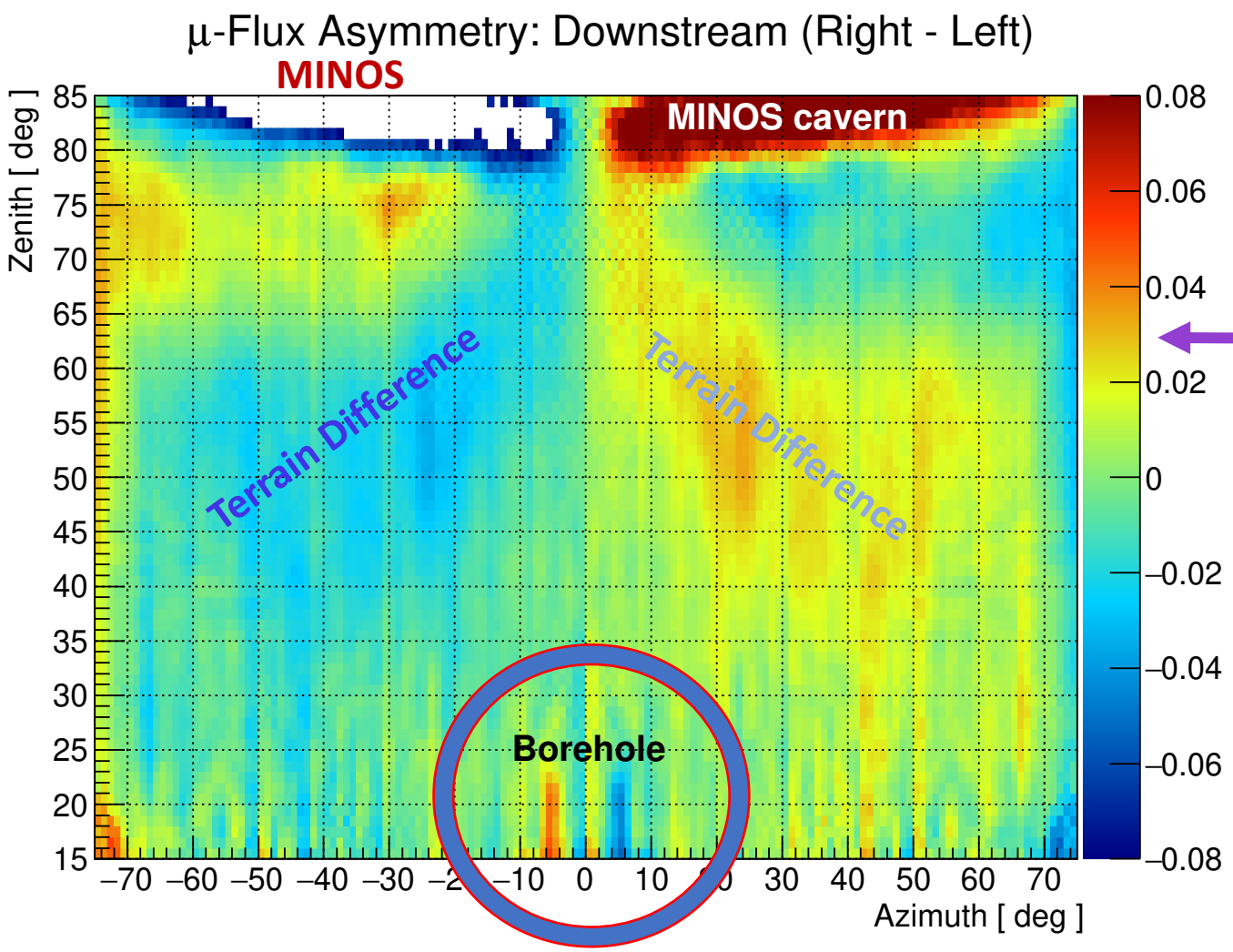
- **APPLICATION**s: Geology surveys, Mines, Volcanology (?)
  in various Muon Radiography techniques

see: Nature 552 (2017) 368

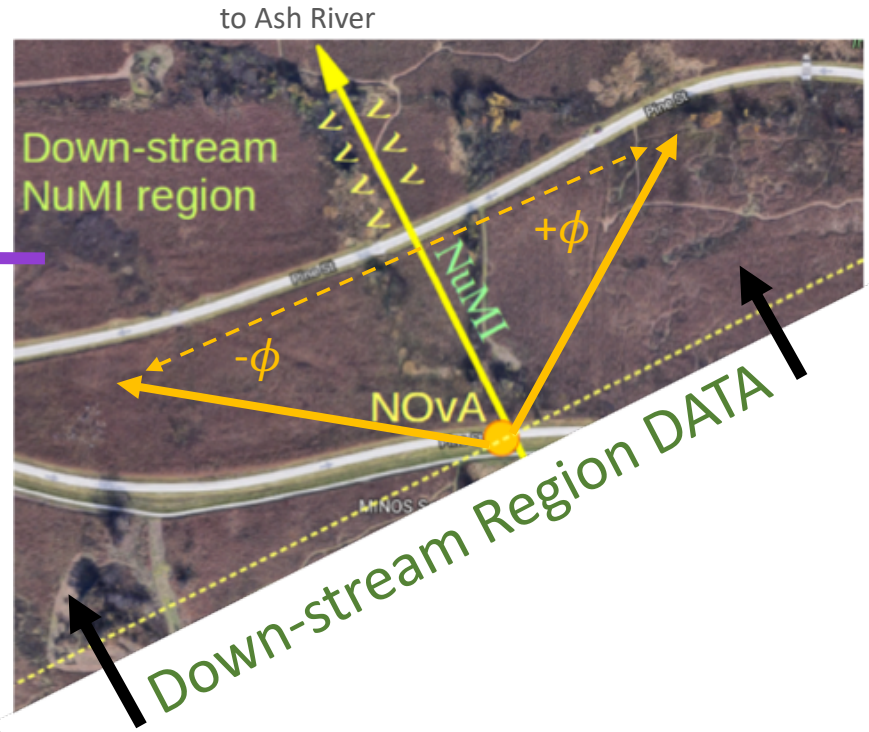
- e.g. Search for the voids in Pyramids (central detector)

- Useful for our (NOvA) studies of backgrounds to time-dependent cosmic ray phenomena

LEFT - RIGHT Difference: in NuMI beam Direction



Satellite 2D view (google maps)



Note: MINOS detector cavern: is near NOvA-ND

→ DEFICIT/EXECESS of muon-tracks

→ excessive muons on the right side: $\theta > 80°$