IceCube実験による宇宙ニュートリノの証拠

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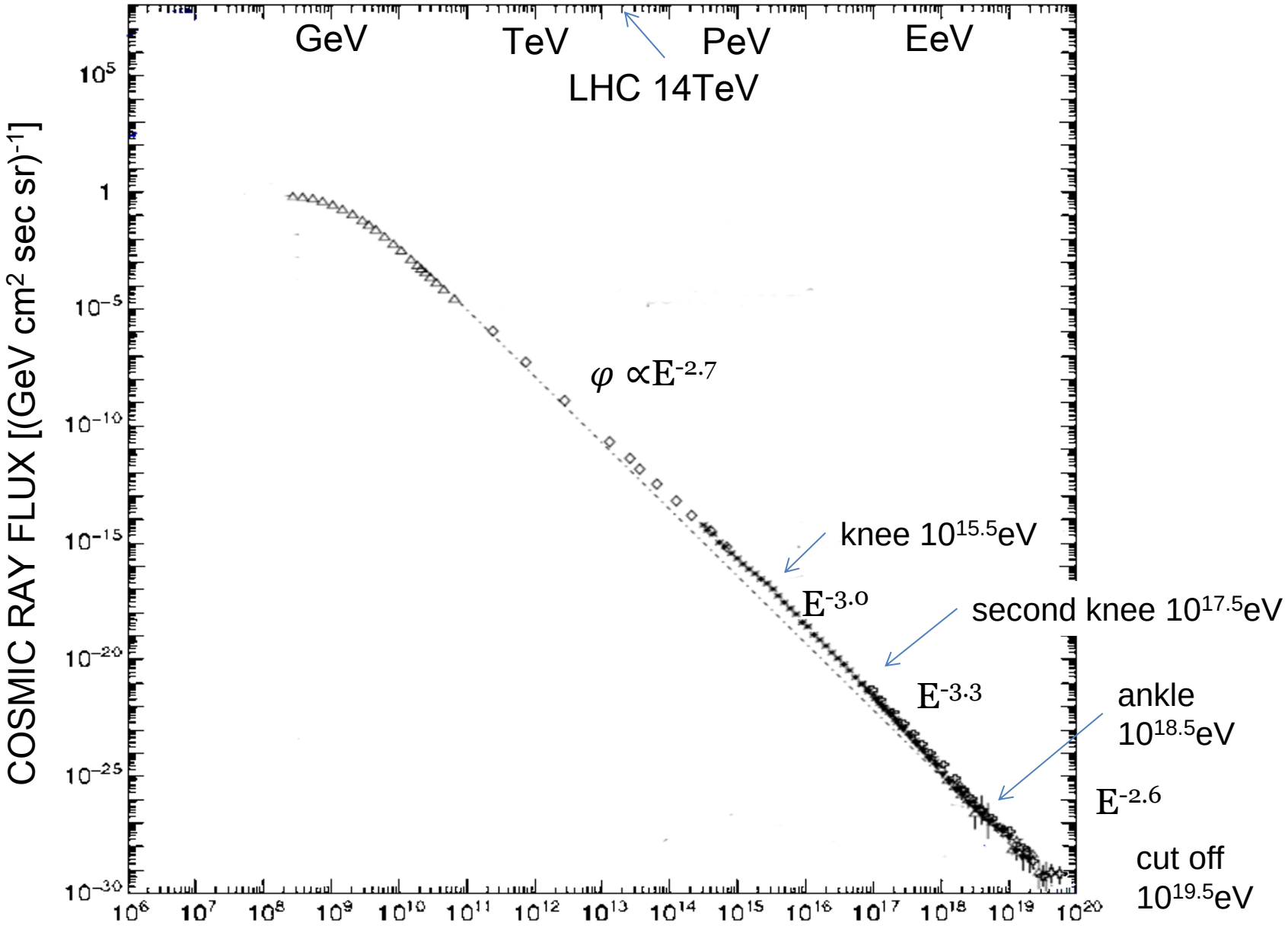
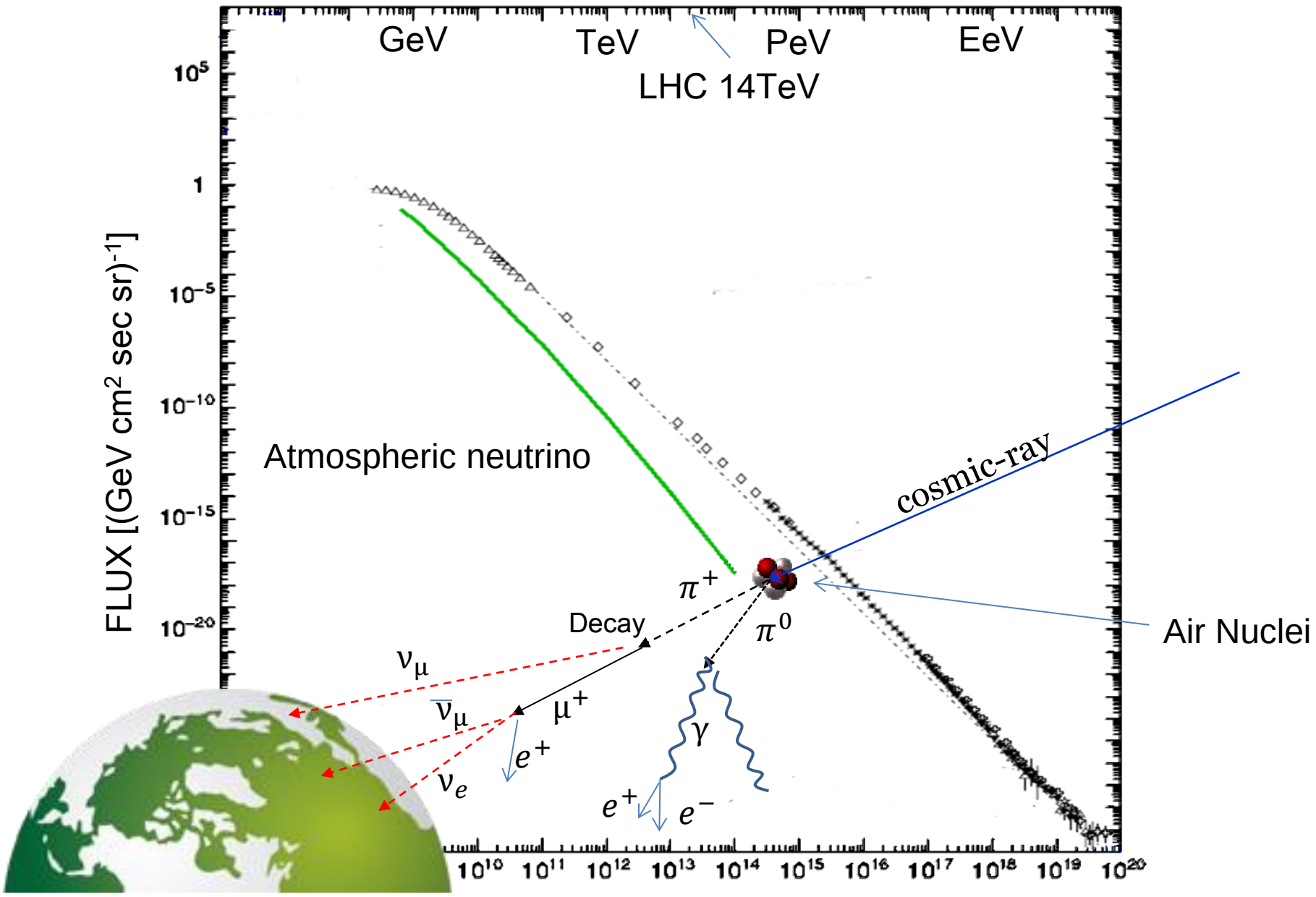
The High Energy Deep Universe Mystery

- 起源のわからない高エネルギー粒子が宇宙から地球に飛来している。どこから？
  エネルギーはLHC加速器の1000万倍以上に達する
  （100EeV＝10keV(x-ray) x 10,000,000,000,000,000!）
- 巨大ブラックホールである活動銀河核（AGN)や宇宙で最も激しい爆発現象であるガンマ線爆発（GRB)といった極限爆発現象は遠方（若い）宇宙に分布
  - 高エネルギー宇宙の進化の歴史には謎が多い

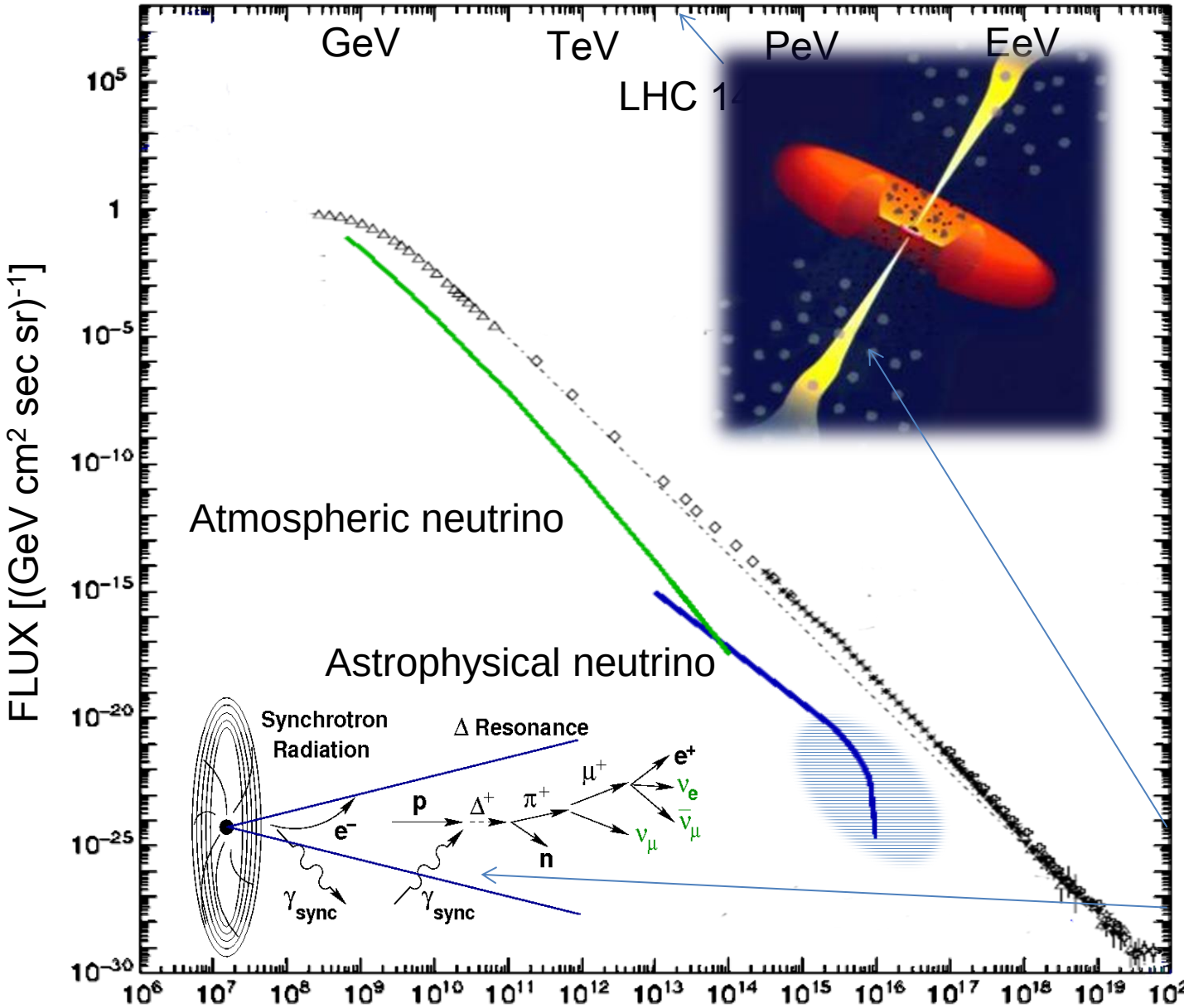
Extremely-high energy emission in the Universe



Extremely-high energy emission in the Universe

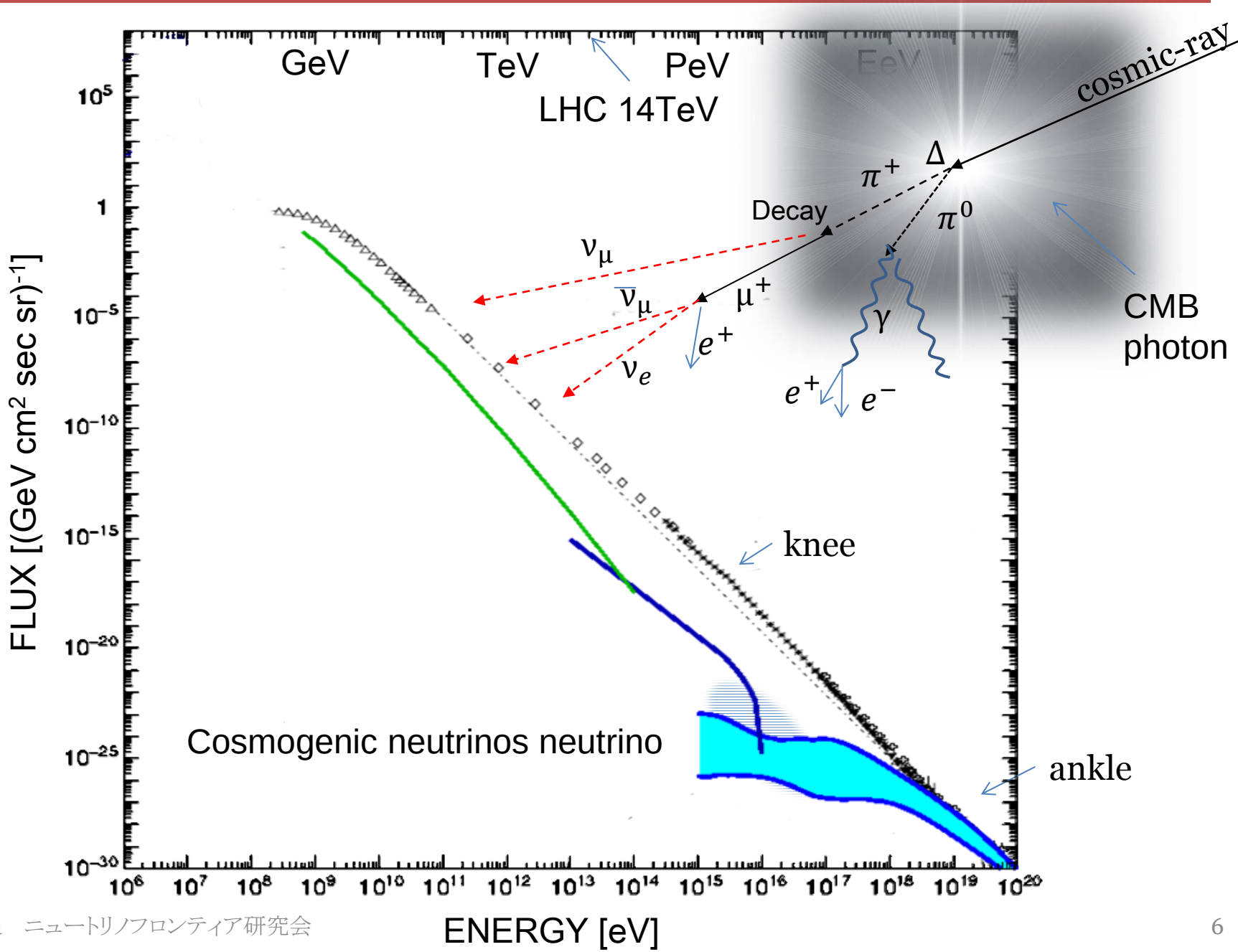


Extremely-high energy emission in the Universe



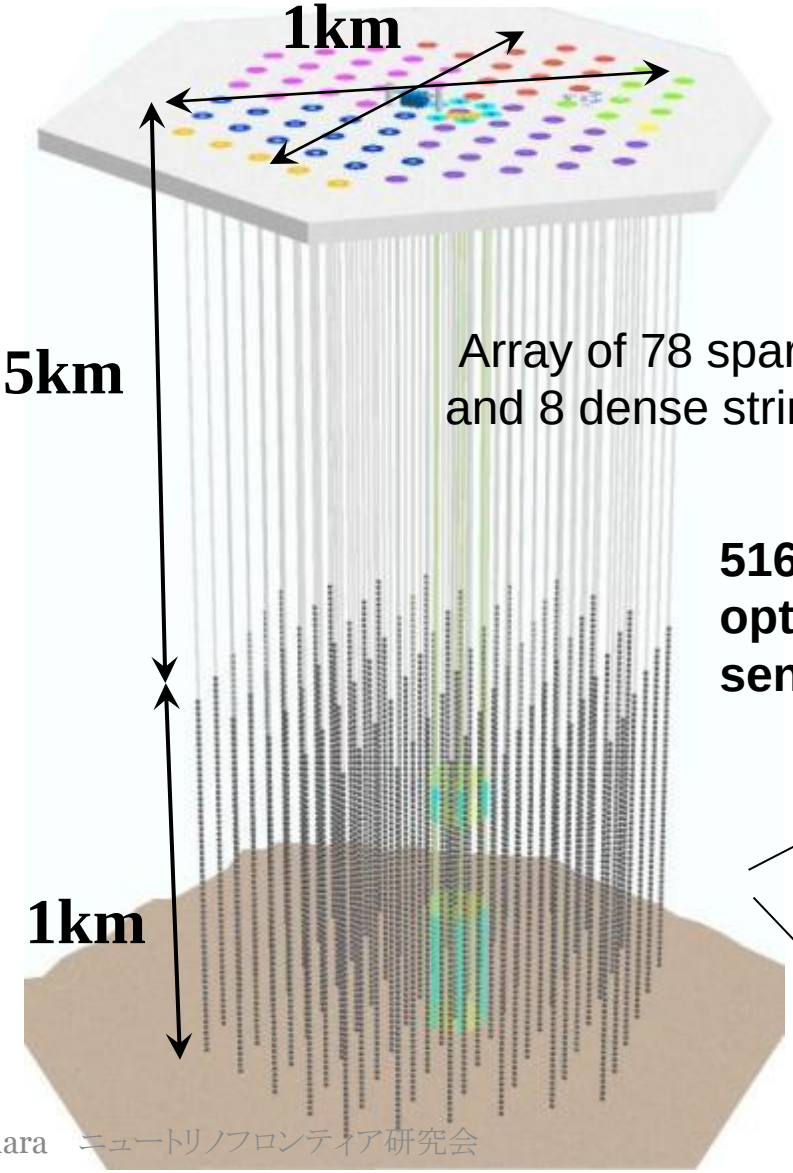
astrophysical photon or matter

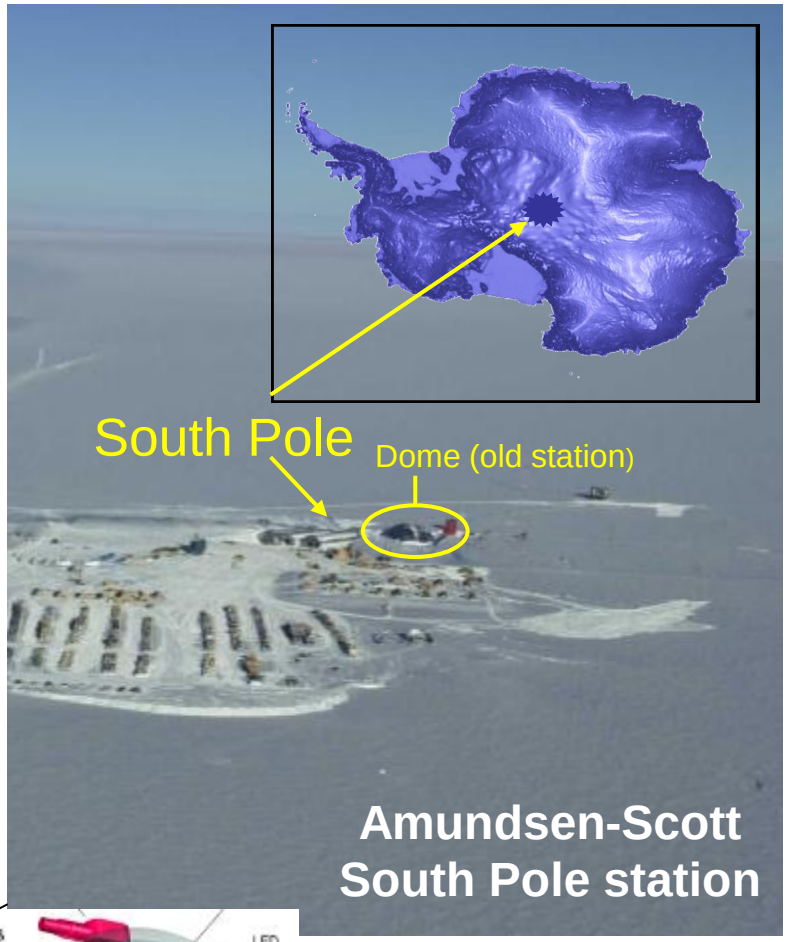
Extremely-high energy neutrinos in the Universe

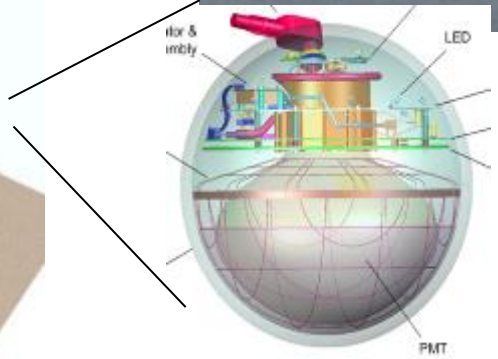


The Largest Neutrino Detector in the world:

The IceCube Detector

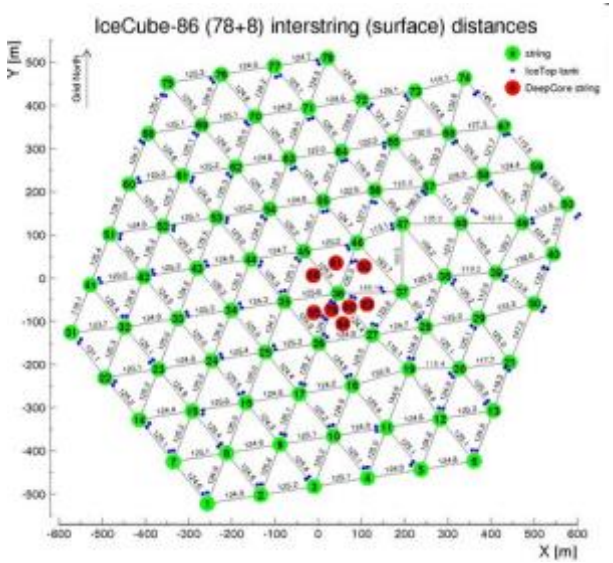




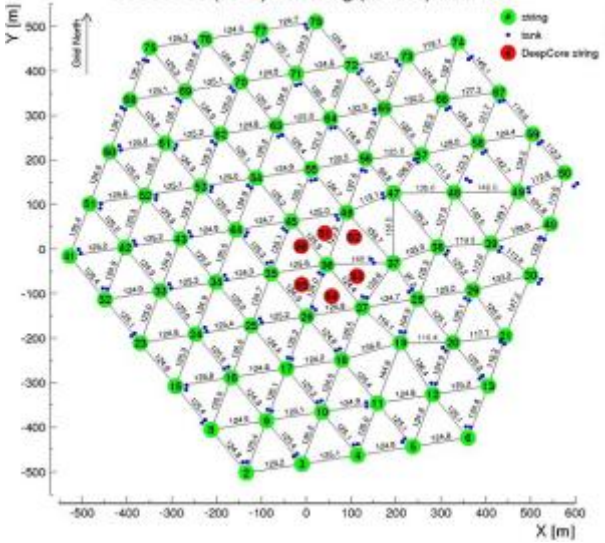


IceCube Construction and Runs

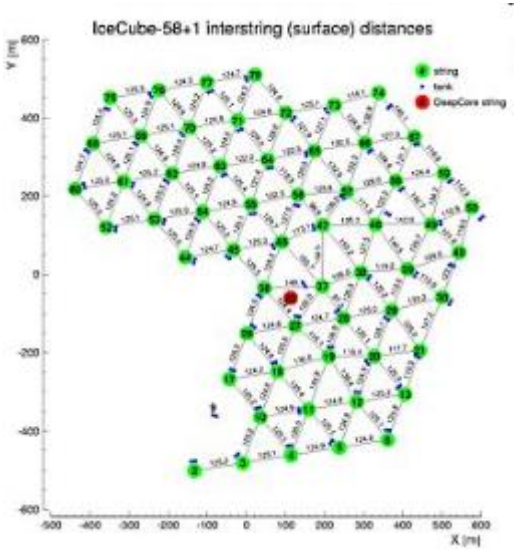
IC86 = full IceCube (2011~)



IC79 (2009-2010)

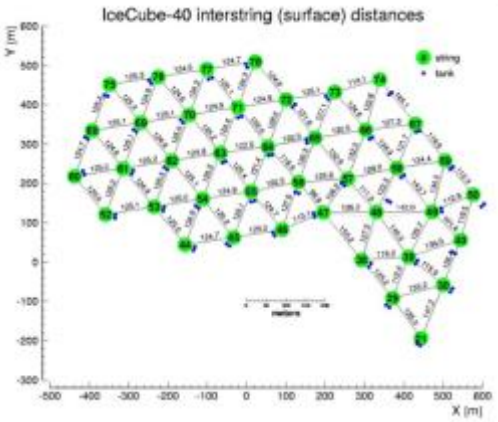


IC59 (2008-2009)



Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per day)
IC40	2008-09	375 days	1100	~40/ day
IC59	2009-10	350 days	1900	~70/ day
IC79	2010-11	320 days	2250	~100/day
IC86-I	2011- 2012	360 days	2700	~120/day
IC86-II	2012- 2013	360 days	2700	~120/day
IC86-III	2013-	TBD	2700	~120/day

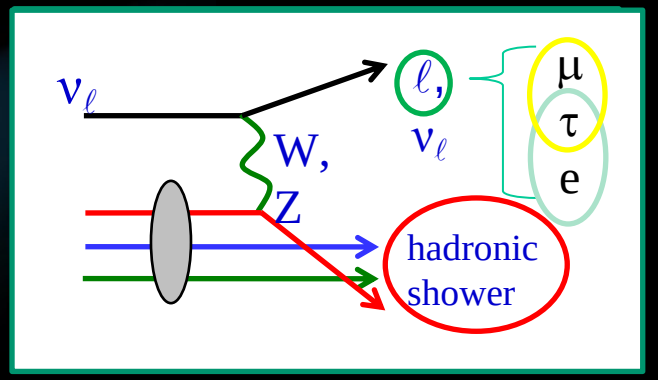
IC40 (2007-2008)



Very stable full operation since May 2011

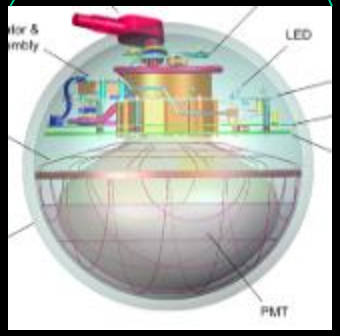
Detection Principle

Dark and transparent material



μ, τ or cascades

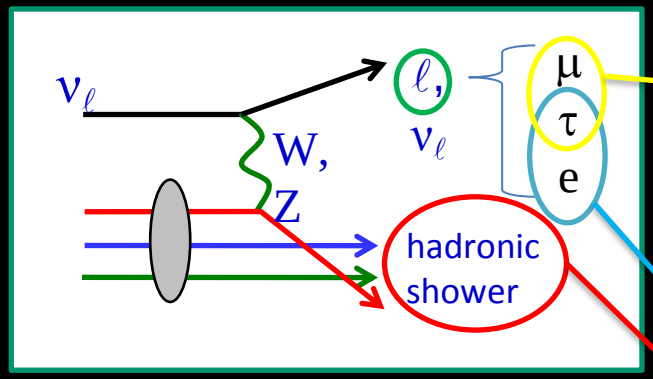
Cherenkov light



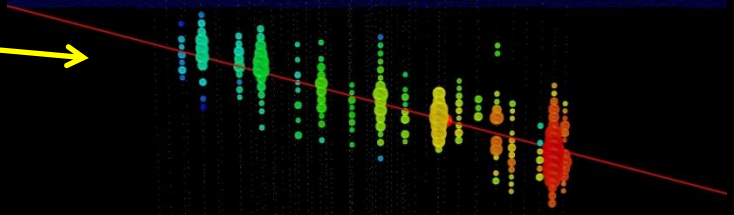
An array of
photomultiplier tubes

ν

IceCube event signatures

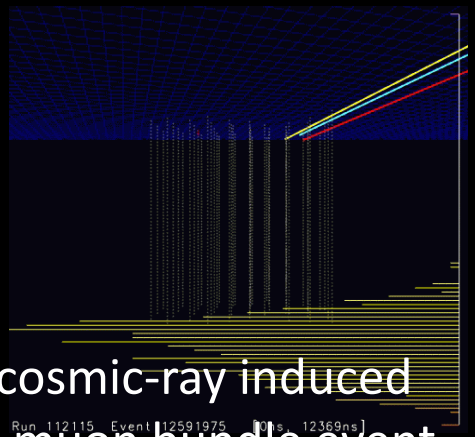


With 59 strings 2009



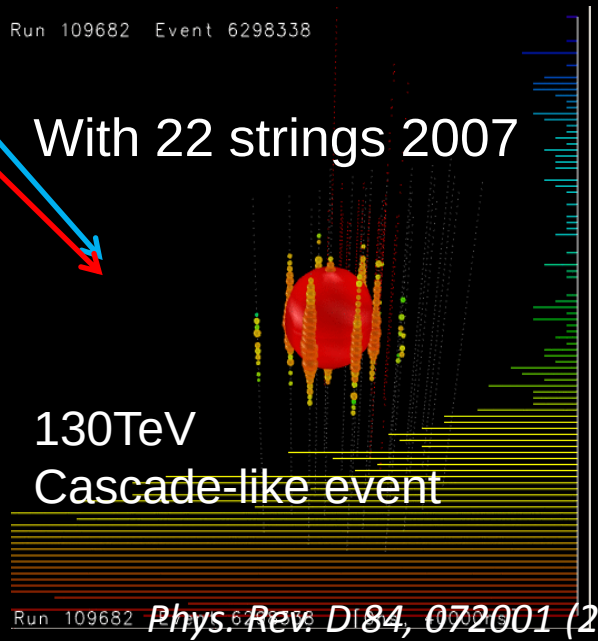
～100TeV up-going muon track event

With 40 strings, 2008 Dec



high energy cosmic-ray induced atmospheric muon bundle event

With 22 strings 2007



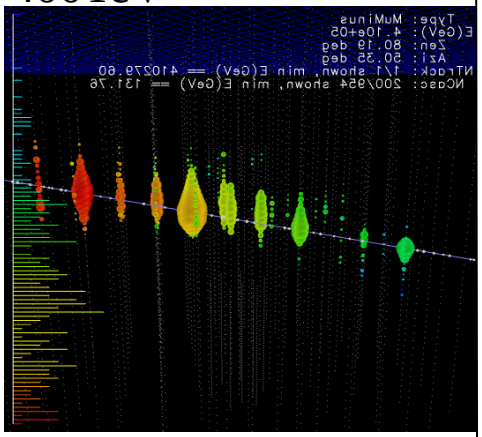
130TeV Cascade-like event

Phys. Rev. D 84, 072001 (2011)

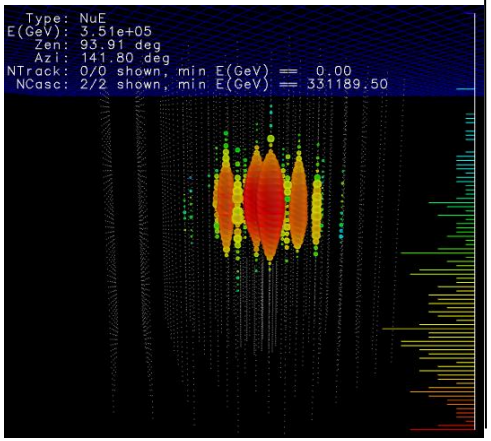
‘Brightness’ is the signature for UHE neutrinos

below ~PeV, upward-going tracks and cascade-like topology is important

400TeV



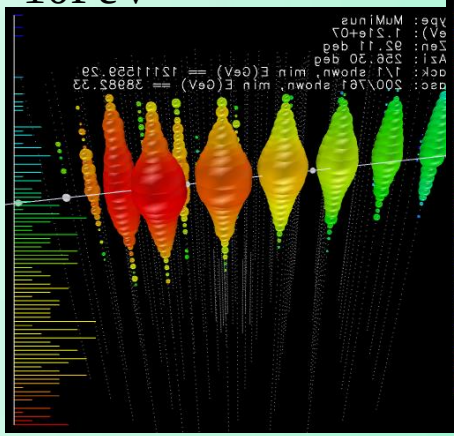
350TeV



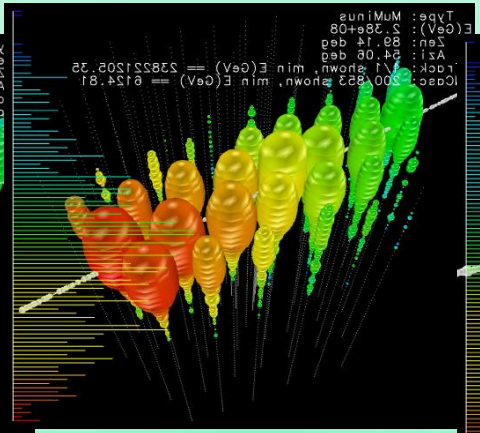
‘Very bright’ is an important feature

A brightness condition can select both type of events

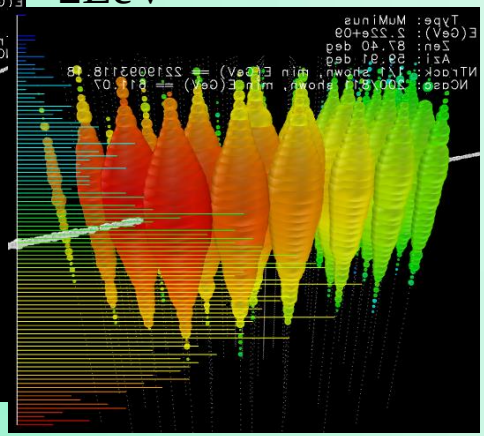
10PeV



200PeV



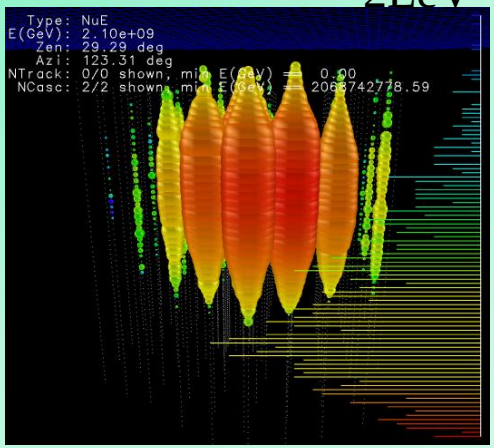
2EeV



$$-\left\langle \frac{dE}{dX} \right\rangle = \alpha + \beta E$$

- NPE is the number of photoelectron signals measured by IceCube detector

2EeV

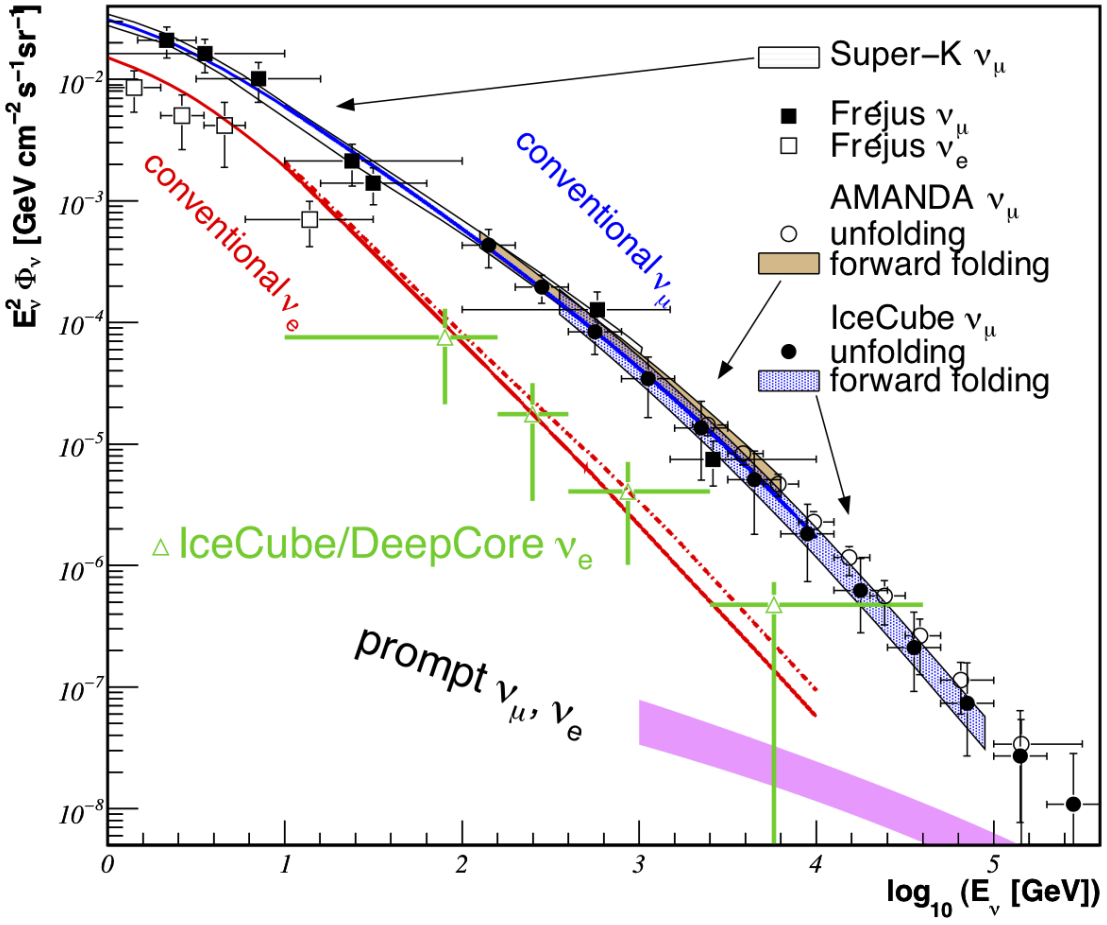


from MC simulation

大気ニュートリノの観測

SK

IceCube/DeepCore



- ν_μ
- Data: 2008-2009
- 100 GeV to 400 TeV

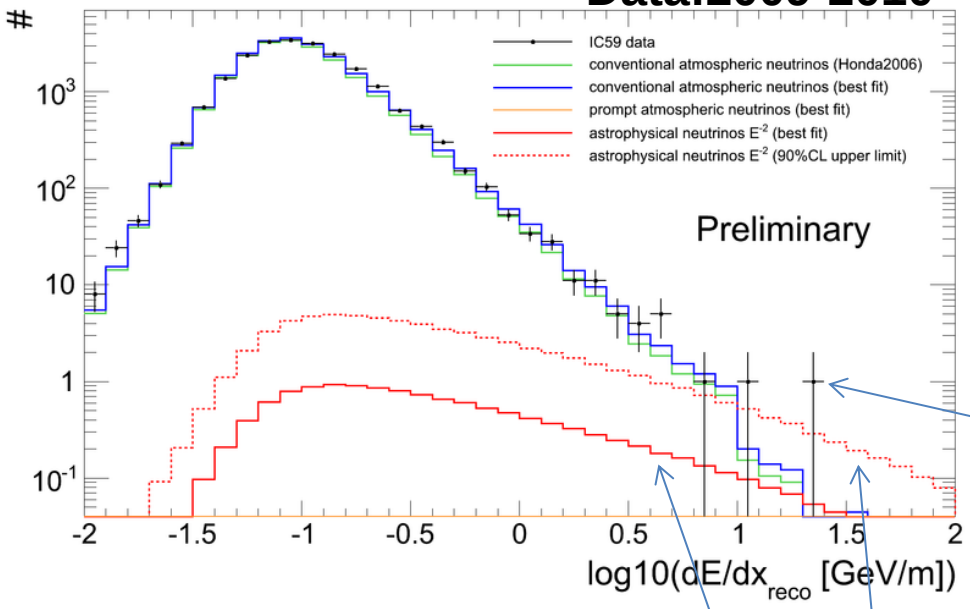
Phys. Rev. D 83, 012001 (2011)

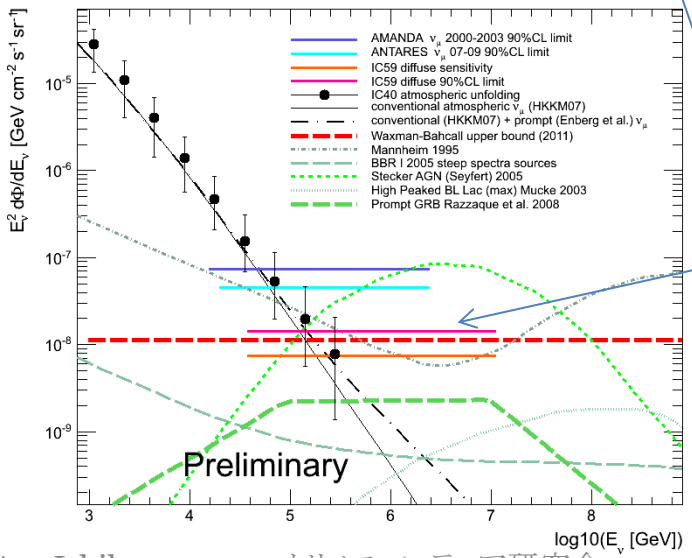
- ν_e
- Data: 2010-2011
- DeepCore
- 80 GeV to 6 TeV

Phys. Rev. Lett. 110, 151105 (2013)

Extraterrestrial neutrino search with ν_μ

Data:2009-2010

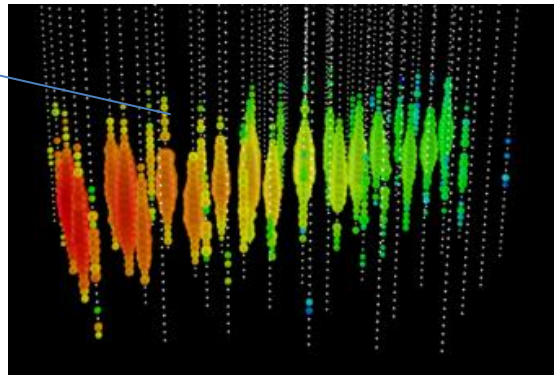




Deviation high energy upward-going muon tracks from the well measured atmospheric neutrino flux

arXive:1302.0127
Anne Schukraft, Dissertation

The found highest energy event

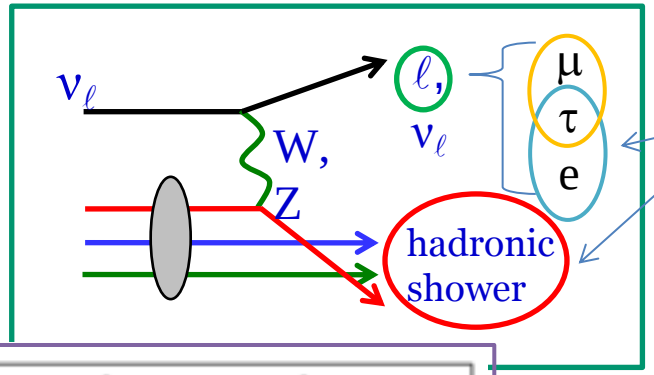


Upperlimit on $\phi_{astro} \propto E^{-2}$ for ν_μ
$E^2\phi = 1.4 \times 10^{-8}$ [GeV cm-1 s-1 sr-1]

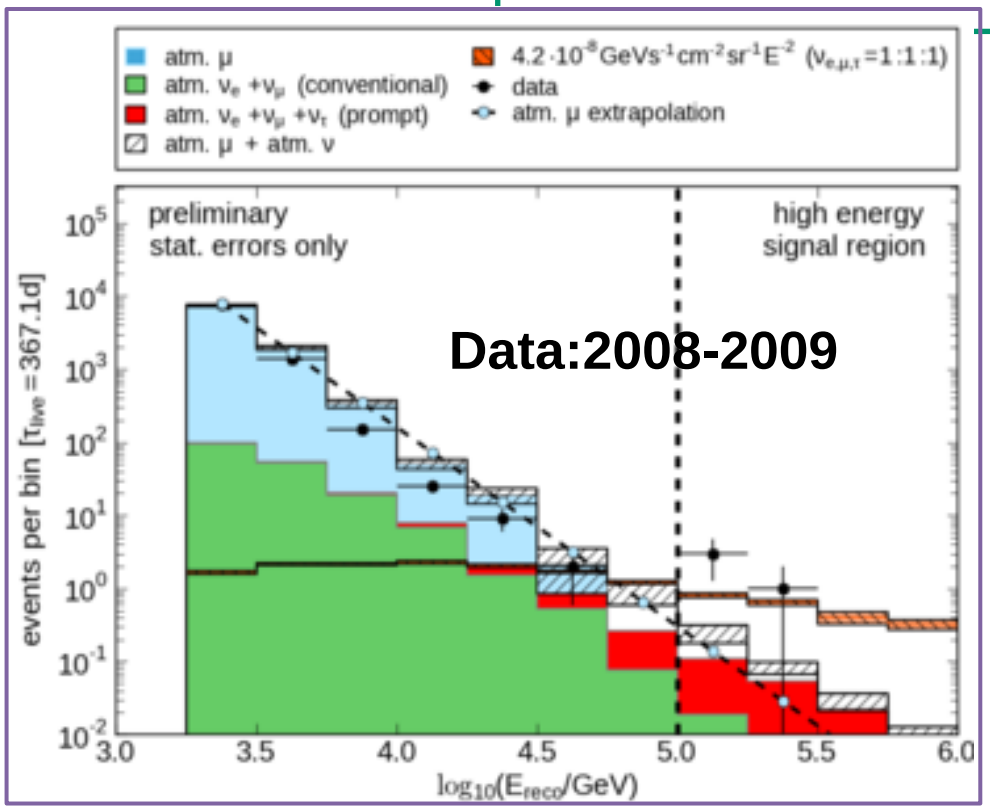
Null hypothesis 1.8σ

Best fit results of $\phi_{astro} \propto E^{-2}$ for ν_μ
$E^2\phi = (2.7 \pm 5.9) \times 10^{-9}$ [GeV cm-1 s-1 sr-1]

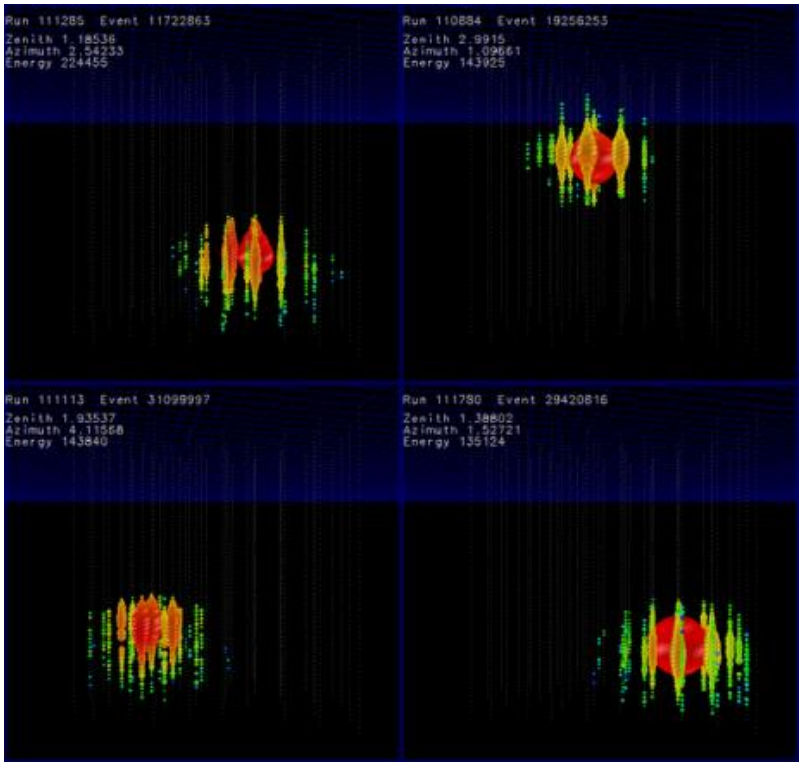
Extraterrestrial neutrino search with cascades



cascade-like signatures



IC40



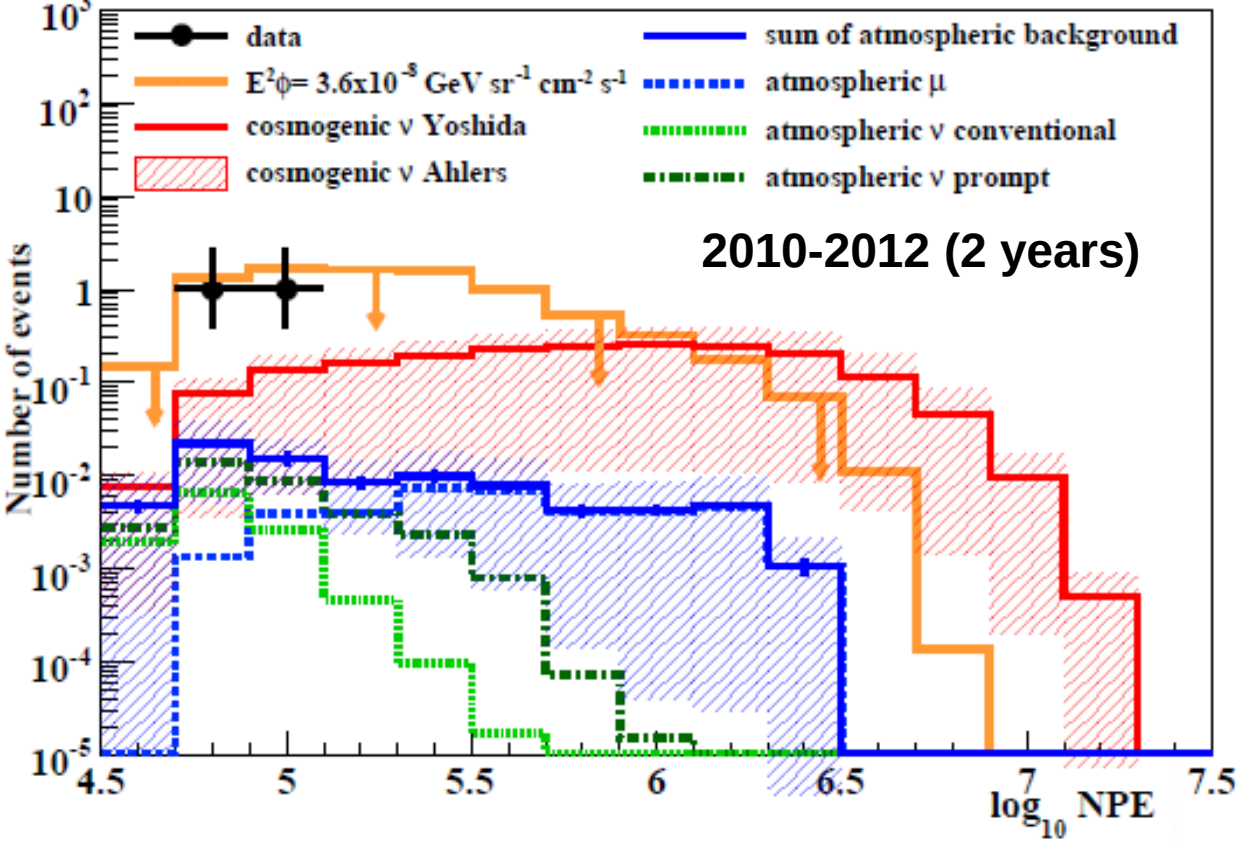
Null hypothesis 2.4σ

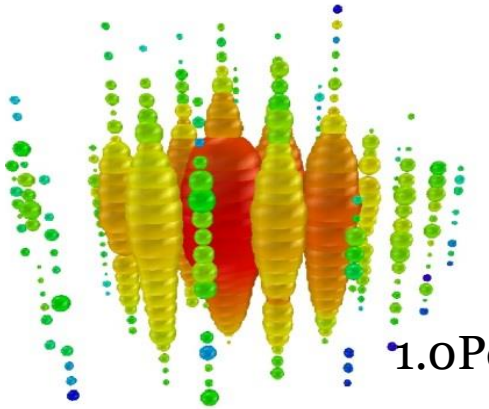
Extremely high energy neutrino search above PeV

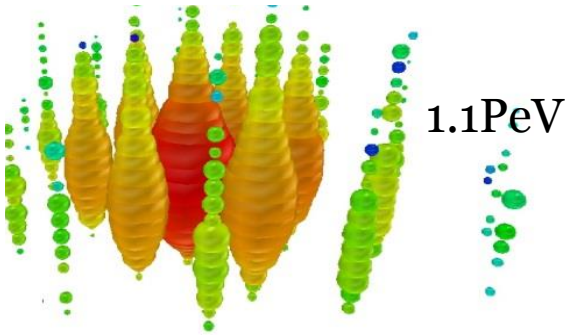
- $\nu_e:\nu_\mu:\nu_\tau$=6:1:2 at 1PeV, 3:4:2 at 10PeV, 2:5:3 at 100PeV
- 2..8sigma excess over $0.08^{+0.04}_{-0.06}$ events of default atmospheric background

IC79＋IC86

Phys. Rev. Lett. 111, 021103 (2013)

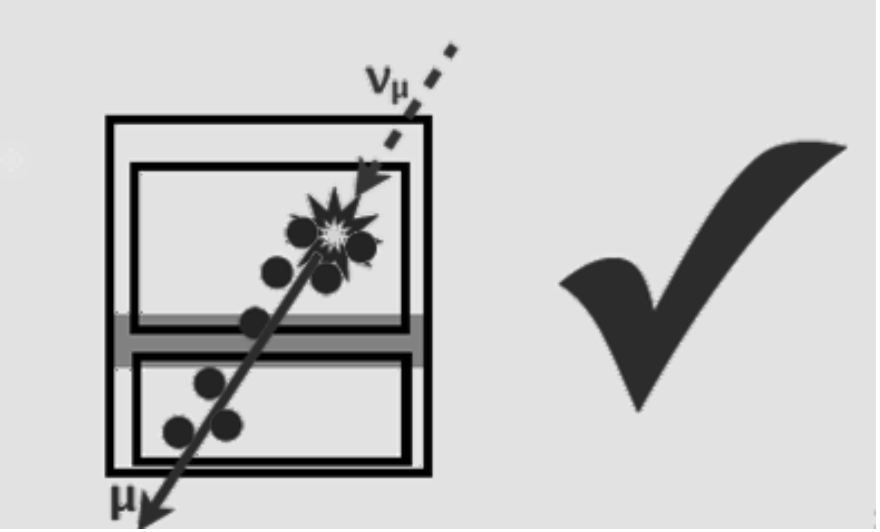


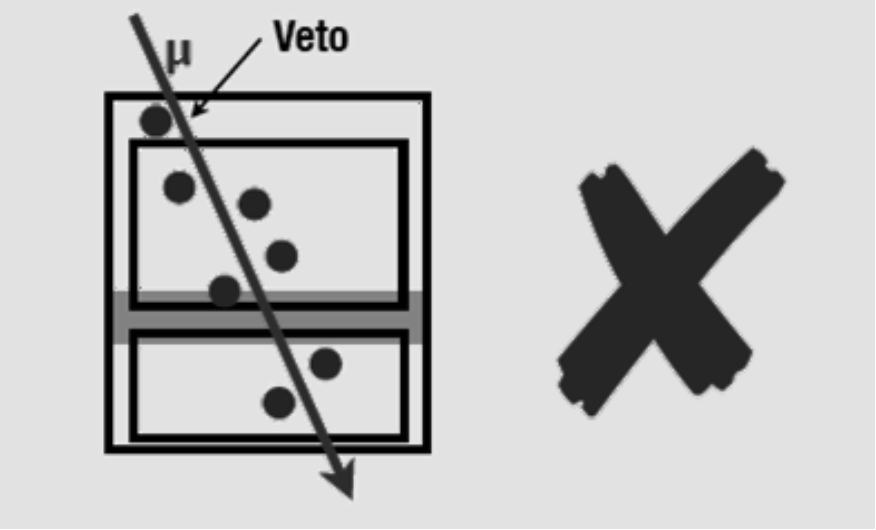




Number of photoelectrons: NPE ∝ Visible Energy

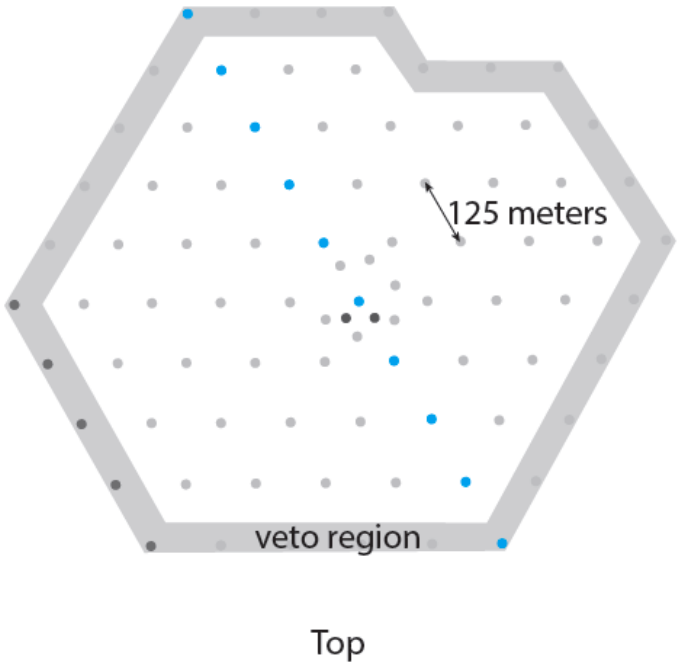
Starting Event Search (cascade+starting track)

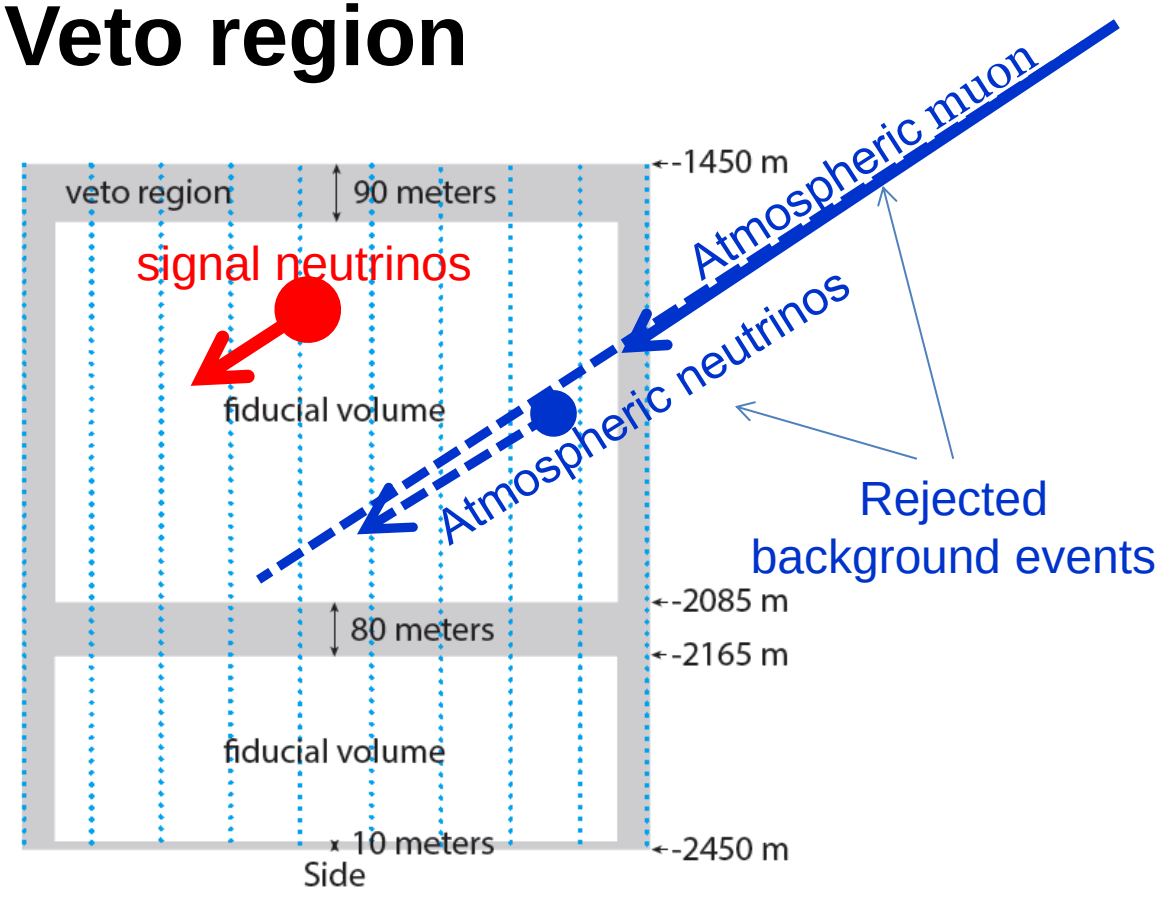




- **Followup analysis on the UHE cascade-like events with sensitivity extended down to 30TeV**
- **Atmospheric muon/neutrino background largely reduced by vetoing events with initial photons in outer layers**

Veto region

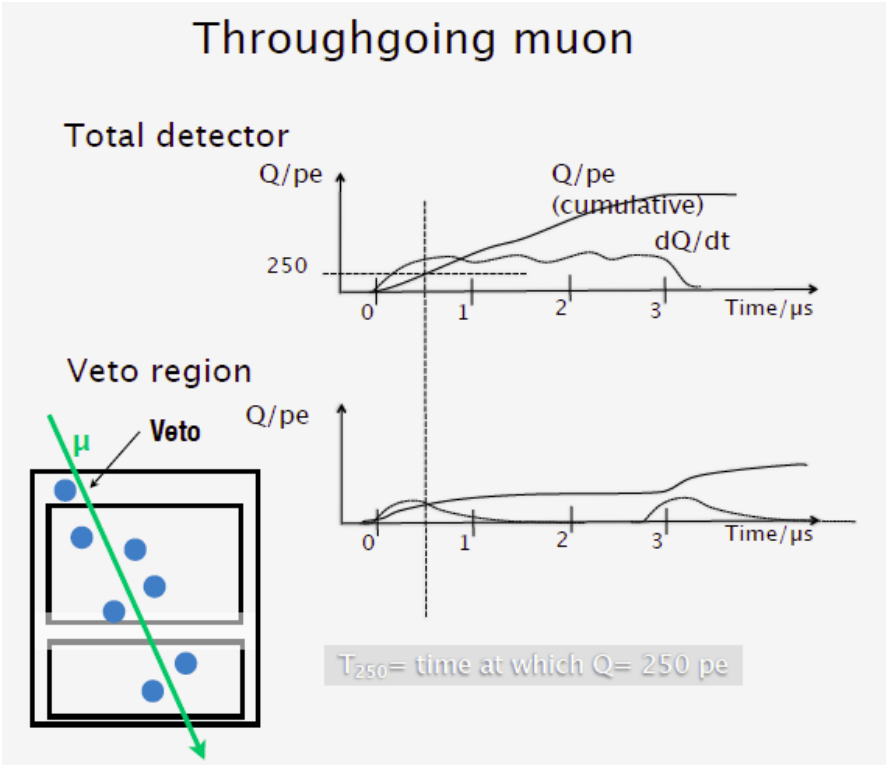


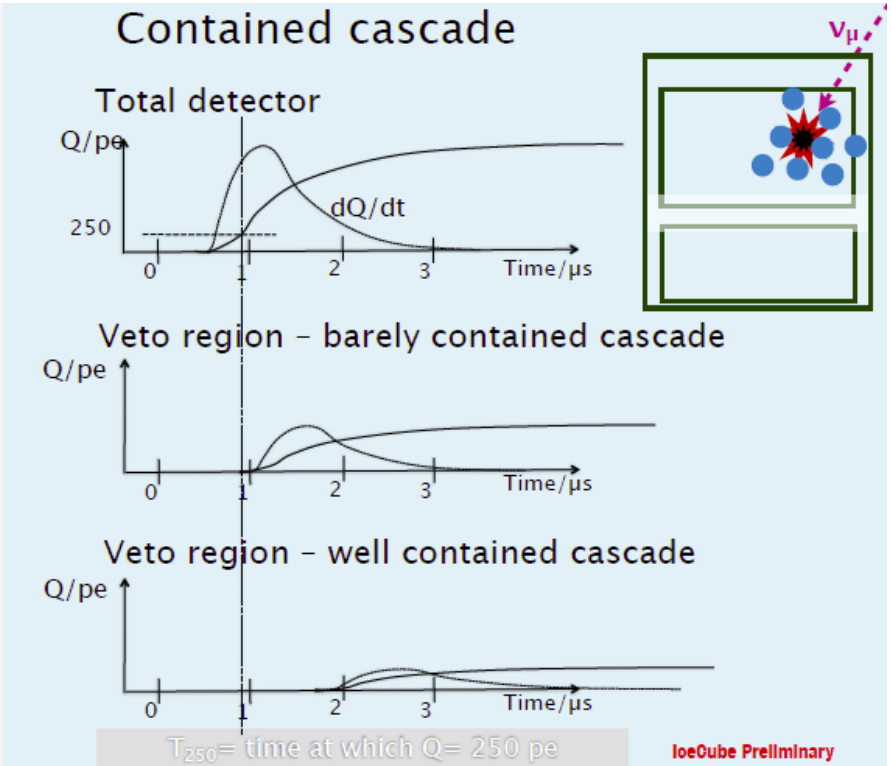


- **Down-going atmospheric neutrinos also reduced by vetoing atmospheric muon events**

High Energy Veto Method

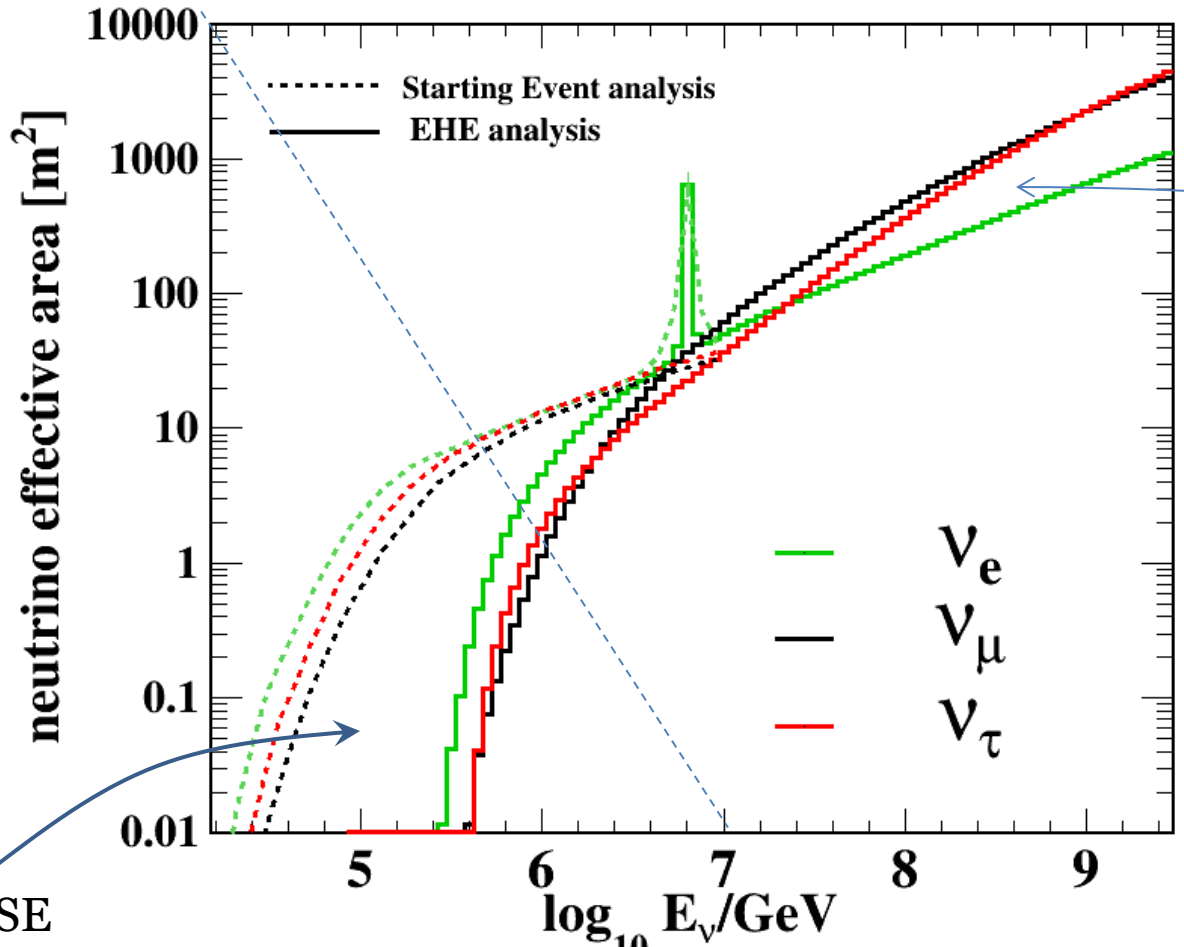
Events with NPE > 6000 (the case for EHE, NPE > 60000)





Effective Areas
Propositional to expected event rates

Area x ν flux x 4π x livetime = event rate

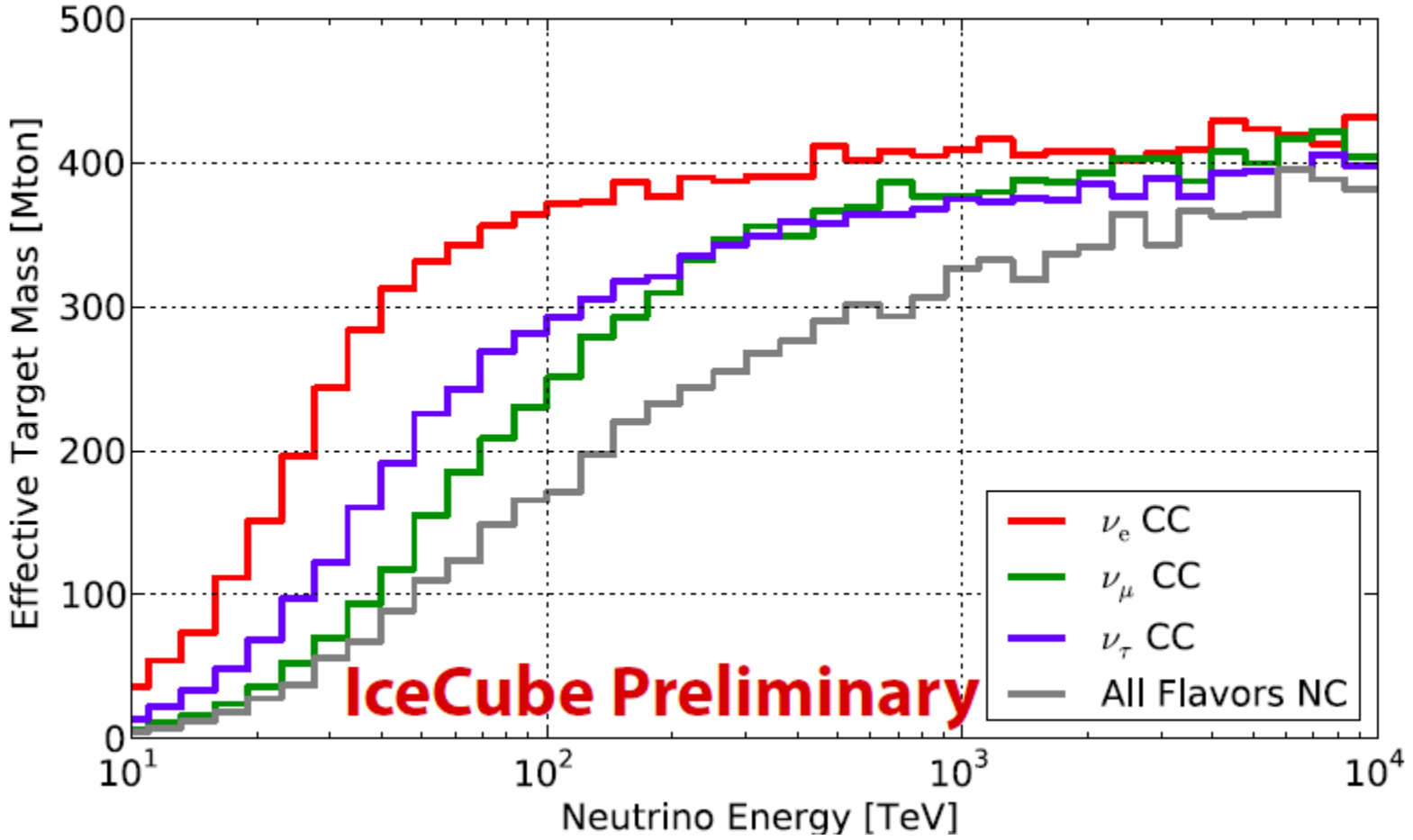


EHE
0.04 BG events/year

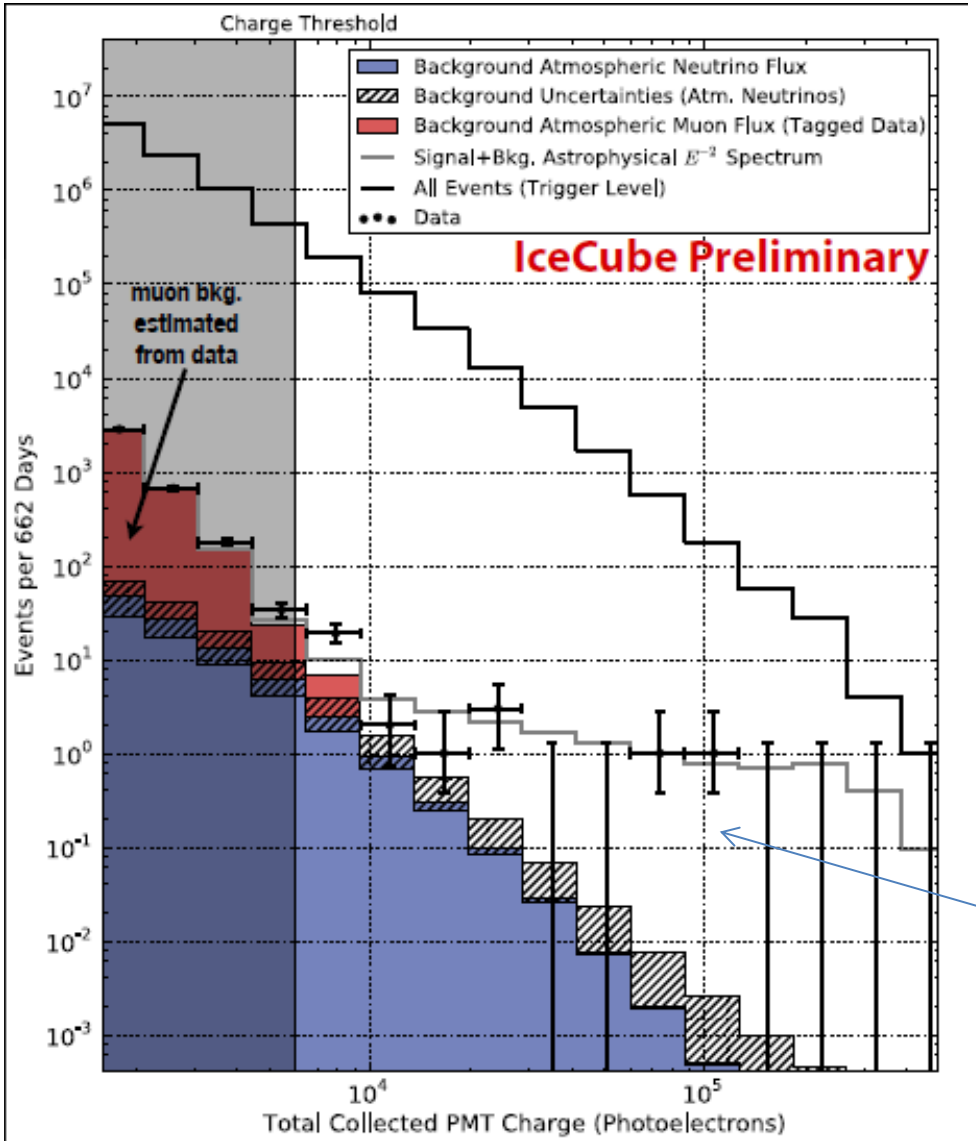
HESE
6 BG events/year

Comparisons of different channels

- 赤＋青＋灰色＝cascades
- 緑＝starting track



Starting eventsのNPE分布

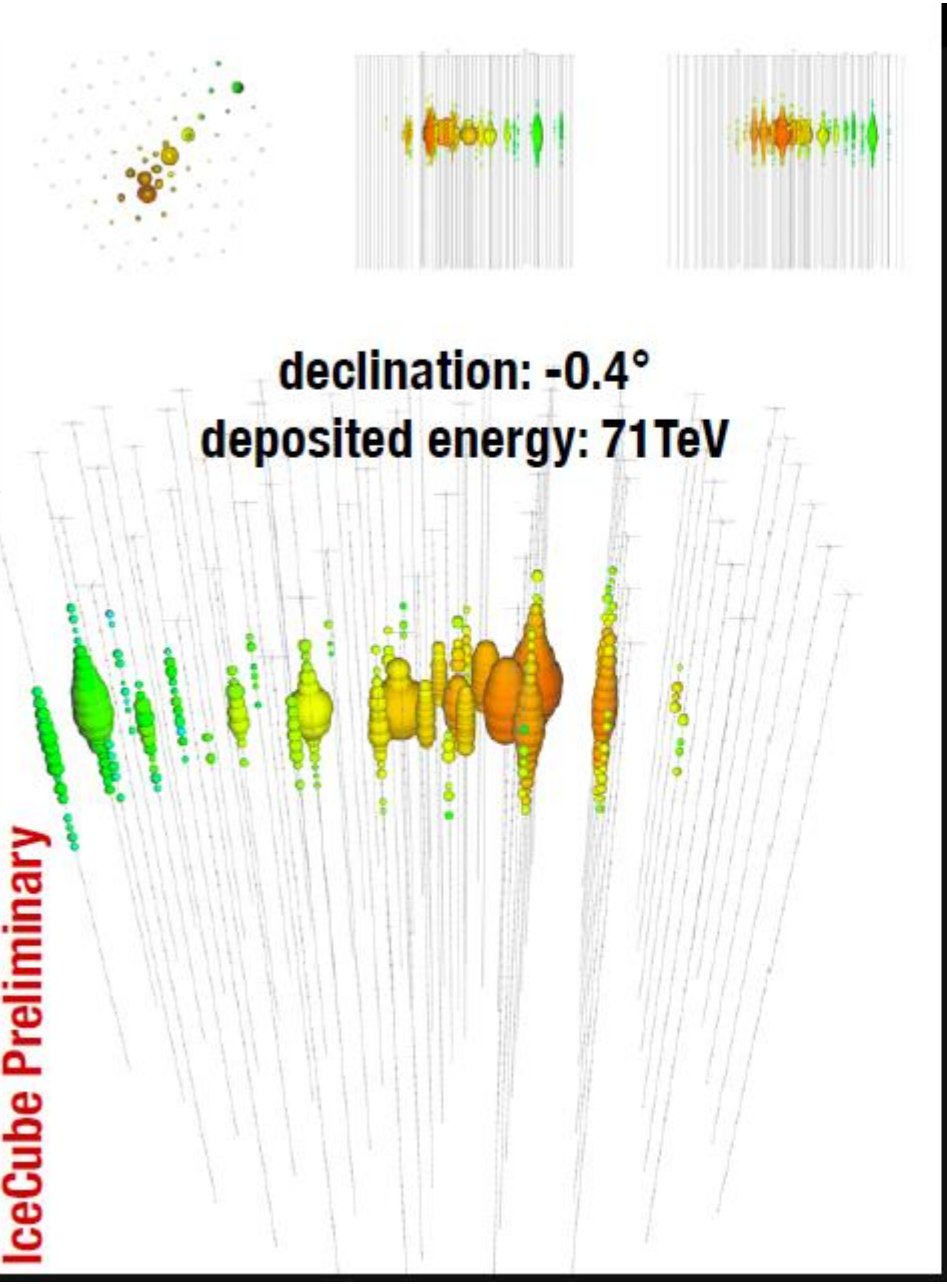


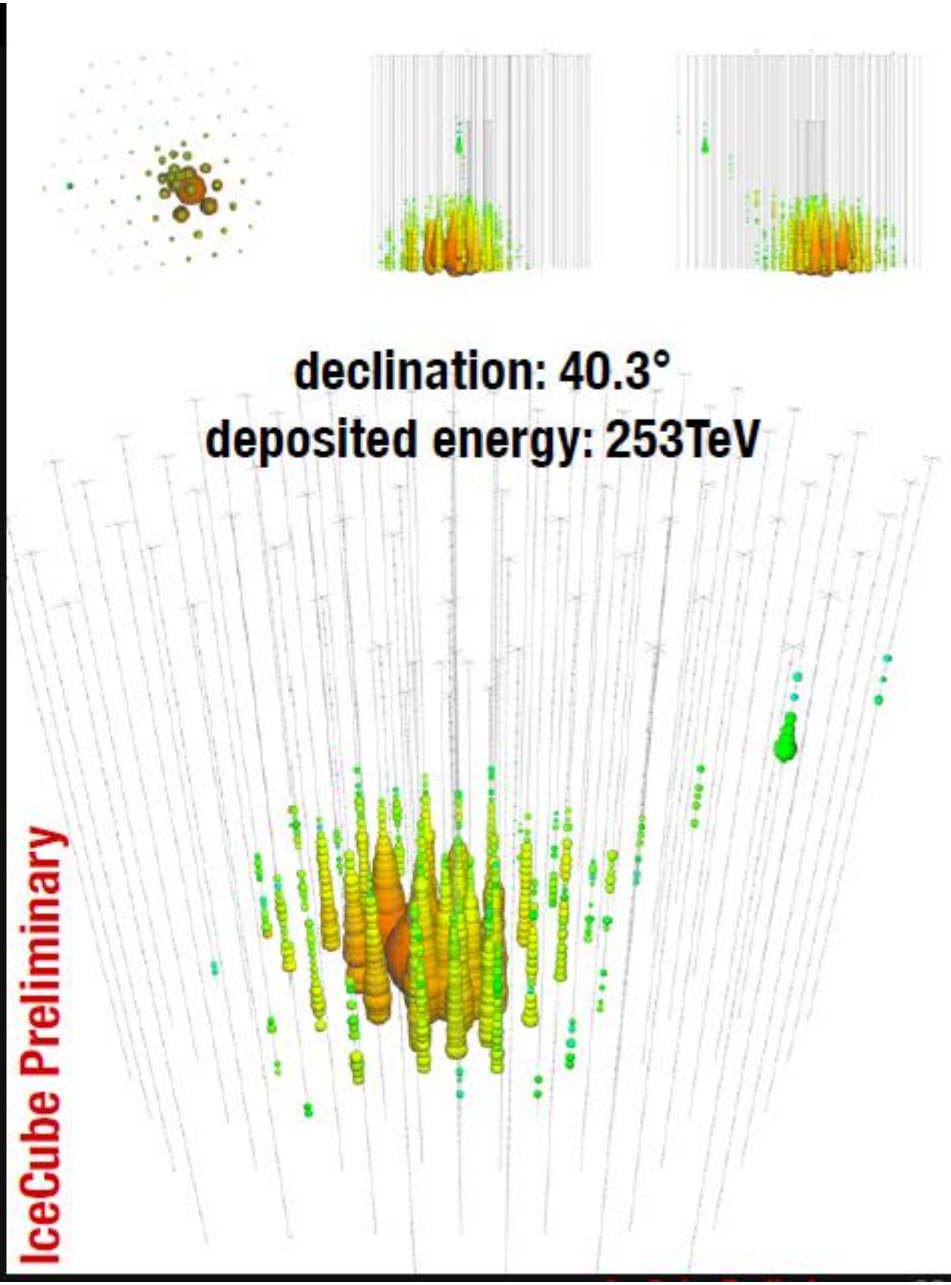
2010-2012 (2 years)

- 26 new events found
(19 cascades, 7 with tracks)
- over background expectation of 12 +/-4 atmospheric muons(6±3) and atmospheric neutrinos(6±2)
- no new events near the PeV region but deviation from background only hypothesis observed

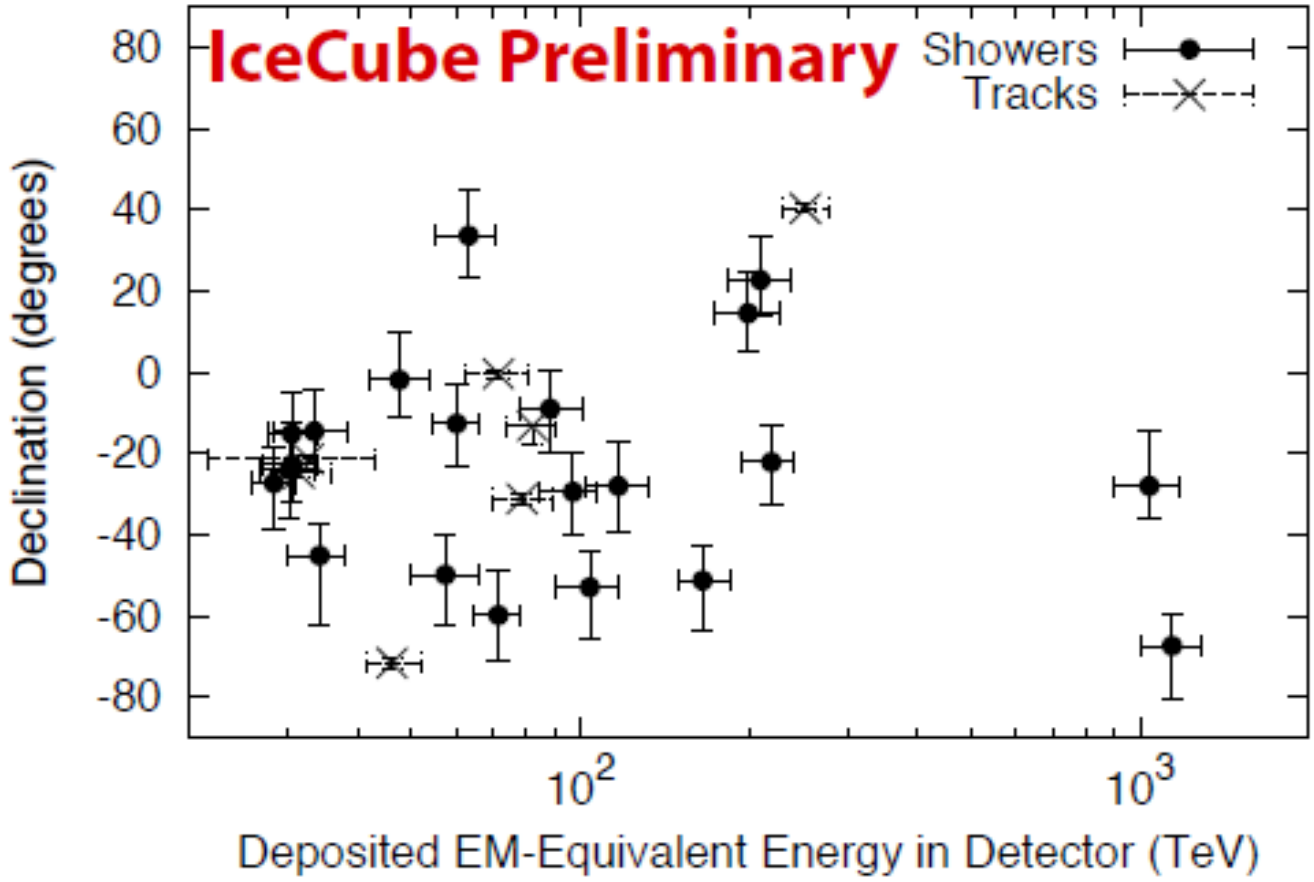
Already observed two events

Examples of events





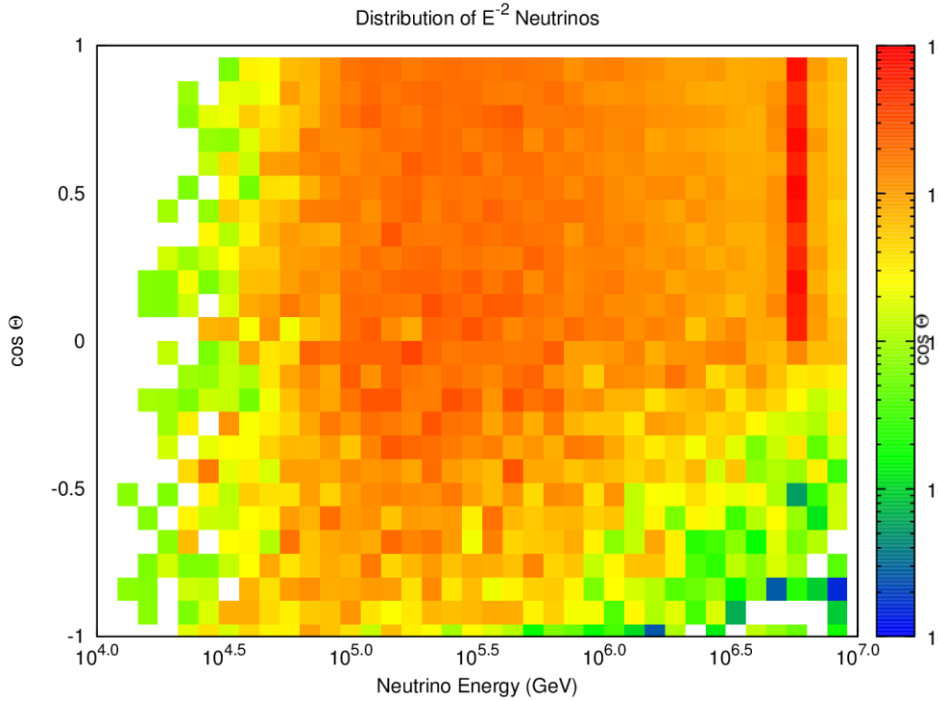
Energy, declination and topology



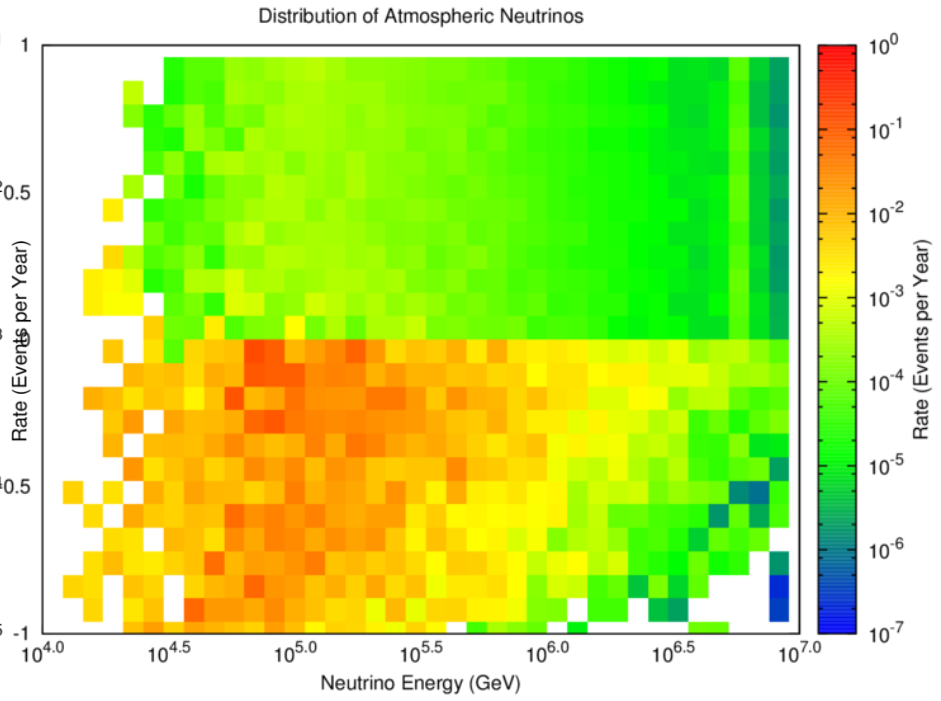
Up-Down Asymmetry

expected Energy vs cos θ distributions

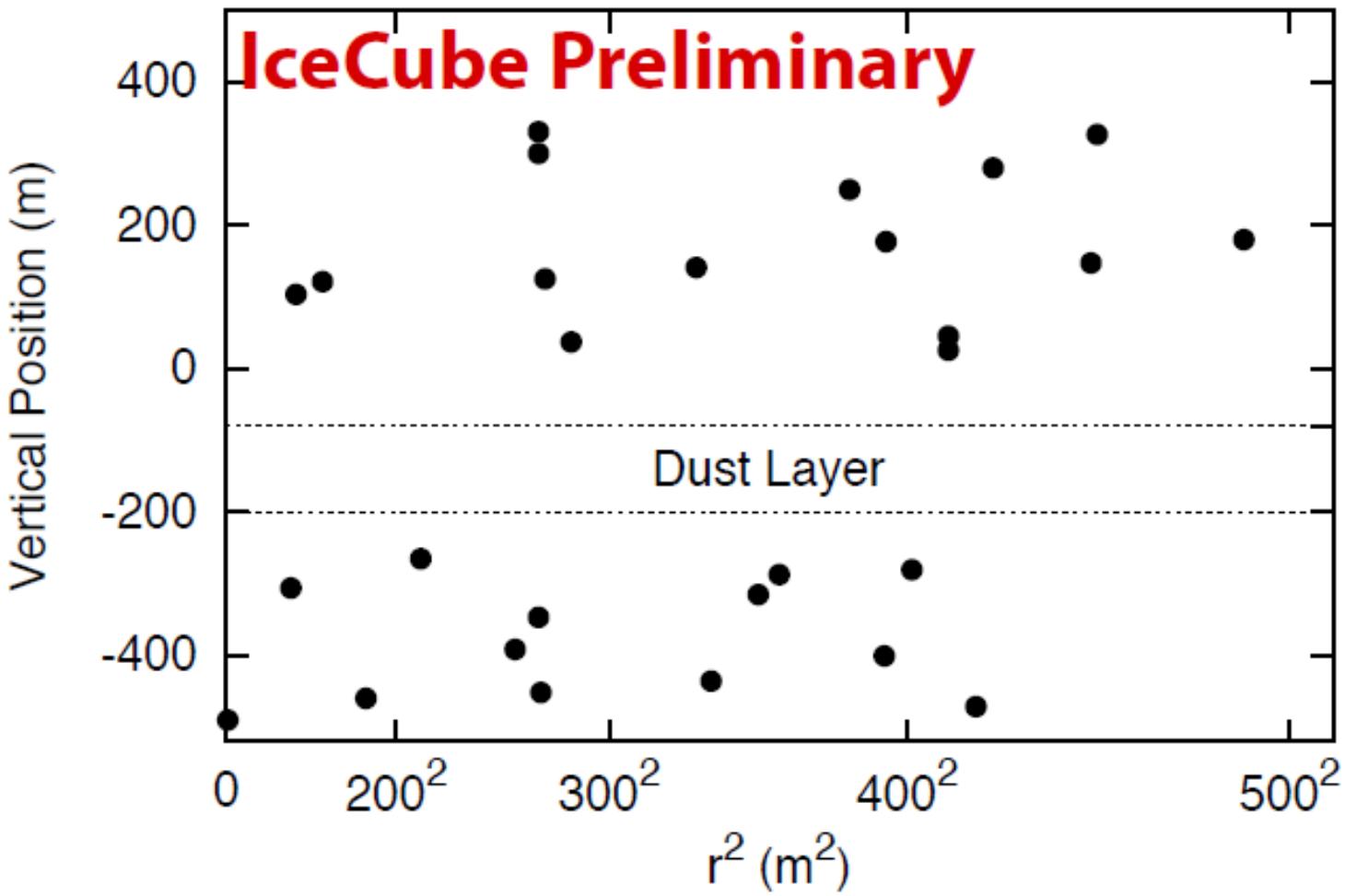
signal



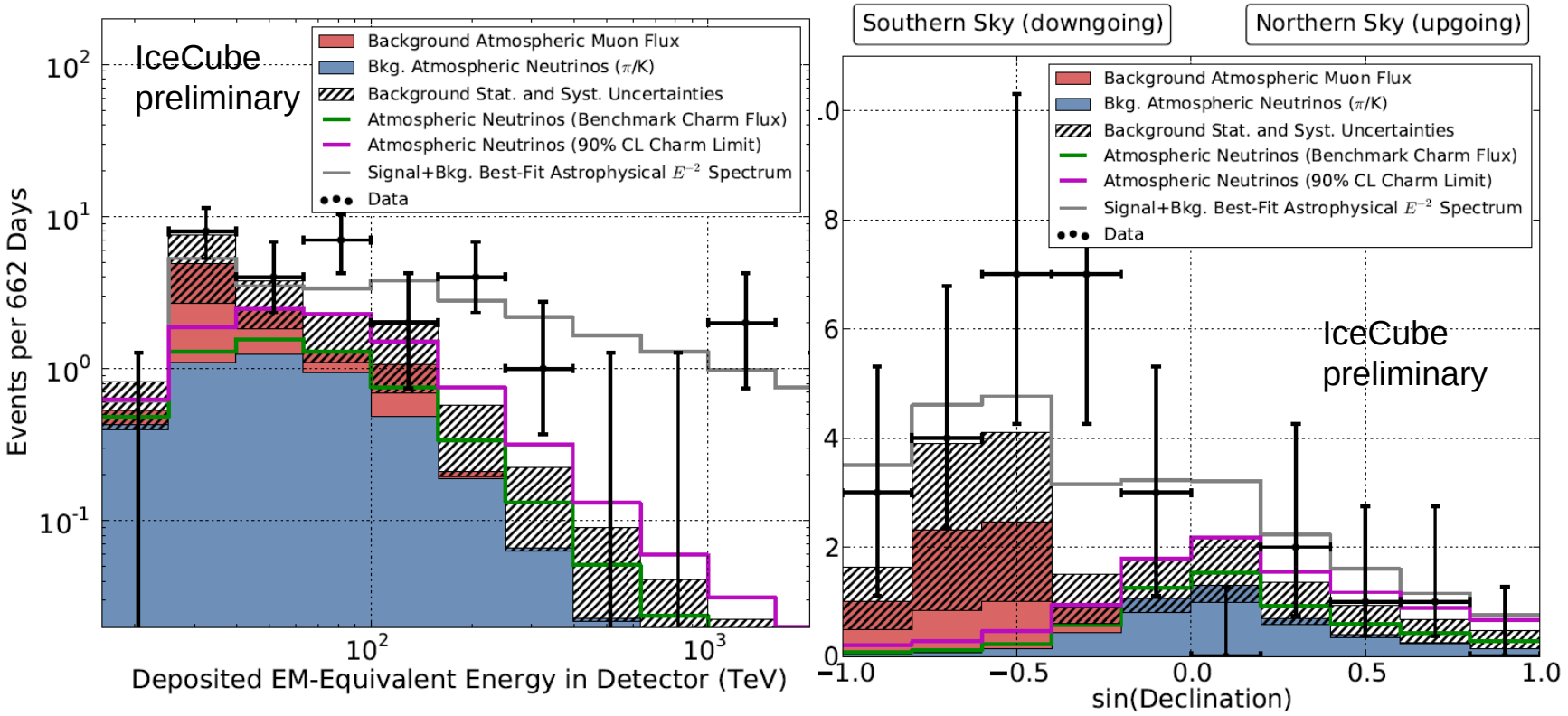
atmospheic neutrinos



Vertex positions

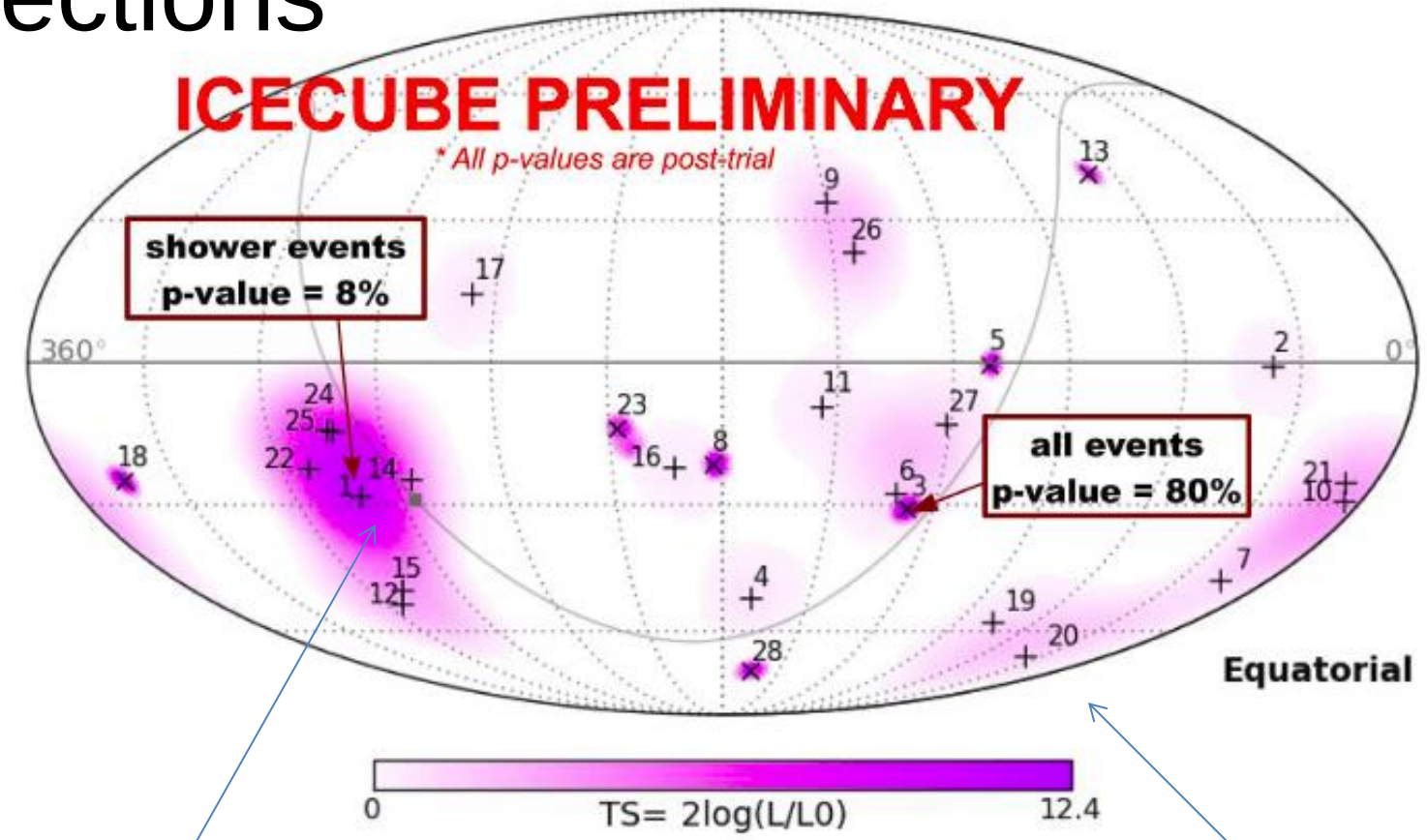


Extraterrestrial neutrino search with starting events



- **Inconsistent with background only model** at 3.3σ for 26 events and 4.1σ with 28 events combined (preliminary)
- Event features (reconstructed energy, zenith angle, vertex positions and topology) **consistent with background + astrophysical ($\phi_{astro} \propto E^{-2}$) fluxes**
- **Best fit results $E^2\phi$**=3.6x10-8 [GeV cm-1 s-1 sr-1] with a hard cut off at 1.6PeV
  - Need to be evaluated with adding more statistics soon!

Directions

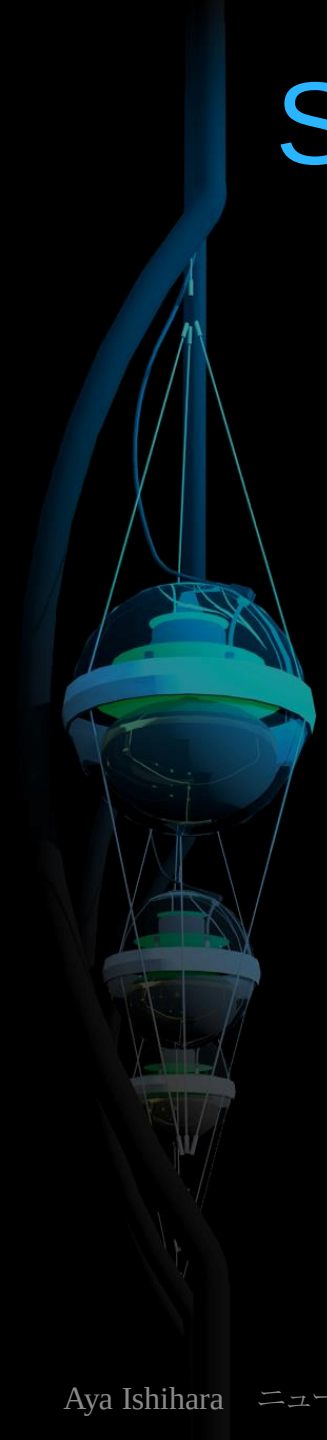


1.04PeV

1.14PeV

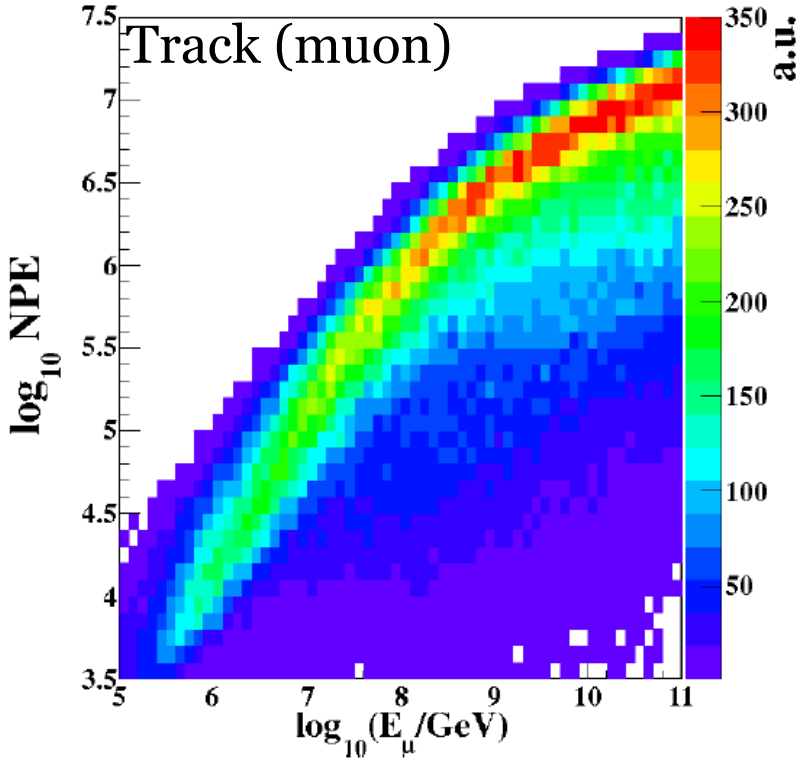
p-values	All 28 Events	21 Cascade Events
Cluster Search	~80%	8%

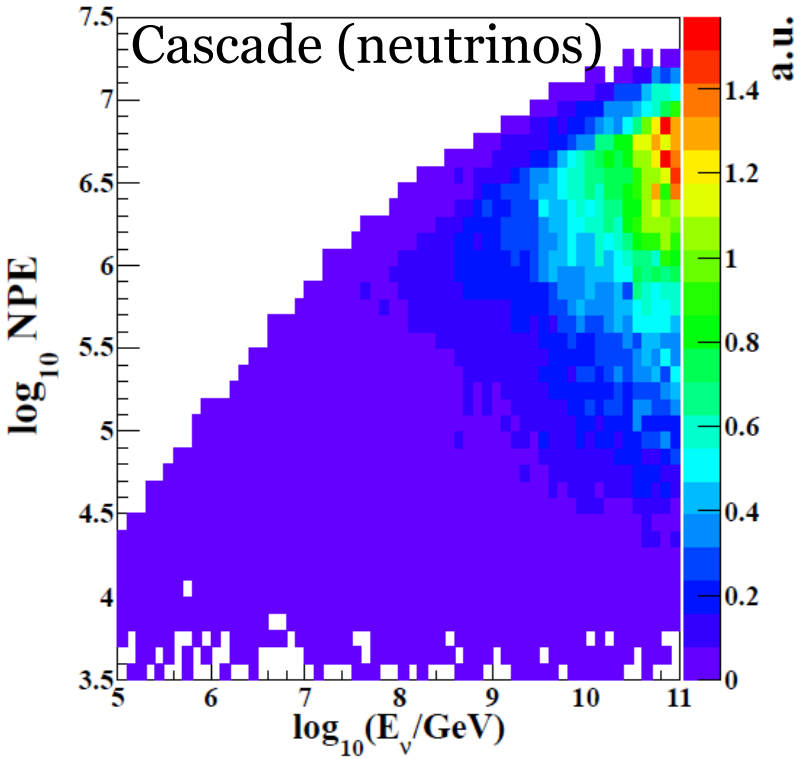
Summary



- IceCube実験完成後データとほぼ完成時のデータ2年分をNPEとVETOによるシンプルな解析で宇宙ニュートリノ探査を行った。
- 背景事象のみの仮説からは4.1σレベルでinconsistent
- 期待される信号分布は今のところisotropic, flavor 1:1:1，背景事象よりハードな $\varphi \propto E^{-2.2\sim-2.0}$ 分布と矛盾はない
- ほかのチャンネルからの結果とも*consistent*

The Energy–Brightness relation

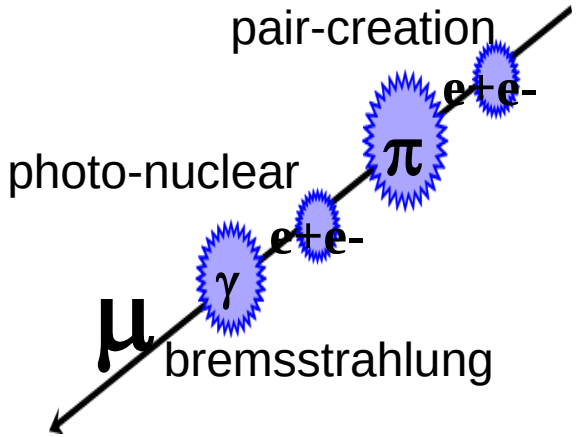




- NPE is the number of photoelectron signals measured by IceCube detector

$$-\left\langle \frac{dE}{dX} \right\rangle = \alpha + \beta E$$

Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)



ID	Dep. Energy (TeV)	Time (MJD)	Decl. (deg.)	R.A. (deg.)	Med. Angular Error (deg.)	Event Type
1	117^{+15}_{-15}	55351	−28.0	282.6	25.4	Shower
2	$47.6^{+6.5}_{-5.4}$	55351	−1.8	35.2	16.3	Shower
3	$78.7^{+10.8}_{-8.7}$	55451	−31.2	127.9	$\lesssim 1.4$	Track
4	165^{+20}_{-15}	55477	−51.2	169.5	7.1	Shower
5	$71.4^{+9.0}_{-9.0}$	55512	−0.4	110.6	$\lesssim 1.2$	Track
6	$28.4^{+2.7}_{-2.5}$	55567	−27.2	133.9	9.8	Shower
7	$34.3^{+3.5}_{-4.3}$	55571	−45.1	15.6	24.1	Shower
8	$32.6^{+10.3}_{-11.1}$	55608	−21.2	182.4	$\lesssim 1.3$	Track
9	$63.2^{+7.1}_{-8.0}$	55685	33.6	151.3	16.5	Shower
10	$97.2^{+10.4}_{-12.4}$	55695	−29.4	5.0	8.1	Shower
11	$88.4^{+12.5}_{-10.7}$	55714	−8.9	155.3	16.7	Shower
12	104^{+13}_{-13}	55739	−52.8	296.1	9.8	Shower
13	253^{+26}_{-22}	55756	40.3	67.9	$\lesssim 1.2$	Track
14	1041^{+132}_{-144}	55782	−27.9	265.6	13.2	Shower
15	$57.5^{+8.3}_{-7.8}$	55783	−49.7	287.3	19.7	Shower
16	$30.6^{+3.6}_{-3.5}$	55798	−22.6	192.1	19.4	Shower
17	200^{+27}_{-27}	55800	14.5	247.4	11.6	Shower
18	$31.5^{+4.6}_{-3.3}$	55923	−24.8	345.6	$\lesssim 1.3$	Track
19	$71.5^{+7.0}_{-7.2}$	55925	−59.7	76.9	9.7	Shower
20	1141^{+143}_{-133}	55929	−67.2	38.3	10.7	Shower
21	$30.2^{+3.5}_{-3.3}$	55936	−24.0	9.0	20.9	Shower
22	220^{+21}_{-24}	55941	−22.1	293.7	12.1	Shower
23	$82.2^{+8.6}_{-8.4}$	55949	−13.2	208.7	$\lesssim 1.9$	Track
24	$30.5^{+3.2}_{-2.6}$	55950	−15.1	282.2	15.5	Shower
25	$33.5^{+4.9}_{-5.0}$	55966	−14.5	286.0	46.3	Shower
26	210^{+29}_{-26}	55979	22.7	143.4	11.8	Shower
27	$60.2^{+5.6}_{-5.6}$	56008	−12.6	121.7	6.6	Shower
28	$46.1^{+5.7}_{-4.4}$	56048	−71.5	164.8	$\lesssim 1.3$	Track