IC170922A opens up a new window to cosmos!

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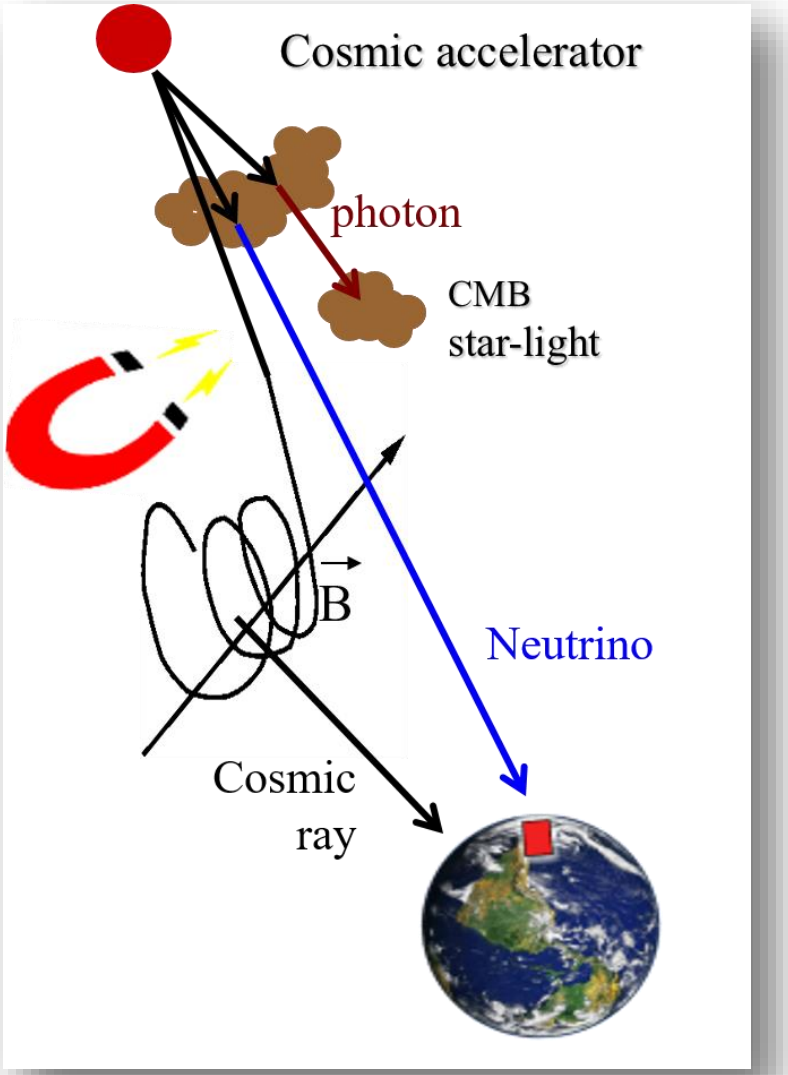
ICEHAP
International Center for Hadron Astrophysics

The 2nd Multi-messenger workshop, Chiba, Japan
March 26, 2018

Outline

- An introduction
- ***Alert-and-follow-up*** program
- The IceCube-170922A event and TXS 0506+056
- An independent point source analysis around TXS
- Prospects – Questions?

Neutrino as a cosmic messenger

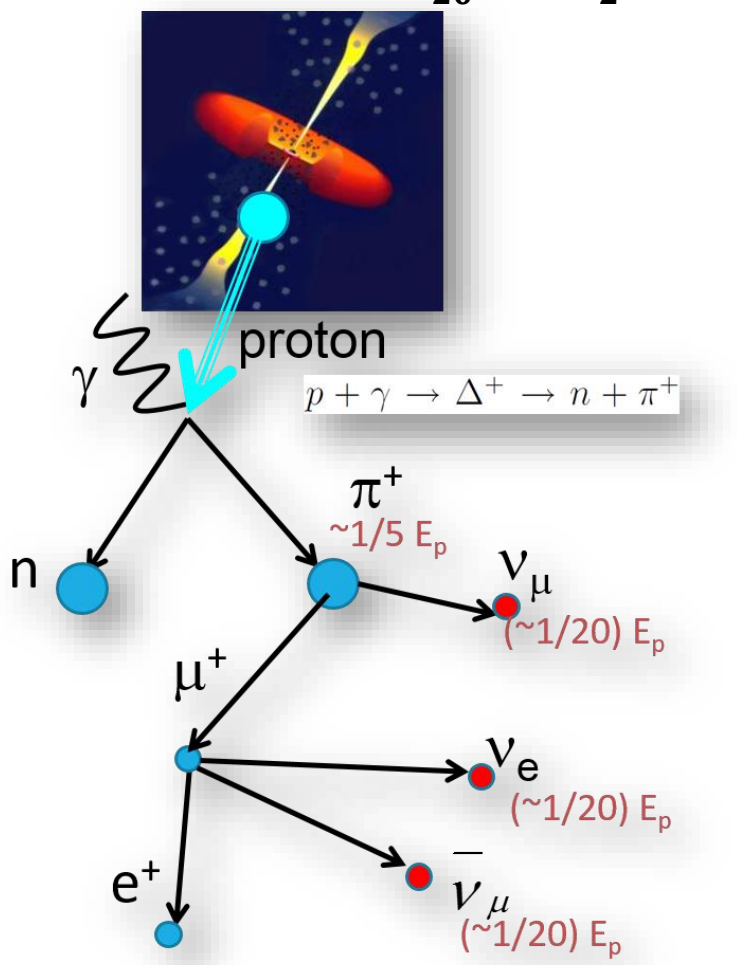


Weak interaction during “propagation”

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

Unsocial neutrino unites UHE sky

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



Simple hadronic "creation"

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

$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^- + \ldots$$
$$p + \gamma \rightarrow p + n + \pi^0 + \pi^+ + \ldots$$

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

$$\pi^0 \rightarrow \boxed{\gamma\gamma}$$
$$\pi^{+,-} \rightarrow \mu^{+,-} + \boxed{\nu_\mu(\bar{\nu}_\mu)}$$

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

Multi-messenger !

Photopion source candidates

min to year time variability

Need

- target photon (or matter)
- proton beam (in jet e.g. by shock acceleration)

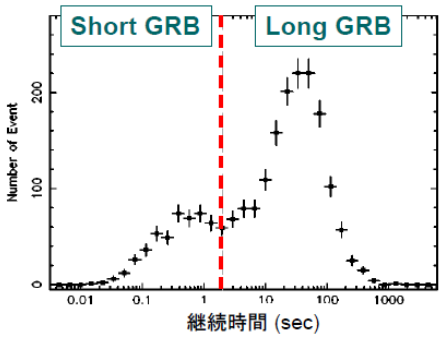
$$E_p E_\gamma \sim \frac{m_\Delta^2 - m_p^2}{2}\left(\frac{\Gamma}{1+z}\right)^2 = 0.147\ \mathrm{GeV}^2\left(\frac{\Gamma}{1+z}\right)^2$$

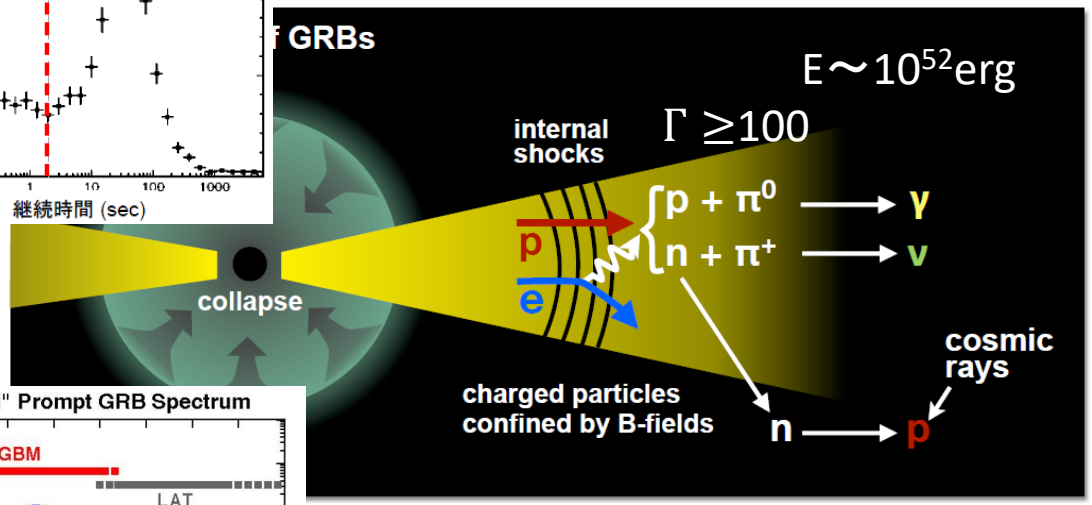
$$E_\nu \simeq 0.05 E_p$$

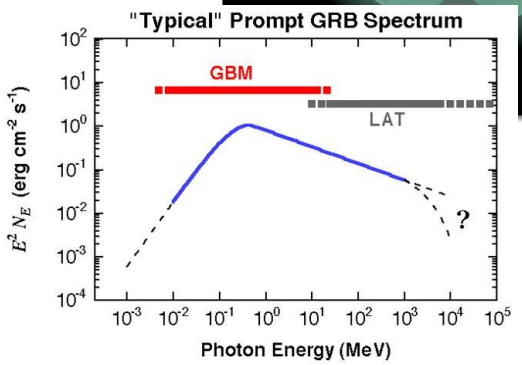
Target photon and beam: GRB and AGNs

- Candidate sources exhibits rapid time variation!

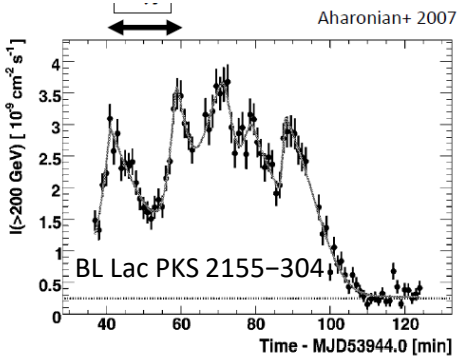
GRB

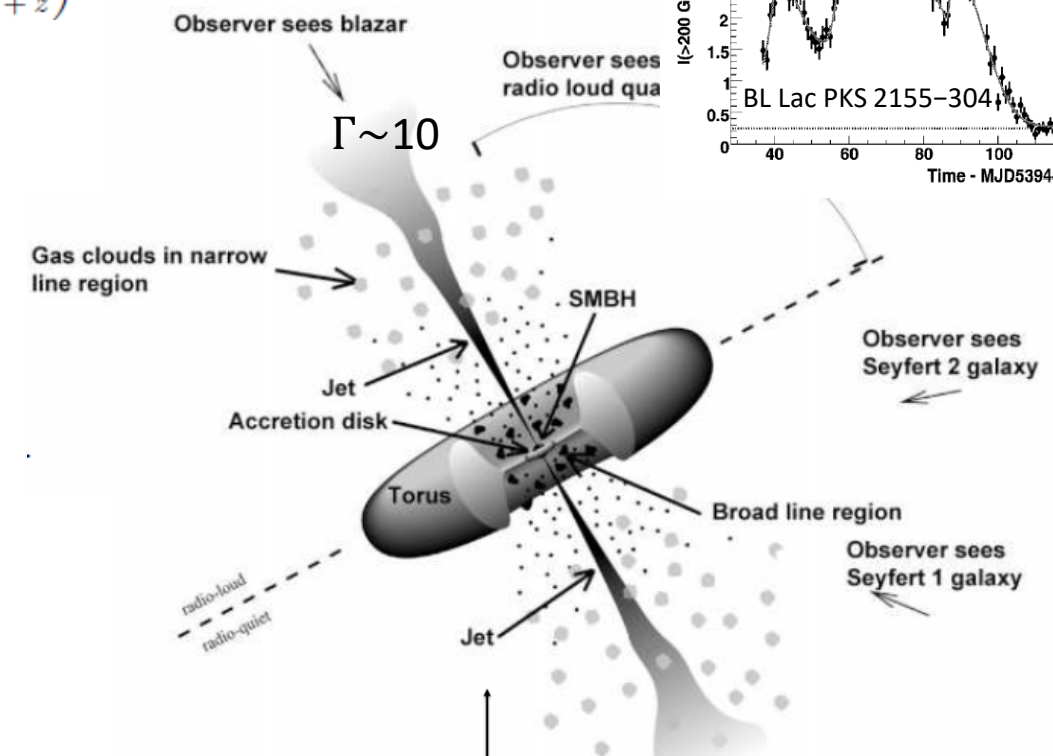


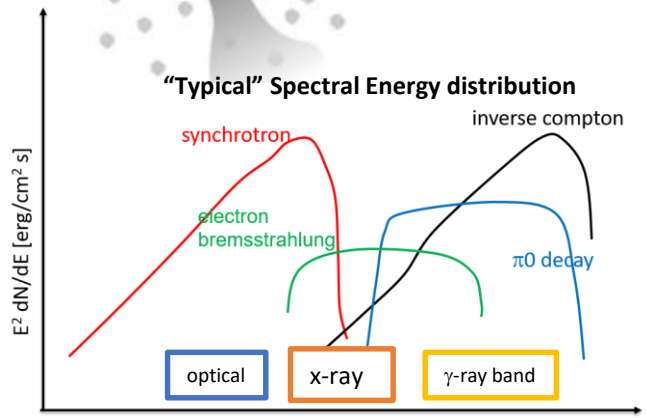




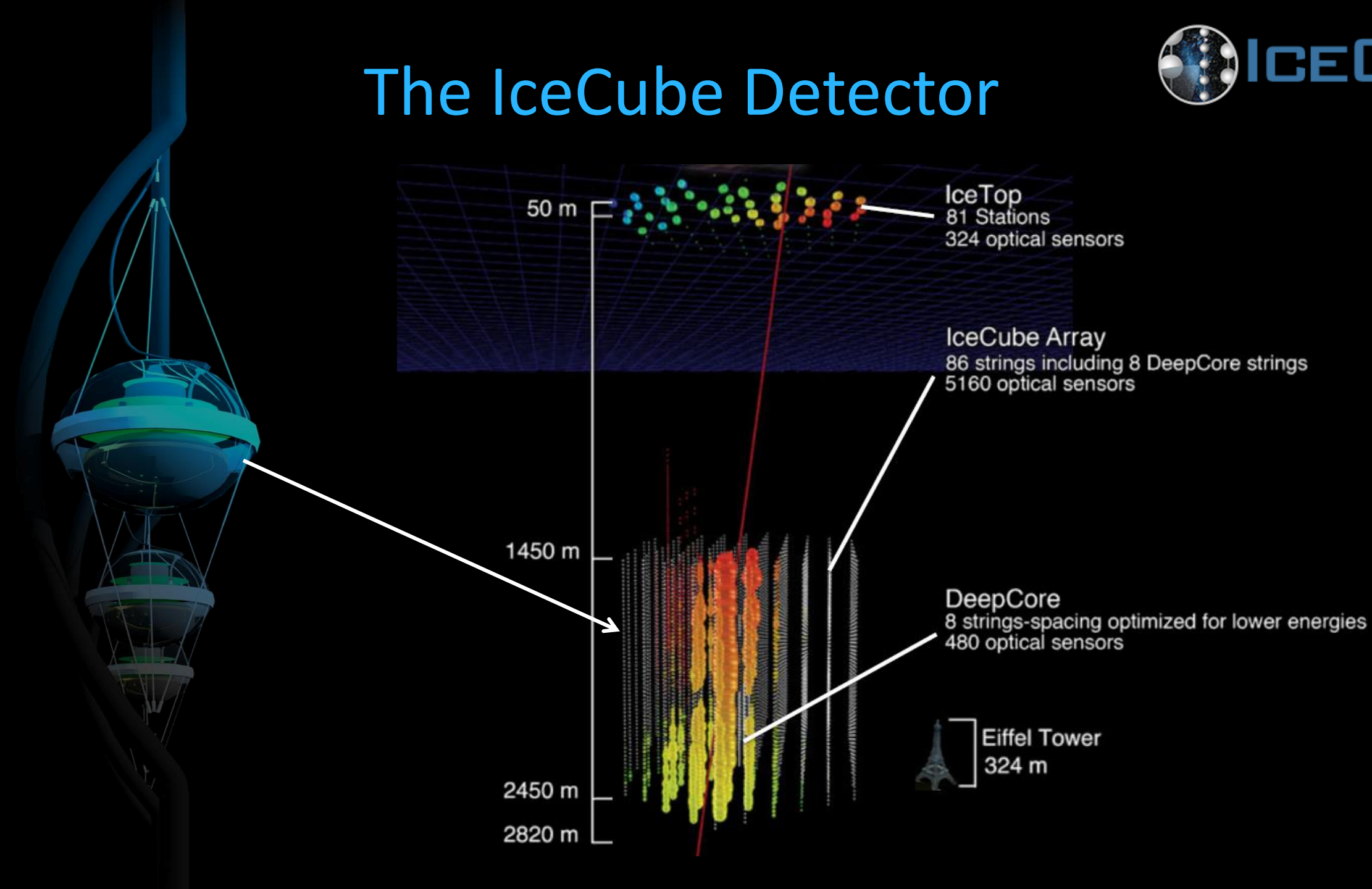
AGN-blazar





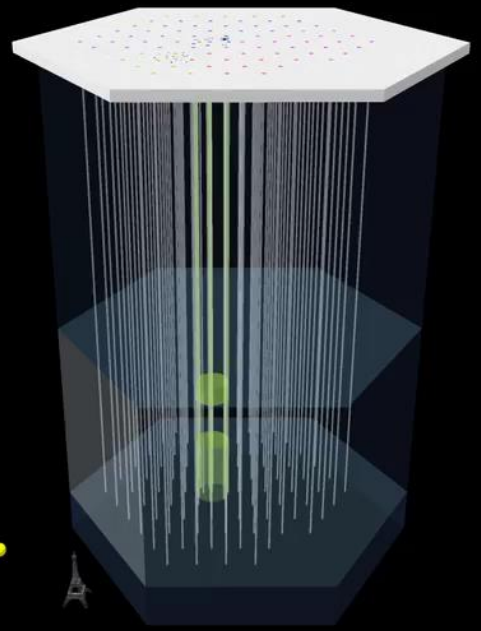


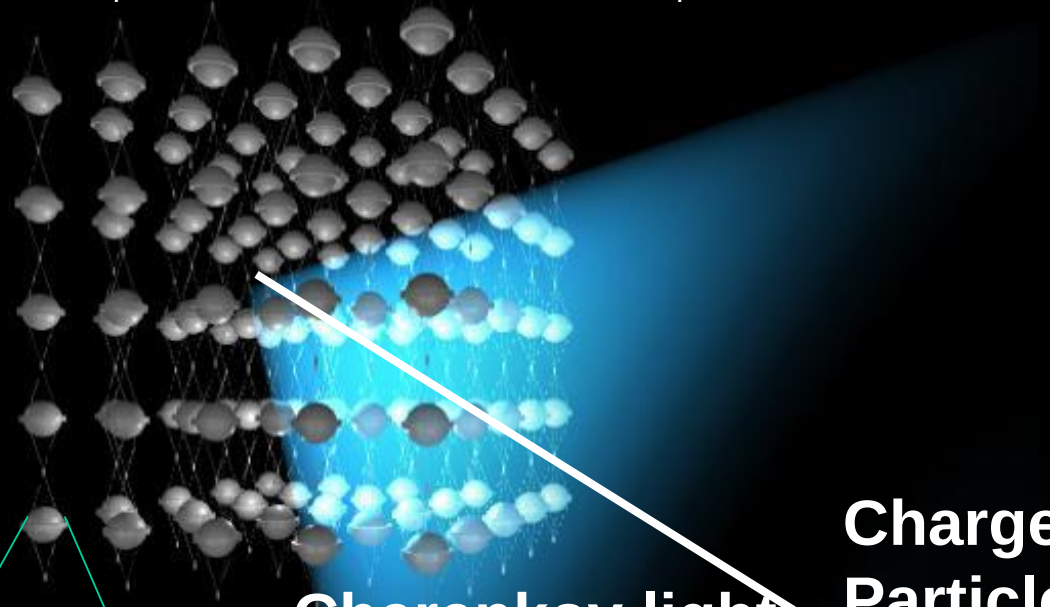
The IceCube Detector



Detection Principle

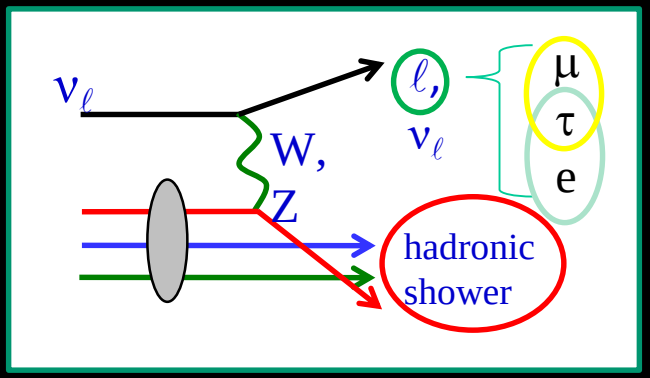
An array of photomultiplier tubes + Dark and transparent material

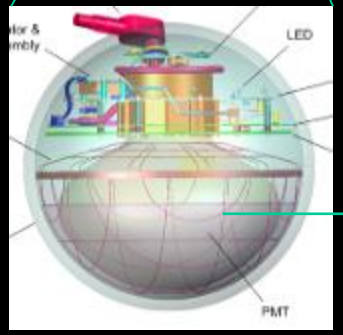


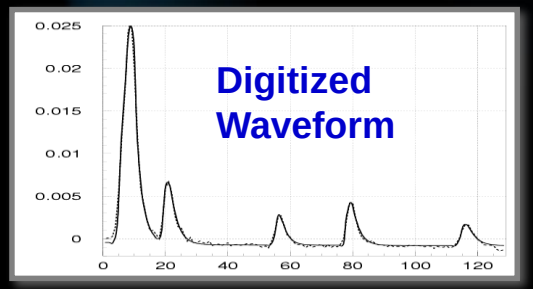


Cherenkov light

Charged Particles







ν

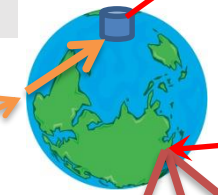
Neutrino online alert

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

Iridium satellites

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

After 2016: Activated public online channel with signal efficiency of >30-50%



ν

high energy ν

Flare and exposure in the universe

Alert!

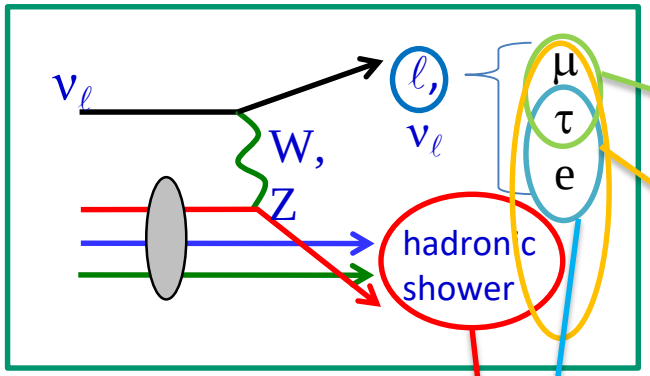
photon and GW

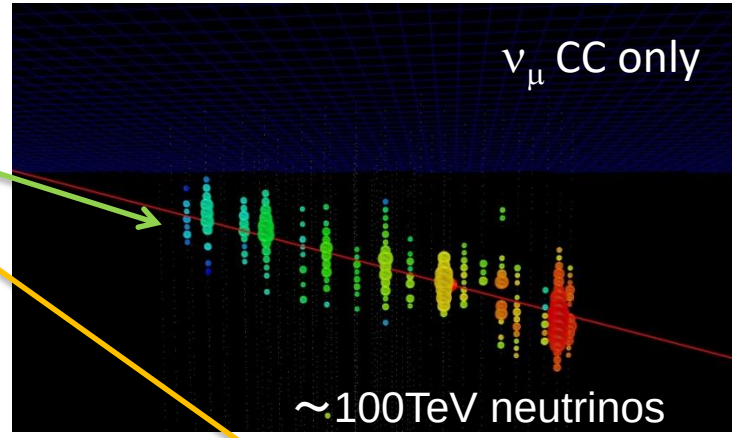
Latency time: a few minutes

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

High energy neutrino signal channels

Upward going track event sensiitve to CC muon neutrino interaction



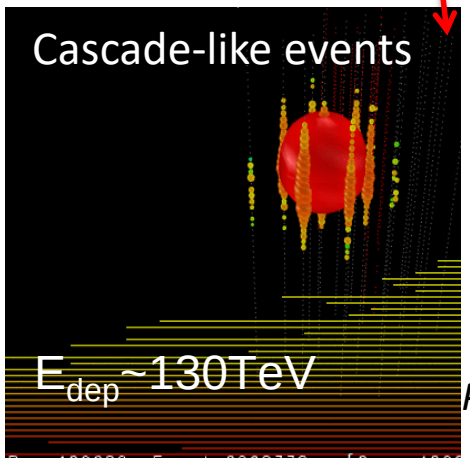


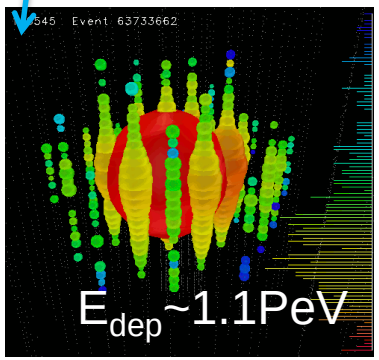
Phys. Rev. Lett. 115, 081102 (2015)

HESE
>60TeV

Starting event inside detector sensitive to all flavor CC/NC

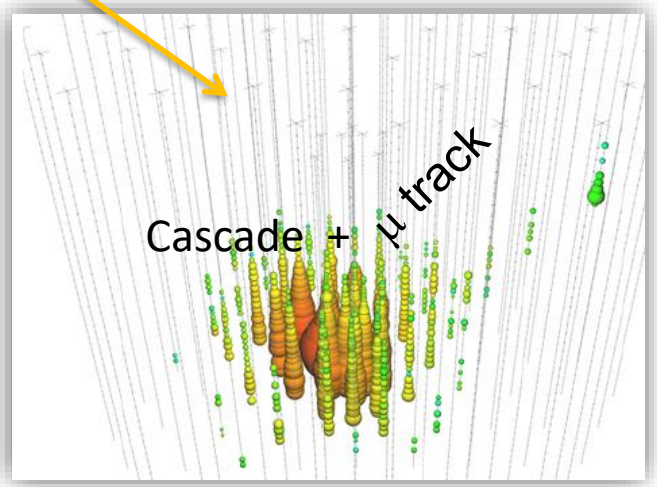
electromagnetic and/or hadronic particle showers (cascade)



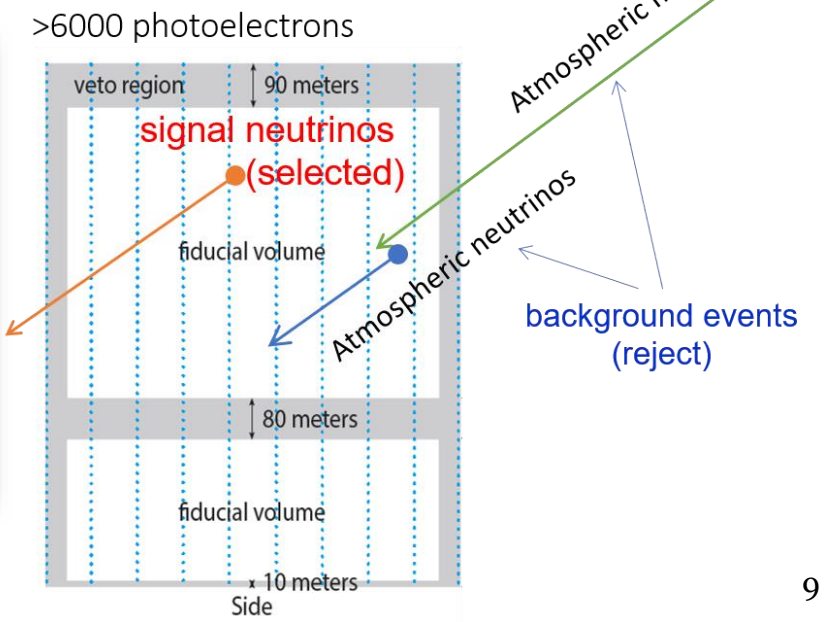


PRL 111 (2013) 021103

Phys. Rev. D 84, 072001 (2011)



Science 22 Vol. 342 (2013)
PRL 113, 101101 (2014)



High energy neutrino signal channels

Upward going track event sensiitve to CC muon neutrino interaction

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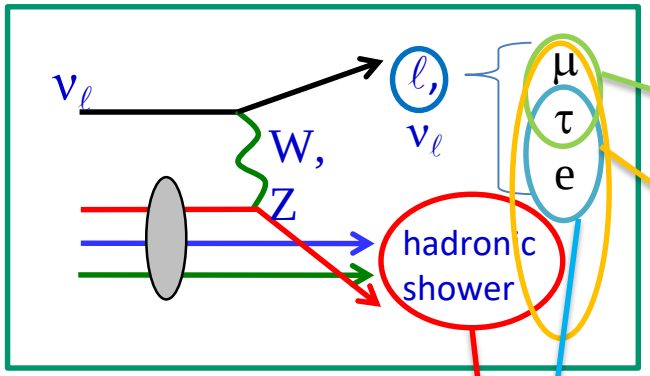
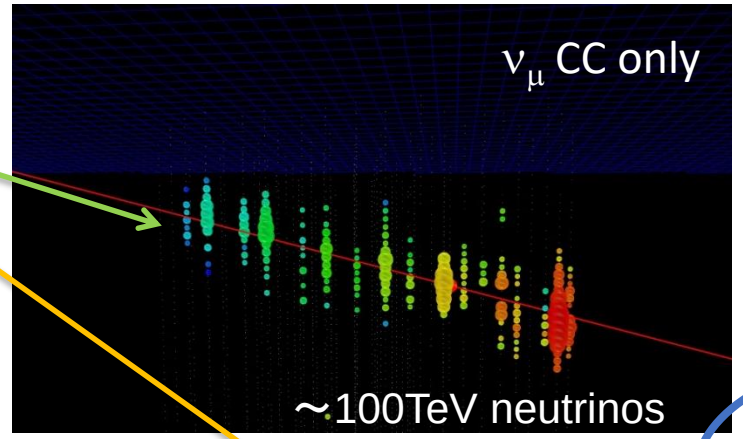
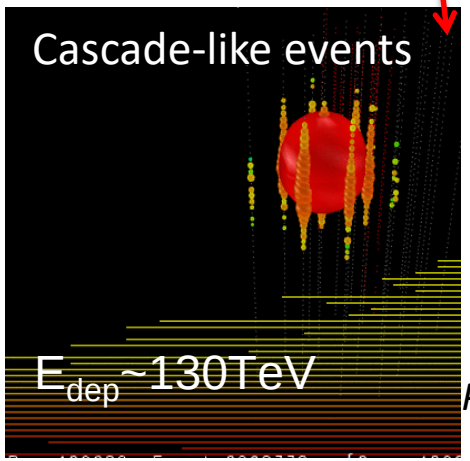
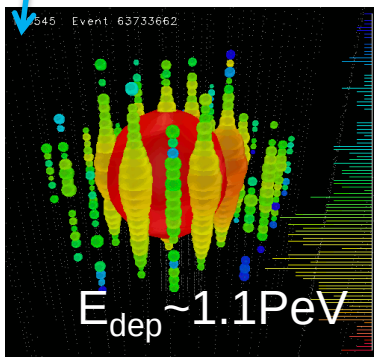




electromagnetic and/or hadronic particle showers (cascade)



Phys. Rev. D 84, 072001 (2011)

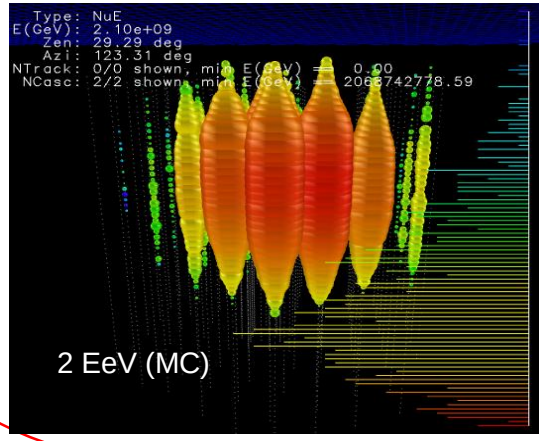


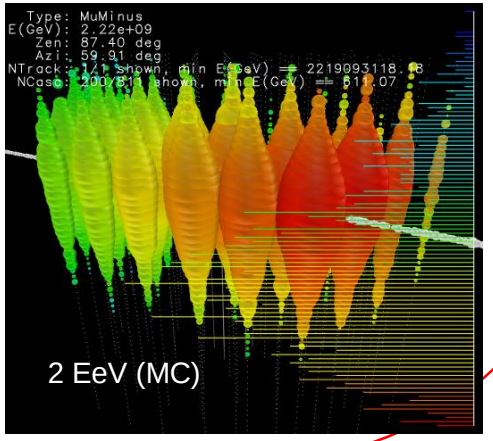
PRL 111 (2013) 021103

EHE

>PeV-10PeV

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

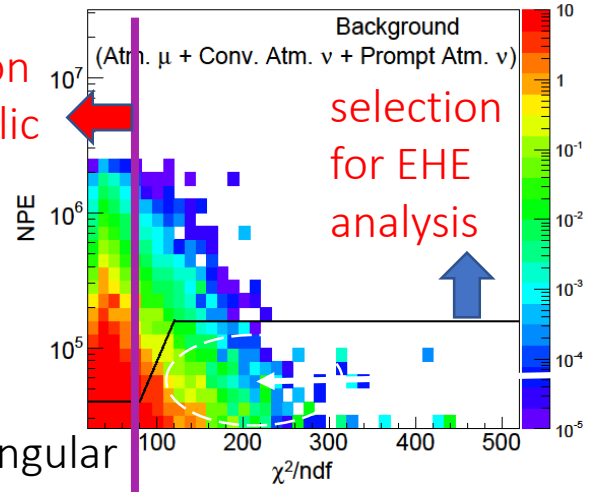




Tracks for better resolution

track hypothesis chi2

track-like ⟷ spherical

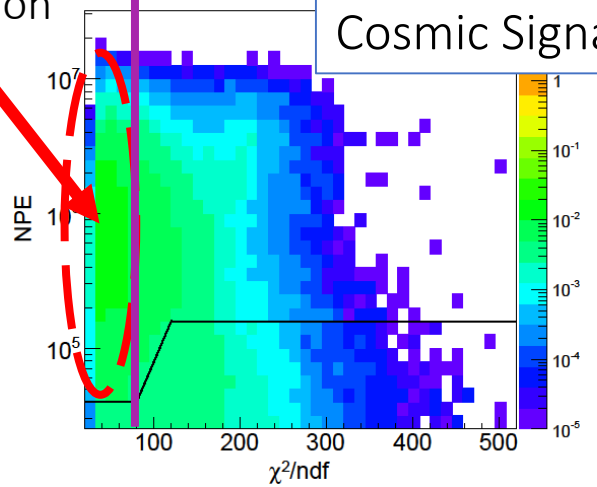


selection for public alert

selection for EHE analysis

Atmospheric BG

Good angular resolution



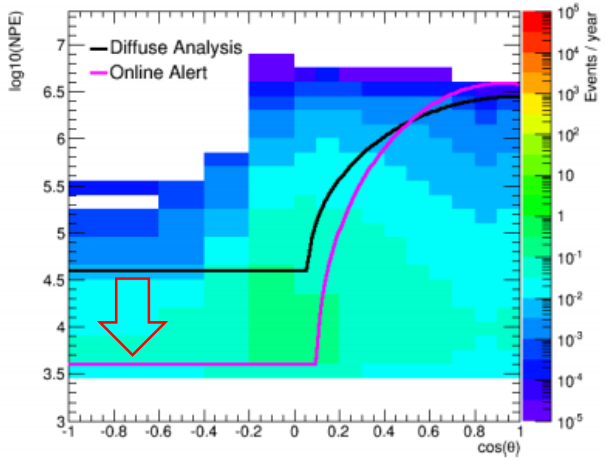
Cosmic Signal

EHE

HESE

EHE >10PeV

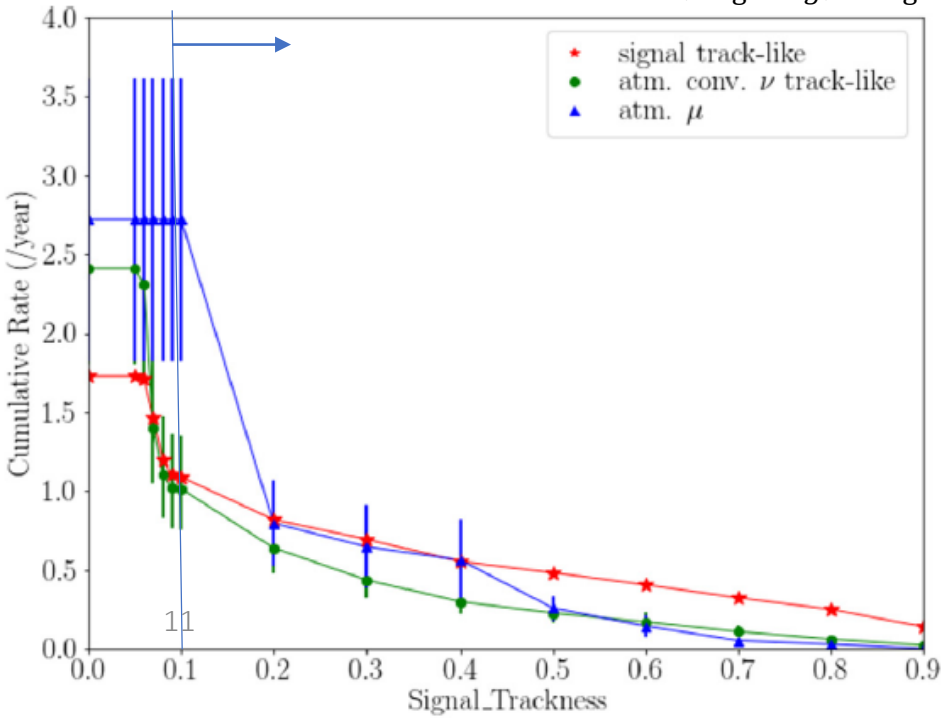
HE >100TeV



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

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

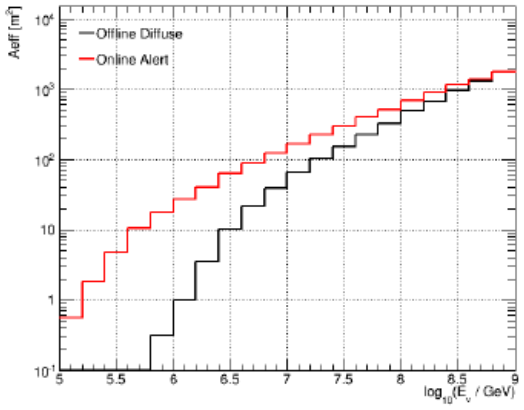
Rates and resolutions

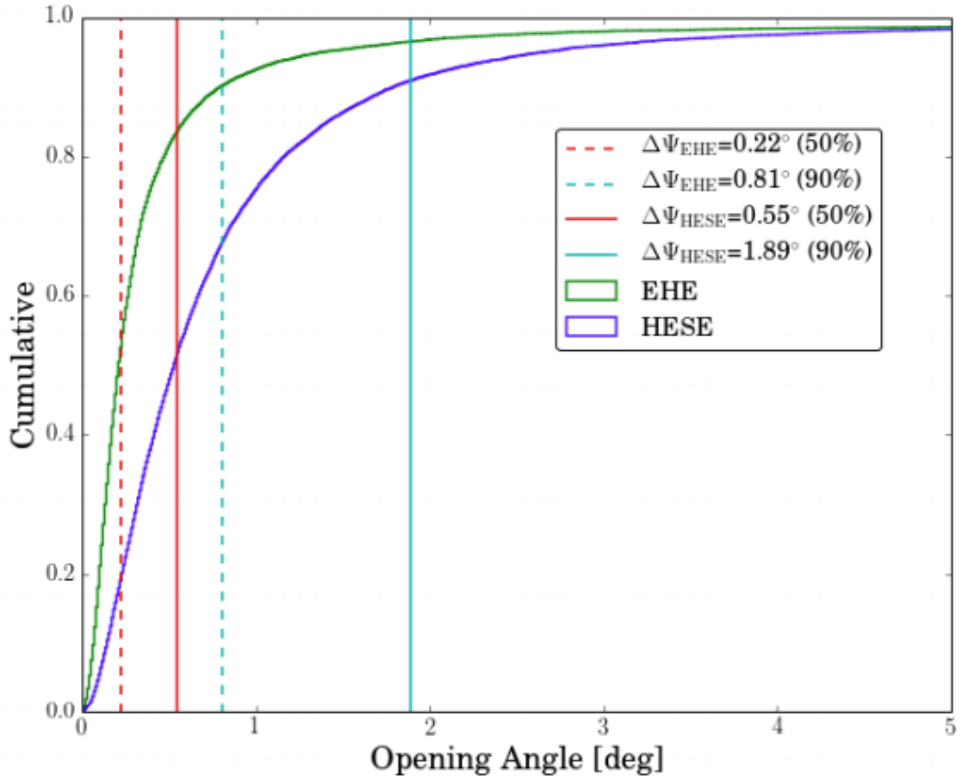
◆ HESE alert channel E_{thres}~100TeV

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}~100TeV

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





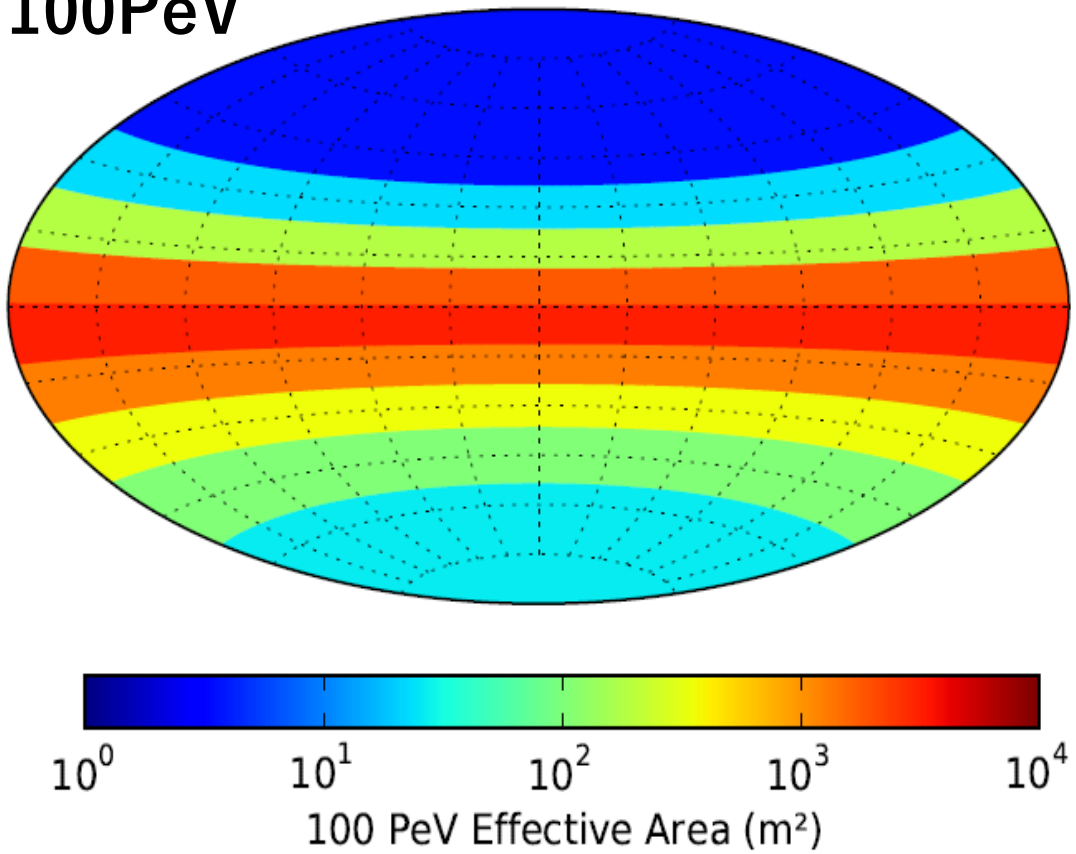
Private alerts for specific telescopes: low energy threshold, more background rates

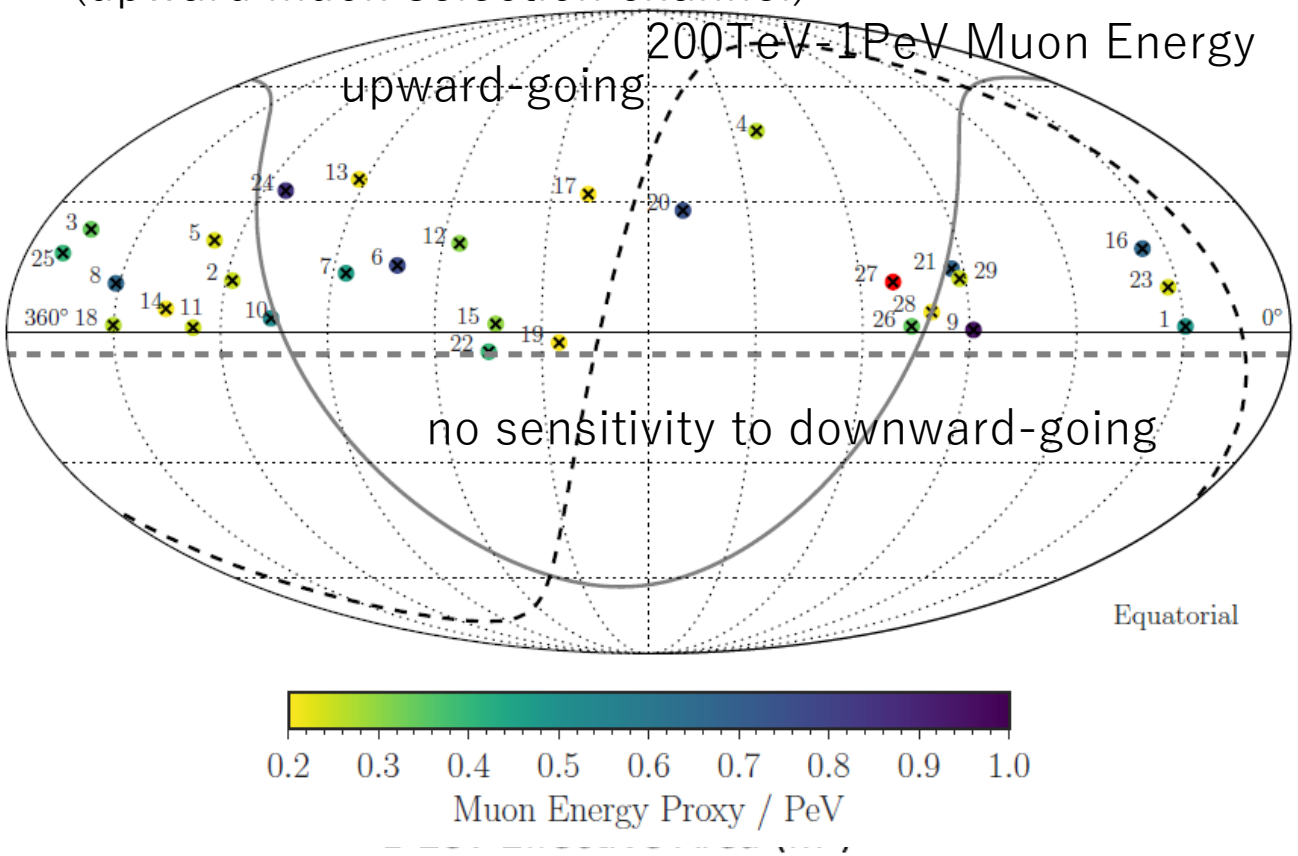
Alert	Event type	Coverage	thres E [TeV]	Median Ang Res [deg]	Time window	Alert rate Sig+BG/yr
GFU	ν_μ track multiplets	All sky	~0.1	<1	variable, max 21d	~2BGs
O(X)FU	up ν_μ track multiplets	Northern sky	~0.1	<1	100s	Varies

EHE alert acceptance

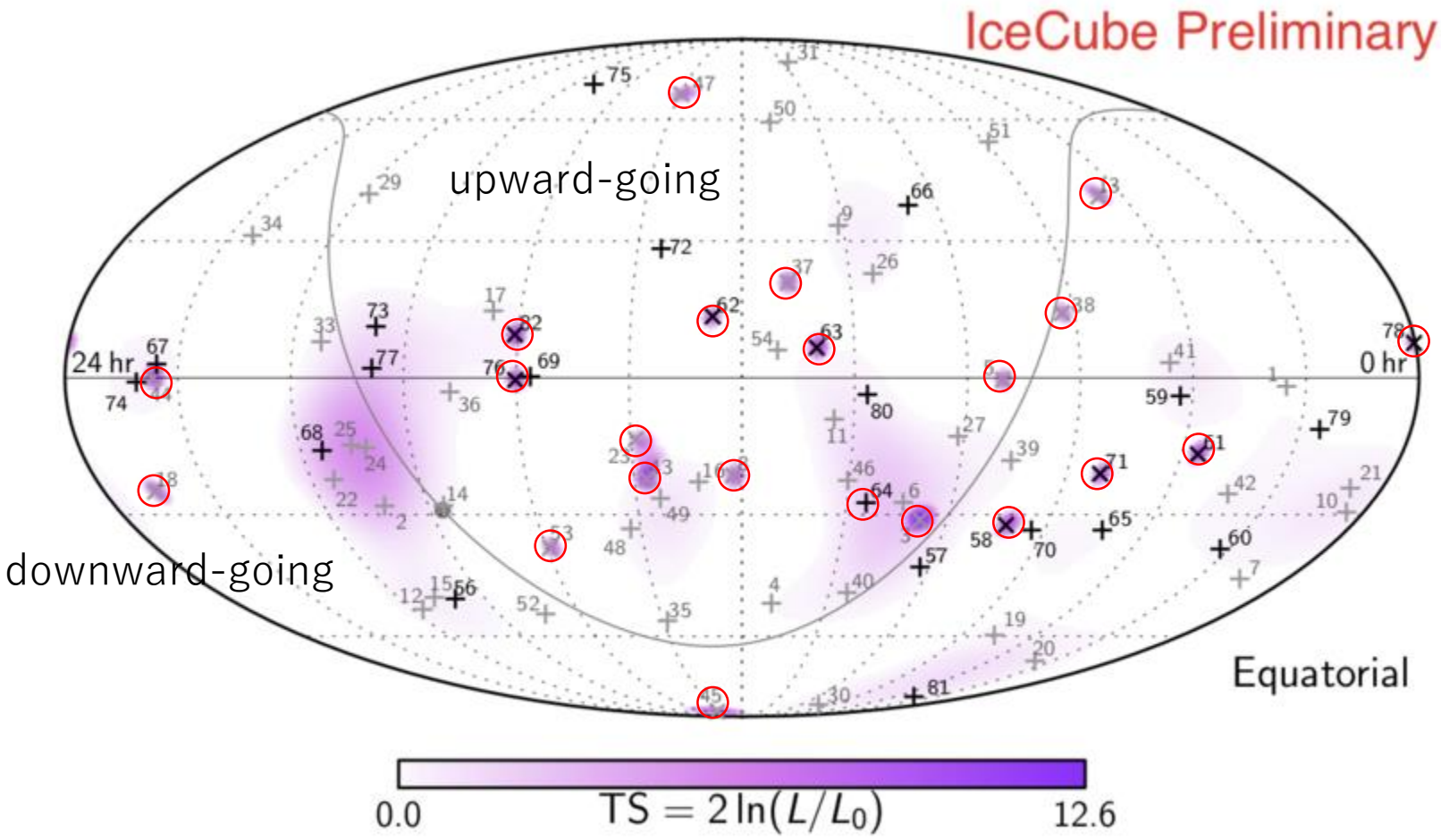
Largest effective area @ horizon
Largest direction shifts towards downward going with increasing energy
(upward muon selection channel)

100PeV





Archived HESE alert events

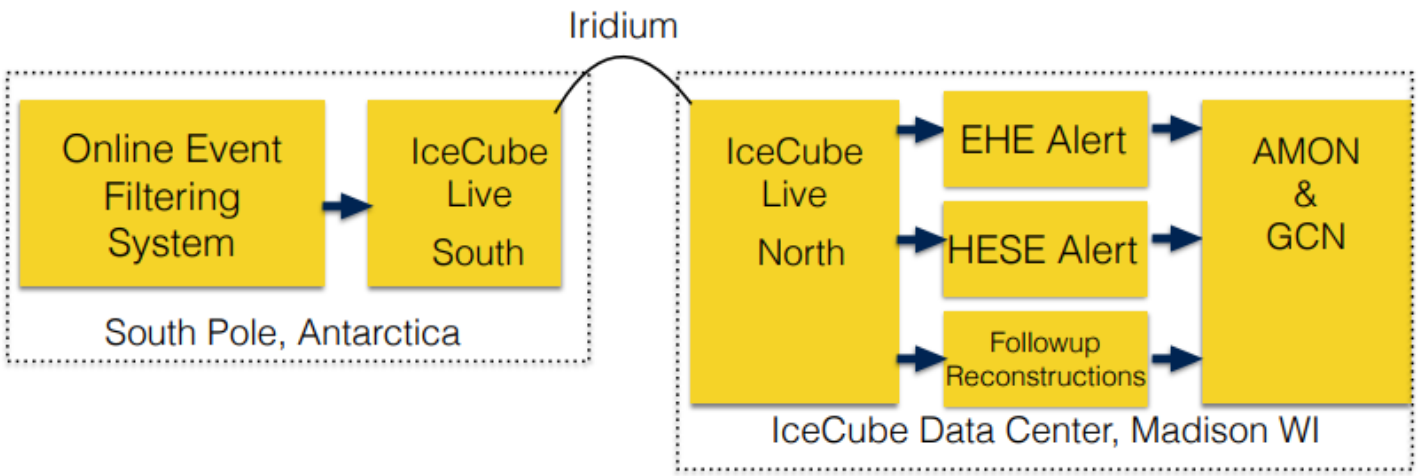


(6 yrs)

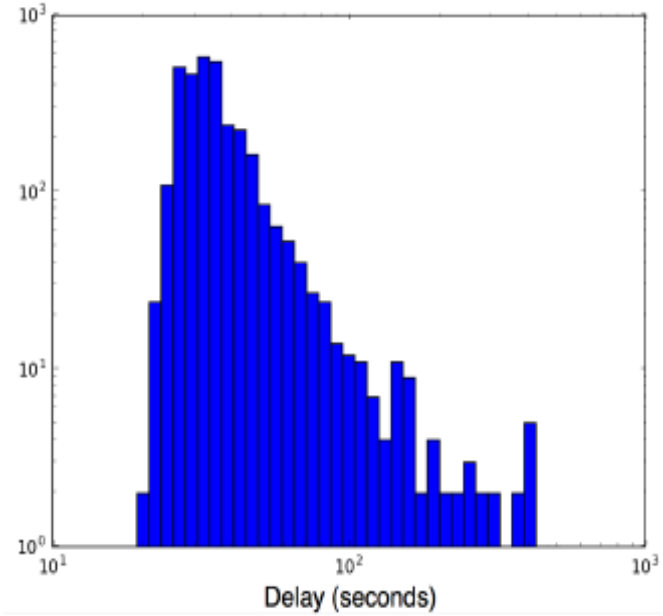
22/82 tracks

The most significant cluster p-value 58% with all events, 44% with shower events

« Public » aleart channels



Median alert latency: 33 seconds



« 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

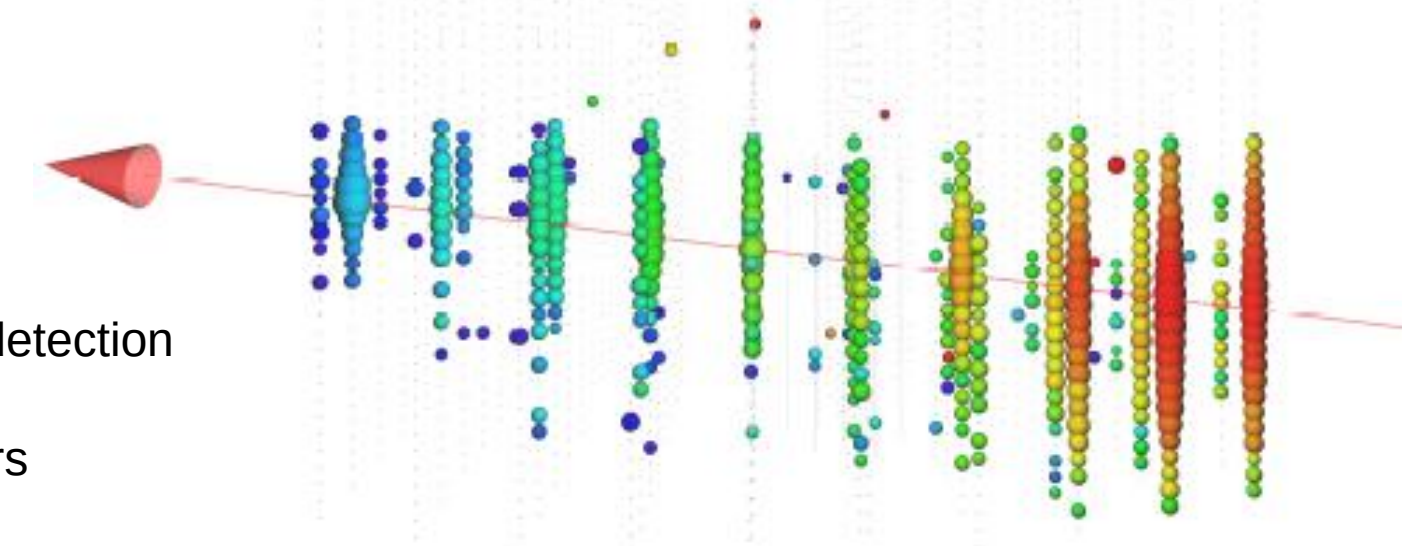
same event

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

The 5th EHE aleart: **EHE-170922A**

- Event occurred at 22nd Sept 2017 20:54:30 UTC
- First notice sent on 22nd Sept 2017 20:55:13 (43s later) ⇒ https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon
- Revised coordinates sent 4 hours later ⇒ GCN#21916



- Follow-up responses
  - GCN 21917 - Integral - No detection
  - GCN 21923/Atel 10773 - ANTARES - No detection
  - GCN 21924 – HAWC - no detection
  - GCN 21930 - SWIFT XRT - 9 x-ray emitters
  - ATel 10787 - H.E.S.S. – no detection
  - ***ATel 10791 - Fermi - increased gamma-ray activity of TXS 0506+056 (RA 77.36 deg, Dec +5.69 deg)***
  - ***ATel 10817 – The First-time detection of VHE gamma rays by MAGIC***
  - ....and observations and reports by many more telescopes: AGILE, ASAS-SN, Kapteyn, Kanata, Kiso, Liverpool, Subaru, VERITAS, VLA

Point source analysis

Likelihood function: assuming N $(= n_s + n_b)$ events observed

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

2D Gaussian

θ-dependent acceptance x power-law signal flux

Flat, square, Gaussian, or the other model

- $P_B = Spacial(\sin\theta) \times \mathrm{Energy}(\mathrm{E_{reco}}, \sin\theta)$

soft spectra $\propto \mathrm{E}^{-3.7}$

spacial distribution of background from off-target sample

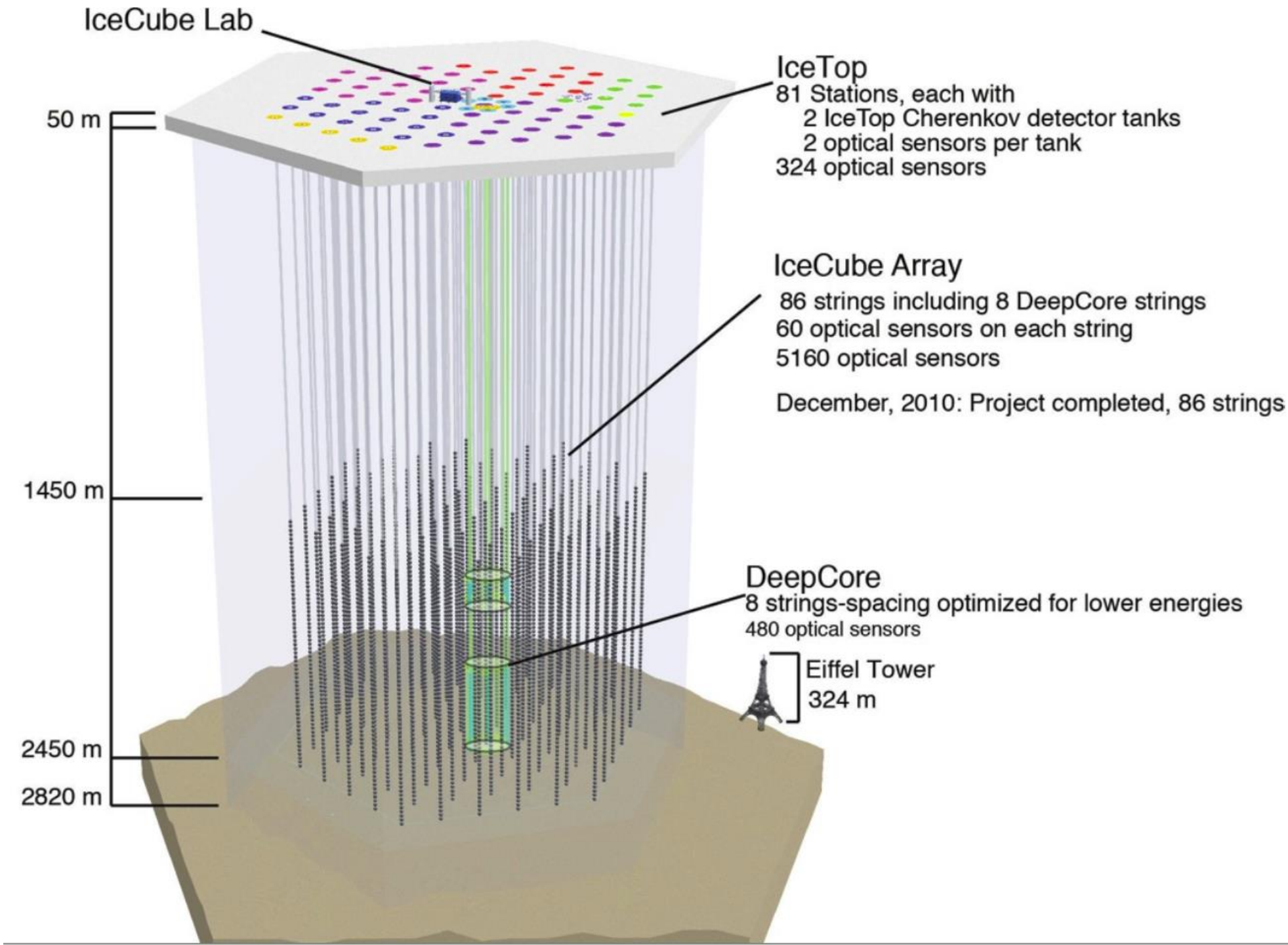
Test statistics

- $TS = 2\log\left(\frac{L(\widehat{n_s})}{L(n_s=0)}\right)$

pseudo-search trials: using off-target, time and azimuth scrambled sample

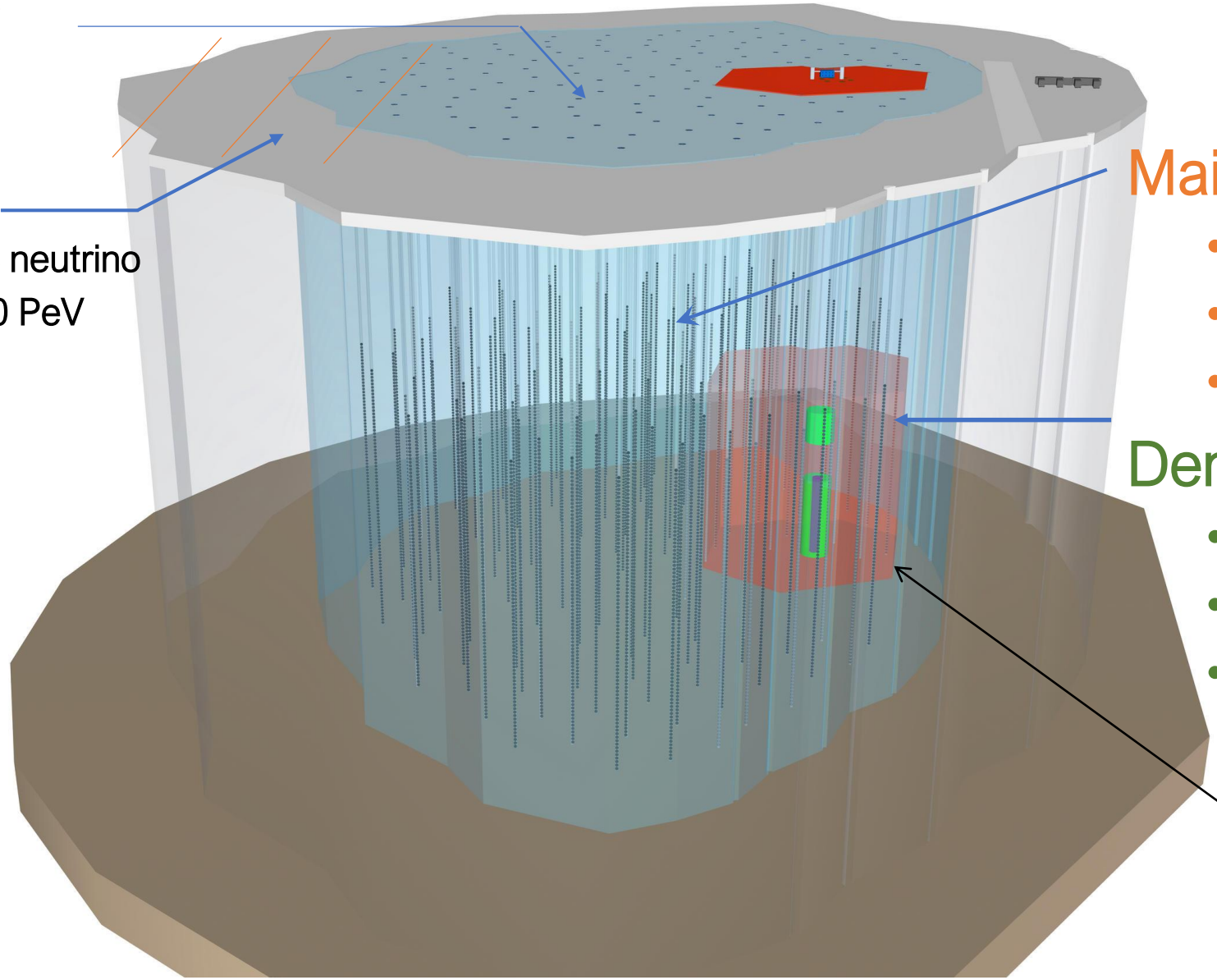
What’s next?

IceCube


IceCube Lab
50 m
1450 m
2450 m
2820 m
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m

IceCube-Gen2 Facility

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

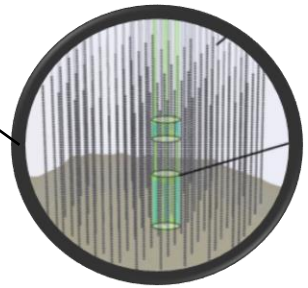


Main array

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

Dense array

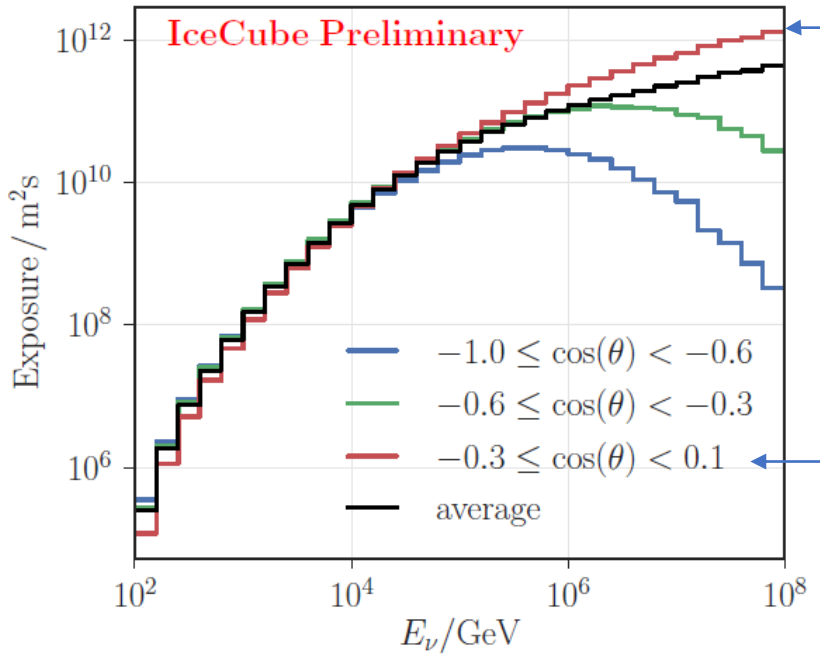
- 26 strings
- 125-192 sensors/string
- ≈25m distance

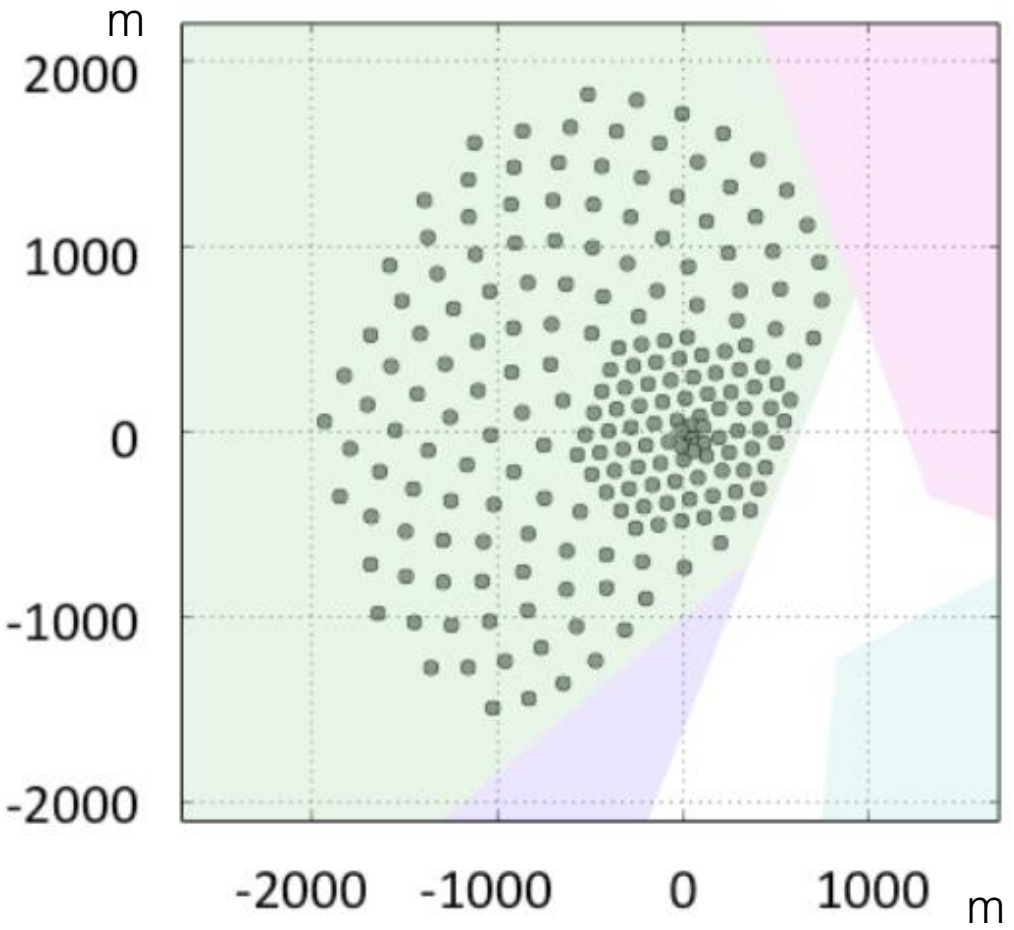


IceCube to Gen2: Point source sensitivity

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

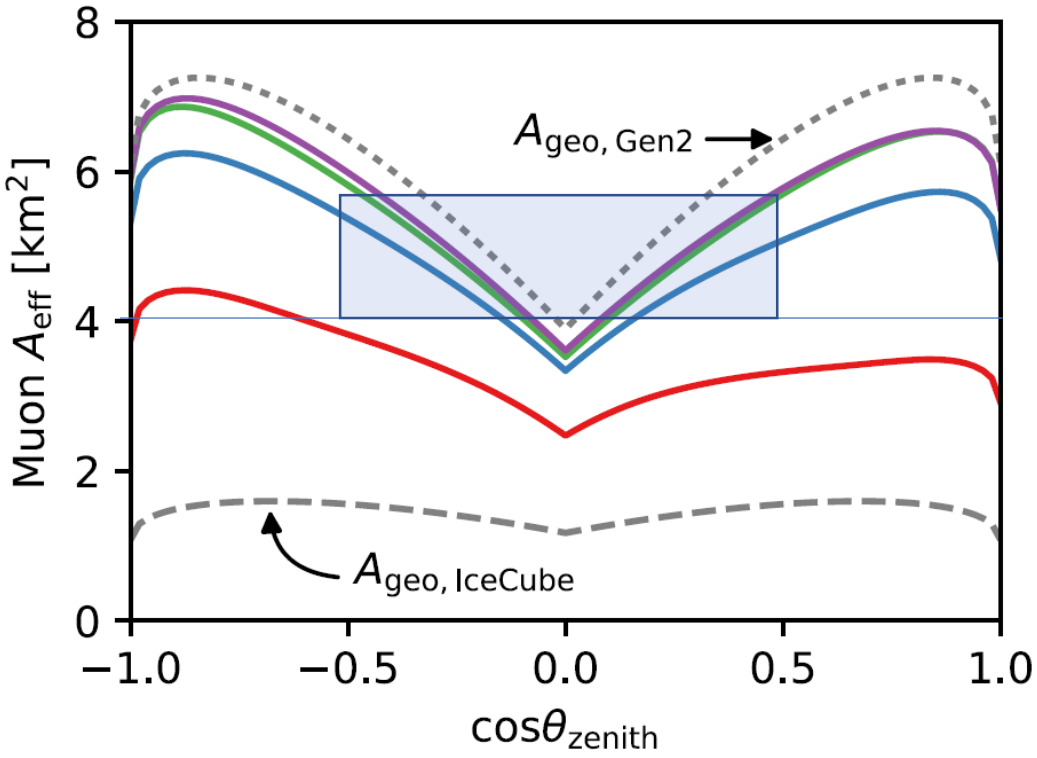
} default factor

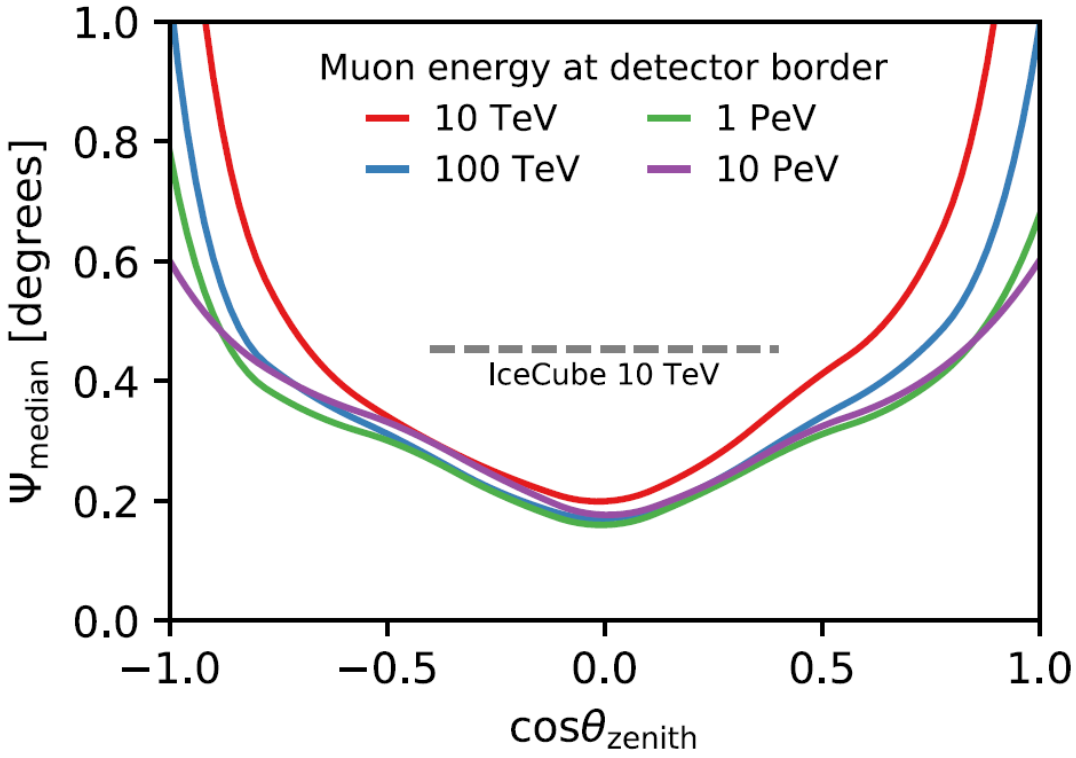




slightly downgoing horizontal direction is important for >100TeV neutrinos

Gen2 Baseline performance with IceCube DOM





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

} default factor 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*) gives us wider window

https://www.nsf.gov/news/news_summ.jsp?cntn_id=244676

NSF Fiscal Year 2019 budget to advance innovation, infrastructure

Budget request sustains current programs, looks toward future

The National Science Foundation invests in fundamental, basic research in science and engineering.
Credit and Larger Version

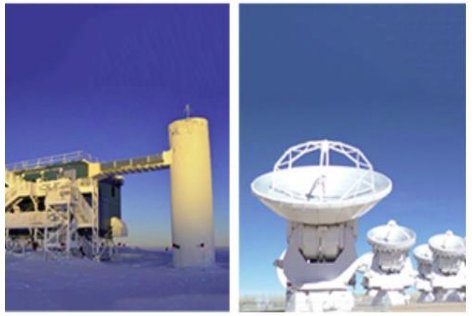
February 28, 2018

The National Science Foundation (NSF) released more detailed information regarding President Donald J. Trump's Fiscal Year (FY) 2019 NSF budget request to Congress.

The FY2019 budget request would represent a $7.47 billion investment in strengthening the nation's economy, security and global leadership through research in cutting-edge science and engineering. At this proposed level of funding, steady with FY2017 congressional appropriations, NSF would continue its work supporting research that advances national priorities such as growth in manufacturing, defense and cybersecurity.

While continuing to support ~~the programs and offices that help maintain~~ the nation's preeminence in innovation, NSF would accelerate the progress of its "10 Big Ideas for Future Investments" in FY2019, dedicating funding and resources to high-priority areas that integrate multiple ~~fields of science and engineering and create~~ opportunities to partner with industry, private foundations, other federal agencies and the education sector.

In 2016, NSF unveiled a set of "Big Ideas" -- 10 bold, long-term research and process ideas that identify areas for future investment at the frontiers of science and engineering. With its broad portfolio of investments, NSF is uniquely suited to advance this set of cutting-edge research agendas and processes that will require collaborations with industry, private foundations, other agencies, science academies and societies, and universities and the education sector. The Big Ideas represent unique opportunities to position our Nation at the cutting edge -- indeed to define that cutting edge -- of global science and engineering leadership and to invest in basic research and processes that advance the United States' prosperity, security, health and well-being.



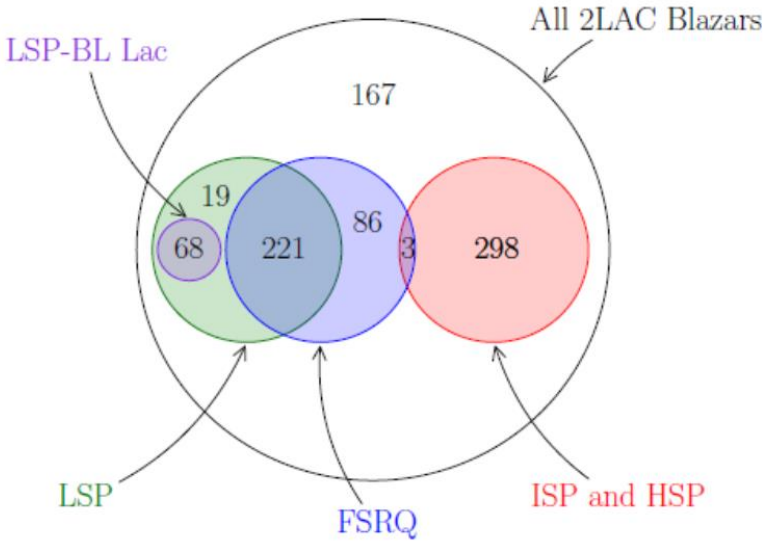
Windows on the Universe: The Era of Multi-Messenger Astrophysics

Using powerful new syntheses of observational approaches to provide unique insights into the nature and behavior of matter and energy and help to answer some of the most profound questions before humankind. Read more.

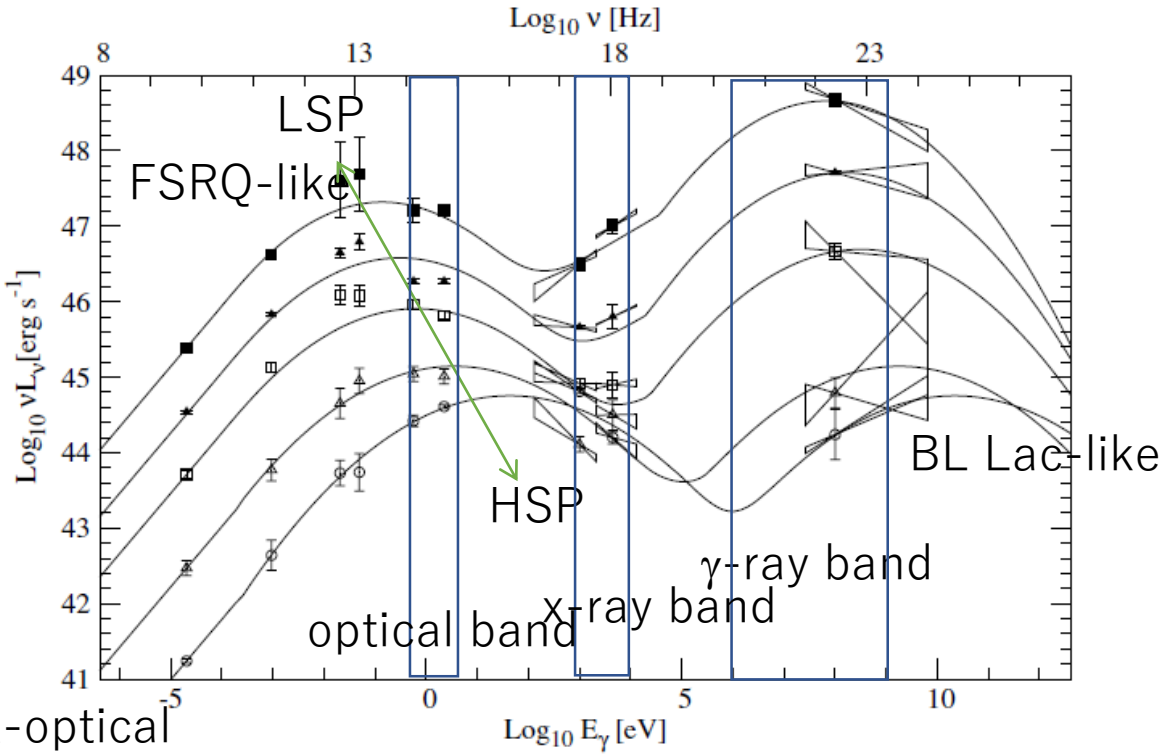
Summary

- The high energy neutrino alerts and follow up system has been in operation since 2016, April (HESE) and May (EHE)
- Follow-up programs are also in good coordination
- 5th EHE alert correlated with gamma-ray flare of the Blazer TXS 0506-056 with significance of 3 sigma
- An independent neutrino point-source analysis found correlated neutrino events in time from direction of the blazer with 3.5 sigma significance
- Modeling of neutrino emission from TXS is not simple – Blazer can not explain the IceCube diffuse flux
- Of course, this is just a beginning. Hope this is a good start of the VHE neutrino astronomy, which leads to more advanced multi-messenger view of Universe

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 n_s of the signal contribution

the spectral index Γ_{SI} of the signal's energy distribution

signal hypothesis PDF

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

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% ($+0.4\sigma$)	6% ($+1.6\sigma$)
FSRQs	34% ($+0.4\sigma$)	34% ($+0.4\sigma$)
LSPs	36% ($+0.4\sigma$)	28% ($+0.6\sigma$)
ISP/HSPs	$> 50\%$	11% ($+1.2\sigma$)
LSP-BL Lacs	13% ($+1.1\sigma$)	7% ($+1.5\sigma$)

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

neutrino luminosity is proportional to gamma-ray luminosity

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

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

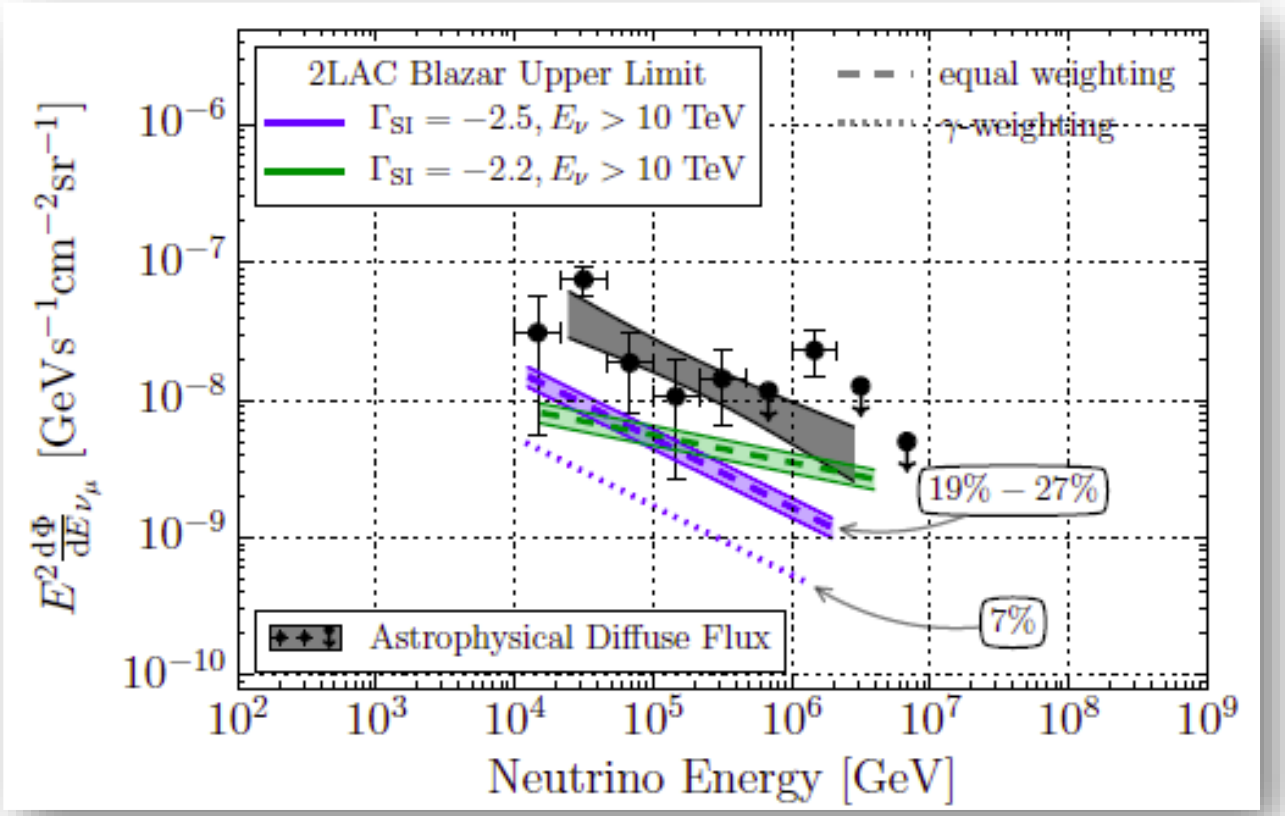
Results: Limits on the blazar contribution

UL on E^{-2} flux

Spectrum: $\Phi_0 \cdot (E/\mathrm{GeV})^{-2.0}$		
Blazar Class	$\Phi_0^{90\%}[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$	
	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)

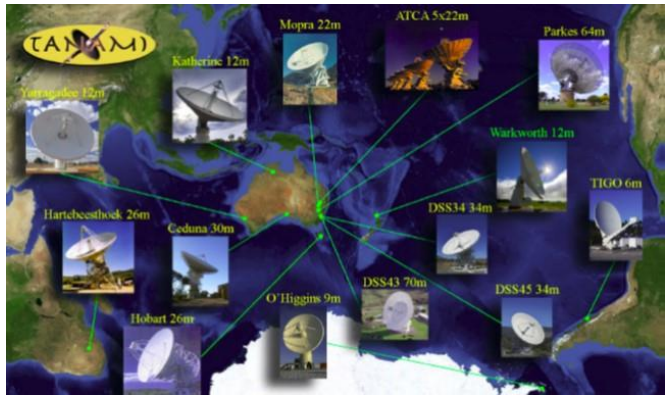


Contribution of the total 2LAC blazar sample to the astrophysical neutrino flux

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

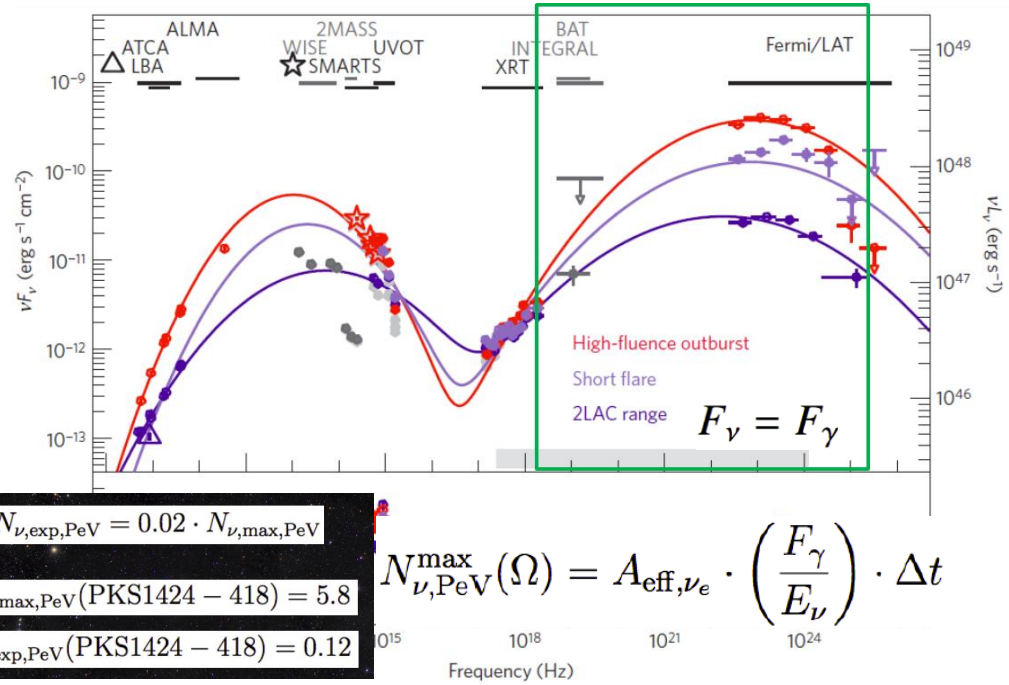
Coincidence of a high-fluence blazar

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%

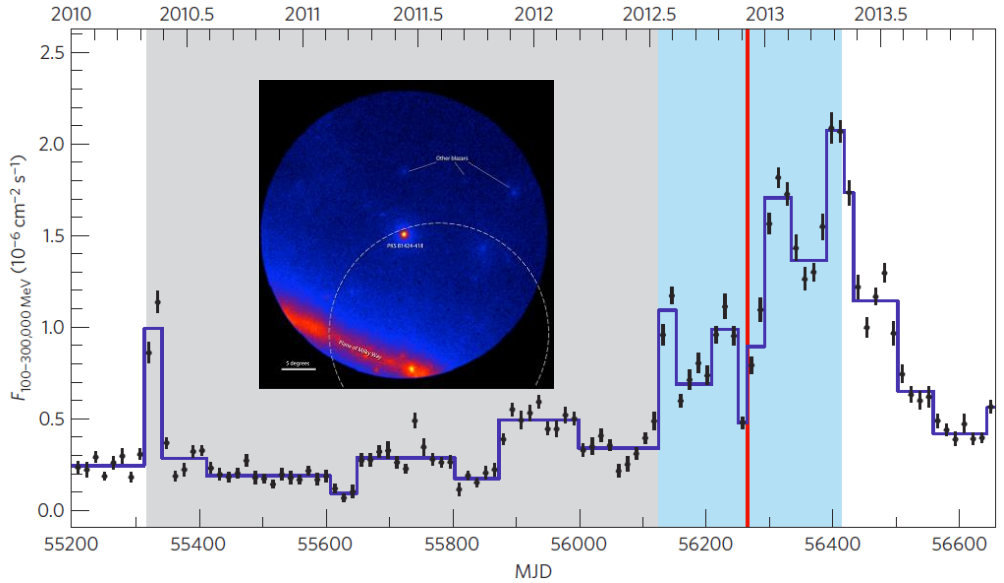


$$N_{\nu,\mathrm{exp,PeV}} = 0.02 \cdot N_{\nu,\mathrm{max,PeV}}$$

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

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

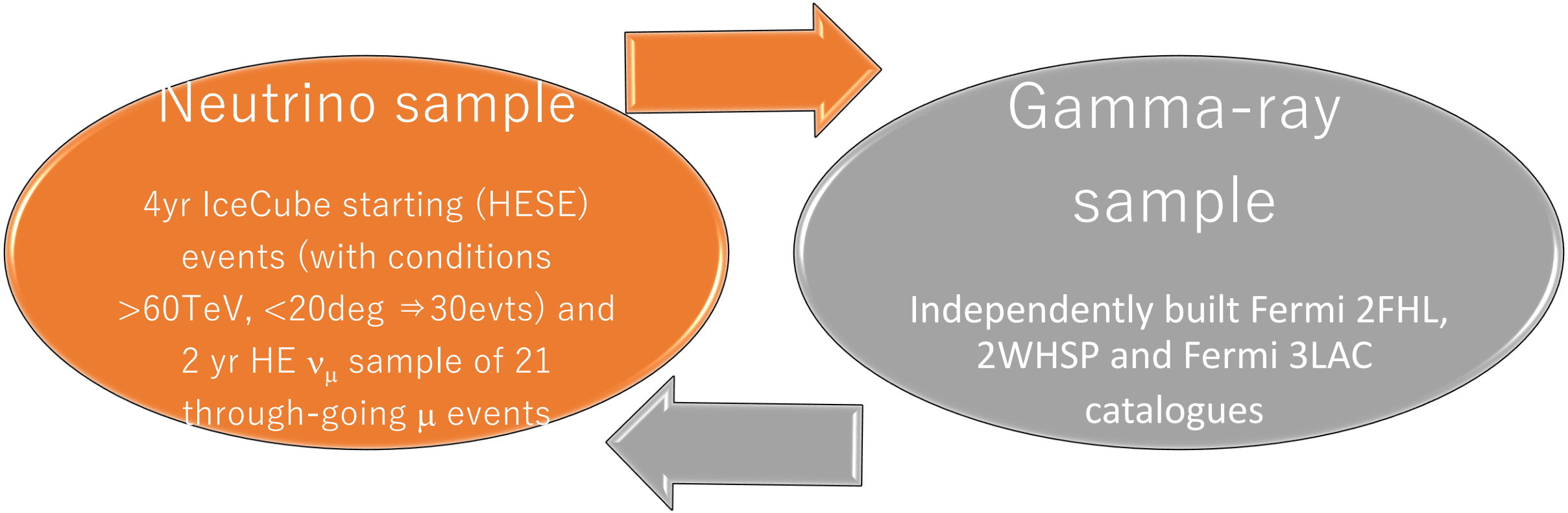
$$N^{\max}_{\nu,\mathrm{PeV}}(\Omega) = A_{\mathrm{eff},\nu_e} \cdot \left(\frac{F_\gamma}{E_\nu}\right) \cdot \Delta t$$



ANTARES did not find events from PKS B1424-418

blazar-ν correlation search

MNRAS 457 (2016) Padovani

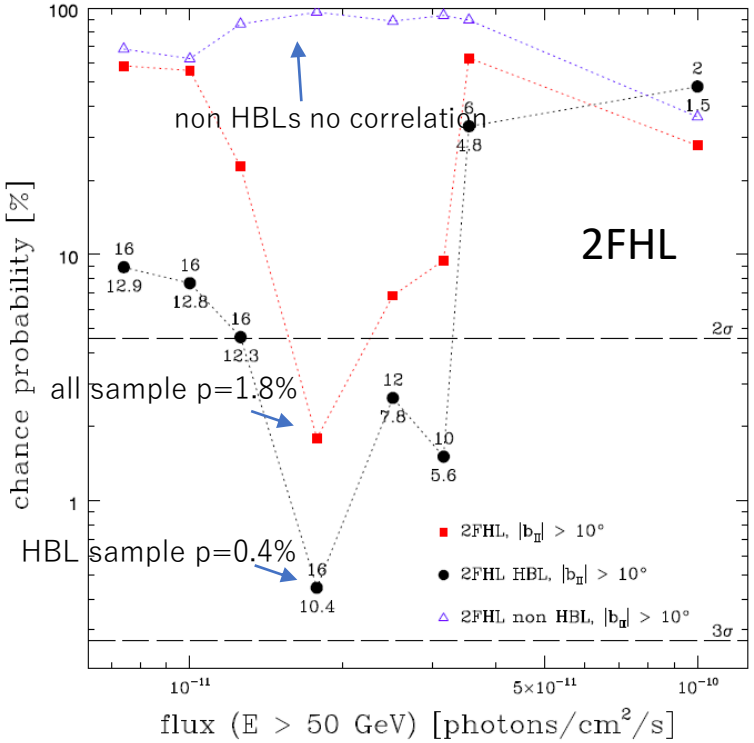


Neutrino events with γ-ray counterparts

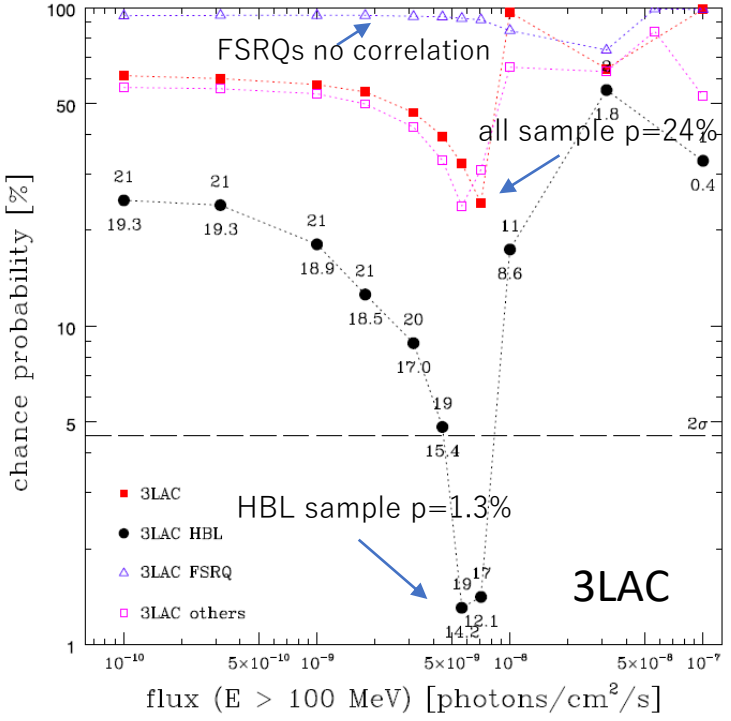
N_ν: the number of ν events with at least one γ-ray counterpart found within the median angular error as function of γ-ray flux threshold f_γ

- 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

MNRAS 457 (2016) Padovani



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

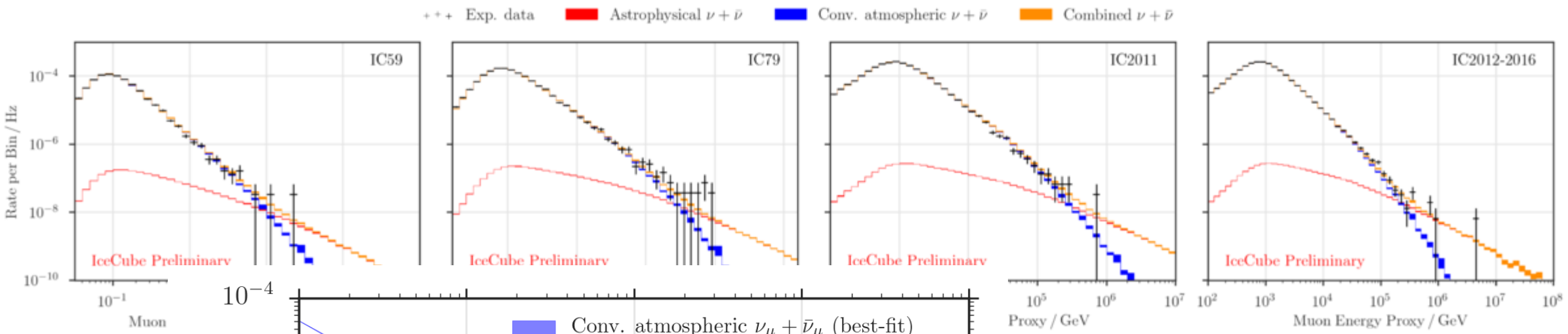


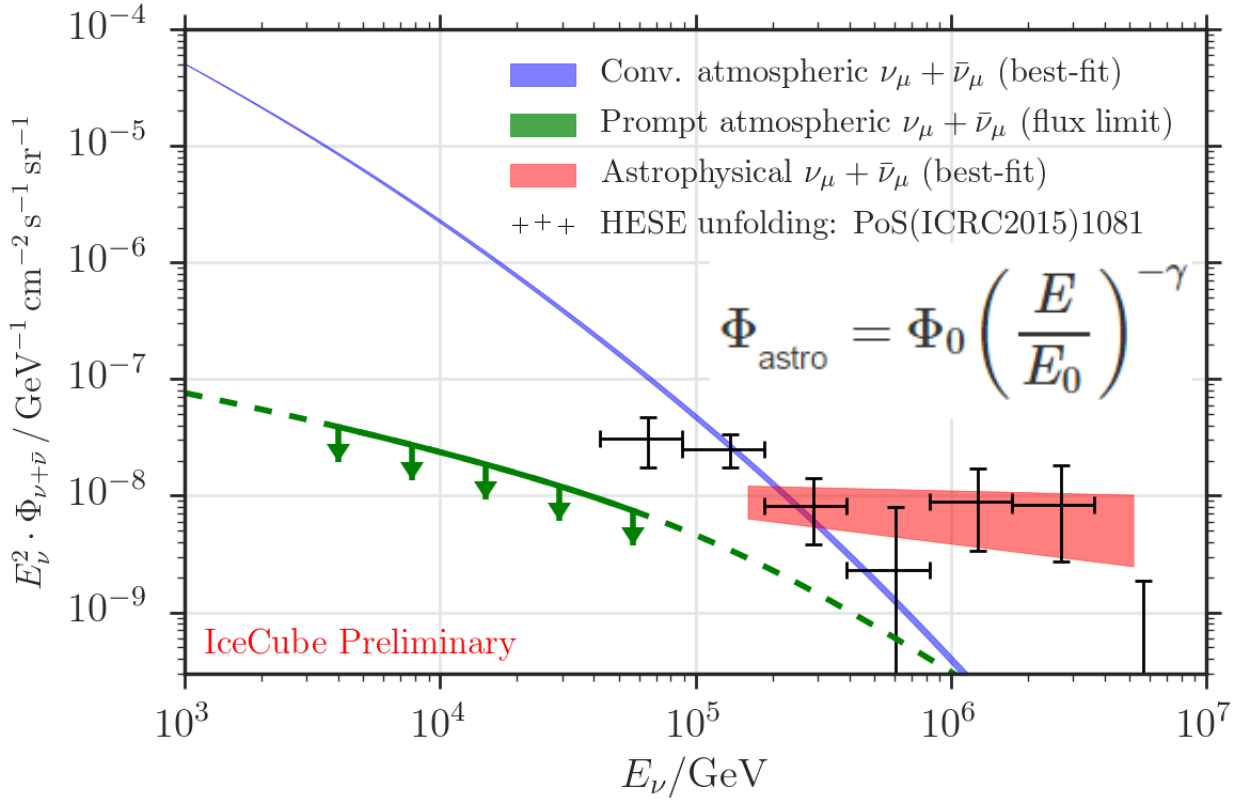
Questions

- We have UL from blazer stacking analysis – limits on diffuse nu contribution

Prospects

upward going muon events





- 2 year sample
  - $\gamma = 2.2 \pm 0.2$ PRL **115**, 081102 (2015)
- 6 year sample
  - $\gamma = 2.13 \pm 0.13$ ApJ **833** 3 (2016)
- 7 year sample
  - $\gamma = 2.16 \pm 0.11$
- 8 year sample
  - $\gamma = 2.19 \pm 0.10$ ICRC(2017)