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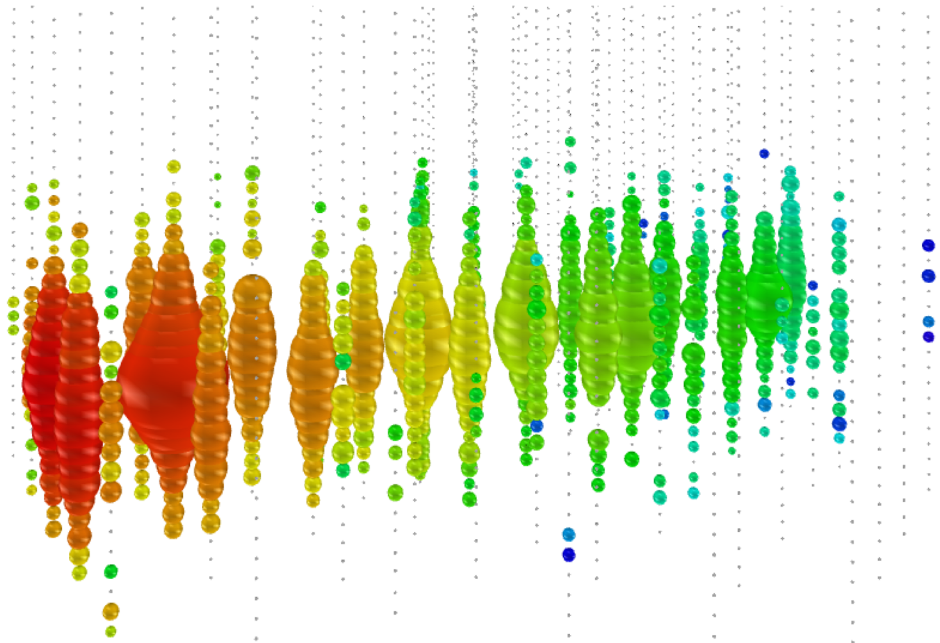

The IceCube Neutrino Observatory

Tim Ruhe

Lectures Series on Astroparticle Physics, Winter 2019/2020

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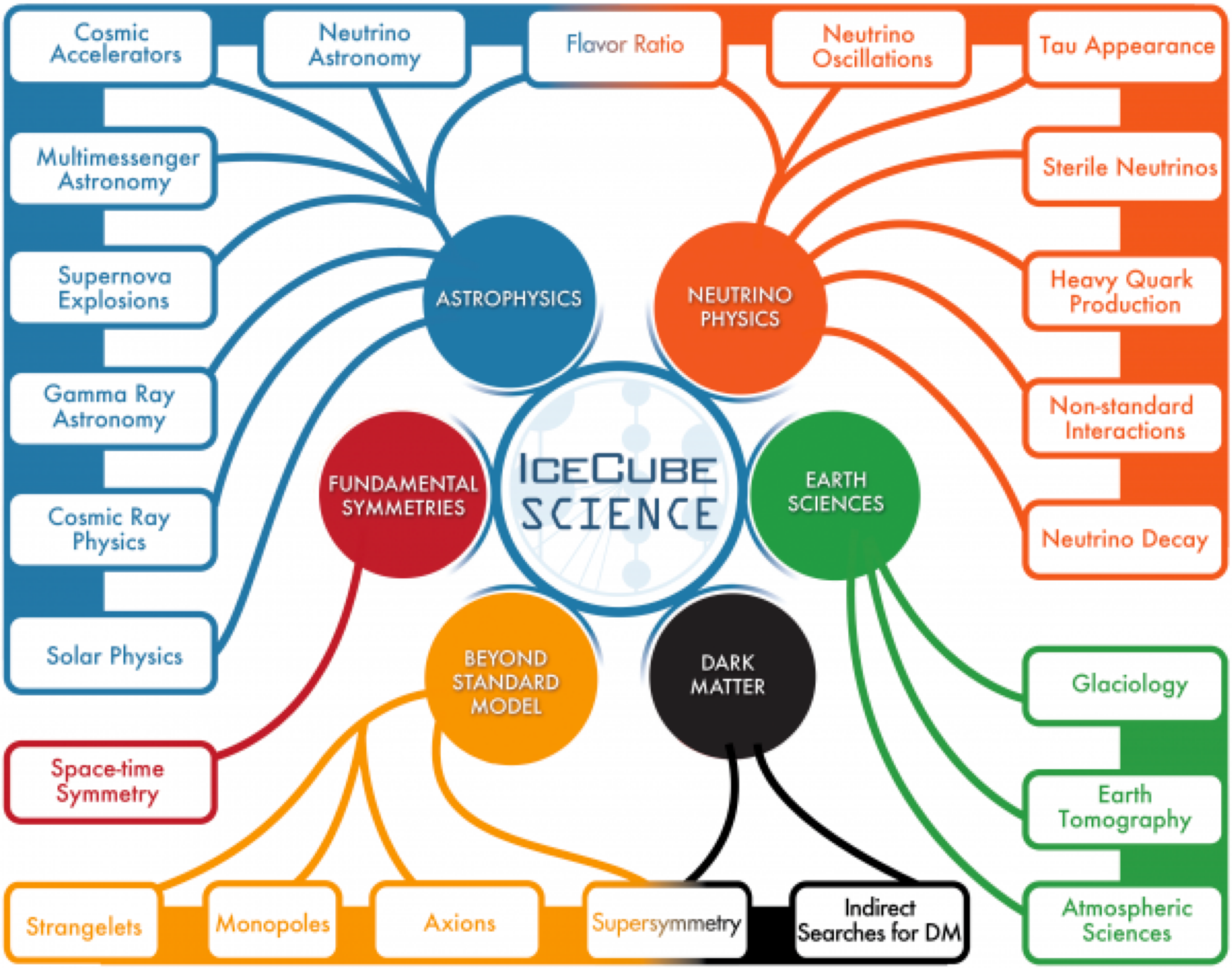
icecube.wisc.edu



Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Earth Tomography
Space-time Symmetry
Atmospheric Sciences
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM

Outline

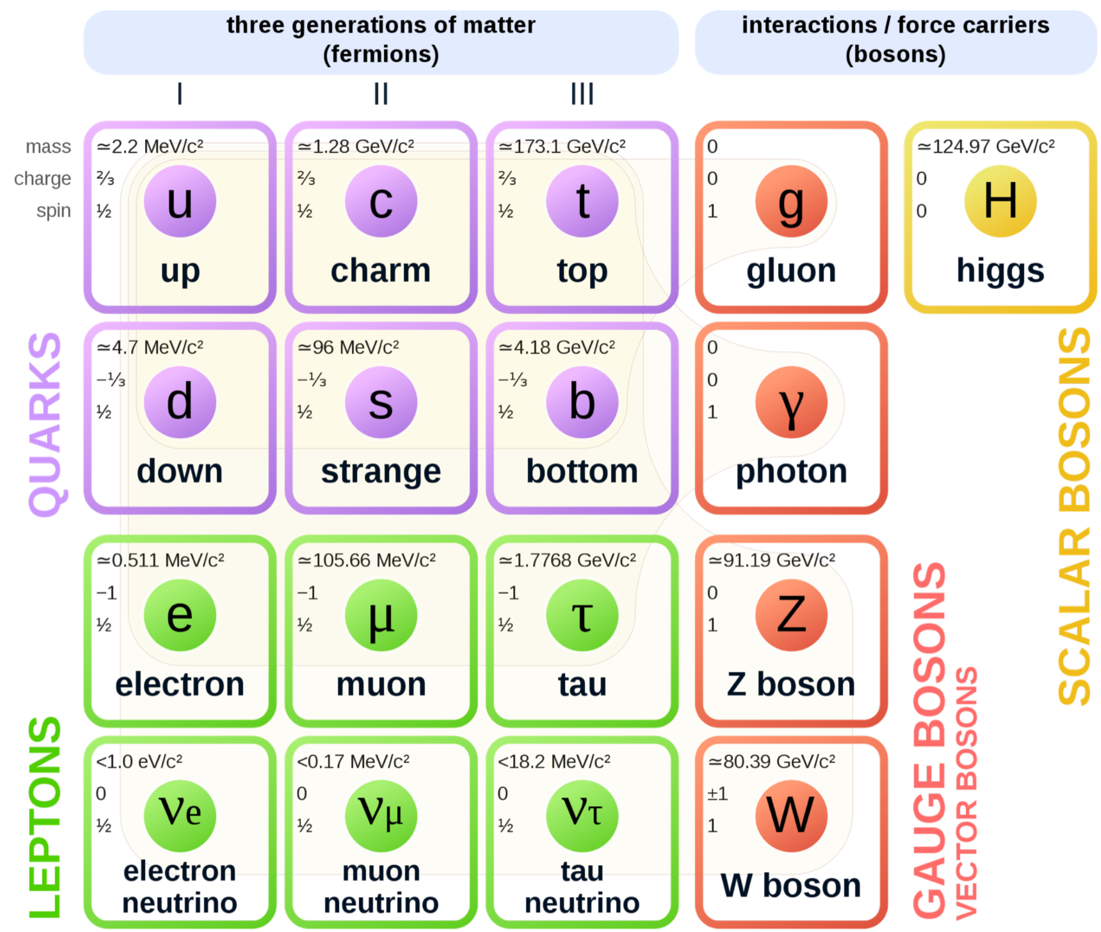
- Neutrinos, their interactions and IceCube
- High Energy Starting Events
- TXS0506 and Multimessenger Astronomy
- Atmospheric Neutrinos and *Data Science*

Neutrinos

Bildquelle: particlezoo.net

Neutrinos have very small mass and very small interaction cross section.

Standard Model of Elementary Particles



IceCube

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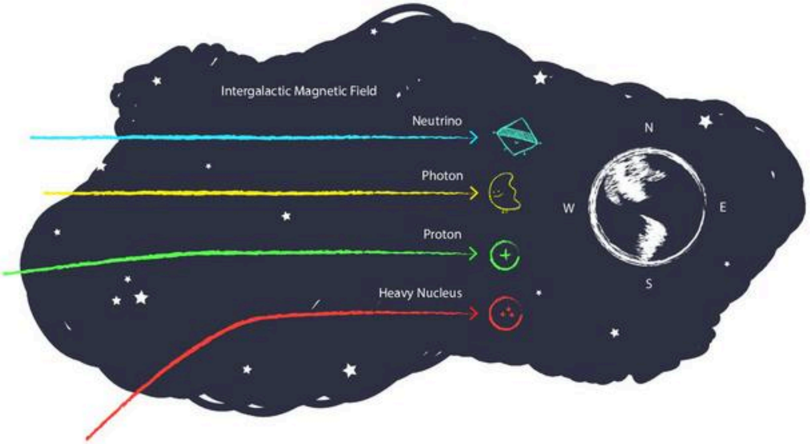
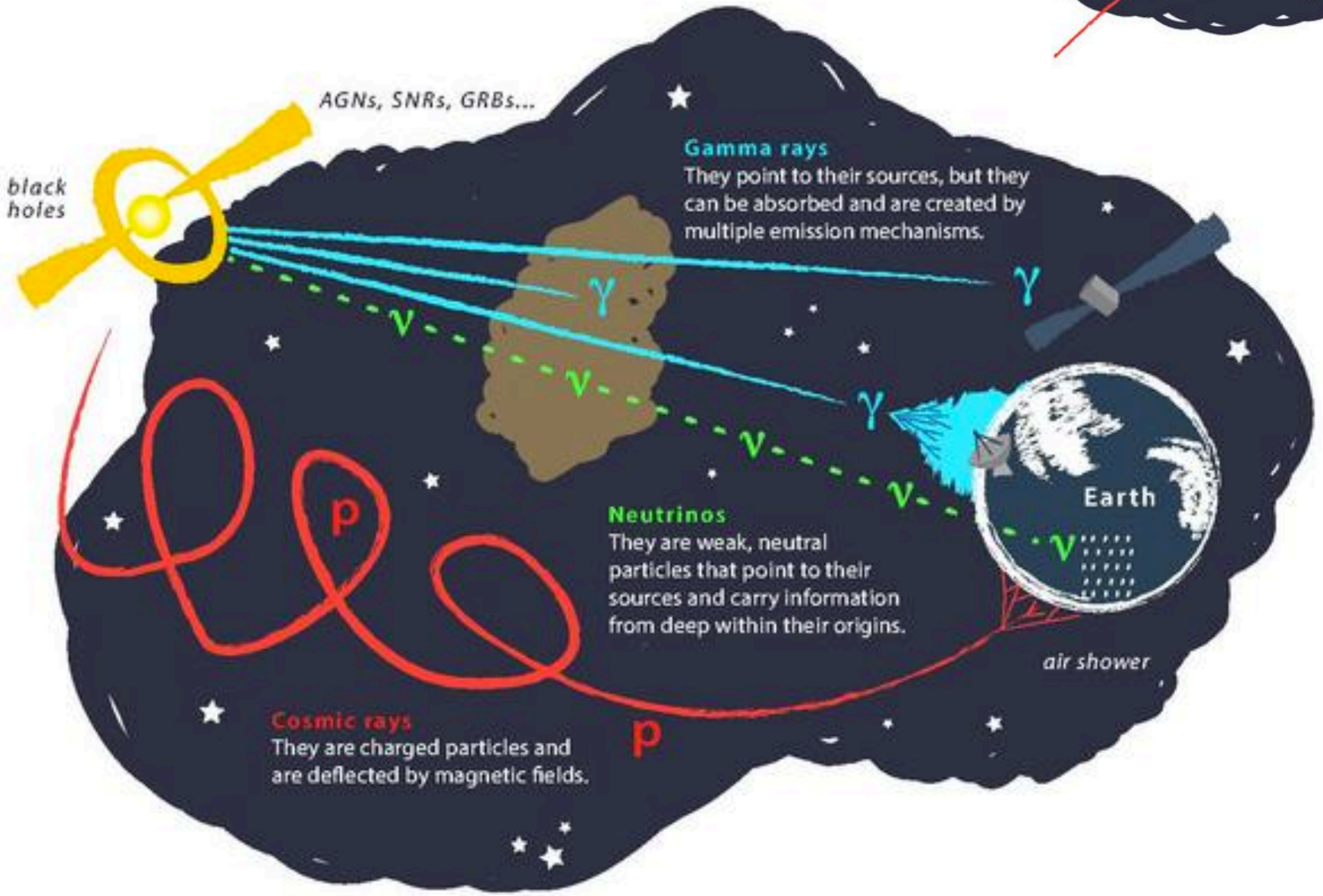
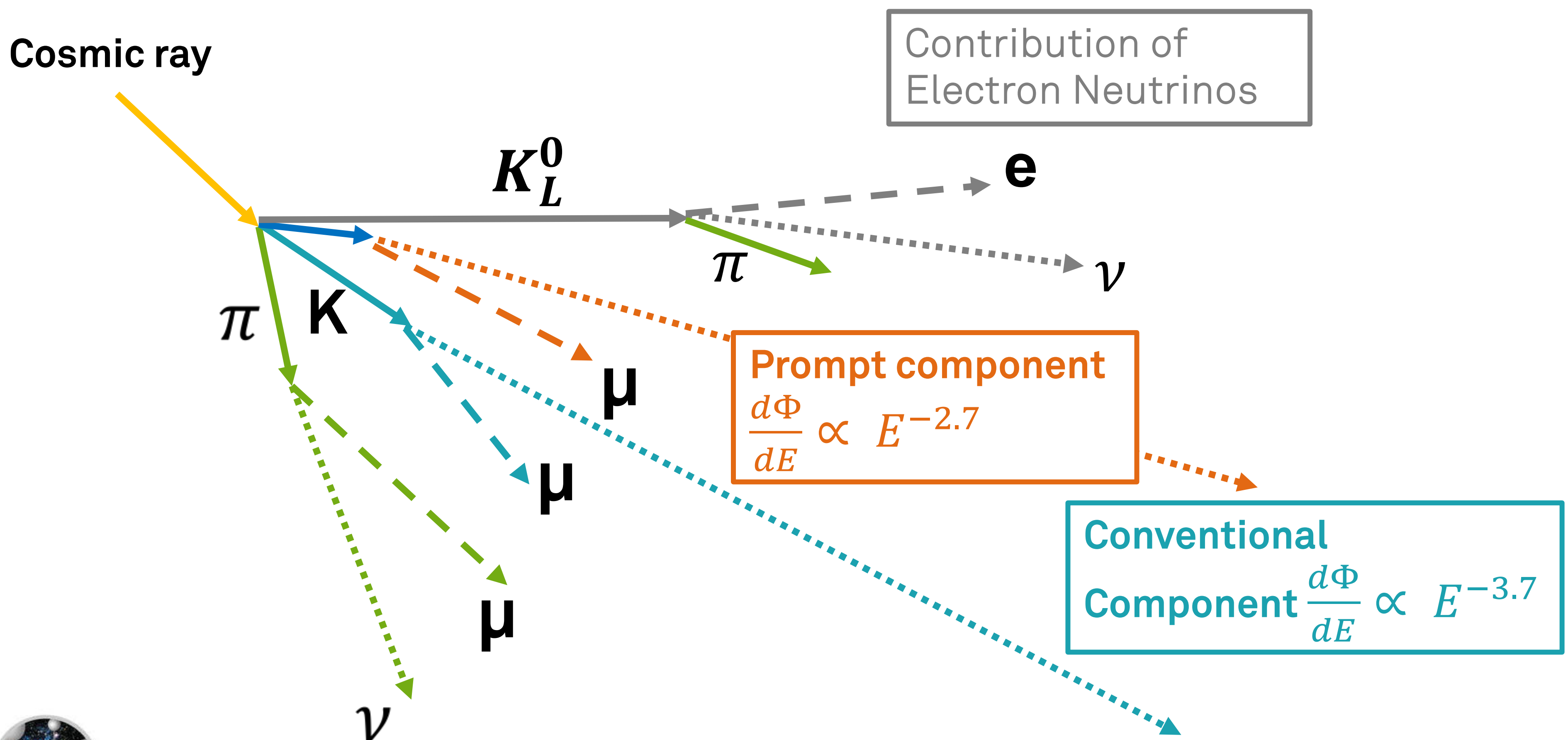
Neutrino Astronomy

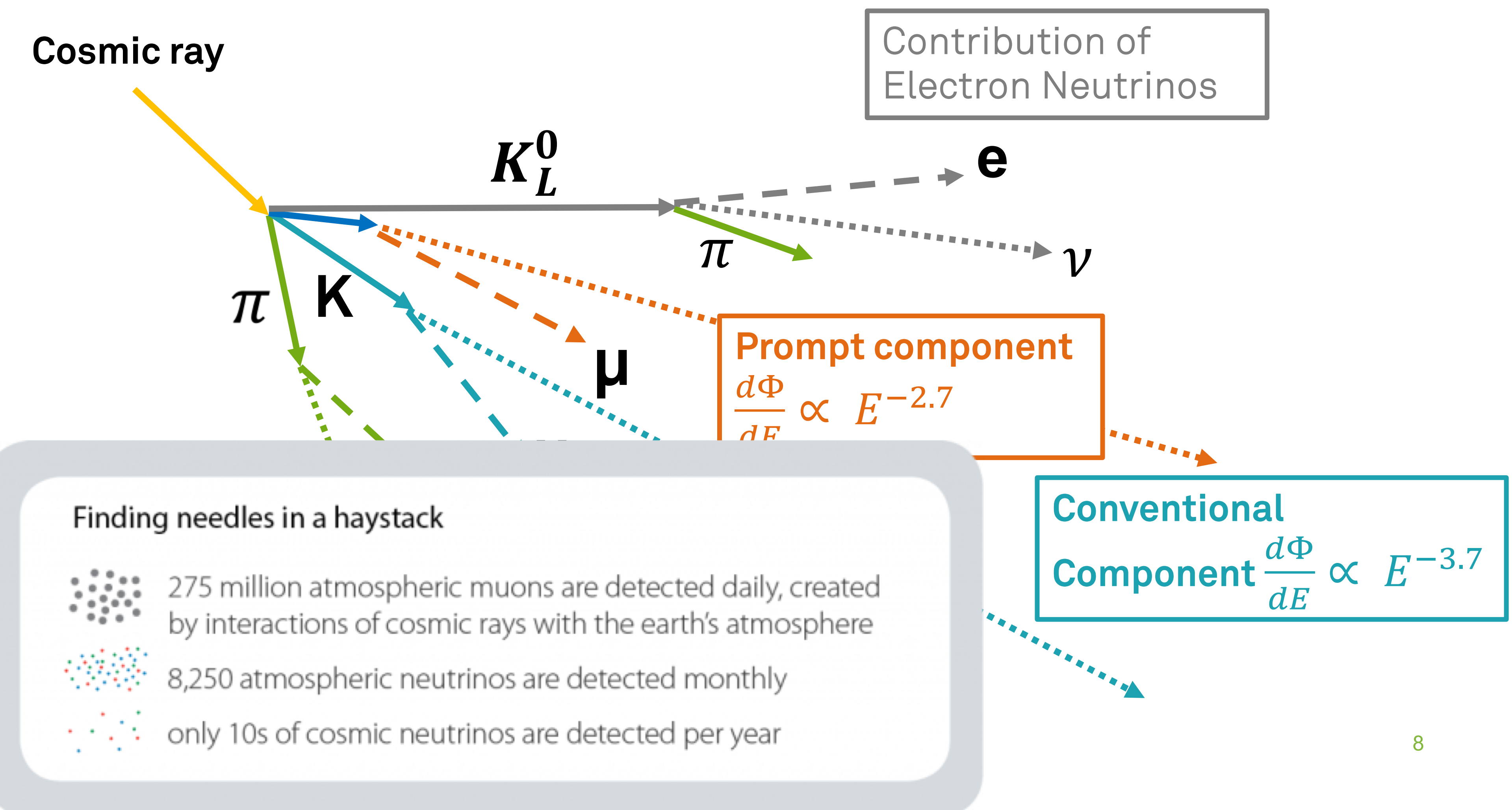




Atmospheric Neutrinos



Atmospheric Neutrinos

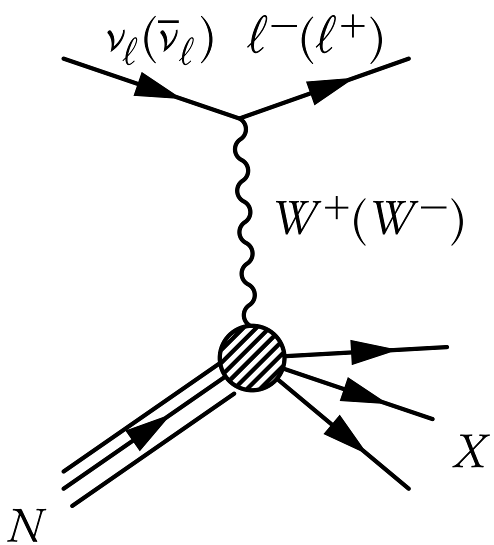


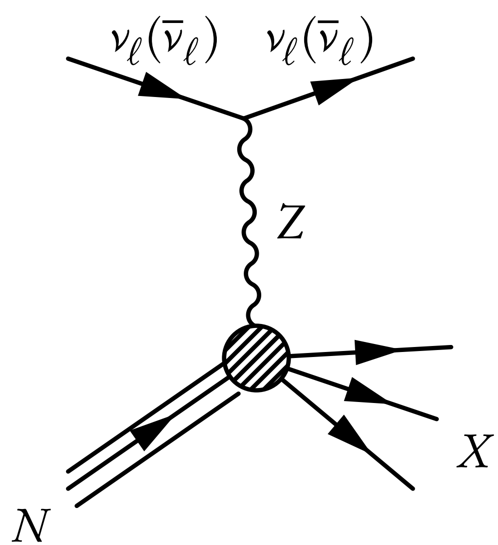
How neutrinos interact

Charged current interaction (CC)

Neutal current interaction (NC)

Glashow-Resonance ($E_\nu > 6.3$ TeV)





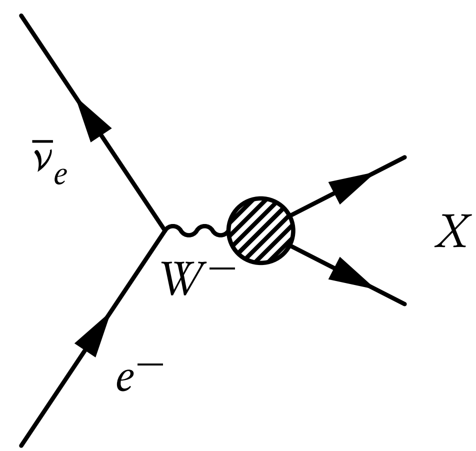
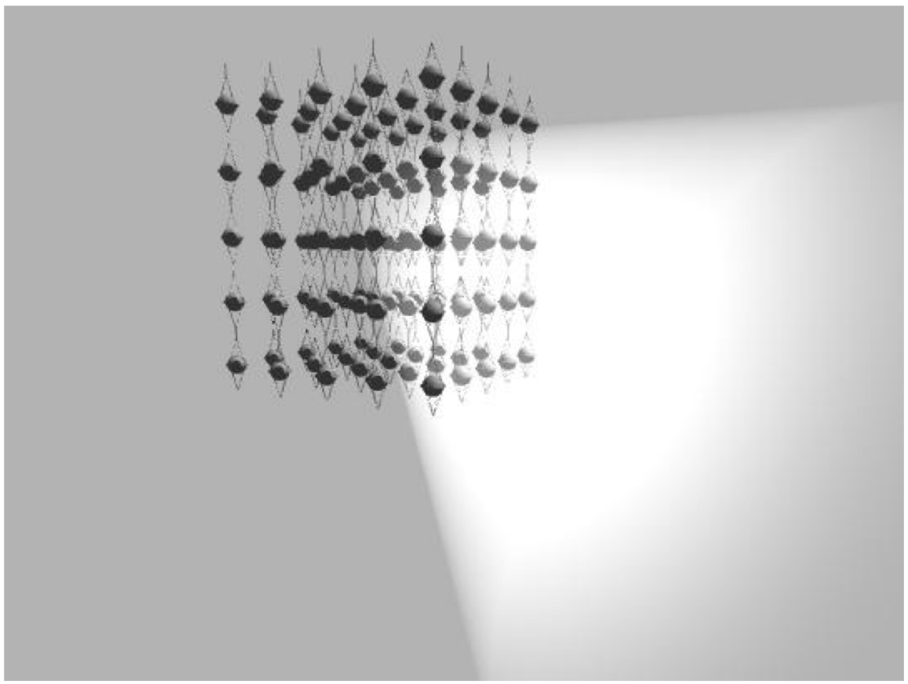


Image: A. Sandrock

Detection Principle

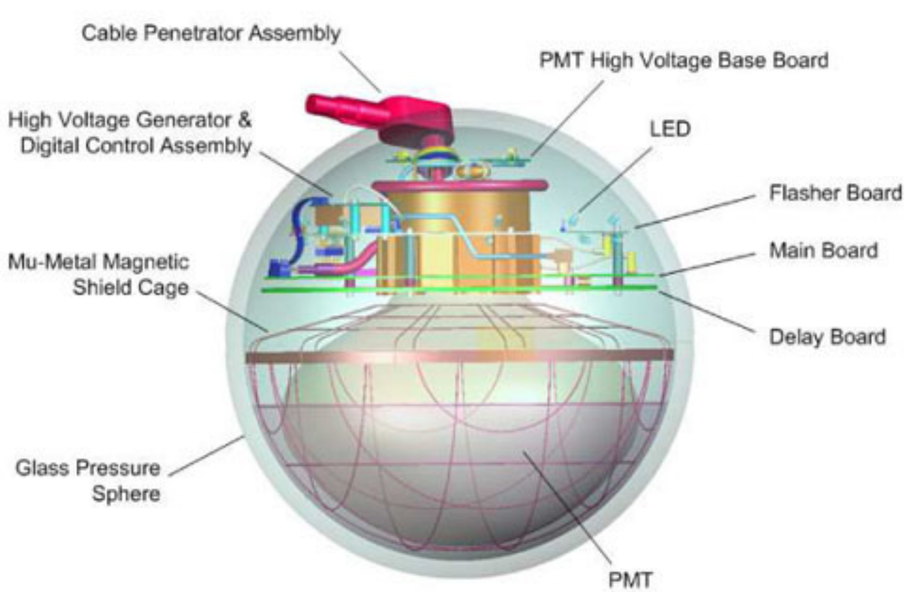


- Neutrino detection via charged leptons:

$$\nu_l + X \longrightarrow l + X'$$

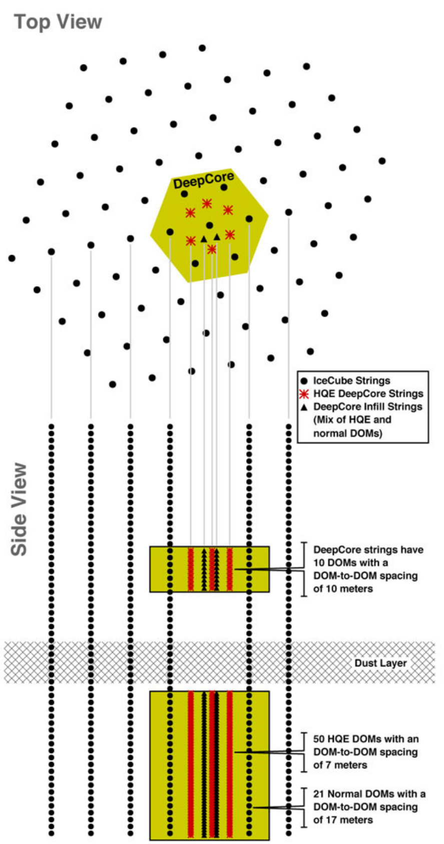
- Interaction in the ice or the bedrock
- Detection of Cherenkov light by Digital Optical Modules (DOMs)

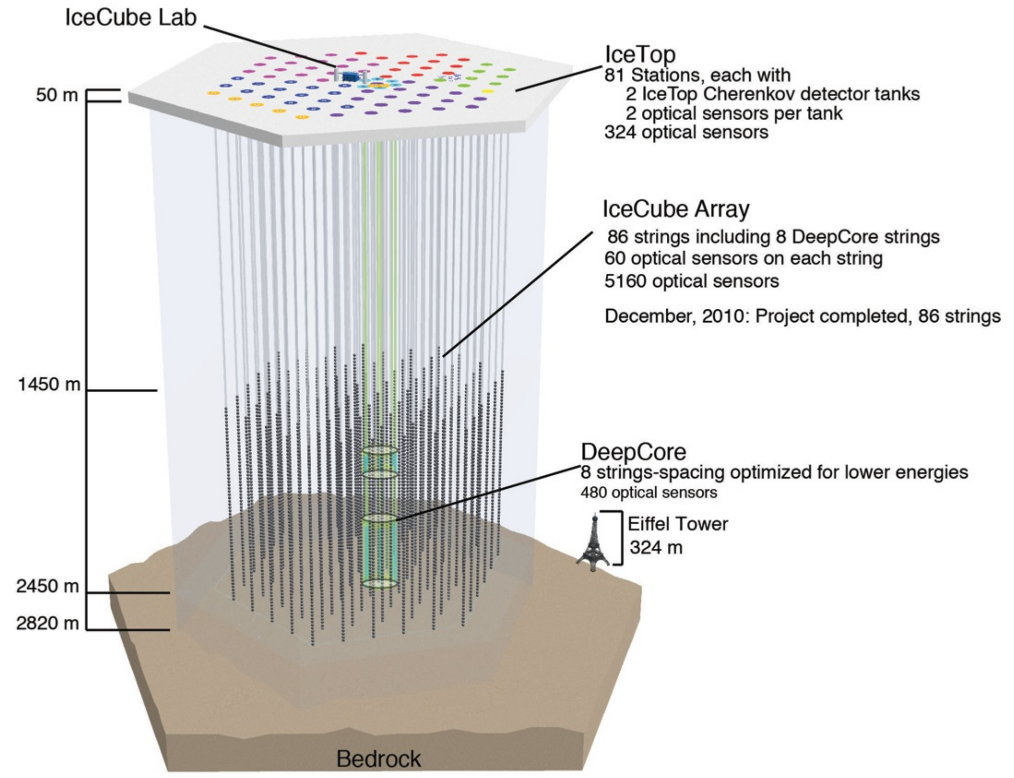
Digital Optical Modules (DOMs)



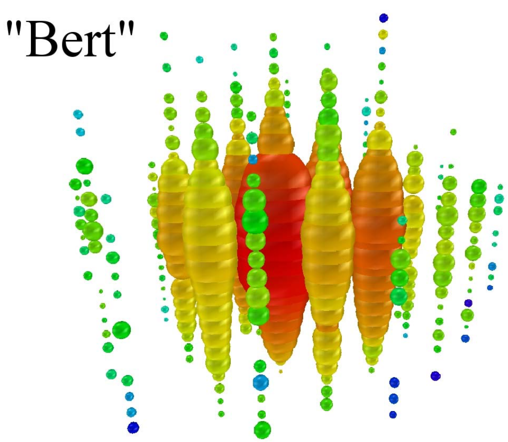
- Downward facing 10“ PMT (Hammamatsu R7081-02), 25% Peak QE
- High Voltage Supply
- Electronics
- Flasher LEDs
- Higher QE (34%) for DeepCore DOMs (Hammamatsu R7081MOD)
- Very few DOM failures (mostly during deployment)
- Slightly larger fraction of DOMs with *issues* (mostly non-standard Local Coincidence)

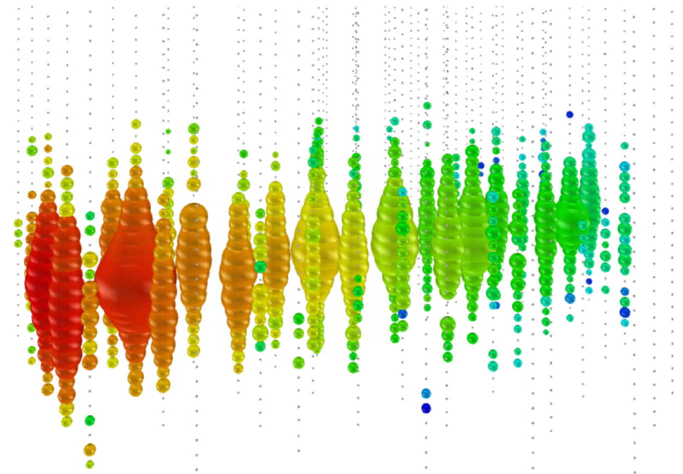
The IceCube Neutrino Observatory





Event Signatures





Cascade like events:

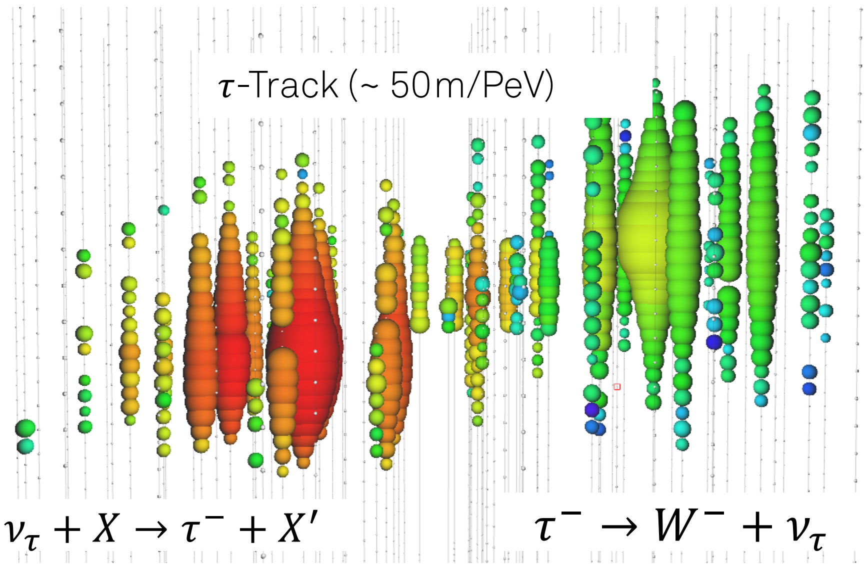
- ν_e - CC and all flavour NC interactions
- Interaction inside instrumented volume
- Poor angular resolution $\approx 15°$
- Good energy resolution

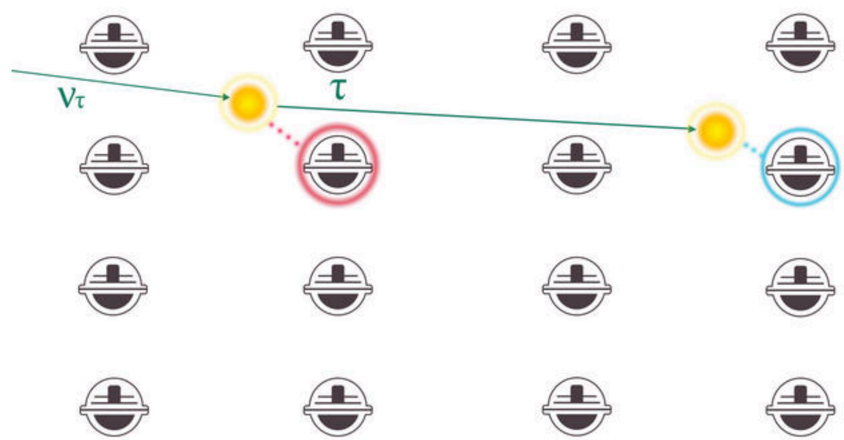
Track like events:

- ν_μ - CC interactions
- Interaction may happen outside instrumented volume
- Good angular resolution $\approx 1°$
- Poor energy resolution

Tau-Neutrino Signatures

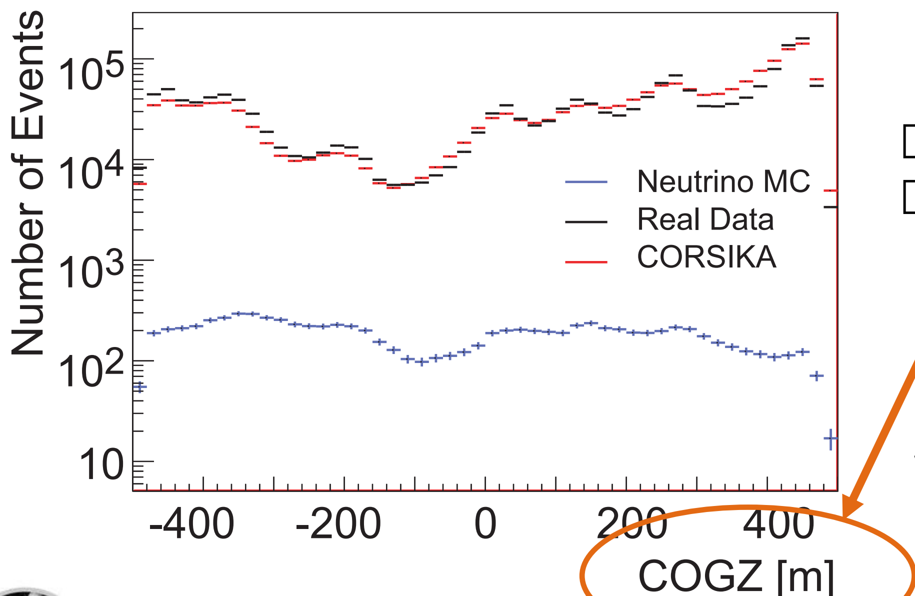
- 2 distinct cascades
- First from tau-neutrino interaction
- Second one from tau-lepton decay
- Connected by track caused by tau-lepton
- Caveat: track length is only 50m/PeV



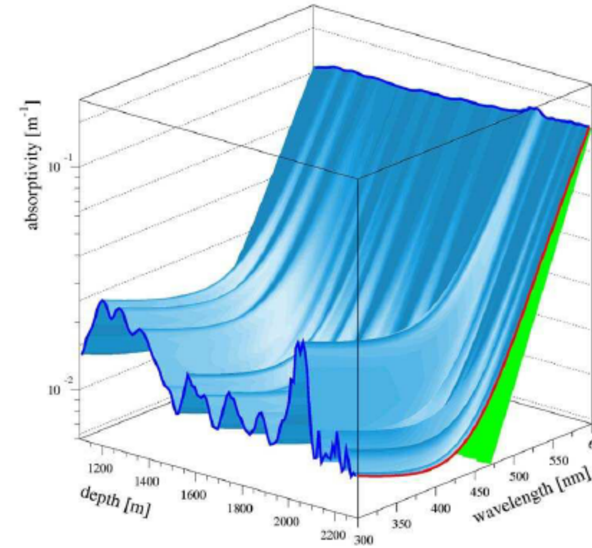


IceCube's Detection Medium: South Pole Ice

Natural Medium: Lots of inhomogenities, smaller and larger layers of dust.

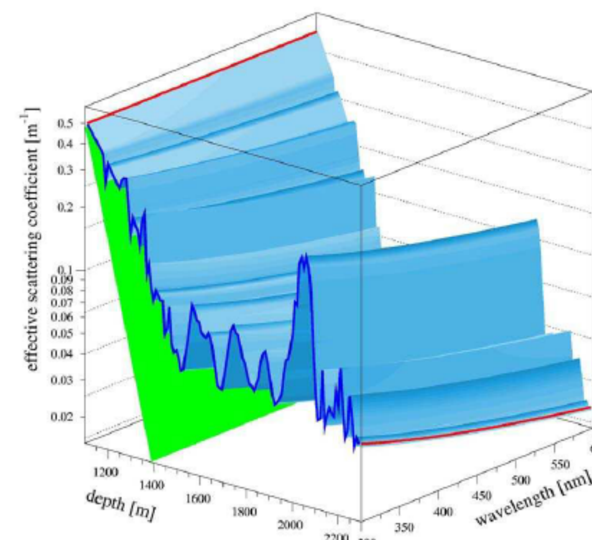


Absoprtion



Depth in Detector

Scattering



Ackermann et al., Journal of Geophysical Research 111, (2006)

IceCube

In Ice Measurements and Ice-Model Evolution

AHA

Ice core measurements

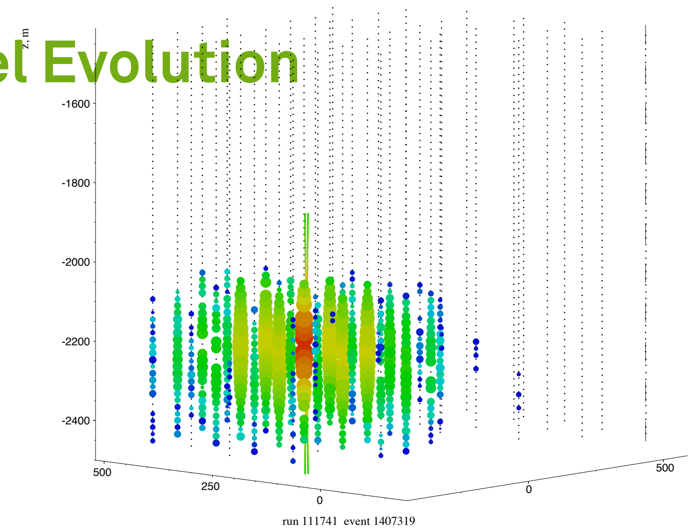
SPICE-1

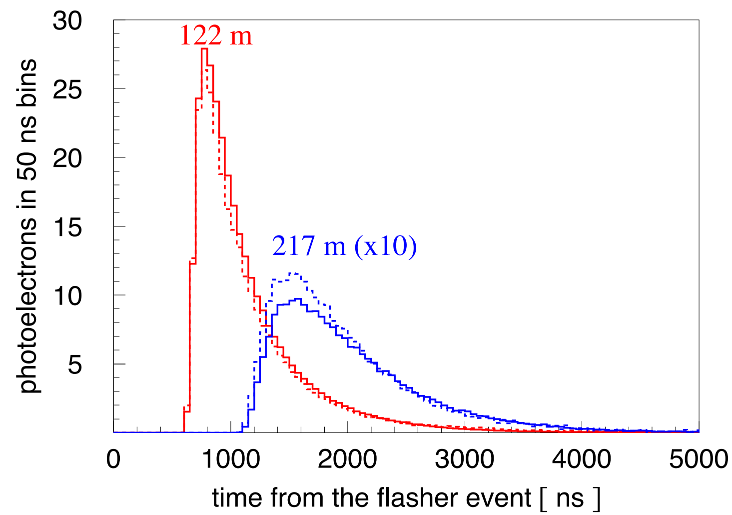
SPICE:Mie

In situ measurements using flasher LEDs

SPICE-Lea

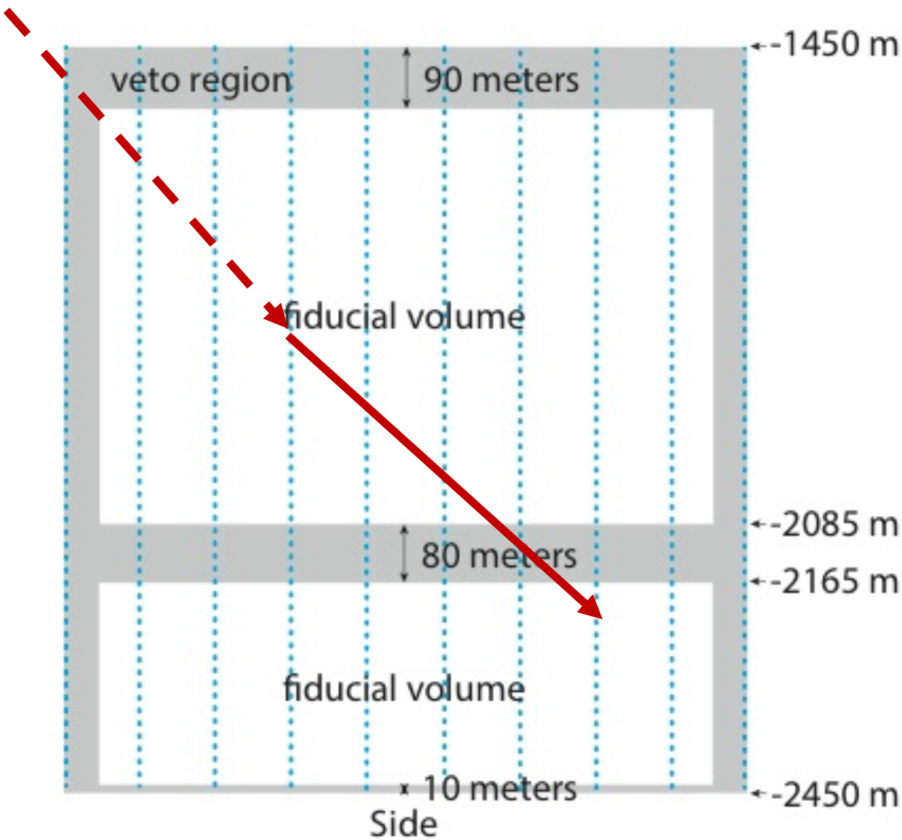
...

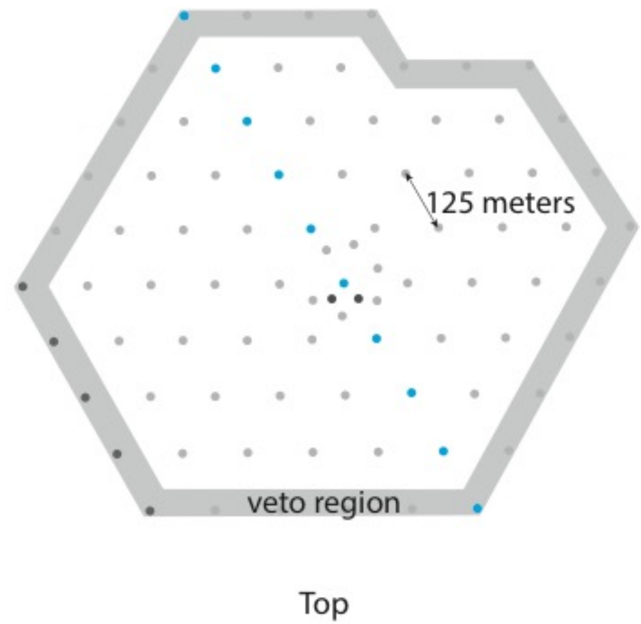




Aartsen et al., NIMA 711, 73 – 89 (20013)

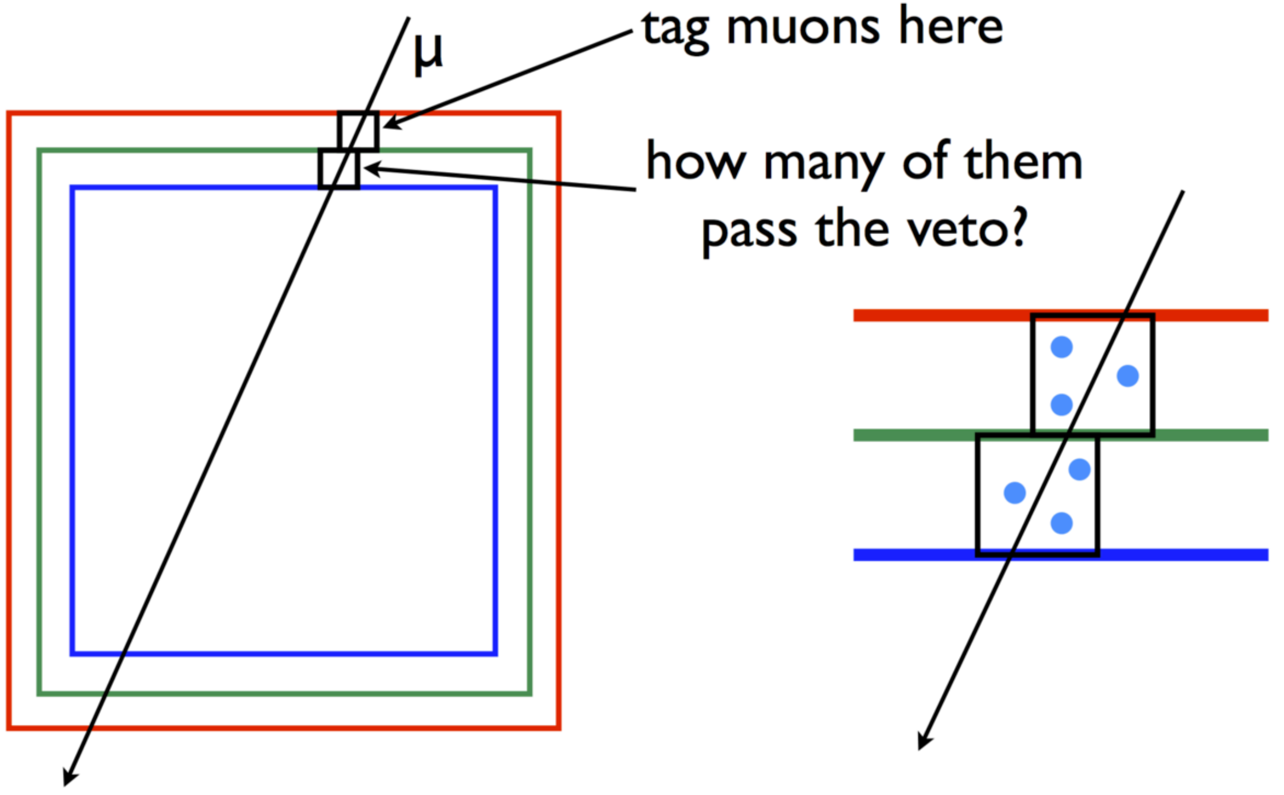
High Energy Starting Events (HESE)





- Select events starting inside the detector
- Charge threshold of 6000 pe
- Less than 3 of first 250 pe in veto layer
- ~ 30 TeV deposited inside the detector

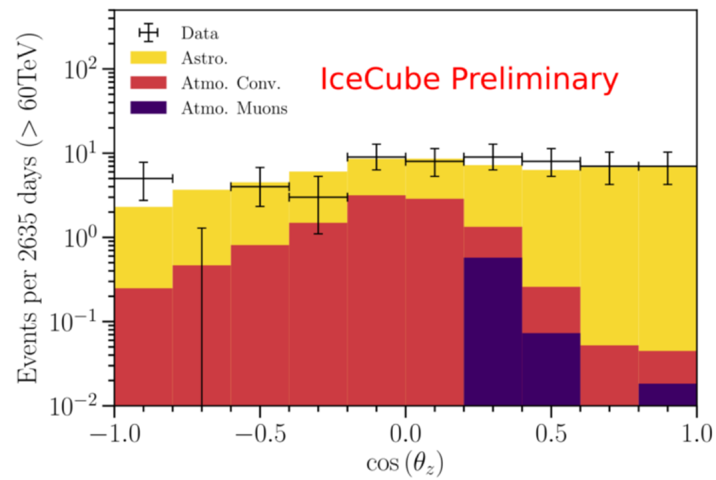
Muon Background Estimation

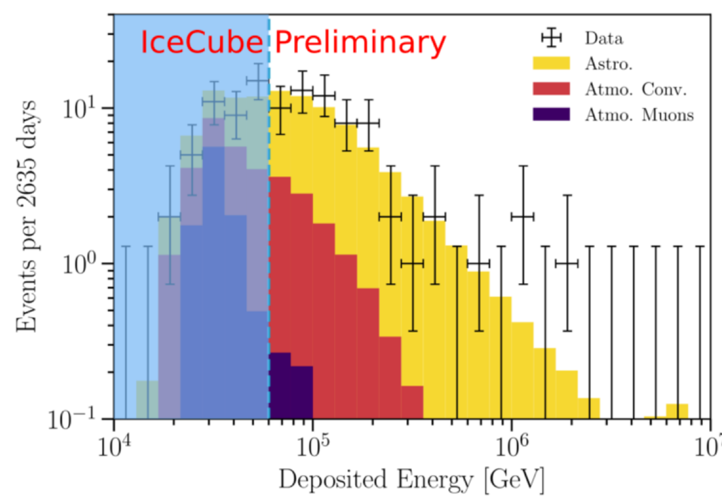


HESE Background Estimation

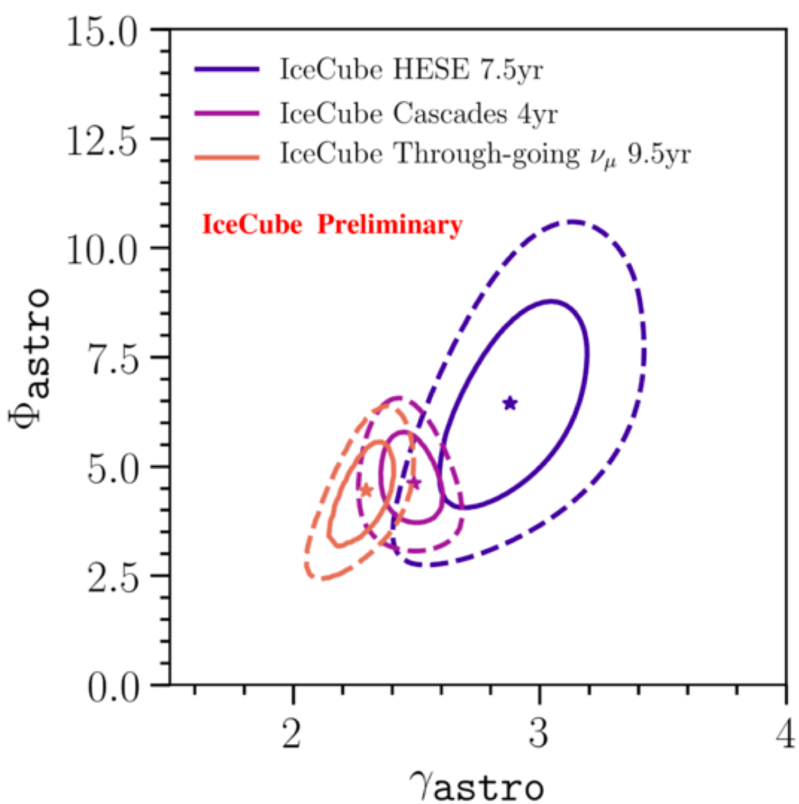
Main backgrounds are:

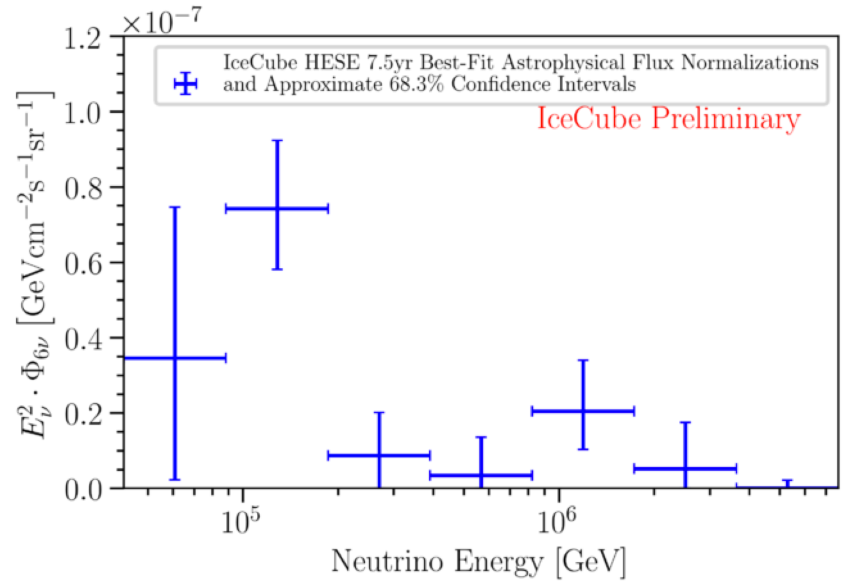
- Atmospheric muons
  - Estimated in data-driven method
  - 10.3 in 7.5 yrs. of data
- Atmospheric neutrinos
  - Strongly disfavored by energy and directional distribution
  - 23.2 events in 7.5 yrs. of data





HESE Results



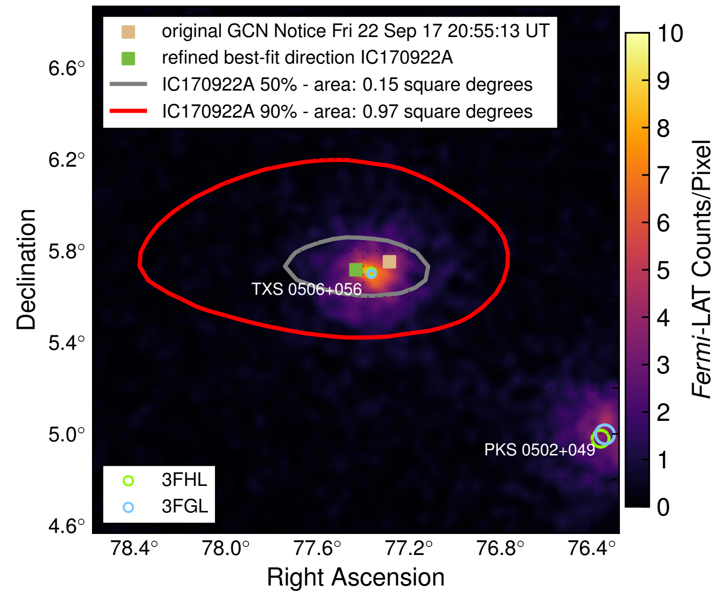


Single Power Law Fit:

$$\gamma = 2.89^{+0.19}_{-0.20}$$

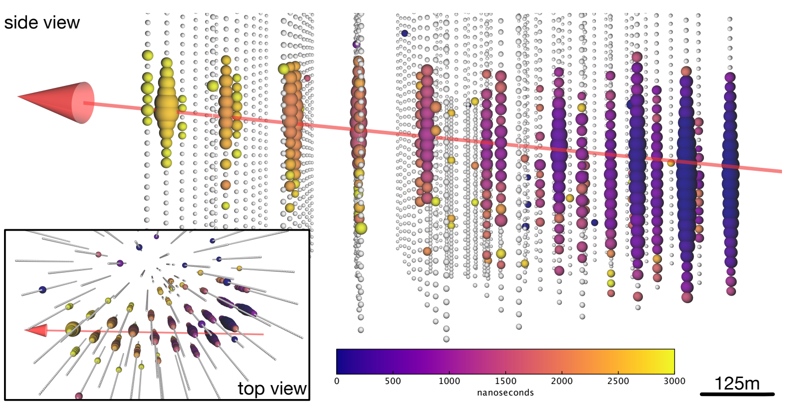
$$\Phi_0 = 6.45^{+1.46}_{-0.46} \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$$

From IC170922A…



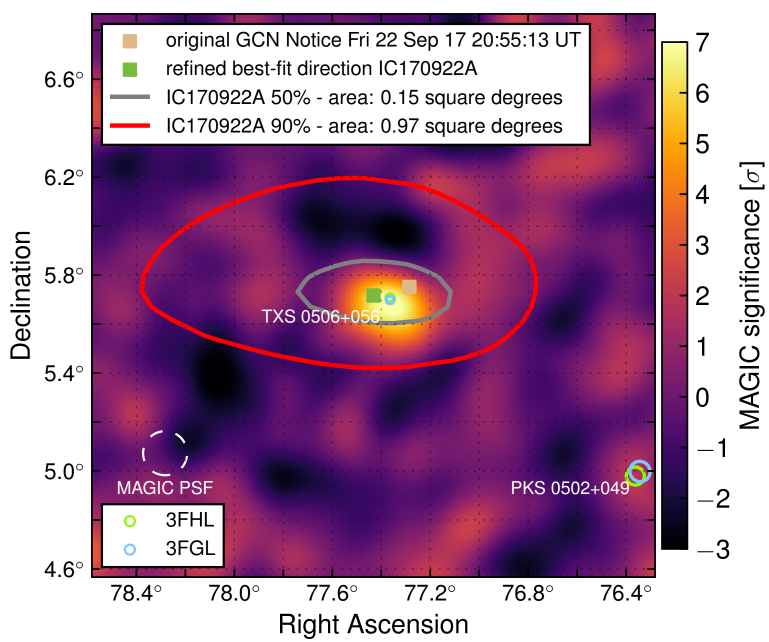
Sep. 22nd 2017:

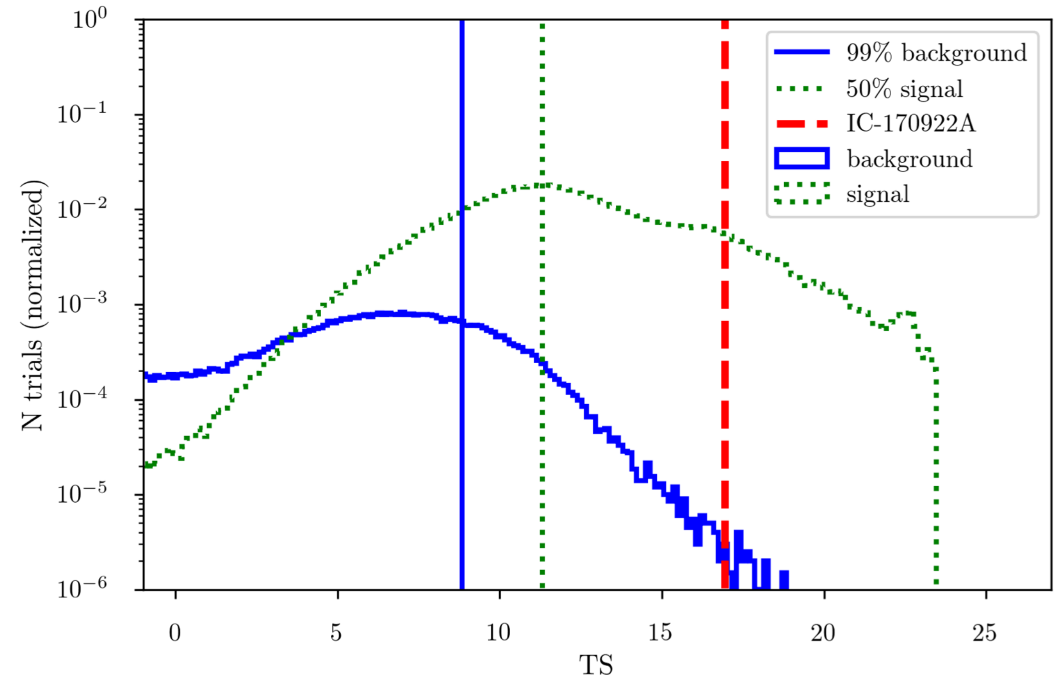
- High energy neutrino event is observed (IC-170922A),
- Energy: 290 TeV, signalness: 56.5%
- Alert issued within ~1 minute



- Event found to originate from direction of known Fermi-LAT source (blazar)
- Source in flaring state for several months

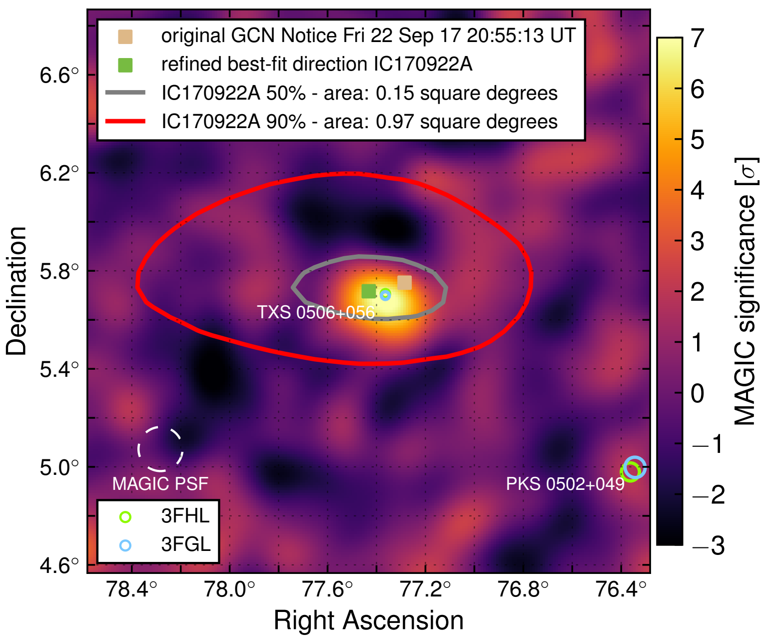
... to TXS 0506 + 056

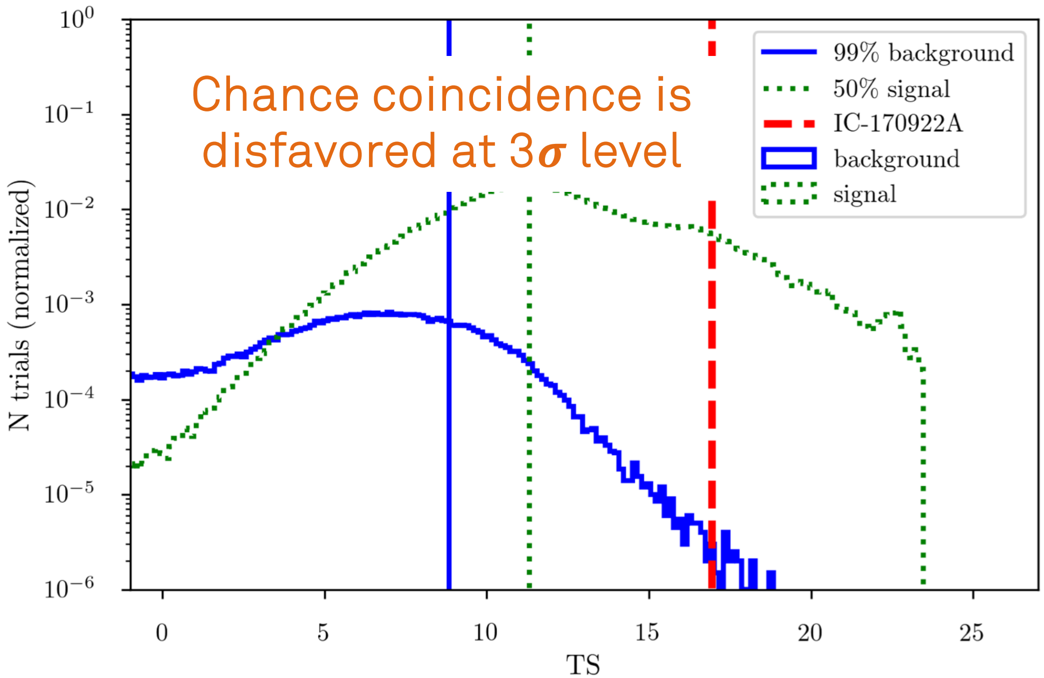




Many, many more follow-up observations at various wavelength by numerous experiments

... to TXS 0506 + 056



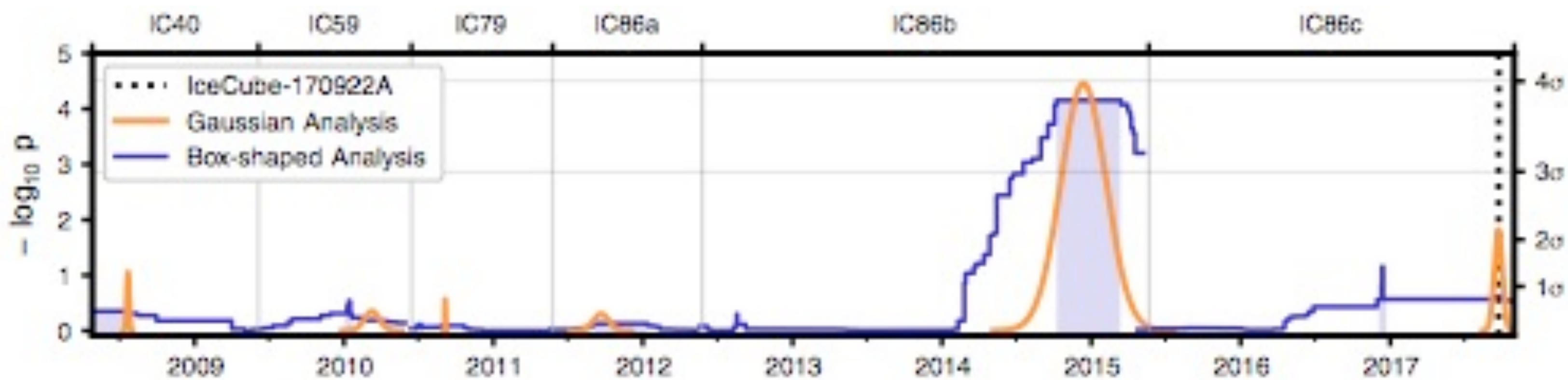


Many, many more follow-up observations at various wavelength by numerous experiments

TXS Time Dependent Analysis

- Unbinned maximum likelihood technique
- Minimal assumptions about time structure of neutrino emission
- Assumption: Emission clustered around some time T_0 with duration T_W
- Time clustering to identify time dependent signal, no characterization of time structure
- Box-shaped and Gaussian time window

Sample	Start	End
IC40	2008 Apr 5	2009 May 20
IC59	2009 May 20	2010 May 31
IC79	2010 May 31	2011 May 13
IC86a	2011 May 13	2012 May 16
IC86b	2012 May 16	2015 May 18
IC86c	2015 May 18	2017 Oct 31



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Time Dependent Analysis Results

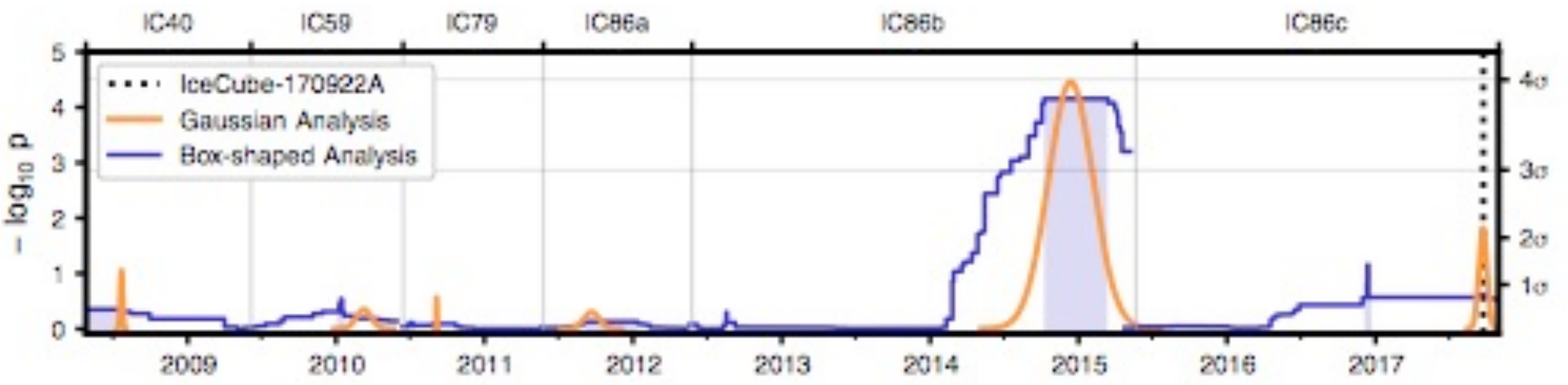
Significant excess of 13 +/- 5 events found in both time windows.

Gaussian Time Window:

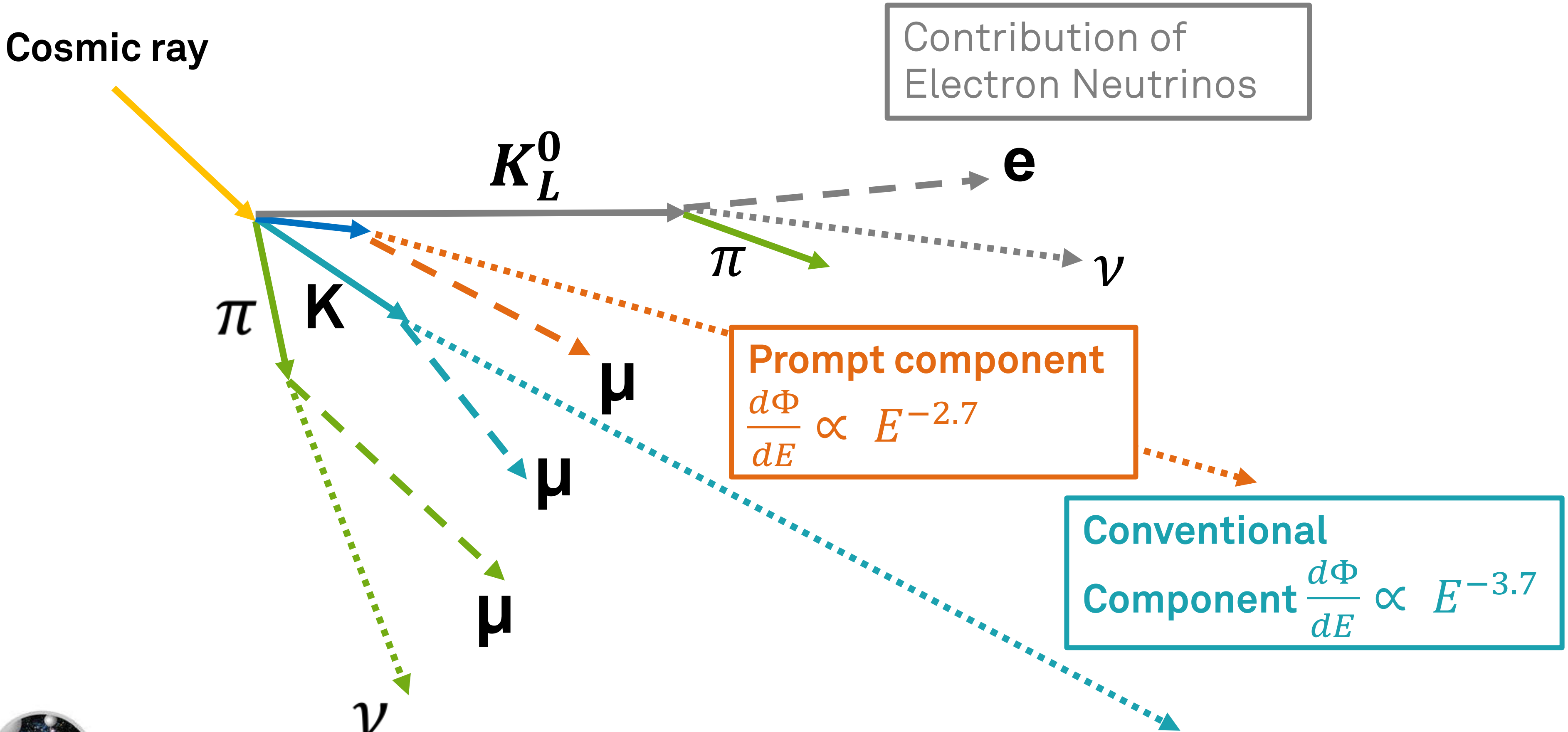
- Centered around Dec. 13th 2014
- Duration: 110^{+35}_{-24} days

Box-Shaped Time Window:

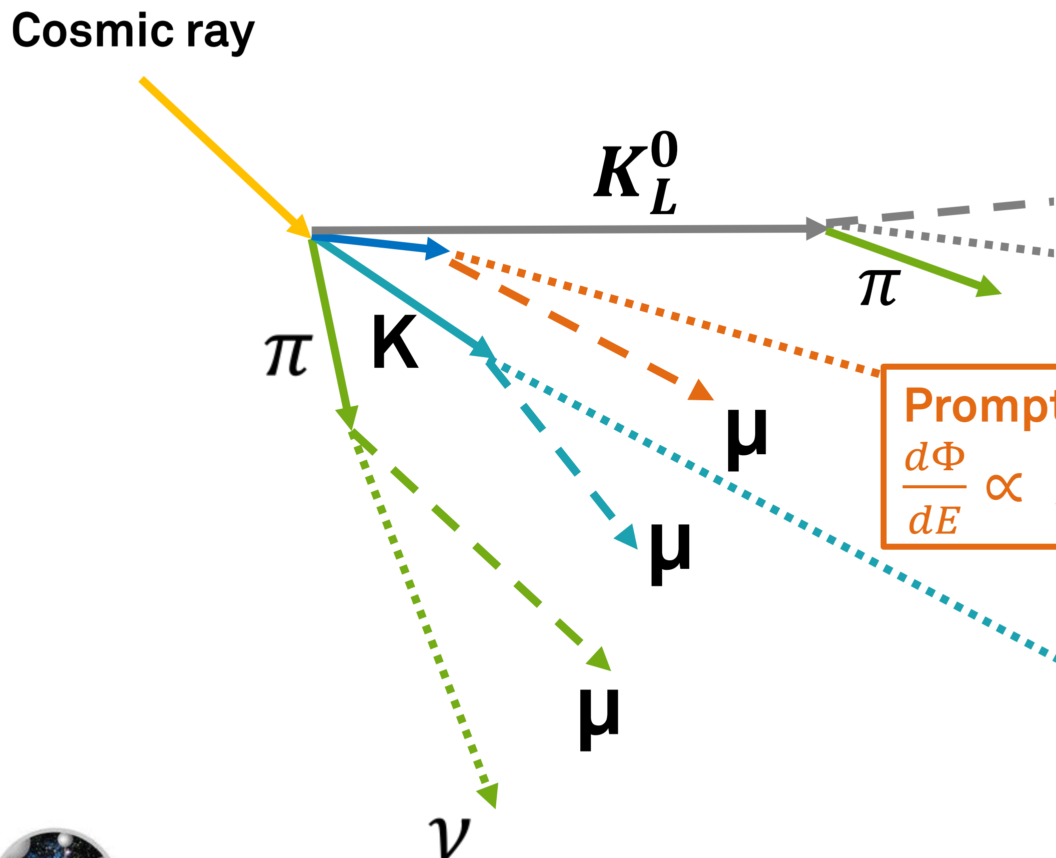
- Centered around Dec. 26th 2014
- Duration: 158 days

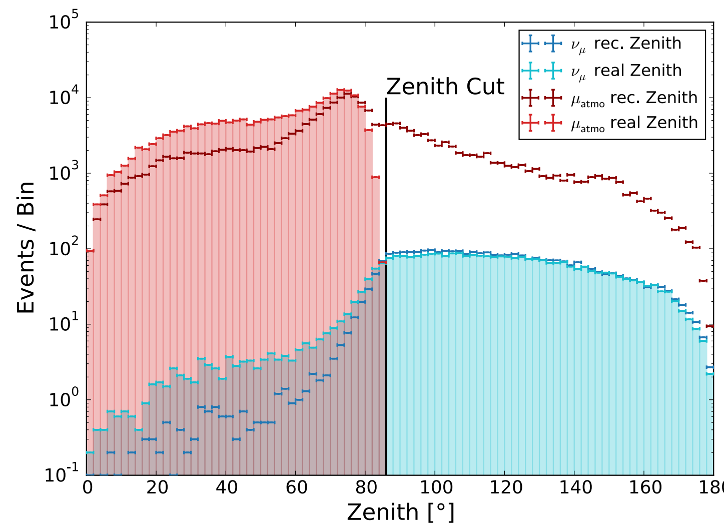


Atmospheric Neutrinos



Atmospheric Neutrinos



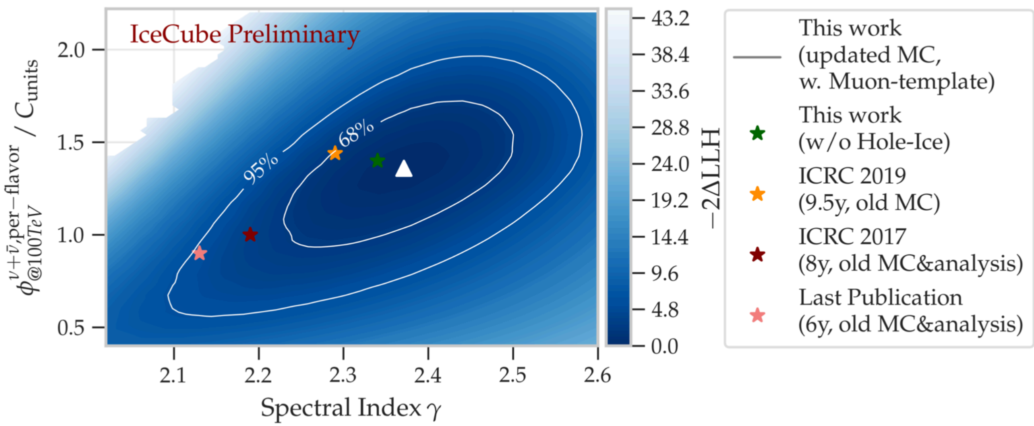


Prompt component $\frac{d\Phi}{dE} \propto E^{-2.7}$

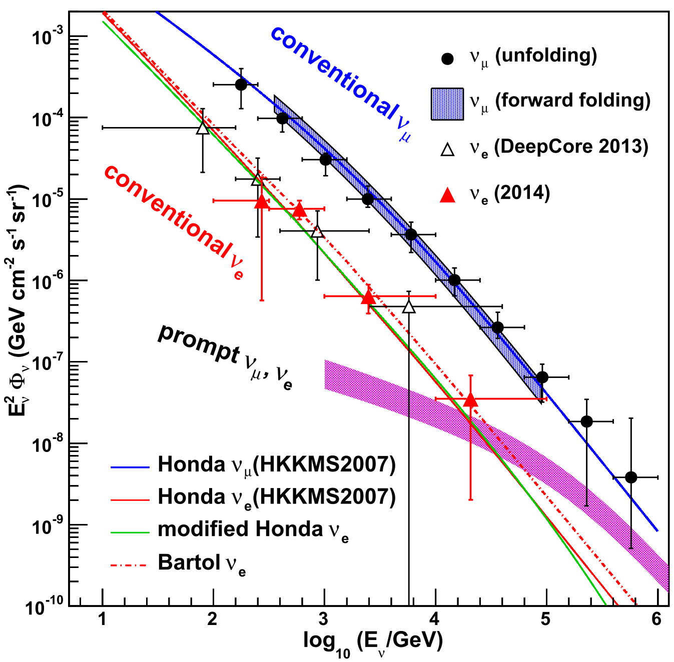
Conventional Component $\frac{d\Phi}{dE} \propto E^{-3.7}$

Two Complementary Approaches to Atmospheric Neutrinos

1. Likelihood Analysis

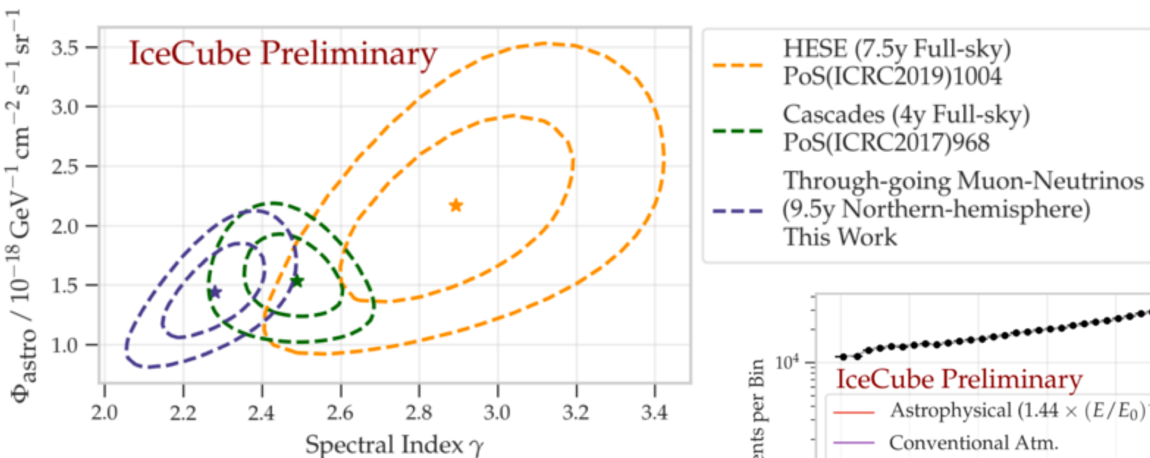


2. Reconstructed Spectrum



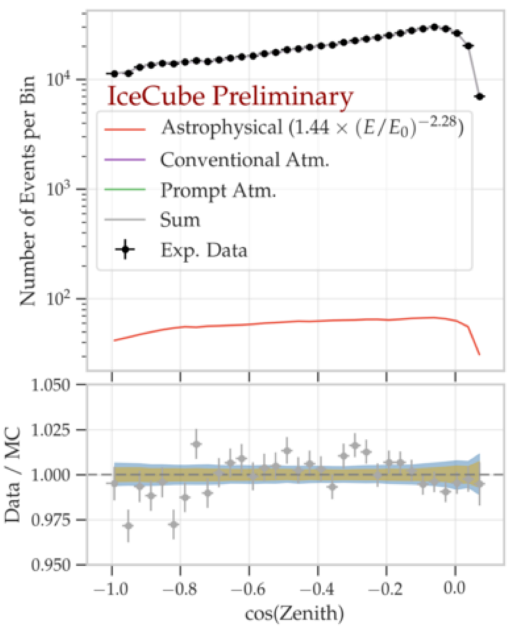
IceCube Coll., PRD 91, 122004 (2014)

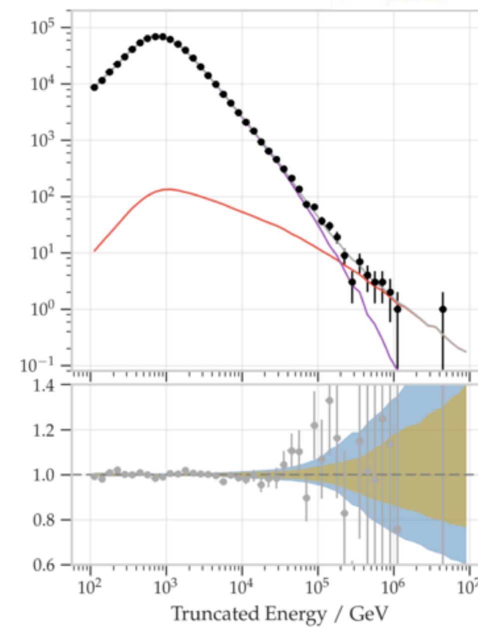
Llh-Fit



arxiv:1908.09918

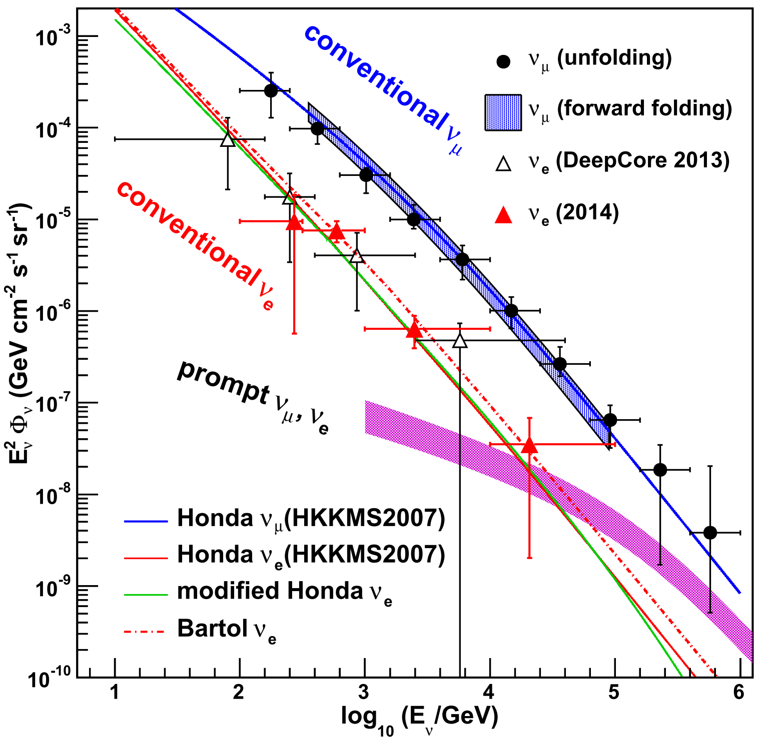
Llh-Fit to extract spectral index and normalization of the different flux components.





Requires more stringent assumptions on the spectral shape (power law).

Spectral Analysis



- Requires less stringent assumptions on spectral shape (*model independent*)

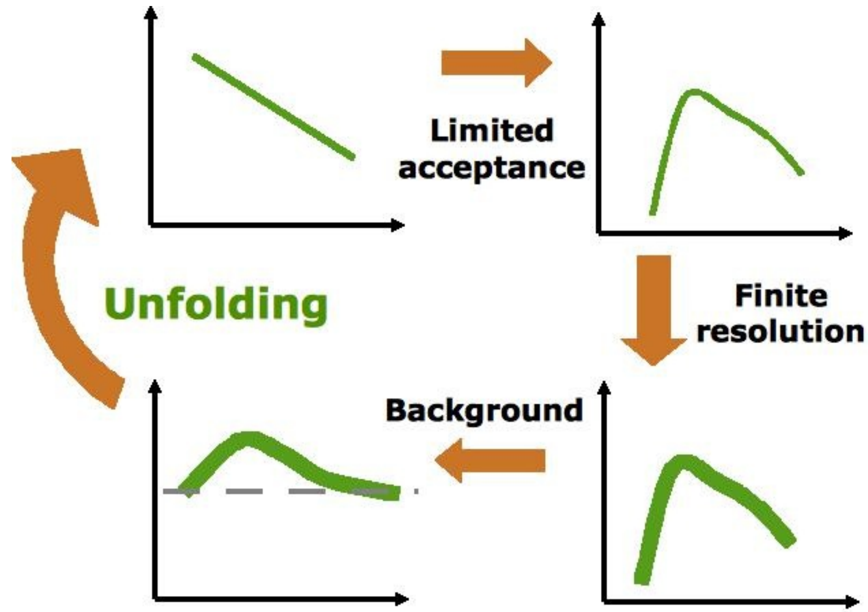
- Allows for comparison between experiments

- Does not give any answers on flux normalizazion or spectral index

- Requires the use of deconvolution

Deconvolution in a Nutshell

$$\underbrace{\frac{dN_\mu}{dE_\mu}}_{\text{Muon energy spectrum}} = \int_{E_\mu}^{\infty} \underbrace{\left(\frac{dN_\nu}{dE_\nu}\right)}_{\text{Neutrino energy spectrum}} \underbrace{\left(\frac{dP(E_\nu)}{dE_\mu}\right)}_{\text{Physics of neutrino interaction}} dE_\nu$$



- Production of charged lepton in neutrino interaction is governed by stochastical processes
- Additional smearing, due to several detector effects

Mathematically: Fredholm integral equation of the first kind:

$$g(y) = \int_{E_{min}}^{E_{max}} A(E, y) f(E) dE$$

Deconvolution in a Nutshell

$$\underbrace{\frac{dN_\mu}{dE_\mu}}_{\text{Muon energy spectrum}} = \int_{E_\mu}^{\infty} \underbrace{\left(\frac{dN_\nu}{dE_\nu}\right)}_{\text{Neutrino energy spectrum}} \underbrace{\left(\frac{dP(E_\nu)}{dE_\mu}\right)}_{\text{Physics of neutrino interaction}} dE_\nu$$

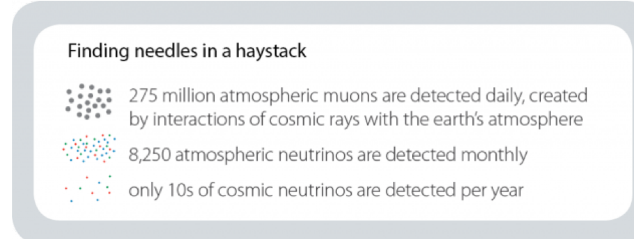
- Production of charged lepton in neutrino interaction is governed by stochastical processes
- Additional smearing, due to several detector effects

In addition: Background needs to be reduced by three orders of magnitude!

Mathematically: Fredholm integral equation of the first kind:

$$g(y) = \int_{E_{min}}^{E_{max}} A(E,y) f(E) dE$$

General Background Rejection Strategy

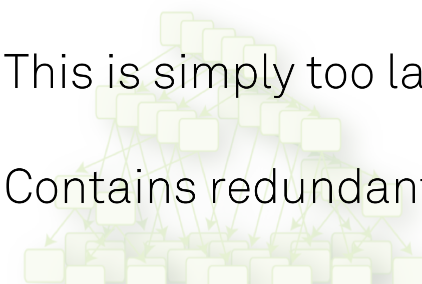


Variable Selection → Classifier Training → Cut on Classifier Output

General Background Rejection Strategy

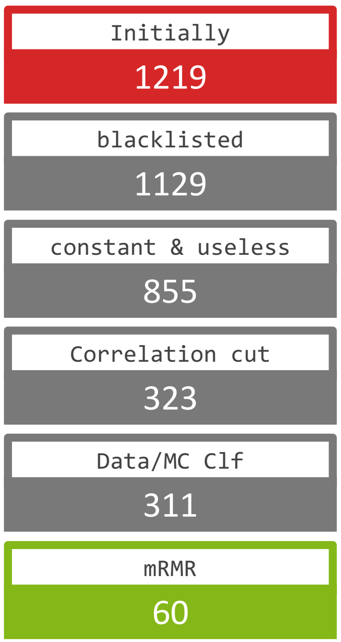
Variable Selection → Classifier Training → Cut on Classifier Output

~1200 Features



- This is simply too large to be fed into a classifier
- Contains redundant features
- Contains useless features (e.g. constant)

Feature Selection



M. Börner, PhD thesis (2018)

- Select features according to relevance and redundancy
- Feature set is built by iteratively adding features that fulfill the following criterion

$$\max_{x_j \,\epsilon\, X - S_{m-1}} \left[I(x_j, c) - \frac{1}{m-1} \sum_{x_i \,\epsilon\, S_{m-1}} I(x_i, x_j) \right]$$

Peng, H.C., Long, F., and Ding, C., IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 27, No. 8, pp. 1226–1238, 2005.

Ding, C., & Peng, H., *Journal of bioinformatics and computational biology*, *3*(02), 185-205. (2005)

General Background Rejection Strategy

Variable Selection → Classifier Training → Cut on Classifier Output

Except for the choice of the classifier, this is fairly straightforward!

Random Forests (Ensemble Methoden)

- Ensemble of many decision trees
- Every tree is build in a randomized way
- Every tree‘s classification is independent from all other trees
- Forest Classification is average over classification of individual trees

$$c_{Signal} = \frac{1}{n_{trees}} \sum_{i}^{n_{trees}} c_i$$

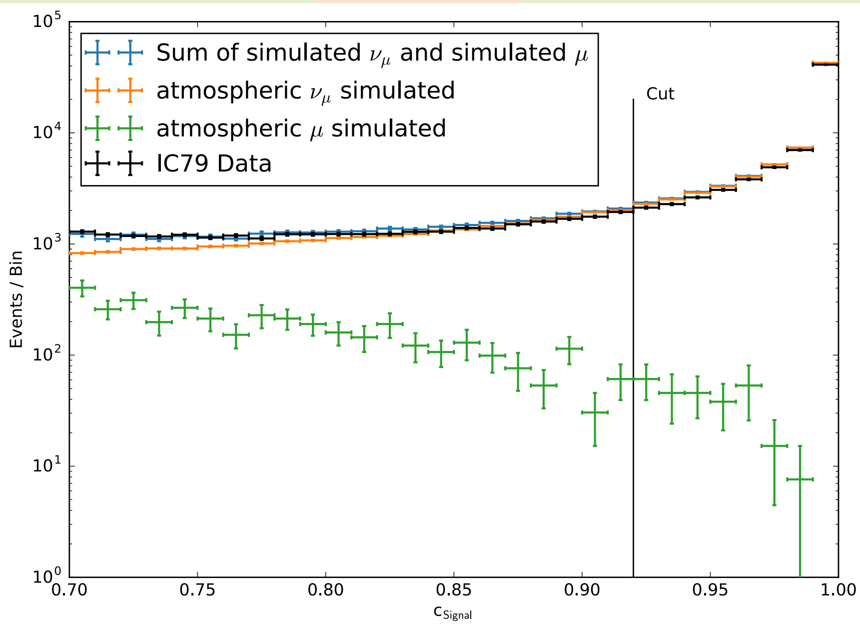
General Background Rejection Strategy

$$c_{Signal} = \frac{1}{n_{trees}} \sum_{i}^{n_{trees}} c_i$$

Variable Selection

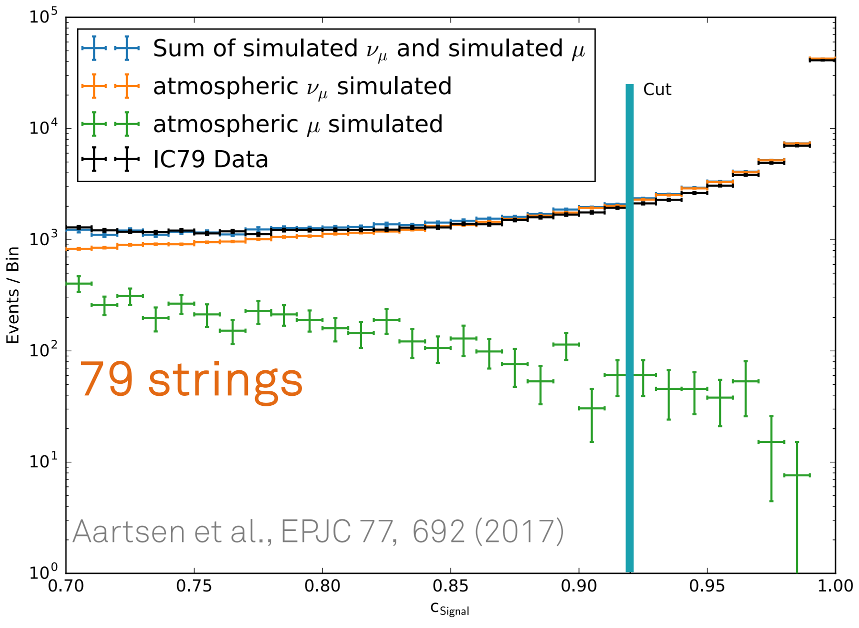
Classifier Training

Cut on Classifier Output

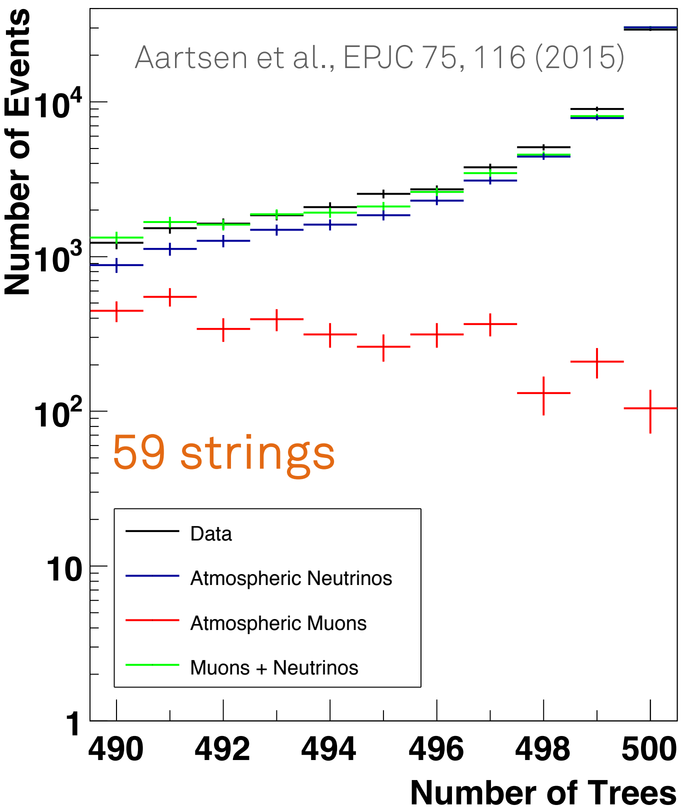


Picture: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=14260

Cut on Classifier Output

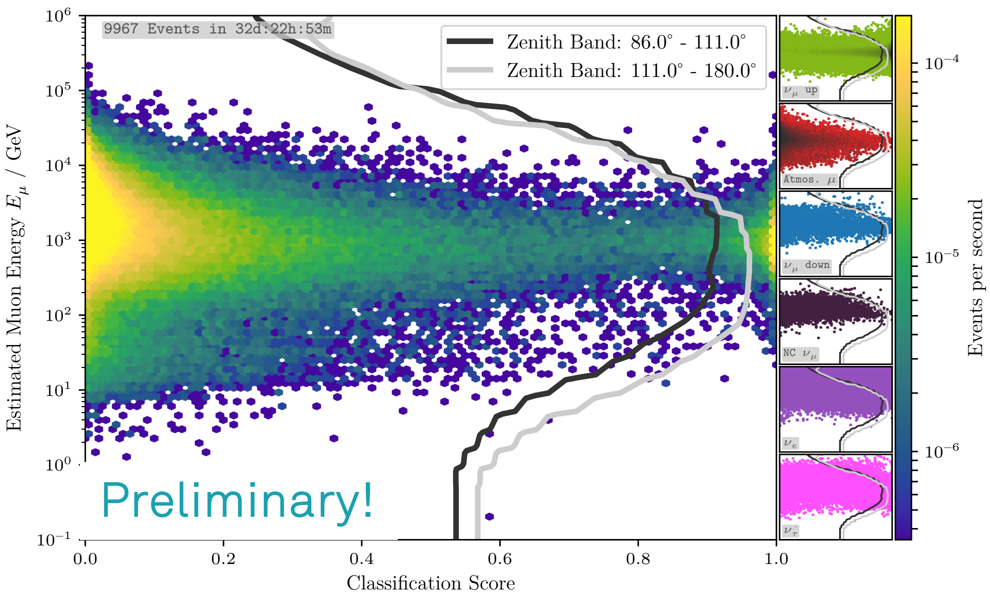


~ 200 neutrino candidates per day

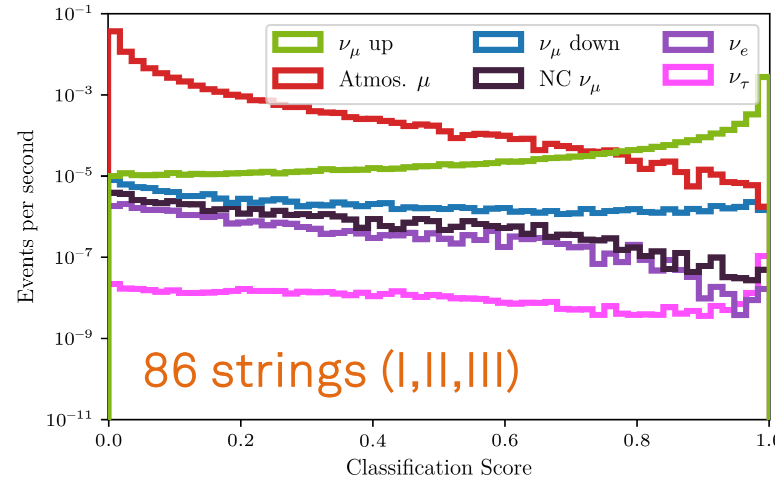


~ 80 neutrino candidates per day

2D-Cut on Classifier Output



~ 300 neutrino candidates per day!!!



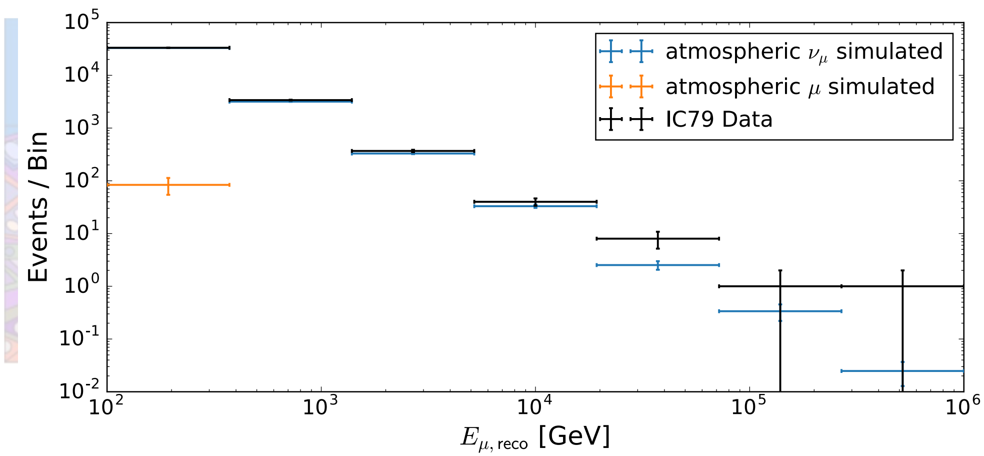
Classifier output is energy and zenith dependent.

Score cut as a function of energy and zenith.

M. Börner, PhD thesis (2018)

General Background Rejection Strategy

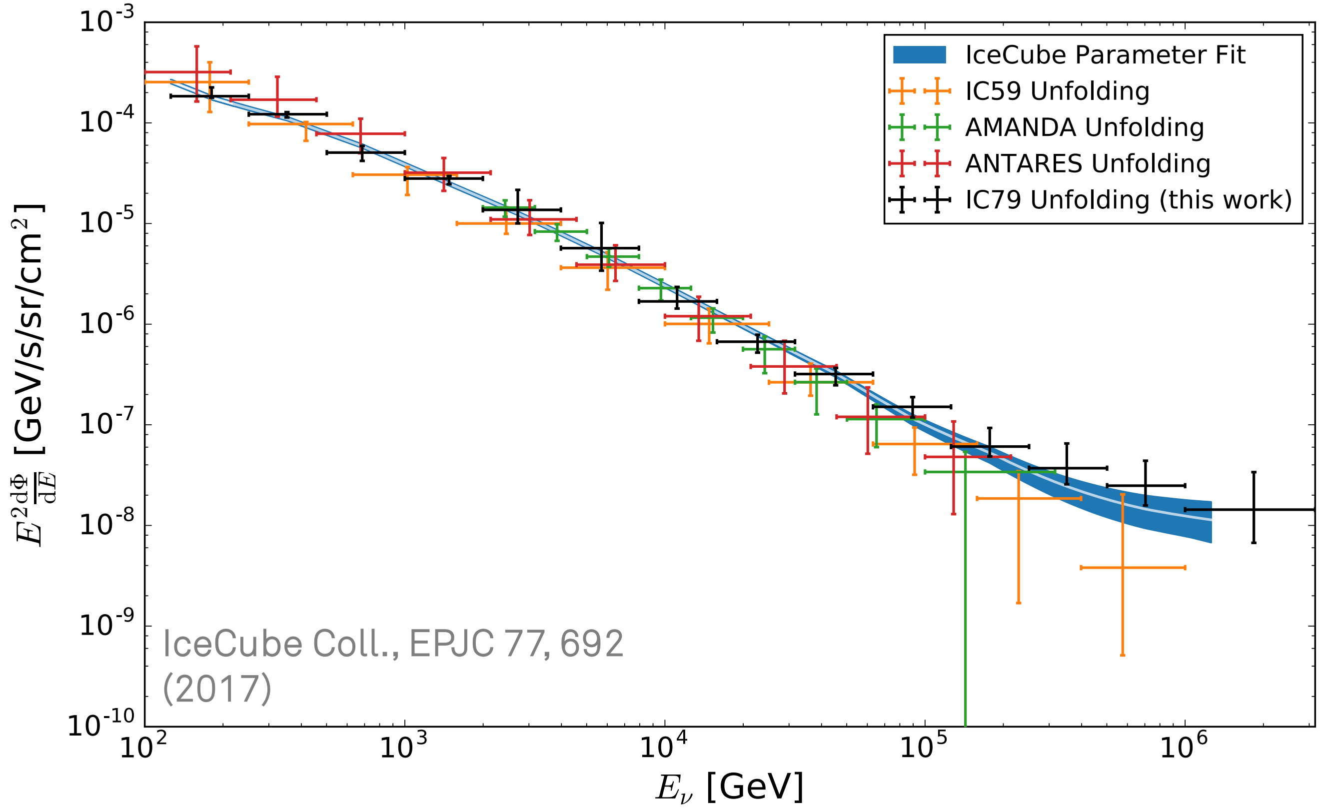
Variable Selection → Classifier Training → Cut on Classifier Output



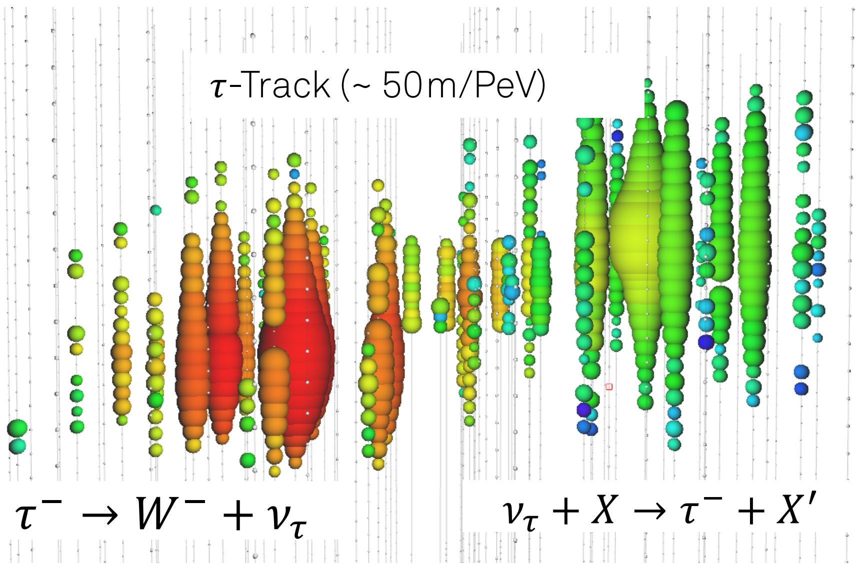
Purity generally above 99%.

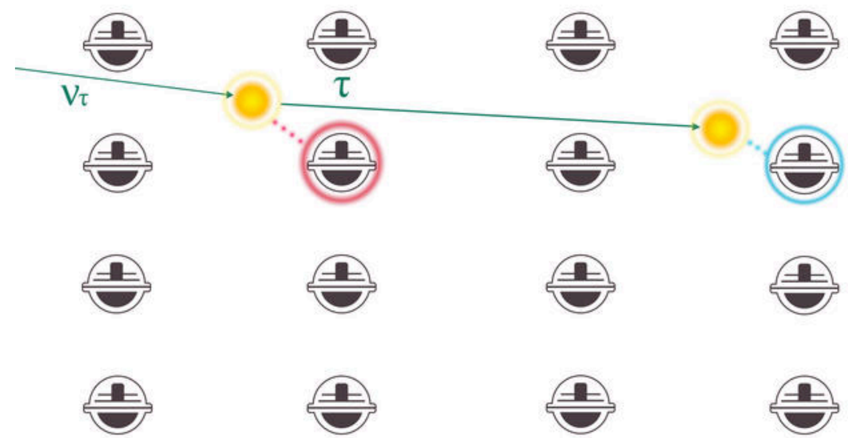
Even more important: Make sure there are no muons in bins with small statistics.

Atmospheric Neutrino Spectra

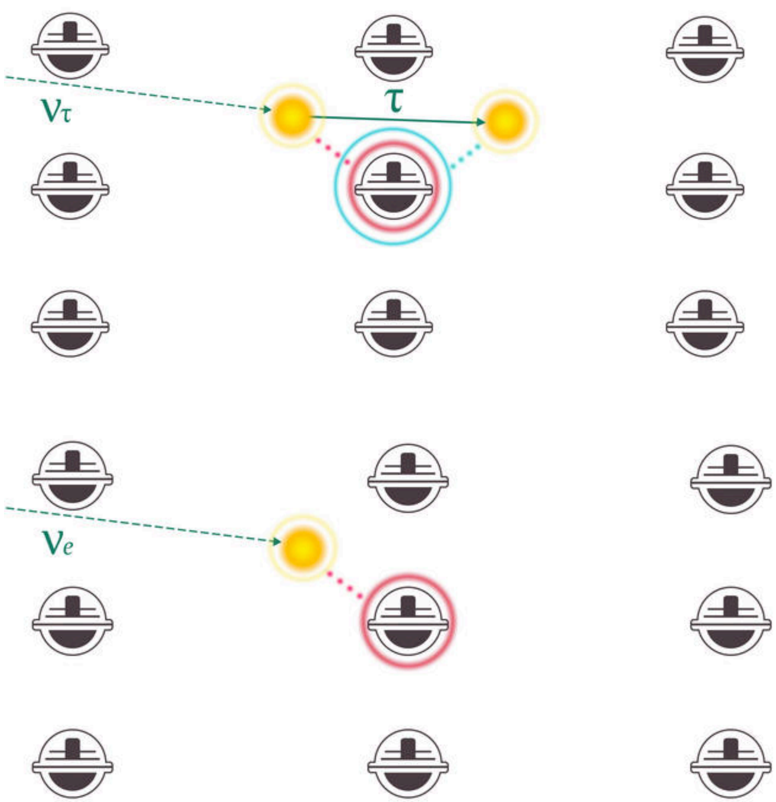


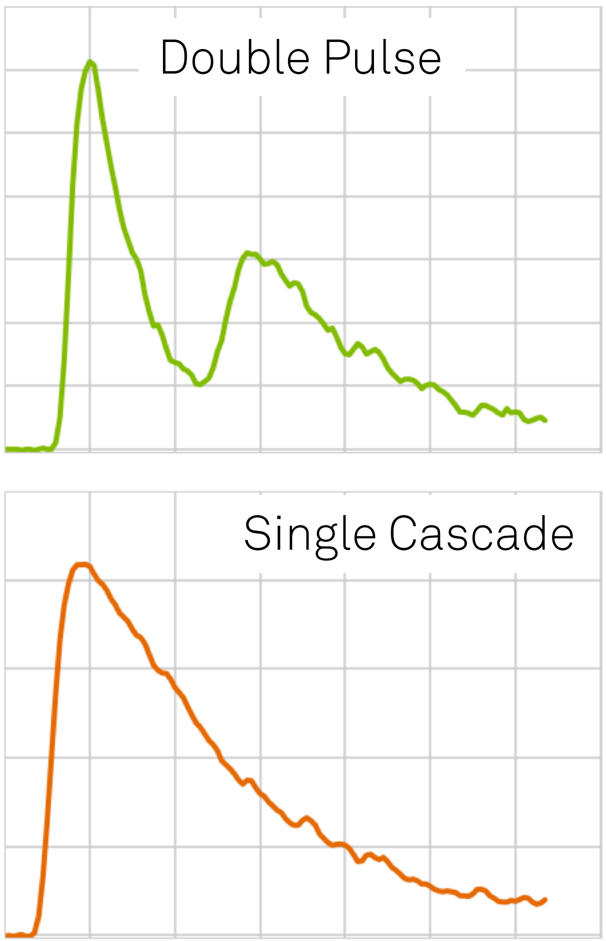
Tau-Neutrino Signatures, Double Cascade





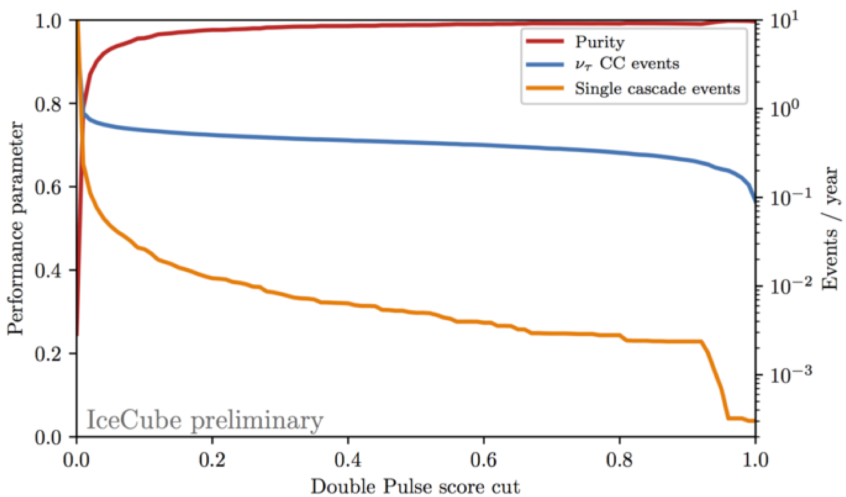
Single- and Double-Pulses





Tau-Neutrino Search with Machine Learning

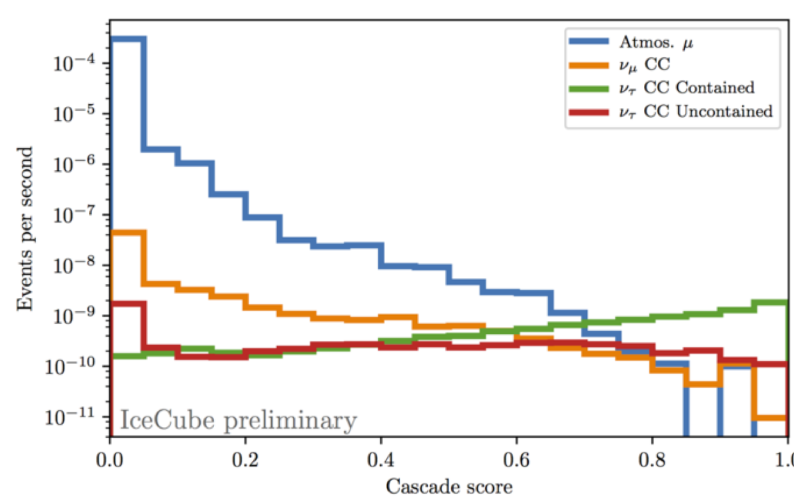
Random Forest #1



Score Cut: 0.2

Purity increases to 97%

Random Forest #2

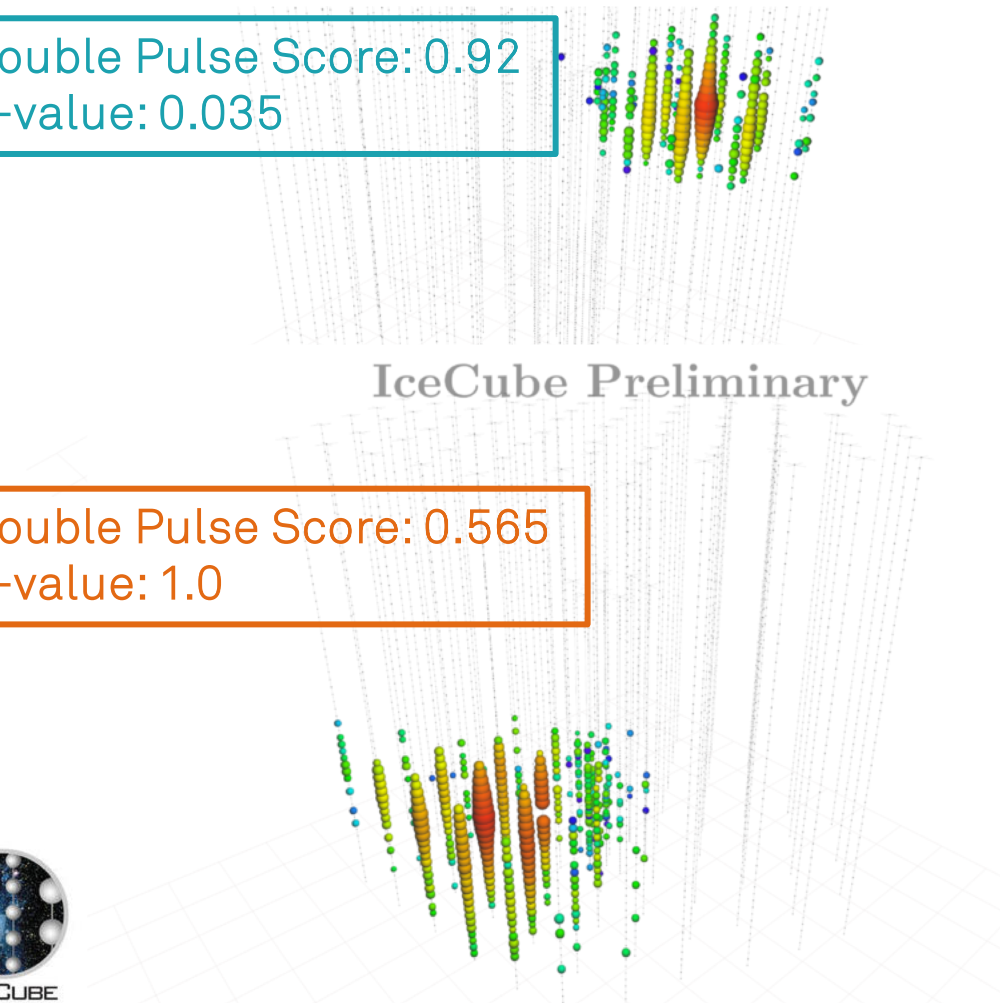


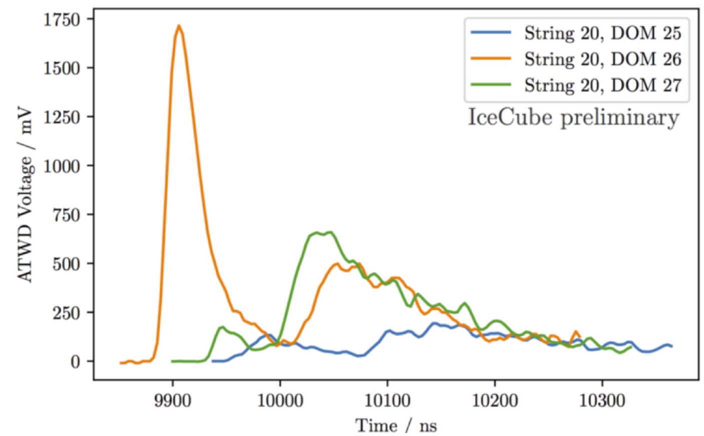
Score Cut: 0.62 (optimized via Model Rejection Factor)

2 Events survive both cuts

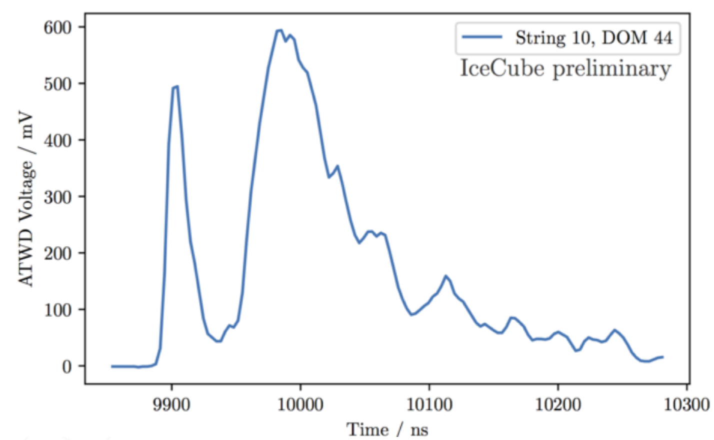
Tau-Neutrino Search with Machine Learning

Double Pulse Score: 0.92
p-value: 0.035

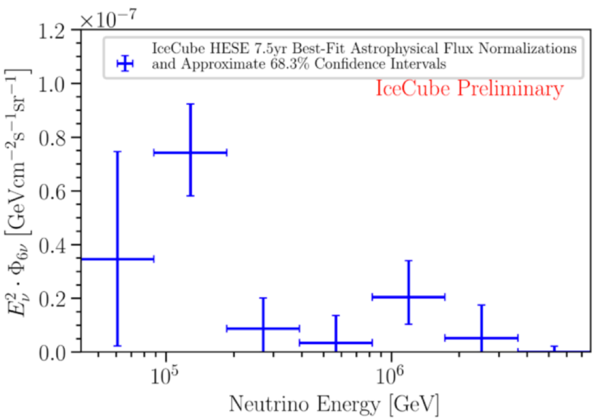


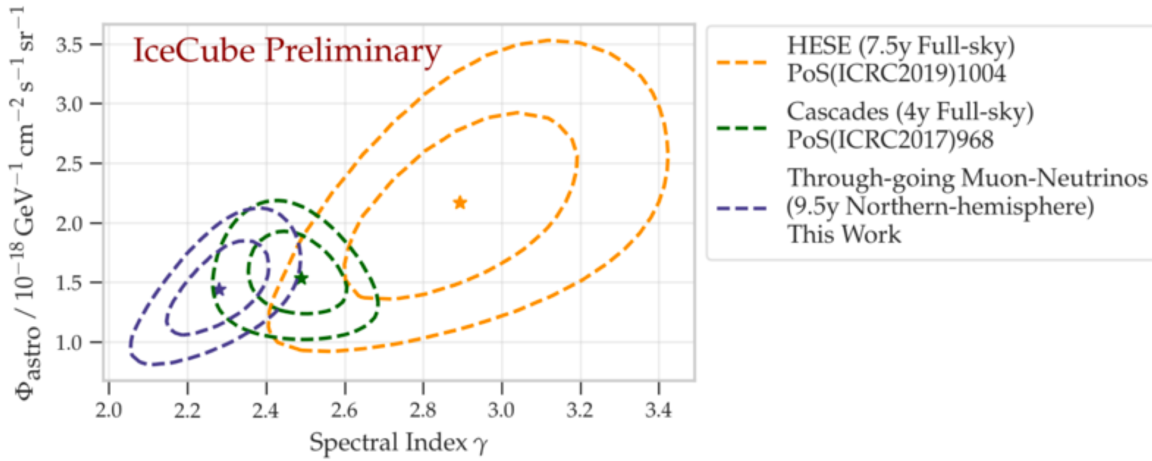


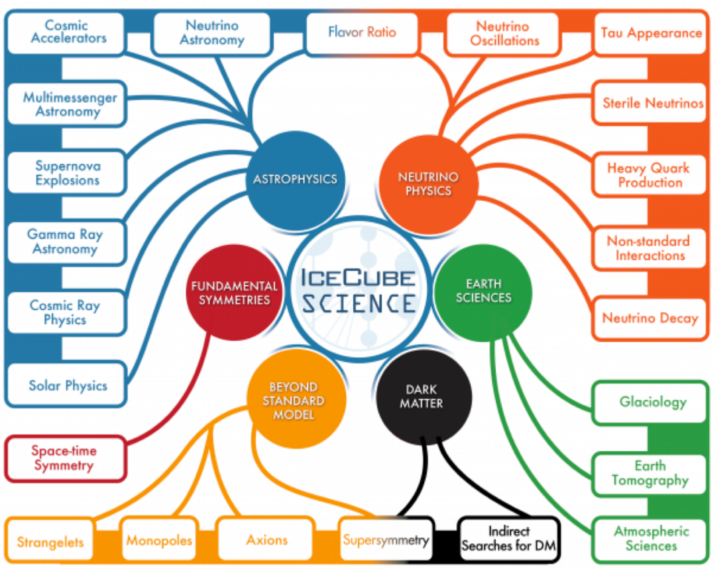
Double Pulse Score: 0.565
p-value: 1.0

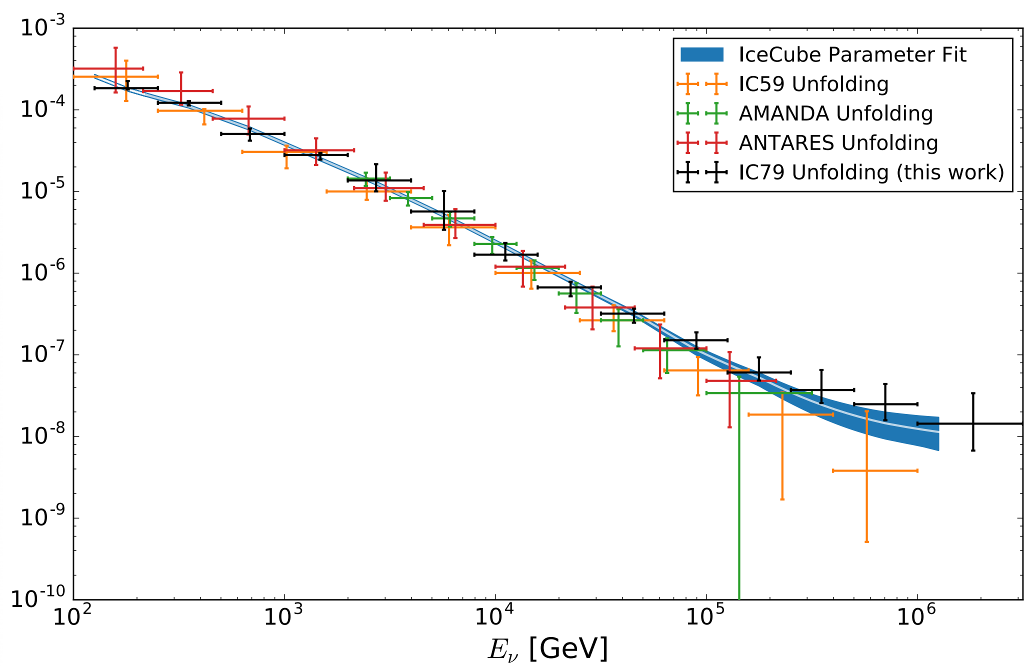


Summary


×10^-7
IceCube HESE 7.5yr Best-Fit Astrophysical Flux Normalizations and Approximate 68.3% Confidence Intervals
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{6\nu}$ [GeV cm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^5
10^6


IceCube Preliminary
HESE (7.5y Full-sky)
PoS(ICRC2019)1004
Cascades (4y Full-sky)
PoS(ICRC2017)968
Through-going Muon-Neutrinos
(9.5y Northern-hemisphere)
This Work
Φ_{astro} / 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
Spectral Index γ
3.5
3.0
2.5
2.0
1.5
1.0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4


Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences


IceCube Parameter Fit
IC59 Unfolding
AMANDA Unfolding
ANTARES Unfolding
IC79 Unfolding (this work)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^2
10^3
10^4
10^5
10^6
E_ν [GeV]