IC170922Aから始まるマルチメッセンジャー天文学

石原 安野 for the IceCube collaboration

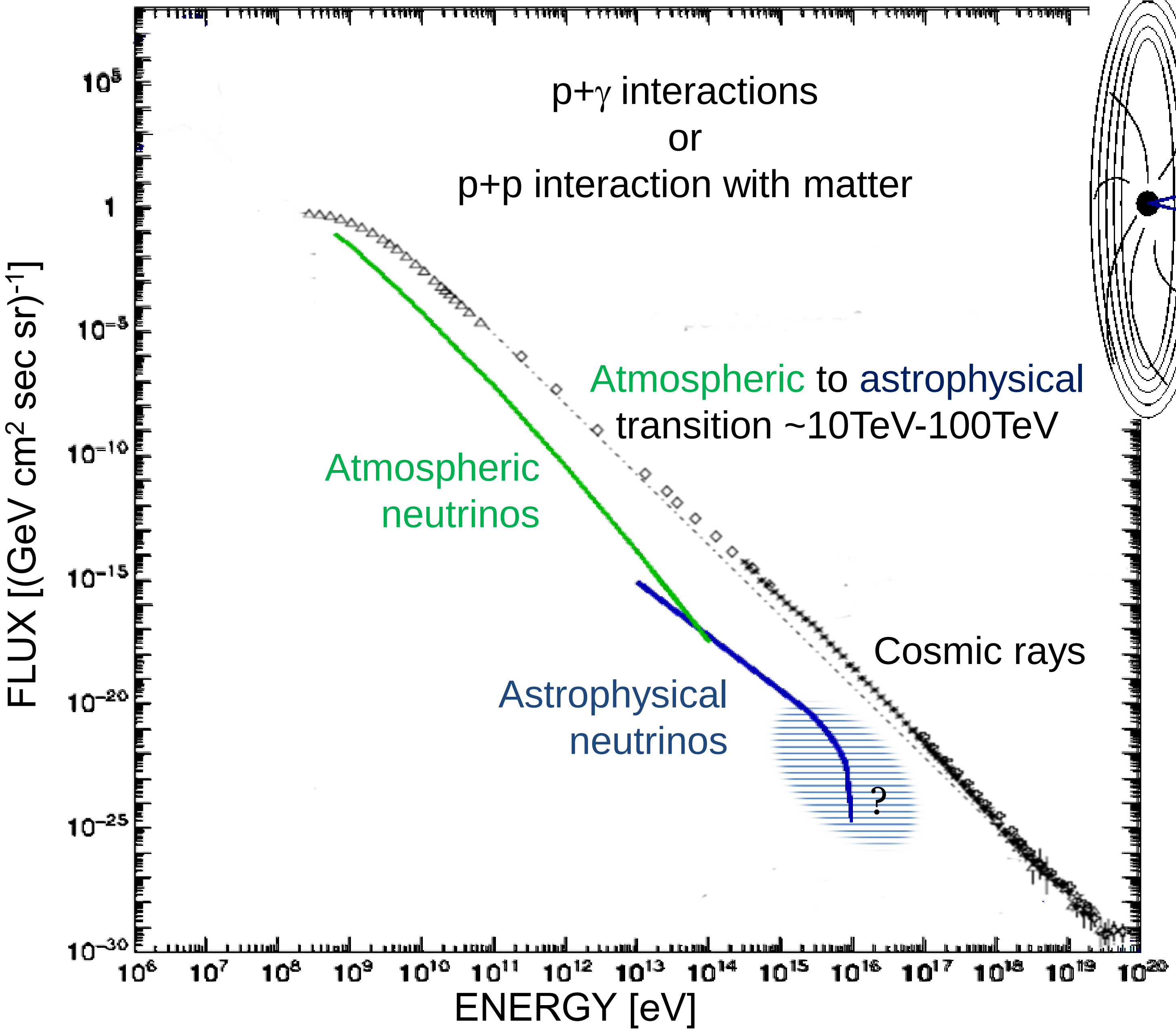
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

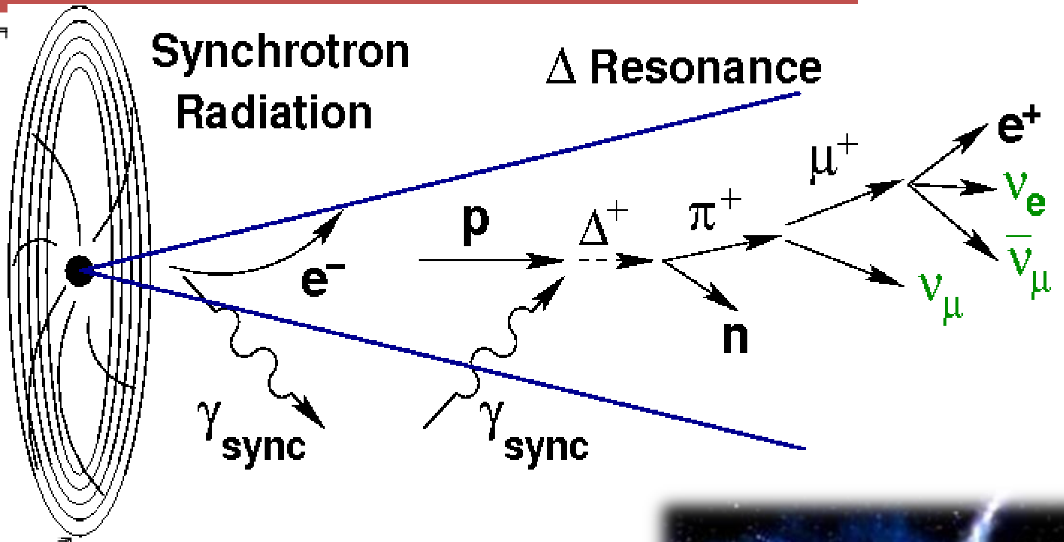
日本天文学会@姫路
September 19, 2018

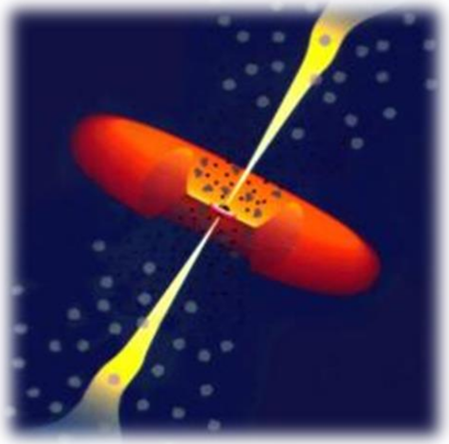
千葉大学
CHIBA UNIVERSITY

ICEHAP
International Center for Hadron Astrophysics

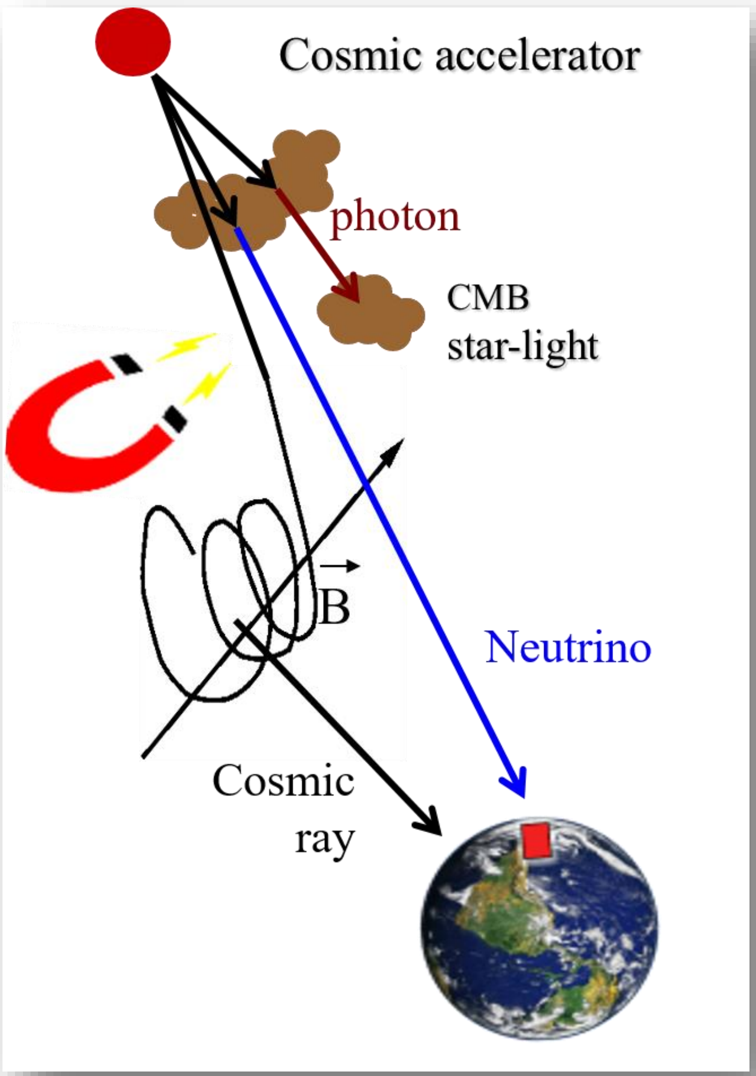
Ultra-high Energy Neutrinos in the Universe







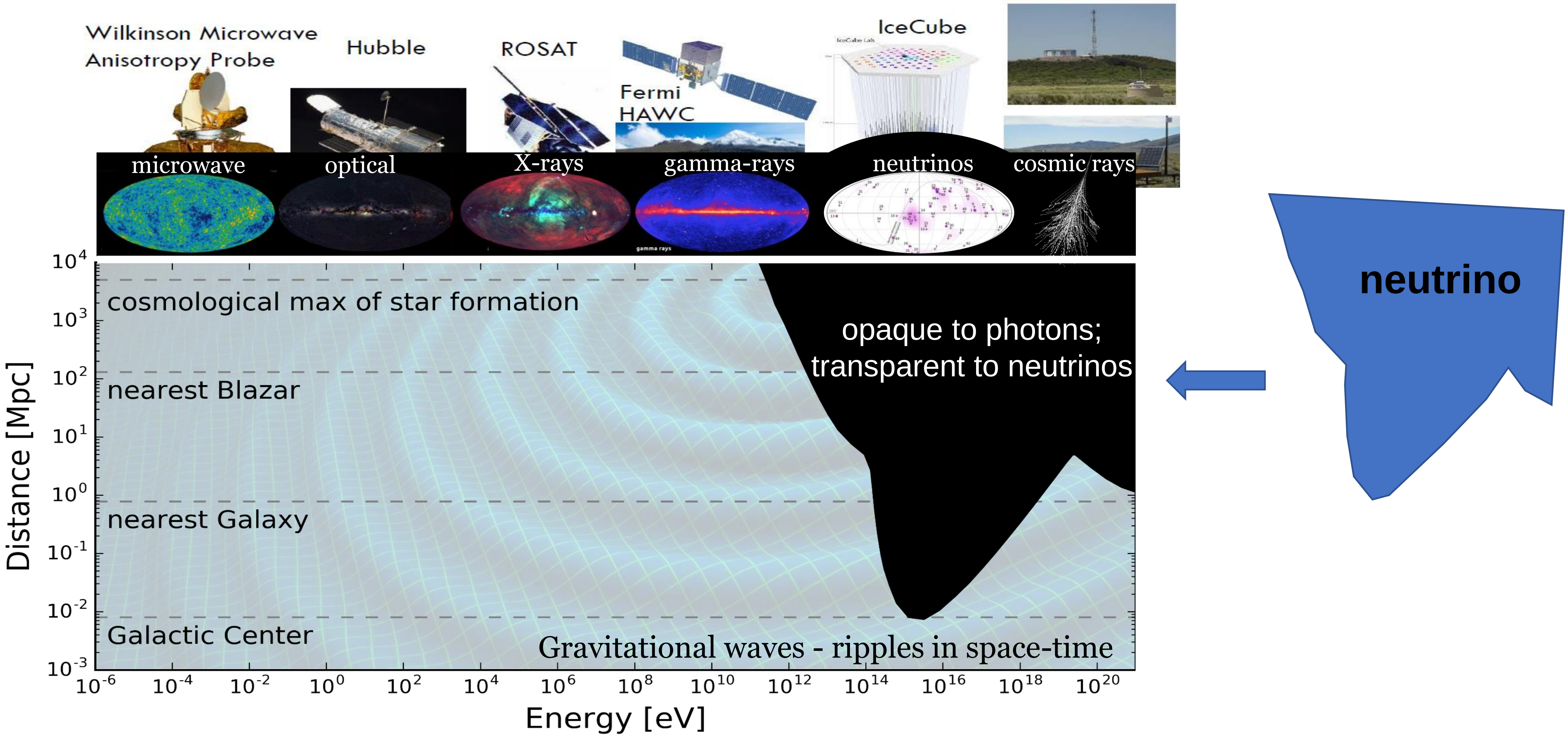
Neutrino as a cosmic messenger



Weak interaction during "propagation"

- **Penetration power**
- **Pointing capability**

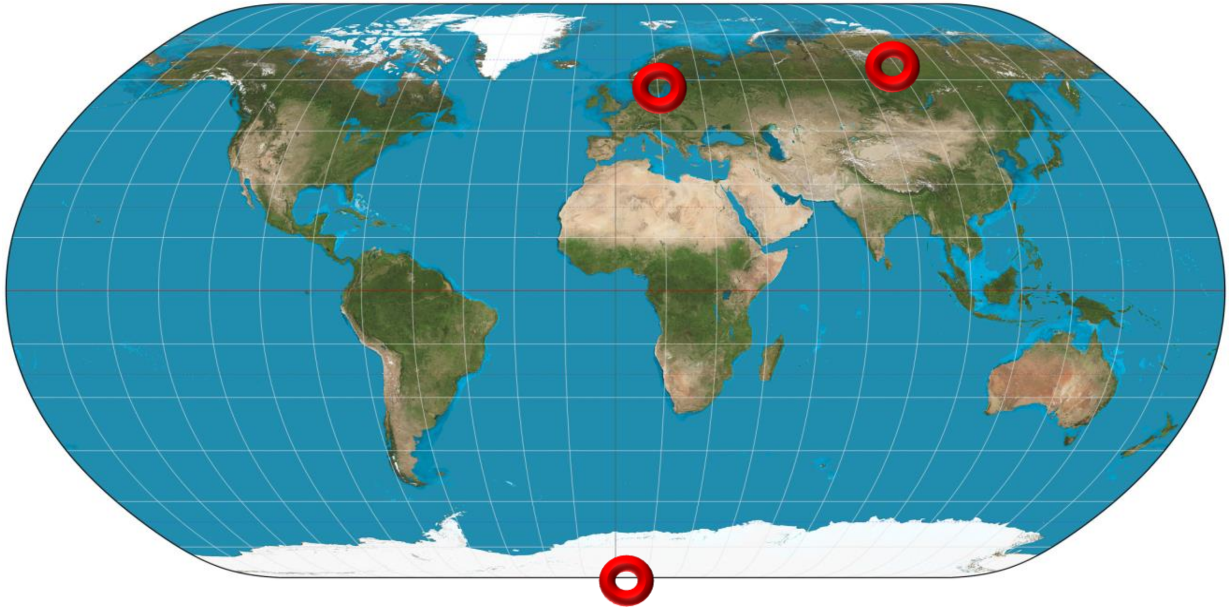
Fill the Gap: Multi-messenger astronomy



Neutrino Telescopes

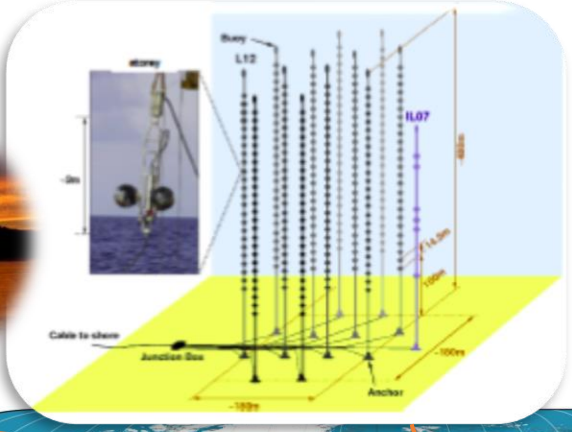
Neutrino Telescopes need to be large

- Benchmark $1km^3$ scale for a few neutrino events/year expected from observed CR energy densities
- Natural photon-transparent materials as neutrino beam dumping and as Cherenkov medium

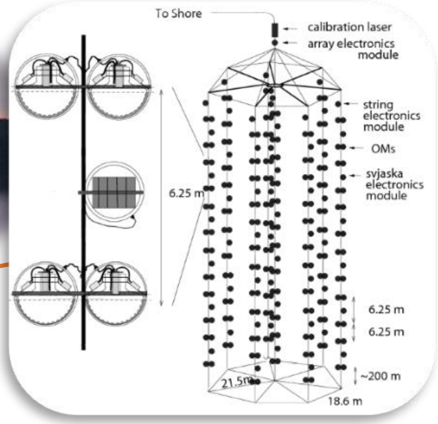


Neutrino Telescopes

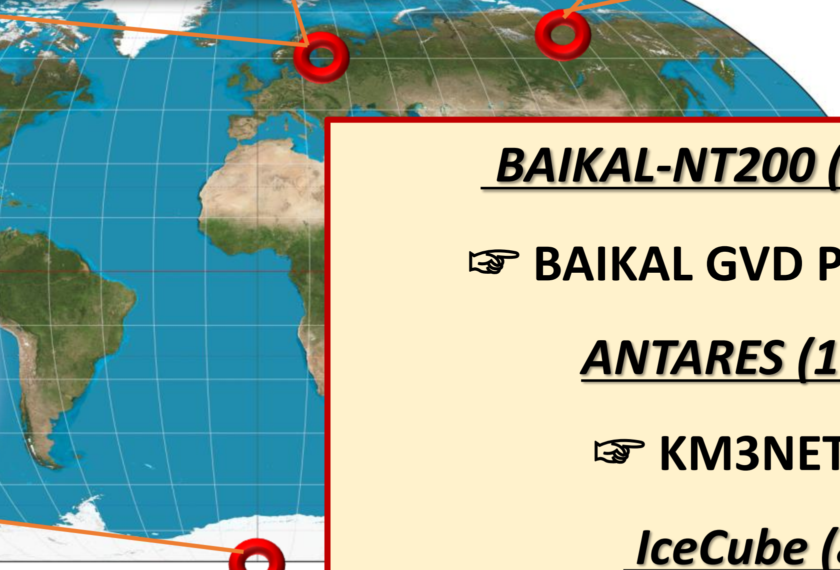
ANTARES



BAIKAL-NT200



IceCube



<u>BAIKAL-NT200 (8strings 192 PMTs) 1/2000km³</u>

☞ **BAIKAL GVD Phase 1** ☞ **BAIKAL GVD full scale**

<u>ANTARES (12lines 882PMTs) 1/100km³</u>

☞ **KM3NET Phase 1** ☞ **KM3NET 2.0**

<u>IceCube (86lines 5160PMTs) 1km³</u>

☞ **IceCube-Gen2 Phase 1** ☞ **IceCube-Gen2** http://icecube.wisc.edu

THE ICECUBE COLLABORATION

AUSTRALIA
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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
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Yale University

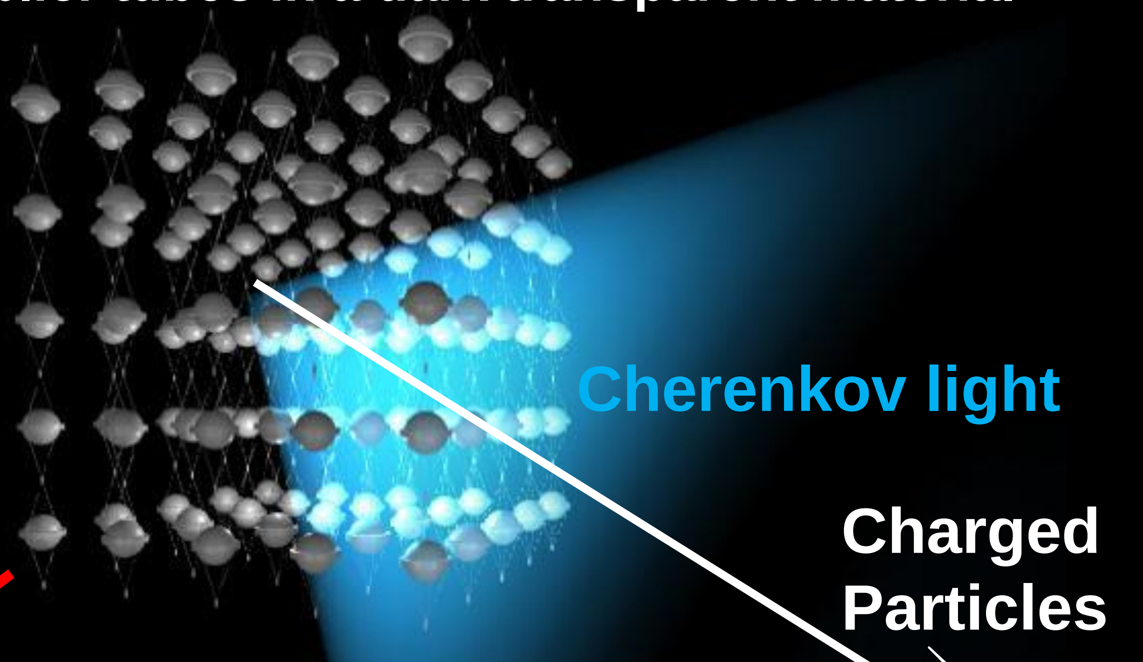
FUNDING AGENCIES

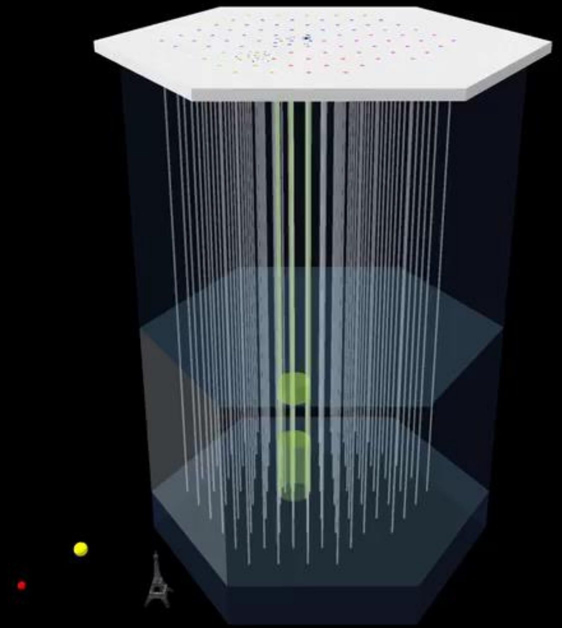
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg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

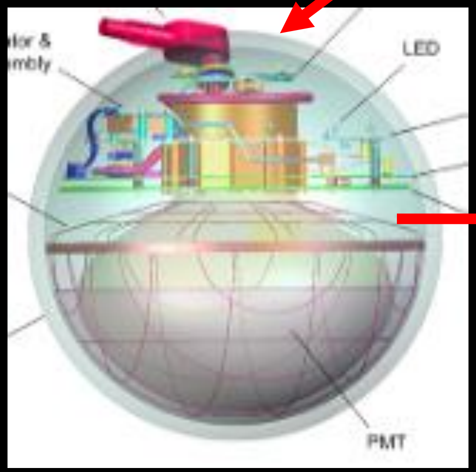
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

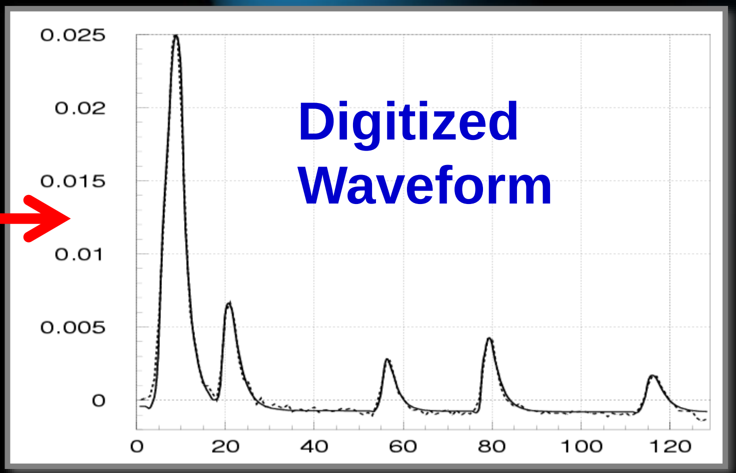
Detection Principle

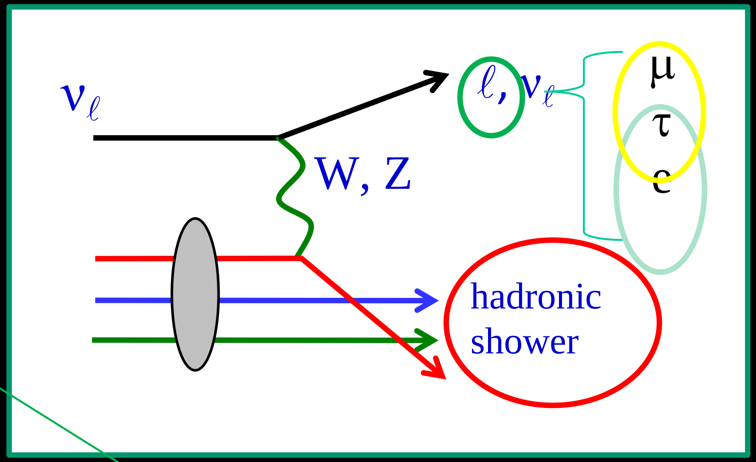
Array of photomultiplier tubes in a dark transparent material



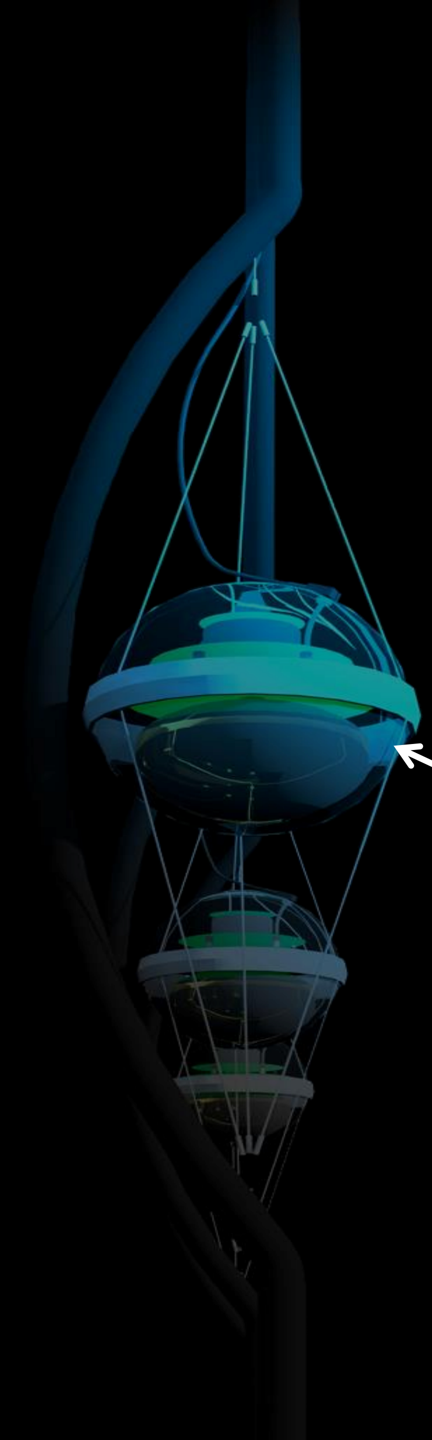


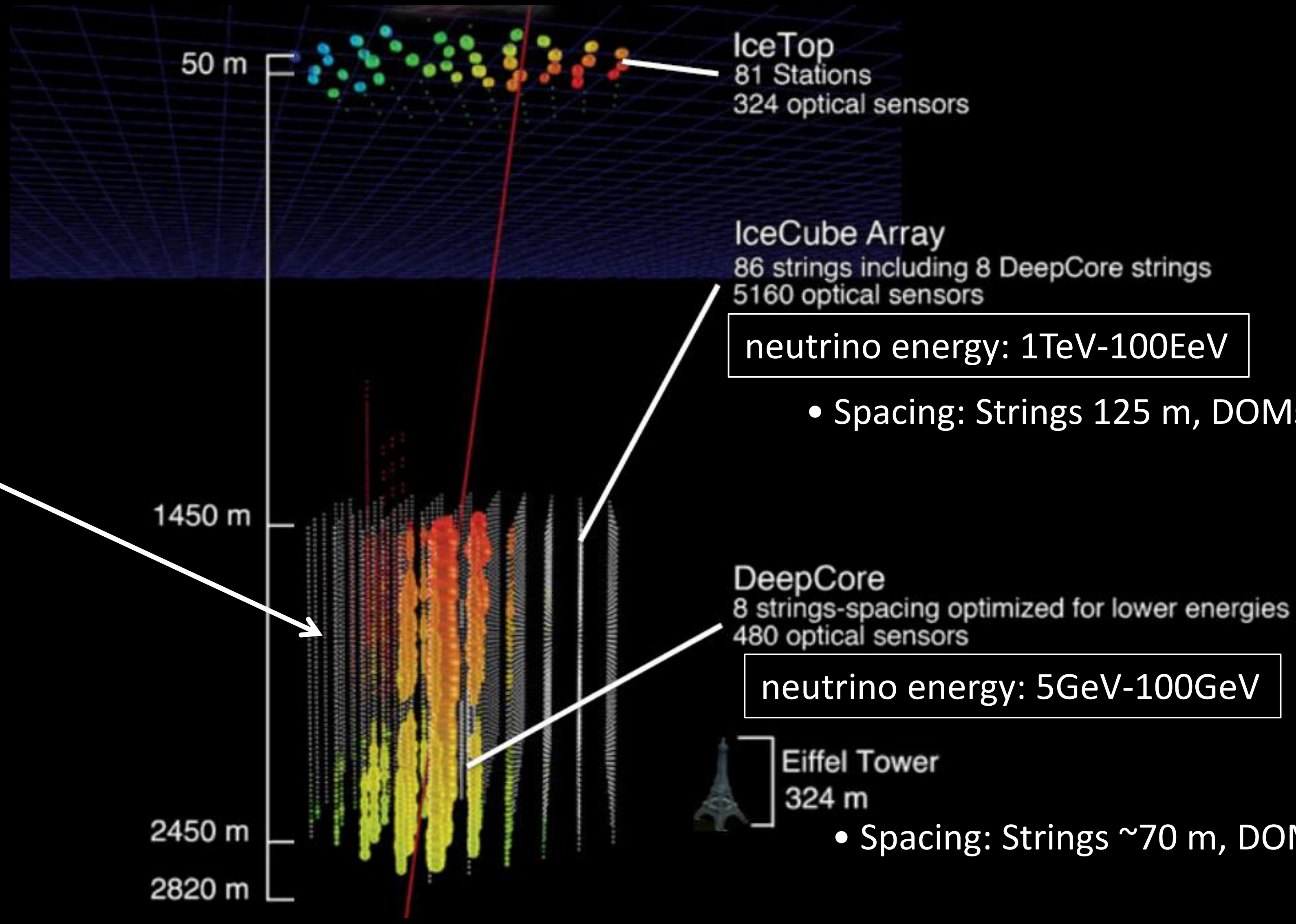






The IceCube Detector





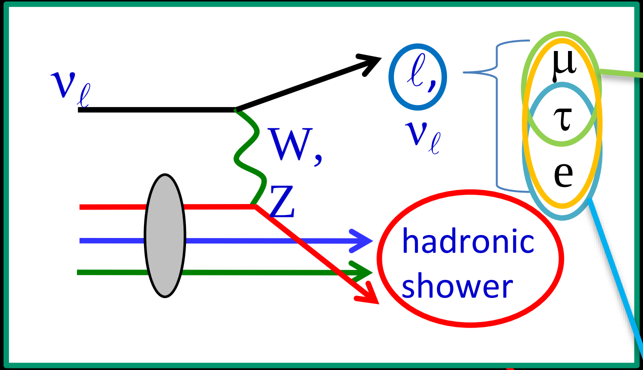
neutrino energy: 1TeV-100EeV

- Spacing: Strings 125 m, DOMs 17 m

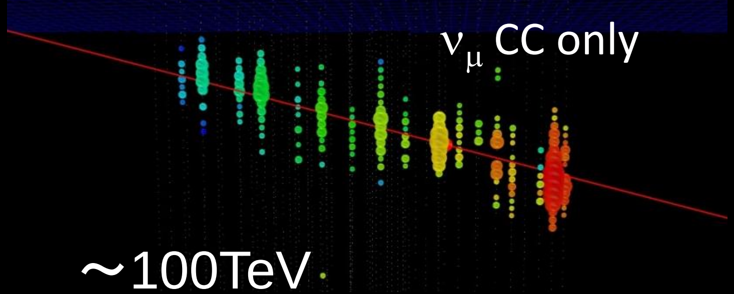
neutrino energy: 5GeV-100GeV

- Spacing: Strings ~70 m, DOMs 7 m

IceCube Flavor Identifications



Up-going muon track event

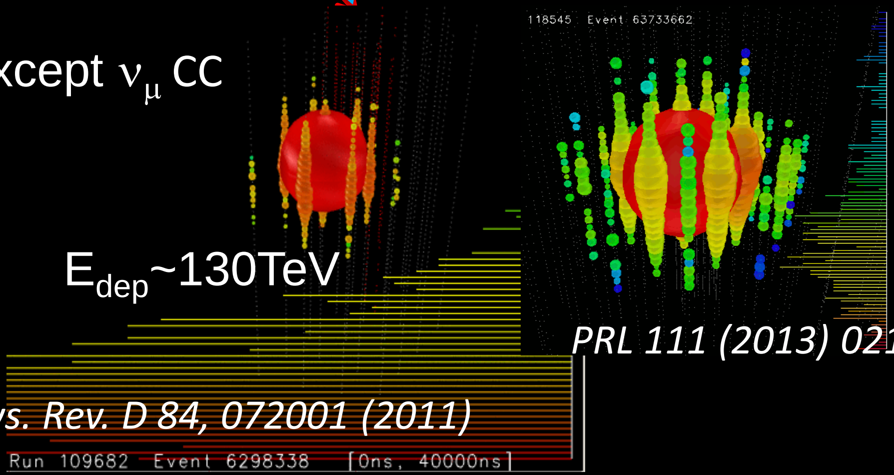


ν_μ CC only

~100TeV

Cascade events

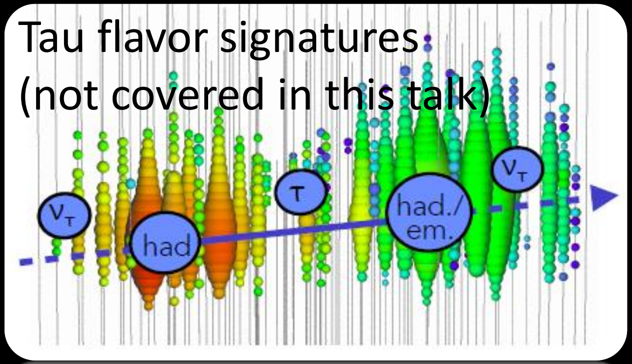
All except ν_μ CC



E_{dep}~130TeV

PRL 111 (2013) 021103

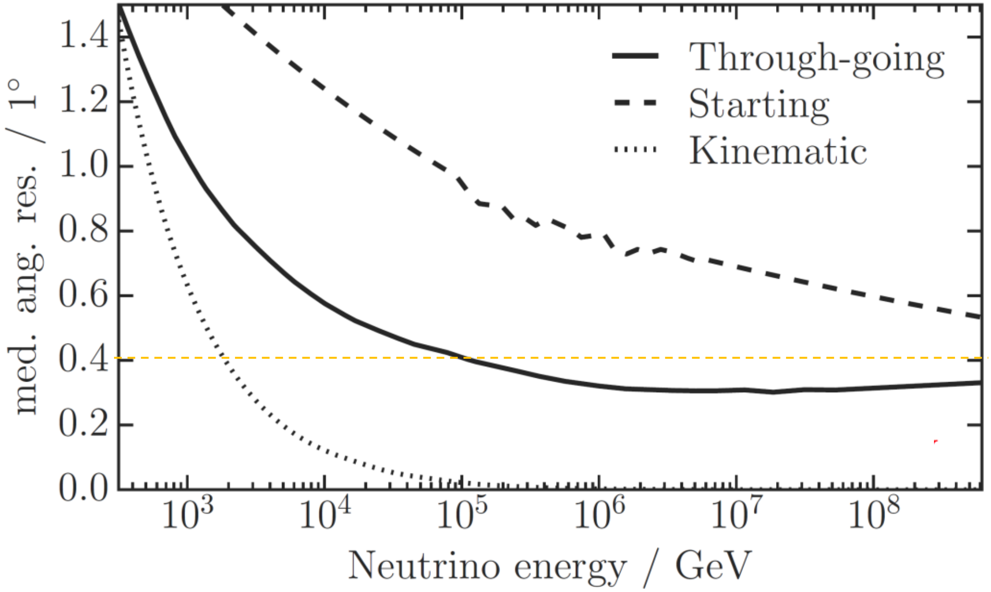
Phys. Rev. D 84, 072001 (2011)



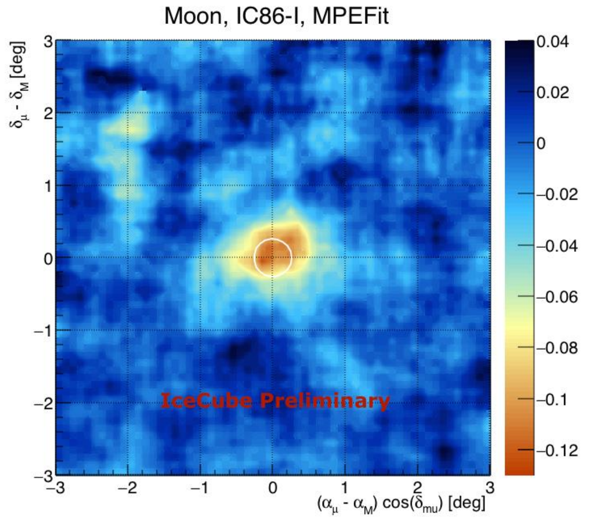
Tracks: induced by ν_μ CC interaction

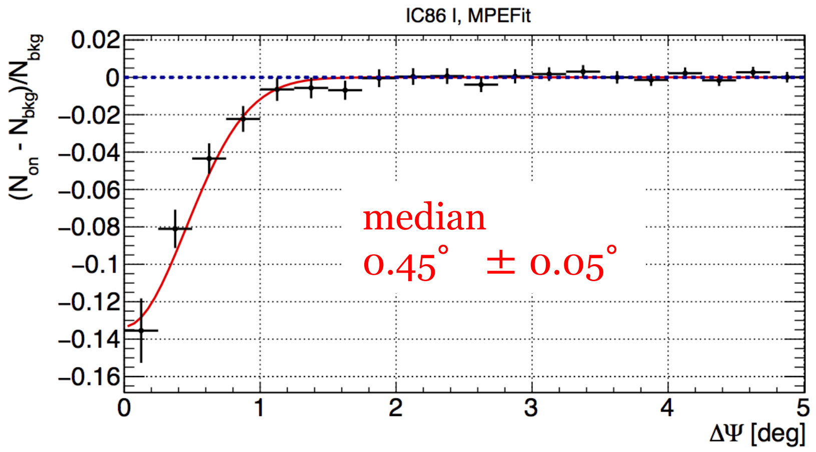
Angular resolution

Median resolution: 0.4° (> 100 TeV)



Moon shadow of cosmic ray muons using one year of data
(cosmic-ray primaries get absorbed in moon)





Background dependent on the directions in the sky

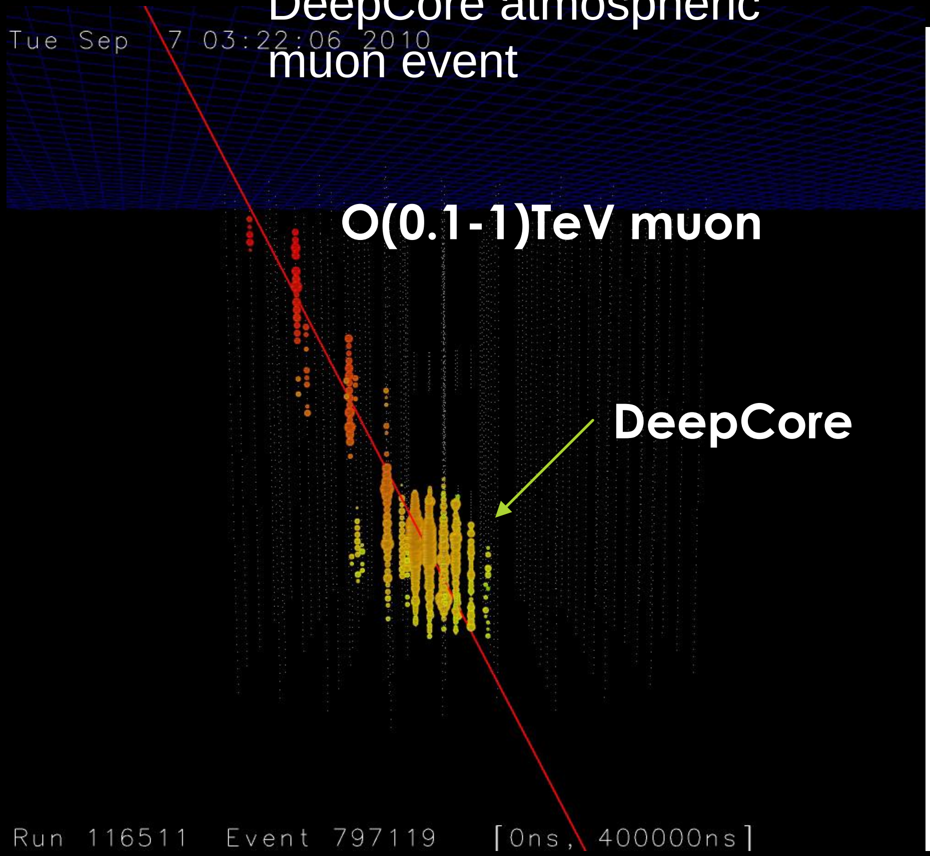
- Southern sky: High energy atm muon BG (signal PeV-EeV)
- Northern sky: Atm neutrino BG (signal TeV-PeV)

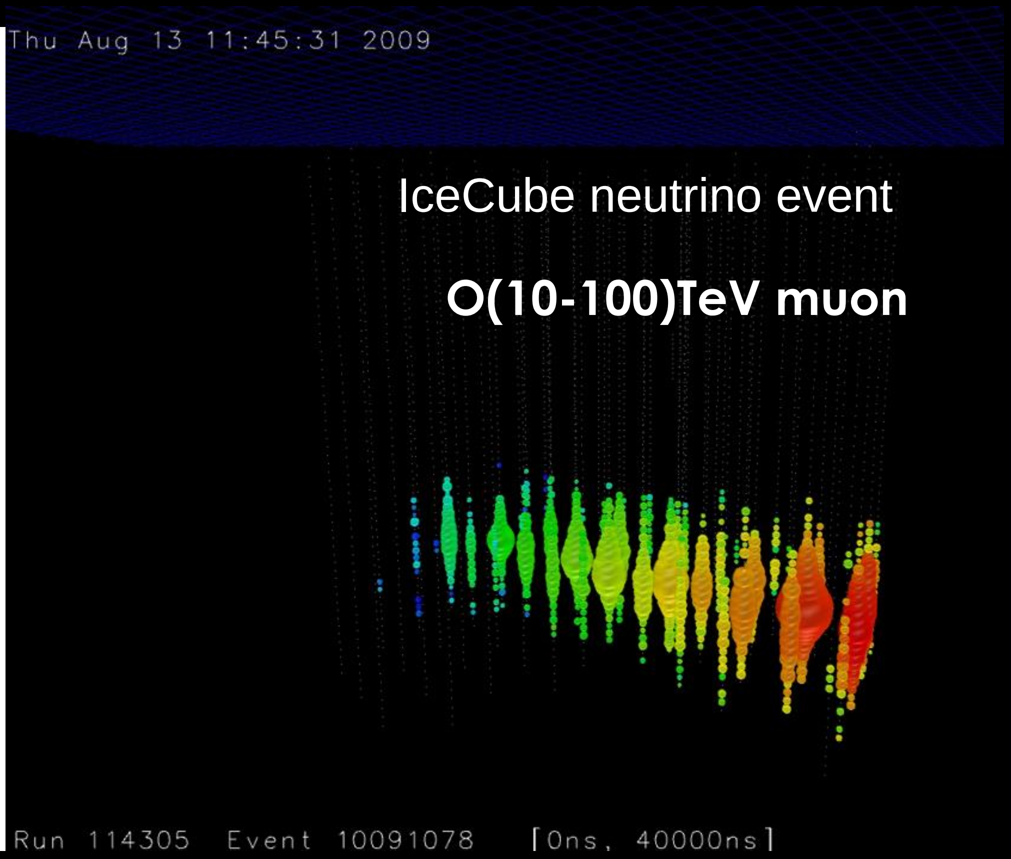
Large energy resolution for through going-muon as muon loose energy before arrival

- Δlog(E)~0.3 for muon energy deposit to muon energy

Energy Range for IceCube/DeepCore

Icecube can measure 10GeV – 10^{11}GeV neutrinos !

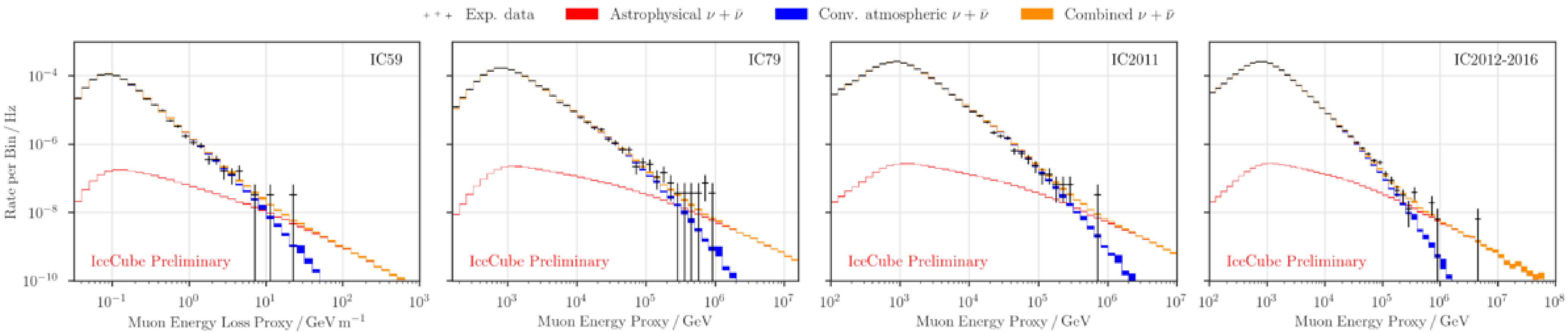




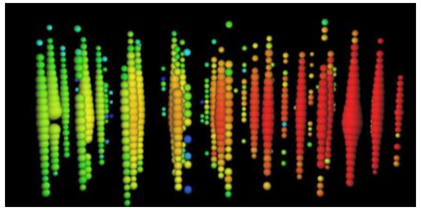
Astrophysical Diffuse Neutrino Flux

Upward going muon* neutrino sample (8 years/2009-2016)

*Select muon induced by muon neutrino CC interactions



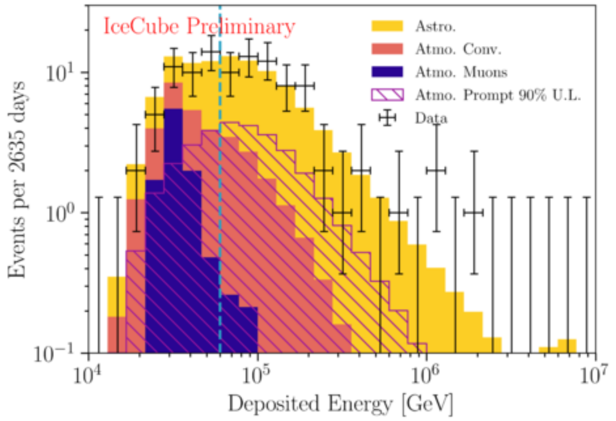
~880TeV upward through-going muon track event

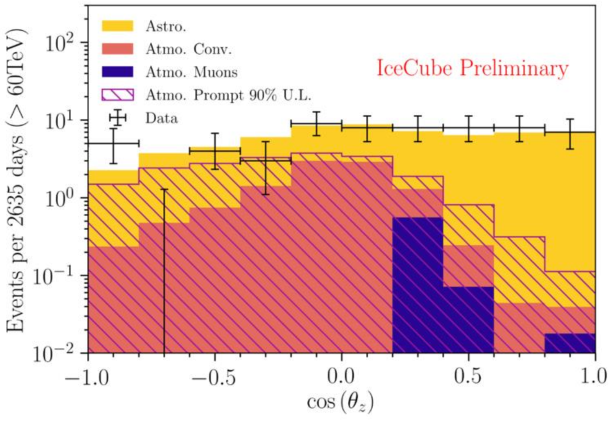


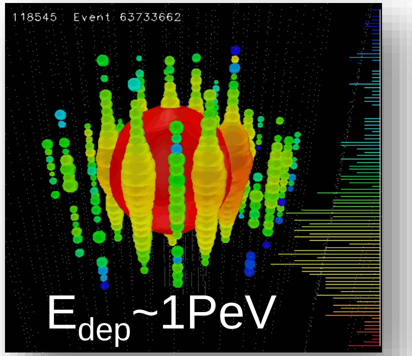
Phys. Rev. Lett. 115, 081102 (2015)

High energy starting event** neutrino sample (7.5 years/2010-2017)

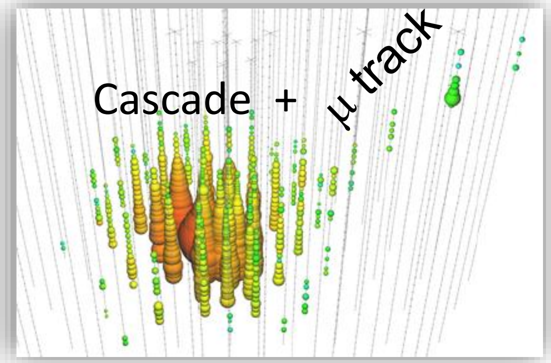
**Select neutrino events with outer layer detector as muon veto







PRL 111 (2013) 021103

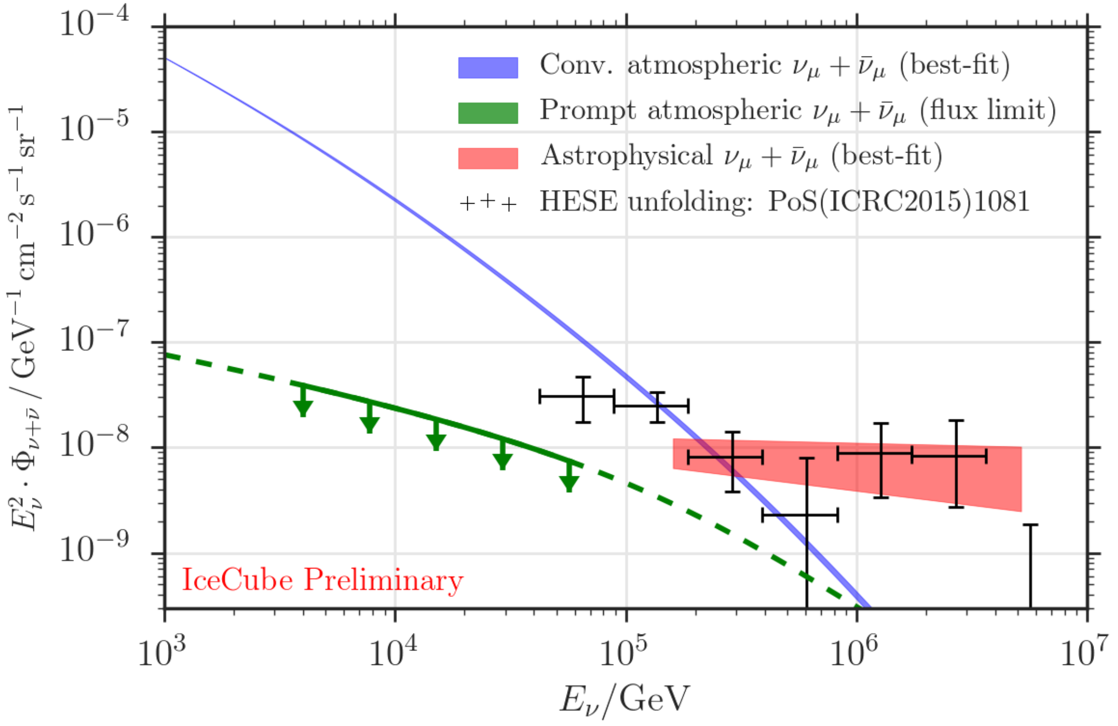


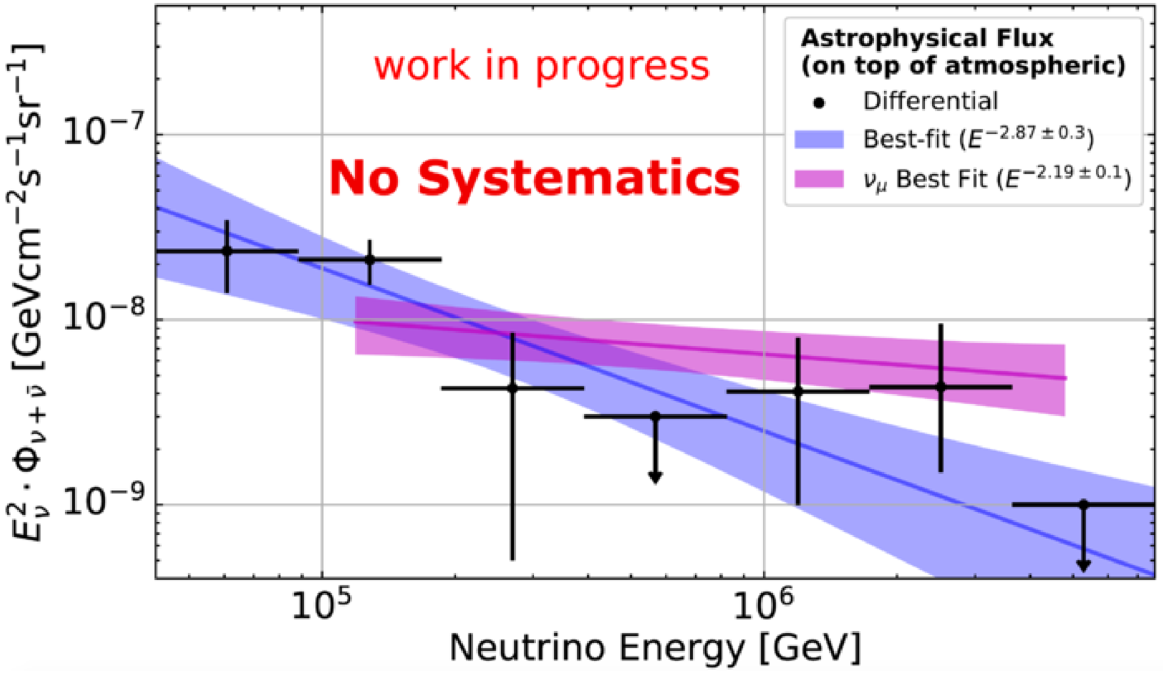
PRL 113, 101101 (2014)

Best Fit Estimate with Independent Samples

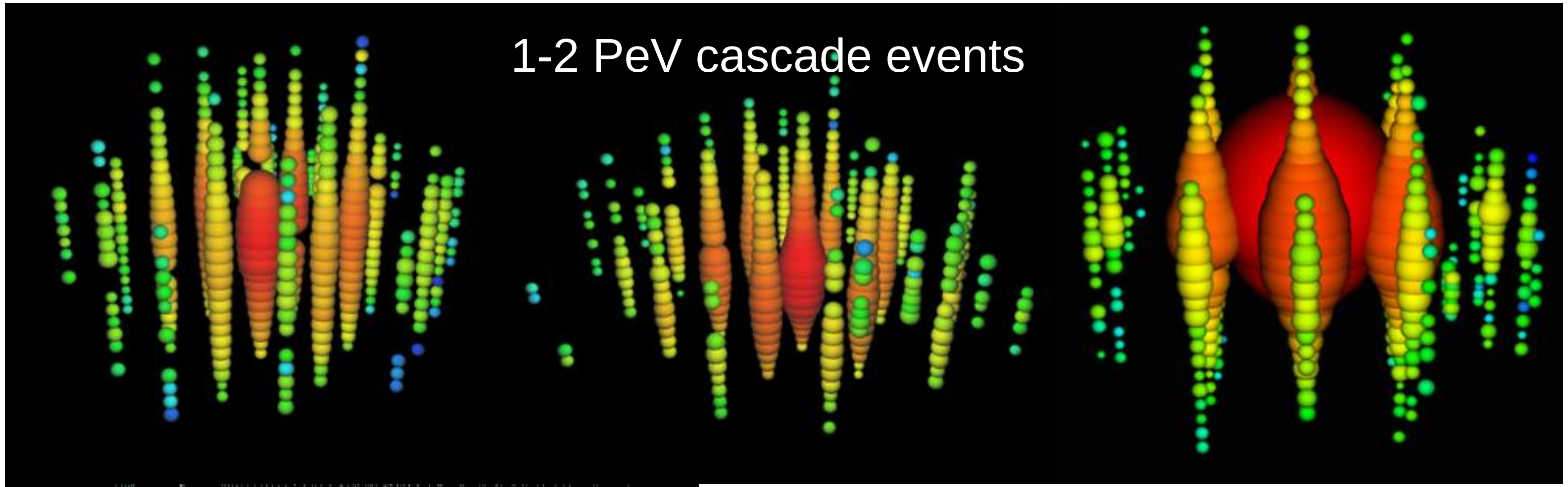
Best single power-law fit results $\Phi_{\text{astro}} = \Phi_0 \left(\frac{E}{E_0} \right)^{-\gamma}$

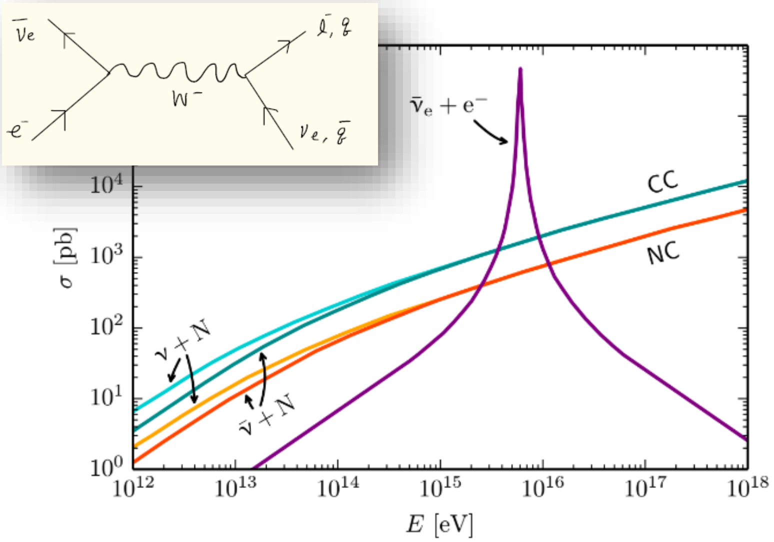
- Good agreements of independent astrophysical neutrino samples above 200TeV
- Detailed consistency studies on <200TeV still on going

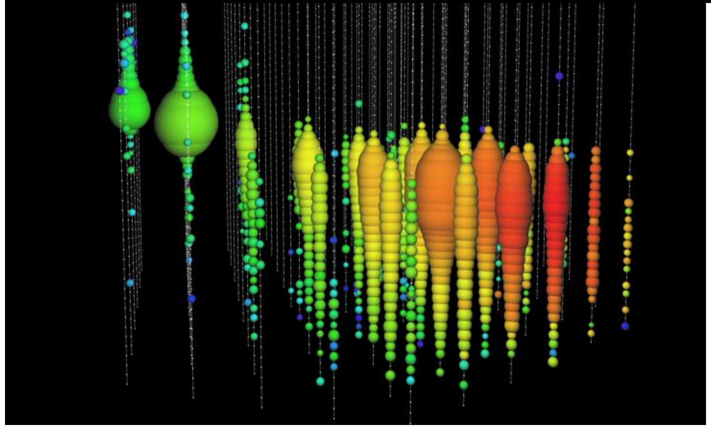




The PeV Universe



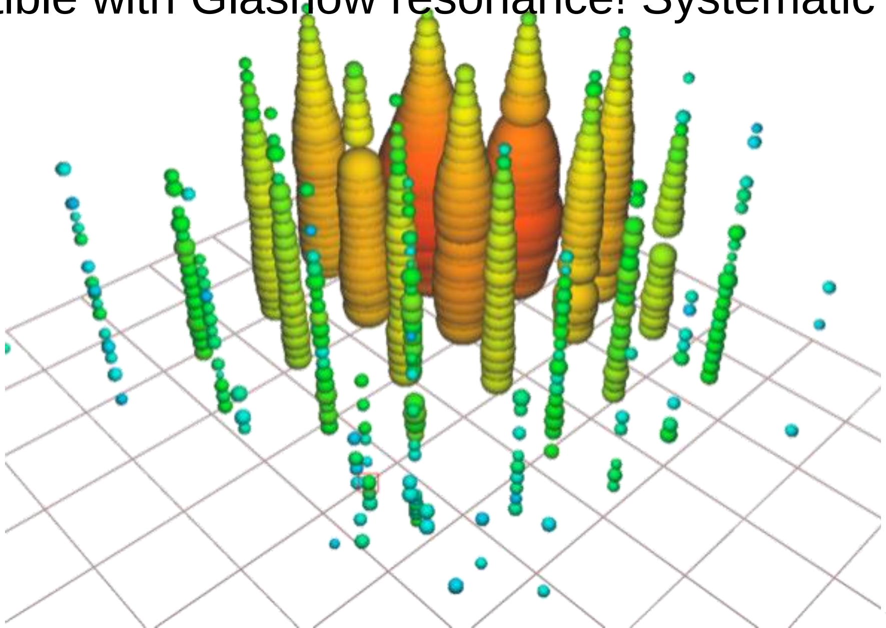




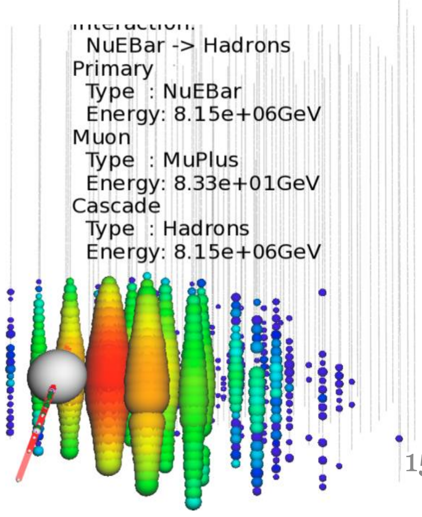
Highest energy event to date,
an upward-going track.

- Deposited energy 2.6±0.3 PeV
- Median neutrino energy 8.7 PeV
- Observed photoelectrons 130,000 pe

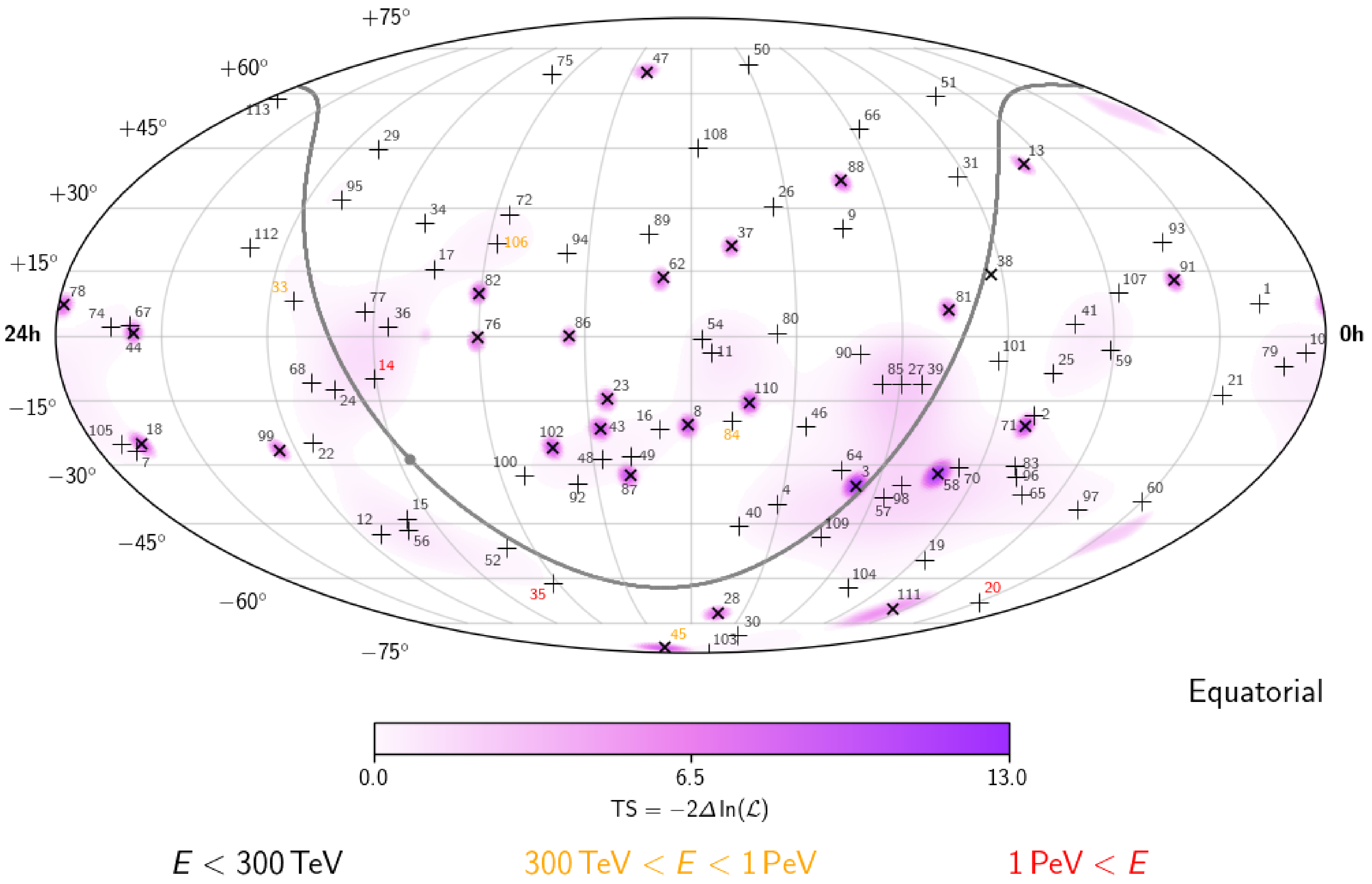
6.0±0.3 PeV cascade events
Well compatible with Glashow resonance! Systematic studies ongoing



Simulated GR event

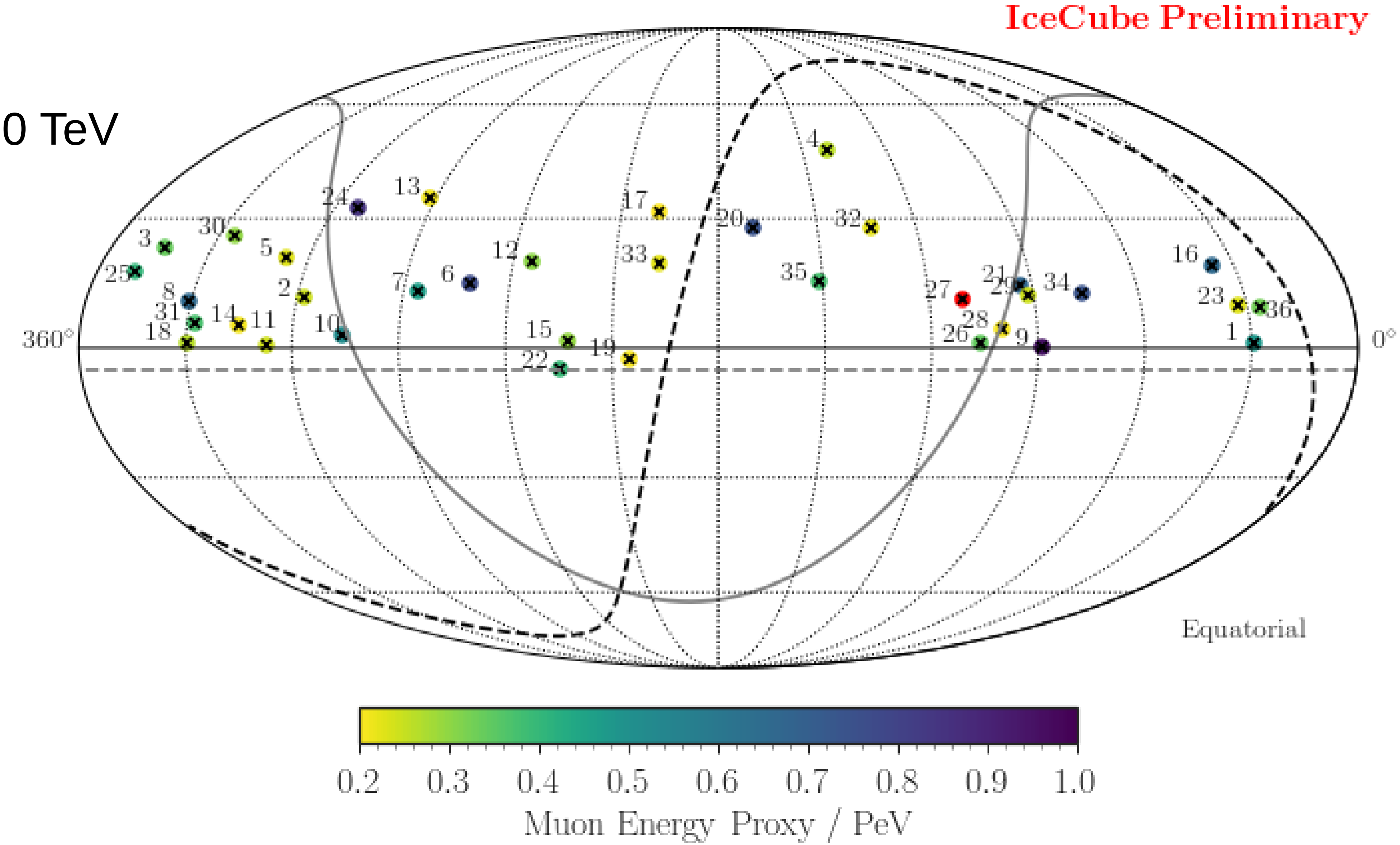


No clustering observed in starting events

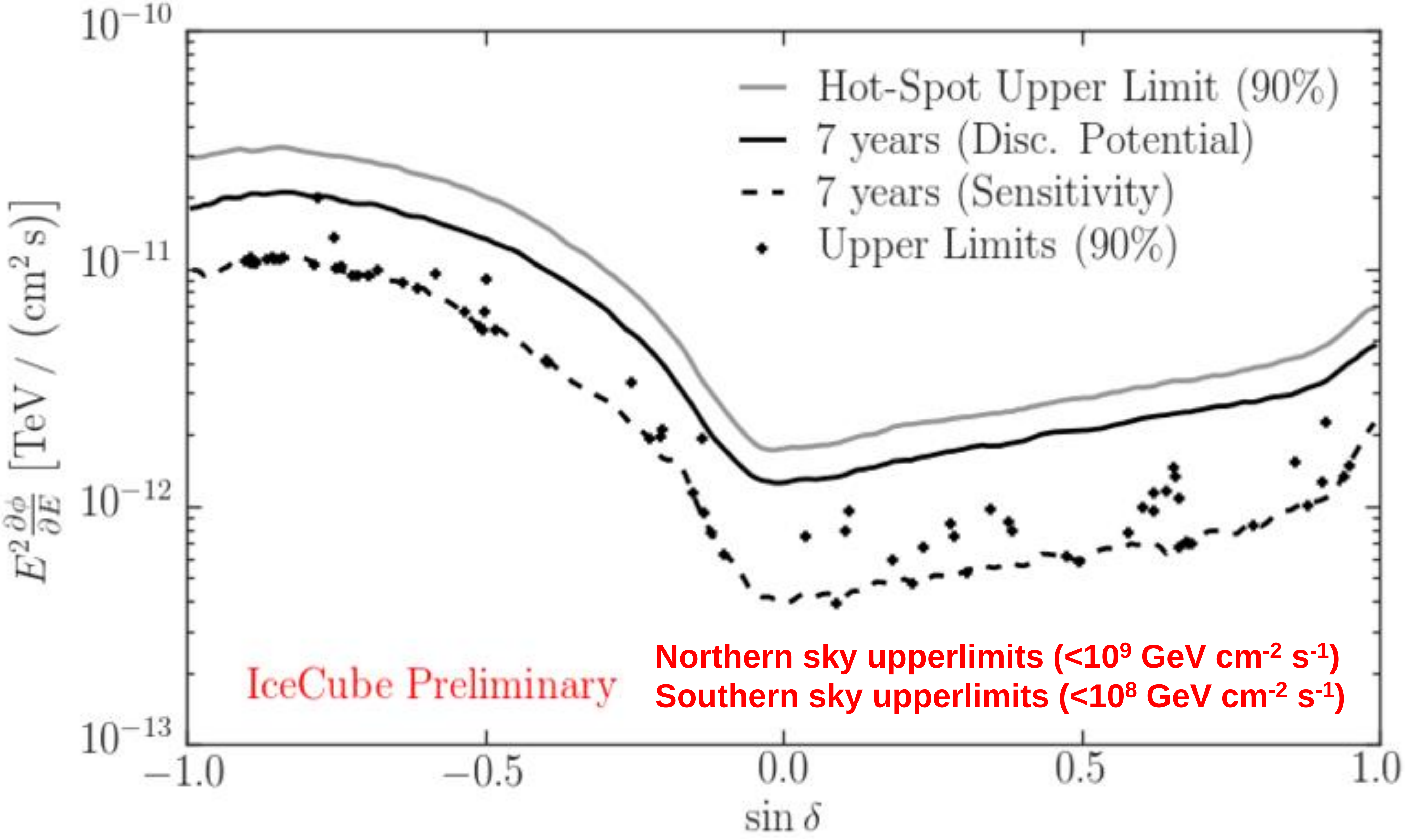


Neither in upward-muon sample

>200 TeV

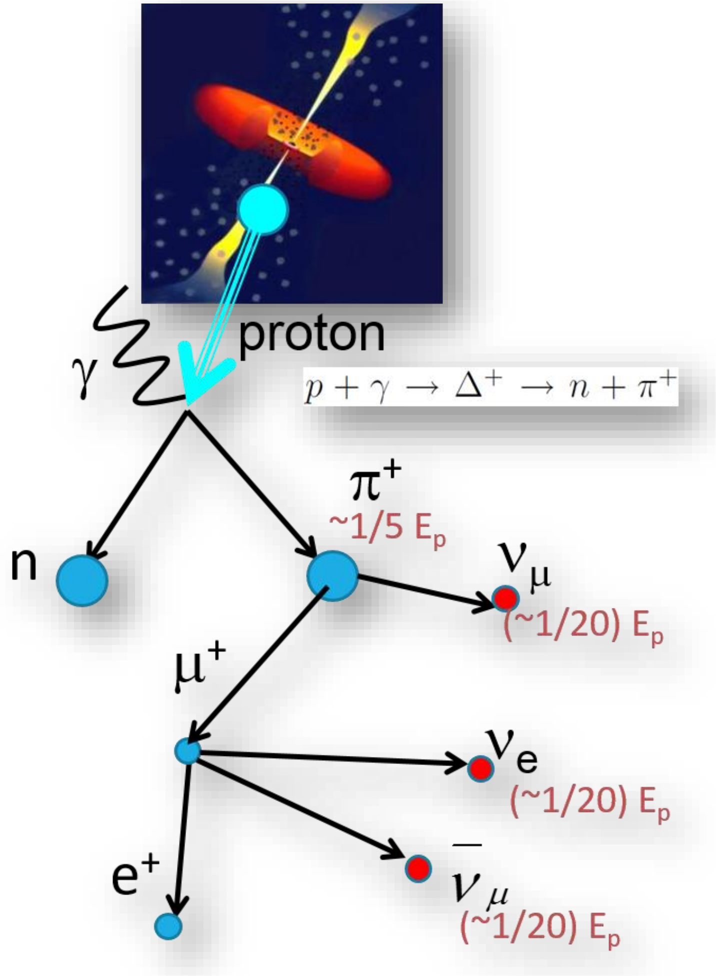


Upperlimits from 7 year point source search



Unsocial Neutrino Unites UHE sky

$$E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma$$



Simple hadronic "creation"

$$p + p \to p + p + \pi^0 + \pi^+ + \pi^- + \ldots$$

$$p + \gamma \to p + n + \pi^0 + \pi^+ + \ldots$$

- **Ingredients**
  - pp or pγ interaction
  - cosmic-ray and target spectra in source

- **Directly accompanying partners**
  - gamma-ray from **neutral pions (π^0)**
  - parent cosmic-rays (p, nuclei)

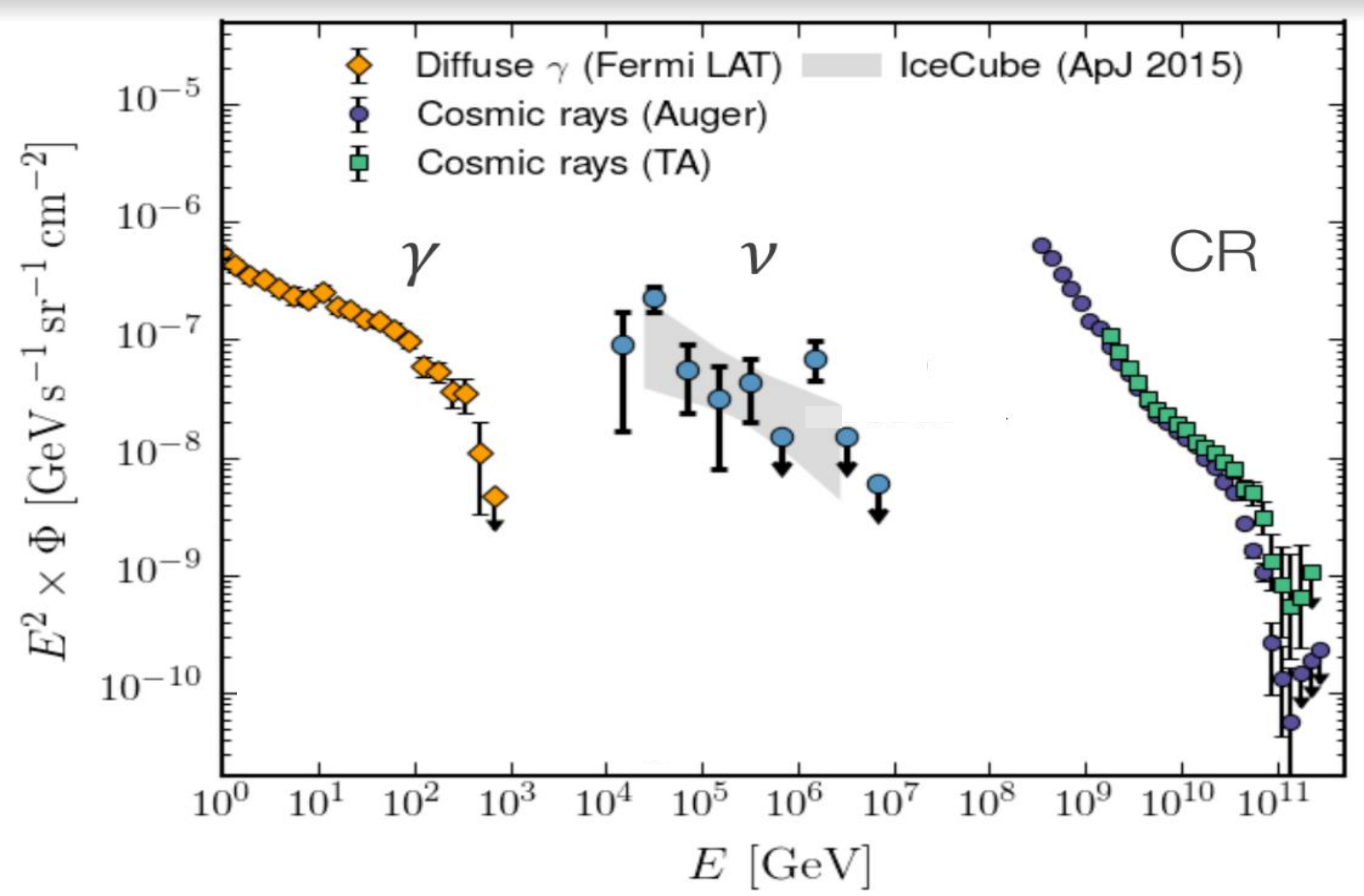
$$\pi^0 \to \boxed{\gamma\gamma}$$

$$\pi^{+,-} \to \mu^{+,-} + \boxed{\nu_\mu(\bar{\nu}_\mu)}$$

- **Indirectly accompanying partners**
  - radio, optical, x-ray...
  - gravitational waves

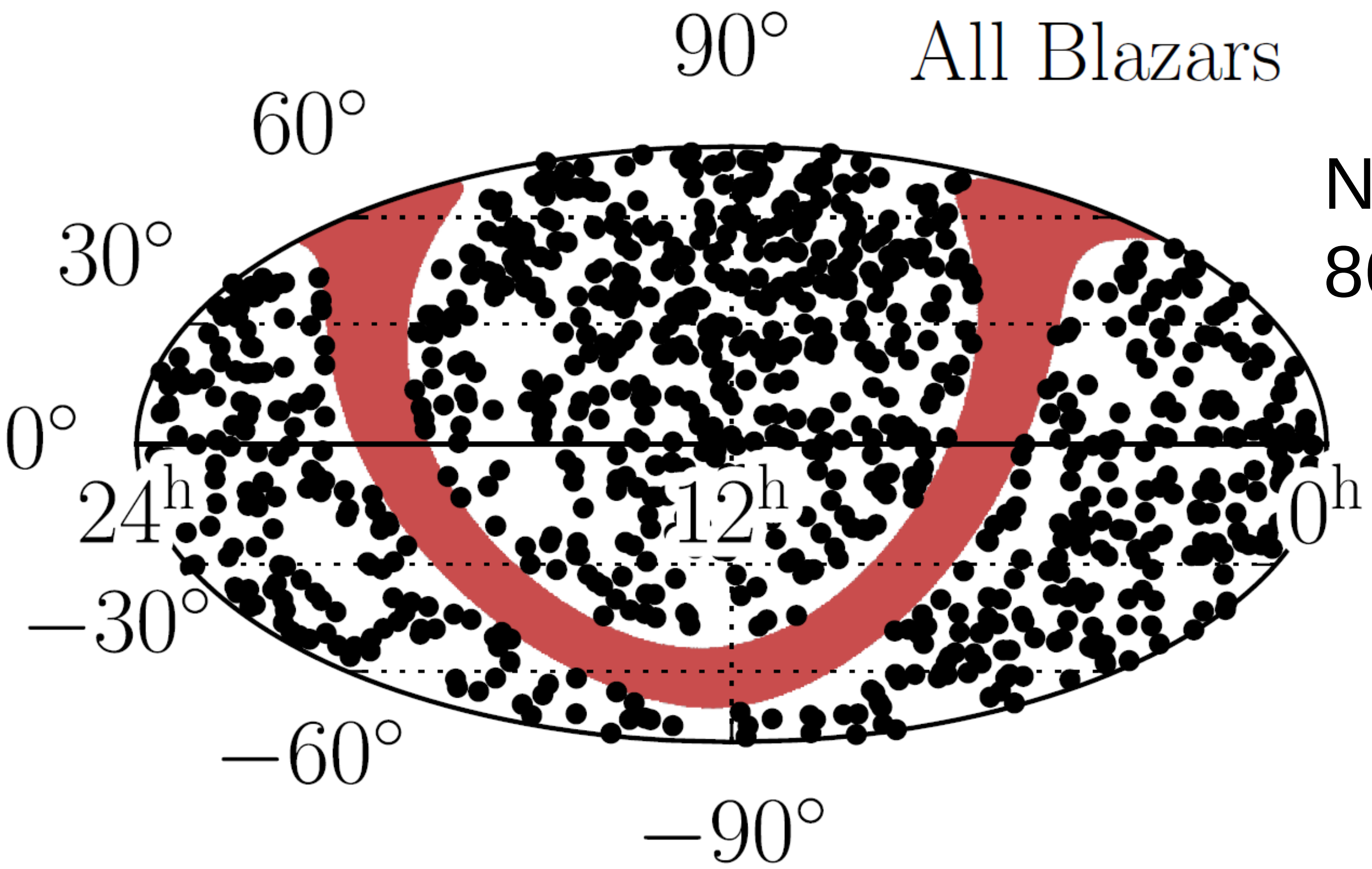
  Multi-messenger!

Multi-messenger Connection?



(c) Marek Kowalski

Blazer stacking analysis with 3year IC data



IceCube arXive:1611.03874

Neutrinos from Fermi 2LAC
862 blazer directions

Northern sky:

TeV < E_ν < PeV

Southern sky:

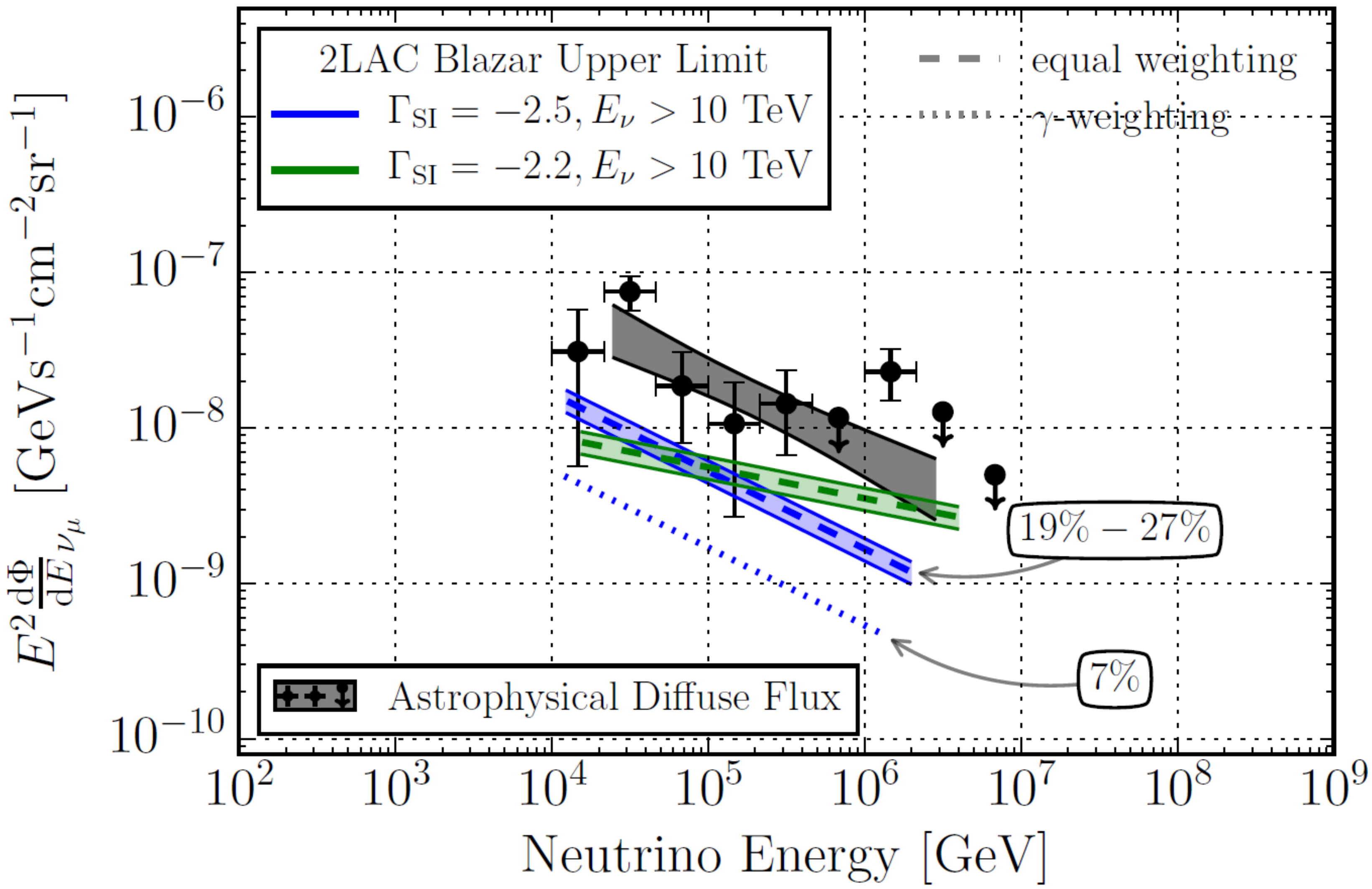
E_ν>PeV

All sources are equal
$(w_{model,j}=1)$

or

$\nu_{lum.} \propto \gamma_{lum.}$
$(w_{model,j} \propto \gamma_{lum.,j})$

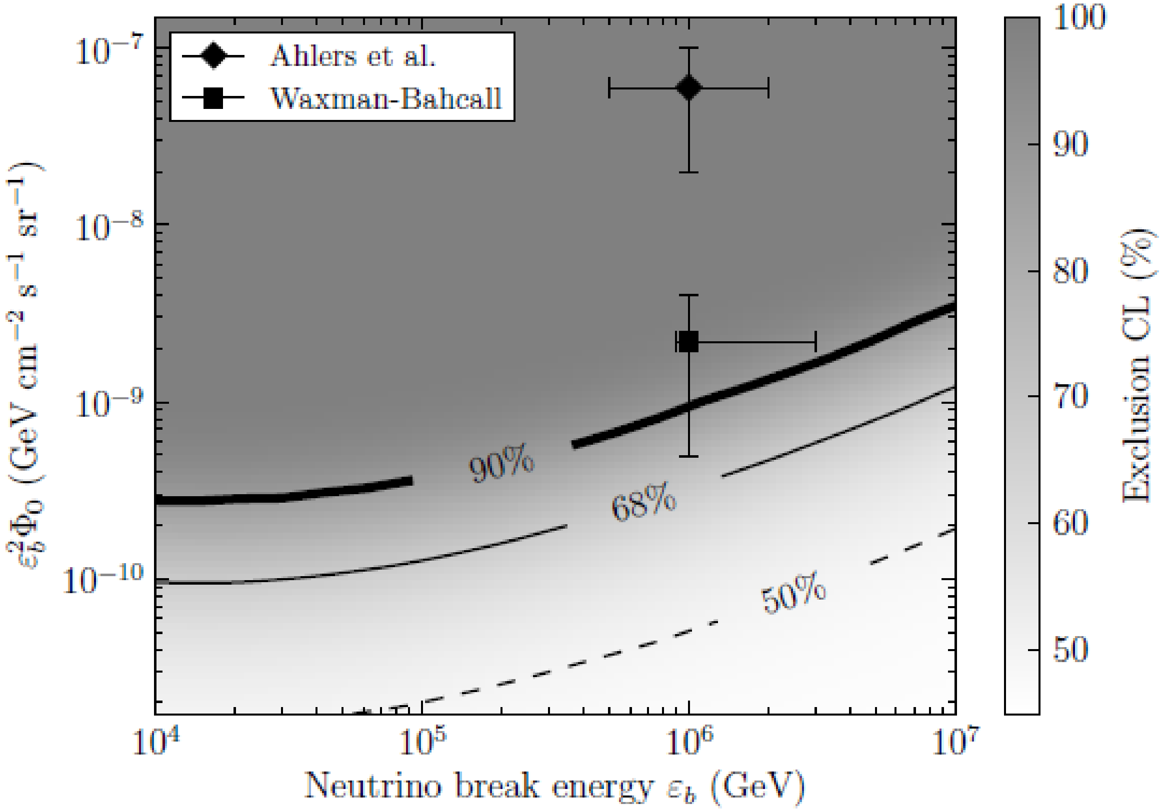
blazar contribution



- The equal-weighting upper limit results in a maximally19%-27% contribution of the total 2LAC blazar sample to the astrophysical neutrino flux
- Sub dominant contribution still possible

Gamma-ray burst contributions

IceCube arXive1412.6510



Temporal and direcitional correated events with 502 bursts from Fermi GBM catalogs

No significantly correlated neutrino events with GRB in 4 years of IceCube data

generic doubly broken power-law model

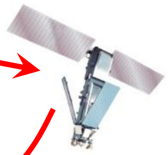
$$\Phi_\nu(E) = \Phi_0 \cdot \begin{cases} E^{-1}\varepsilon_b^{-1} & E < \varepsilon_b, \\ E^{-2} & \varepsilon_b \le E < 10\varepsilon_b, \\ E^{-4}(10\varepsilon_b)^2 & 10\varepsilon_b \le E\,. \end{cases}$$

contribute no more than 1% of the observed diffuse flux

Neutrino Online Alert System

IceCube:
on-site event analysis and alert system has been in operation

Iridium satellites



Before 2016 April, private alert system existed. BUT background dominant

April 2016: Activated public online channel with signal efficiency of >30-50% (EHE and HESE channels)

ν

high energy ν

Flare and exposure in the universe

photon and GW

Alert!

Latency time: a few tens of seconds

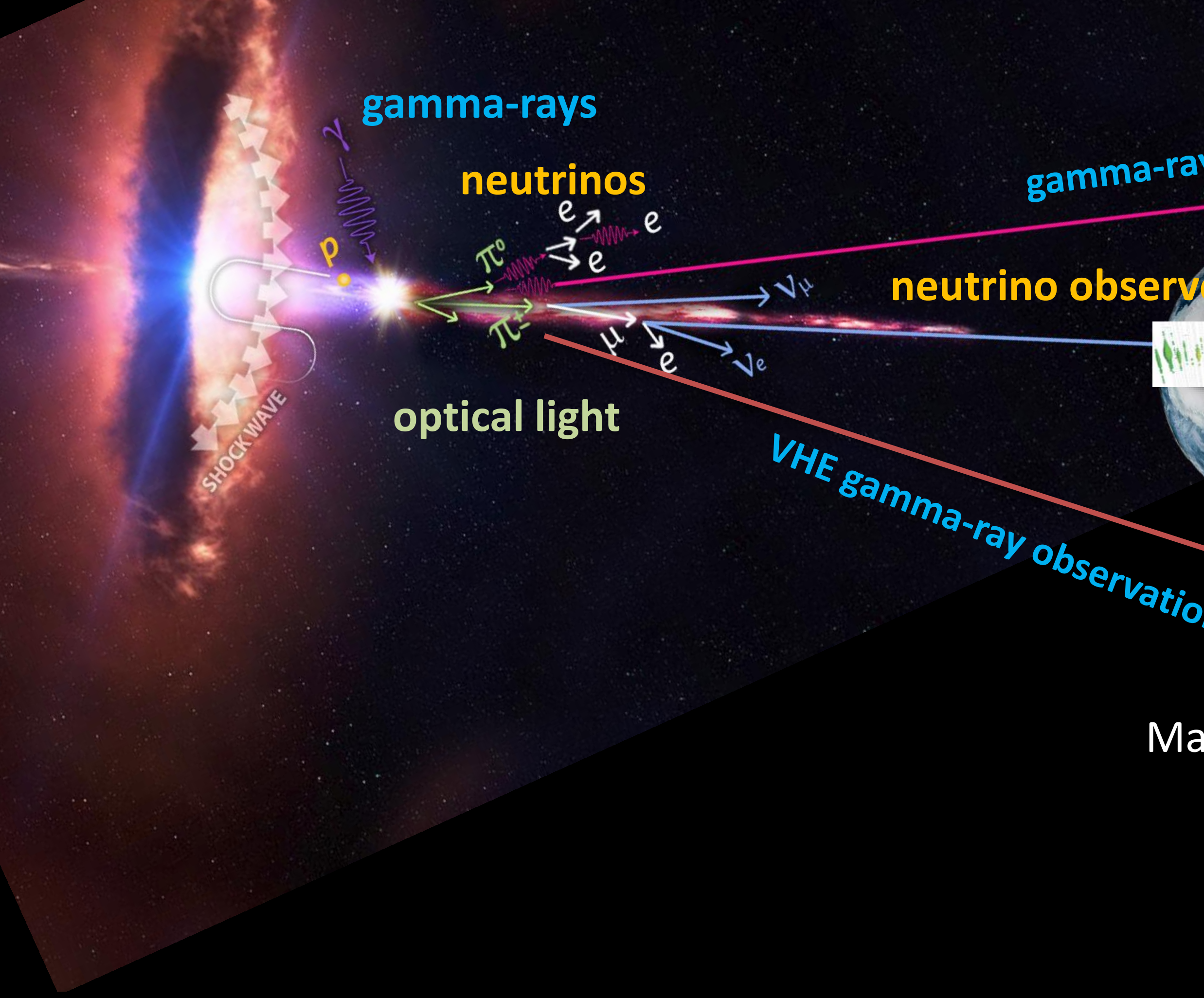
“The IceCube realtime alert system”, Astroparticle Physics, 92, 30–41,(2017)

Telescopes over the world!
(Good opportunities for telescopes of all sizes everywhere)

IceCube-170922A event

Science 361 (2018)

- 2017/9/22 20:54:30.43 UTC
- 5th and the most cosmic neutrino signal like EHE alert
- automated alert was distributed to observers just 43 seconds later



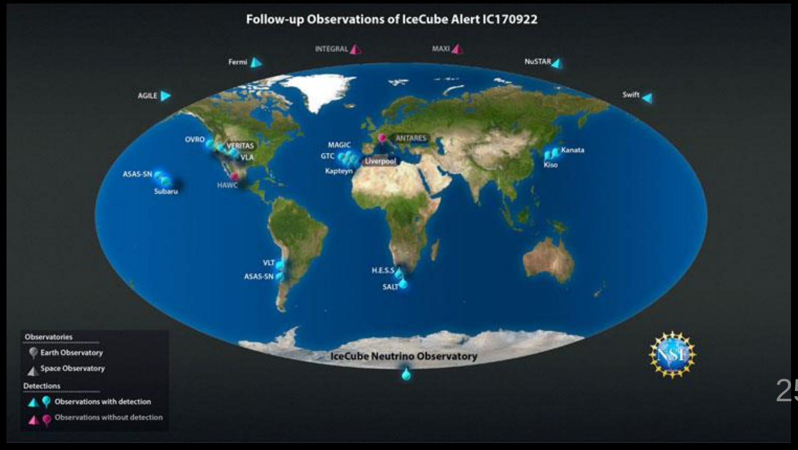
Fermi Telescope

Optical telescopes

Kanata telescope

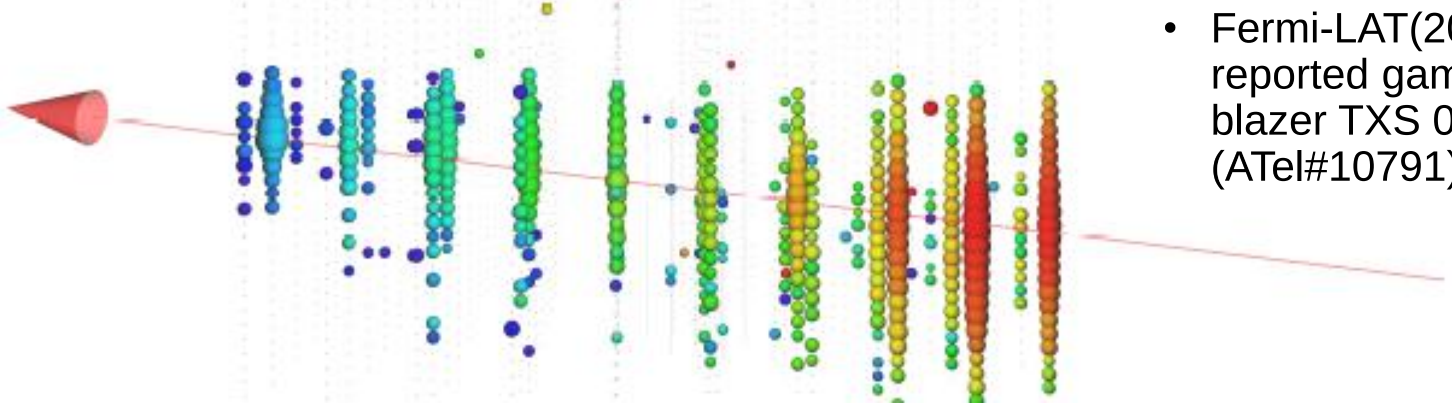
Magic telescope

...and many more telescope

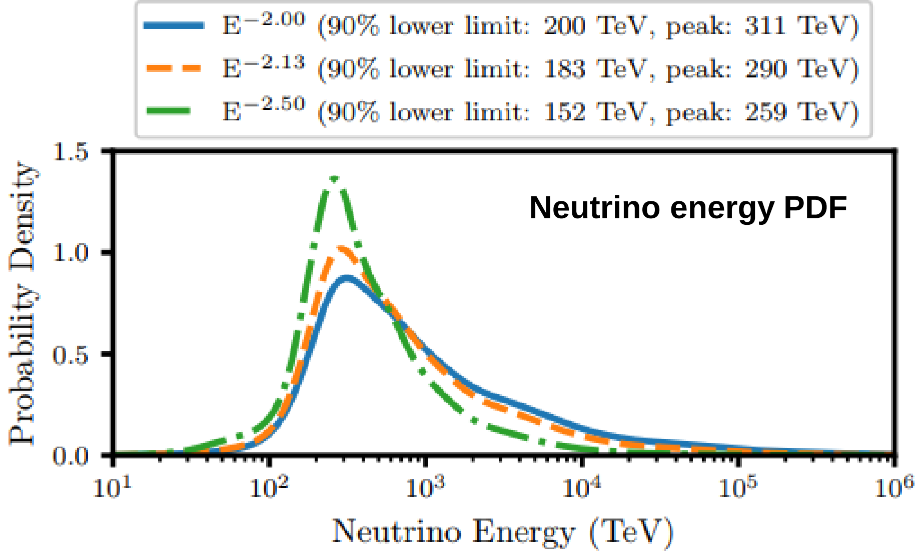


IceCube-170922A Follow up

23.7 ± 2.8 TeV muon energy loss in the detector

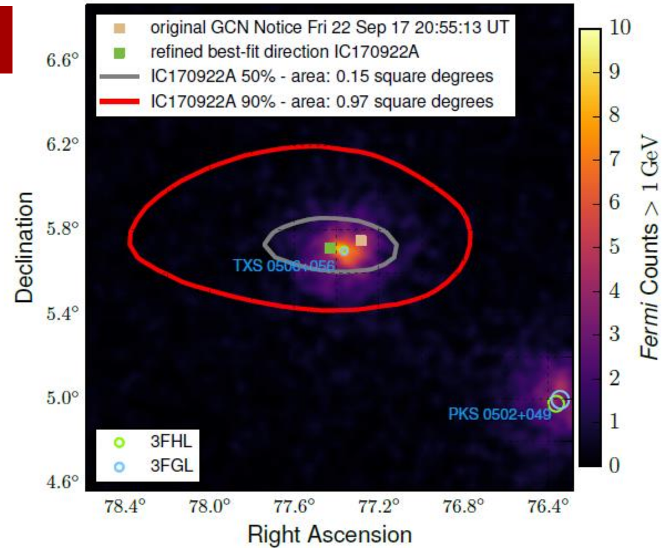


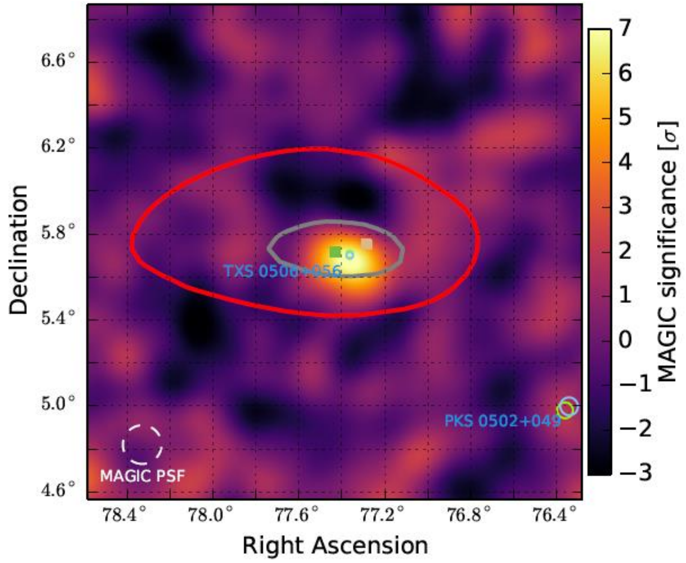
a most probable neutrino energy of 290 TeV



HE gamma-ray observations

- Fermi-LAT(20MeV - 300 GeV) reported gamma-ray flaring blazer TXS 0506+056 (ATel#10791)

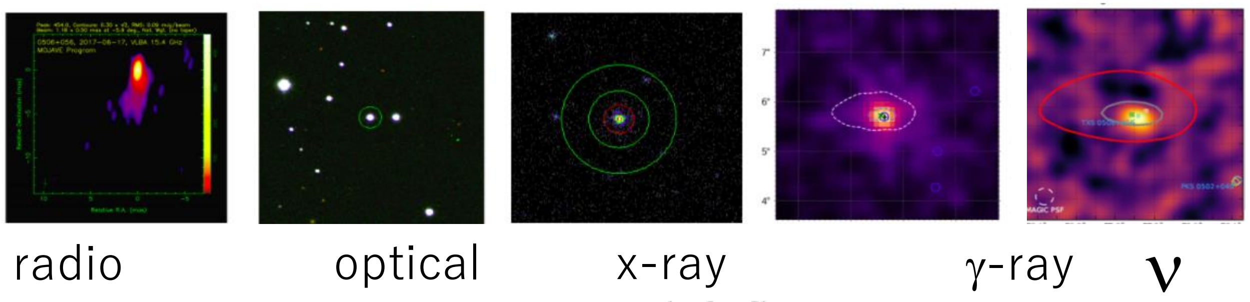


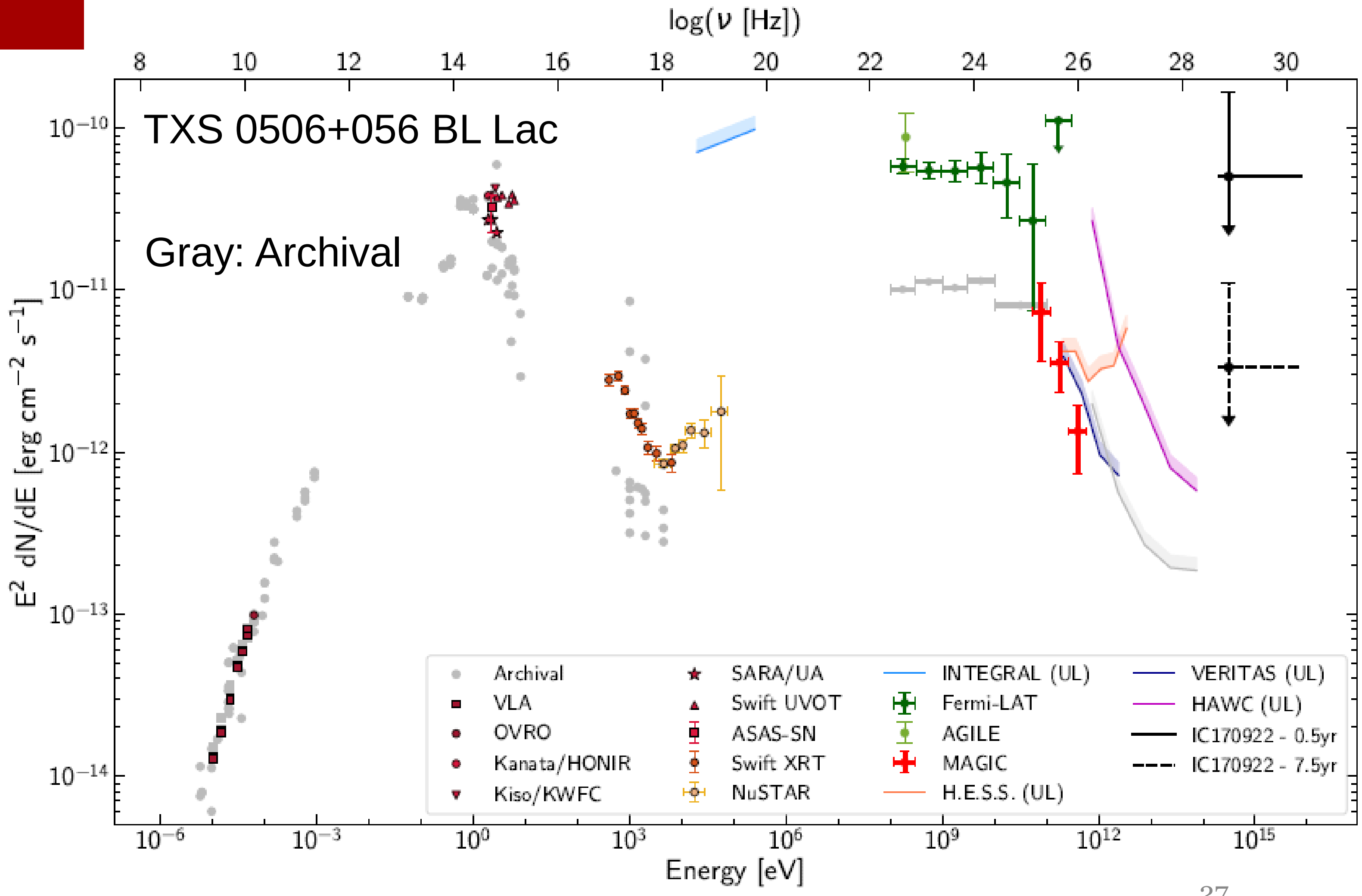


VHE gamma-ray observations

- Furthermore TXS 0506+056 was observed VHE gamma-ray Magic telescope (E > 100GeV) with >6.2σ (ATel#10817)

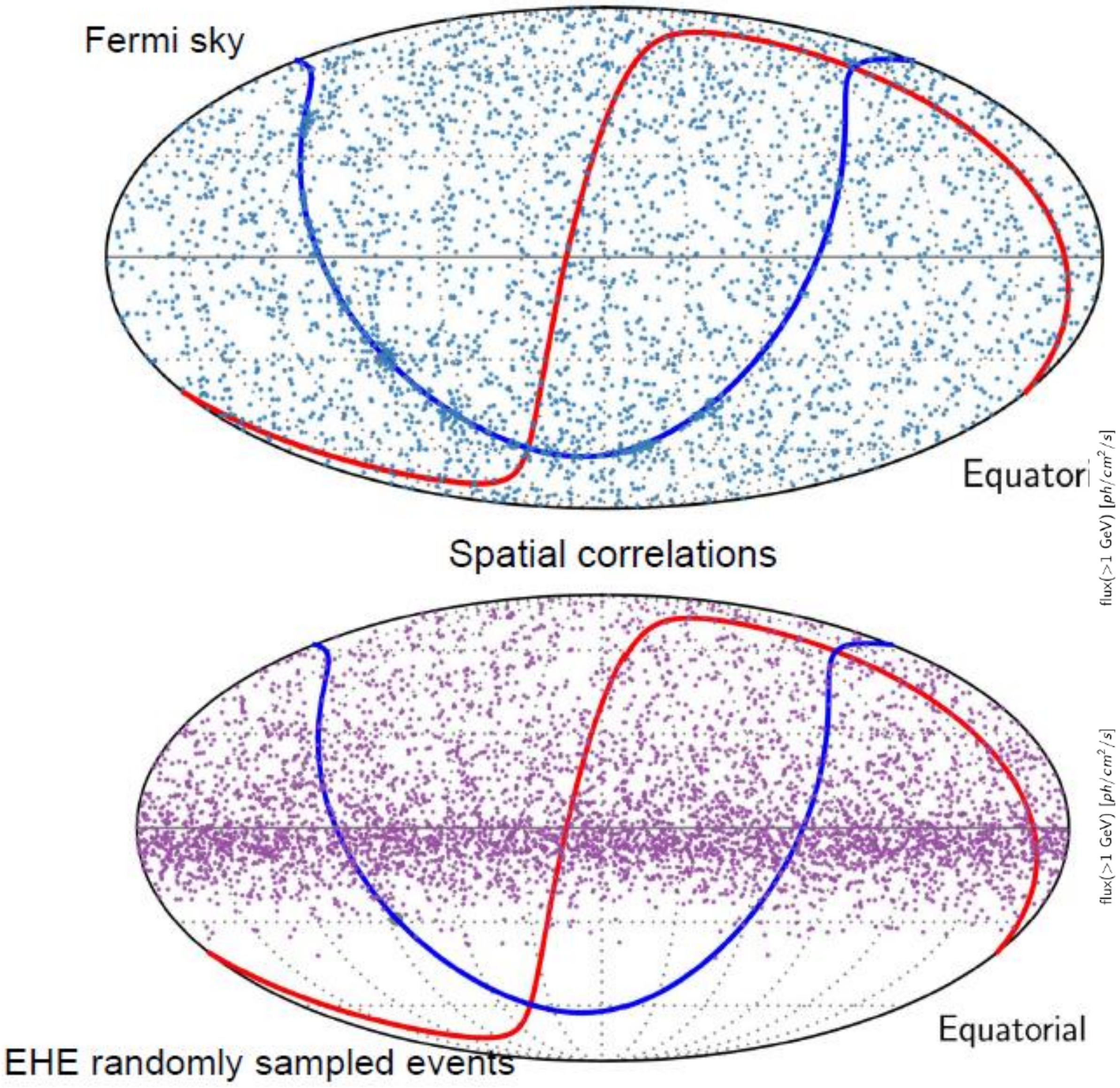
A successful Multiwavelength Campaign with ν!





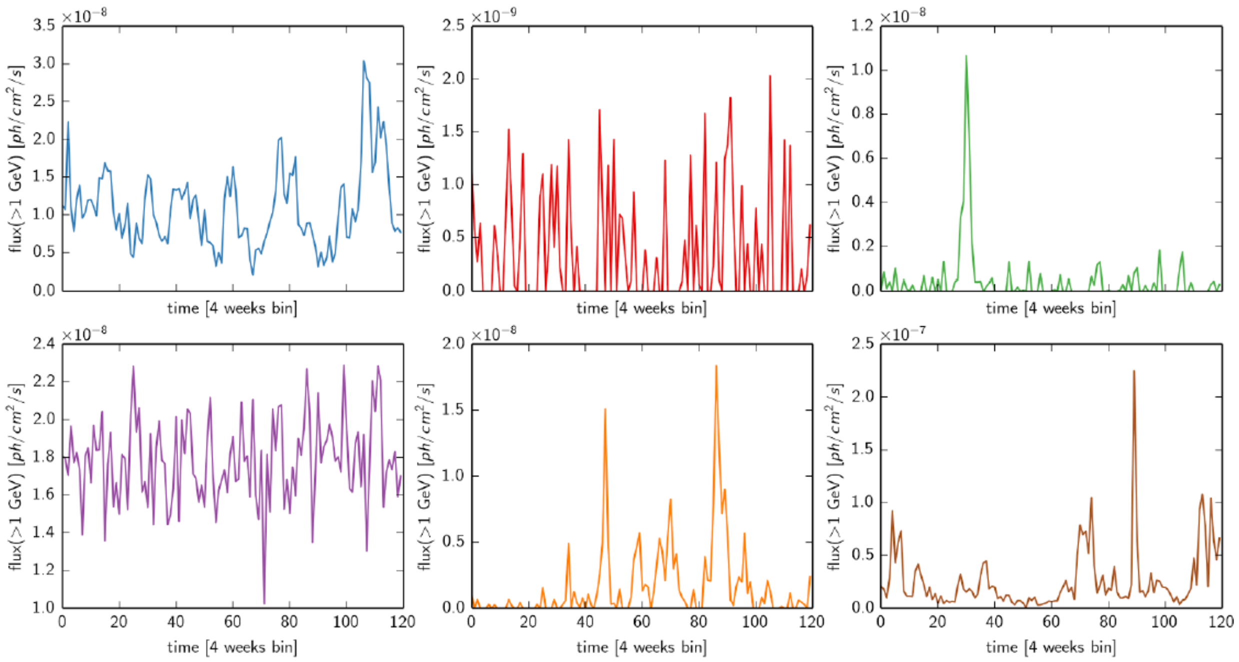
- Double-bump feature
- Neutrino flux upper limits to produce 1 detection
  - 1.8×10^{-10} erg cm^{-2} s^{-1} over 0.5yr
  - 1.2×10^{-11} erg cm^{-2} s^{-1} over 7.5yr
- (Paiano et al. 2018) the 10.4m Gran Telescopio Canarias, an optical spectroscopy ⇒ z = 0.3365 +/- 0.0010
- γ-luminosity between 100MeV and 100GeV
  - $\sim 1.7 \times 10^{47}$ erg s^{-1} at high state
  - $\sim 3.7 \times 10^{46}$ erg s^{-1} at all time average

Correlation Analysis: Materials

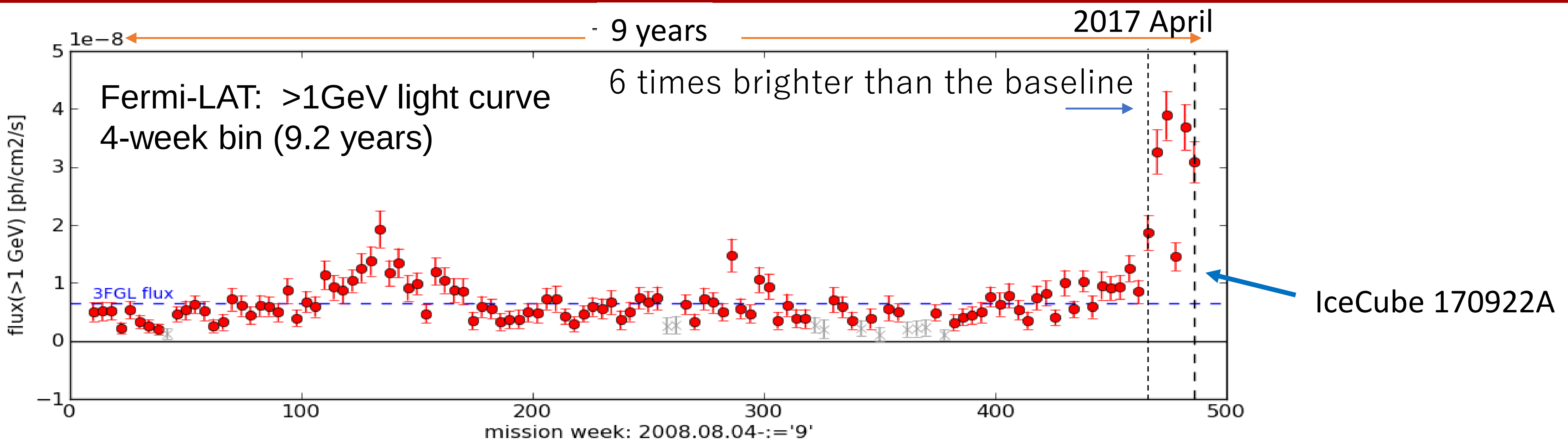


- ≈95.5% seen no gamma-ray
- ≈4.4% seen one gamma-ray source

3000 fermi light curves from Masaaki Hayashida



ν-γ Correlation Analysis



- $L = \prod_i^N \left(\frac{n_s}{N} P_S + \frac{n_b}{N} P_B\right) \rightarrow TS(N=1) \propto \log\frac{P_S}{P_B}$
- $P_S = \underline{P_{spatial}(\vec{x})} \cdot \underline{W_{acceptance}(\sin\theta)} \cdot \underline{W_{temporal}(t)}$

2D Gaussian from ν ang resol. $\frac{1}{2\pi\sigma^2} e^{-(\vec{x}_s - \vec{x})^2/(2\sigma^2)}$

θ-dependent acceptance

from light curve

① flux variability

$$W_{tempral} \propto \frac{I_\gamma(t)}{< I_\gamma(t) >}$$

② energy flux

$$W_{tempral} \propto \int_{1GeV}^{100GeV} E_\gamma \frac{dI_\gamma(t)}{dE_\gamma} dE_\gamma$$

Both cases: no correlation vs correlation → 4.1σ → Corrections for all 10 alerts issued previously and the 41 archival events → **≈3σ**

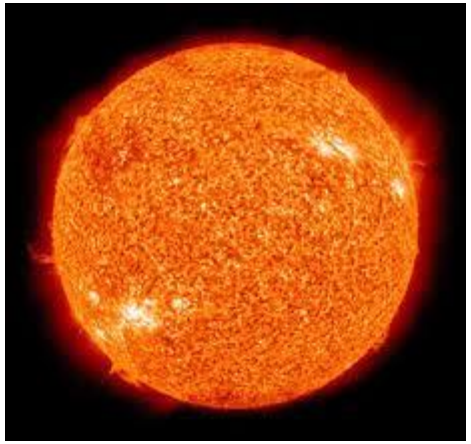
Objects Shining with Neutrinos (so Far)

Earth

typical geo-neutrino energy
<4MeV

Distance to the object
0 light years

Sun



typical neutrino energy
<20MeV

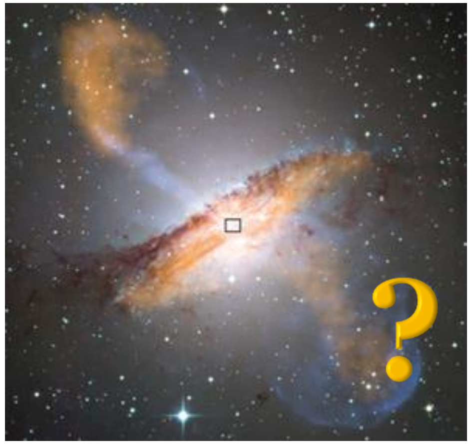
Distance to the object
0.00001581 light years
(149,600,000km)

supernova

typical neutrino energy
<100MeV

Distance to the object
160,000 light years

active galactic nuclei (blazar)



likely neutrino energy
>100,000,000MeV

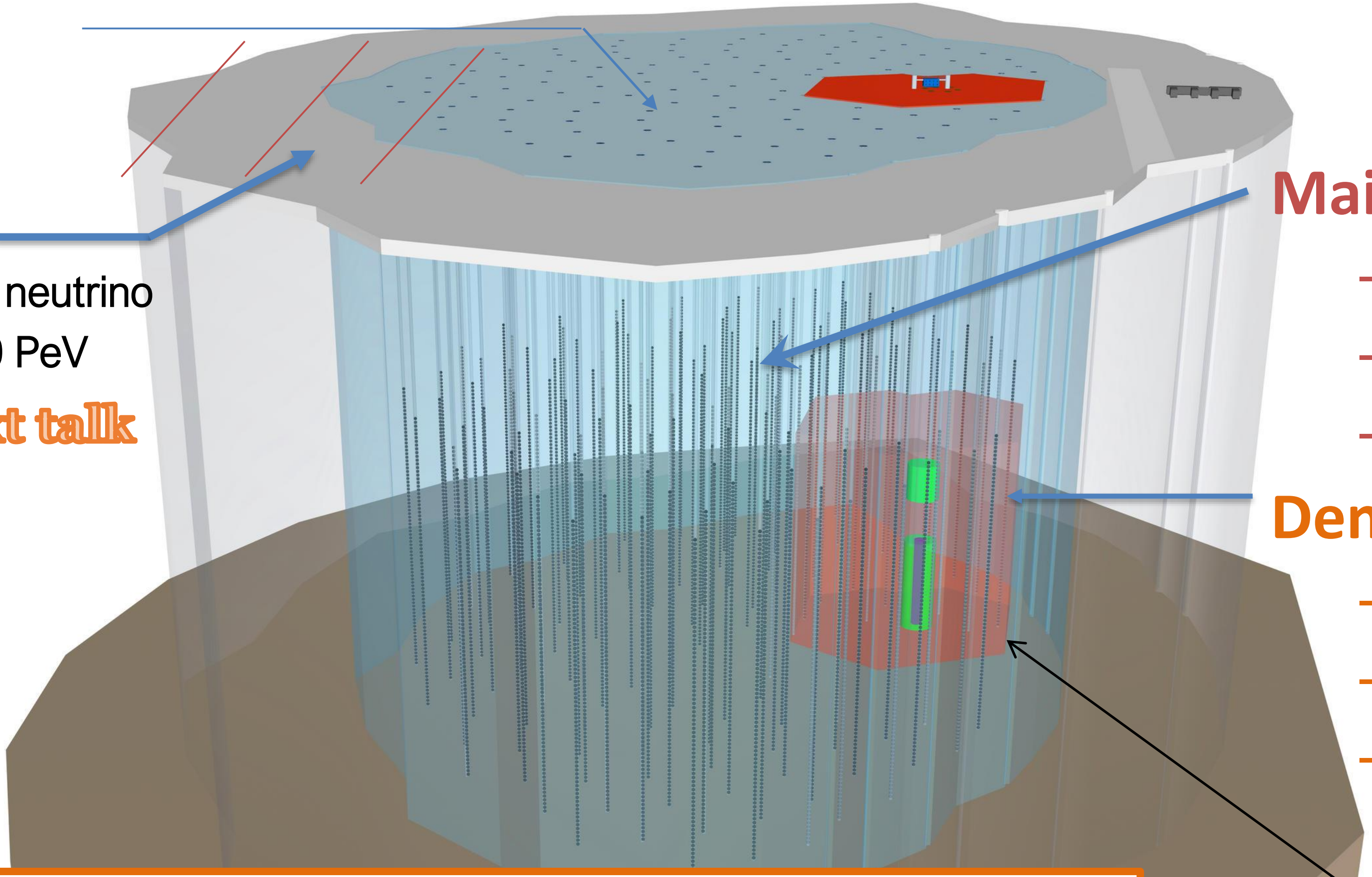
Distance to the object
4,000,000,000 light years

Distance from the Earth to Galactic center
28,000 light years

Future: IceCube-Gen2 Facility

- Surface array
  - muon veto
  - CR physics
- Radio array
  - cosmogenic neutrino
  - neutrino >10 PeV

See the next talk

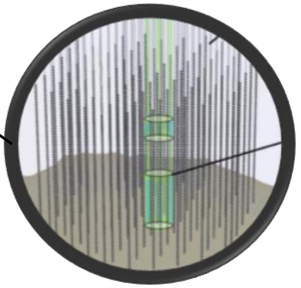


Main array

- ≈100 strings
- ≈100 sensors/string
- ≈240m distance

Dense array

- 26 strings
- 125-192 sensors/string
- ≈25m distance

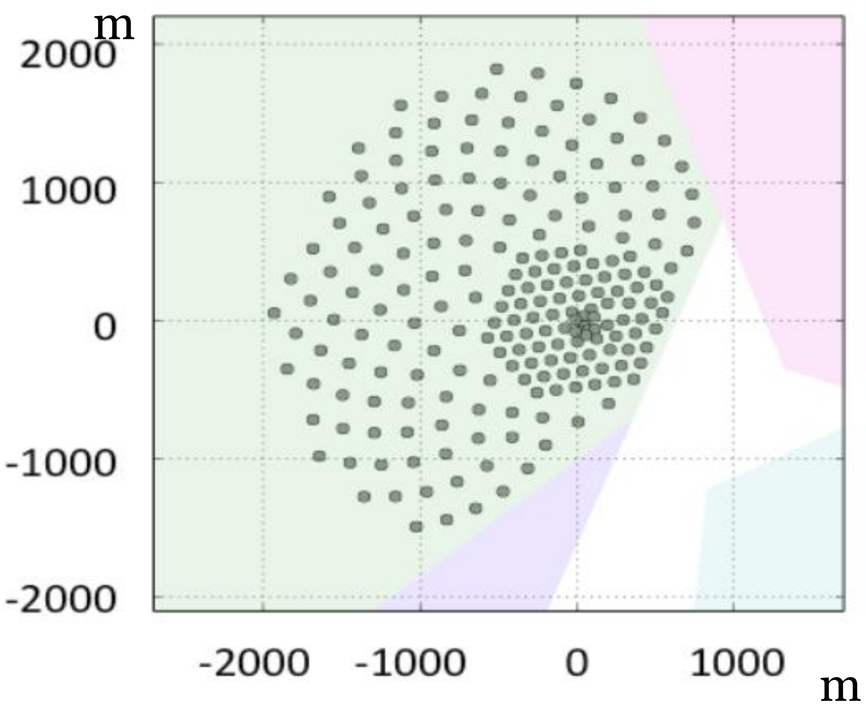


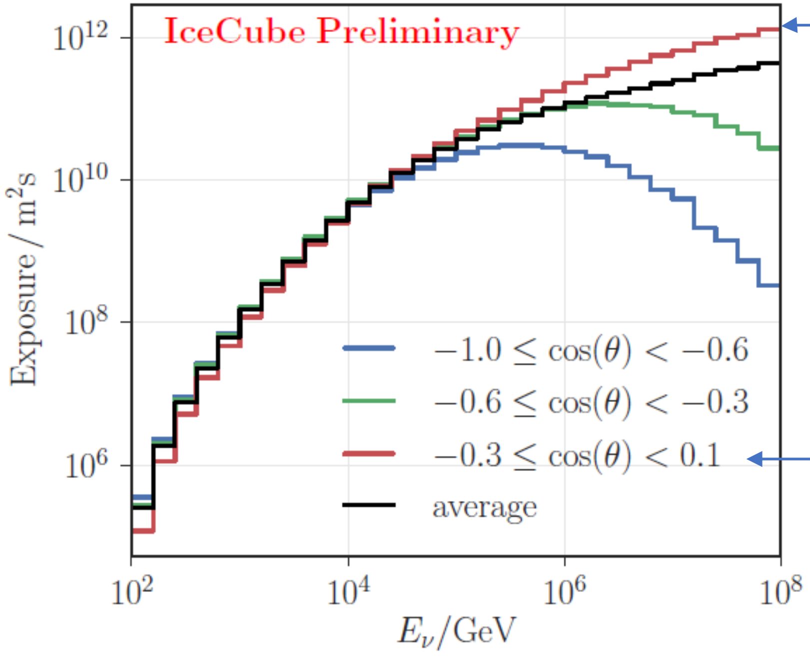
Initial step toward the realization of IceCube-Gen2 has started as the IceCube Gen2 ***Phase-1***!
(***Official approval from NSF, the last week***)

IceCube to Gen2: Point source sensitivity

- ∝sqrt(x): Livetime, Detector size
- ∝x: Angular resolution
- Signal selection efficiency
- BG rejection efficiency

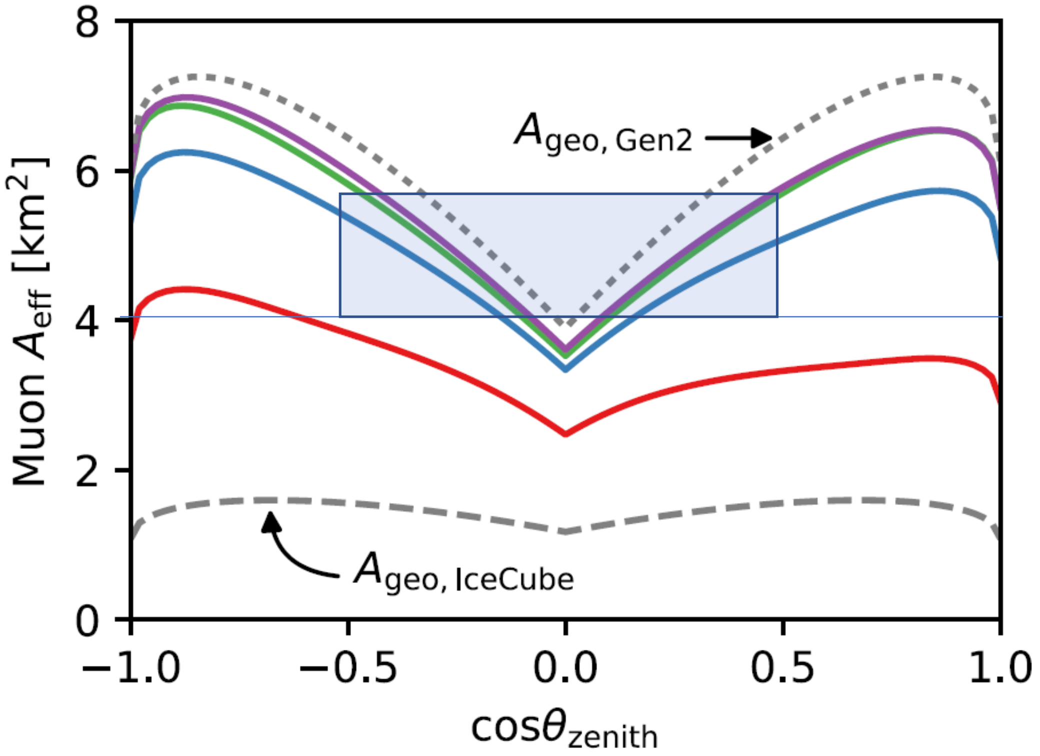
} default factor

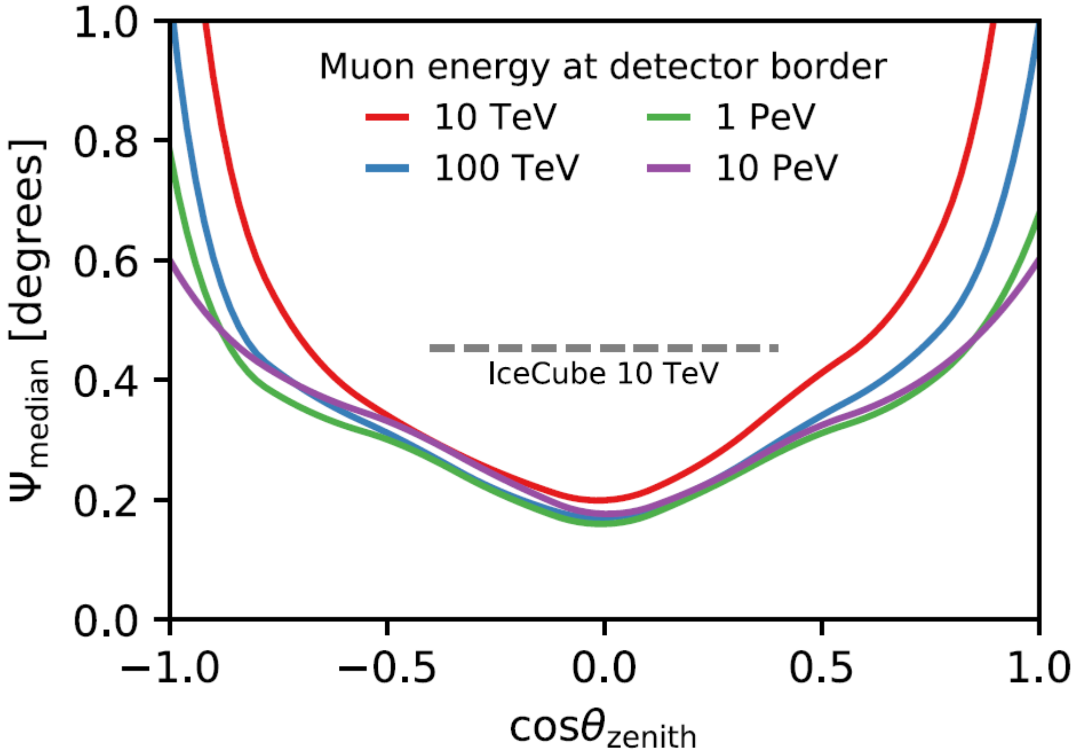




slightly downgoing horizontal direction is important for >100TeV neutrinos

Gen2 Baseline performance with default sensors



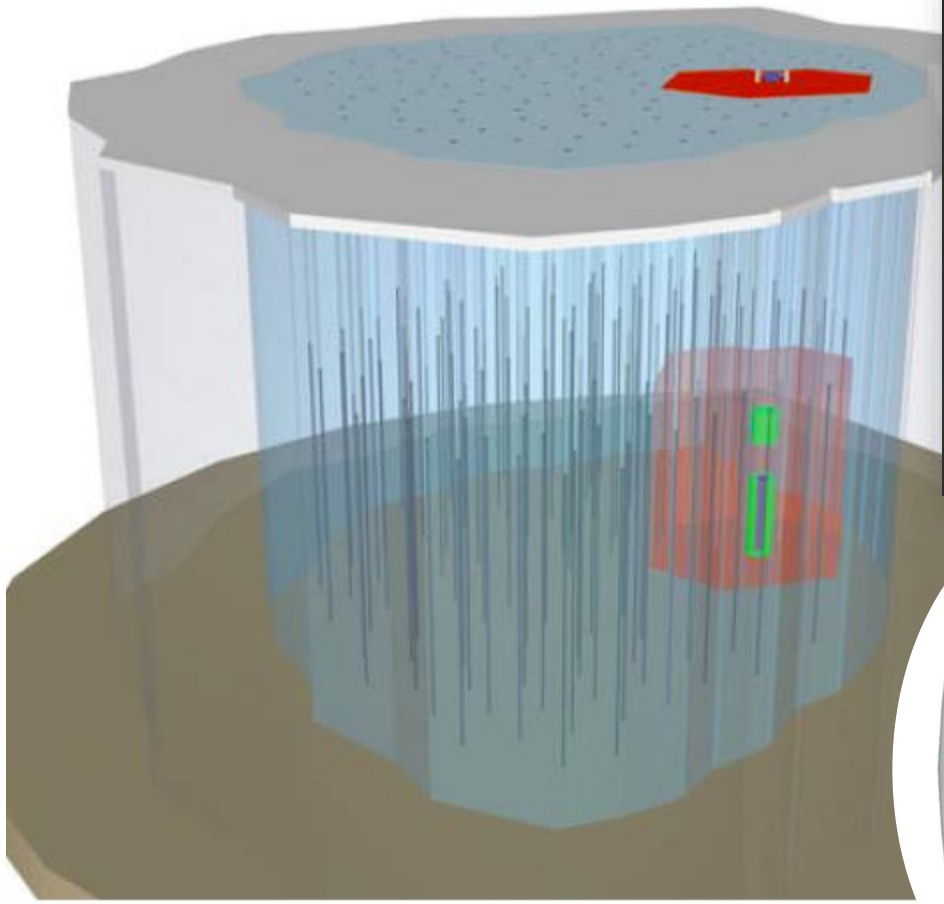


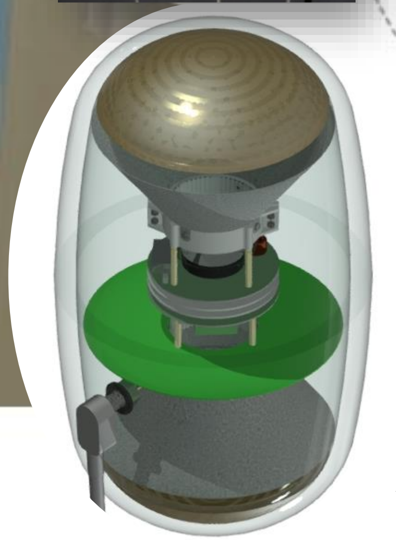
- Detector effective muon area — x 4∼5 (horizontal)
- angular resolution — x ∼ 0.45 (horizontal)

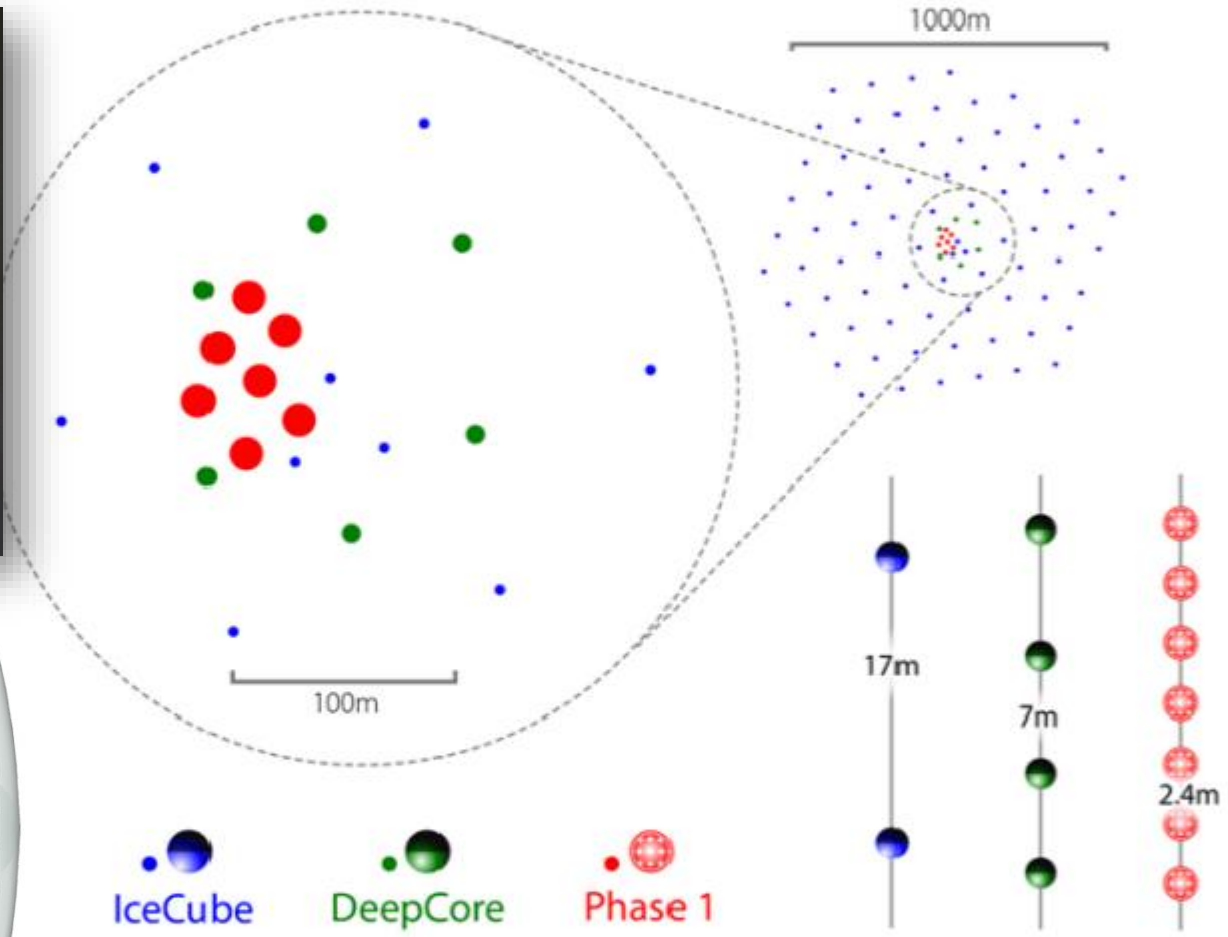
} default factors gives a factor of 5 better sensitivity

- **Further signal/bg improvements with new optical sensors (*cascade and muon reconstruction quality and BG reduction, detector/ice systematics*) are important!**

IceCube-Gen2 Phase-1

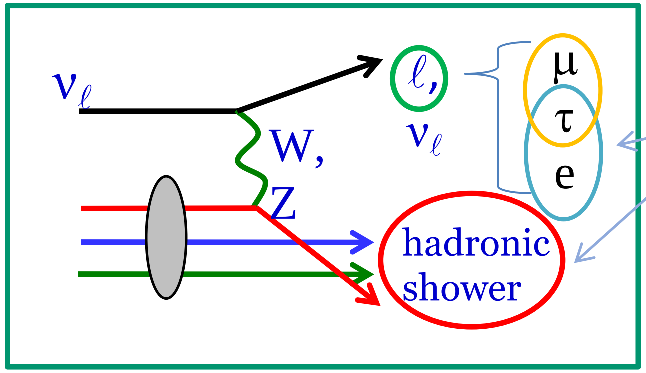


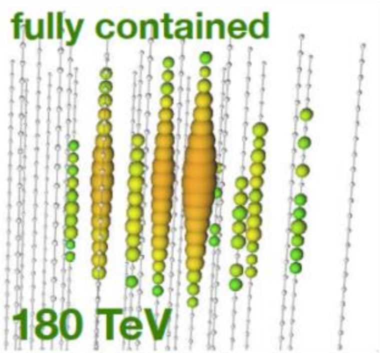


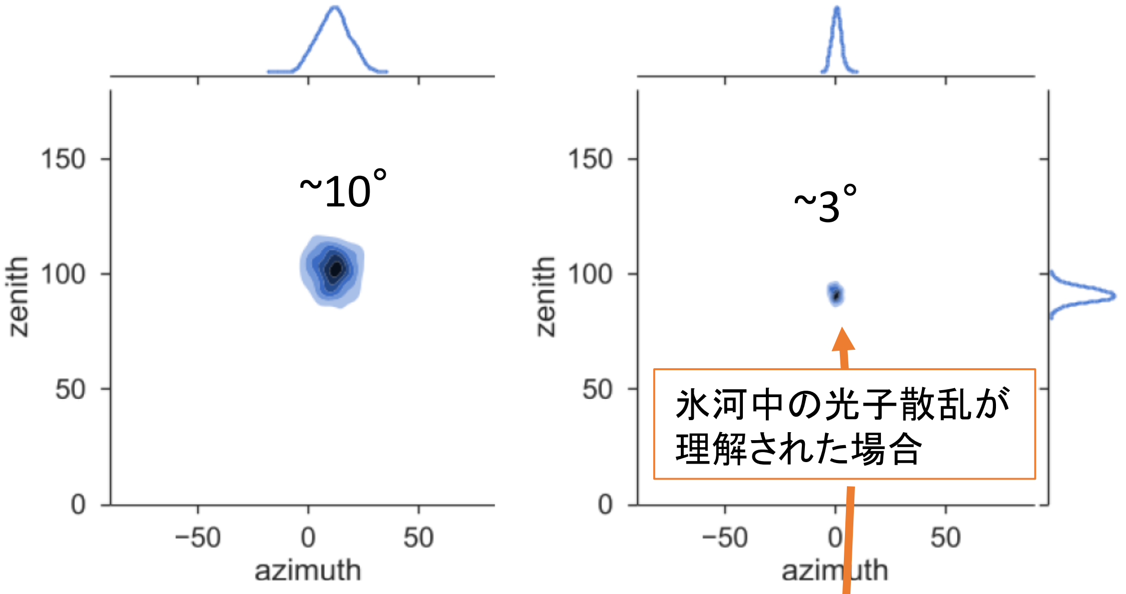


Japanese design sensors DEgg to be installed

Ice Systematic Challenge with Phase-1

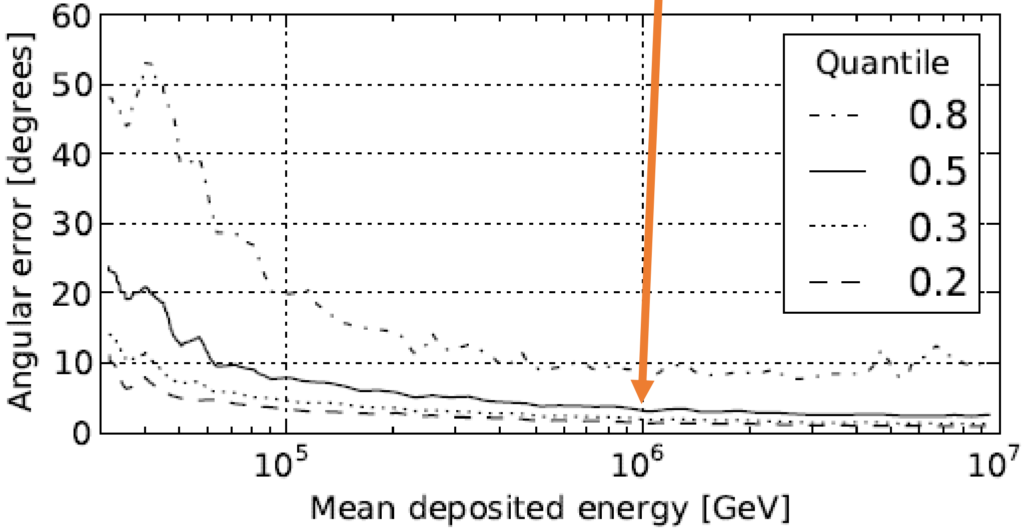






Cascade channel is complementary to upward muon track channel

- Good energy resolution of ~10%
- Directional resolution is ~10° (ice systematic dominant)
- Less atmospheric neutrino background
  - lower energy threshold (10TeV – 100TeV)
- Sensitive to full sky

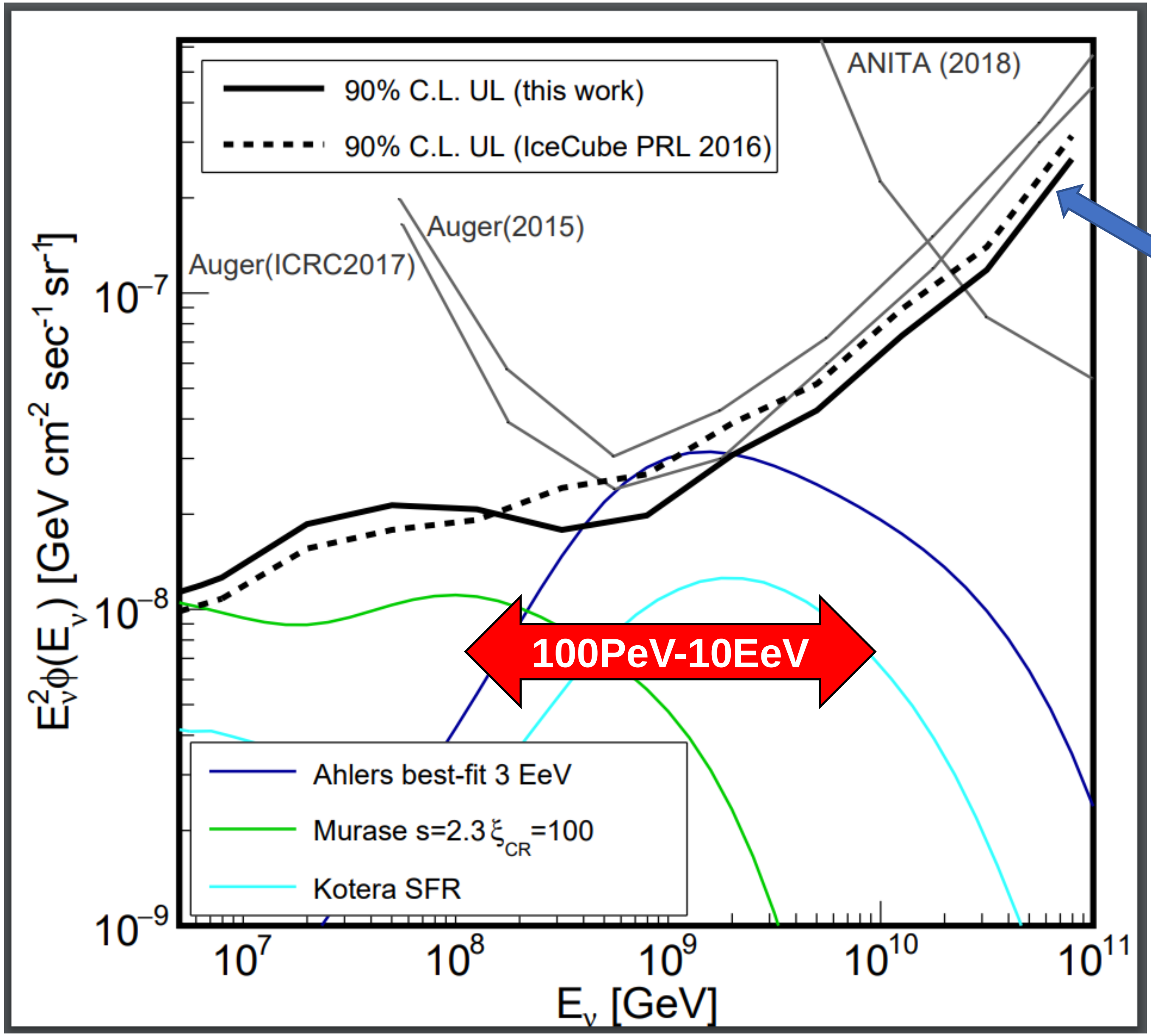


密に埋めた光子伝搬較正装置による、系統誤差の低減により
カスケード事象の角度分解能を向上！

Conclusions and Outlook

- IceCube sees neutrino beams created in the atmosphere and the far Universe
- IceCube has discovered high energy cosmic neutrinos
- 3σ observation of the first cosmic neutrino and flaring blazer coincidence with multi-messenger techniques
- The ongoing IceCube-Upgrade followed by IceCube-Gen2 construction will significantly improve the performance
- More events – more sources!

Beyond PeV Universe: GZK Neutrinos?



IceCube (2018)
Phys Rev D accepted

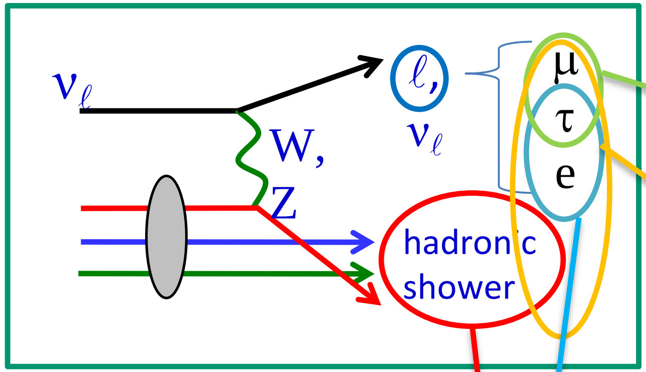
GZK neutrino unobserved in 9 years of IceCube data

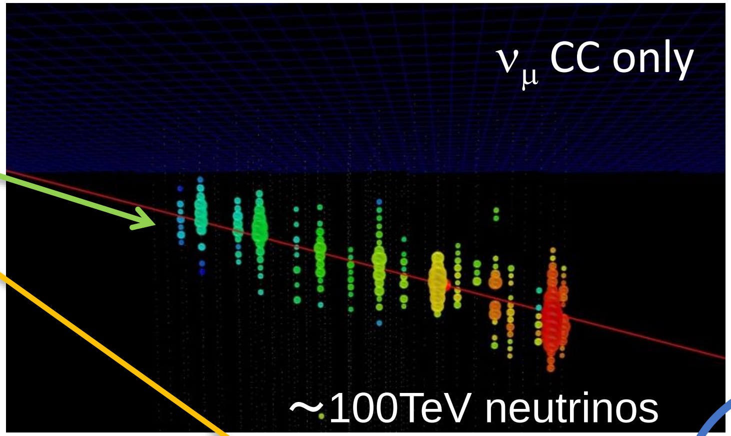
- Strong constraints on sources of proton dominant UHECRs
- Mildly evolving (e.g. star formation rate) models disfavored

IceCube is sensitive to cosmic neutrinos from O(10TeV) to O(10,000,000TeV)

High energy neutrino signal channels

Upward going track event sensiitve to CC muon neutrino interaction



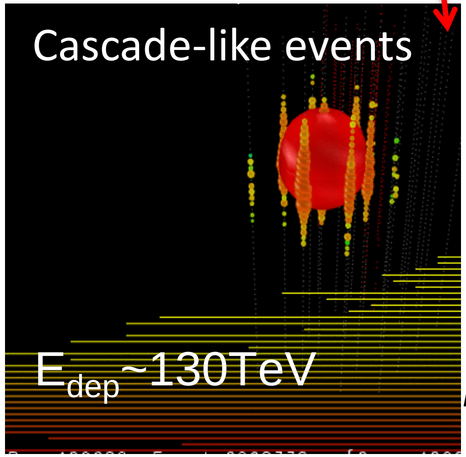


Phys. Rev. Lett. 115, 081102 (2015)

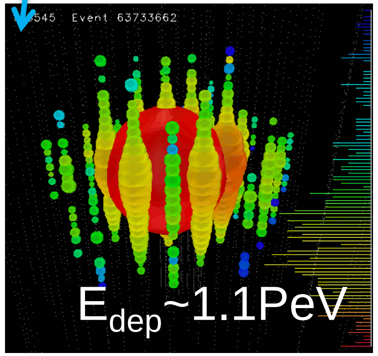
EHE

>PeV-10PeV

electromagnetic and/or hadronic particle showers (cascade)

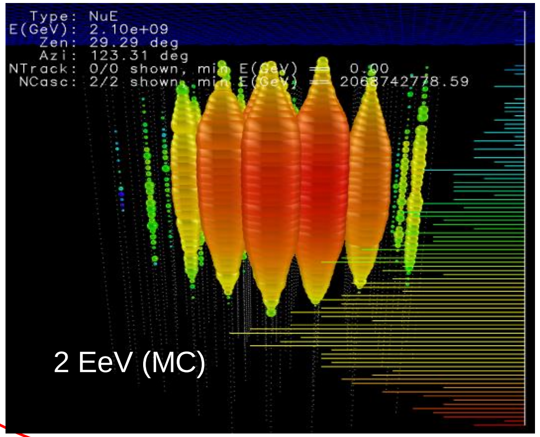


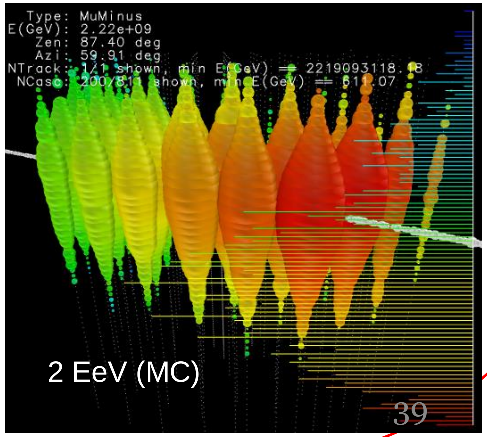
Phys. Rev. D 84, 072001 (2011)



PRL 111 (2013) 021103

Calorimetrical selection of high brightness events
EHE signals: All flavors
elongated cascades and highly stochastic tracks





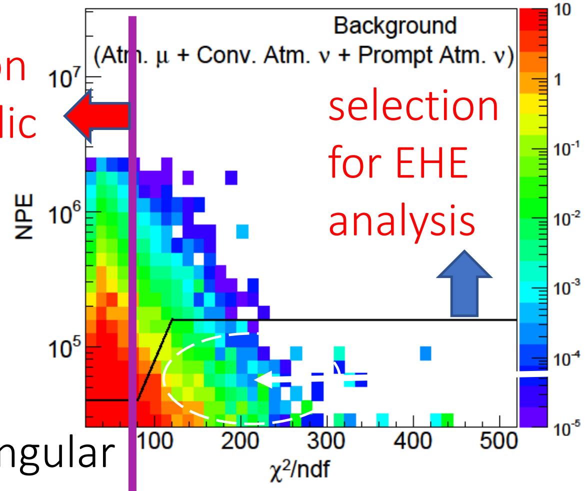
Tracks for better resolution

EHE

track hypothesis chi2

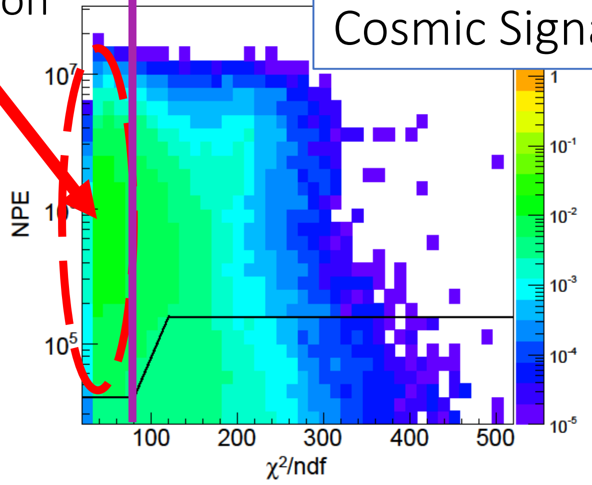
track-like ⟷ spherical

selection for public alert



Atmospheric BG

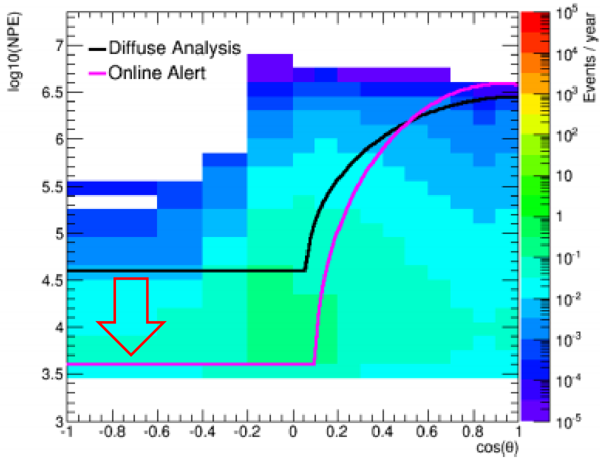
Good angular resolution



Cosmic Signal

EHE >10PeV

HE >100TeV

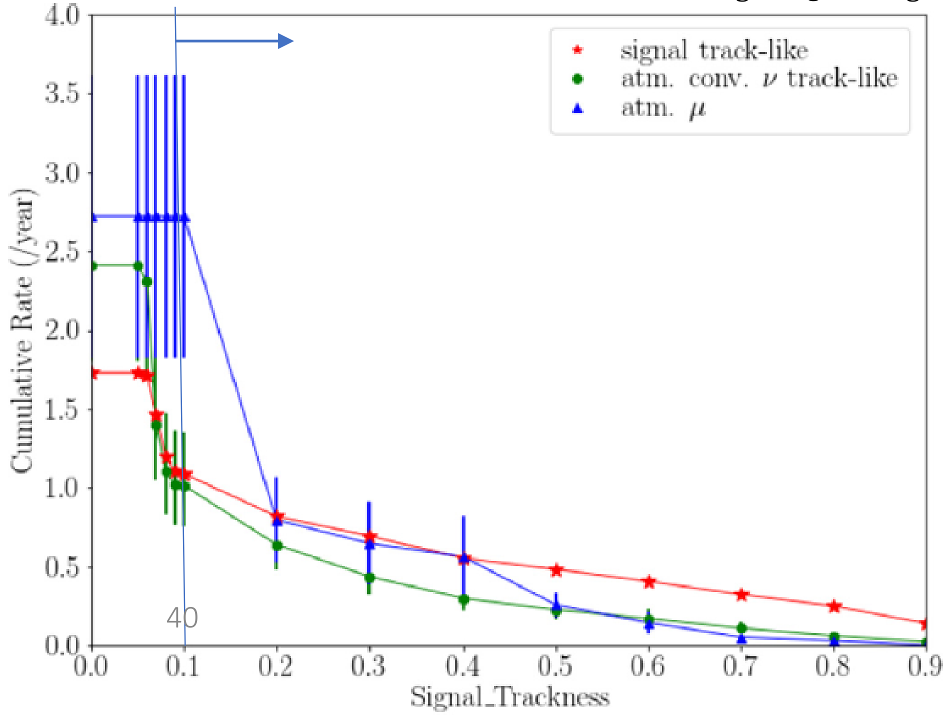


Reduced threshold HE selection is called **EHE-alert**

HESE

14 events out of 54 HESE events (4yr) are HESE track

$$Signal\_Trackness = \frac{f_{track}P_{track}}{f_{track}P_{track} + f_{shower}P_{shower} + (f_{bkg}/f_{sig})\,P_{bkg}}$$



- Ps are PDF from likelihood ratios e.g. value from the shower reconstruction divided by that of the track reconstruction
- fs are expected ratio of categories

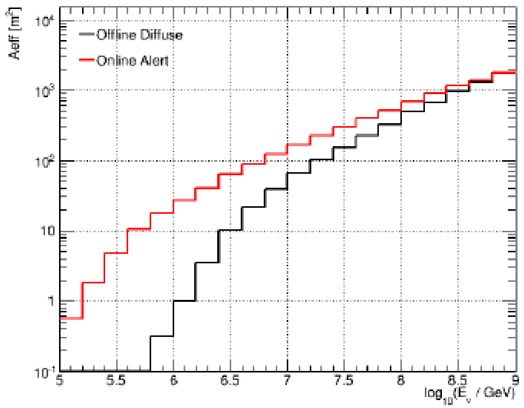
Rates and resolutions

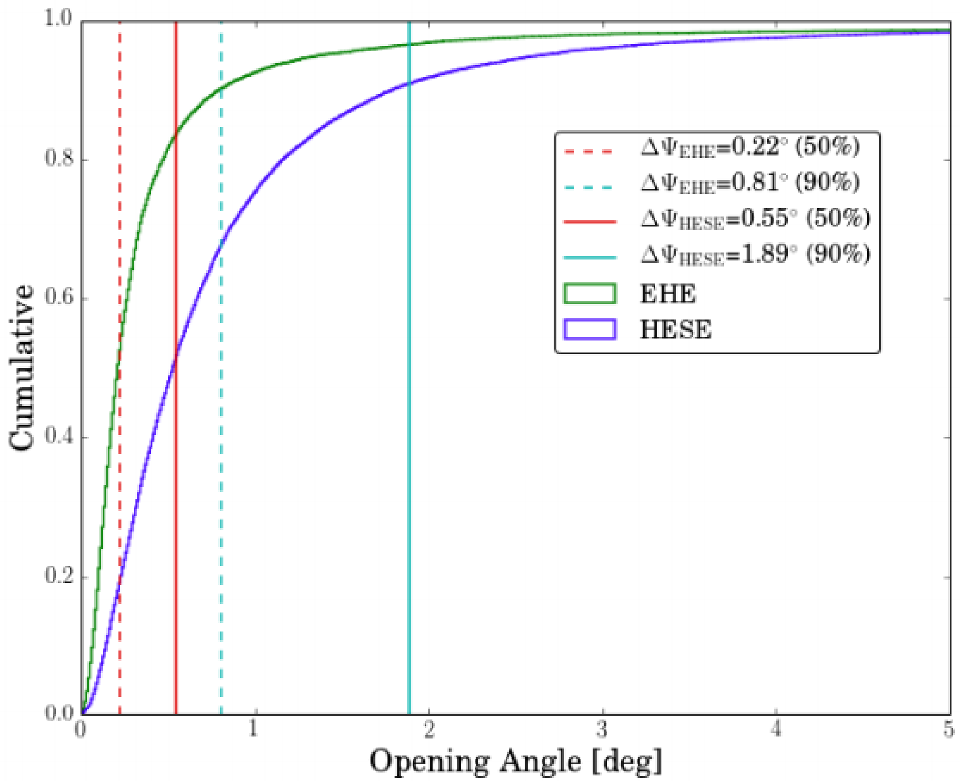
◆ HESE alert channel $E_{thres} \sim 100$TeV

Charge	Signal Rate (yr^{-1}) (R_s)	Background Rate (yr^{-1}) (R_b)
6000	1.09 (0.50 N + 0.59 S)	3.73 (0.67 N + 3.06 S)

◆ EHE alert channel $E_{thres} \sim 100$TeV

Sample	Events / year
Atmospheric muon	0.52
Conv. Atmos. ν_μ	1.20
Prompt Atmos. ν_μ	0.19
Total Background	1.91
Astro. ν_μ (E^{-2})	4.09
Astro. ν_μ ($E^{-2.49}$)	2.48

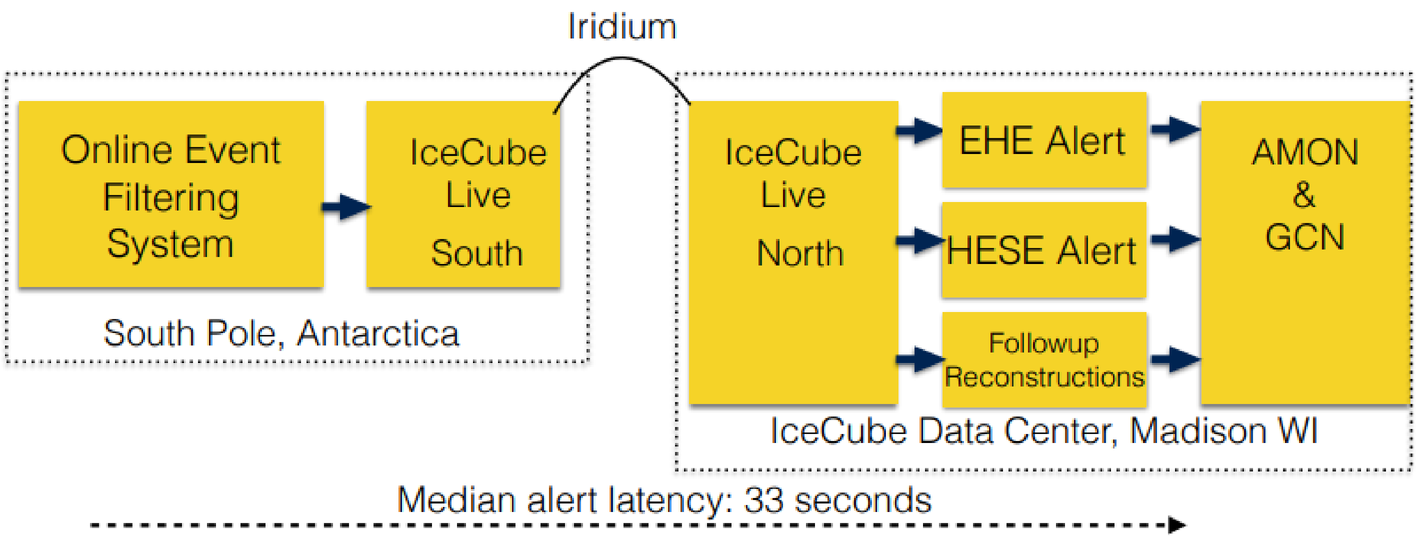


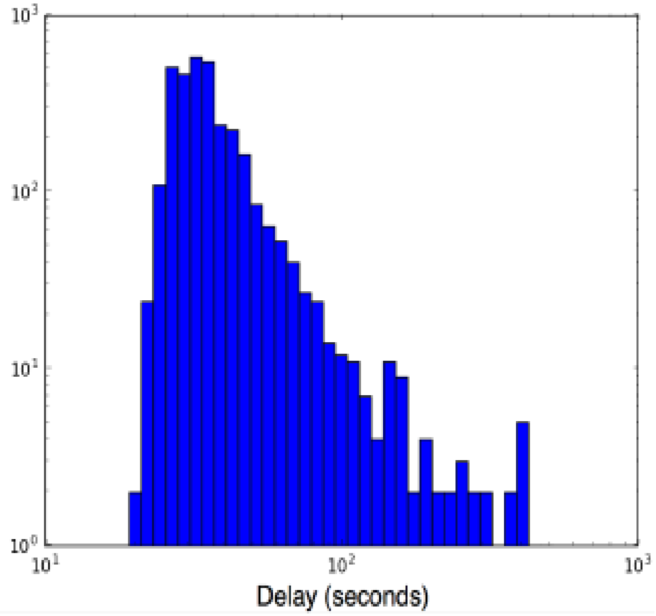


Private alerts for specific telescopes: low energy threshold, more background rates

Alert	Event type	Coverage	thres E [TeV]	Median Ang Res [deg]	Time window	Alert rate Sig+BG/yr
GFU	ν_μ track multiplets	All sky	~0.1	<1	variable, max 21d	~2BGs
O(X)FU	up ν_μ track multiplets	Northern sky	~0.1	<1	100s	Varies

« Public » aleart channels





« Public » aleart history

- From April (May) 2016 to the end of 2017: 6 EHE alerts and 8 HESE alerts with 1 overlapping event

AMON ICECUBE_EHE EVENTS – Since June 2016 archived at https://gcn.gsfc.nasa.gov/amon_ehe_events.html							
EventNum_RunNum	Date	Time UT	RA	Dec	Error(arcmin)	Signalness	
17569642_130214	17/11/06	20:54:30.43	340.2500	+7.3140	14.99	0.74593	6
50579430_130033	**17/09/22**	**18:39:39.21**	**77.2853**	**+5.7517**	**14.99**	**0.56507**	5
80305071_129307	17/03/21	07:32:20.69	98.3268	-14.4861	19.48	0.2801	4
80127519_128906	16/12/10	20:06:40.31	46.5799	+14.9800	60.00	0.49023	3
26552458_128311	16/08/06	12:21:33.00	122.7980	-0.7331	6.67	0.28016	2
6888376_128290	16/07/31	01:55:04.00	214.5440	-0.3347	20.99	0.84879	1

same event

AMON ICECUBE_HESE EVENTS – Since April 2016 archived at https://gcn.gsfc.nasa.gov/amon_hese_events.html								
EventNum_RunNum	Date	Time UT	RA	Dec	Error	Charge	SignalTr	
34032434_130171	17/10/28	08:28:14.81	275.0760	+34.5011	534.0	6317.82	0.30	8
56068624_130126	17/10/15	1:34:30.06	162.5790	-15.8611	73.79	13906.14	0.51	7
32674593_129474	17/05/06	12:36:55.80	221.6750	-26.0359	73.79	8685.07	0.35	6
65274589_129281	17/03/12	13:49:39.83	304.7300	-26.2380	73.79	8858.64	0.78	5
38561326_128672	16/11/03	09:07:31.12	40.8252	+12.5592	66.00	7546.05	0.30	4
58537957_128340	16/08/14	21:45:54.00	199.3100	-32.0165	89.39	10431.02	0.12	3
6888376_128290	16/07/31	01:55:04.00	215.1090	-0.4581	73.79	15814.74	0.91	2
67093193_127853	16/04/27	05:52:32.00	240.5683	+9.3417	35.99	18883.62	0.92	1

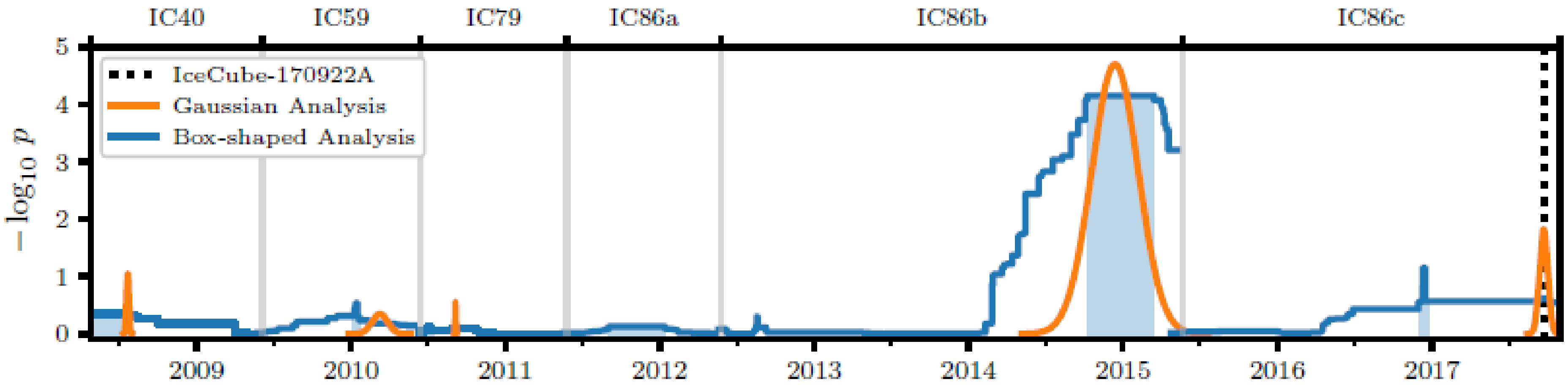
Independent point source analysis around TXS 0506-05 (RA 77.36° Dec +5.69°)

- $L = \prod_i^N (\frac{n_s}{N} P_S + \frac{n_b}{N} P_B)$
- $P_S = Spacial(\vec{x}) \times \mathrm{Energy}(\mathrm{E_{reco}}, \sin\theta) \times Temporal(t)$

2D Gaussian

θ-dependent acceptance x power-law signal flux
parameters: spectral index and normalization

square and Gaussian
parameters: center time and time window

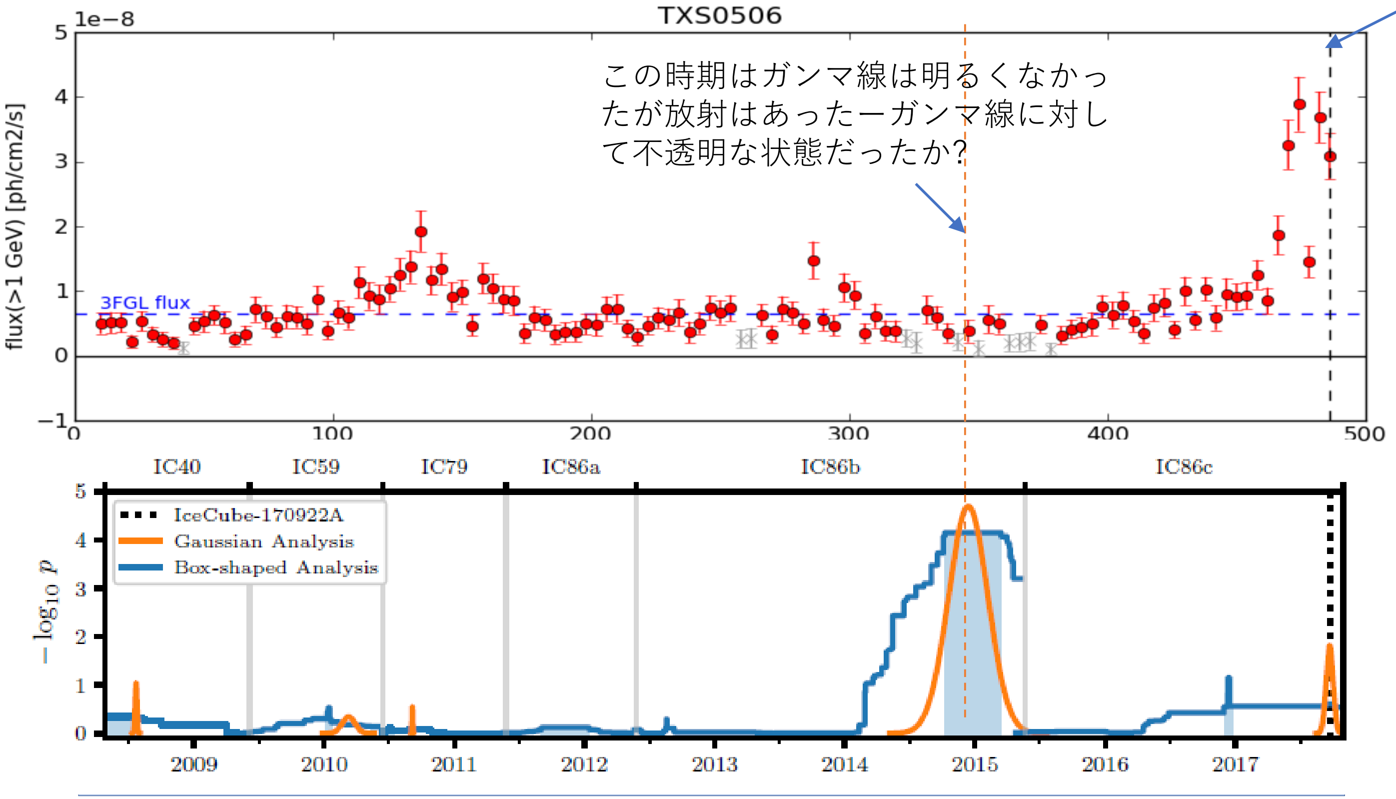


- **p-values from scrambled data**
- **corrected look-elsewhere effect**

Time dependent LLH point source analysis around TXS 0506+56 **(neutrino only analysis)**

- Signal(n_s, γ, T_0, T_W)+BG vs BG only
- Best fit $(n_s = 13.3, \gamma = 2.1, T_0, =$ 2014 Dec 13$, T_W = 110 days)$
- $p = 1.0 \times 10^{-4}, corresponds\ to\ 3.7\sigma$ $(3.5\sigma\ after\ livetime\ correction)$

この時期はガンマ線は明るい

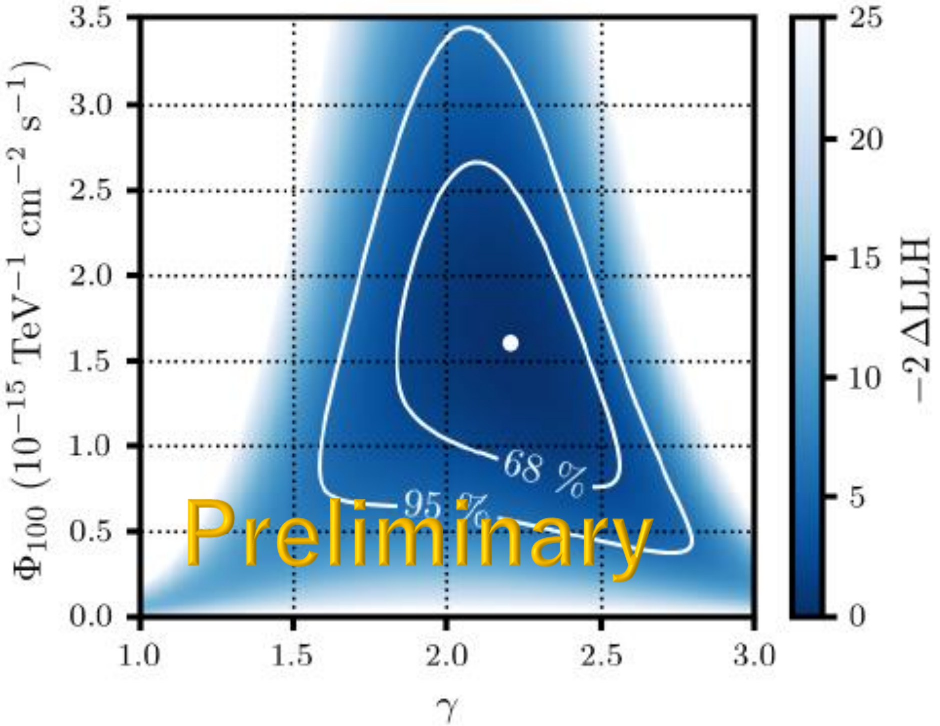


Gaussian shaped time profile, box time results similar

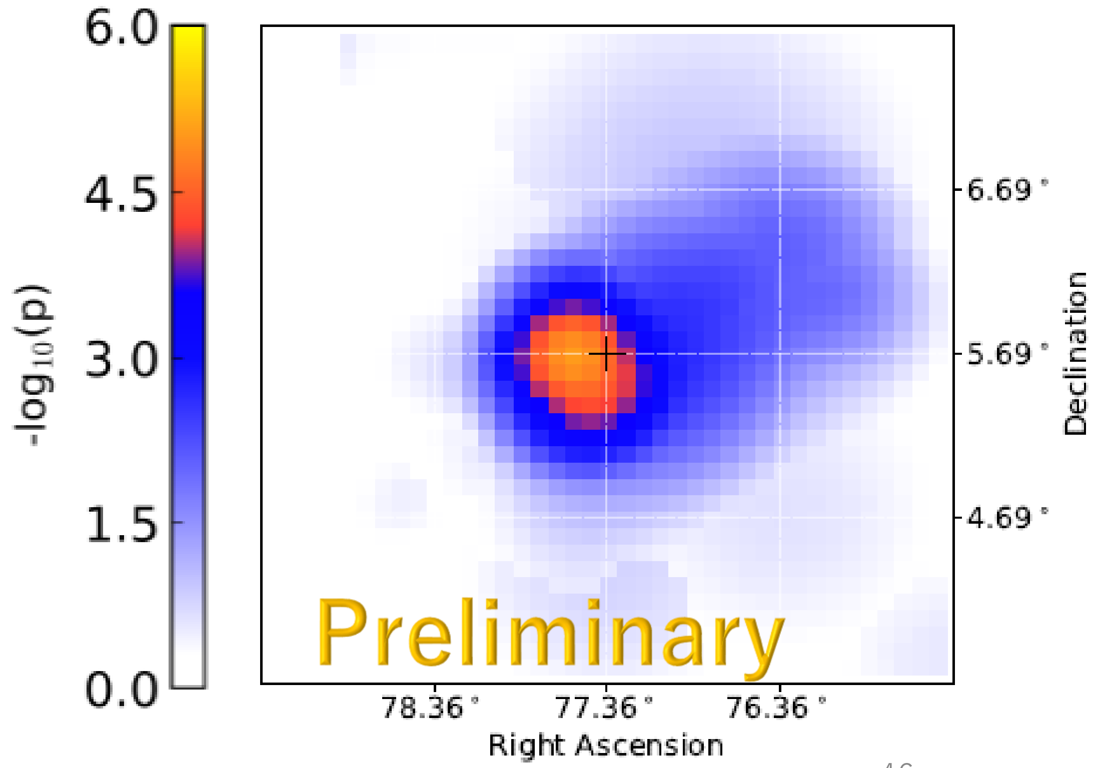
(May be) the first observation of multiple neutrino emitting source

$$\Phi = \Phi_{100}(E/100\,\mathrm{TeV})^{-\gamma}$$

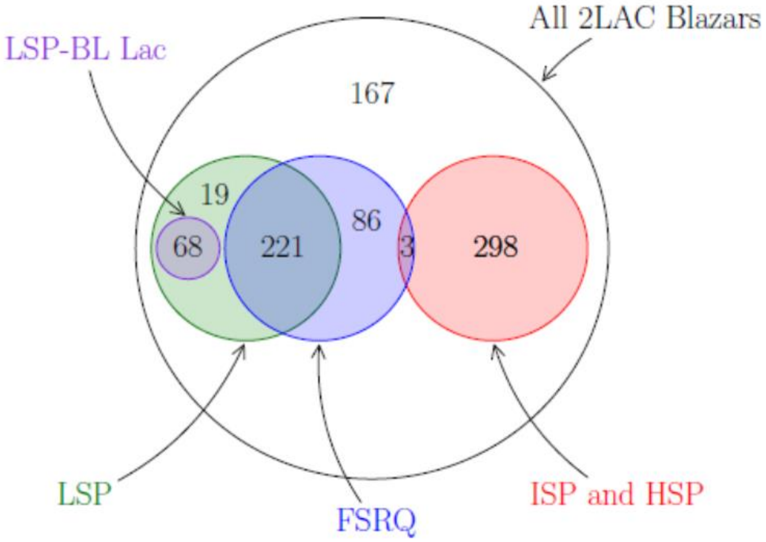
$$\Phi_{100} = 1.6 \times 10^{-15}\ TeV^{-1}cm^{-2}\ s^{-1}$$
$$\gamma = 2.1$$



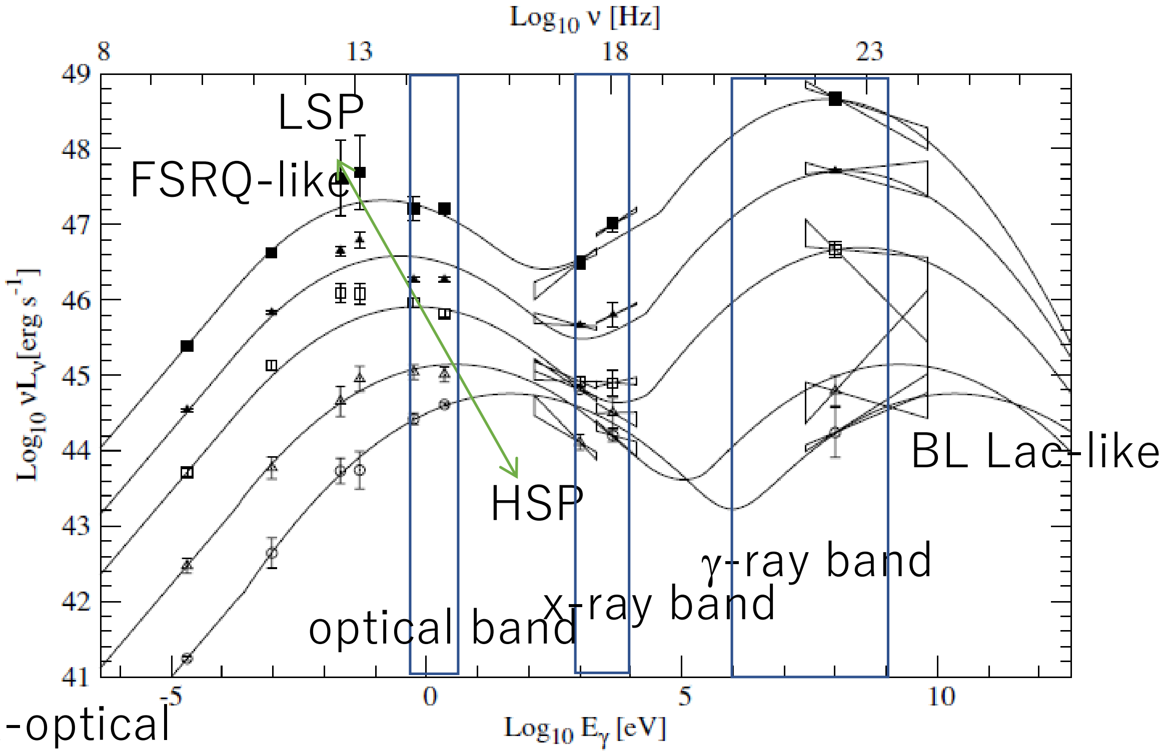
The analysis around the TXS object



Blazer coincidence analysis: classification



"two-hump" Spectral Energy distribution



Fossati+98

- ☐ Radio: FR1 vs FR2
- ☐ Optical: FSRQs vs BL Lacs
- ☐ SED (synchrotoron-peaked)
  - LSP low-synchrotron peaked $>10^{14}$Hz – IR-optical
  - HSP high-synchrotron peaked $>10^{15}$Hz – x-rays
  - ISP intermediate – UV

Essentially all FSRQs are LSPs

Neutrino weighting

$$\ln(L)\{n_s, \Gamma_{\rm SI}\} = \sum_{i=1}^{N} \ln\left(\frac{n_s}{N} \cdot S(\delta_i, RA_i, \sigma_i, \varepsilon_i; \Gamma_{\rm SI}) + \left(1 - \frac{n_s}{N}\right) \cdot B(\cos(\theta_i), \varepsilon_i)\right)$$

the normalization ns of the signal contribution

the spectral index ΓSI of the signal's energy distribution

signal hypothesis PDF

$$S(\delta_i, {\rm RA}_i, \sigma_i, \varepsilon_i; \Gamma_{\rm SI}) = \frac{\sum_{j=1}^{N_{src}} w_j \cdot S_j(\delta_i, {\rm RA}_i, \sigma_i, \varepsilon_i; \Gamma_{\rm SI})}{\sum_{j=1}^{N_{src}} w_j}$$

BG is from

$$B(\cos(\theta_i), \varepsilon_i) = \frac{1}{2\pi} \cdot f(\cos(\theta_i), \varepsilon_i)$$

$$w_j = C\, w_{j,model} \cdot w_{j,acceptance}$$

hypothesis test results

Population	p-value	
	γ-weighting	equal weighting
All 2LAC blazars	36% (+0.4σ)	6% (+1.6σ)
FSRQs	34% (+0.4σ)	34% (+0.4σ)
LSPs	36% (+0.4σ)	28% (+0.6σ)
ISP/HSPs	> 50%	11% (+1.2σ)
LSP-BL Lacs	13% (+1.1σ)	7% (+1.5σ)

All sources are equal

$$(w_{model,j} = 1)$$

neutrino luminosity is proportional to gamma-ray luminosity

$$\nu_{lum.} \propto \gamma_{lum.}$$

$$w_{j,\rm model} = \int_{100\rm MeV}^{100\rm GeV} E_\gamma \frac{d\phi_{\gamma,j}}{dE_\gamma}\, dE_\gamma$$

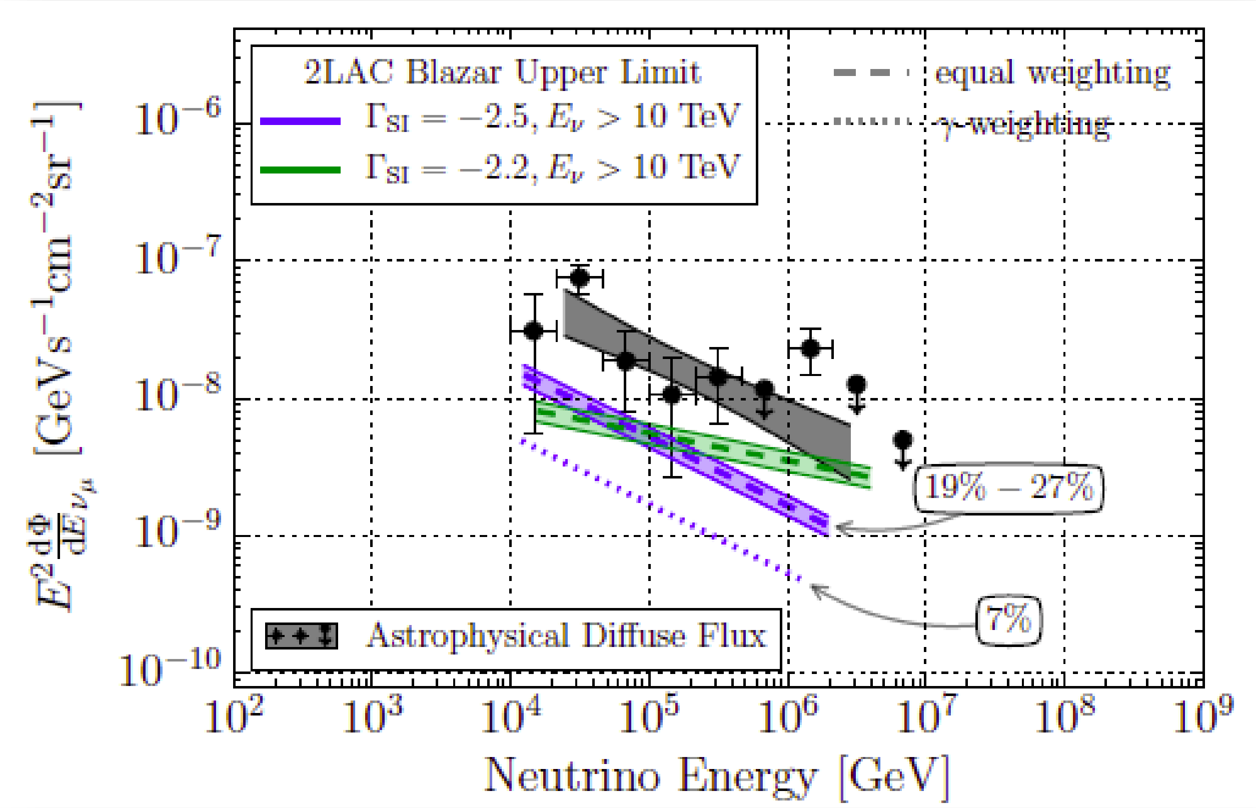
Results: Limits on the blazar contribution

UL on E^{-2} flux

Spectrum: $\Phi_0 \cdot (E/\text{GeV})^{-2.0}$		
Blazar Class	$\Phi_0^{90\%}[\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$	
	γ-weighting	equal weighting
All 2LAC Blazars	1.5×10^{-9}	$4.7\ (3.9 - 5.4) \times 10^{-9}$
FSRQs	0.9×10^{-9}	$1.7\ (0.8 - 2.6) \times 10^{-9}$
LSPs	0.9×10^{-9}	$2.2\ (1.4 - 3.0) \times 10^{-9}$
ISPs/HSPs	1.3×10^{-9}	$2.5\ (1.9 - 3.1) \times 10^{-9}$
LSP-BL Lacs	1.2×10^{-9}	$1.5\ (0.5 - 2.4) \times 10^{-9}$

UL on $E^{-2.2\sim2.5}$ flux

Equal weighting follows Fermi SCD ApJ, 720:435 (2010)

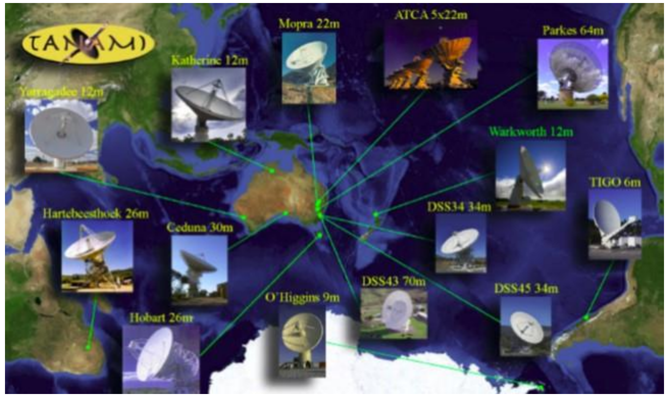


Contribution of the total 2LAC blazar sample to the astrophysical neutrino flux

- The equal-weighting upper limit maximally19%-27%,
- gamma-weighting 7%

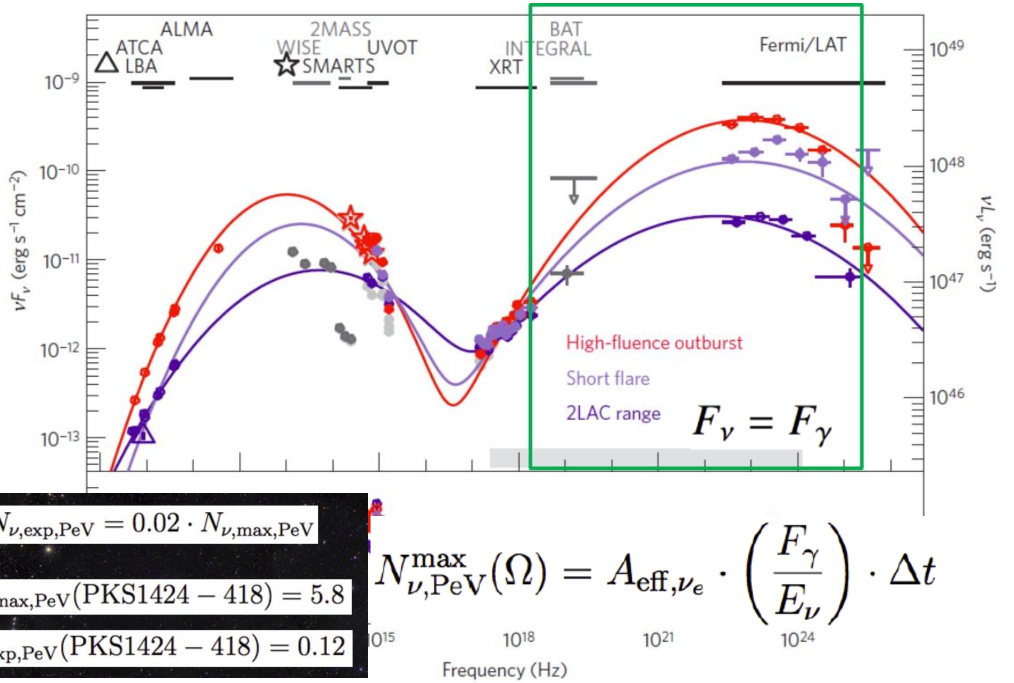
Coincidence of a high-fluence blazar

M. Kadler et al Nature Phys (2016)



TANAMI – Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry – **is a multiwavelength program that monitors extragalactic jets of the Southern Sky (δ < −30 ○)**

- Studied blazars in the 3 PeV events – 6 TANAMI monitoring blazars (mostly FSRQ) in the first two PeV events
- a high fluence blazar PKS B1424-418 outburst showed temporal/positional coincidence with the third PeV event with an approximate chance coincidence of ～5%

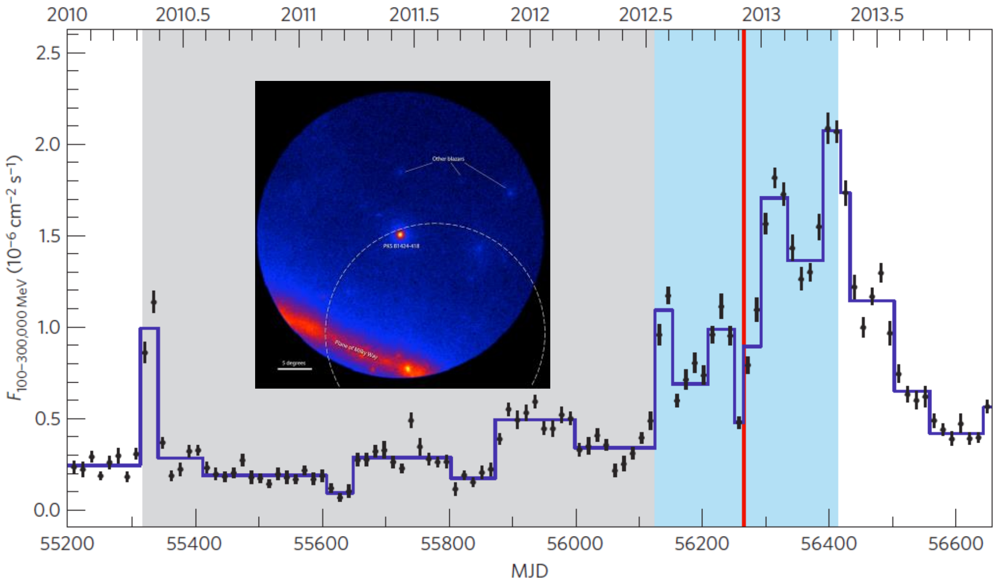


$$N_{\nu,\mathrm{exp,PeV}} = 0.02 \cdot N_{\nu,\mathrm{max,PeV}}$$

$$N_{\nu,\mathrm{max,PeV}}(\mathrm{PKS1424-418}) = 5.8$$

$$N_{\nu,\mathrm{exp,PeV}}(\mathrm{PKS1424-418}) = 0.12$$

$$N^{\mathrm{max}}_{\nu,\mathrm{PeV}}(\Omega) = A_{\mathrm{eff},\nu_e} \cdot \left(\frac{F_\gamma}{E_\nu}\right) \cdot \Delta t$$



ANTARES did not find events from PKS B1424-418

blazar-ν correlation search

MNRAS 457 (2016) Padovani

Neutrino sample

4yr IceCube starting (HESE) events (with conditions >60TeV, <20deg ⇒30evts) and 2 yr HE ν_μ sample of 21 through-going μ events

Gamma-ray sample

Independently built Fermi 2FHL, 2WHSP and Fermi 3LAC catalogues

Neutrino events with γ-ray counterparts

N_ν: the number of ν events with at least one γ-ray counterpart found within the median angular error as function of γ-ray flux threshold f_γ

- For a N_ν (with given catalog, f_γ), chance probability of randomly producing equal or larger N_ν is calculated by randomization of gamma-ray source coordinates – generate ~10^5 randomized maps

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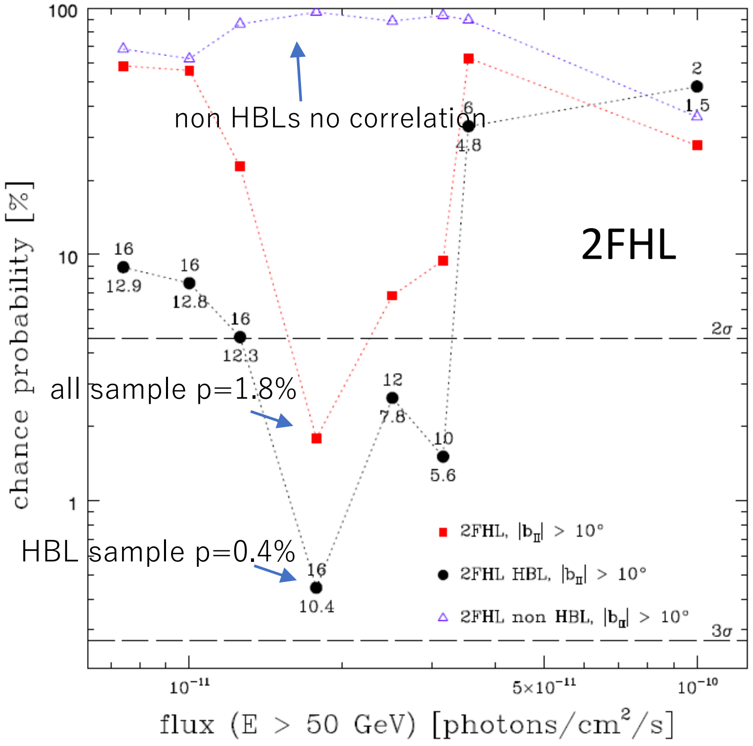

- Correlation of High synchrotron peaked BLLacs with p-value of 0.4-1.3%