Multi-messenger astronomy with **Icecube**

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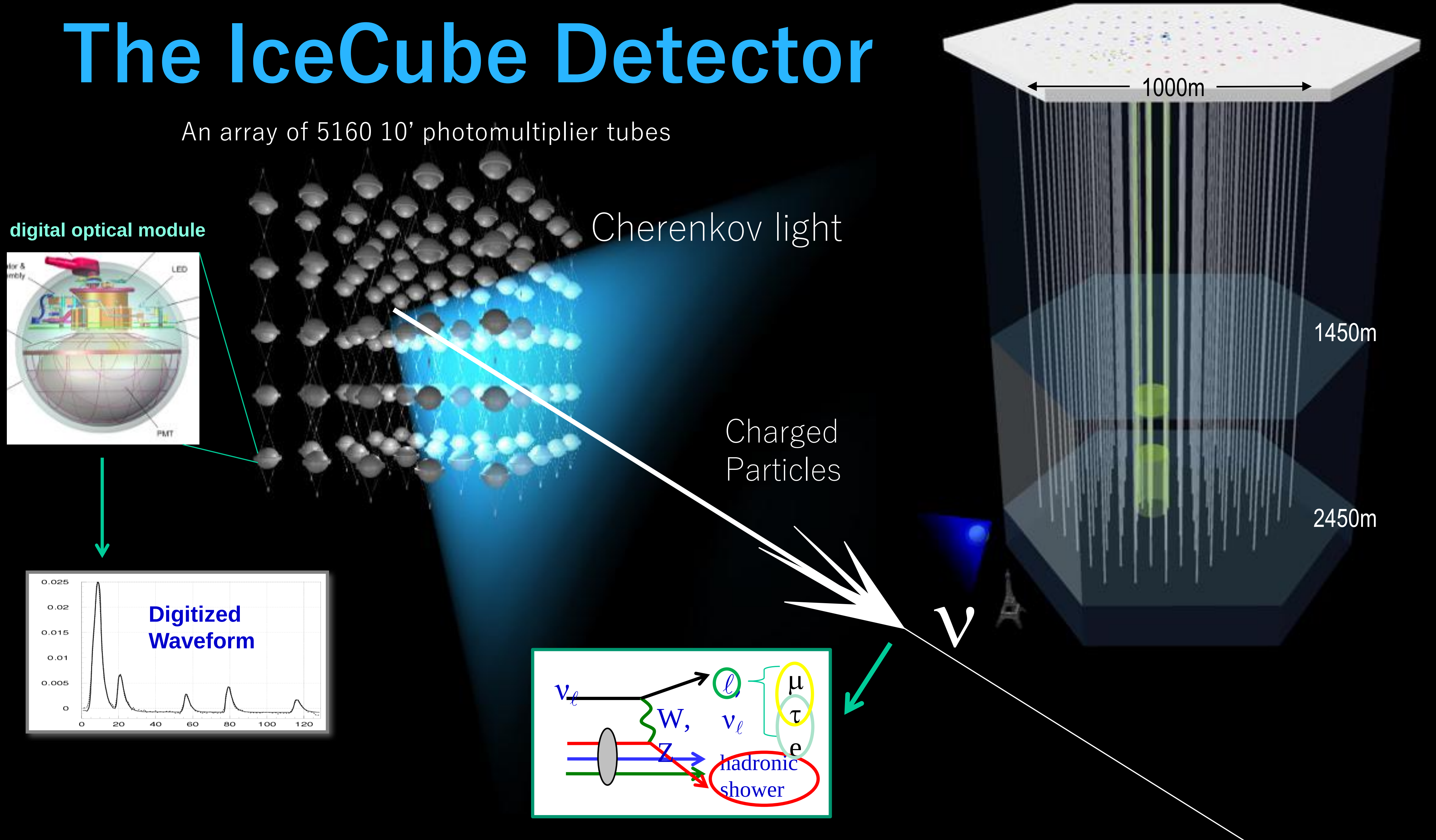
  - multiplets alert
    - gamma-ray follow up
    - optical/x-ray follow up
- Summery

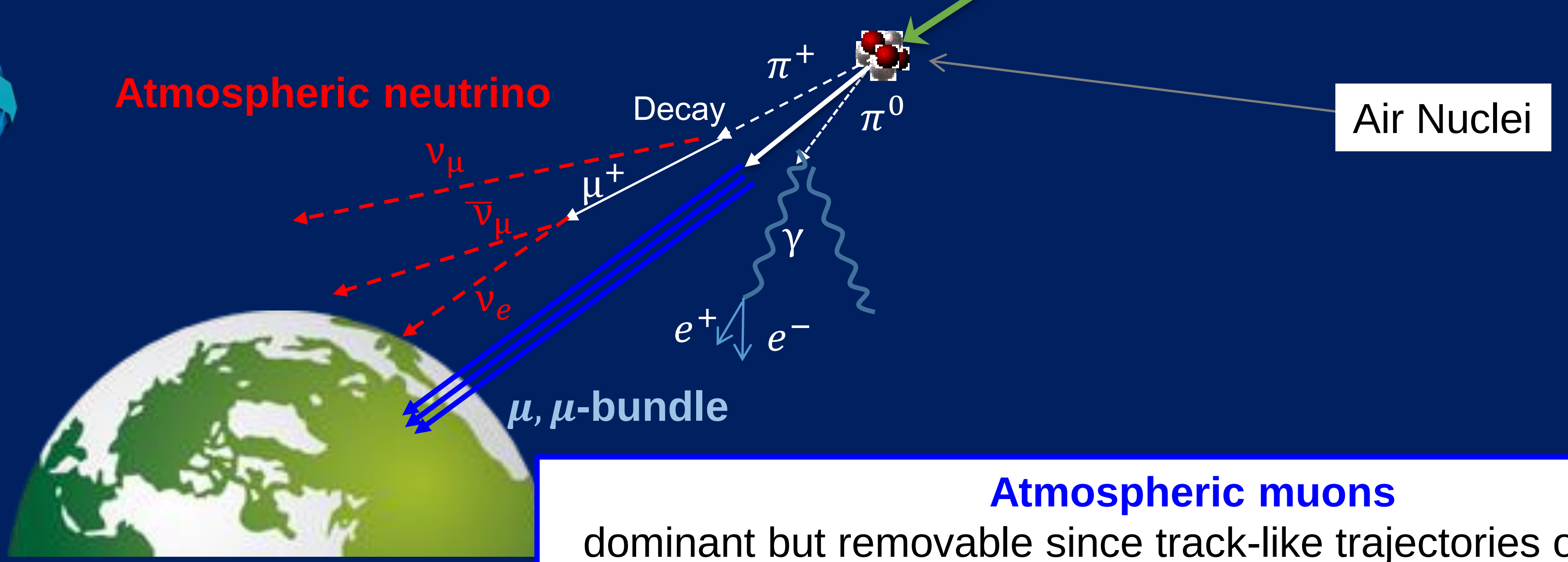
The IceCube Detector

An array of 5160 10’ photomultiplier tubes



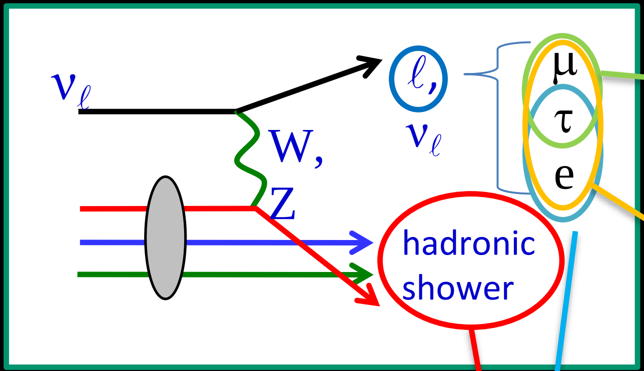
Background

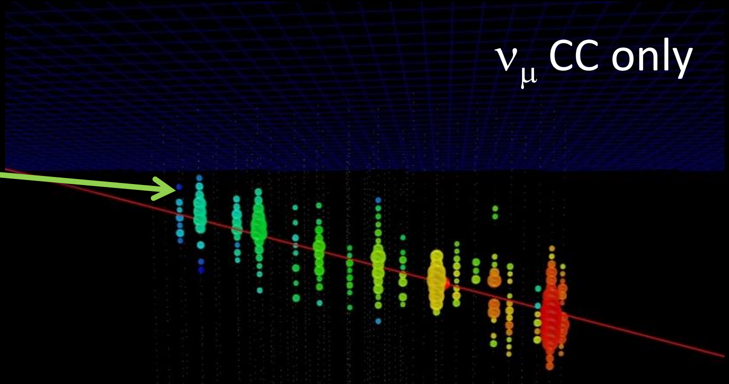
Atmospheric Neutrinos
cosmic-ray up to knee : ν from π and K decay
around and above knee: ν from charmed meson decay



Atmospheric muons
dominant but removable since track-like trajectories of Cherenkov photons and its directions is able to be reliably reconstructed

High energy neutrino detection channels

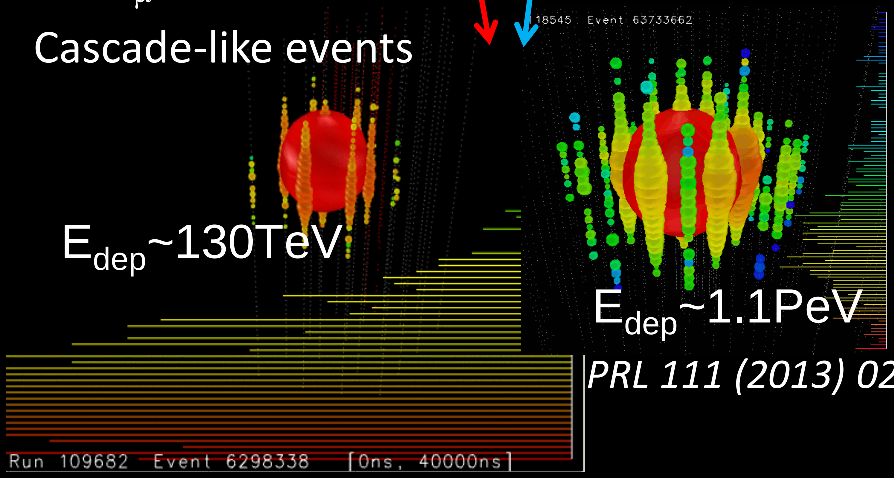




~100TeV up-going muon track event

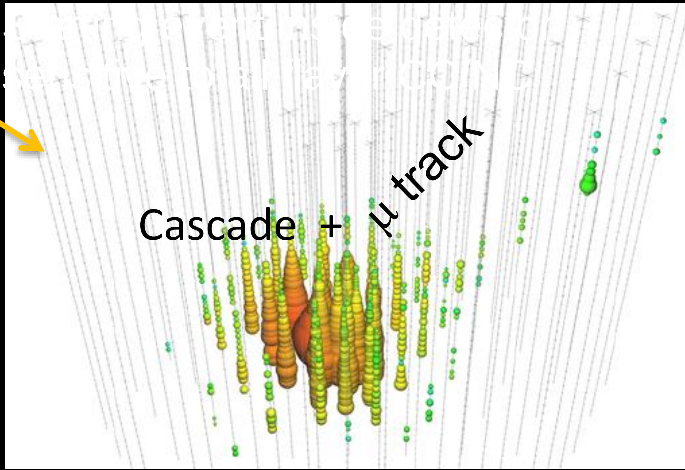
All except ν_μ CC

Cascade-like events



Phys. Rev. D 84, 072001 (2011)

PRL 111 (2013) 021103



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

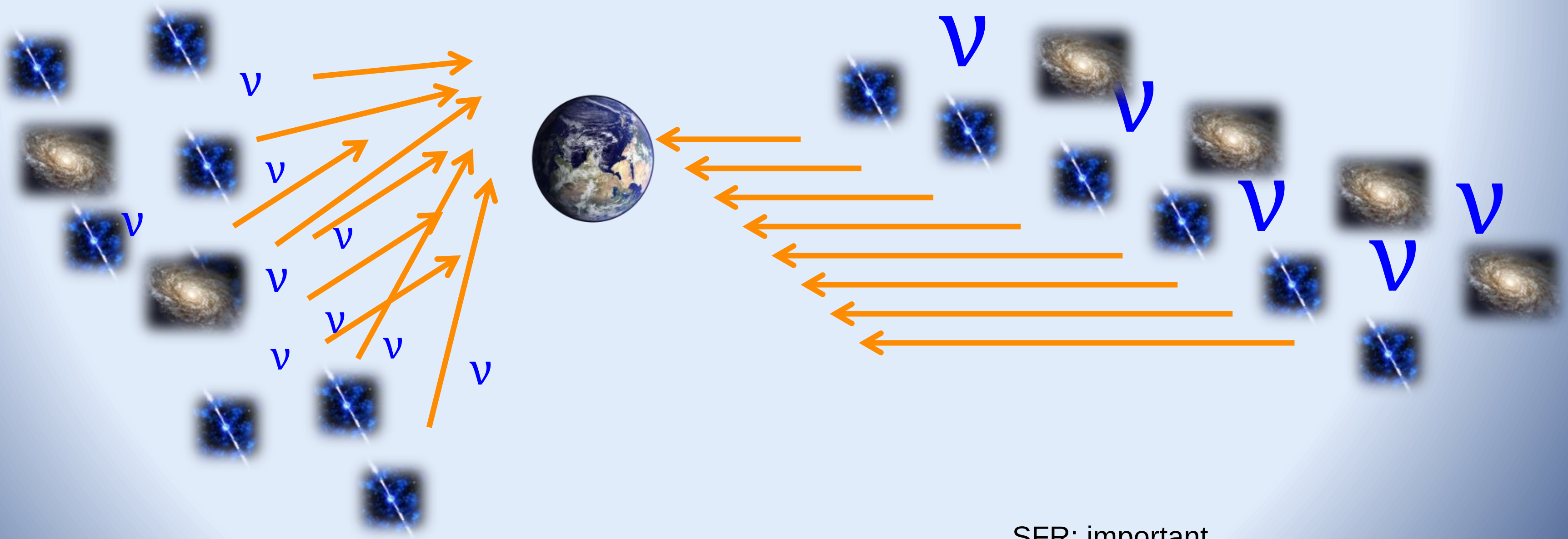
Diffuse neutrino spectra

Diffuse neutrino flux: Powerful tool to search abandant sources

- Accumulate neutrinos from many sources even at very far Universe, or very weak. Different direction or timing, and of different types
- Diffuse flux give hints to build a better point source observation strategy

$$\phi^{\nu}_{diff}\,(E_\nu) = \frac{c}{4\pi}\iint \left|\frac{dt}{dz}\right| \frac{\phi^{\nu}(E_\nu, z)}{dE_\nu dz}\, dz d\Omega$$

different directions different cosmological distances



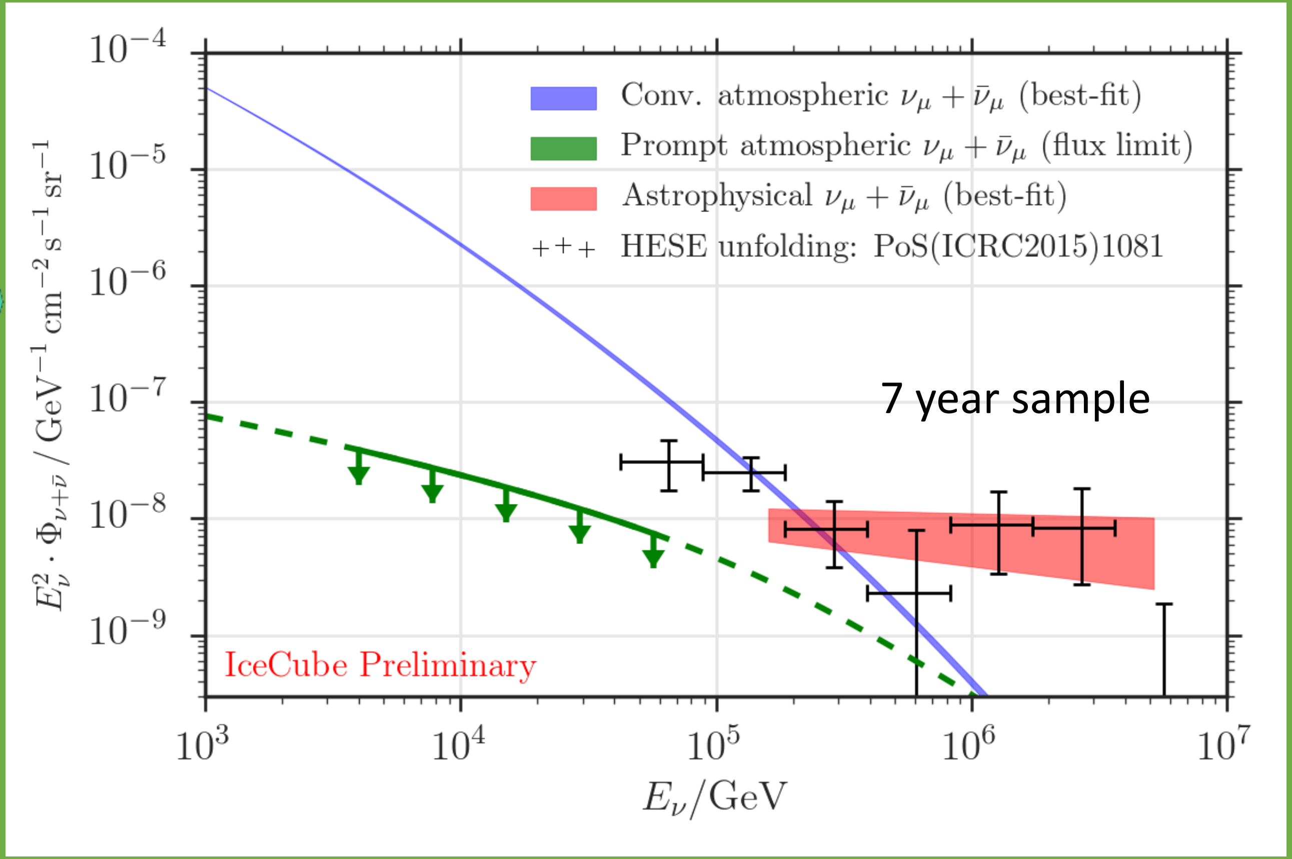
unresolved week sources far sources

SFR: important contributions upto z~1-2

Upward-going muon track diffuse flux

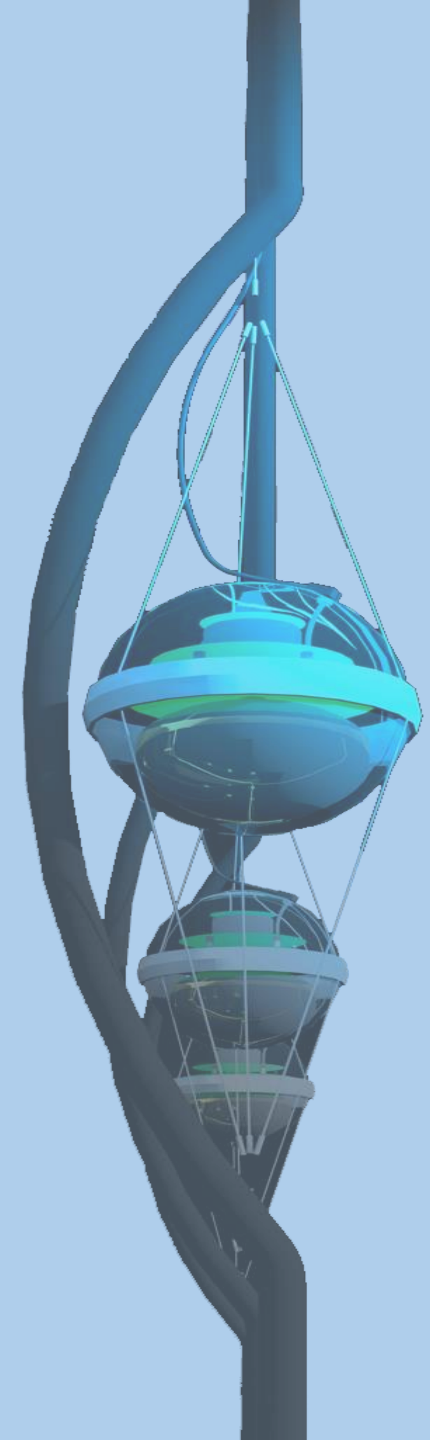
IceCube ApJ 833 3 (2016)

Energy range of the astrophysical flux: 160TeV - 5.2PeV



$$\Phi_{\text{astro}} = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma}$$

- 6 year sample
  - ApJ 833 3 (2016)
  - γ=2.13±0.13
- 7 year sample
  - γ= 2.16±0.11



Starting event diffuse flux

- Best fit spectral index

$$\Phi_{astro} = \Phi_0 \left(\frac{E}{E_0} \right)^{-\gamma}$$

was

γ= 2.2 ± 0.4 (2 yrs)

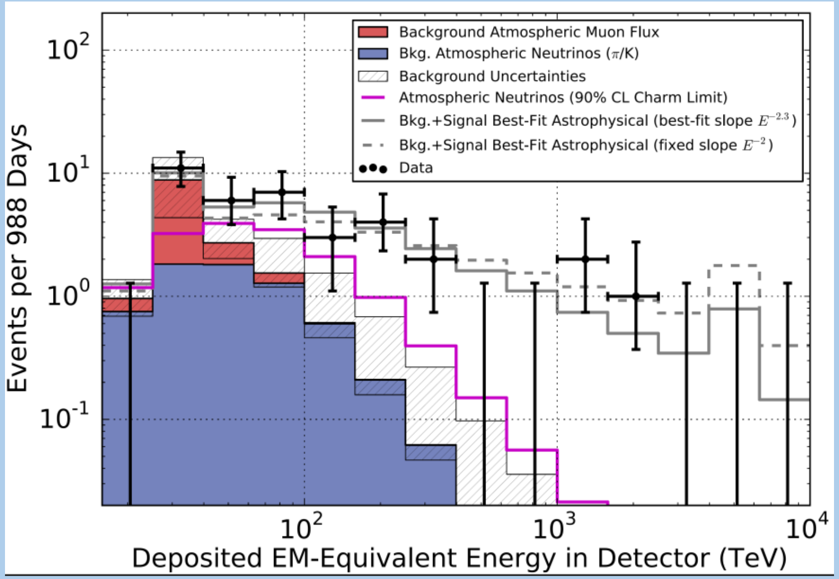
γ= 2.3±0.3 (3 yrs)

and currently

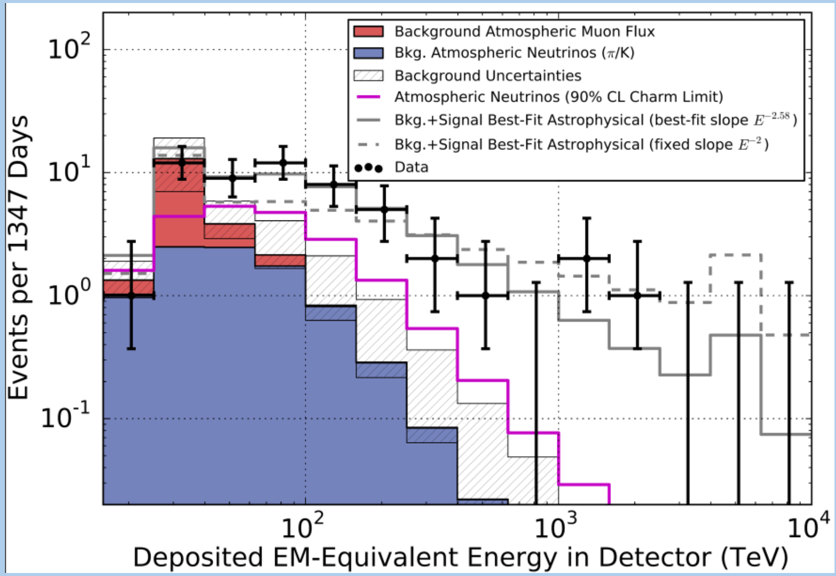
γ= 2.58±0.25 (4 yrs)

  – Energy threshold ~60GeV

3 year (2010/5-2013/5) sample, PRL 113, 101101



4 year sample, ICRC2015 POS (1081)



Reduced threshold starting events

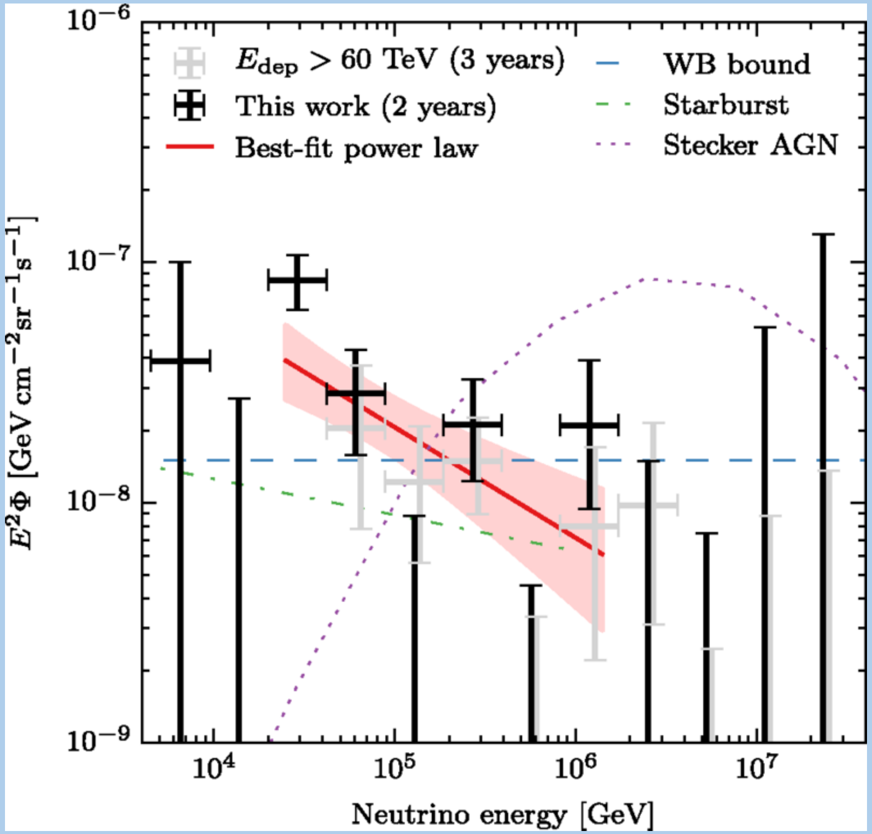
IceCube Phys. Rev. D **91**, 022001 (2015)

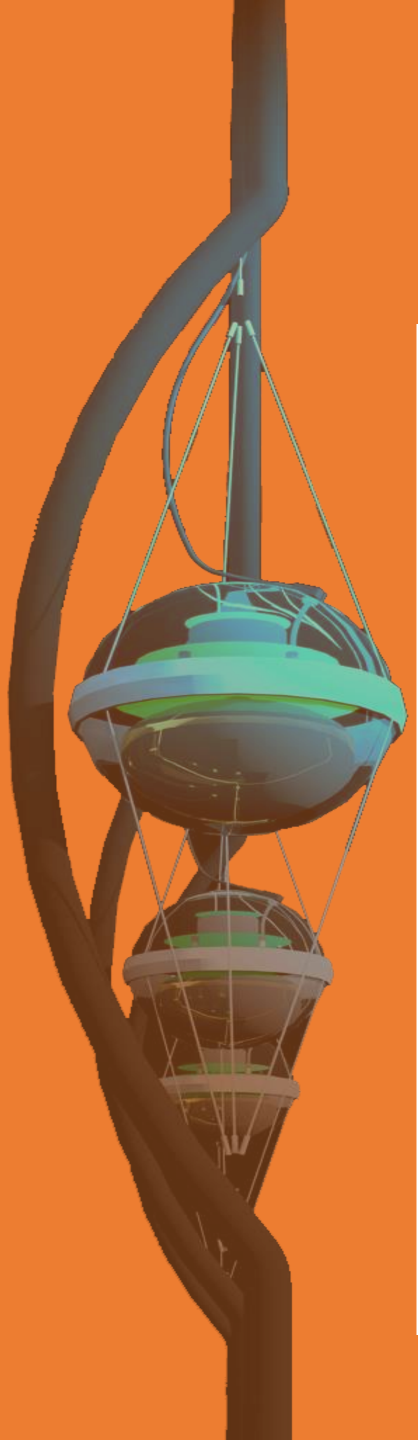
Lower energy extension of (2 years) analysis down to 1TeV

$\gamma = 2.46 \pm 0.12$

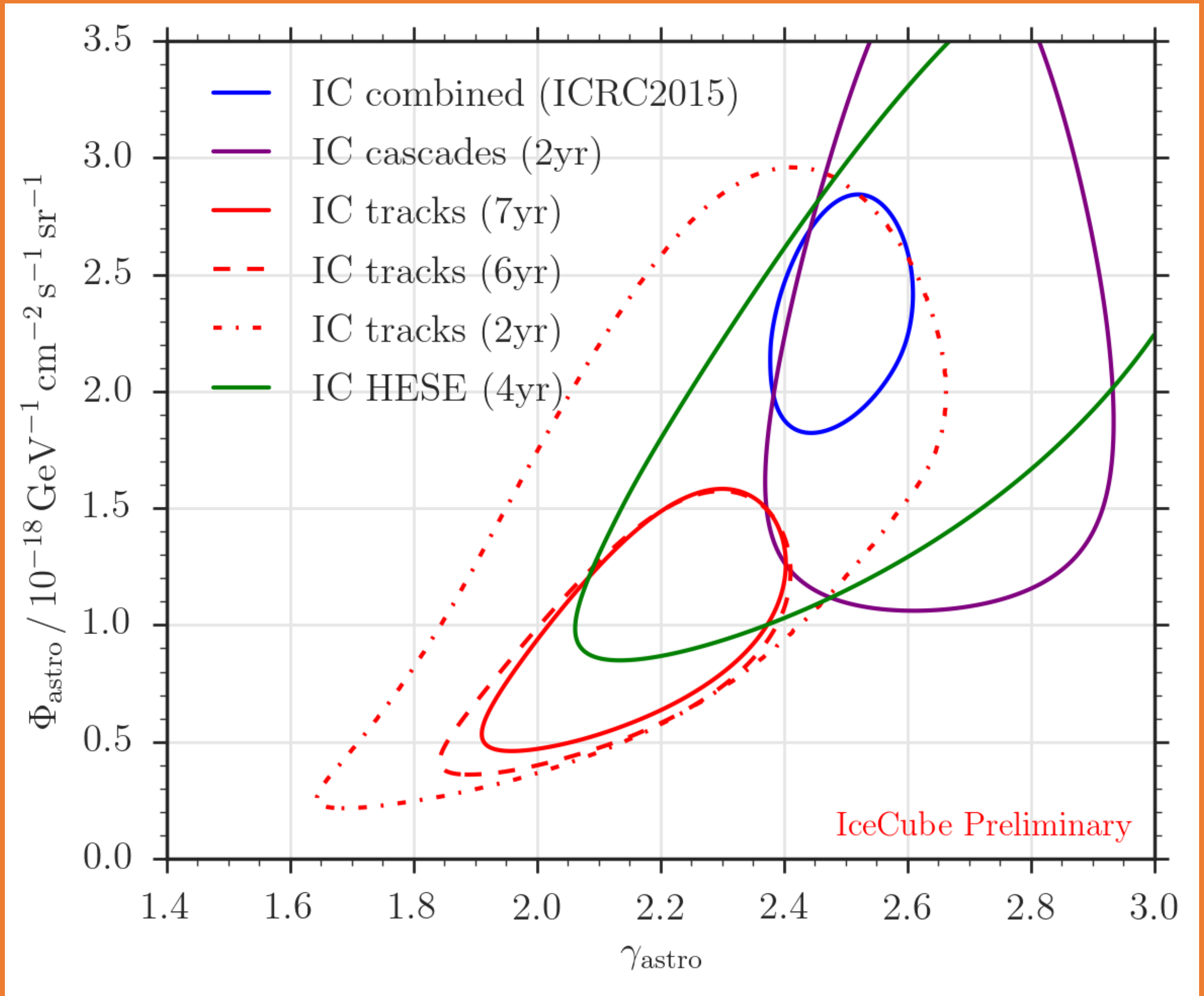
$$\Phi_{\text{astro}} = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma}$$

Parameter	Best-fit value	Number of events
Penetrating μ flux	$1.73 \pm 0.40 \Phi_{\text{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\, \Phi_{\text{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52 \Phi_{\text{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ GeV^{-1} cm^{-2} sr^{-1} s^{-1}	87^{+14}_{-10}
Astrophysical γ	2.46 ± 0.12	





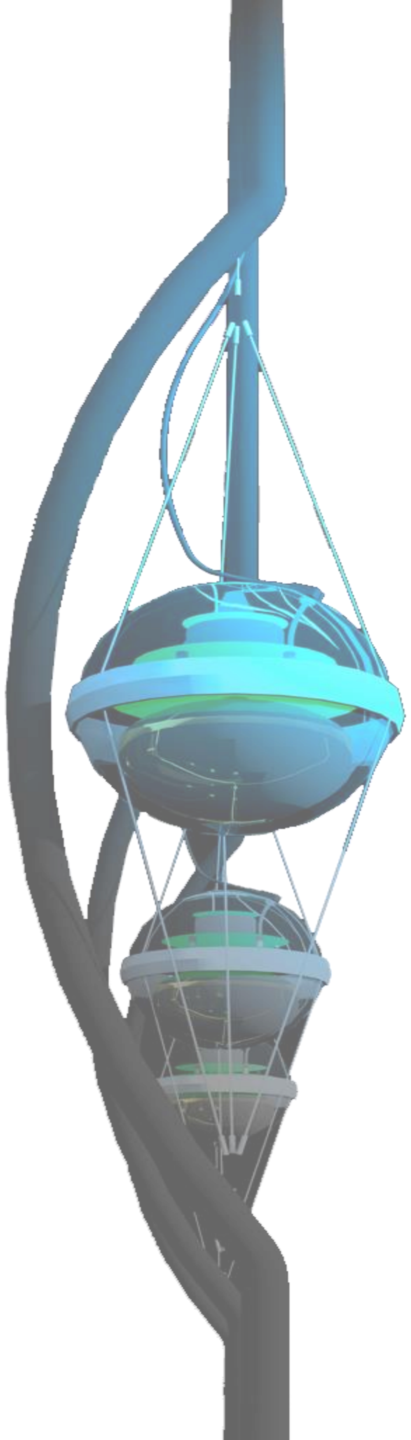
A best fit comparison

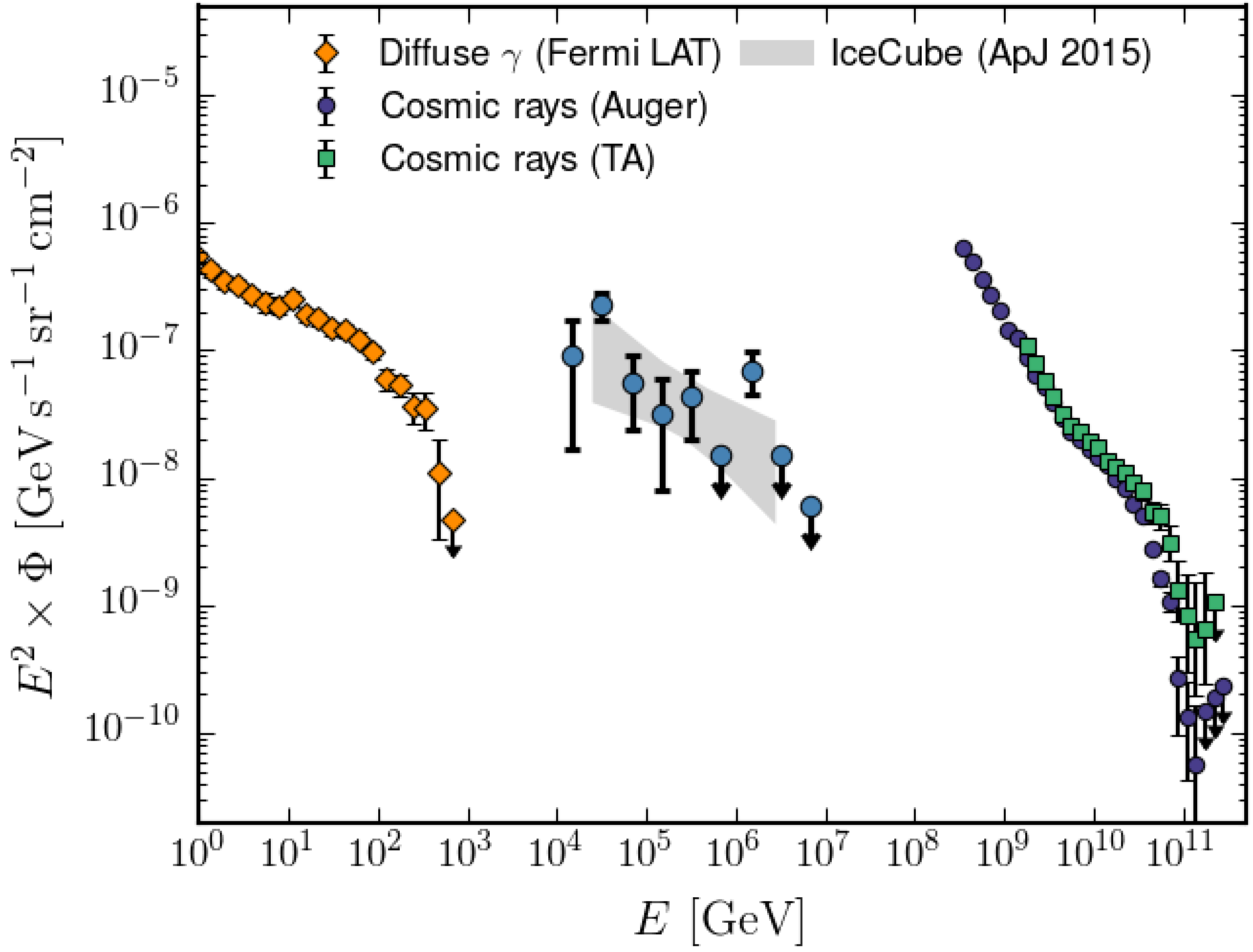


- Results are consistent

but,

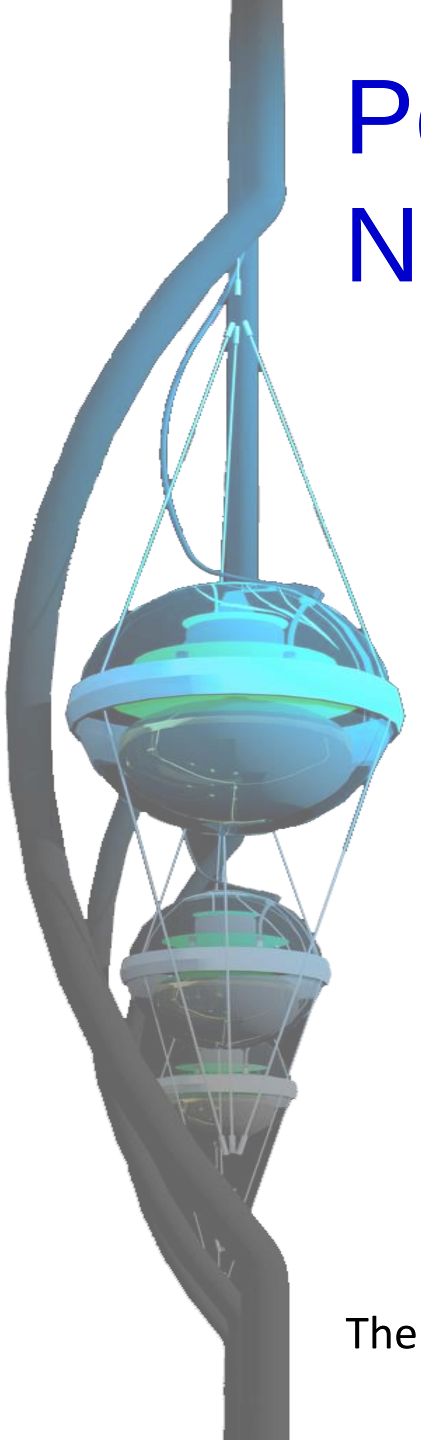
- Keep eye on the insignificant 2σ level of tension between cascade(≈ reduced starting) and upward track analysis

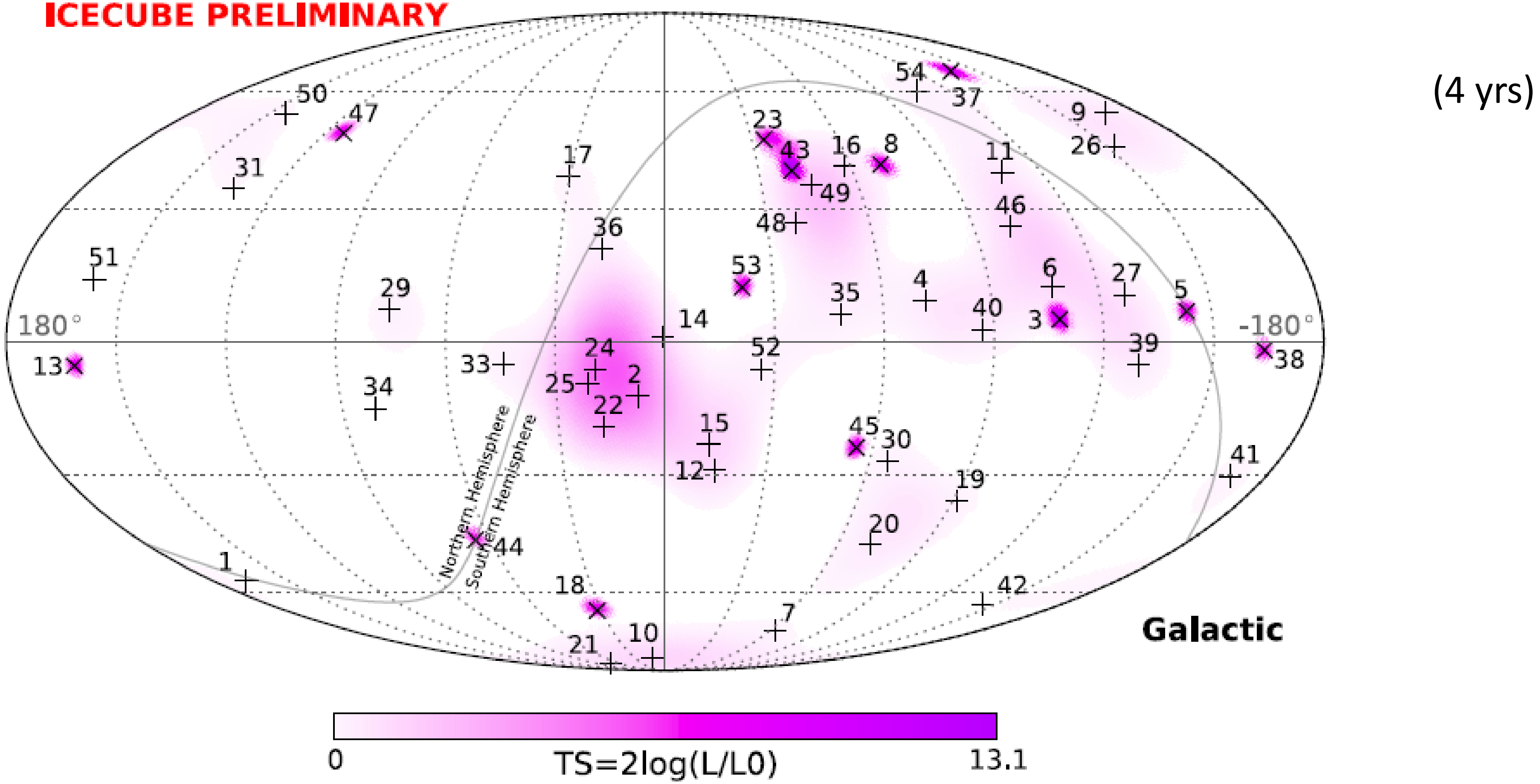




Diffuse γ (Fermi LAT)
IceCube (ApJ 2015)
Cosmic rays (Auger)
Cosmic rays (TA)
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
E [GeV]

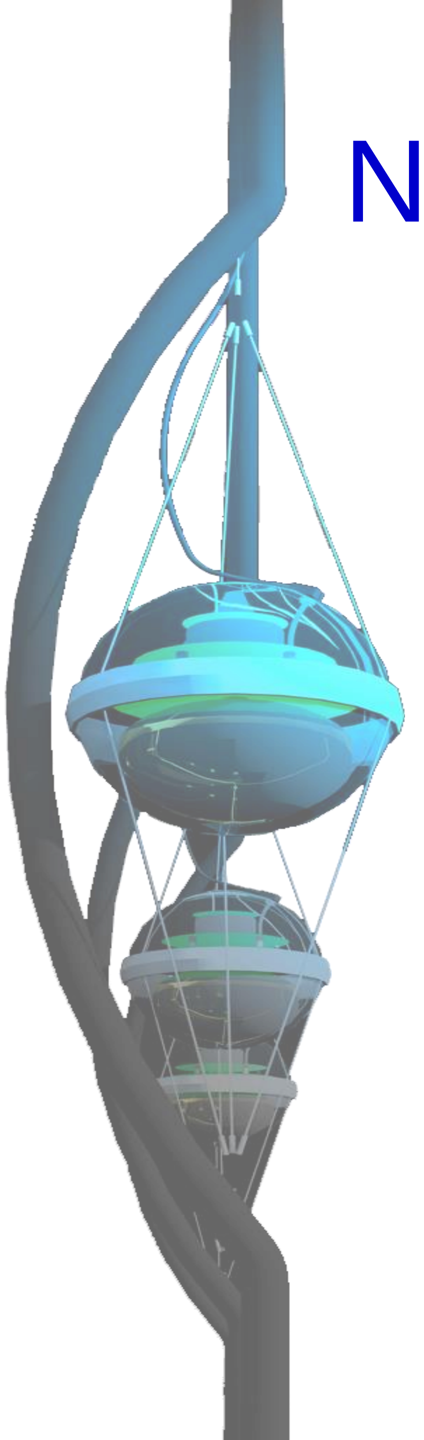
Point source analysis
No clustering observed in starting events

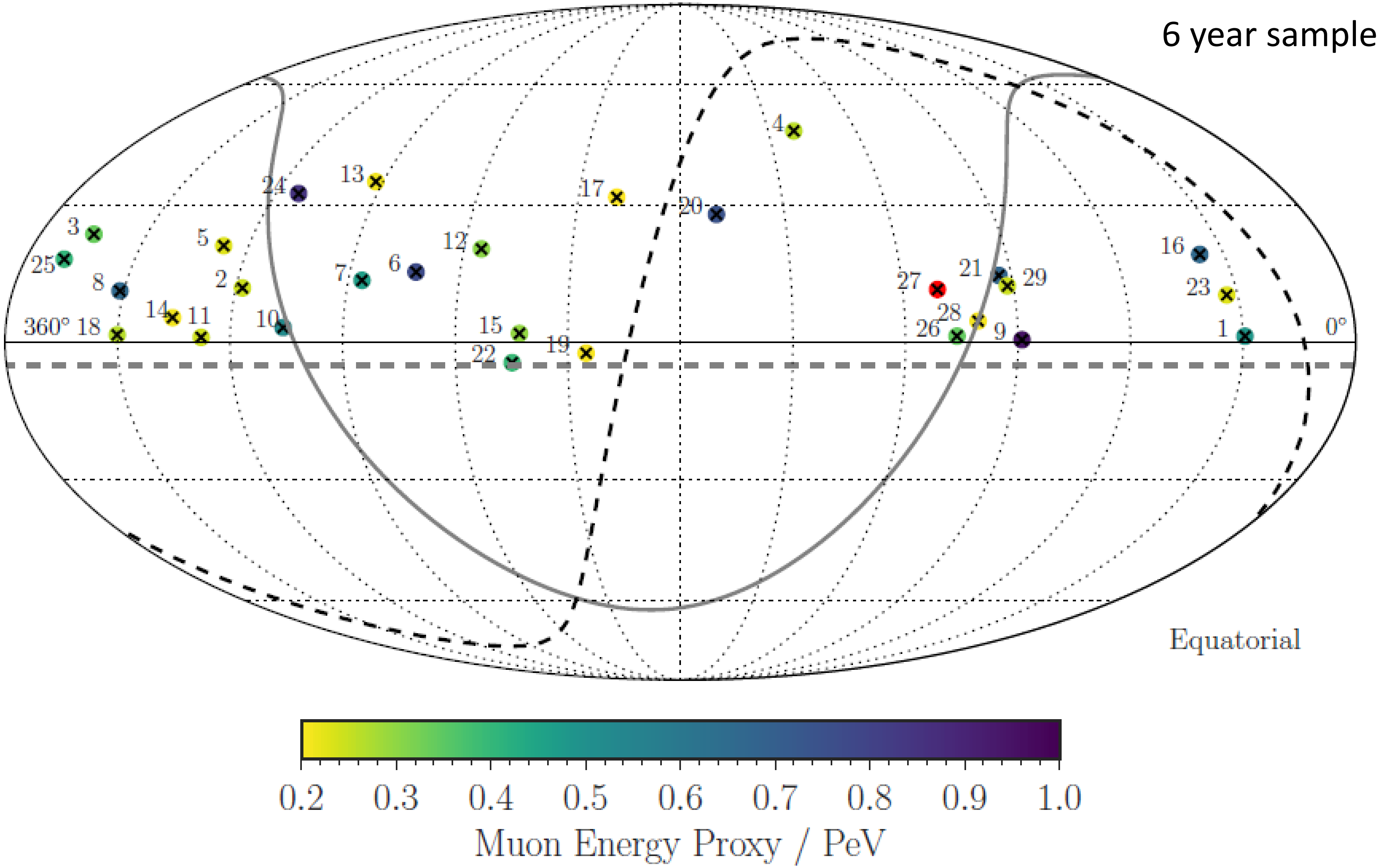


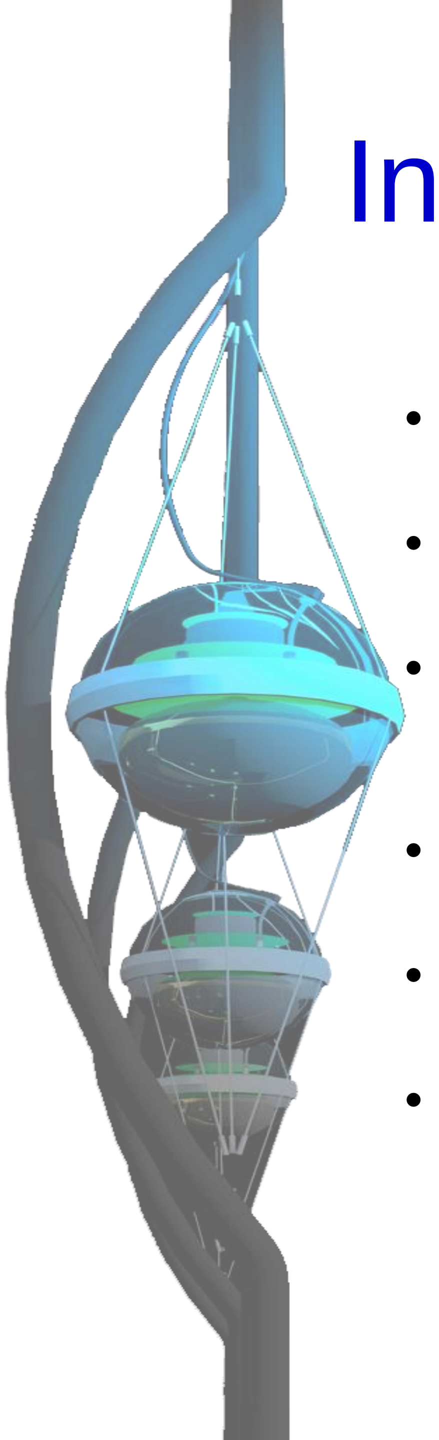


The most significant cluster p-value 58% with all events, 44% with shower events

Neither in upward-muon sample







Ingredient for point source analysis

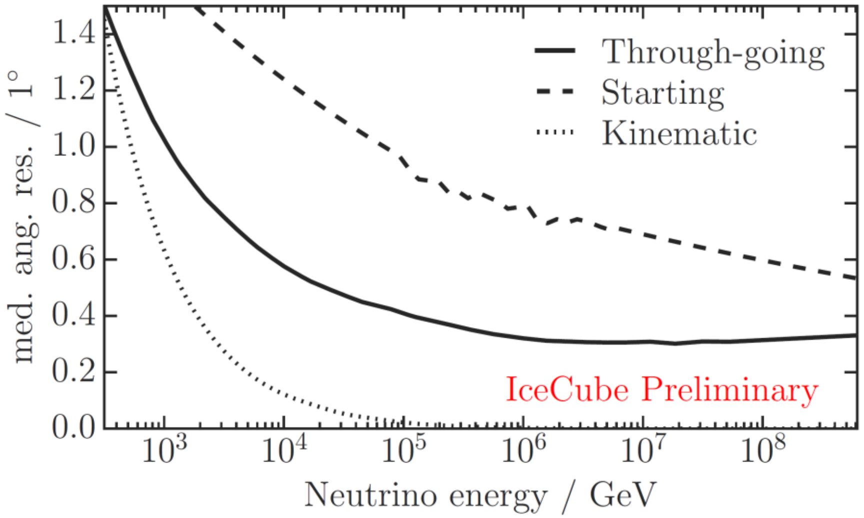
To improve point source sensitivity

- Livetime, detector size (cross section of detector in the direction to the object)
  - sqrt(N)
- Angular resolution
  - linear
- Background veto
  - Down BG: atm muons, UP BG: atm nu
  - Surface veto can reduce down muon BG from Southern sky
- Neutrino follow up for transient sources - Timing coincident BG cut
  - GRB
- Stacking of the “right” class of object
  - Hints from diffuse neutrinos, point source upperlimits and gamma-ray observations
- ***Multimessenger!!***
  - Trigger optical/x-ray/gamma-ray telescopes by neutrino for transient sources

Tracks: induced by ν_μ CC interaction

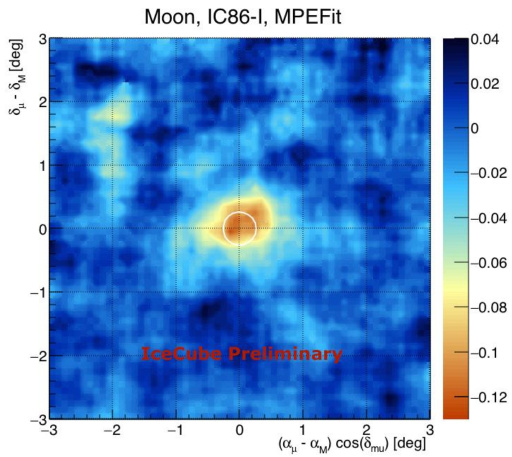
- angular resolution

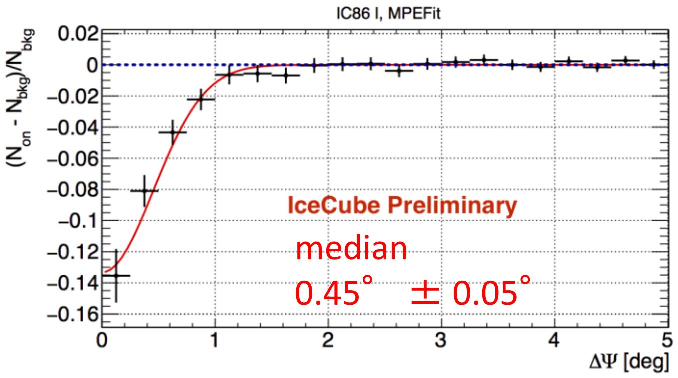
Median resolution: 0.5° at 100 TeV



- Moon shadow of cosmic ray muons using one year of data

(cosmic-ray primaries get absorbed in moon)

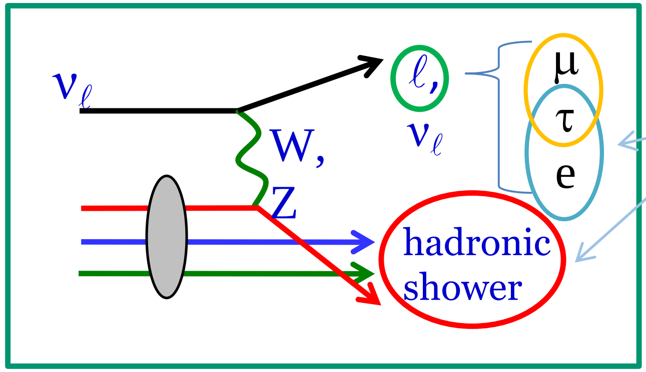


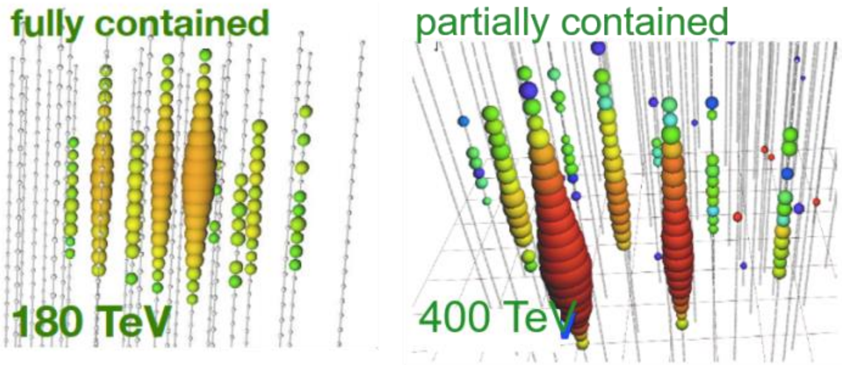


- Background dependent on the directions in the sky
  Southern sky: High energy atm muon BG (Signal PeV-EeV)
  Northern sky: Atm neutrino BG (signal TeV-PeV)

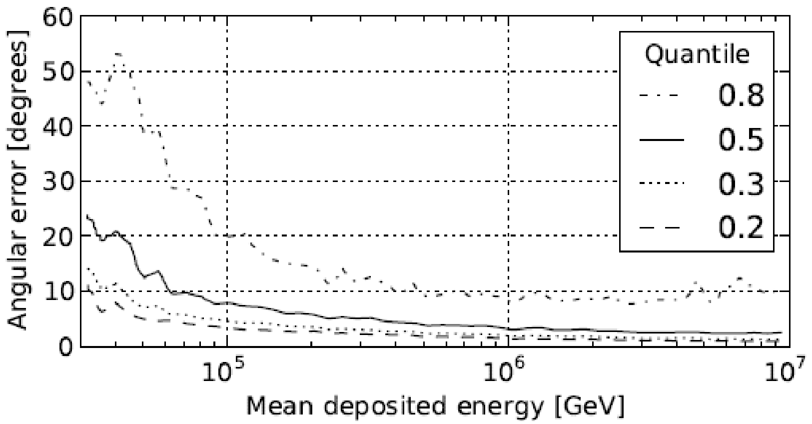
- Large energy resolution for through going-muon as muon loose energy before reaching IceCube
  - Δlog(E)~0.3 for muon energy deposit to muon energy

Cascade: particle showers





- Good energy resolution of ~10%
- Directional resolution is ~10°
- Sensitive to full sky
- Less atmospheric neutrino background
    - atm muons are reduced by their topology
    - turn over energy from BG to signal is lower; sensitive to lower energy region (10TeV – 100TeV)
      (upward muon channel sensitive above ~100TeV)



Source candidates

Need

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

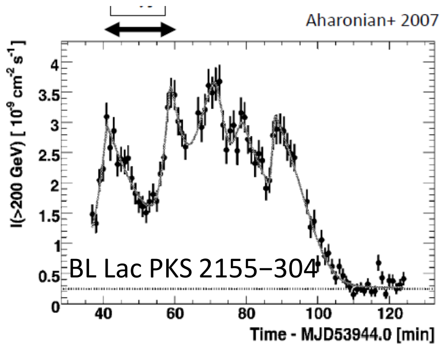
$$E_p E_\gamma \sim \frac{m_\Delta^2 - m_p^2}{2}\left(\frac{\Gamma}{1+z}\right)^2 = 0.147\ \mathrm{GeV}^2\left(\frac{\Gamma}{1+z}\right)^2$$

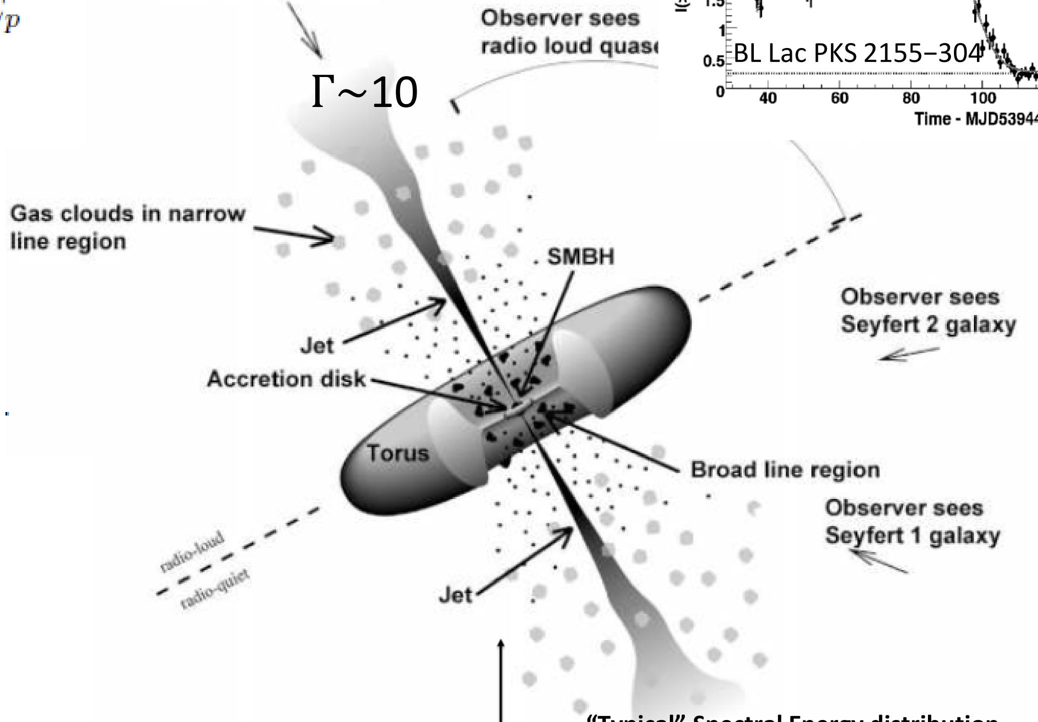
$$E_\nu \simeq 0.05 E_p$$

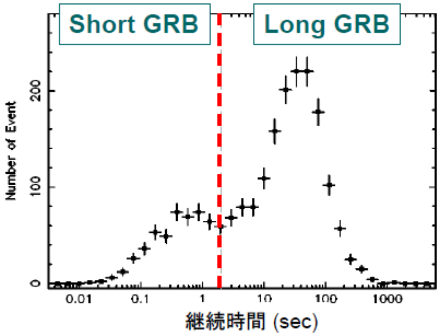
GRB and AGNs

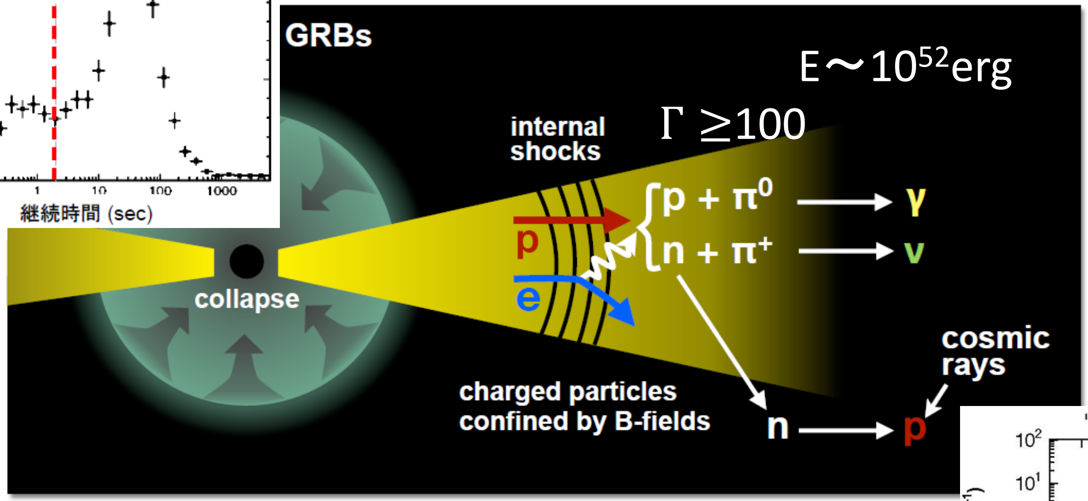
- Candidate sources exhibits rapid time variation!

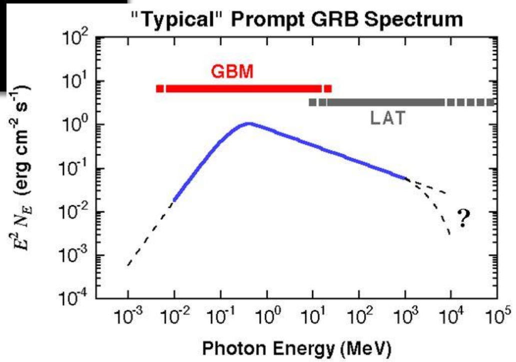
min to year time variability

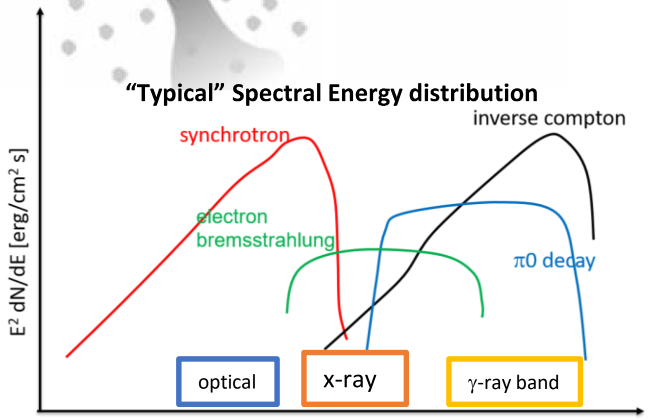












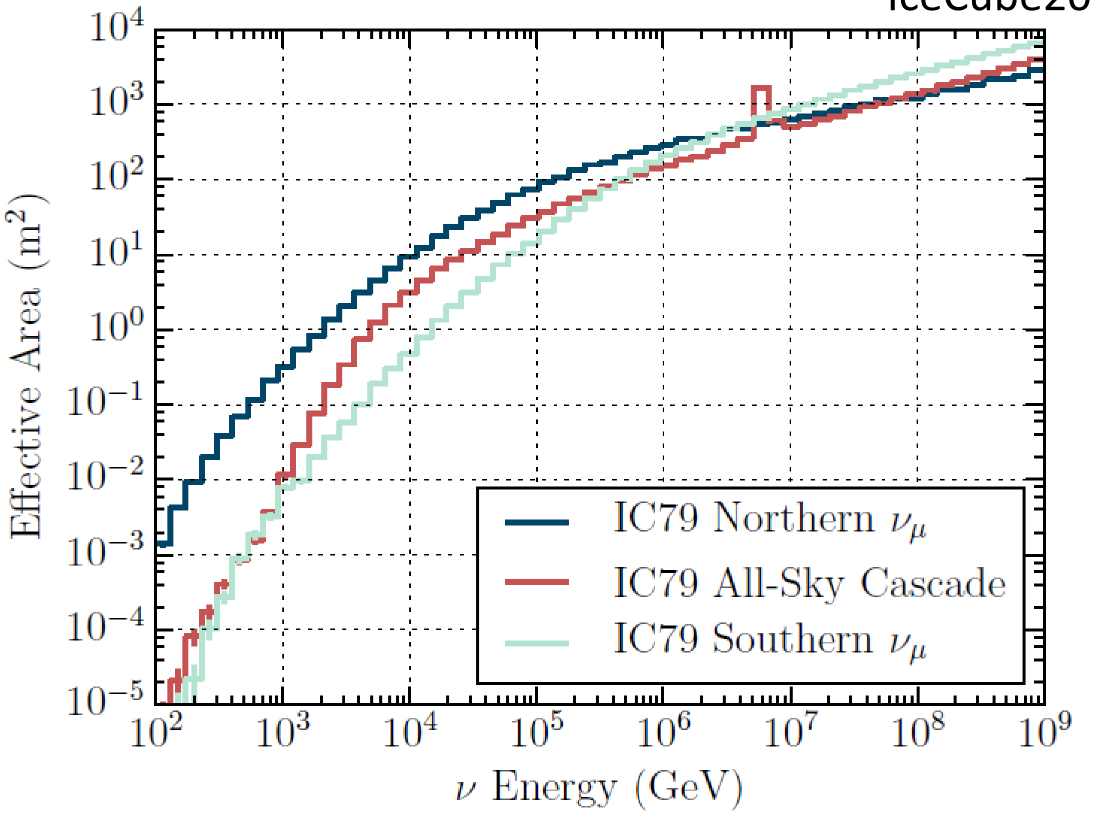
GRB-correlated neutrino Search

1172 gamma-ray bursts (IceCube 2017, arXive:1702.06868) + 506 GRBs previously analyzed from GCN and the Fermi GBM database

Searched temporally and directionally

- coincident tracks with
  - Southern Hemisphere GRB in May 2010 and May 2015 (5 yrs sample)
  - Northern Hemisphere GRB in May 2008 and May 2015 (7 yrs sample)
- coincident cascade with
  - All sky GRBs between May 2010 and May 2013 (3 yrs sample)

IceCube2017



Model Dependent Constraints

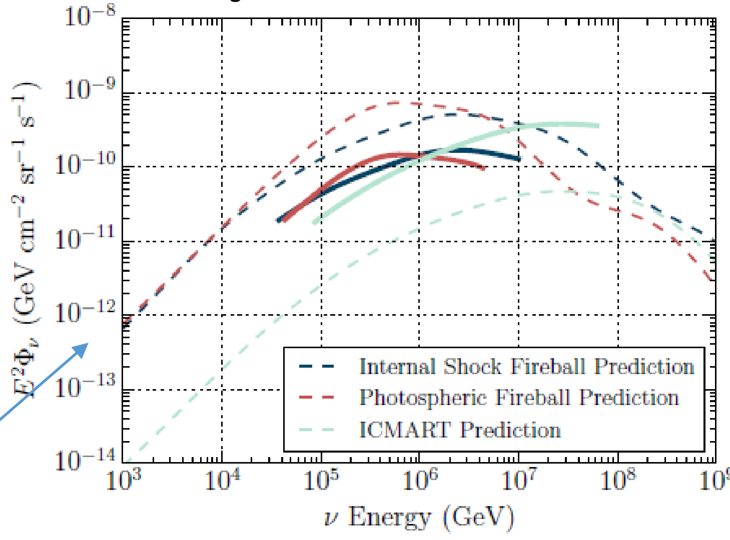
No significant correlation yield tighter constraints on model predictions

Zhang+13

- internal shock model - radius R_{IS} where protons are accelerated and the radius R_γ where gamma ray photons are generated are the same
- photosphere model - $R_{IS} > R_\gamma$
- ICMART model (internal collision-induced magnetic reconnection and turbulence) $R_{IS} < R_\gamma$

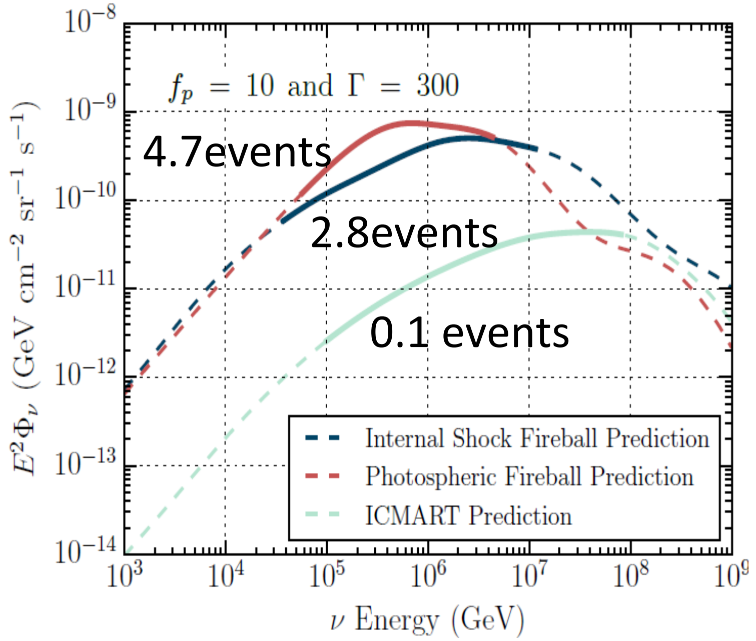
Only single zone models – multiple emission region model predict flux lower than IceCube sensitivity

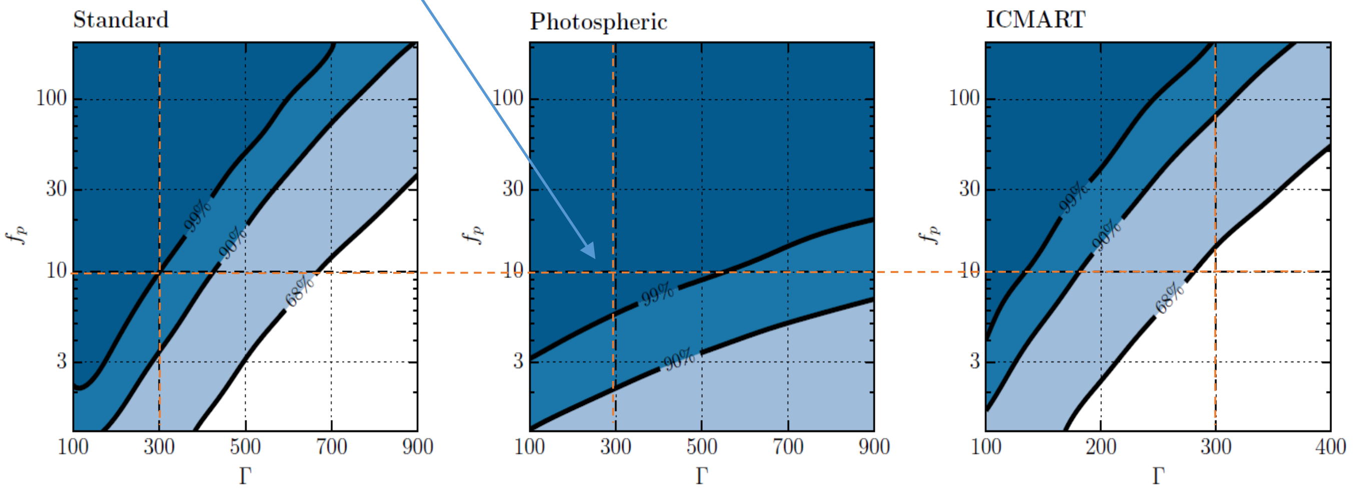
Combining all channels, 6.5, 11.0 and 0.3 events



Benchmark model

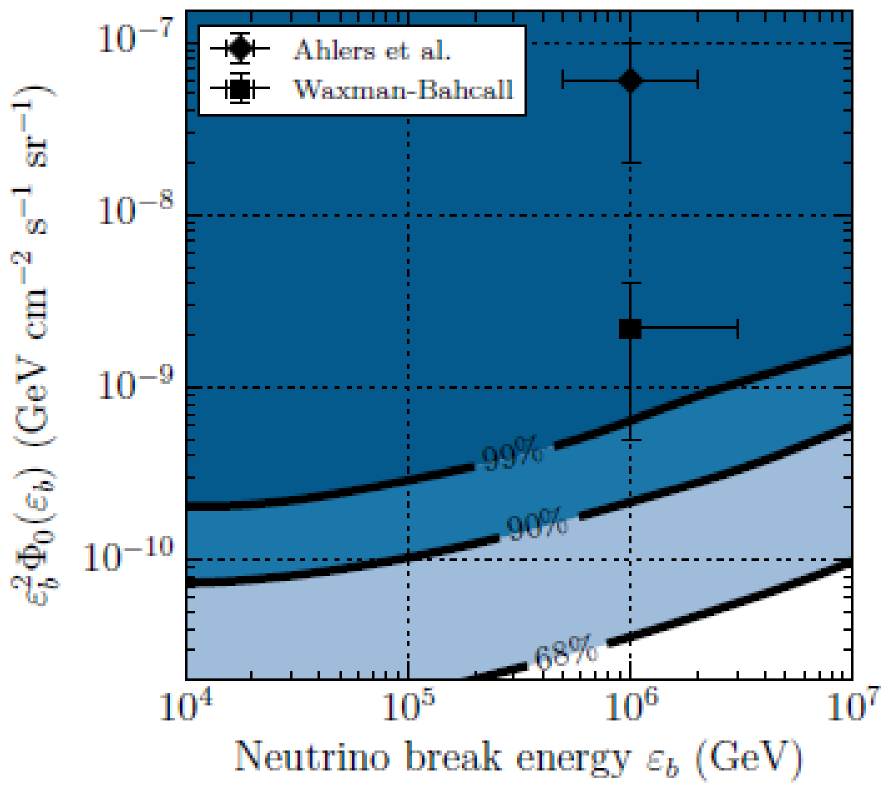
$f_p = 10$ and $\Gamma = 300$





IceCube2017

Model Independent Constraints



IceCube2017

Generic broken power-law spectra

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

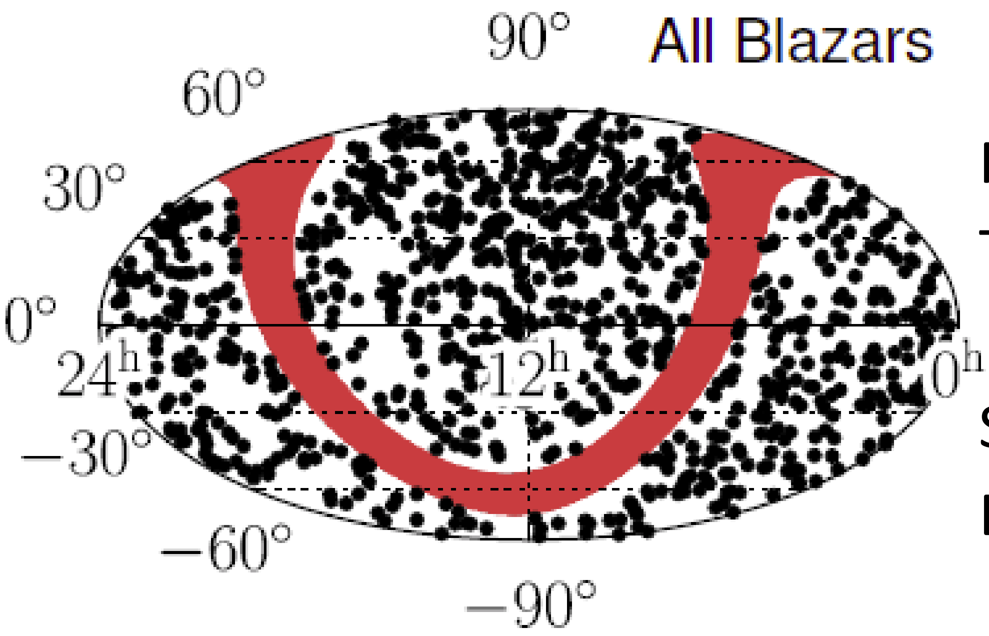
- More than a factor of 4 improved limits since 2013 nature
- Constrained model predictions normalized to the observed ultra-high energy cosmic ray flux (10^44 $^{erg}/_{Mpc^3\,yr}$)

GRBs contribute no more than 0.4% of the observed diffuse flux

blazar stacking analysis

ApJ vol. 835, no. 1, p. 45 (2017)

Neutrinos from Fermi 2LAC 862 blazar directions

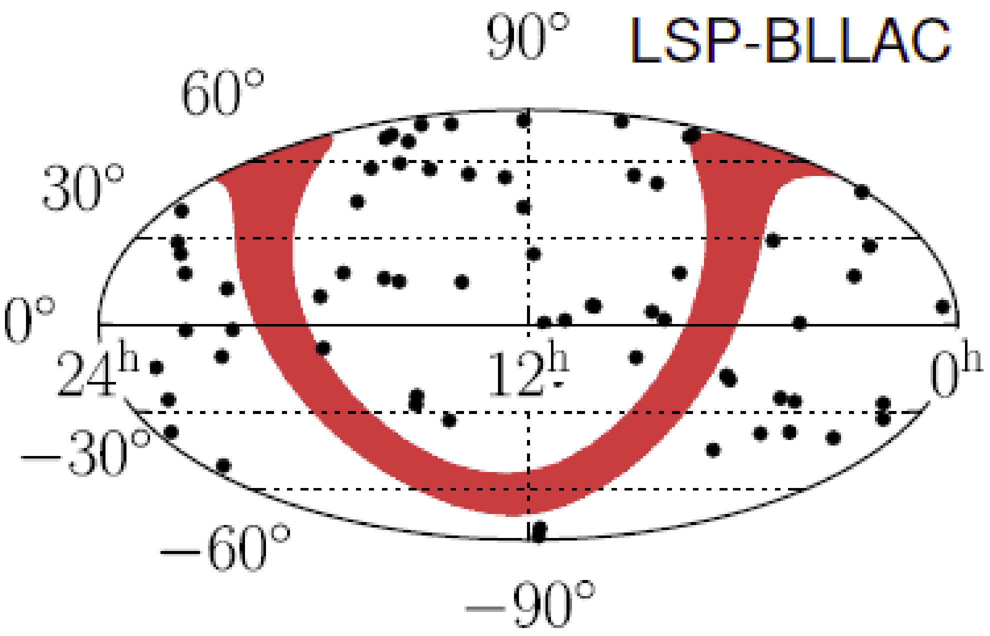


Northern sky:

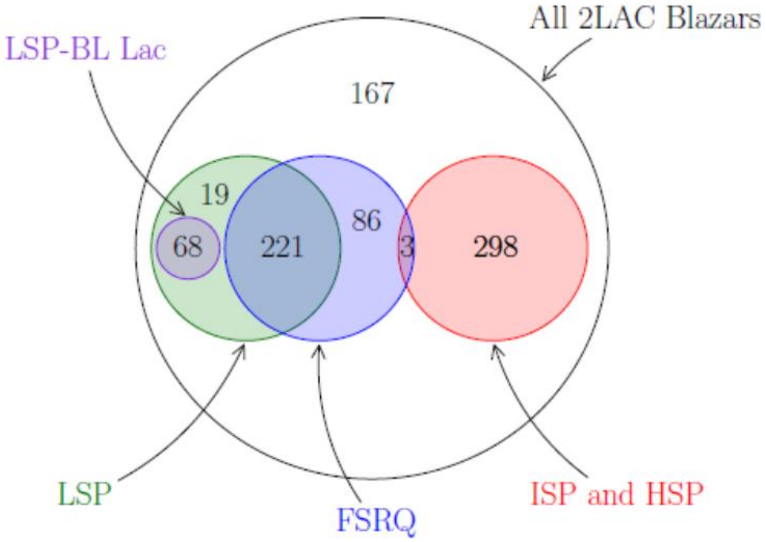
TeV < E_n < PeV

Southern sky:

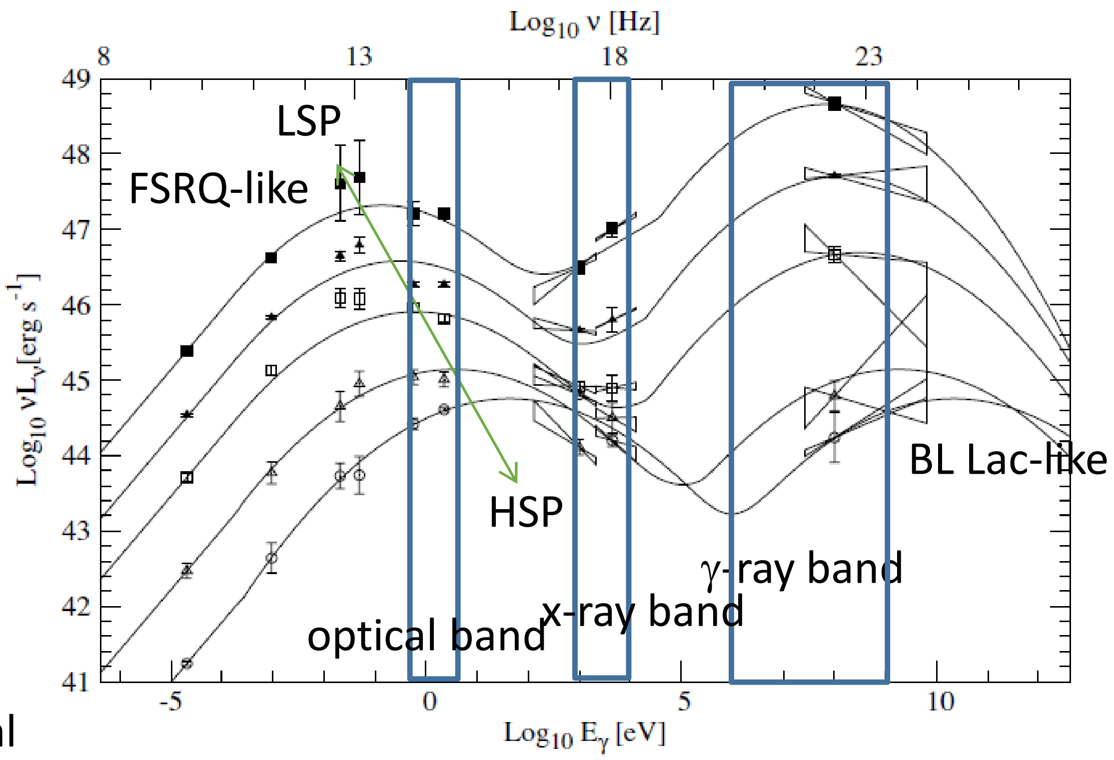
E_n>PeV



2LAC blazar 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

Require: the total # of observed to be the sum of the signal and background events

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

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 data

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

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

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

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

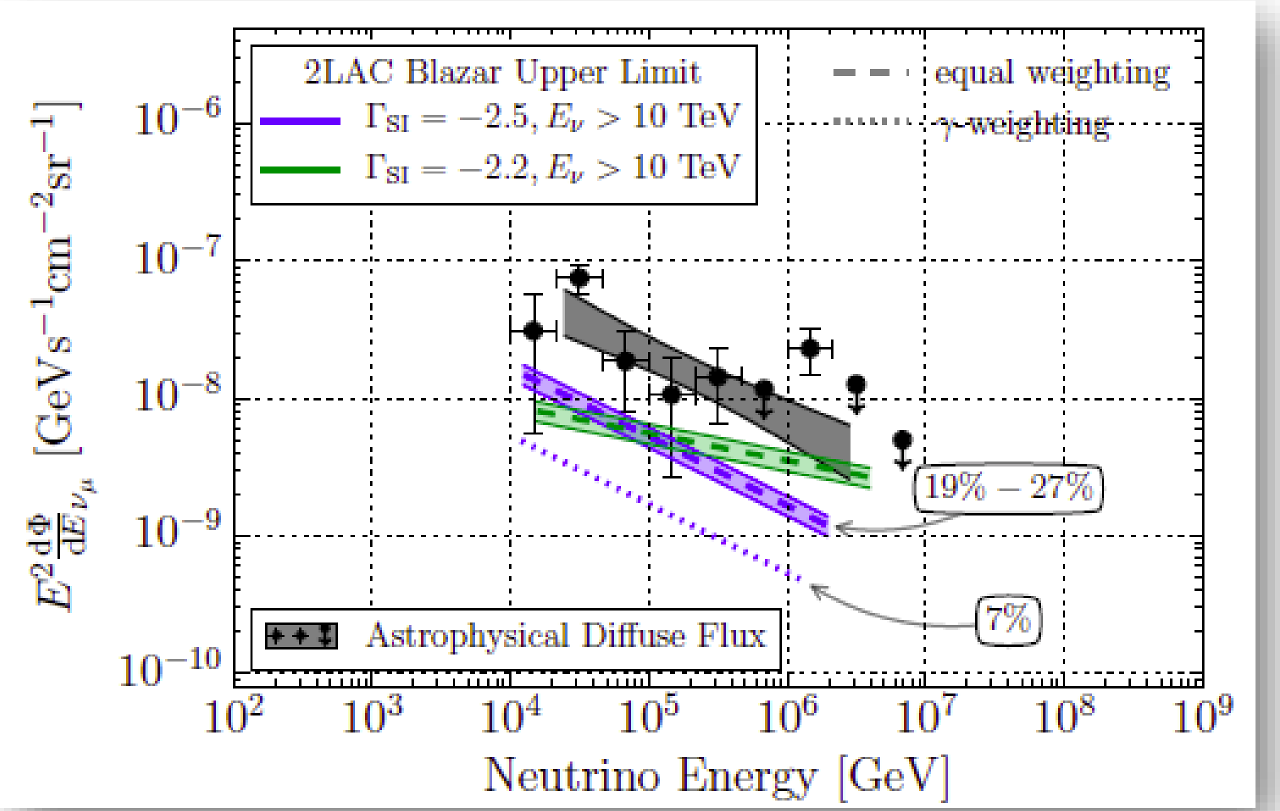
Results: Limits on the blazar contribution

UL on E^{-2} flux

Spectrum: $\Phi_0 \cdot (E/\mathrm{GeV})^{-2.0}$		
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)

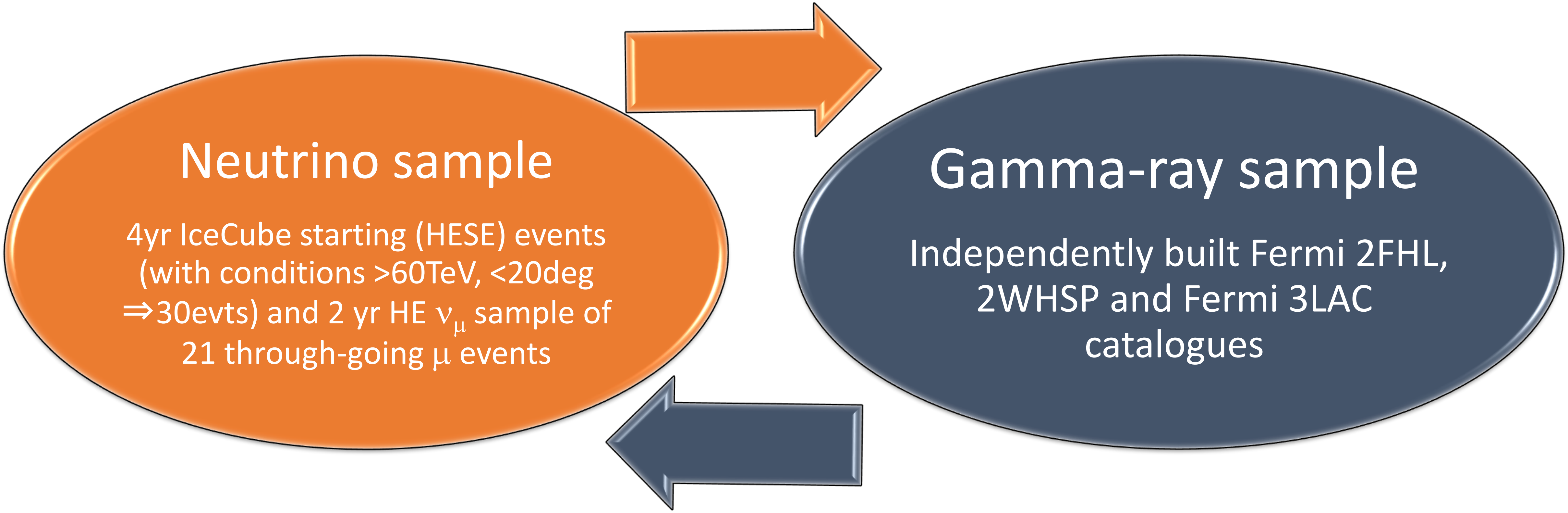


Contribution of the total 2LAC blazar sample to the astrophysical neutrino flux

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

blazar-ν correlation search

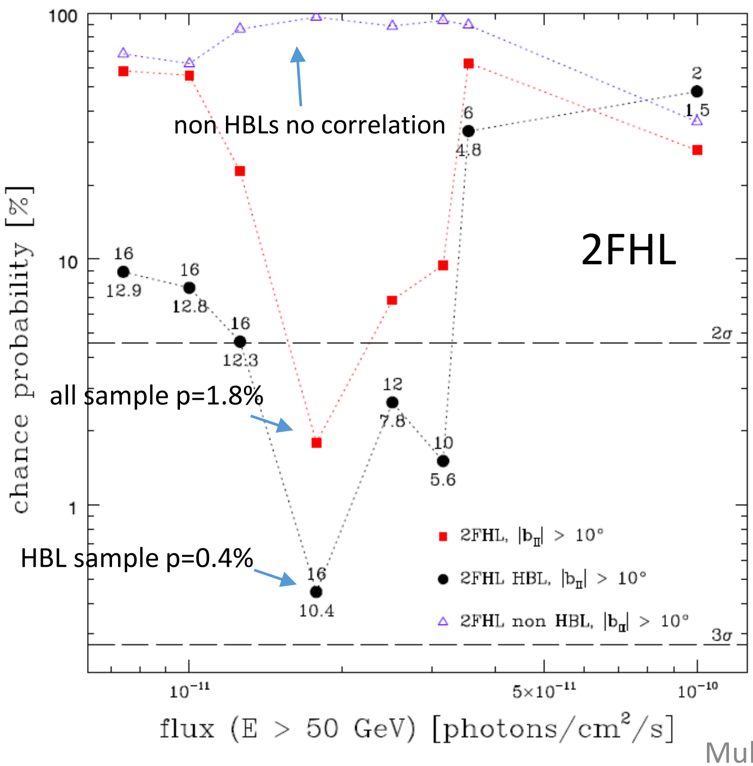
MNRAS 457 (2016) Padovani



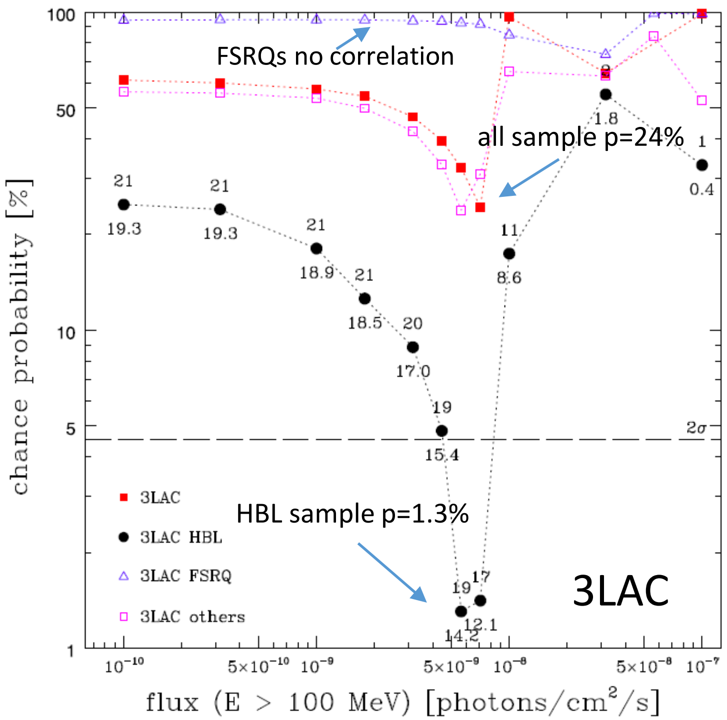
Neutrino events with γ-ray counterparts

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

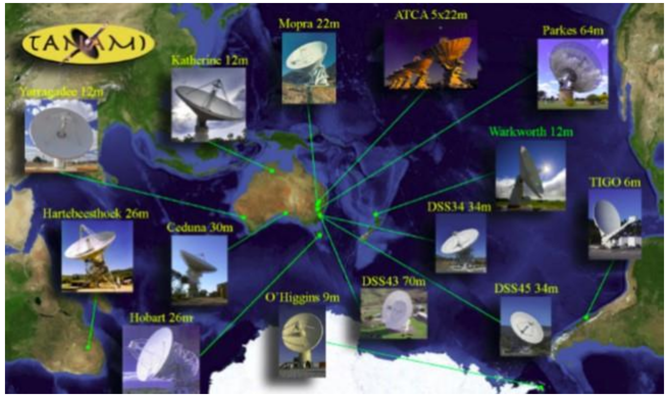


- Correlation of High synchrotron peaked BLLacs with p-value of 0.4-1.3%



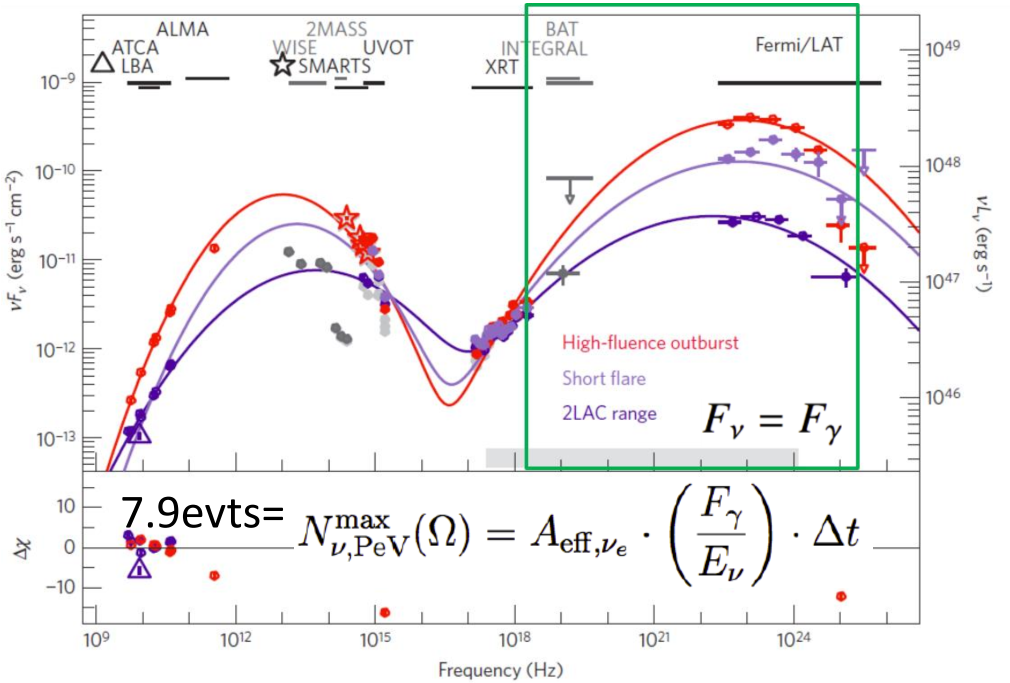
Coincidence of a high-fluence blazar

M. Kadler et al Nature Phys (2016)

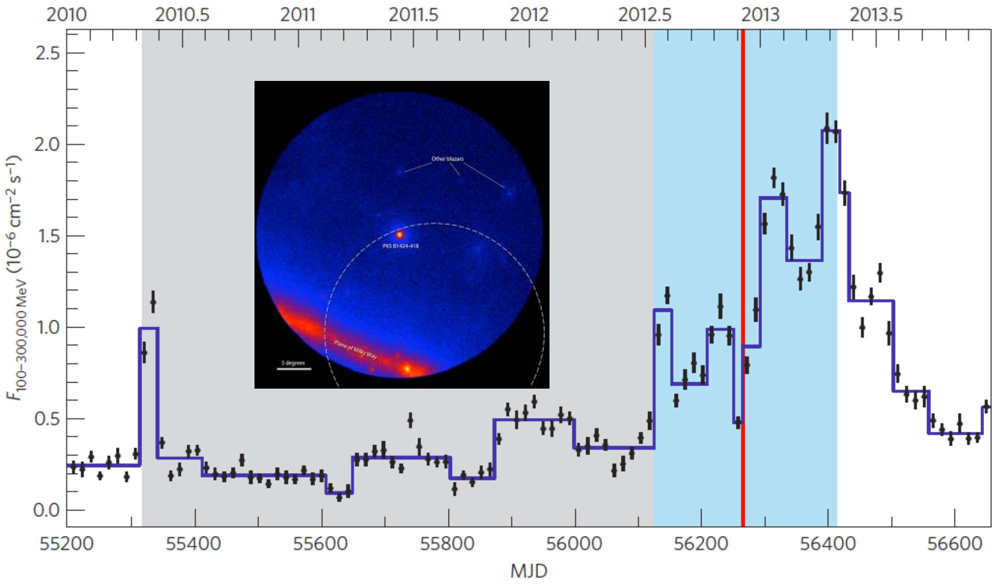


TANAMI – Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry – **is a multiwavelength program that monitors extragalactic jets of the Southern Sky (δ < −30°)**

- 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%



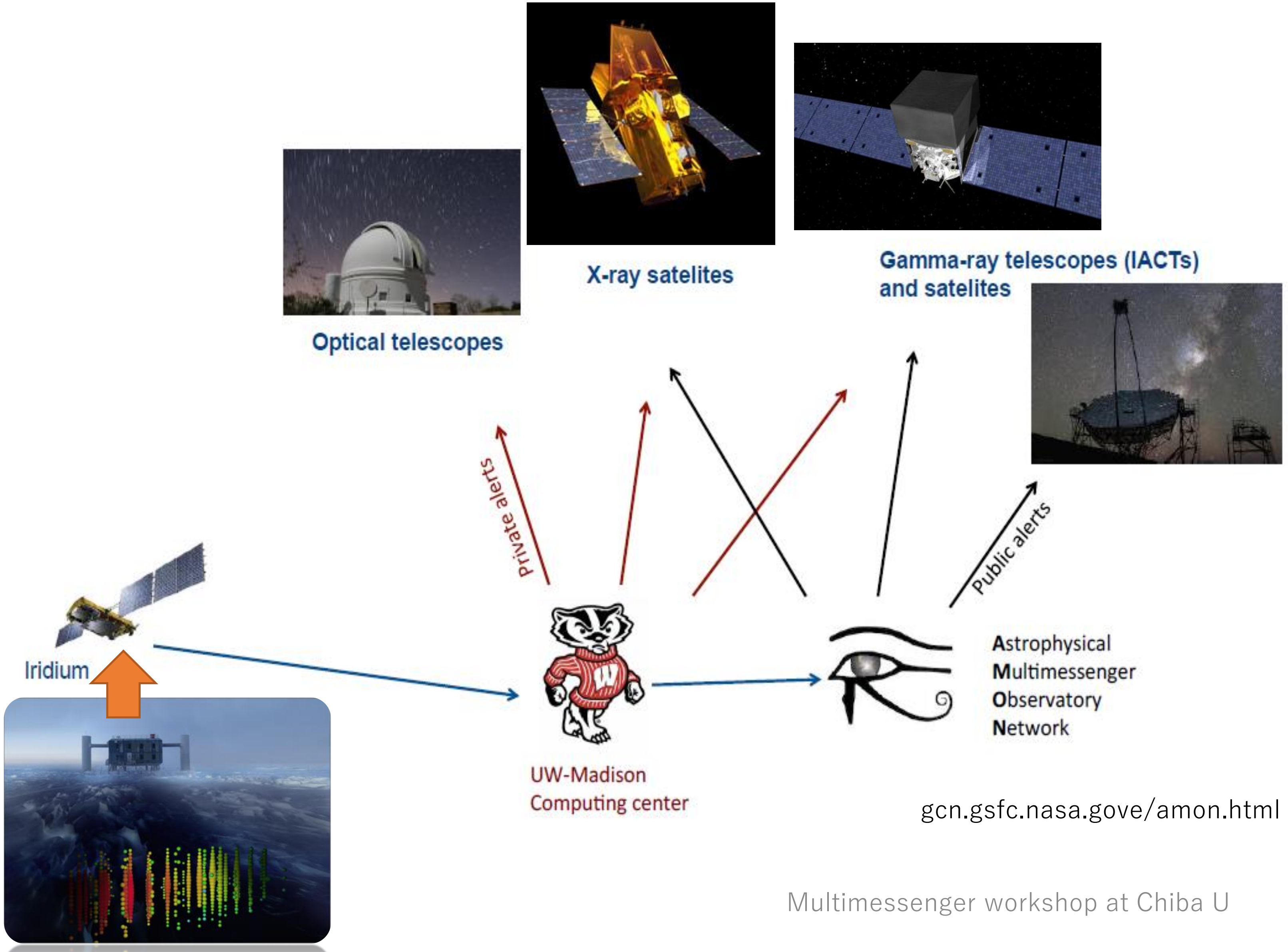
7.9evts= $N^{\max}_{\nu,\mathrm{PeV}}(\Omega) = A_{\mathrm{eff},\nu_e} \cdot \left(\frac{F_\gamma}{E_\nu}\right) \cdot \Delta t$



ANTARES did not find events from PKS B1424-418

IceCube’s followup program overview

Depending on the source classes, most accessible wavelength differs



gcn.gsfc.nasa.gove/amon.html

<u>IceCube public event alert</u>

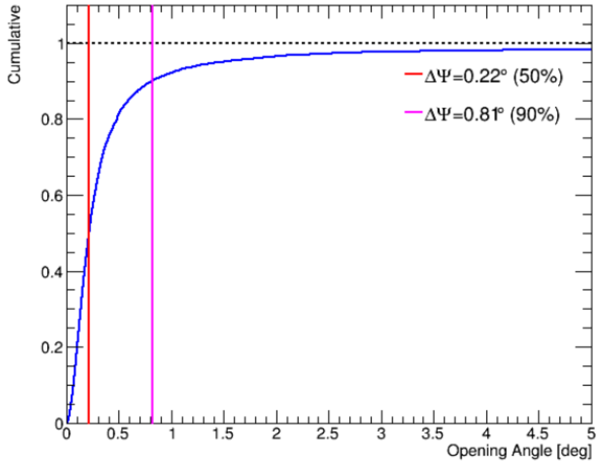
- HESE/EHE Public Events
  - General purpose high signal/noise sample
  - GCN alerts to the follow-up observatories via AMON

<u>Target of Opportunity Program</u>
(private alert)

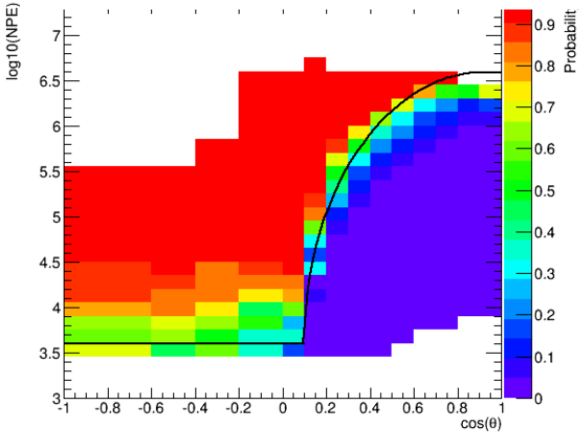
- Multiplet
  - GFU - gamma by imaging atmospheric-Cherenkov telescopes, longer time scale upto 3weeks
  - OFU - optical and x-ray searching time scale upto 100s

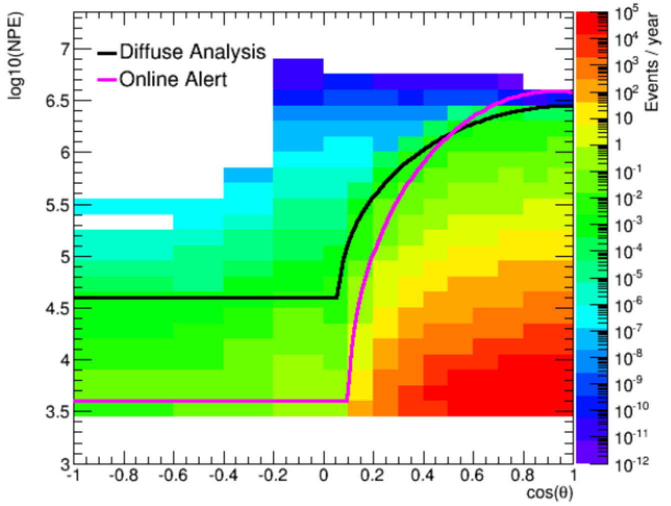
Extremly High Energy (EHE) through going muon track

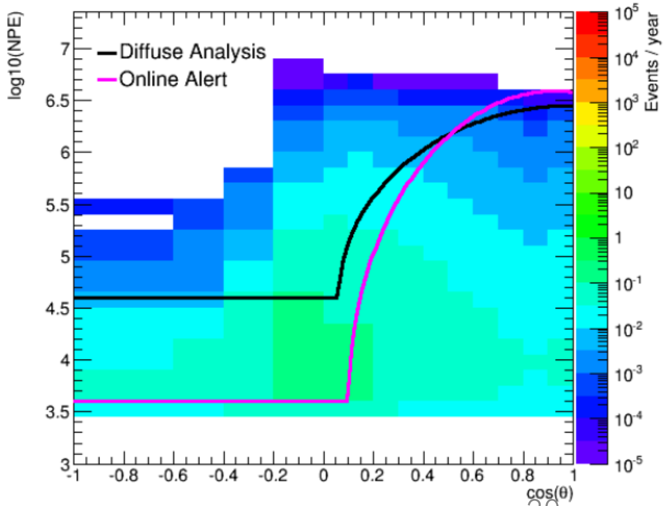
- Targets > PeV
- Simple detected **photo-electron number threshold** taking the advantage of effectively no background in the highest energy region - as the first hints for the cosmic neutrinos
- Modified for alert to select PeV **track** events
- 2.5-4.1 signal events/yr from $E^{-2.49}$ and E^{-2} flux with 1.9 BG events/yr



$$P_{i,j} = N^{sig}_{i,j}/(N^{sig}_{i,j}+N^{bkg}_{i,j}),$$



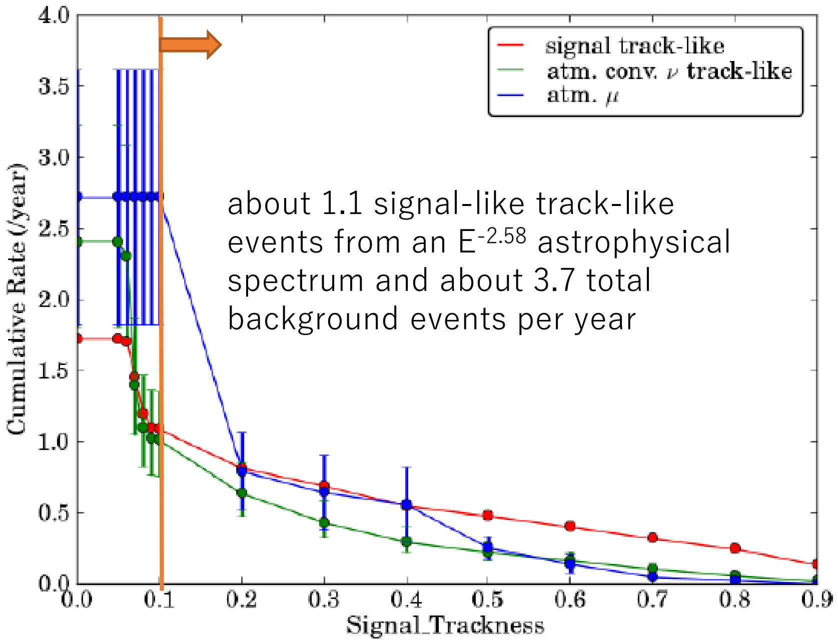


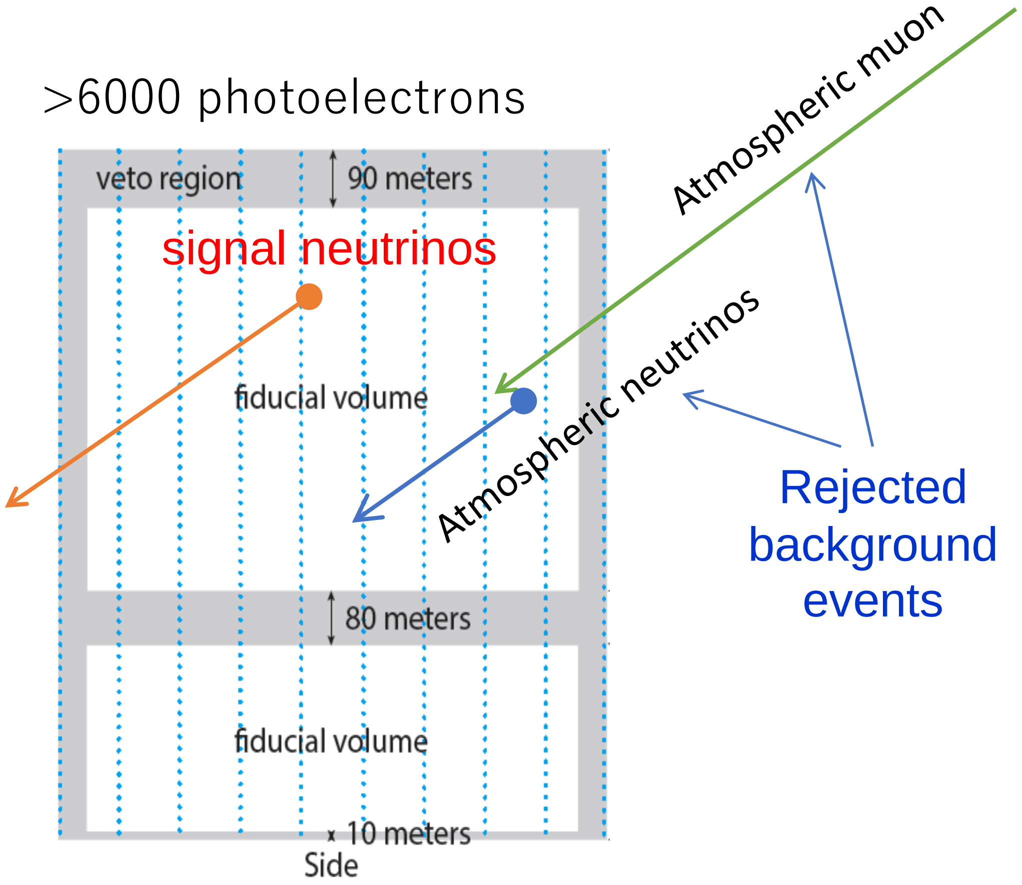


High energy starting muon event

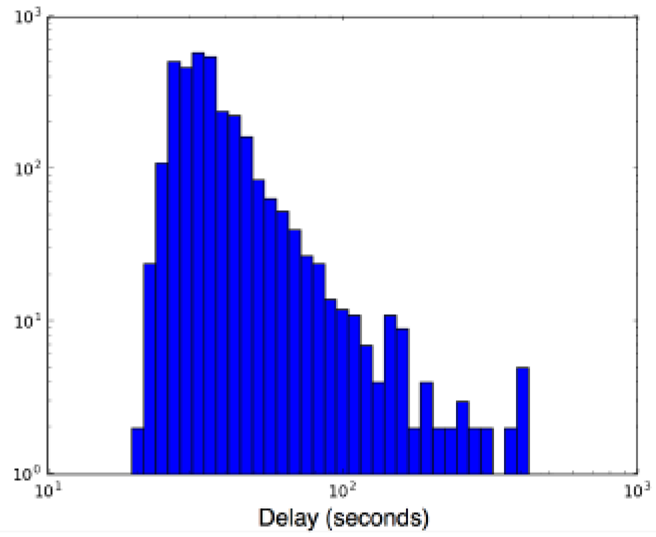
- HESE channel dominates cascade events – only send alert with a higher trackness

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





2016 Public Alerts

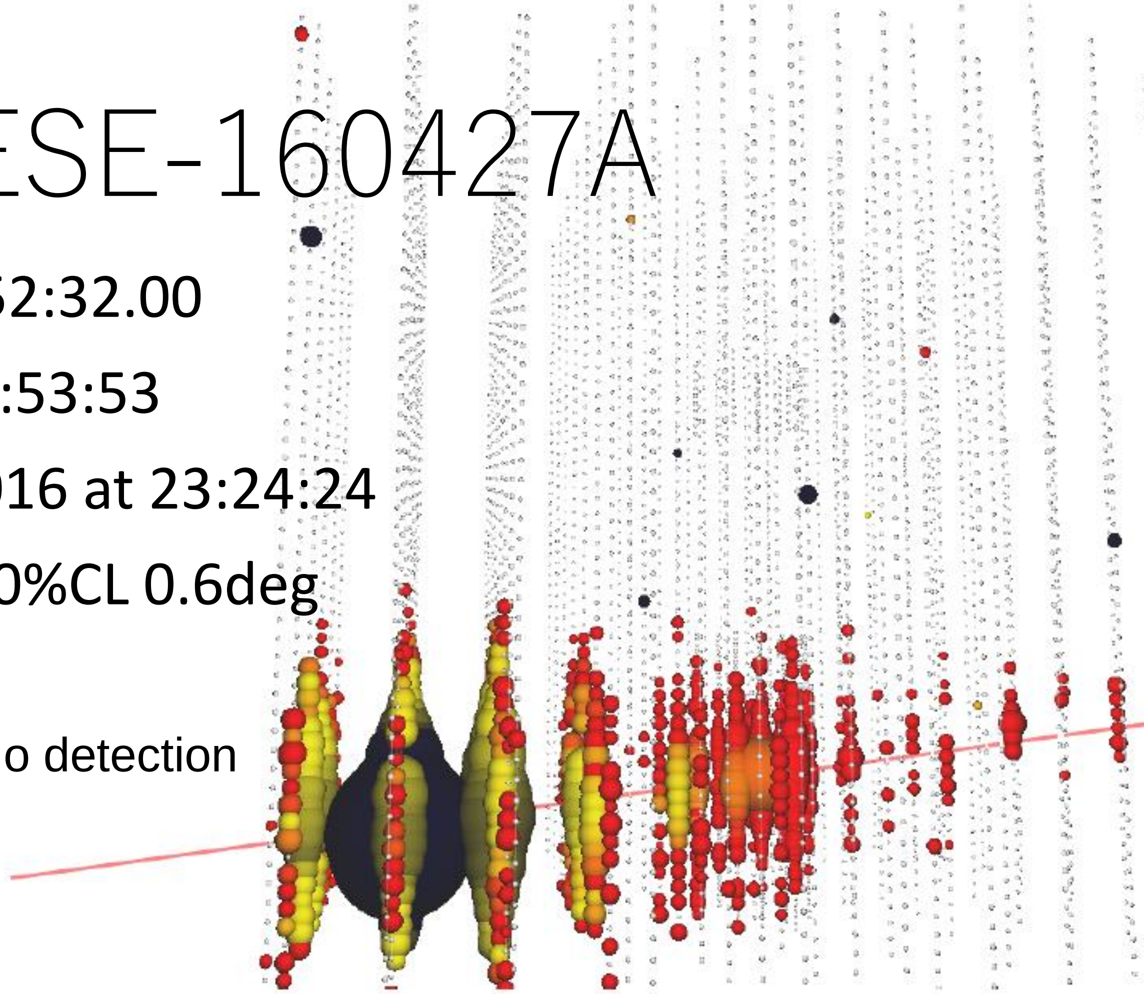


AMON ICECUBE_EHE EVENTS – Since June 2016 archived at https://gcn.gsfc.nasa.gov/amon_ehe_events.html							
EVENT			OBSERVATION				
EventNum_RunNum	Date	Time UT	NoticeType	RA	Dec	Error	**Signalness**
80127519_128906	16/12/10	20:06:40.31	EHE	46.5799	+14.9800	60.00	**0.49023**
26552458_128311	16/08/06	12:21:33.00	EHE	122.7980	-0.7331	6.67	**0.28016**
6888376_128290	16/07/31	01:55:04.00	EHE	214.5440	-0.3347	20.99	**0.84879**

same event

AMON ICECUBE_HESE EVENTS – Since April 2016 archived at https://gcn.gsfc.nasa.gov/amon_hese_events.html								
EVENT	OBSERVATION							
EventNum_RunNum	Date	Time UT	NoticeType	RA	Dec	Error	Charge	**SignalTr**
38561326_128672	16/11/03	09:07:31.12	HESE	40.8252	+12.5592	66.00	7546.05	**0.30**
58537957_128340	16/08/14	21:45:54.00	HESE	199.3100	-32.0165	89.39	10431.02	**0.12**
6888376_128290	16/07/31	01:55:04.00	HESE	215.1090	-0.4581	73.79	15814.74	**0.91**
67093193_127853	16/04/27	05:52:32.00	HESE	240.5683	+9.3417	35.99	18883.62	**0.92**

The first GCN notice: HESE-160427A



- Event occurred at Wed 27th April 2016 at 05:52:32.00
- First notice sent on Wed 27th April 2016 at 05:53:53
- Revised coordinates sent at Wed 27th April 2016 at 23:24:24
- Event direction RA 16.04deg, Dec 9.34 deg, 90%CL 0.6deg
- Follow-up responses
  - GCN 19364 - Fermi Gamma-Ray Burst Monitor - No detection
  - GCN 19360 - Fermi LAT – 5 unrelated blazars
  - GCN 19361 - HAWK – no detection
  - GCN 19362 - MASTER – no detection
  - GCN 19377 - VERITAS – no detection
  - GCN 19392 - iPalomar Transient Factory – 3 transients, all AGN
  - GCN 19427 - FACT Cherenkov TeV Telescope – no detection
  - GCN 19426 - Interplanetary Network – no detection
  - GCN 19381 – Pan-STARRS 6 SN candidates. The most interesting object is PS16cgx which is consistent with type Ic supernova at z 0.1-0.2 exploded on/around April 27.2

The multiplet event alert

Event sample: High quality muon track events

Rejecting BG events based on a multivariate classifier

- mis-reconstructed events
- down-going atmospheric muons for Northern sky (a bit tighter cut for GFU than OFU)
- low energy atmospheric muons for Southern sky (GFU only)

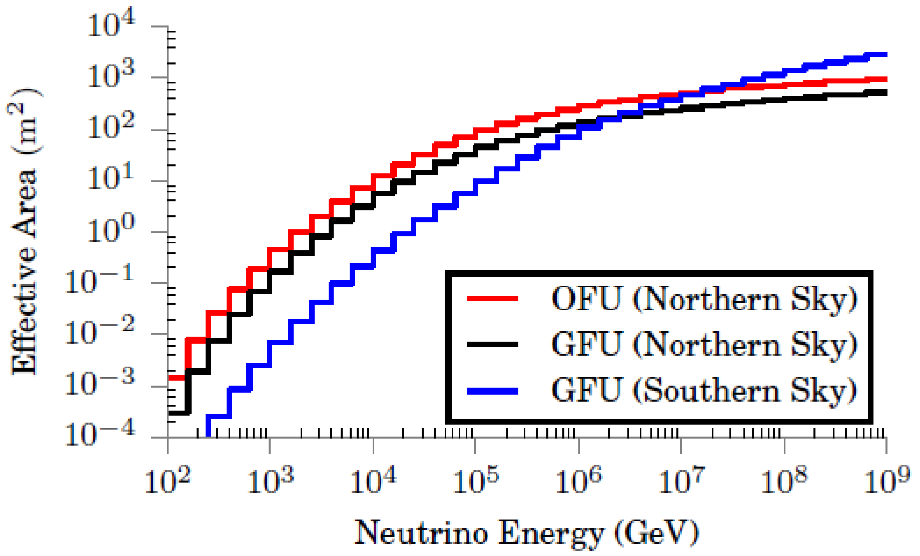
Making multiplets

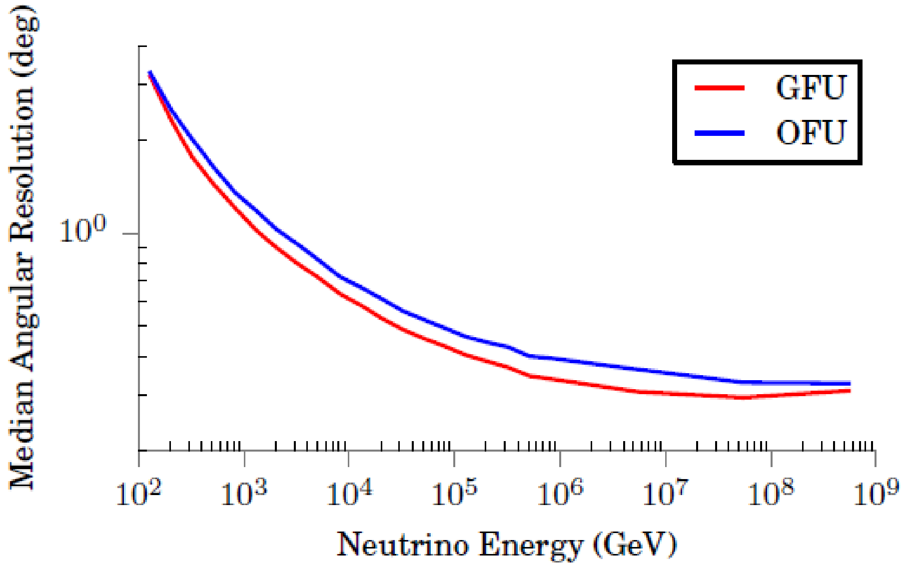
OFU

- multiple (≥2) neutrino events within 100s an angular difference of ≤3.5°
- Quality parameter $\lambda = \frac{\Delta\Psi^2}{\sigma_q^2} + 2\ln(2\pi\sigma_q^2) - 2\ln\left(1 - \exp\left(-\frac{\theta_A^2}{\sigma_w^2}\right)\right) + 2\ln\left(\frac{\Delta T}{100s}\right)$
- triplet or more automatically sent

GFU

- Each event detected at time t_i, define a time window $\Delta t_{ij} = t_i - t_j (t_j < t_i)$ to get the expected background N_{BG}^{ij} using randomized data and the observed N_{SIG}^{ij}.
- Poisson probability of observing N_{SIG}^{ij} or larger multiplet with given expected background N_{BG}^{ij} is a quality parameter





Optical (x-ray) Follow-up Program

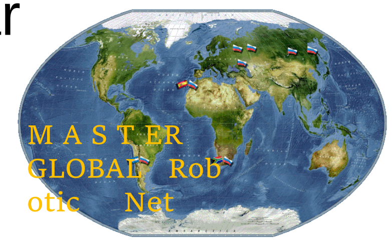
Have been in operation since 2008

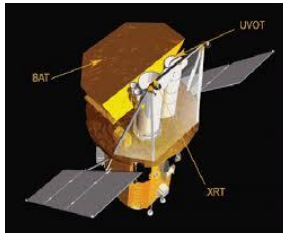
Targets

- GRB, core-collapse supernovae (SNe), GRB afterglow or the rising SN light curve
- Less than 1 minute

Alerts are sent to (with different alert quality threshold, all >90% BG):

- the Robotic Optical Transient Search Experiment (ROSTE, from 2008, now decommissioned) was ～25 alerts/year
- Palomar Transient Factory (since 2010) ～7 alerts/year
- Swift-XRT for X-ray follow-up (since 2011) ～3 alerts/year
- MASTER (since 2016) ～7 alerts/year
- ASAS-SN (to come soon)
- LCOGT (to come soon)

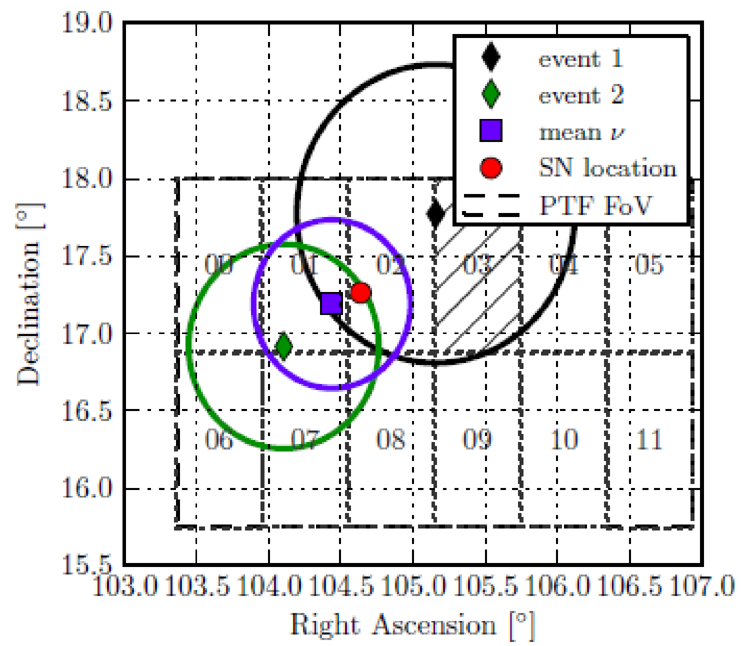




The OFU most significant alerts

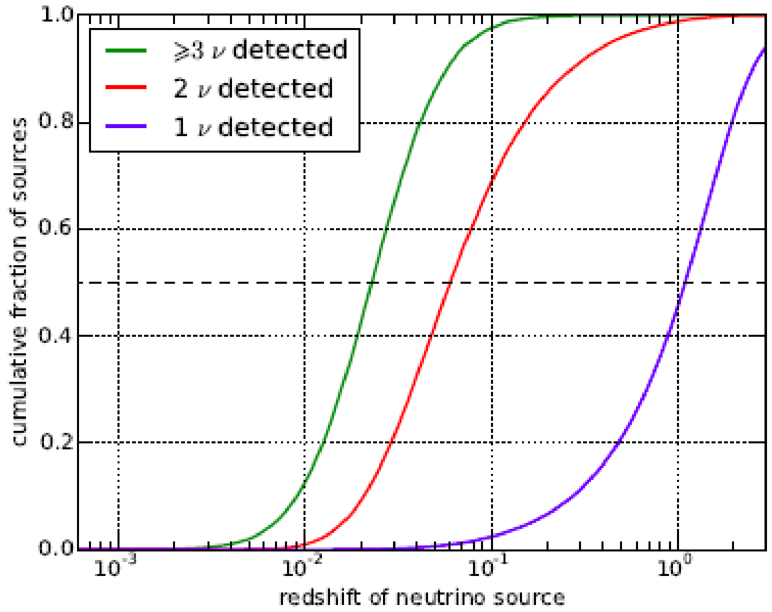
arXive:1506.03115

- In March 2012, the most significant alert during the first 3yrs OFU program was issued
- PTF followed up, a Type IIn supernova PTF12csy was found 0.2deg away from the neutrino alert direction.
- The supernova has a redshift of z = 0.0684, corresponding to a luminosity distance of about 300 Mpc
- Pan-STARRS1 survey shows that its explosion time was at least 158 days (in the host-galaxy rest frame) before the neutrino alert, implying that a causal connection is unlikely



arXive:1702.06131

- In February 2016, the first and only triplet alert to date was issued
- Expected background cumulative rate of this type of alert is 0.38 since 2008 to the alert time of 2012



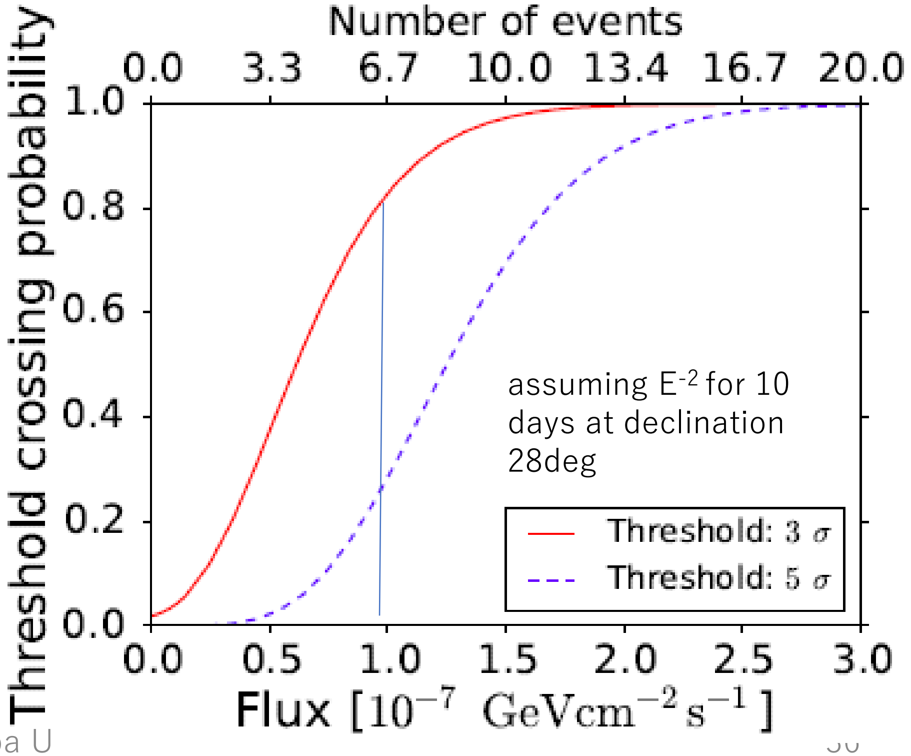
Gamma-ray Follow up Program

Searches for an excess of neutrino events on time scale of **up to 3 weeks** around sources from **a predefined source catalog**

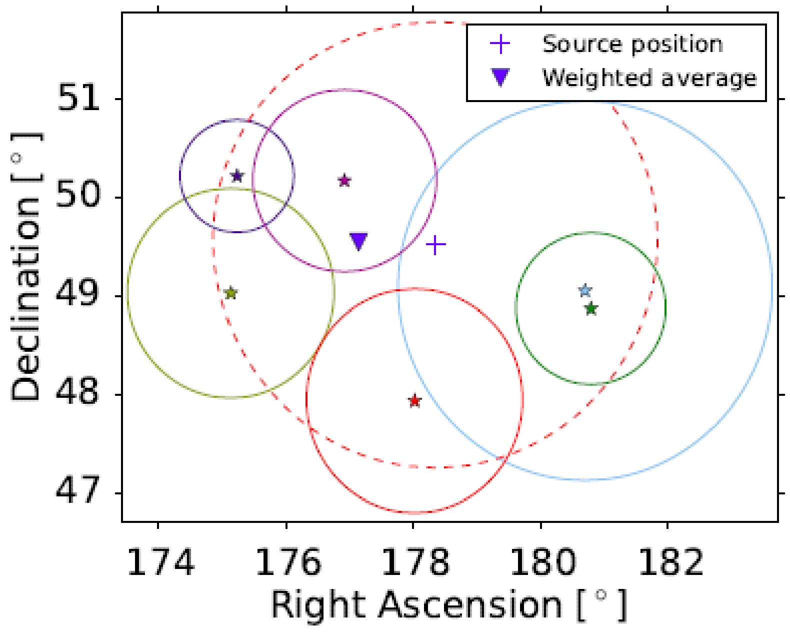
- Monitored sources based on the Fermi-LAT 2nd catalog, containing mostly BL-Lac objects and FSRQs, which have exhibited previous variable behavior

- Operating since 2012, private alerts to the MAGIC and VERITAS telescopes. HESS in preparation
- MAGIC with 0.1 alerts/source/year (3.2σ) total 3BG/yr
- Higher threshold for VARITAS (3.6σ) 1BG/yr

- 14 March to 31 December 2015, 14 alerts and 4 were followed up by MAGIC or VERITAS
  - Follow up is not always possible due to limited IACT (moon light, bad weather)



The GFU most significant alert

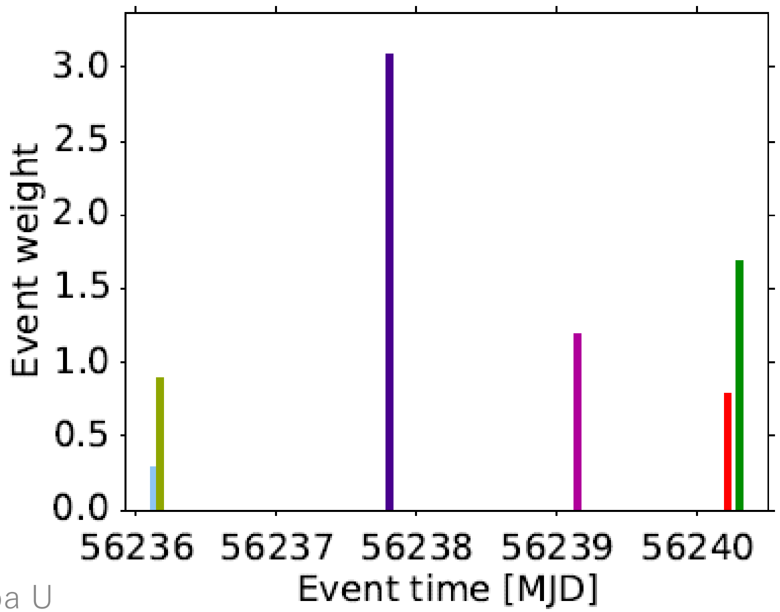


Nov 9, 2012 the most interesting alert, six events during 4.17days with the position of the source SBS 1150+497

- pre-trial $-\log10(p_{obs})=4.64$
- post-trial $-\log10(p_{obs}) = 2.60$

VARITAS followed up -

- Due to poor weather and bright moonlight, VARITAS could follow only at the end of Nov 12, 2012 night and continued to the following night - the total exposure time 71.5m
- No evidence of gamma ray flux
- Setting an integrated flux limit (99%CL) above 300GeV at 3.0×10^{-10} $cm^{-2}s^{-1}$ for an assumed differential spectrum with spectral index $\gamma = 2.5$.



Summary of alert channels

Alert	Event type	Coverage	thres E [TeV]	Median Ang Res [deg]	Time window	Alert rate Sig+BG/yr	Alert type
EHE	through going ν_μ track	All sky	~100	0.25	n/a	~ 2+2	Public
HESE	starting ν_μ track in detector volume	All sky	~60	~1.6	n/a	~ 1+3	Public
GFU	ν_μ track multiplets	All sky	~0.1	<1	variable, max 21d	~2BGs	Private
O(X)FU	up ν_μ track multiplets	Northern sky	~0.1	<1	100s	Varies	Private

Summary

- IceCube discovered diffuse neutrino flux of which energy budget consistent with that of UHECR and diffuse gamma-ray background
- However, still no significant neutrino event cluster
- Limits on the GRB/Blazar components in the observed neutrino flux
- But, there are correlation of HESE/PeV with blazars reported.
  - Neutrino triggering follow-up!
- IceCube has started public alert of neutrino events since 2016
- Private alerts in operation since 2008 – and glowing
  - a couple of interesting SNs (type Ic, type IIn) discovered
- Stay tuned for IceCube Gen-2 – Significant point source sensitivity improvements expected!!