千葉大学
CHIBA UNIVERSITY

RWTH AACHEN UNIVERSITY

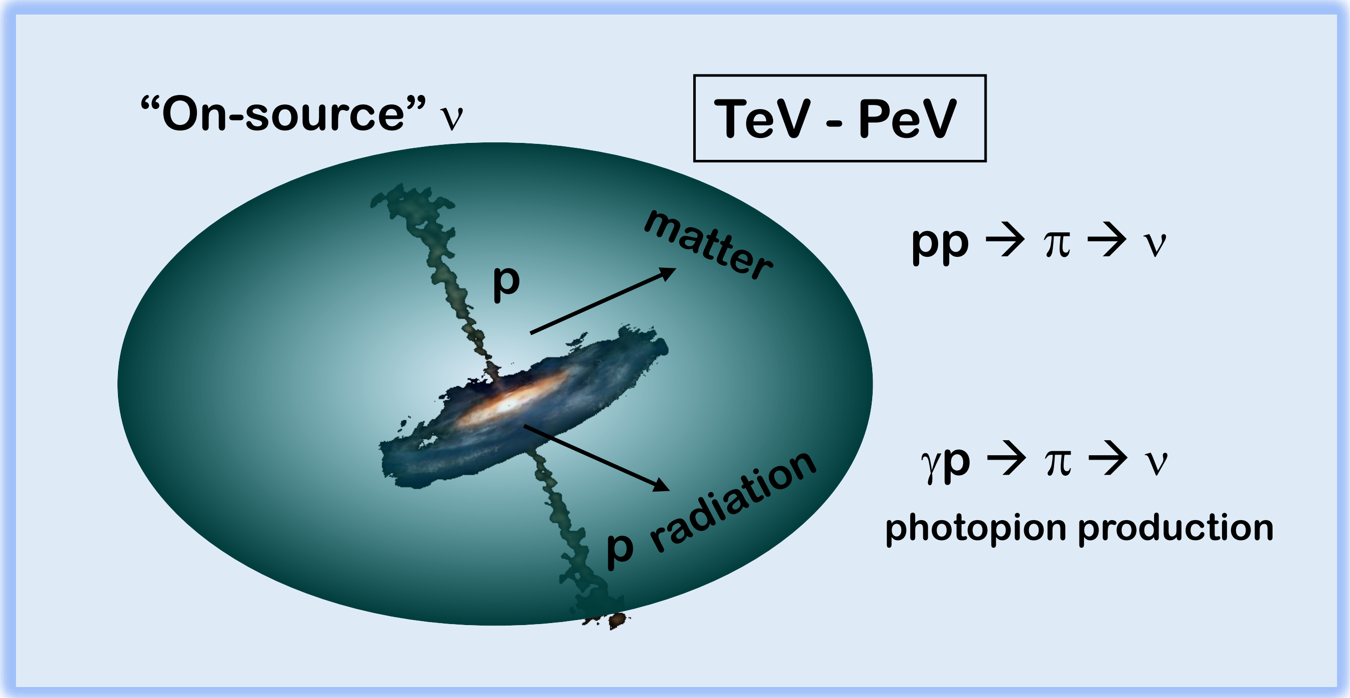
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

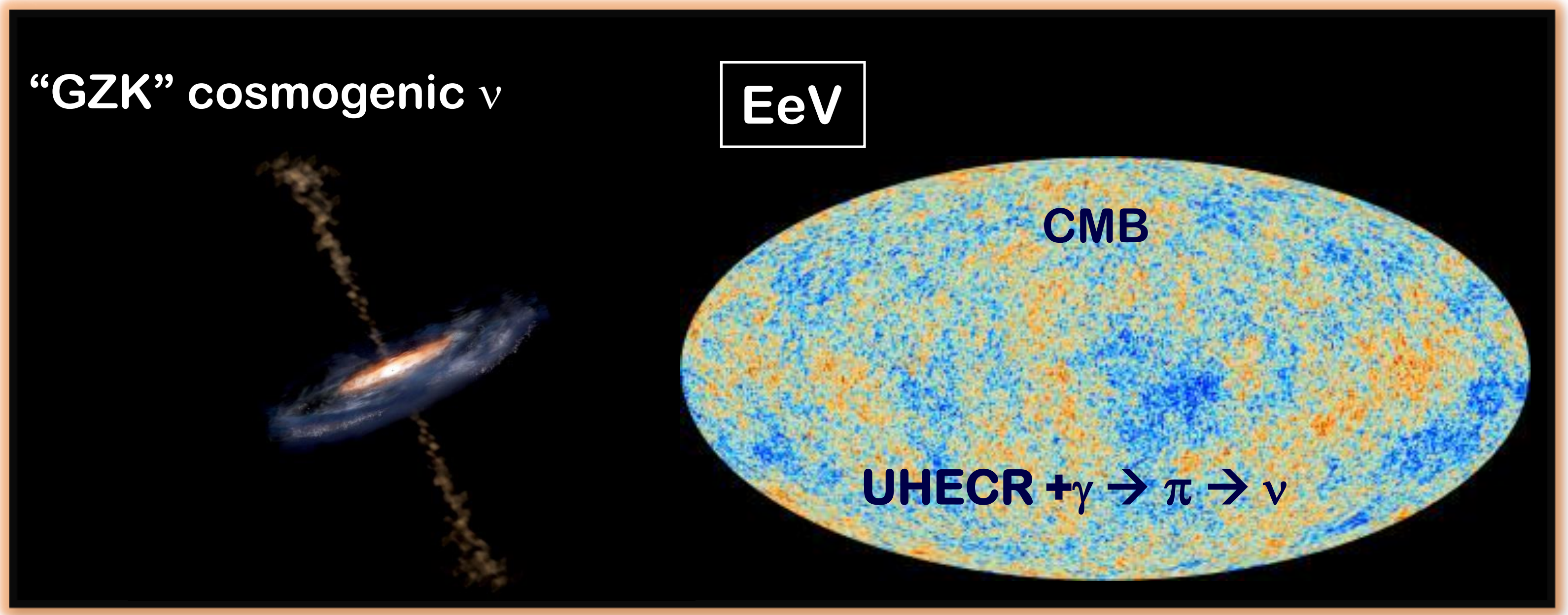
ICECUBE RECENT RESULTS: HINT OF FIRST GLASHOW RESONANCE & THE POSSIBLE FIRST NEUTRINO SOURCE

Lu Lu, Christian Haack and Tianlu Yuan for the IceCube Collaboration

lu.lu@icecube.wisc.edu

The Cosmic Neutrinos from TeV to EeV



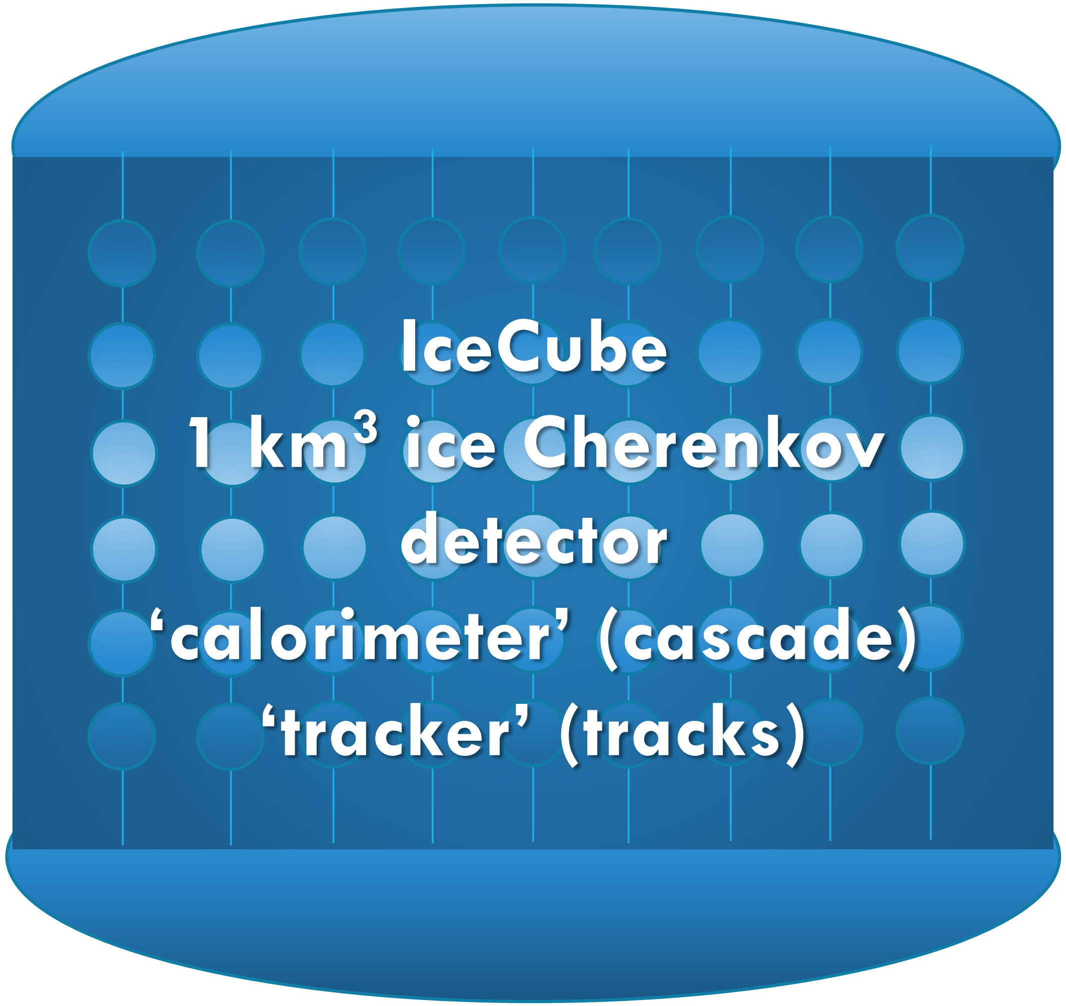


Are UHECRs correlated with IceCube ~TeV neutrinos?
(see talk from joint working-group)

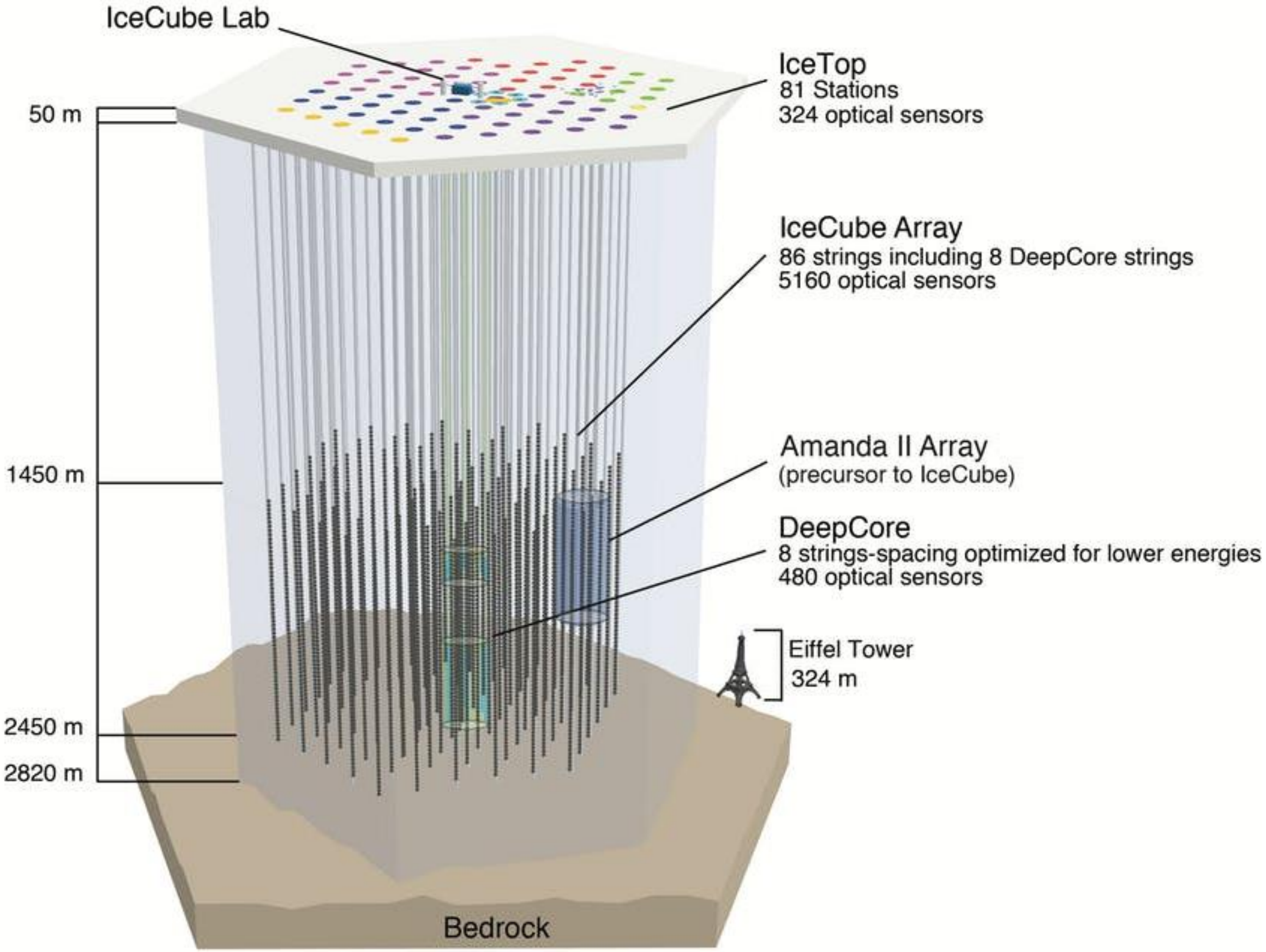
DETECTING NEUTRINOS IN ICE

Auger: 1500 water tanks (H=1.2m, Φ=3.6 m)

Auger/TA uses atmosphere as calorimeter
Sensitive to down-going and horizontal events



4 pi coverage of sensitivity



IceCube neutrino observatory

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

WHAT HAVE WE ACHIEVED SO FAR

- ✓The detector works well with ~99% uptime
- ✓Astrophysical spectrum more than 8 sigma in two independent channels
- ✓Cross-section measurements at energies beyond accelerators
- ✓…
- ✓ World's best limits on cosmogenic neutrino flux

new

- ✓First hint of the **Glashow resonance**! (in this talk)
- ✓First compelling evidence of **correlation** between a high-energy IceCube neutrino with blazar **TXS 0506+056** thanks to the **realtime** global network (in this talk)

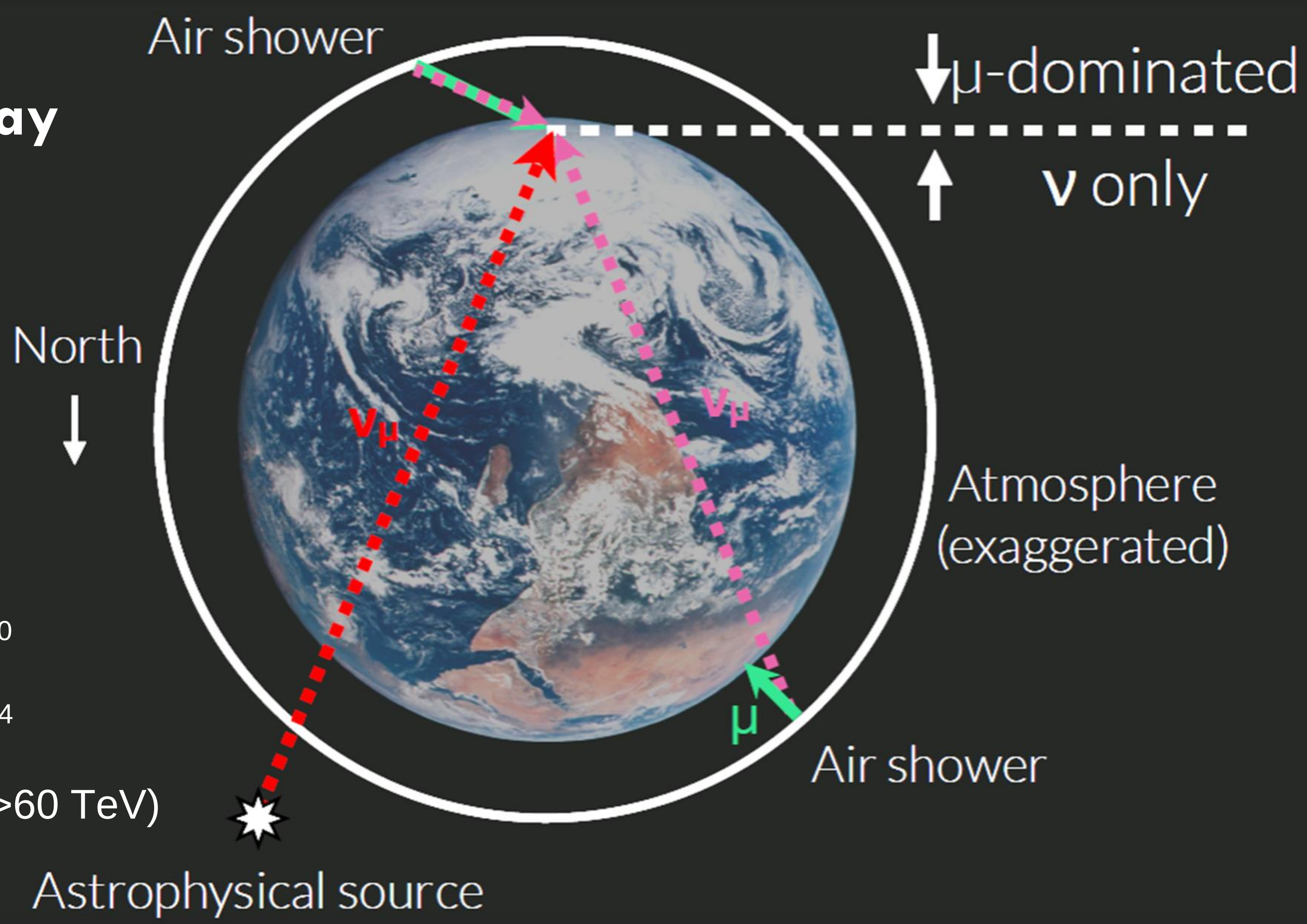
Part 1.
the first hint of Glashow resonance

IceCube is an efficient cosmic-ray detector, too…

Cosmic-ray summary see talk from Karen Andeen

Muons detected per year:

- atmospheric μ 7×10^{10}
- atmospheric $\nu \rightarrow \mu$ $> 8\times10^{4}$
- cosmic $\nu \rightarrow \mu$ ~10 (>60 TeV) starting events)

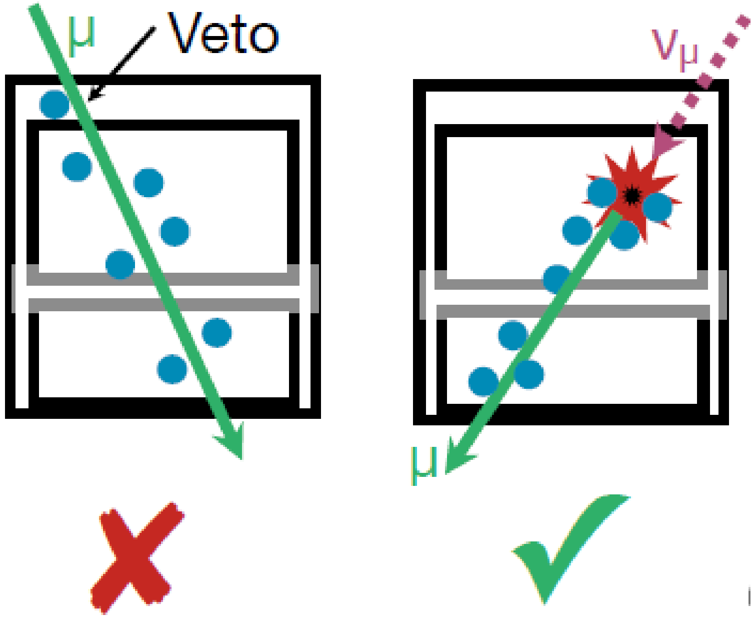


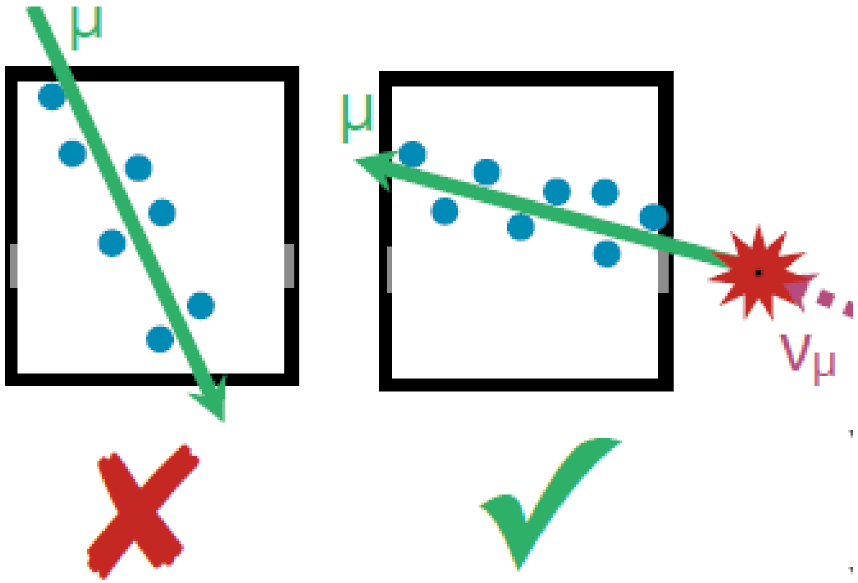
HOW TO REJECT COSMIC-RAY BACKGROUND

Two ‘golden’ neutrino channels from IceCube

Starting events (outer layer detector as veto)

Select up-going events travelled through earth



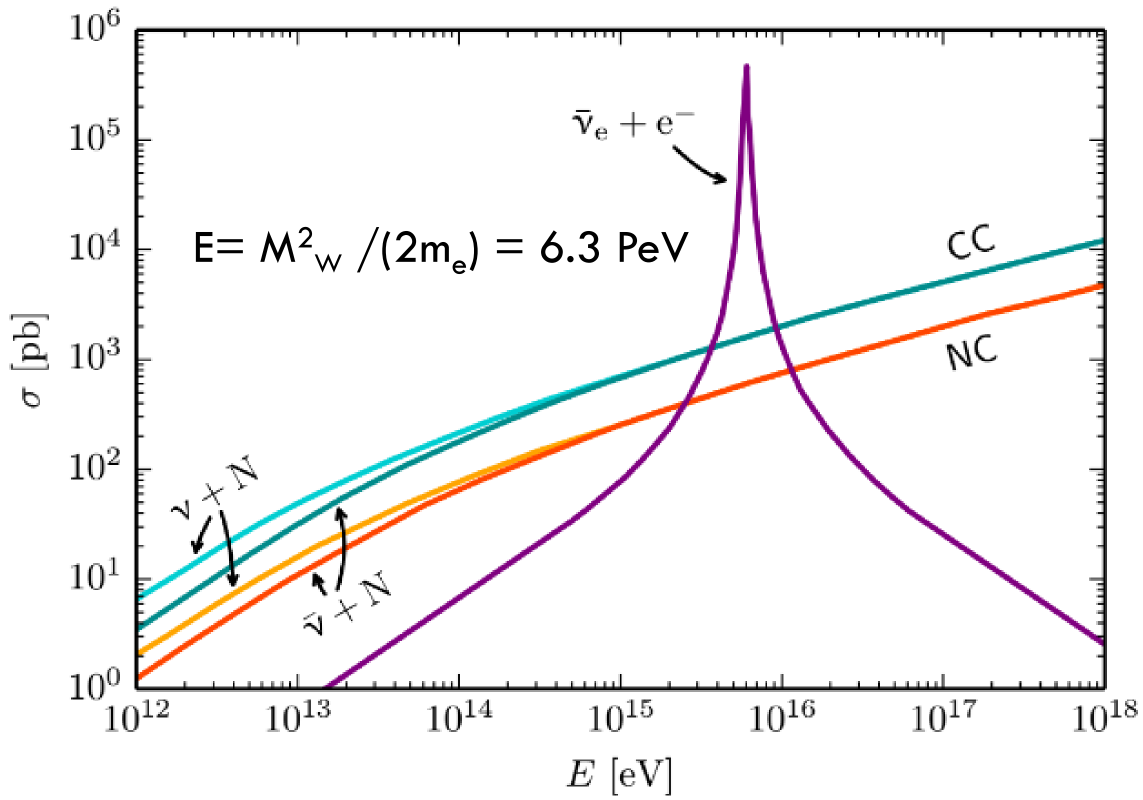


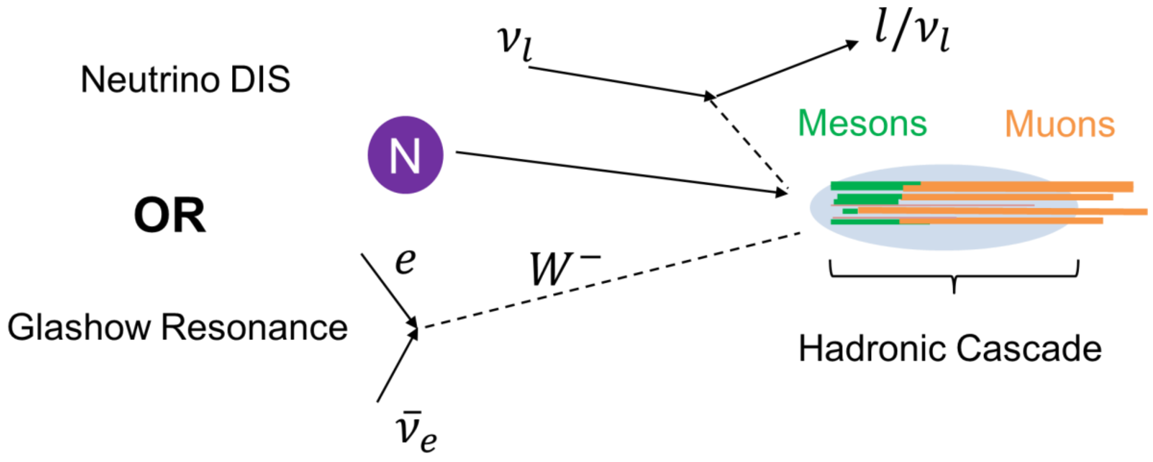
High Energy Starting Events – HESE (4pi)

Diffuse numu sample (northern sky)

MOTIVATION TO DEVELOP NEW TECHNIQUES

A gift from nature – Glashow resonance at 6.3 PeV



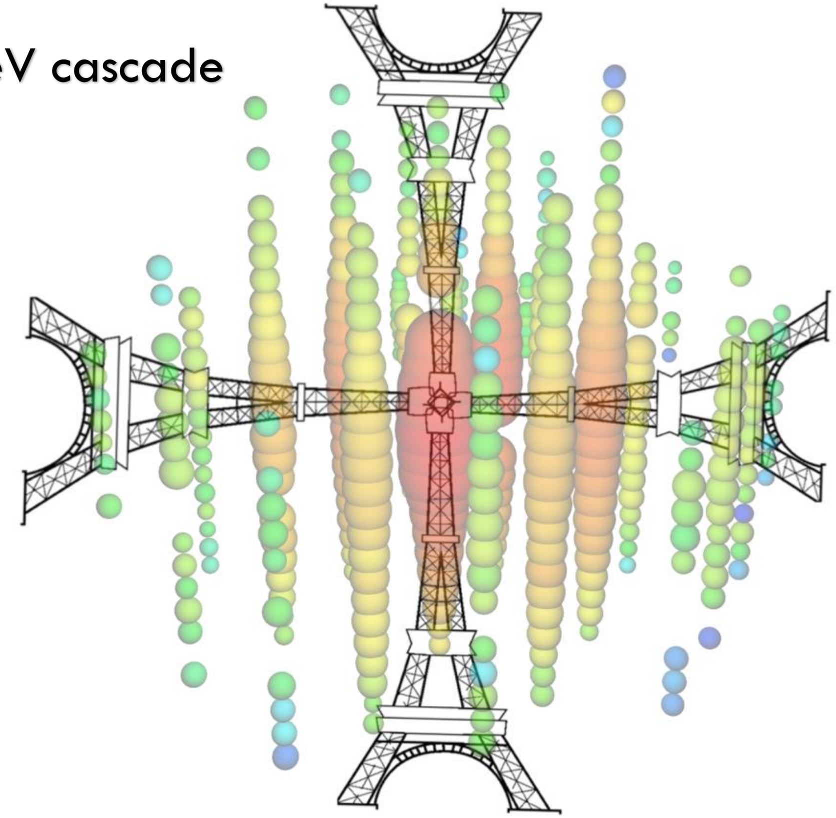


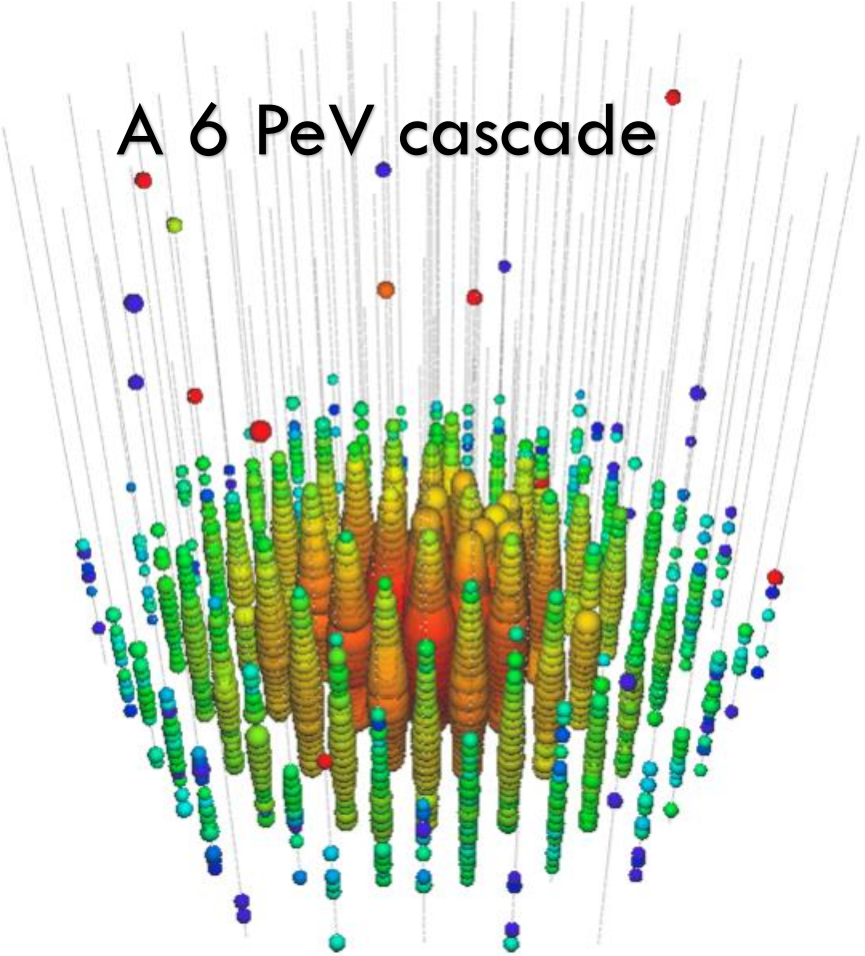
A boost of cross-section by a factor of 300!

At ~68% in hadronic cascade channel

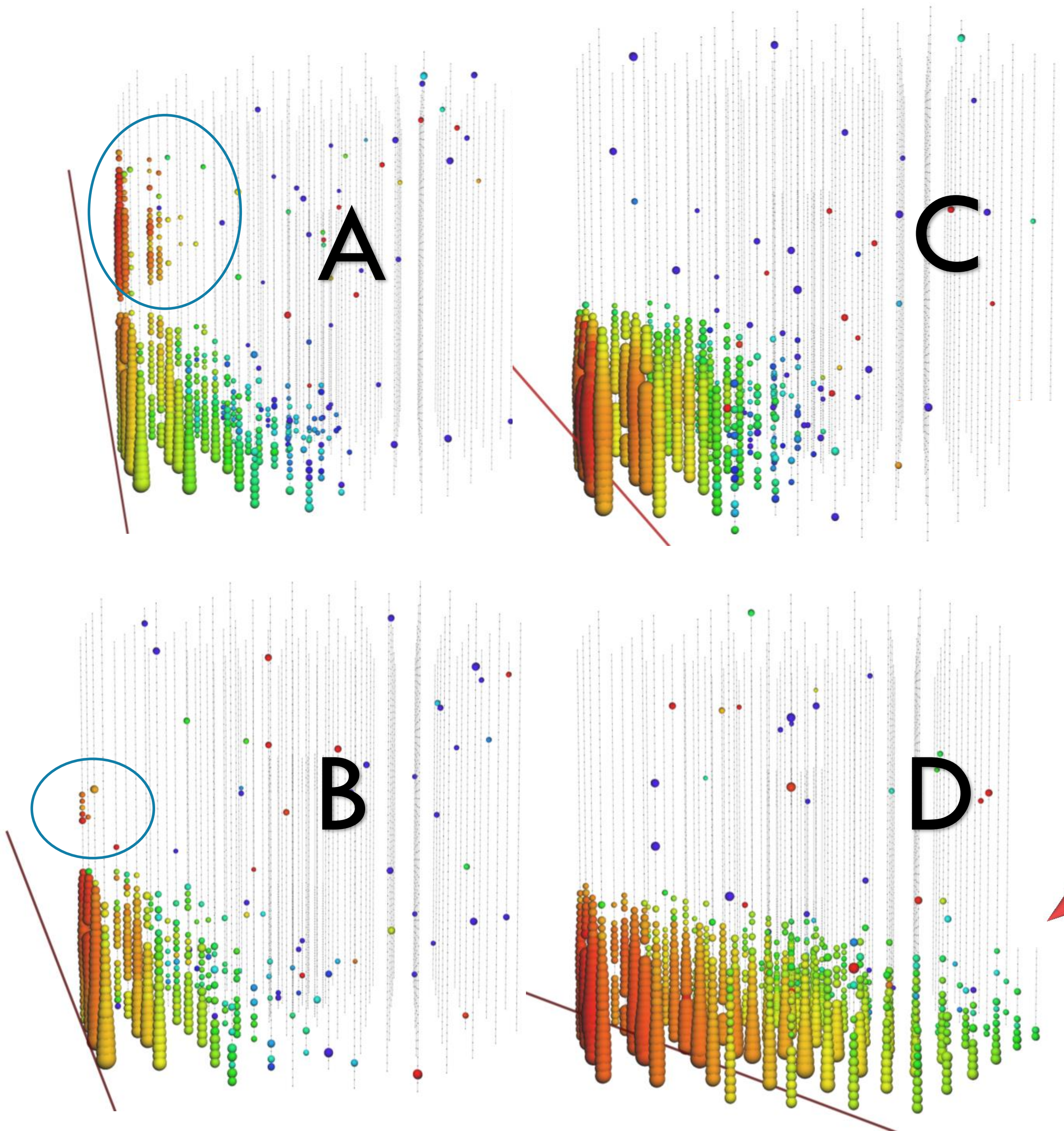
THERE ARE A LOT OF PHOTONS FROM PEV CASCADES, CAN AFFORD PARTIALLY CONTAINED FOR RECONSTRUCTION

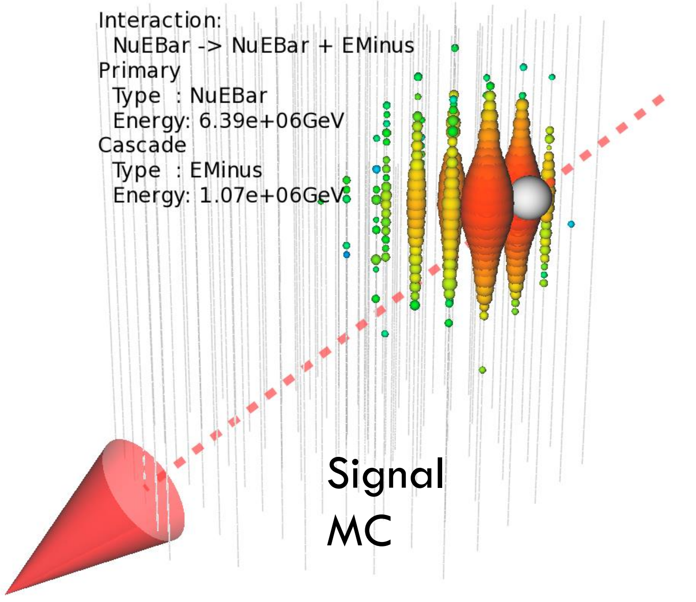
A 1 PeV cascade

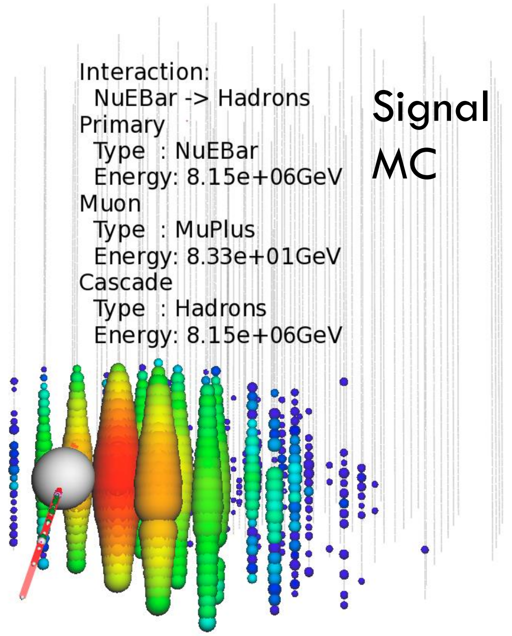




HOW TO REJECT COSMIC-RAY BACKGROUND?







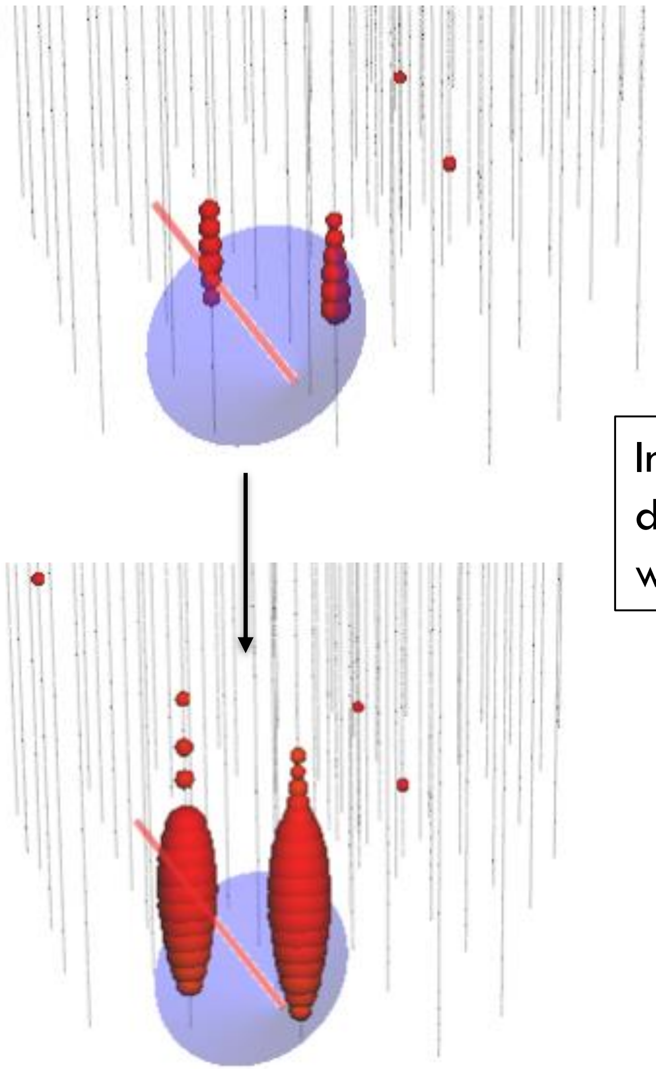
A, B, D from simple topology and by eye can already distinguish they are background

C is more tricky and need to use timing information

USING TOPOLOGY AND TIMING TO REJECT BACKGROUND

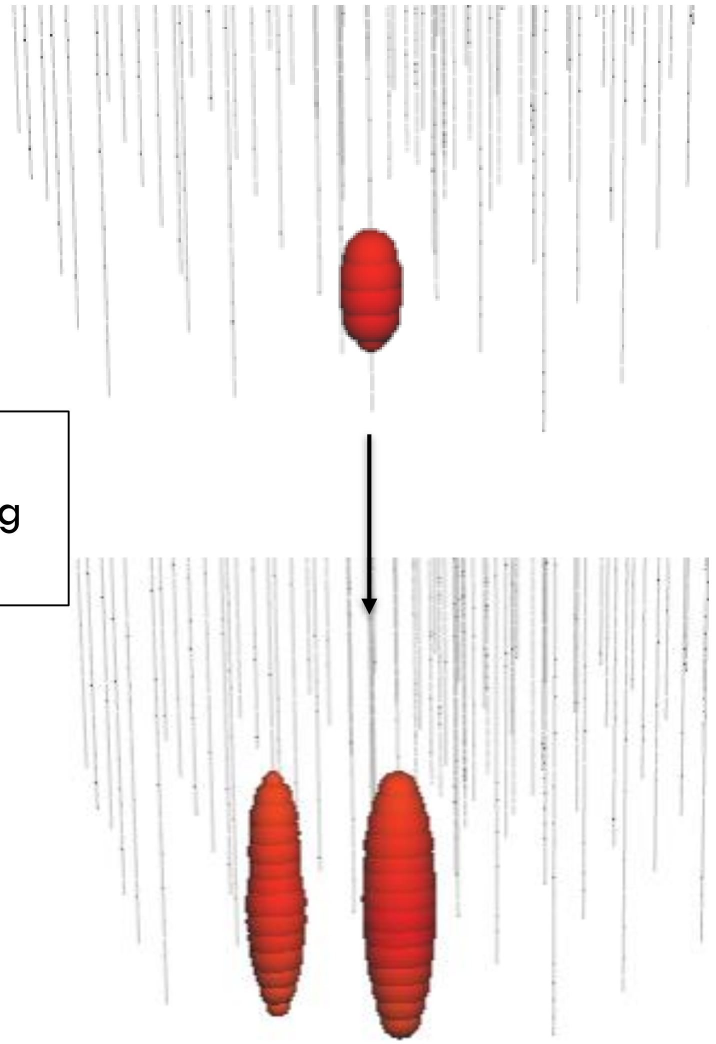
If muonic origin, Cherenkov cone would register large-scale (usually couple of strings since muon unlikely to stop in the detector) stochastic loss patterns on DOMs and light up DOMs earlier than if just approximate point-like cascade source

background



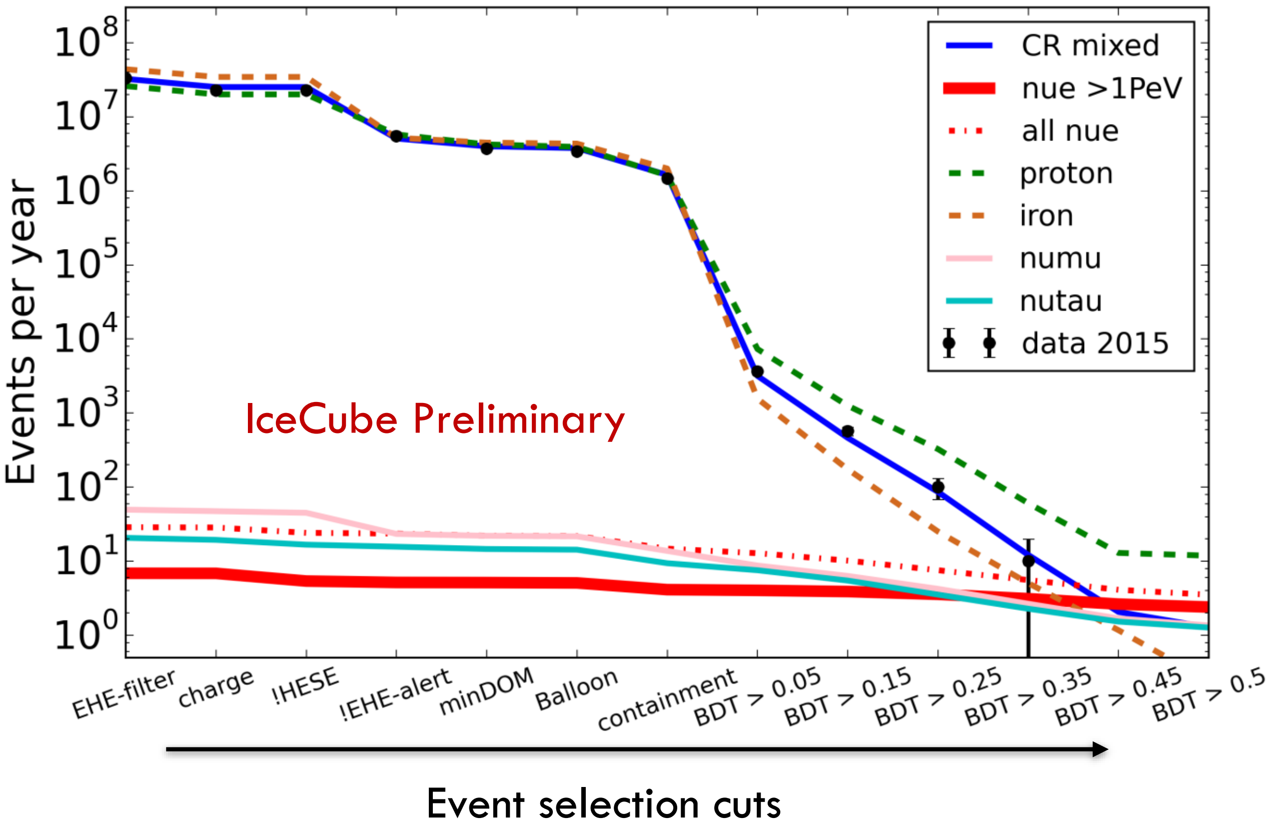
In total 11 observables to describe topology and timing were used to train BDT

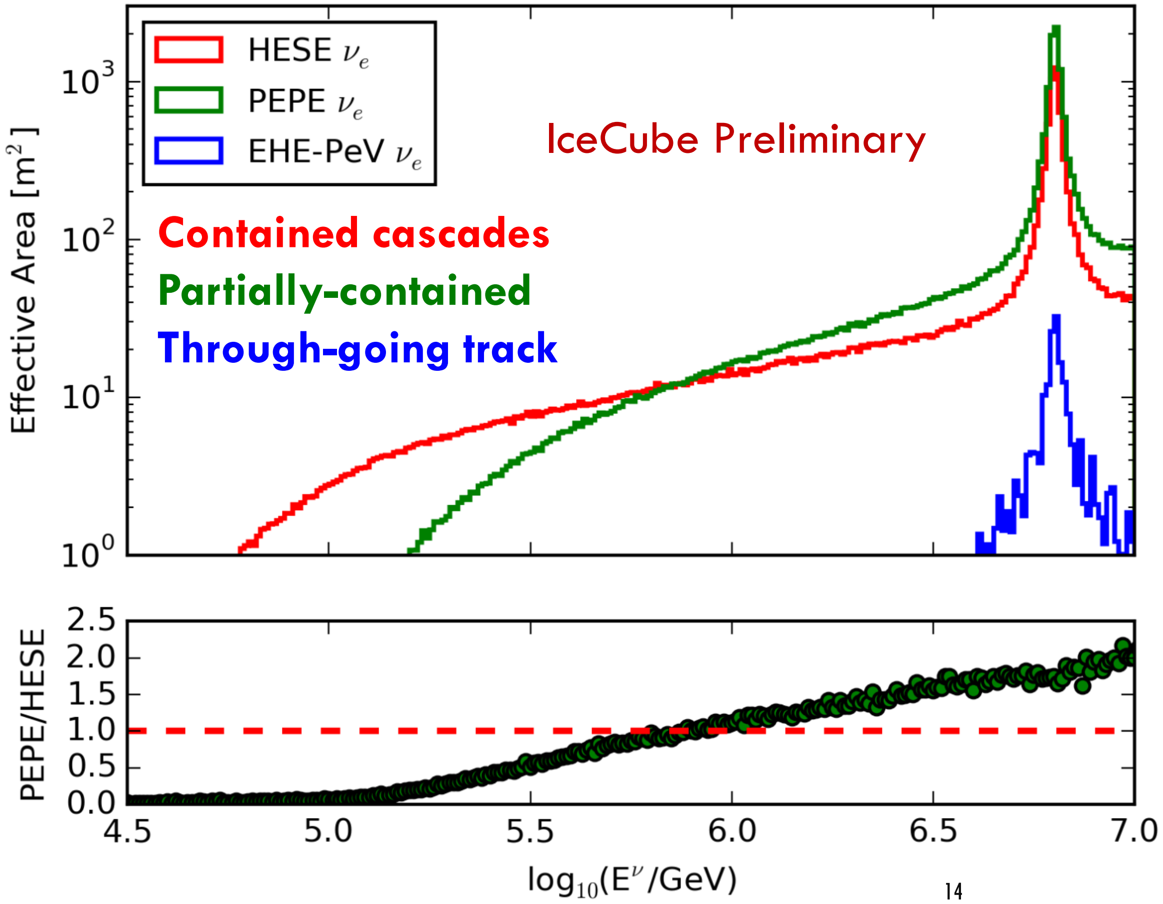
signal



BDT TRAINING: EFFECTIVE AREA AT GLASHOW X2

PeV **E**nergy **P**artially-contained **E**vents: PEPE

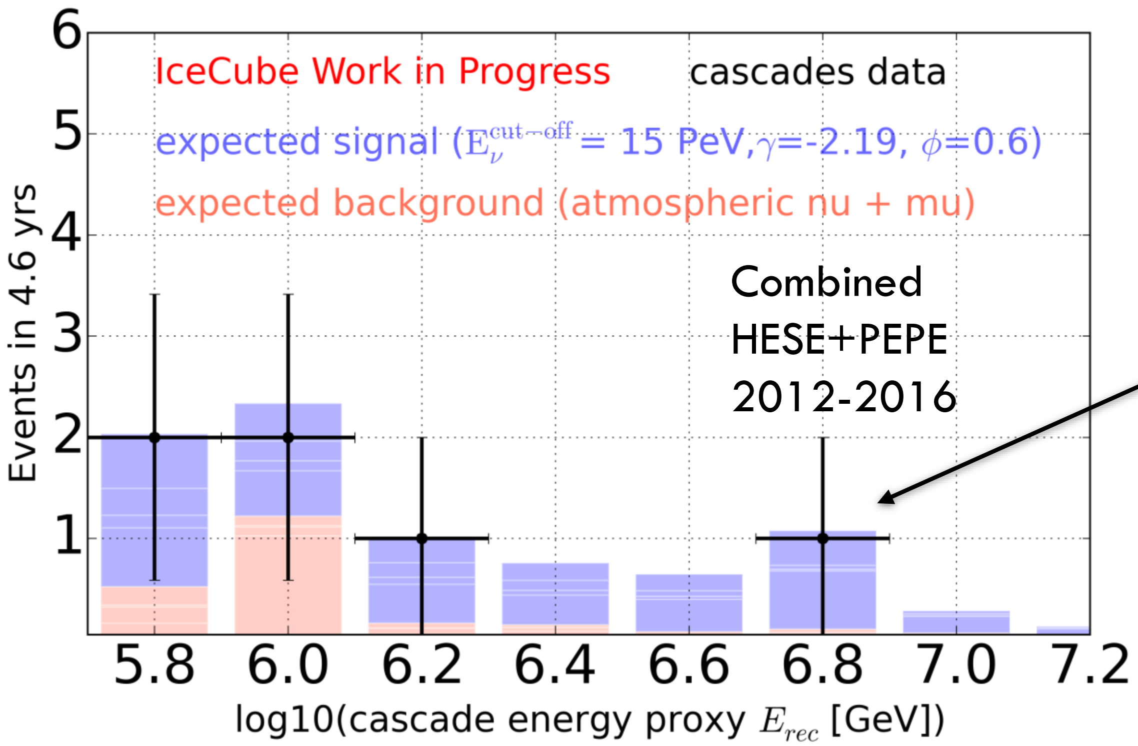




UNBLINDING RESULTS

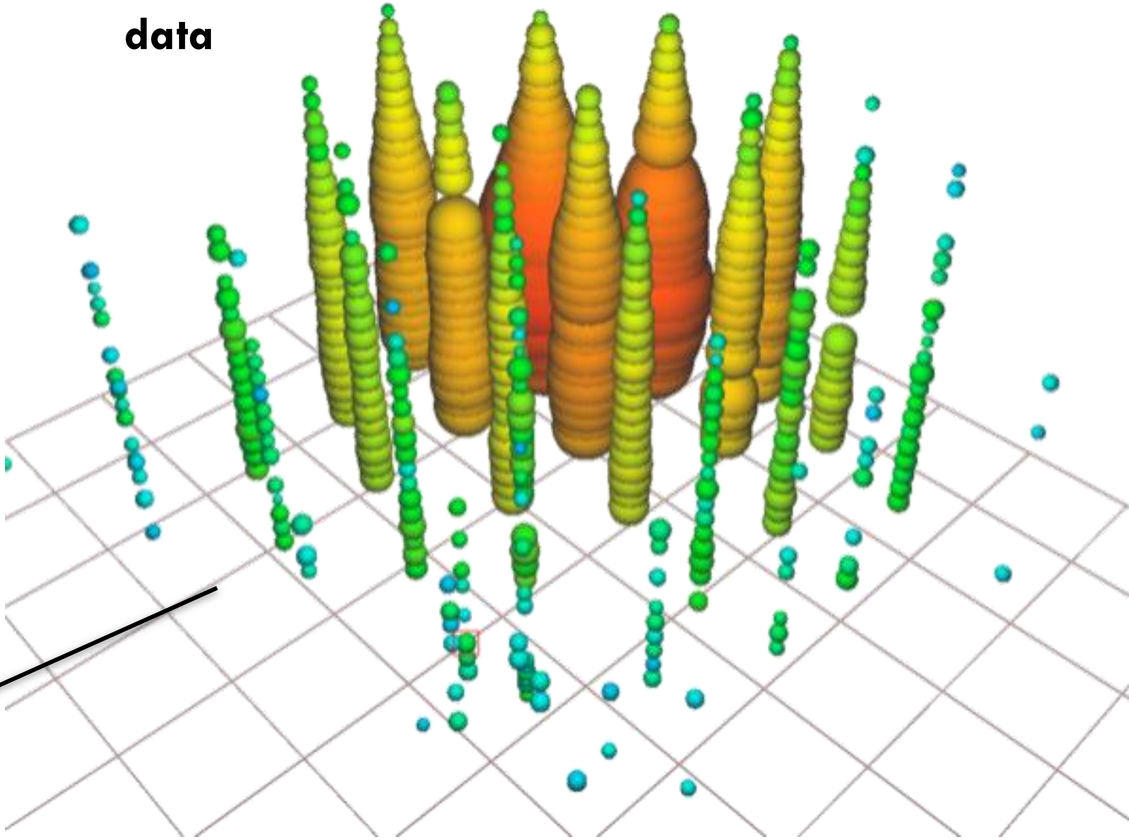
4 events >500 TeV in PEPE. Consistent with expectations assuming IceCube diffuse spectrum

1:1 signal:bkg at 1 PeV but high purity at > 2 PeV



*Ernie and Bert were in 2011 data and not included in the plot

data

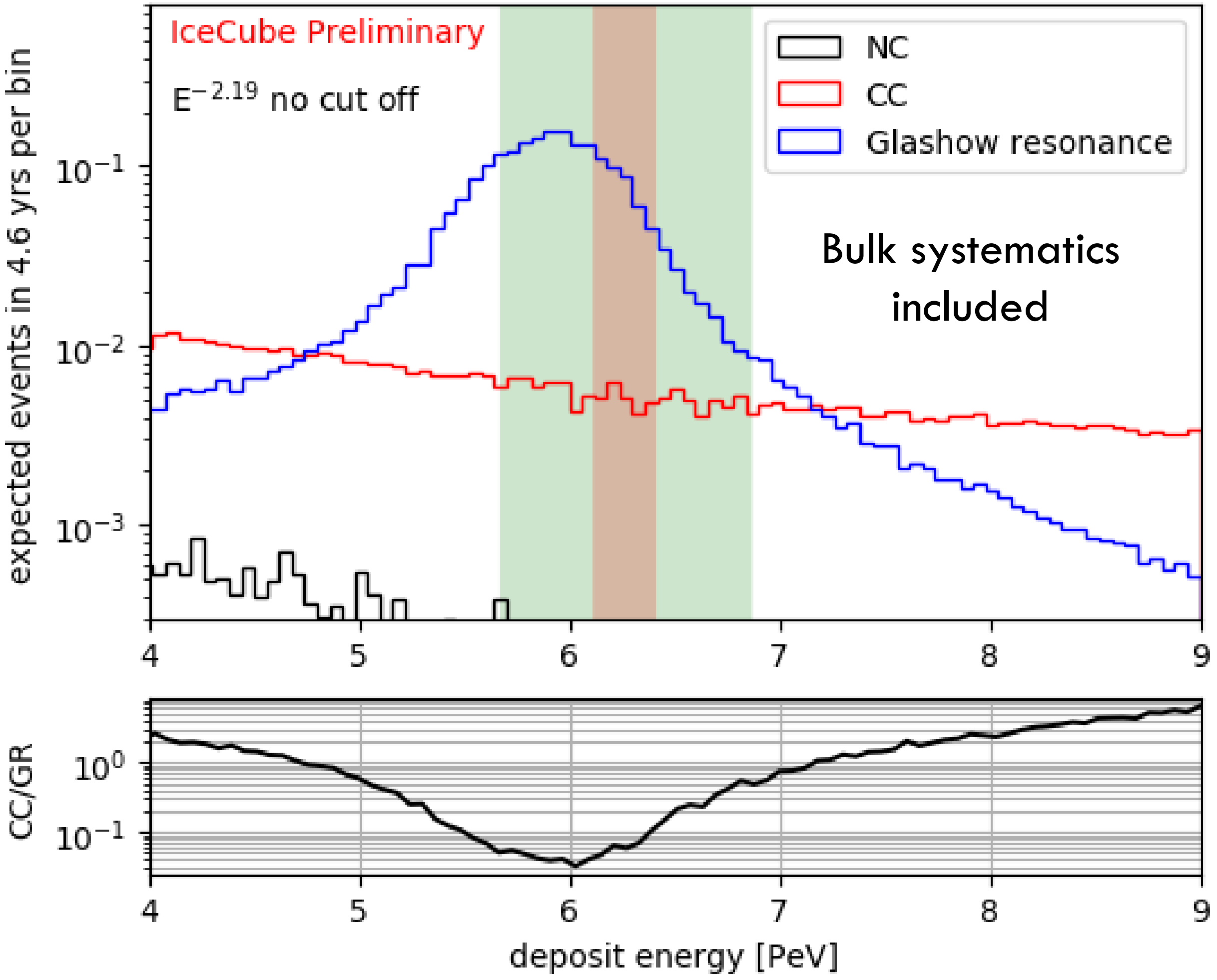


4.6 years (2012-2016) of data. One event is at Glashow bin!

It is brighter than all IceCube PeV events even only partially-contained

THE NEW 6 PEV EVENT

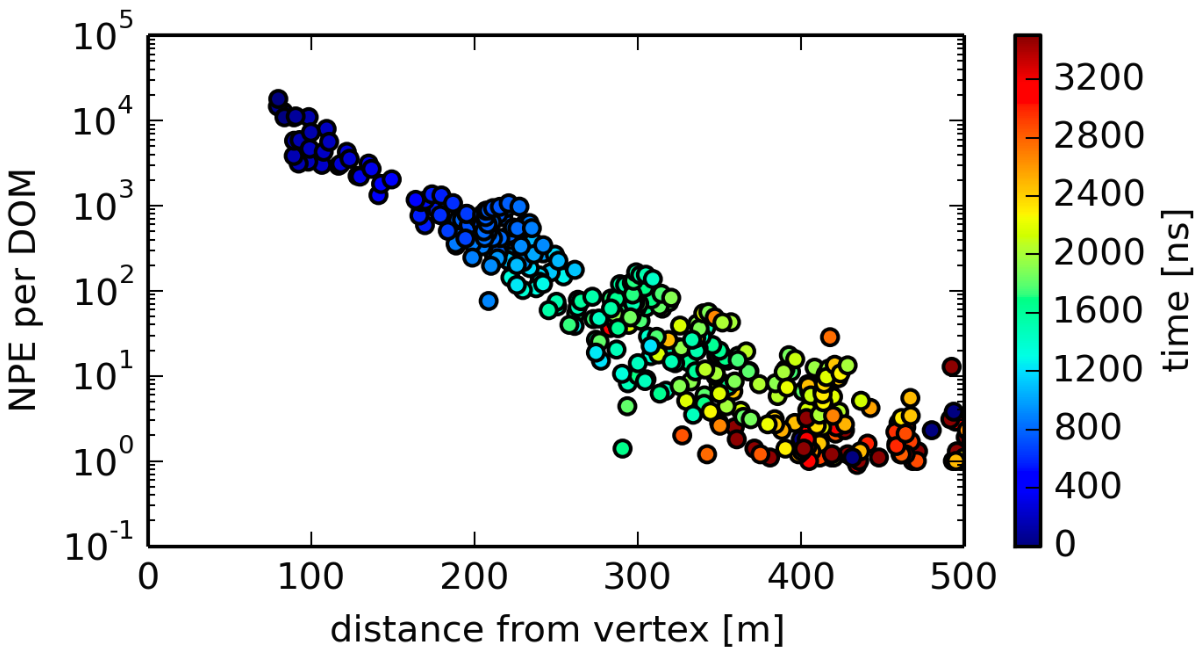
The reconstructed energy is in the region where we expect Glashow resonance over CC/NC



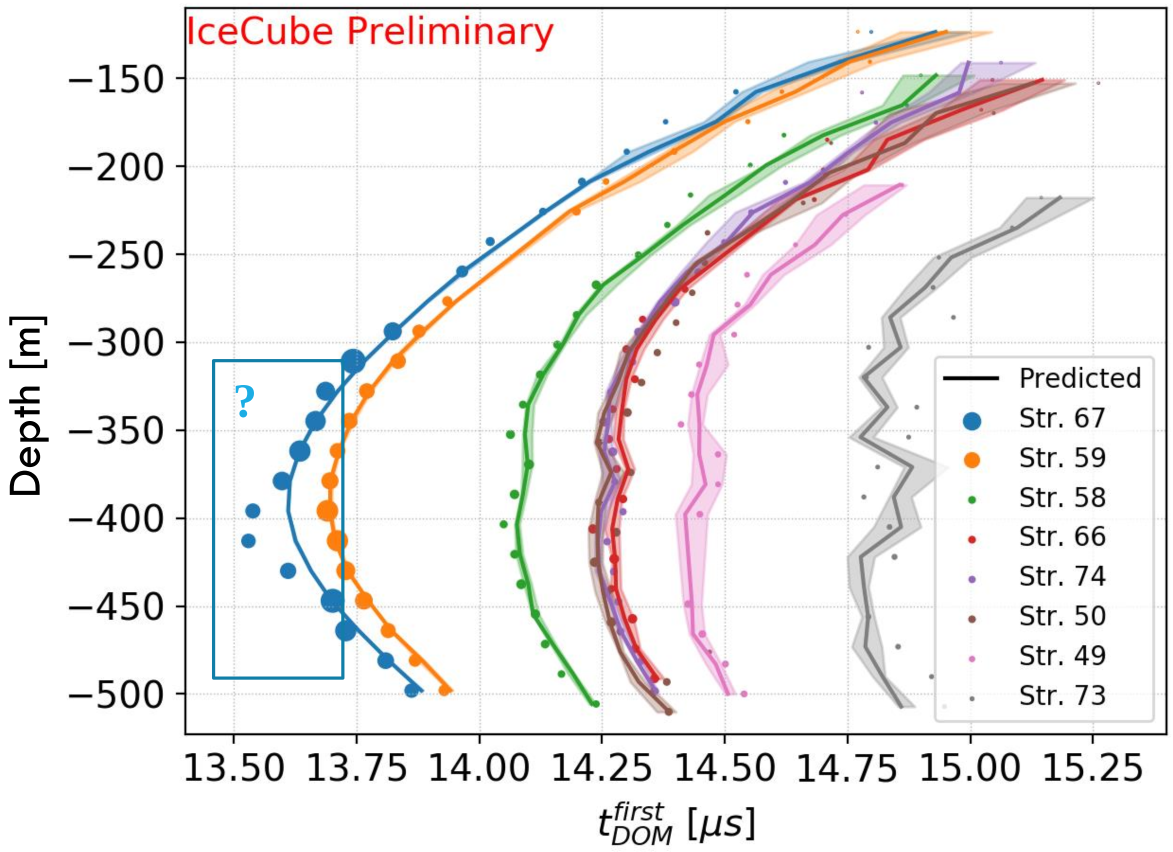
The BDT score of the event is 0.65, which is much higher than the cut threshold 0.5

The topology is consistent with expectation of a ~6 PeV cascade

“lateral distribution function”



AN INTERESTING FEATURE SEEN IN TIME DELAY



Dots are data, lines are simulations of **EM cascades** of ~6 PeV.

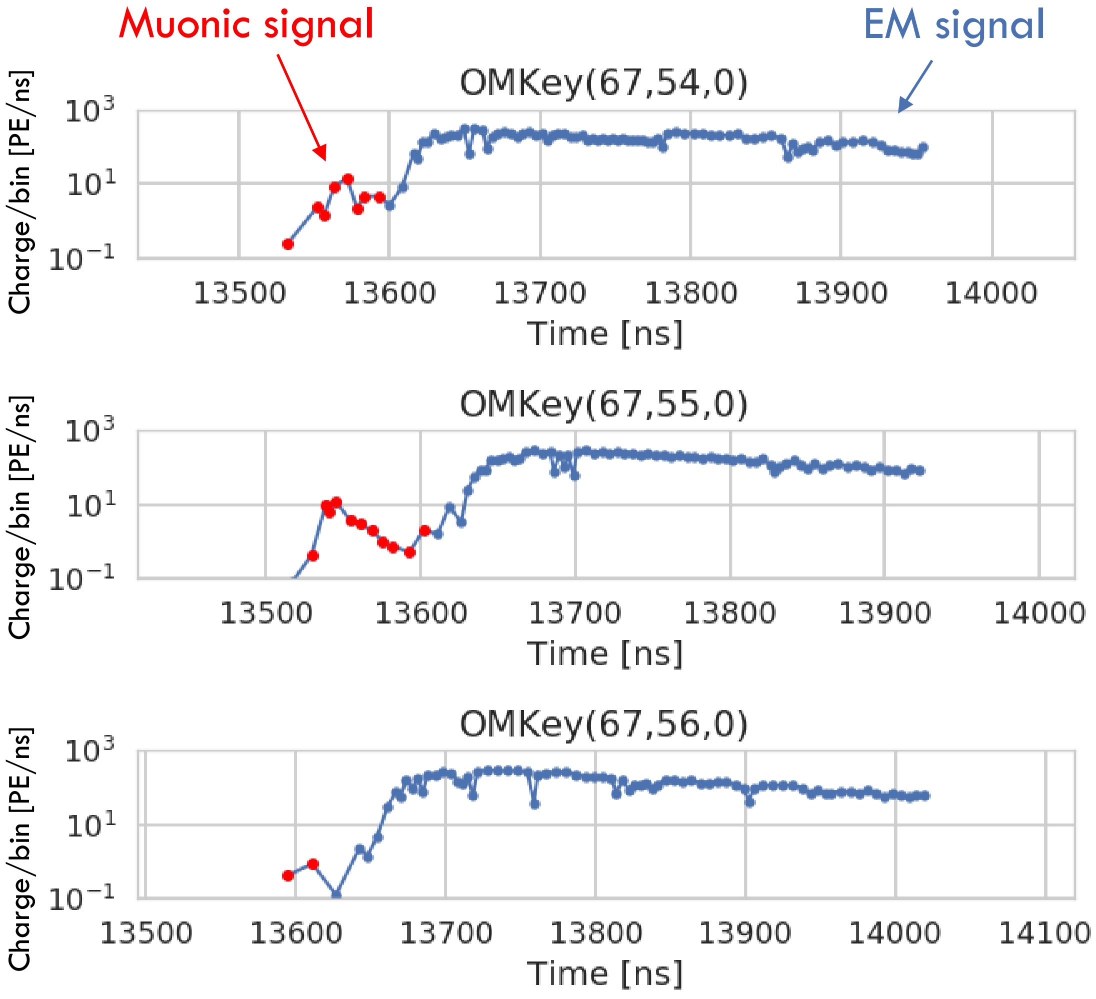
For an ideal cascade the leading edge of bright strings should be determined from the distance from vertex to the DOM position. i.e., what MC shows.

However, in data, we saw a sharp structure on the brightest string 67, which is typically observed when muons passing as a signature of photons from **Cherenkov cone**.

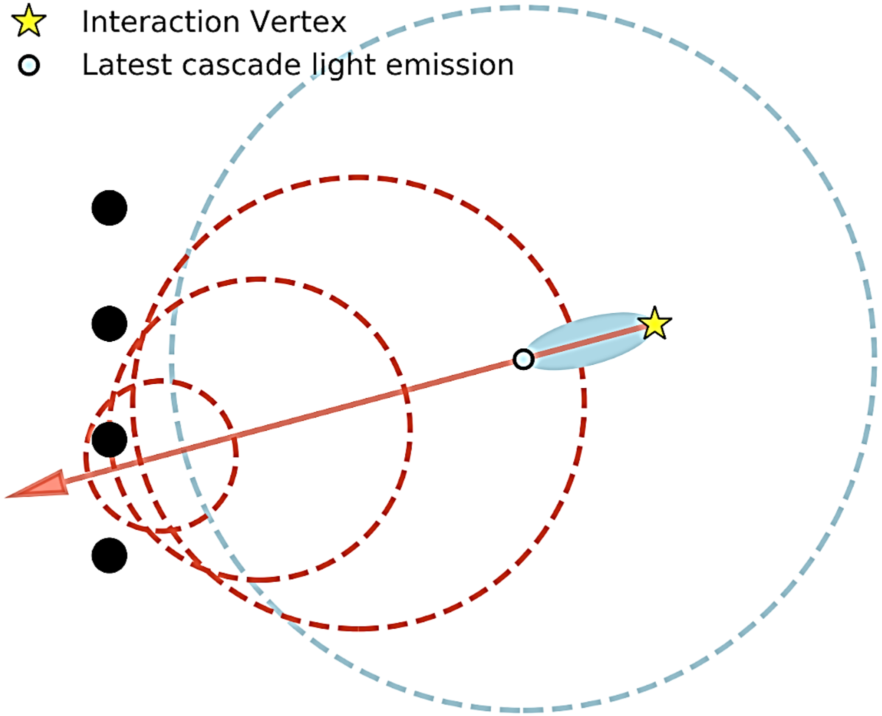
Do we expect to see muons in cascades?

EARLY MUONS FROM HADRONIC CASCADES

Double-pulse structure in waveforms: evidence of pulses from early muons!

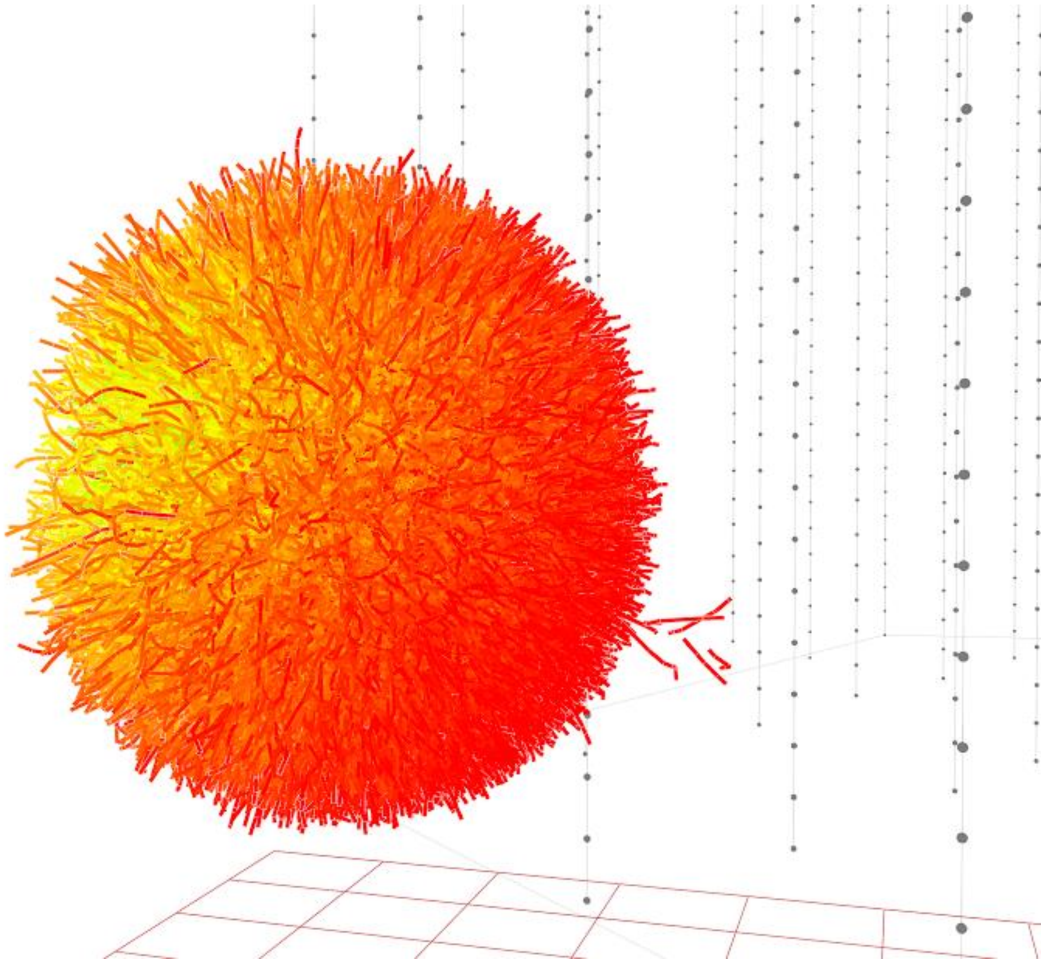


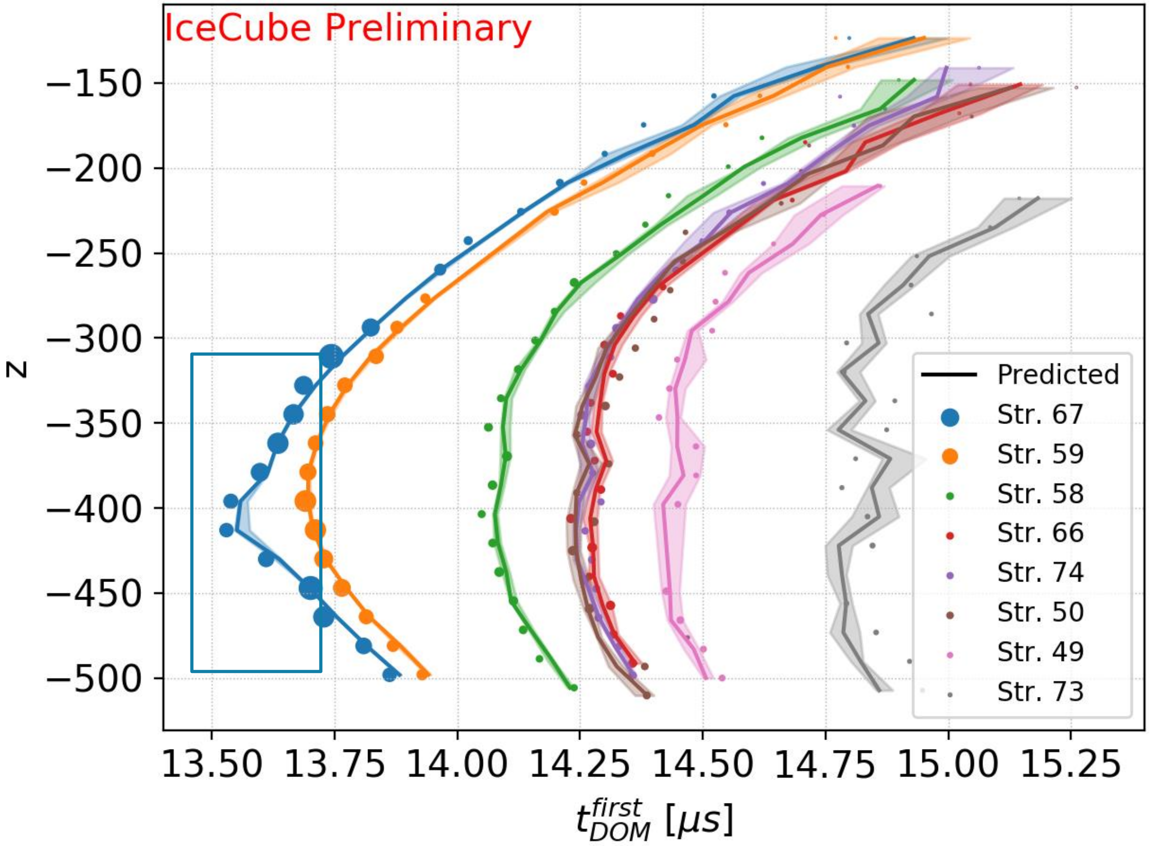
In a hadronic shower,
muons travel in c ahead of photons in c/n



Same physics principles as seen in young airshowers

IT IS AN ICE HADRONIC SHOWER OF ~6 PEV

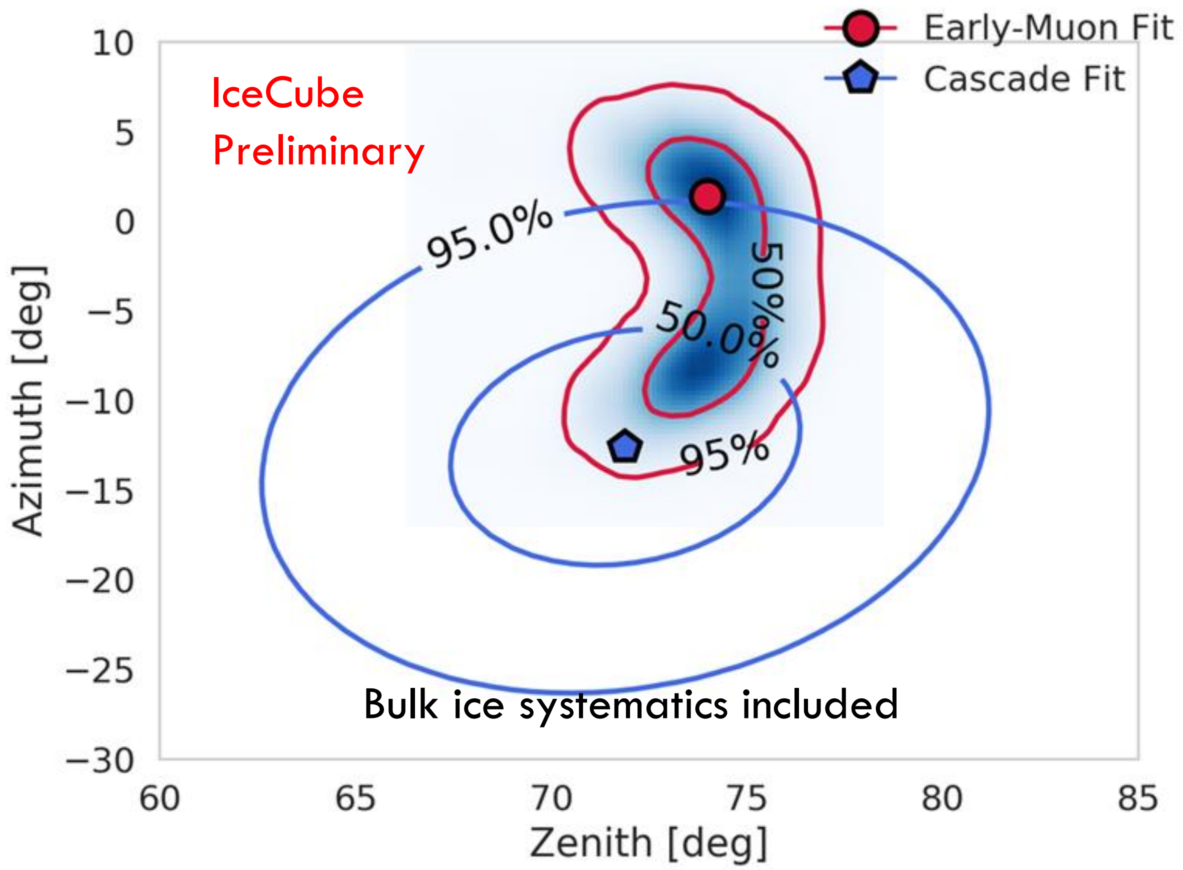




Resimulation shows good data-MC agreement on time-delays if assuming hadronic cascades with leading muon ~40 GeV

MUONS SHARE SAME ORIGINS WITH EM COMPONENT

The direction of the event is independently reconstructed using muonic component and EM component. They agree very well!



What are the **energies** of muons?

Can the muons come from **cosmic-ray** bundles?

Do we expect to see these muons from **Glashow** resonance?

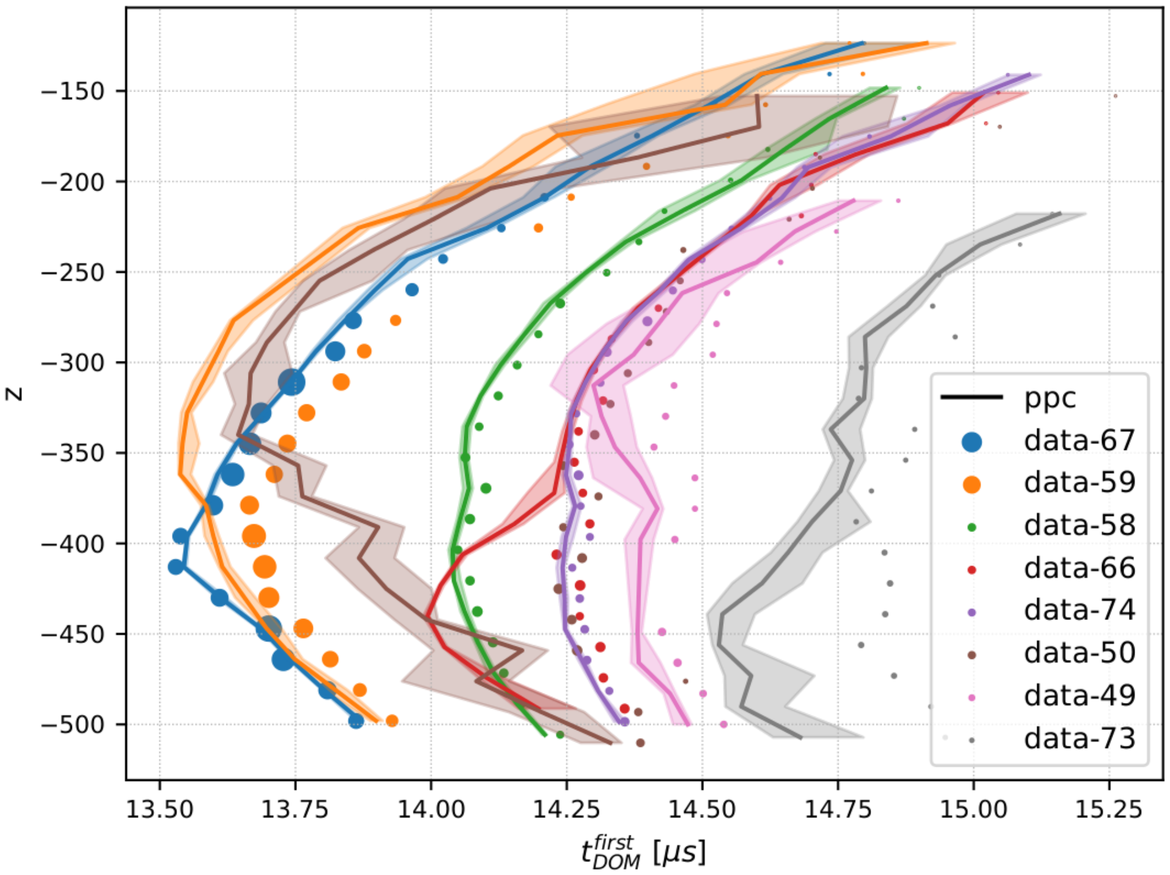
Do we expect to see these muons from **charged current** interactions?

WHAT HAPPENS IF COSMIC-RAY MUON BACKGROUND

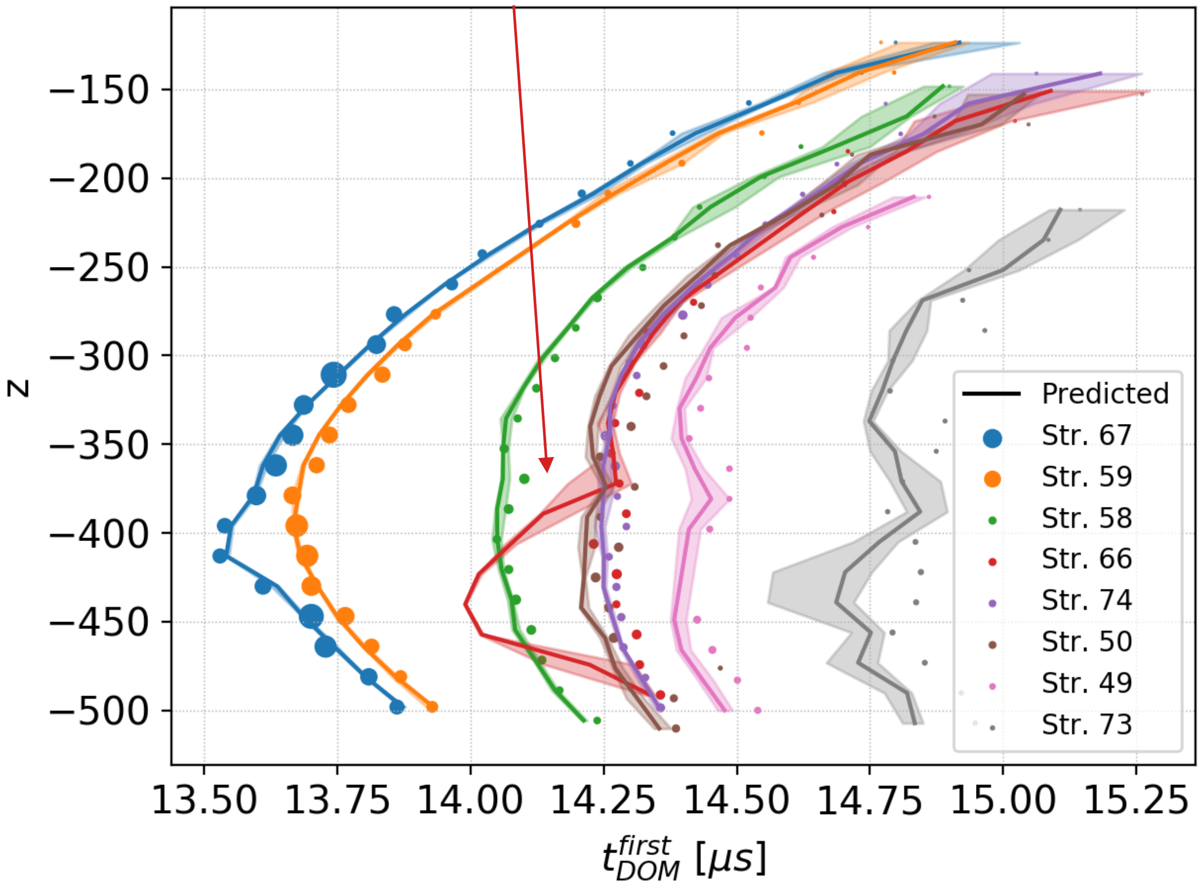
The **key** is **the maximum muon energy accompanying the EM cascade**

100 TeV muon is highly stochastic. We would have seen early muon signals on multiple strings across a large area of detector such as **59**, **66** and **50**

60 GeV muon can still describe data for the first-hit strings. However, since it is unlikely to stop after 100 m it would cause more strings seen early muons such as on string **66**



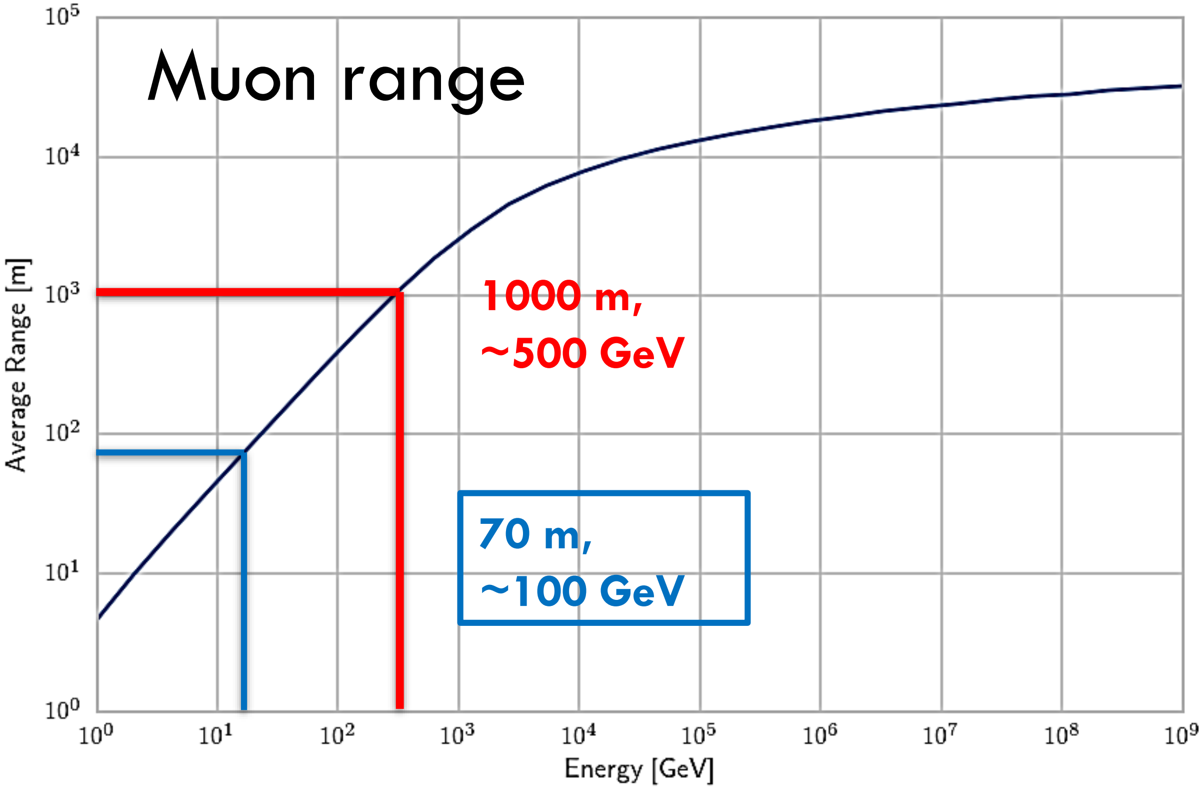
6 PeV EM cascade + 100 TeV muon



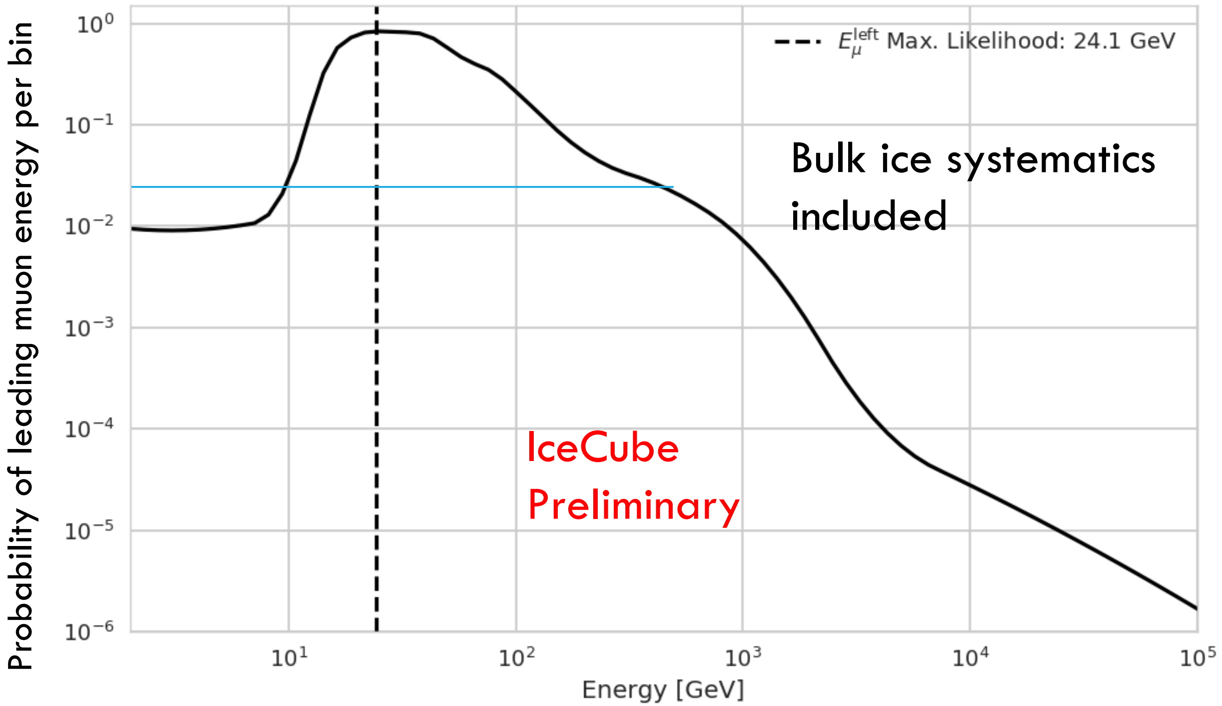
6 PeV EM cascade + 60 GeV muons

LEADING MUON ENERGY

Reconstruct leading muon energy in the cascade



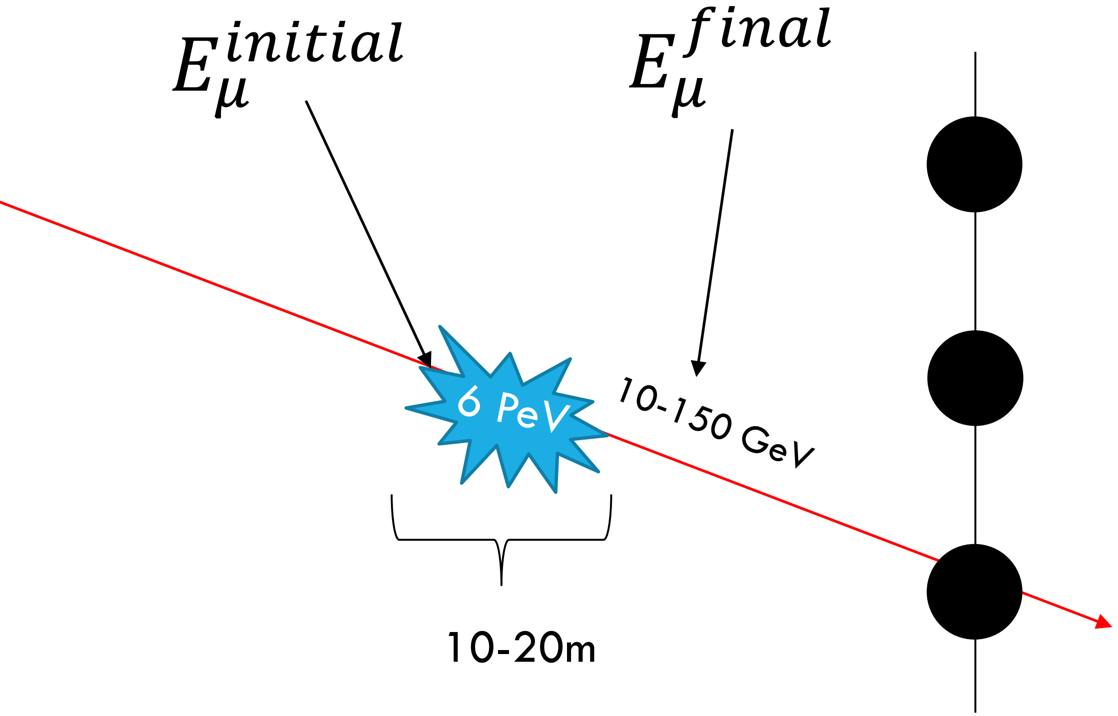
~10-150 GeV

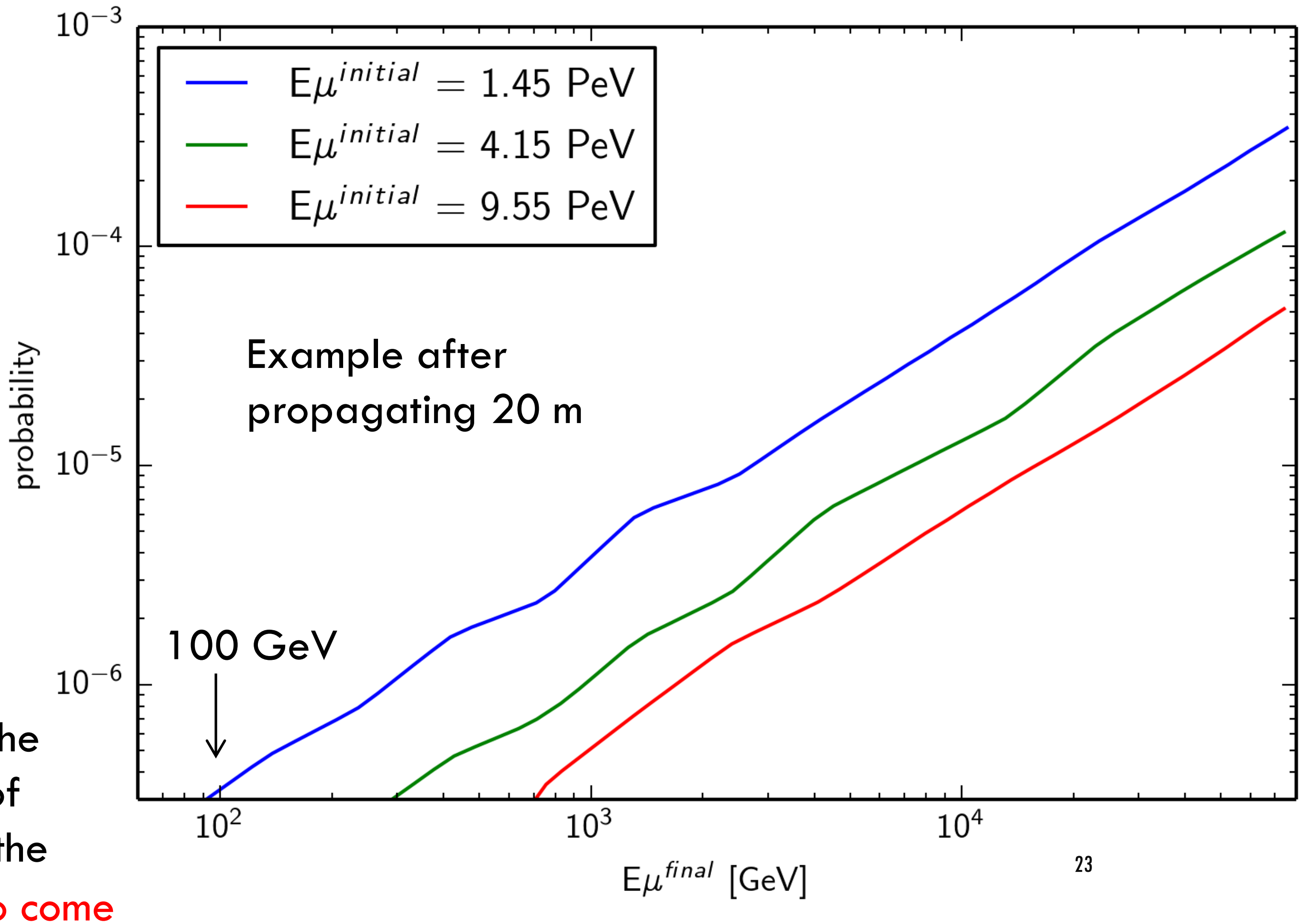


10 GeV	100 GeV	1 TeV	10 TeV	100TeV
~3%	~20%	~9e-3	~5e-5	~2e-6

PROBABILITY OF BEING A COSMIC-RAY?

How likely is it for a muon to deposit ~6 PeV and then be left with ~10 – 150 GeV?



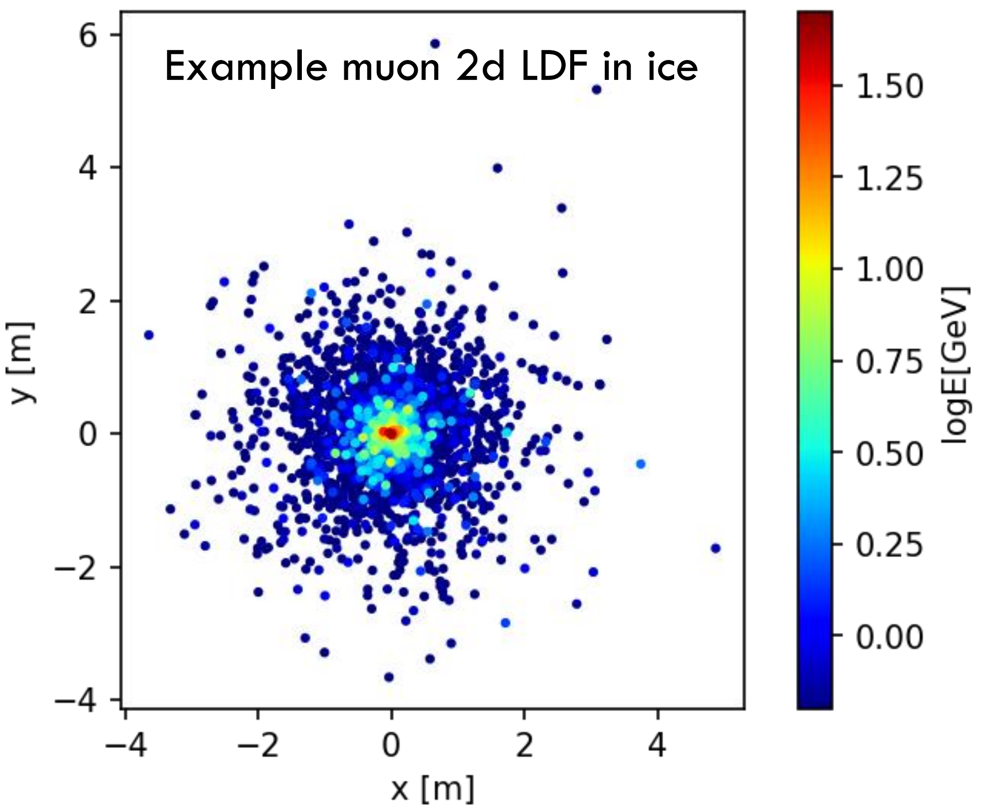


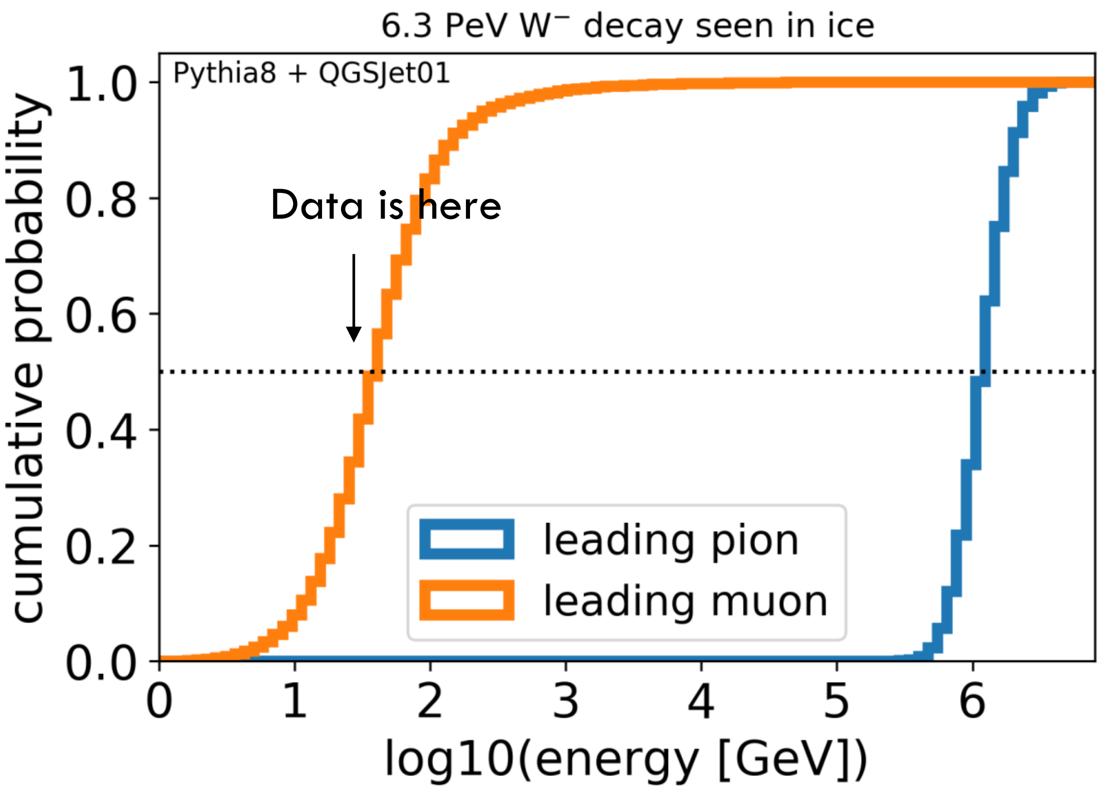
From preliminary simulations of CR muon events with catastrophic energy losses, taking into account the limit on the outgoing muon energy, we find that the expected number of such events is ~1e-7, which corresponds to an exclusion of the CR muon hypothesis at ~5 sigma. Full statistical analysis to come

DO WE EXPECT TO SEE EARLY MUONS IN GLASHOW RESONANCE? - YES!

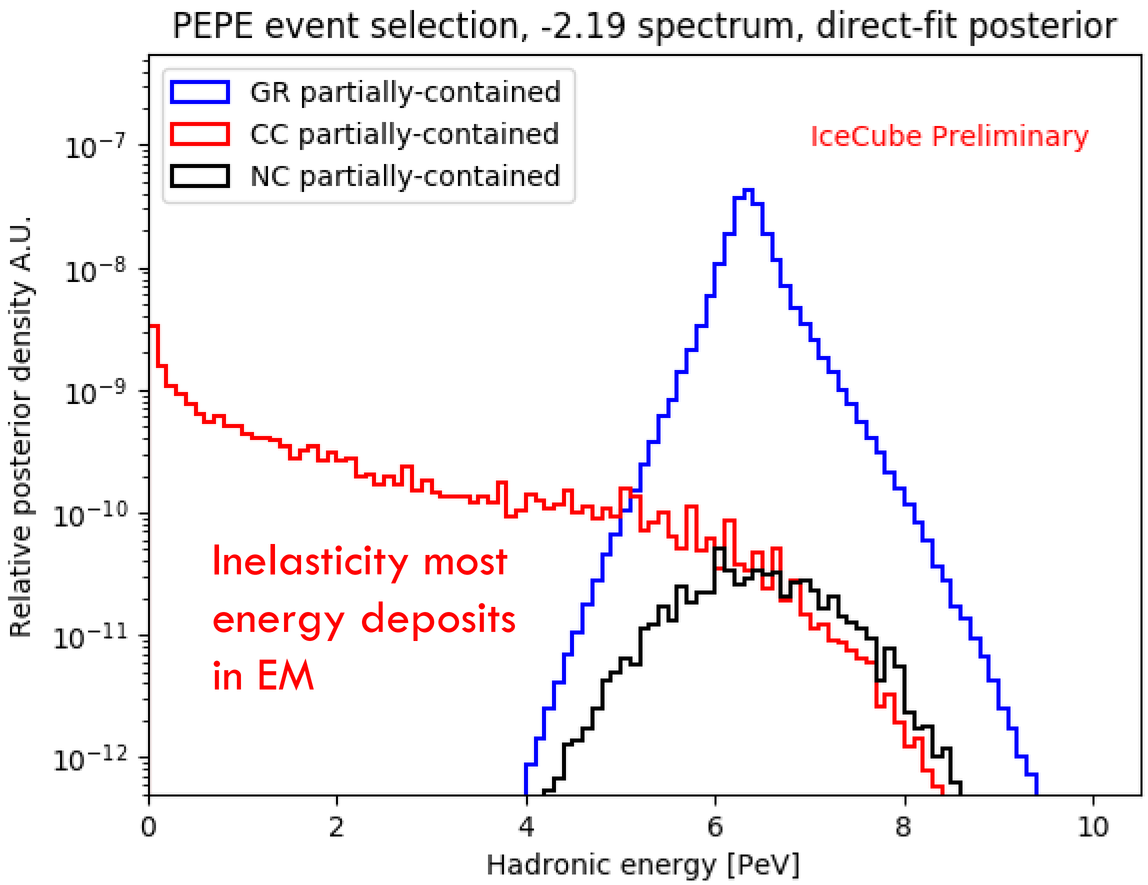
Ice shower!

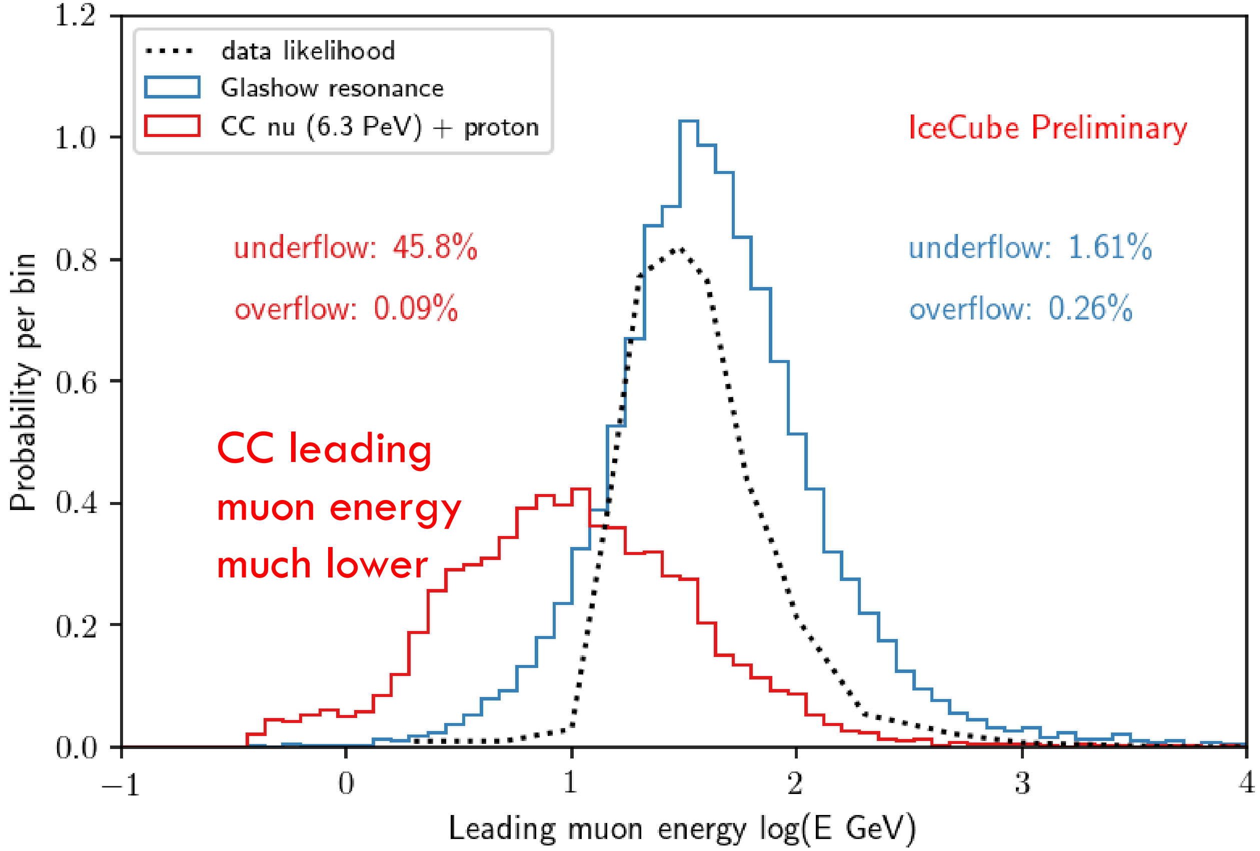
Pythia simulation for W- decay, final state particles (including charm and rare mesons) propagate to corsika-in-ice





WHAT ABOUT EARLY MUONS IN NUE CHARGED CURRENT?



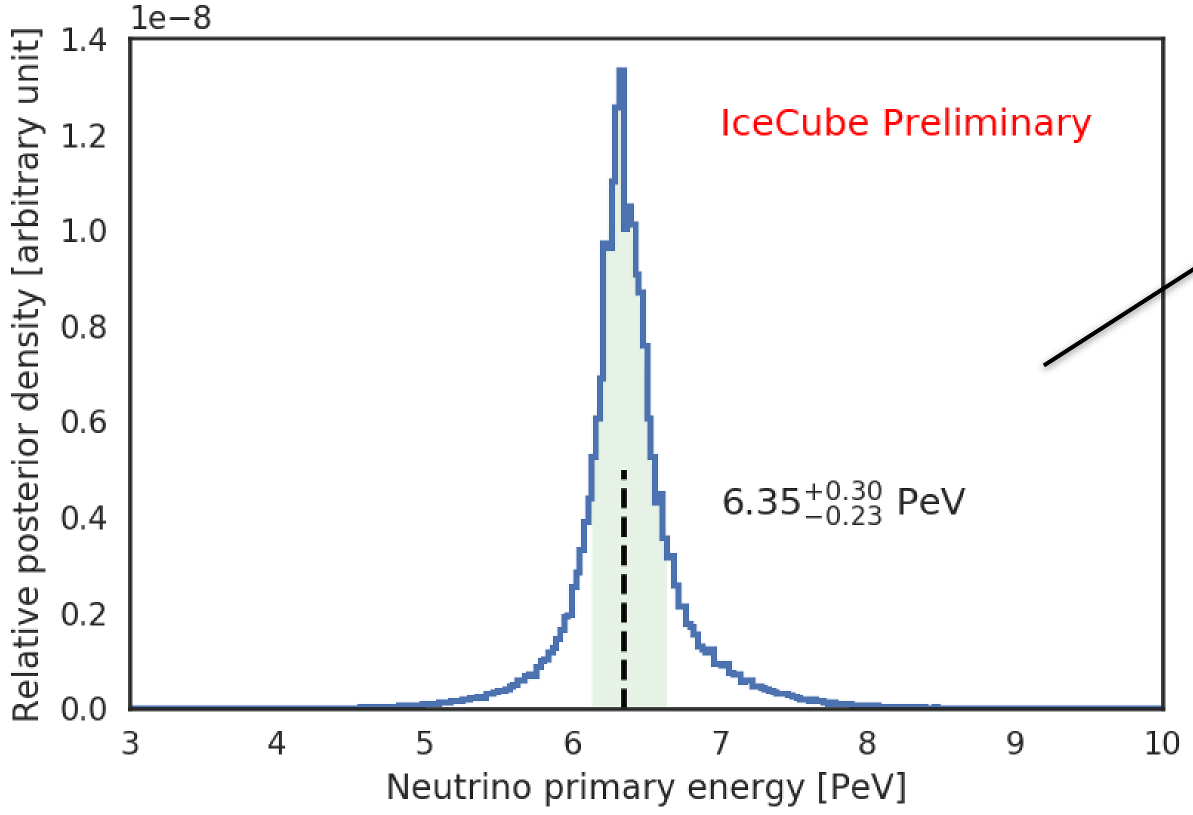


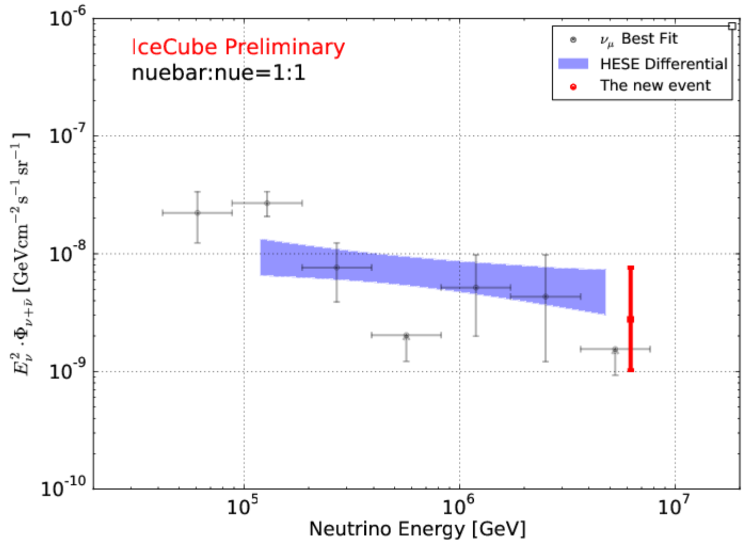
p(recE|CC) x p(mu_max|recE CC) / p(recE|GR) x p(mu_max|recE GR) ~ 3% [not a p-value]

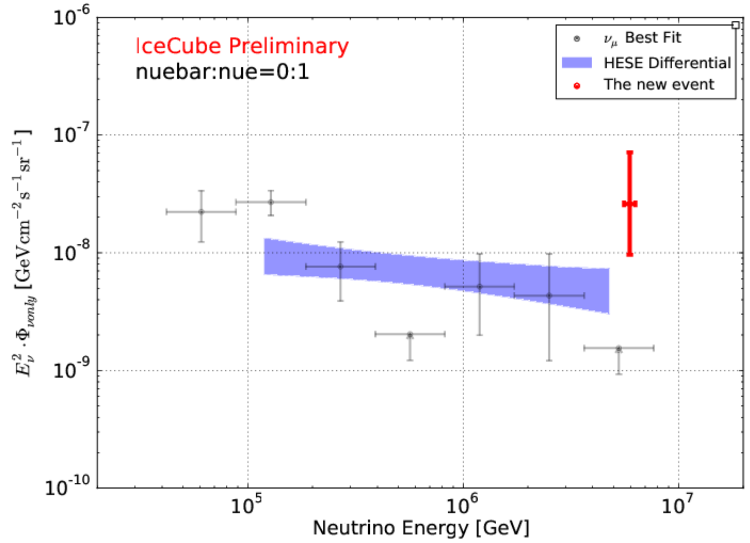
THE MOST PROBABLE NEUTRINO ENERGY

How consistent is the newly observed event with IceCube diffuse flux? – it depends on the nu/nubar ratio!

Assume best fit diffuse-numu, 1:1 = nuebar:nue





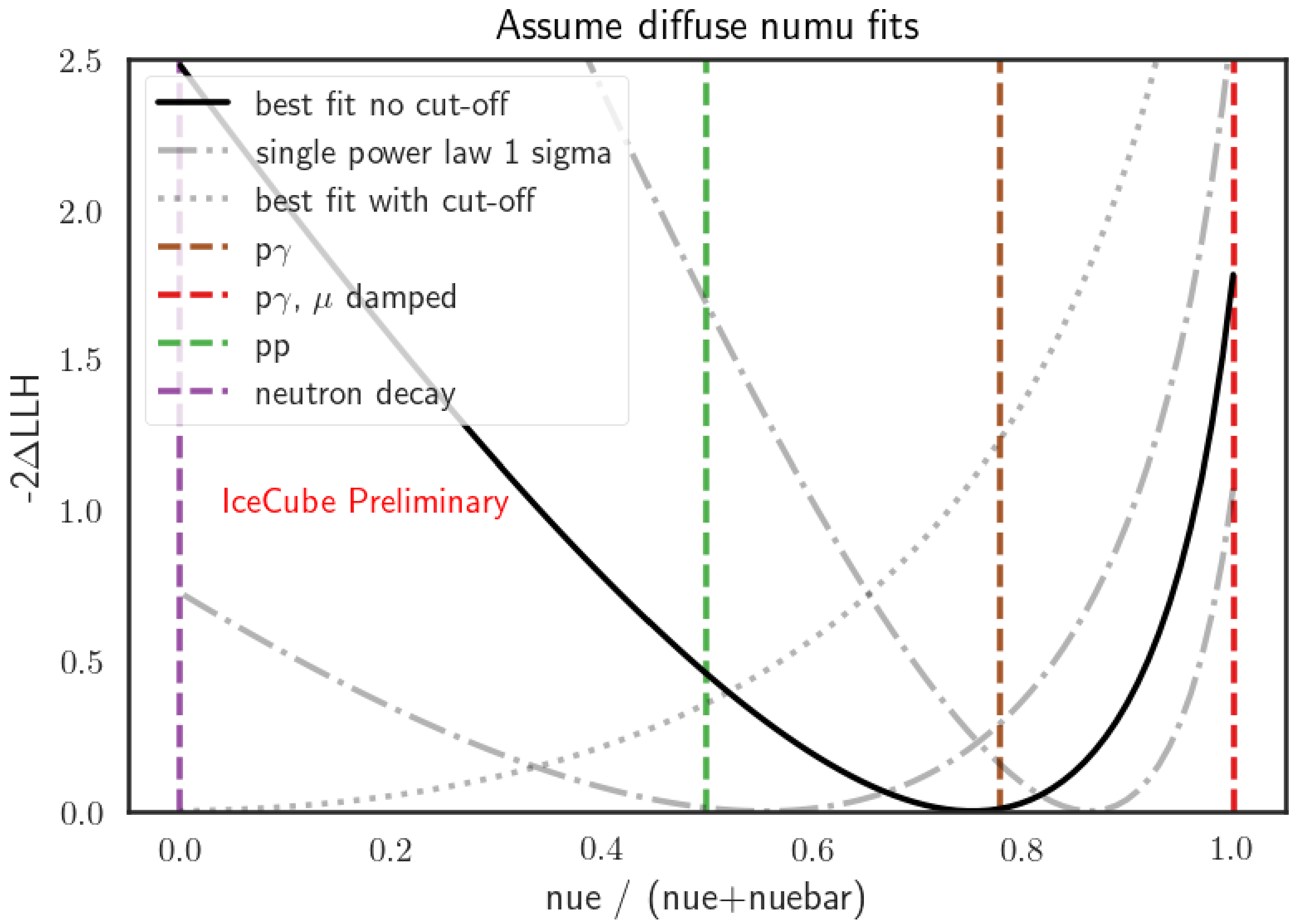


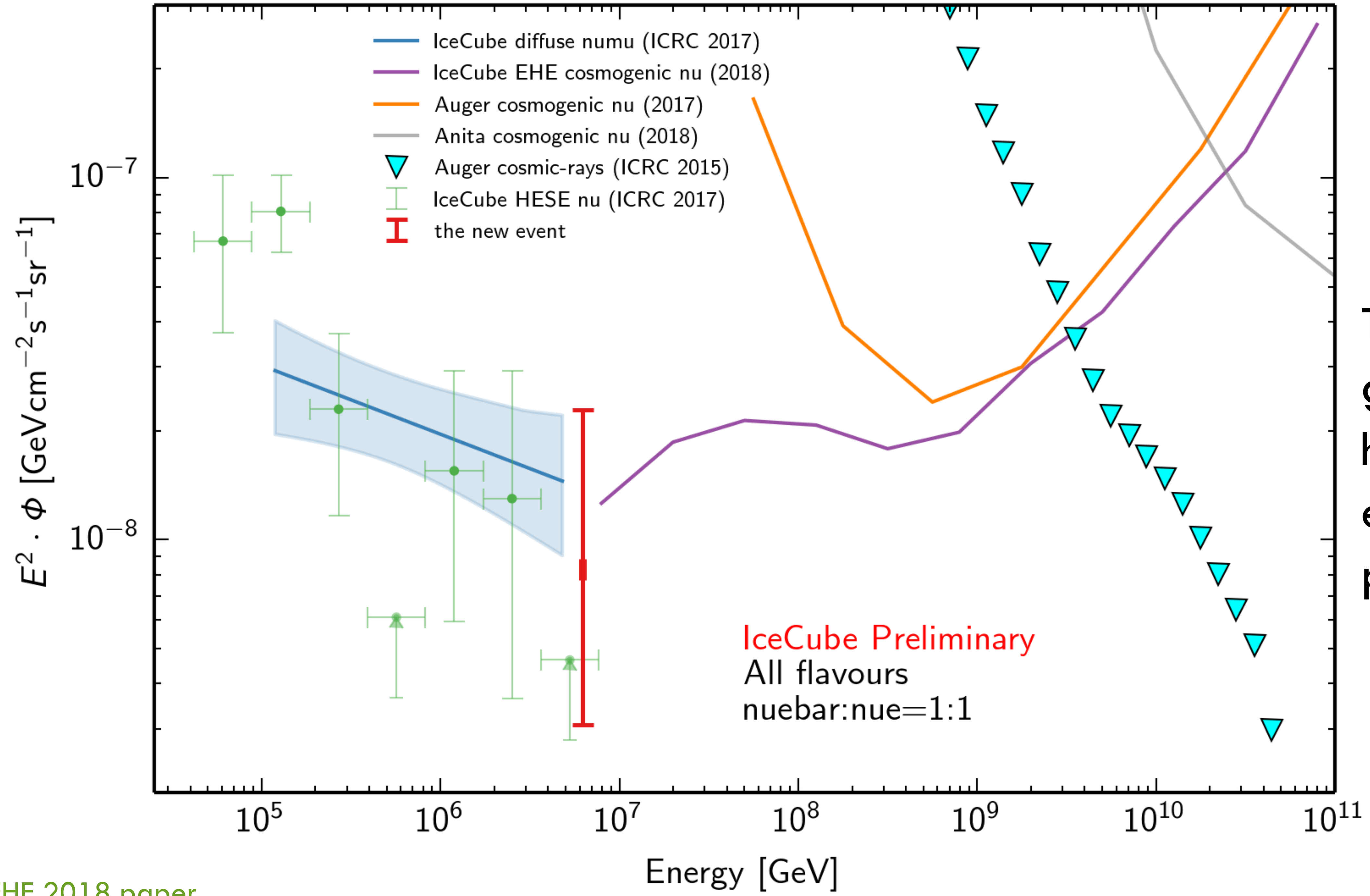
LIKELIHOOD SCAN ON NUE/NUEBAR RATIO

Poisson(k=1|model)

- Assume diffuse numu 2.19 spectrum (ICRC 2017)
- Even with a fixed 2.19 spectrum one cannot distinguish pp/pϒ

However, this is the first time we could calculate nu/nubar thanks to the Glashow candidate => inspiration for Gen2!





The global high-energy picture

[Link to EHE 2018 paper]

THE FUTURE: GEN2

In-ice upgrade:

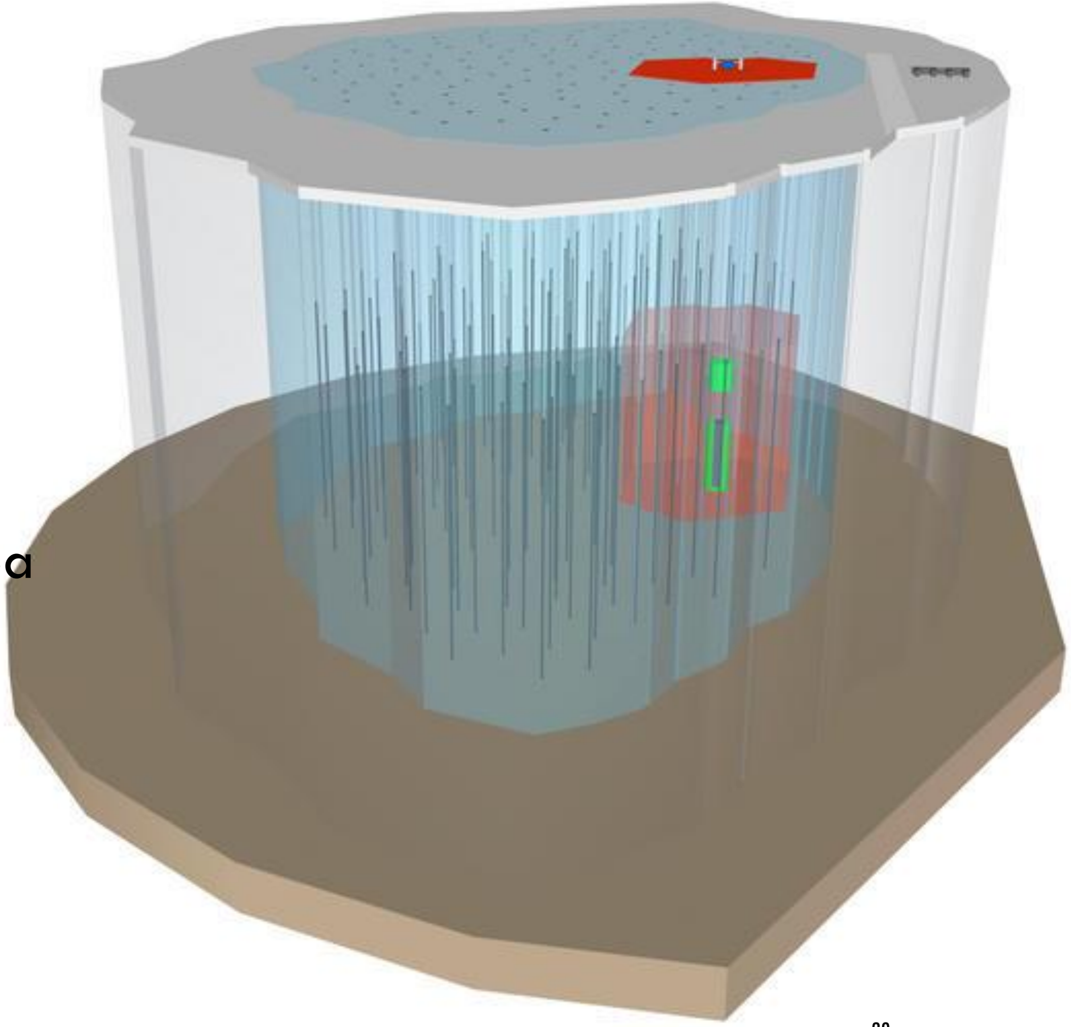
- ~ 10,000 more optical sensors
- 5 – 10 km^3 instrumented volume
- ~ 120 strings

Wish-list:

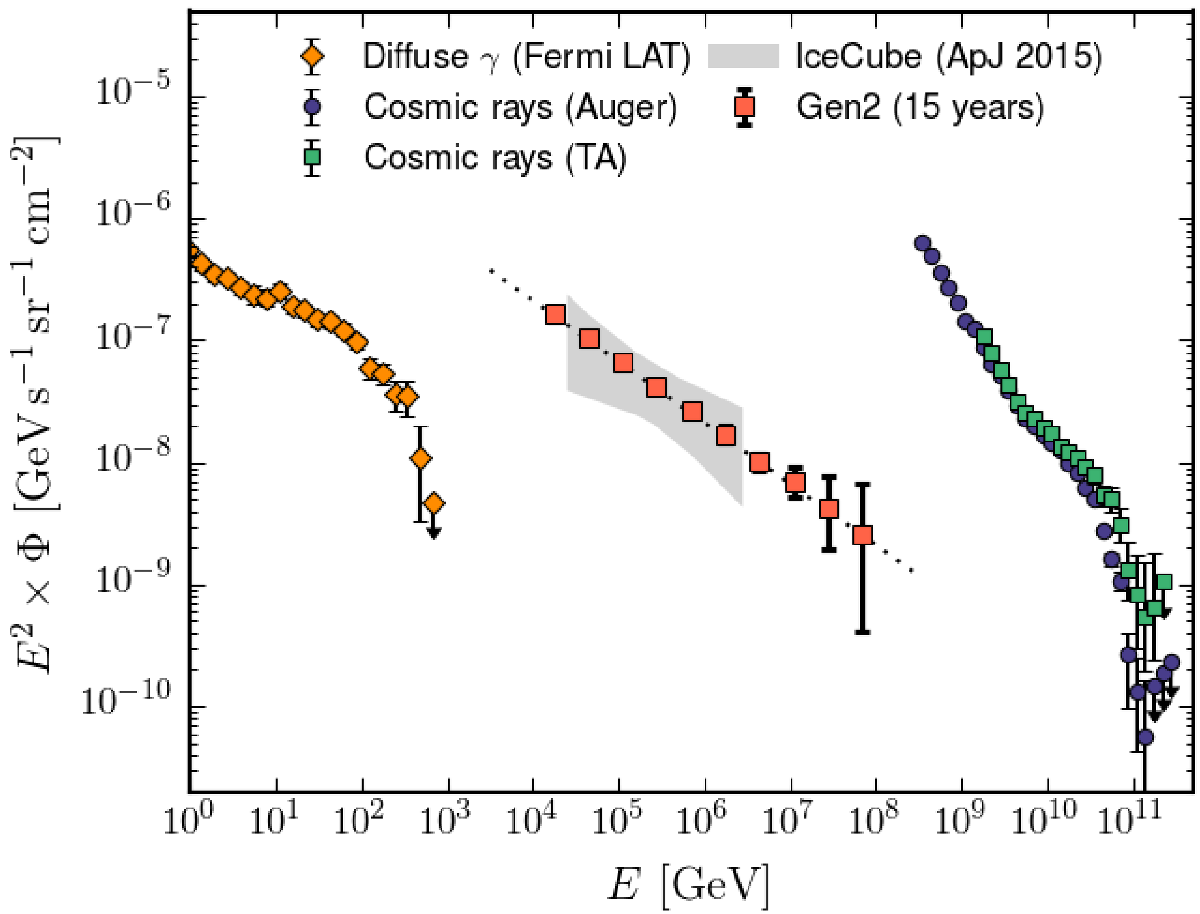
- **sensors** with directionality and more effective area
- smaller holes to reduce drilling cost
- a **surface array** for veto cosmic-ray background

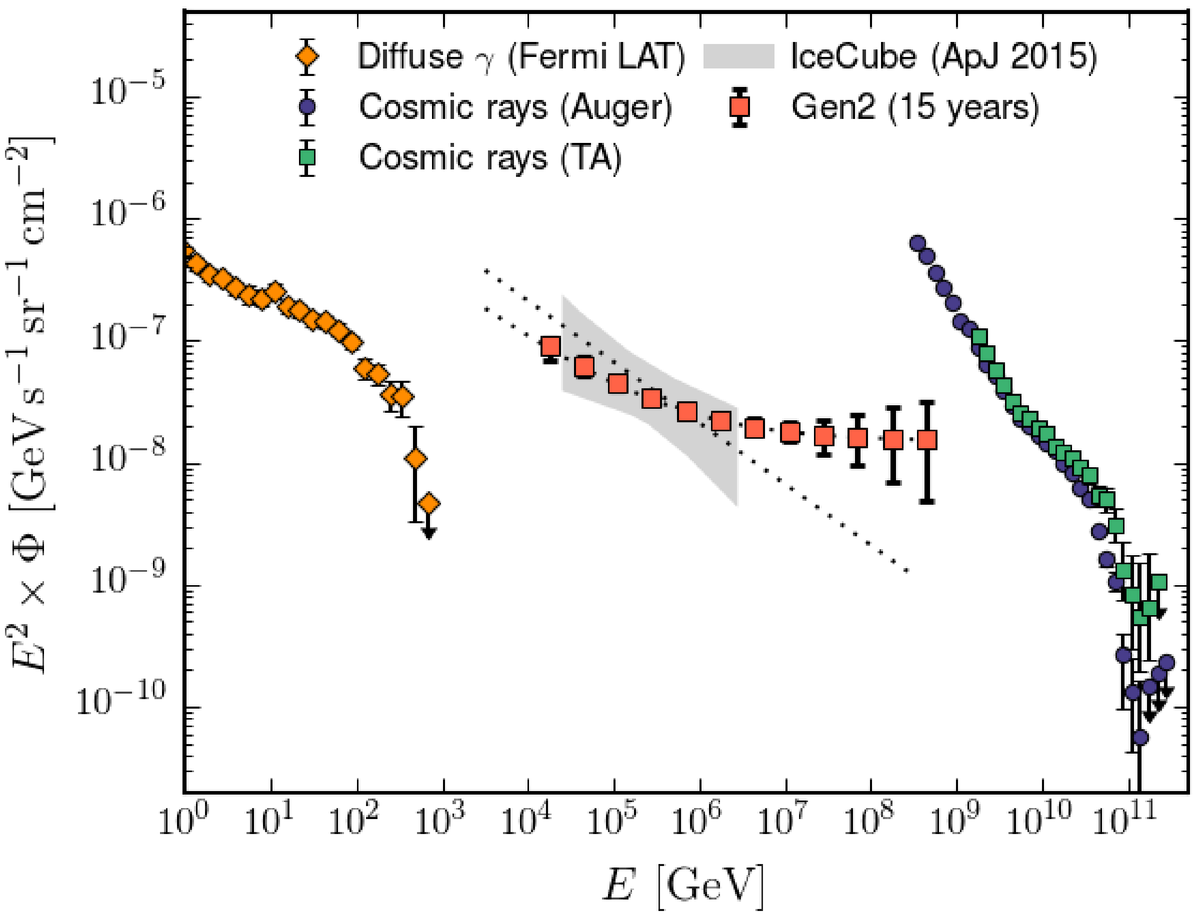
Challenges:

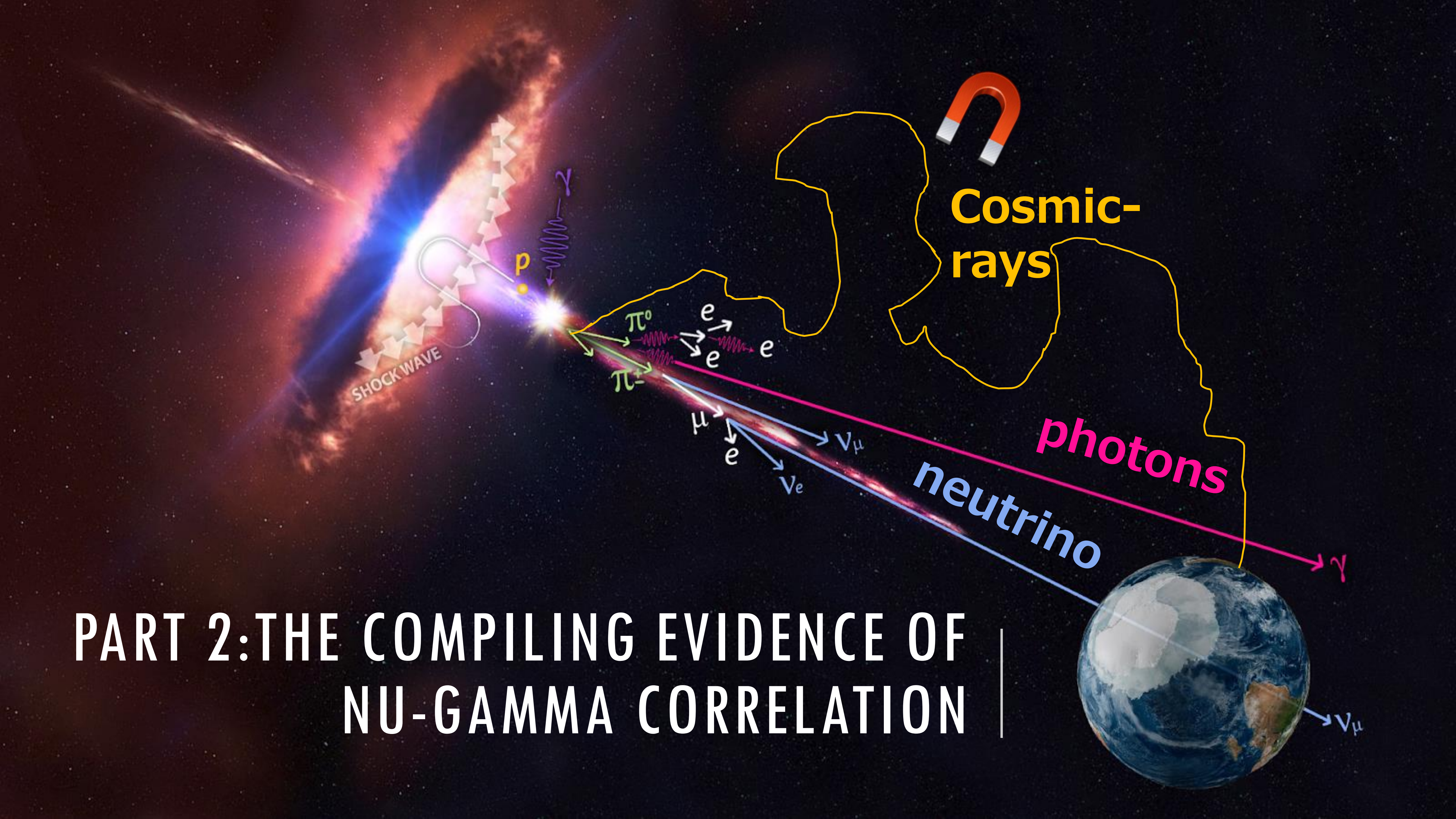
- -45°C, 10,000 psi, logistics



GEN2 WILL ALLOW PRECISE SPECTRUM MEASUREMENT FOR 1-100 PEV







PART 2: THE COMPILING EVIDENCE OF NU-GAMMA CORRELATION

Neutrinos as smoking-gun for hadronic sources

$p\,\gamma \longrightarrow (p,n)\,\pi$

$\pi \rightarrow 2\gamma$ → **γ-ray observations**

$\pi \rightarrow \mu\,\nu$

$\mu \rightarrow e\,\nu\,\nu$ (e → **γ-ray observations**)

(p,n) → **Cosmic Ray observations**

But $eZ \rightarrow e\gamma Z$ (Bremsstrahlung)
$e\gamma \rightarrow e\gamma$ (inverse Compton)

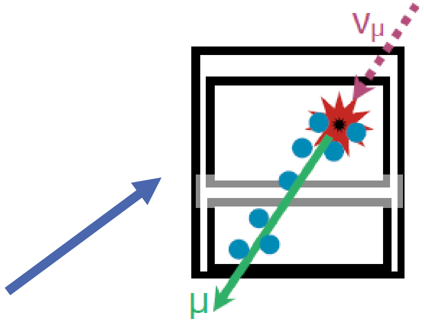
could produce γ-ray

Neutrino observations

||

The smoking gun

IceCube real-time stream



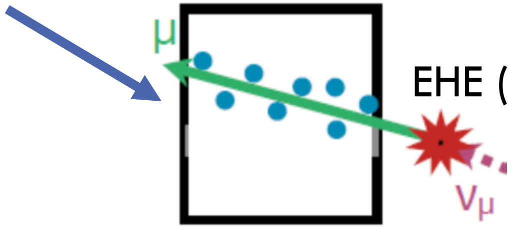
veto-based
HESE

all neutrino flavor sensitive

High cosmic n purity samples.
Launched in 2016!

high chance of real cosmic neutrino signals

starting events



EHE (Extremely High Energies)

IC170922 was in this channel

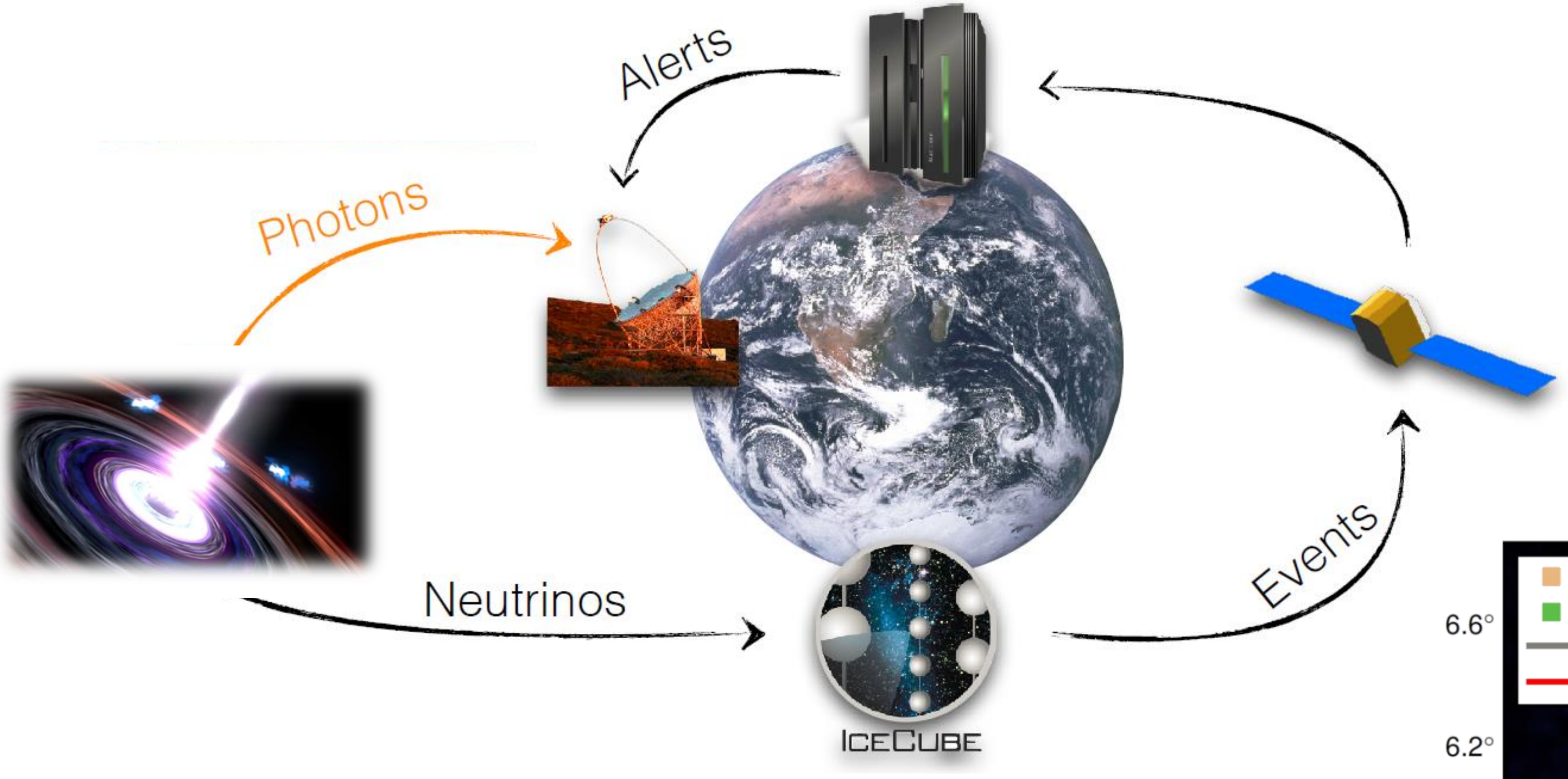
all neutrino flavor sensitive

high chance of real cosmic neutrino signals

good angular resolutions

signal flux highly uncertain

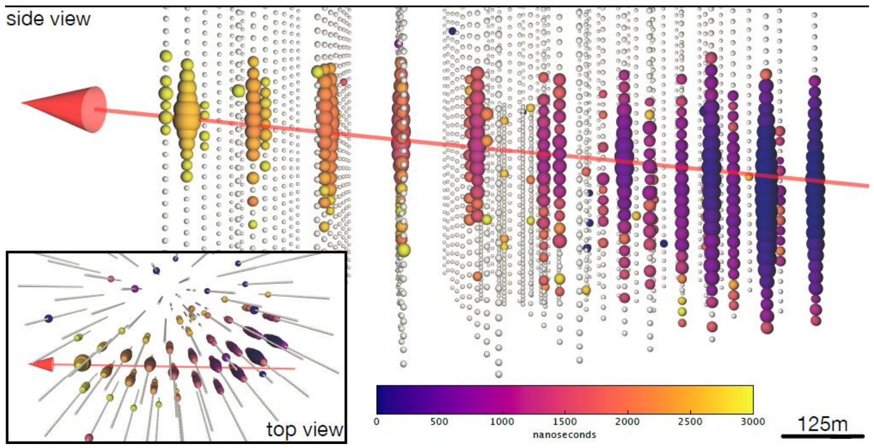
IC170922
2017/09/22
EHE alert stream

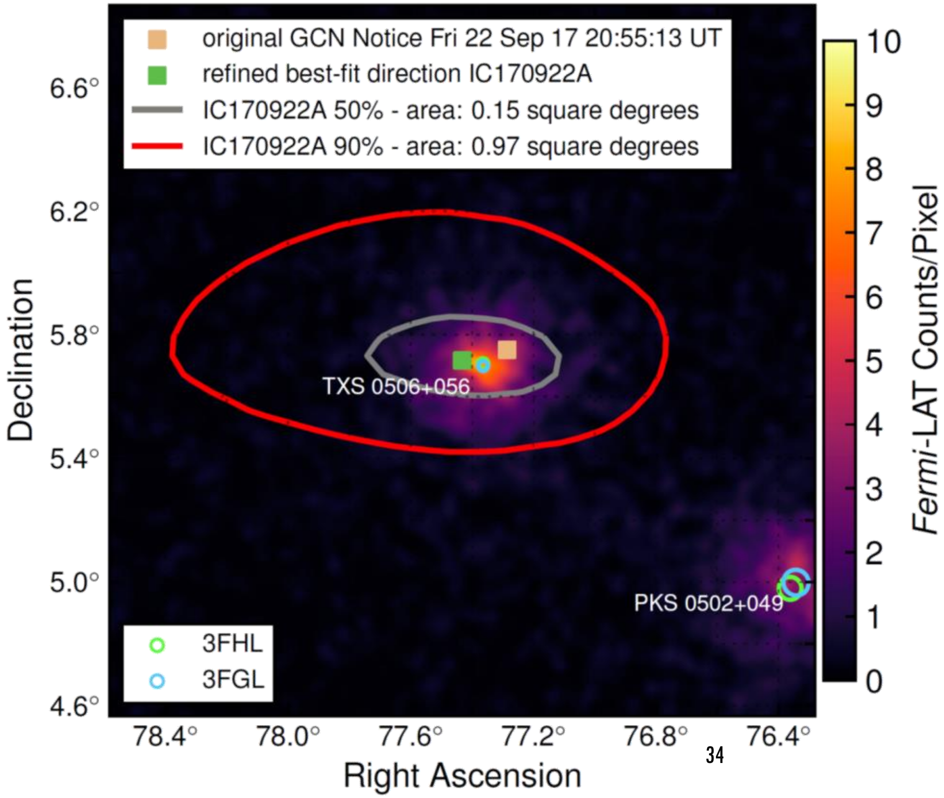


Alert sent in 43 seconds

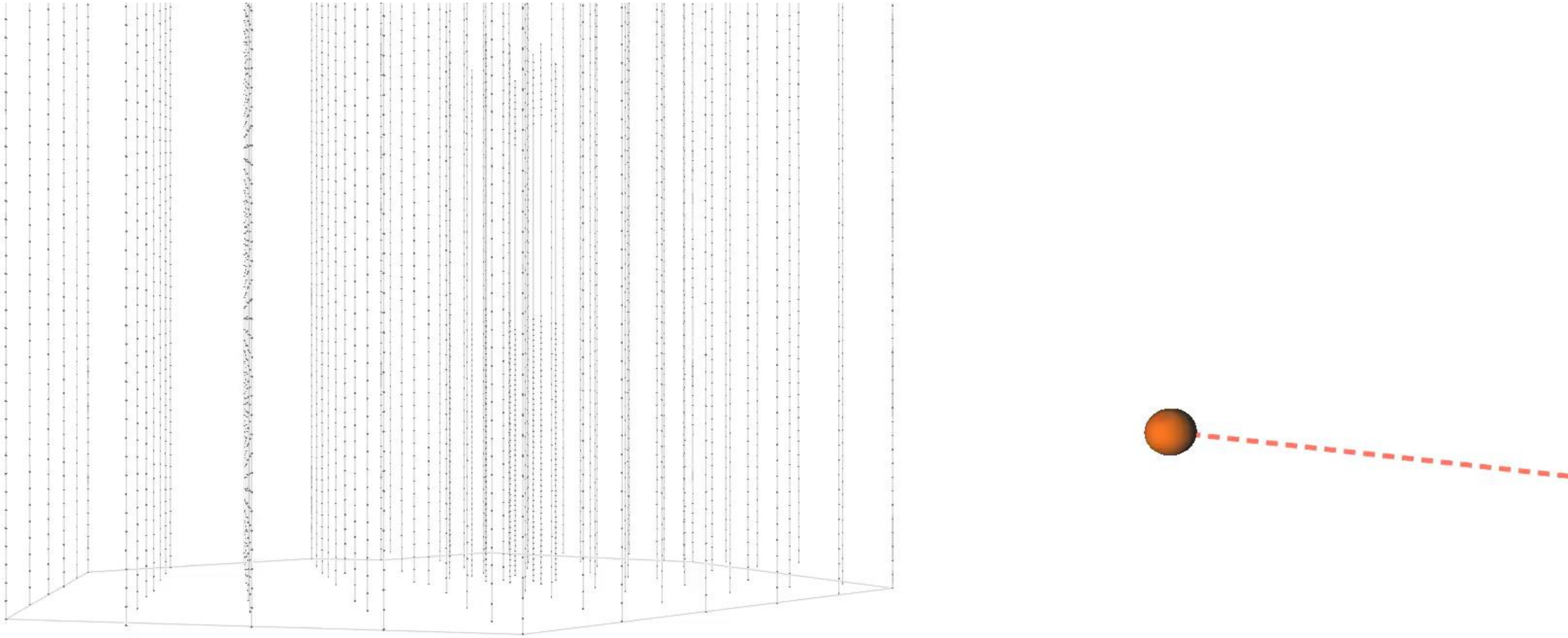
Data centre in south pole

170922A



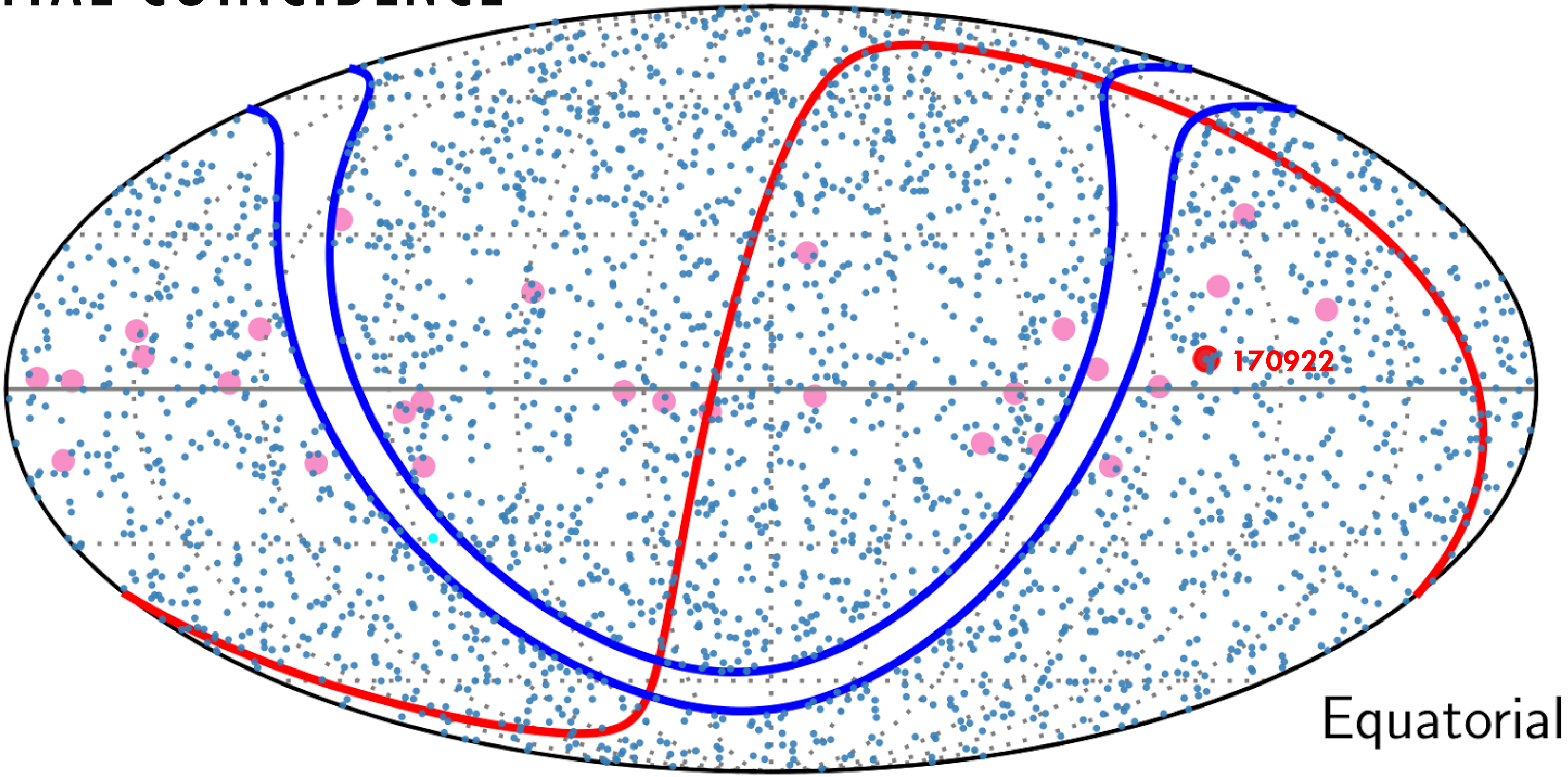


http://www.ppl.phys.chiba-u.jp/~lulu/170922/170922.gif



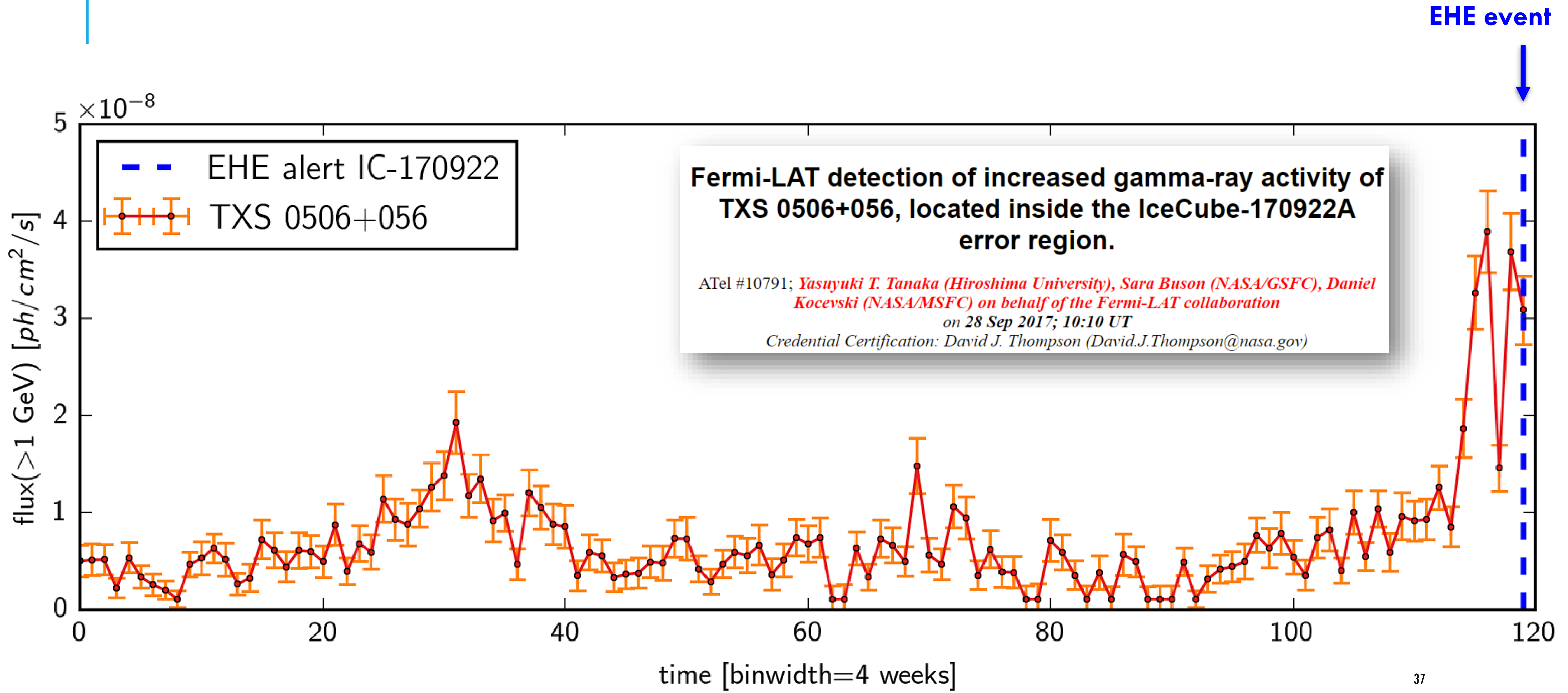
The movie is a simulation for photon ray-tracing inside of ice for a 290 TeV numu (best-fit vertex and direction from 170922)

‘SPATIAL COINCIDENCE’



3 FGL sources All EHE historical events

'TIME COINCIDENCE' : LIGHT CURVE OF TXS 0506+056



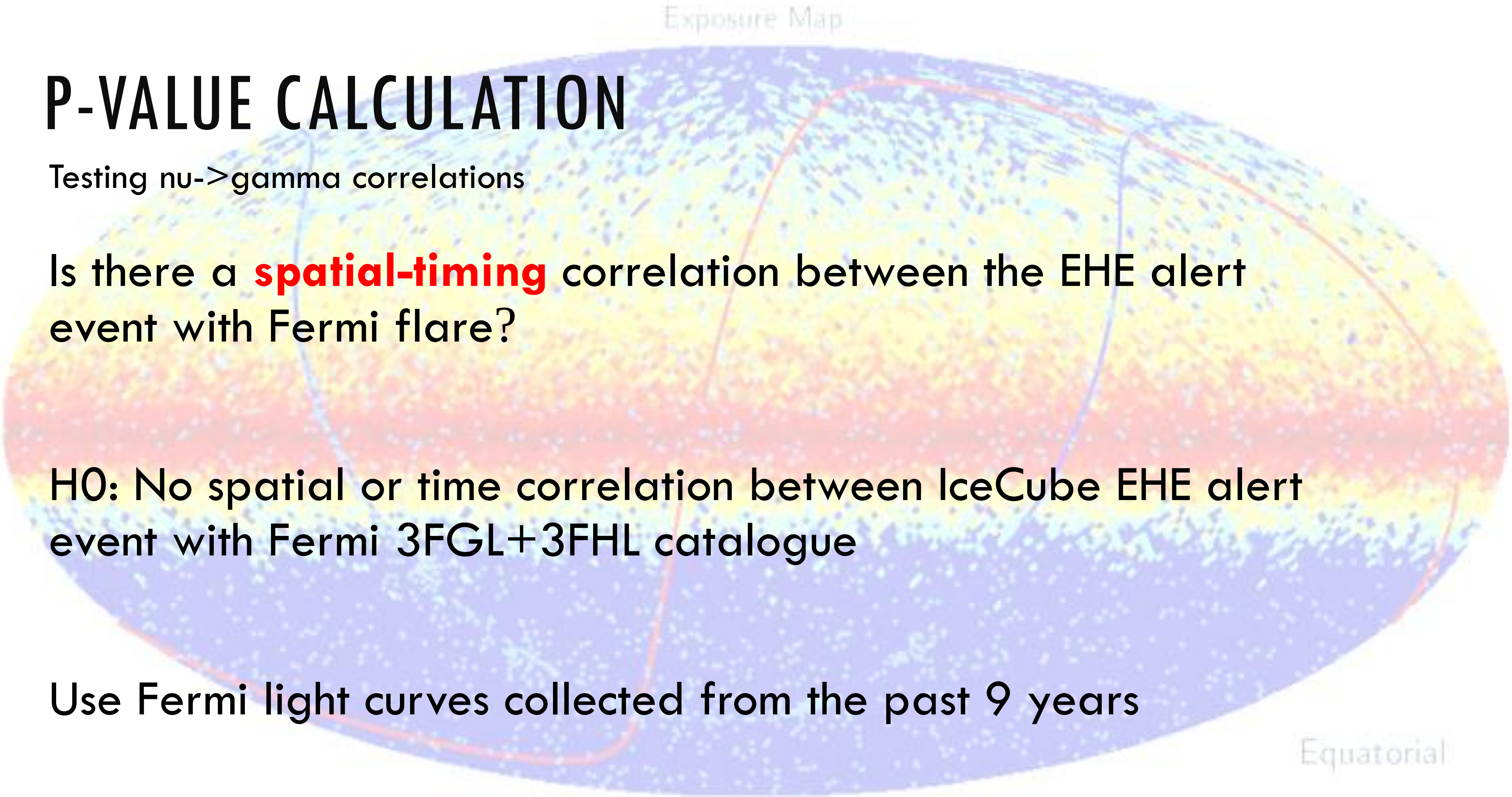
P-VALUE CALCULATION

Testing nu->gamma correlations

Is there a **spatial-timing** correlation between the EHE alert event with Fermi flare?

H0: No spatial or time correlation between IceCube EHE alert event with Fermi 3FGL+3FHL catalogue

Use Fermi light curves collected from the past 9 years



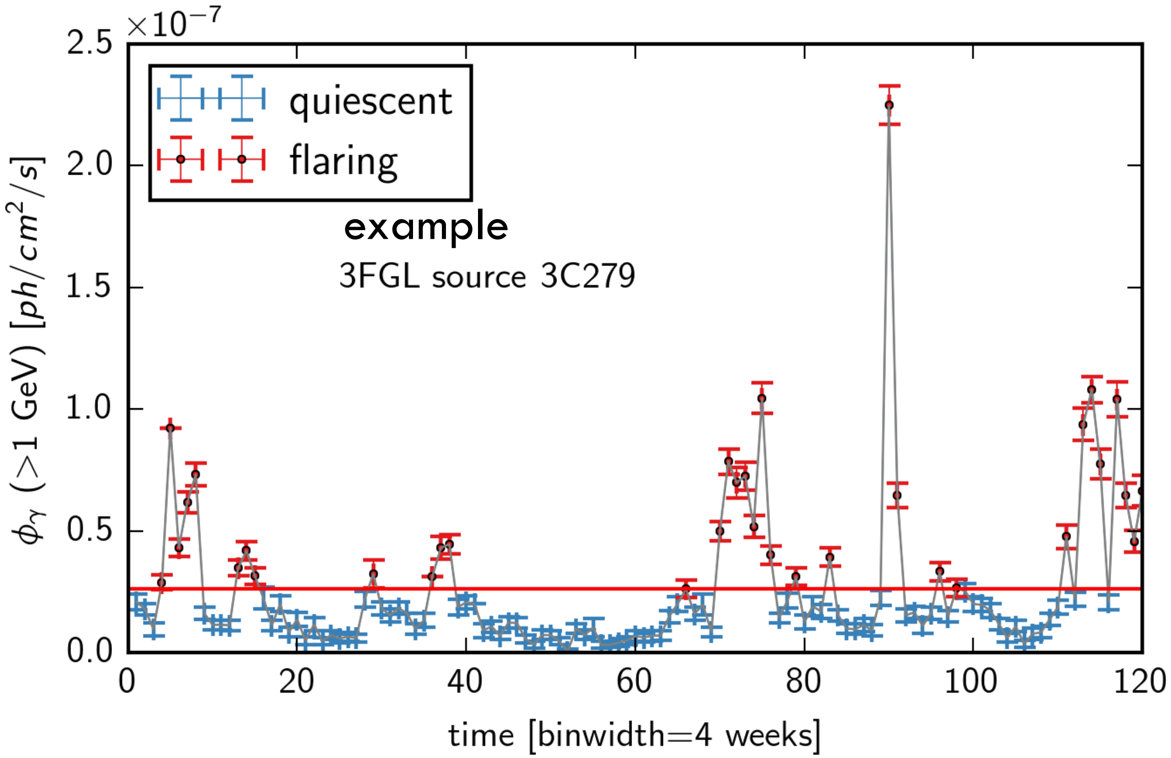
P-VALUE CALCULATION

How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

$$\mathcal{L}_{\text{flux}} \propto I_\gamma(t) / \langle I_\gamma \rangle$$

Hypo 1: ν detection scales to ***variations*** in γ flux of the source, regardless of γ luminosity



P-VALUE CALCULATION

How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

$$\mathcal{L}_{\text{flux}} \propto I_\gamma(t) / \langle I_\gamma \rangle$$

$$\mathcal{L}_{\text{flux}} \propto \frac{\phi_E(t)}{\sum_s^{N_s} \sum_i^{N_t} \phi_E(t_i)}$$

Hypo 1: ν detection scales to ***variations*** in γ flux of the source, regardless of γ luminosity

Hypo 2: ν detection scales linearly to γ energy flux. Brighter γ source more likely

P-VALUE CALCULATION

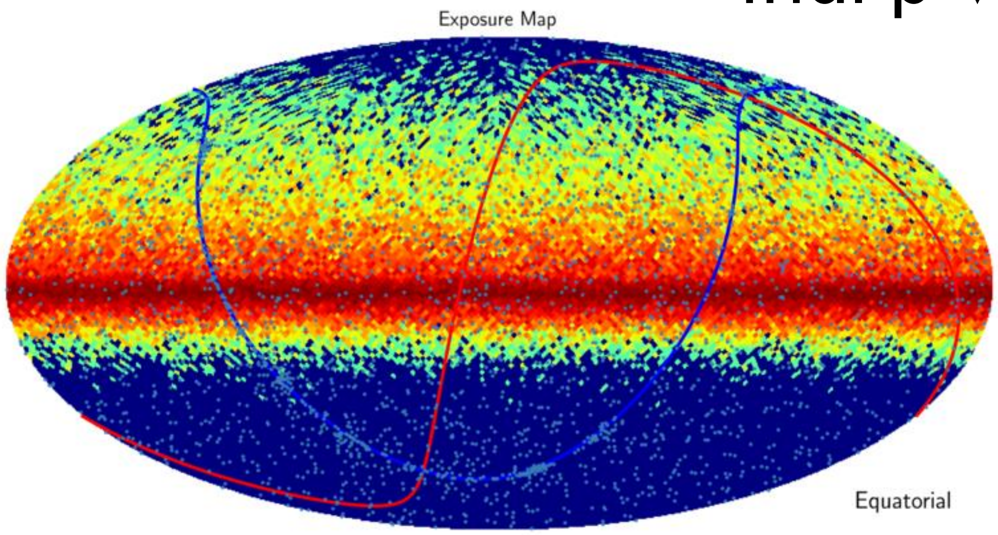
How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

Scales with variations of γ flux of the source

Or

Scales with γ energy flux, the brightness of the source



- Both hypotheses return pre-trial p-value: **4.1σ**
- 10 public alerts + 41 archival events post-trial p-value: **3.0σ**

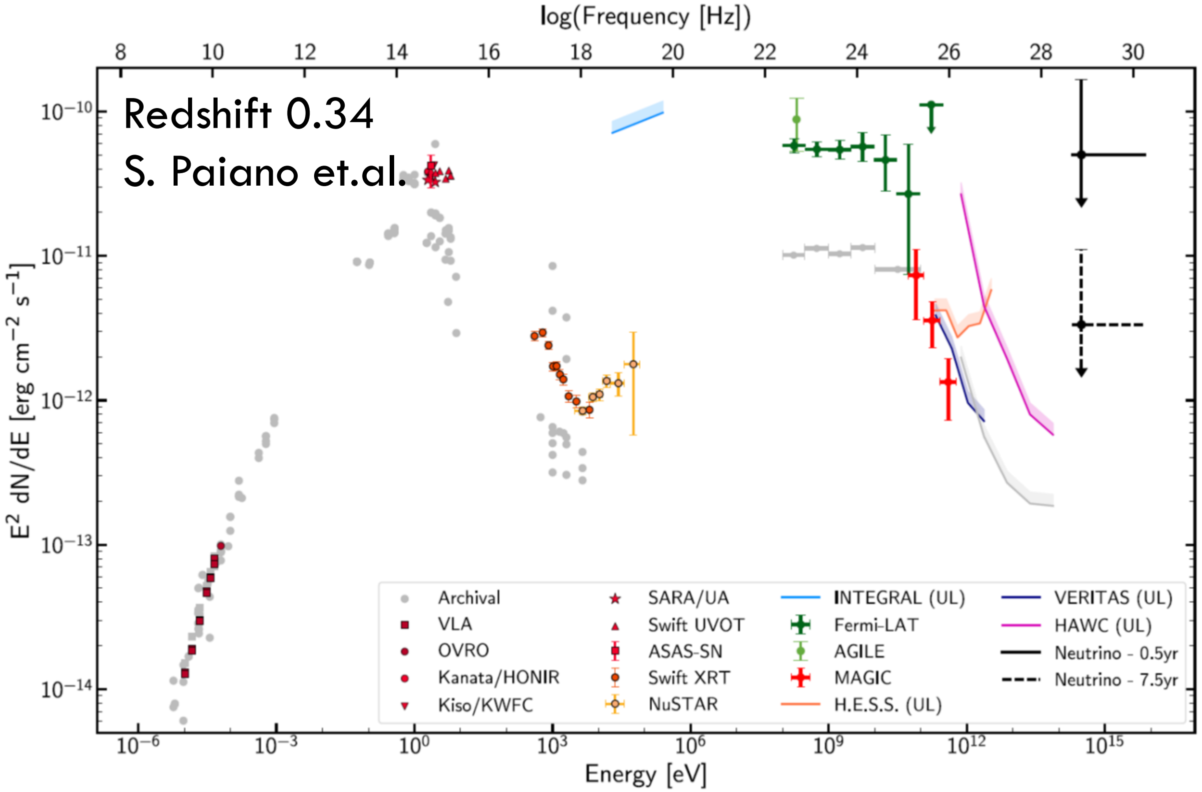
http://science.sciencemag.org/content/early/2018/07/11/science.aat1378

THE MULTI-MESSENGER OBSERVATION OF 0506+056

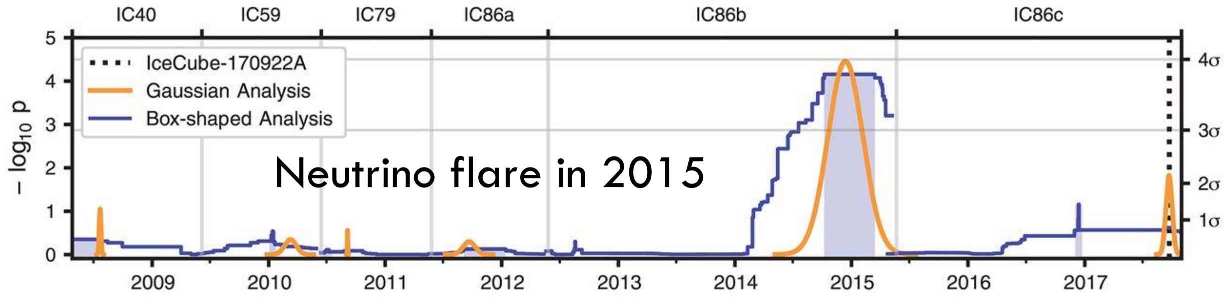
This is the start of multi-messenger era for '**Astroνmy**'.

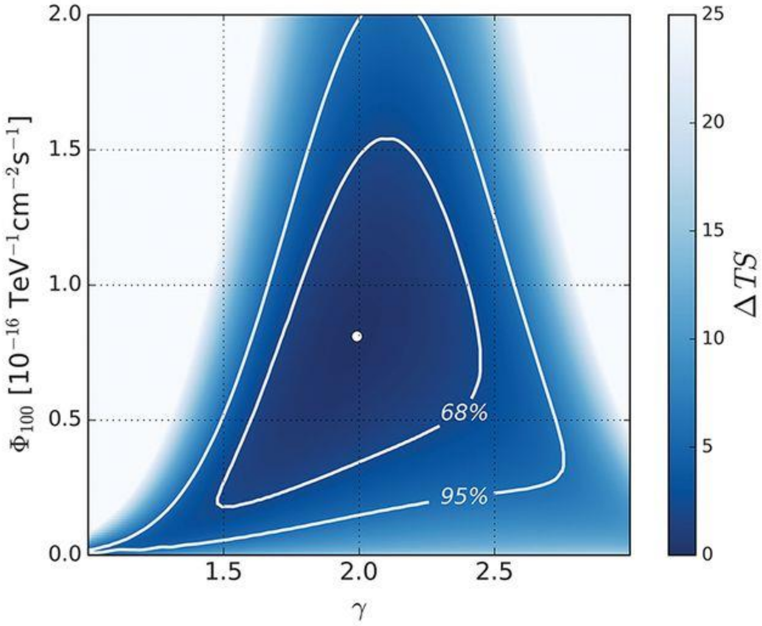
Redshift 0.34

S. Paiano et.al.



Neutrino flare in 2015





9.5 years time-integrated spectra fit for TXS 0506+056

http://science.sciencemag.org/content/early/2018/07/11/science.aat2890

BETTER SENSORS FOR FUTURE GEN2

Larger effective area + better reconstruction (segmented sensors)

IceCube DOM

35 cm

mDOM

36 cm

36 cm

- Directional information
- More sensitive area per module

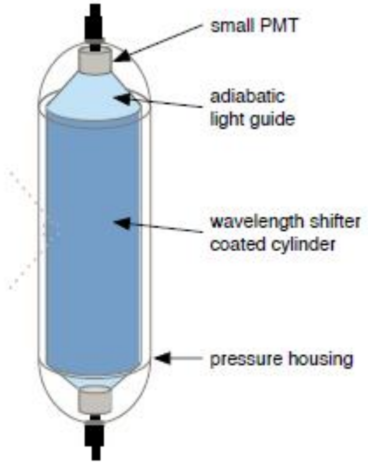
D-Egg

30 cm

30 cm

- Directional information
- More sensitive area per module
- Smaller geometry

WOM



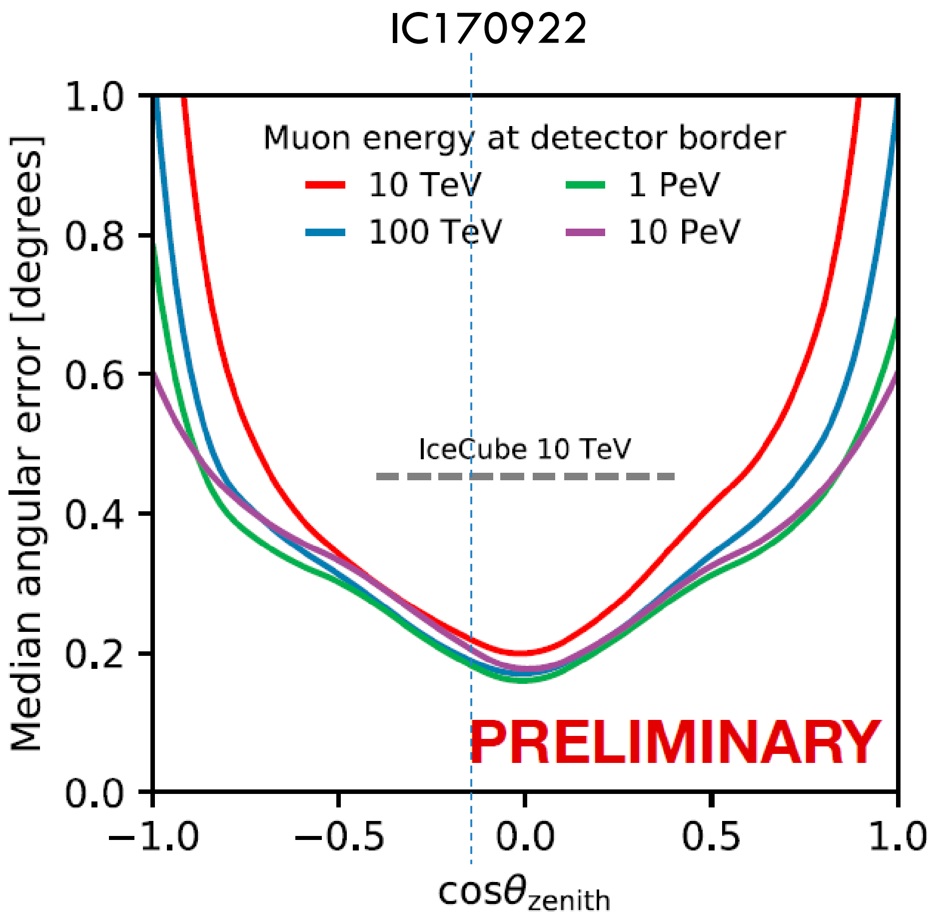
11 cm

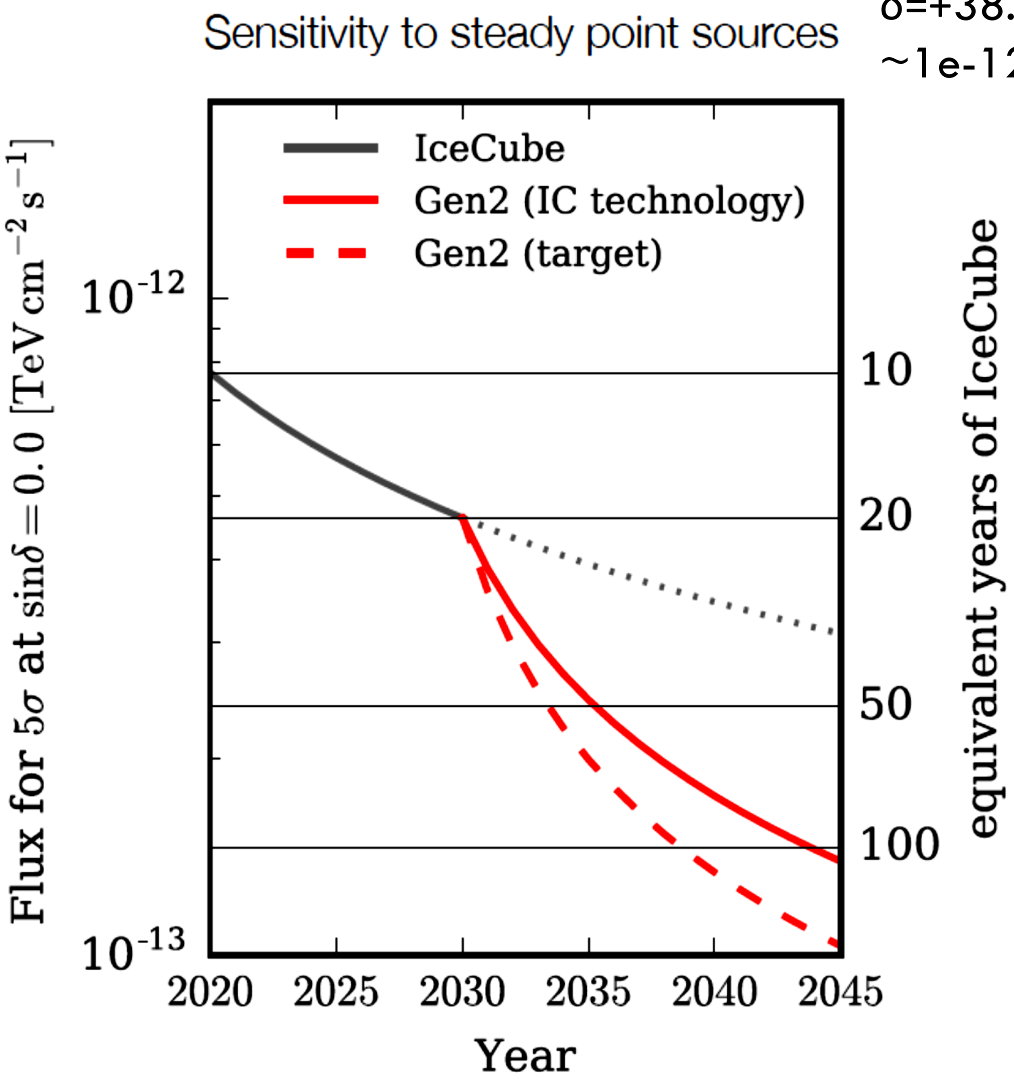
11 cm

- more sensitive area per $
- Small diameter
- Lower noise rate

GEN2 POINT SOURCE SENSITIVITY

Markarian421
122 Mpc
δ=+38.21°
~1e-12





CONCLUSIONS

1. First hint of Glashow resonance **(preliminary)**:
   - Cosmic-ray muon hypothesis significantly incompatible with observed event (rejection at ~5 sigma)
   - Probability ratio of nue CC: Glashow ~3%
   - First time measurement of astrophysical flux at ~6 PeV. Result is consistent with 1:1 nuebar:nue ratio

Direction and timing of the event will be public soon!

2. First compelling evidence of high-energy nu with EM counterparts in a wide range of wavelengths from BL Lac (TXS 0506+56)

Future Gen2 would allow precise PeV+ diffuse measurements and improve point source sensitivity significantly

HADRONIC GLASHOW IN AUGMENTED REALITY

Visualise IceCube and ray-tracing for ice hadronic shower via Microsoft HoloLens