Recent progresses on *the cosmogenic neutrino* searches and *the multi-messenger view with neutrinos*

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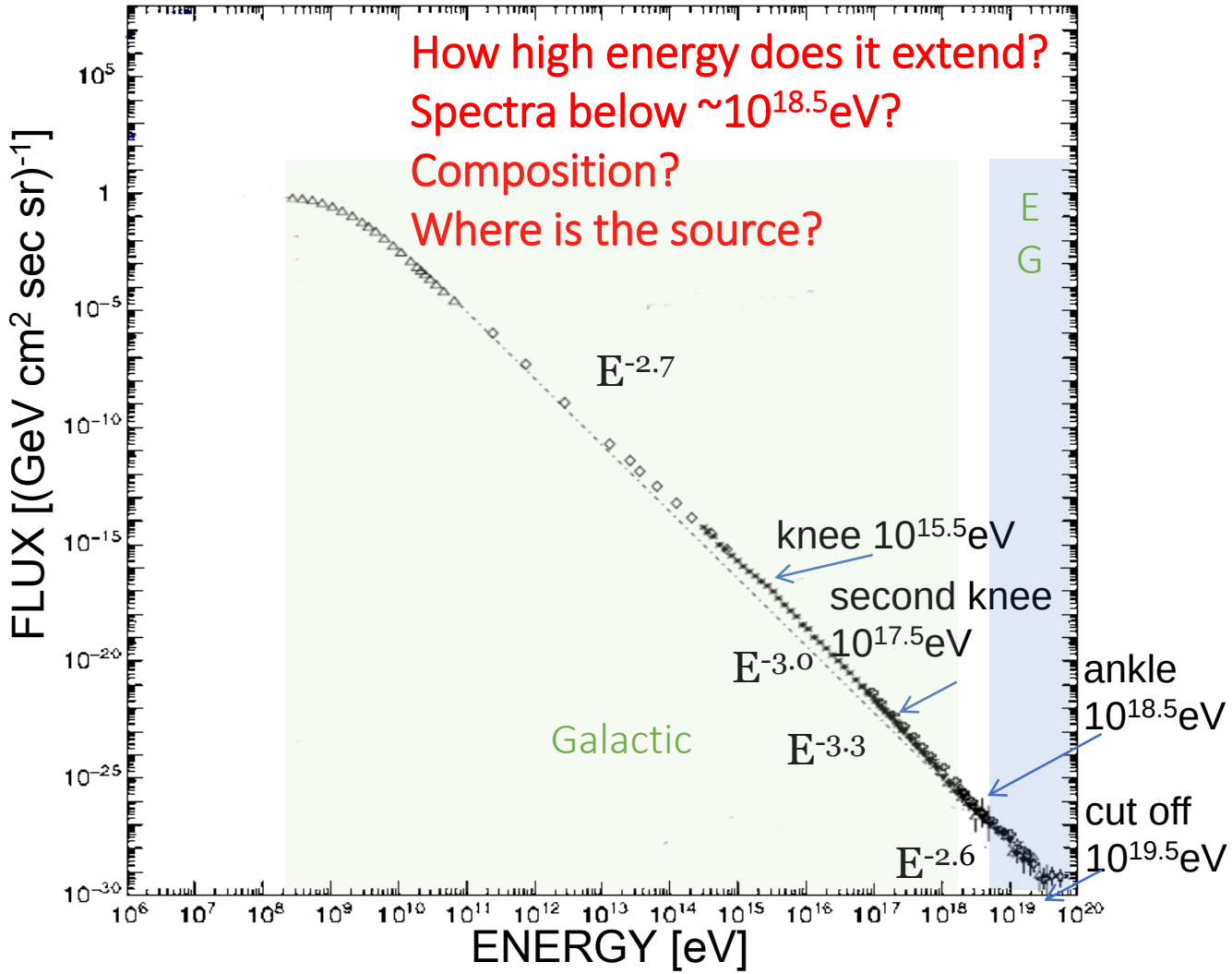
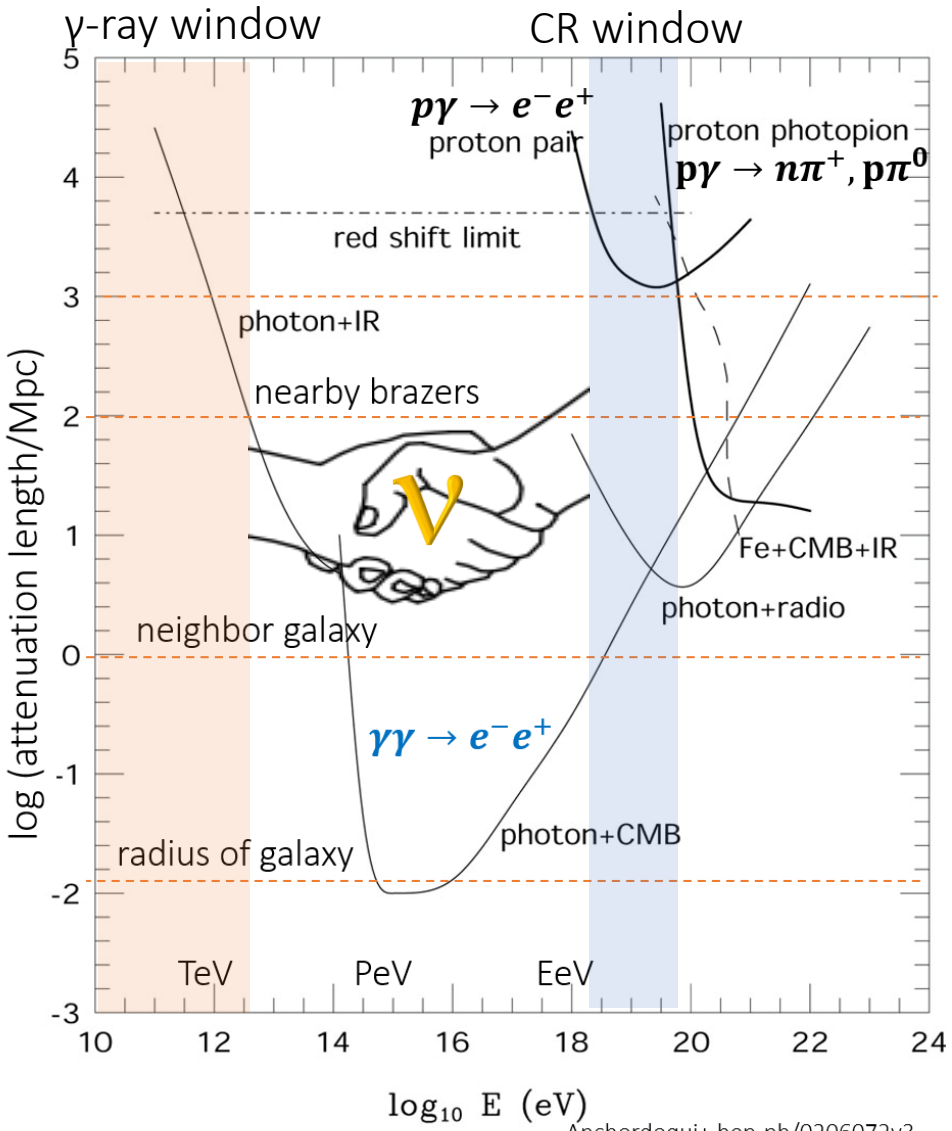
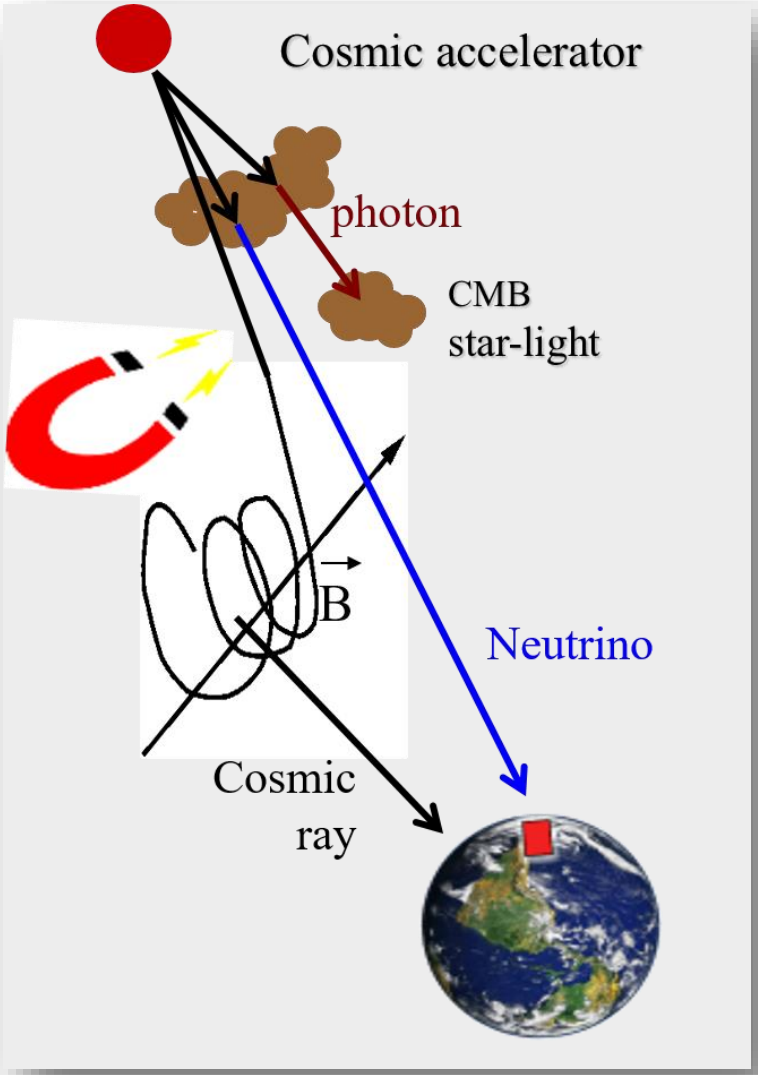
The origin of extragalactic cosmic-rays





Anchordoqui+ hep-ph/0206072v3

Neutrino as a cosmic messenger

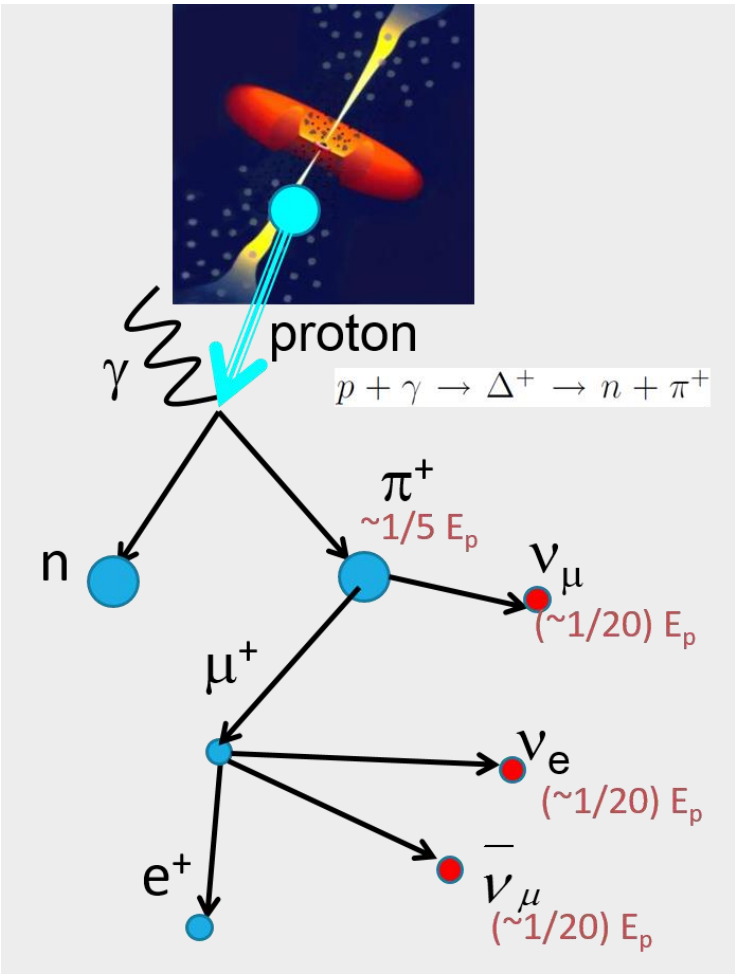


Weak interaction during "propagation"

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

Unsocial neutrino unites UHE sky

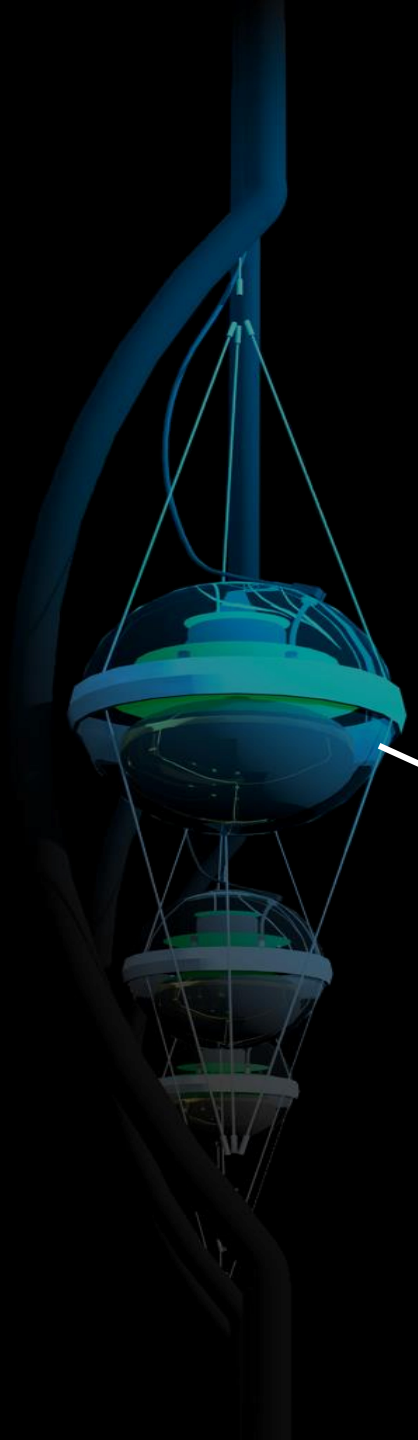
$$E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma$$

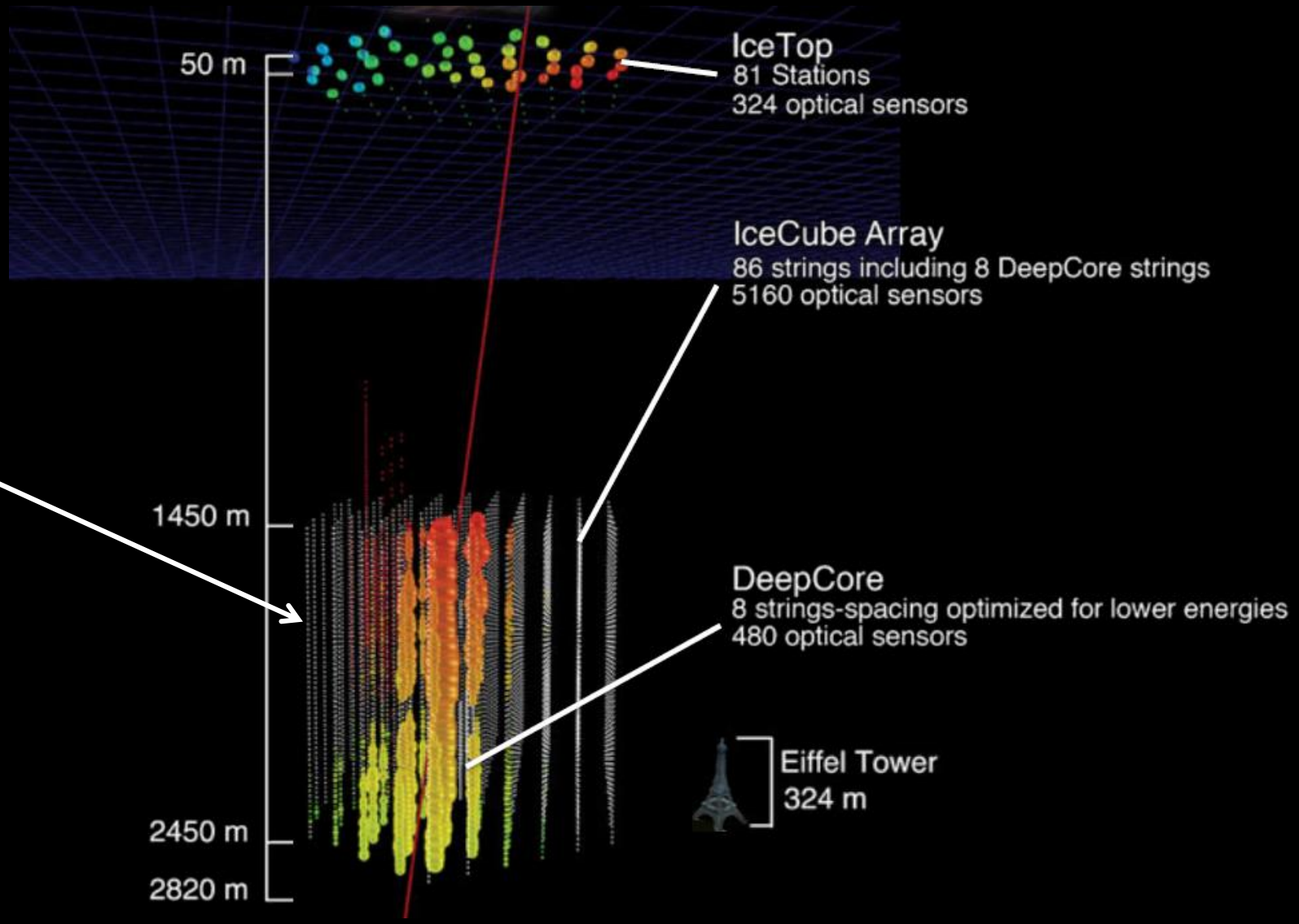


- **Simple modeling ingredients**
  - pp or pγ interaction
  - cosmic-ray and target spectra in source
- **Directly accompanying partners**
  - gamma-ray from neutral pions
  - parent cosmic-rays
- Indirectly accompanying partners
  - radiations optical, x-ray
  - Gravitational waves

Multi-messenger !

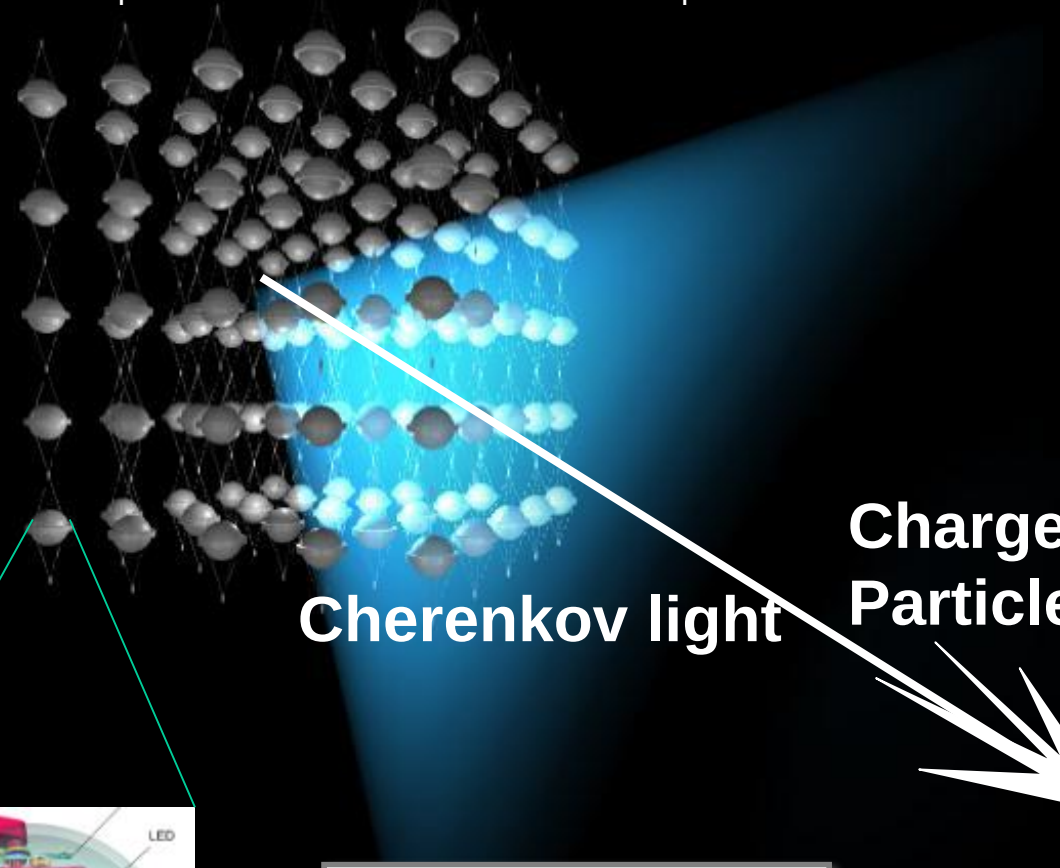
The IceCube Detector

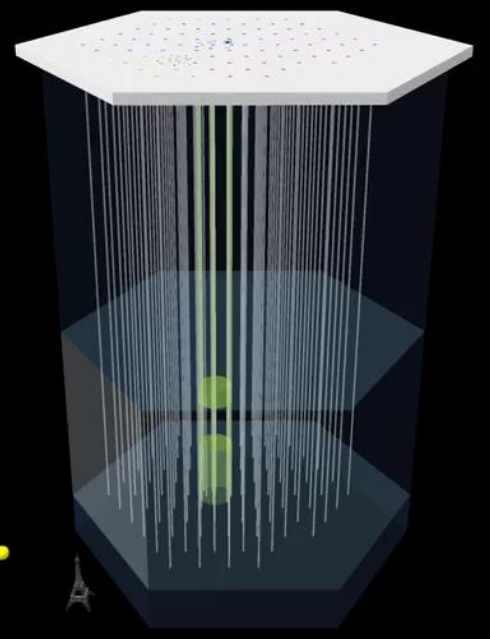




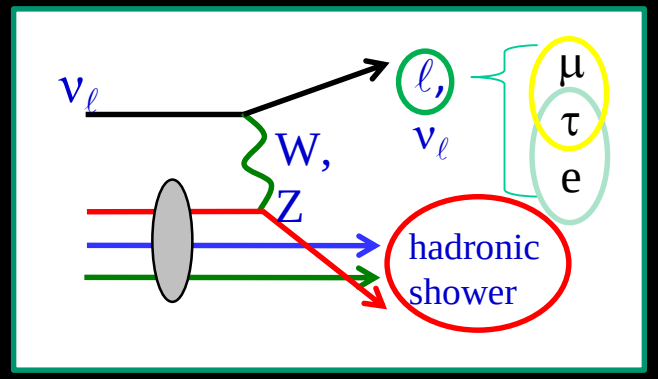
Detection Principle

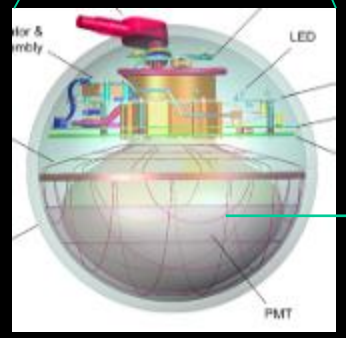
An array of photomultiplier tubes + Dark and transparent material

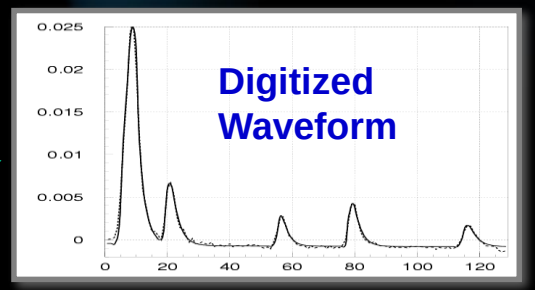




Charged Particles







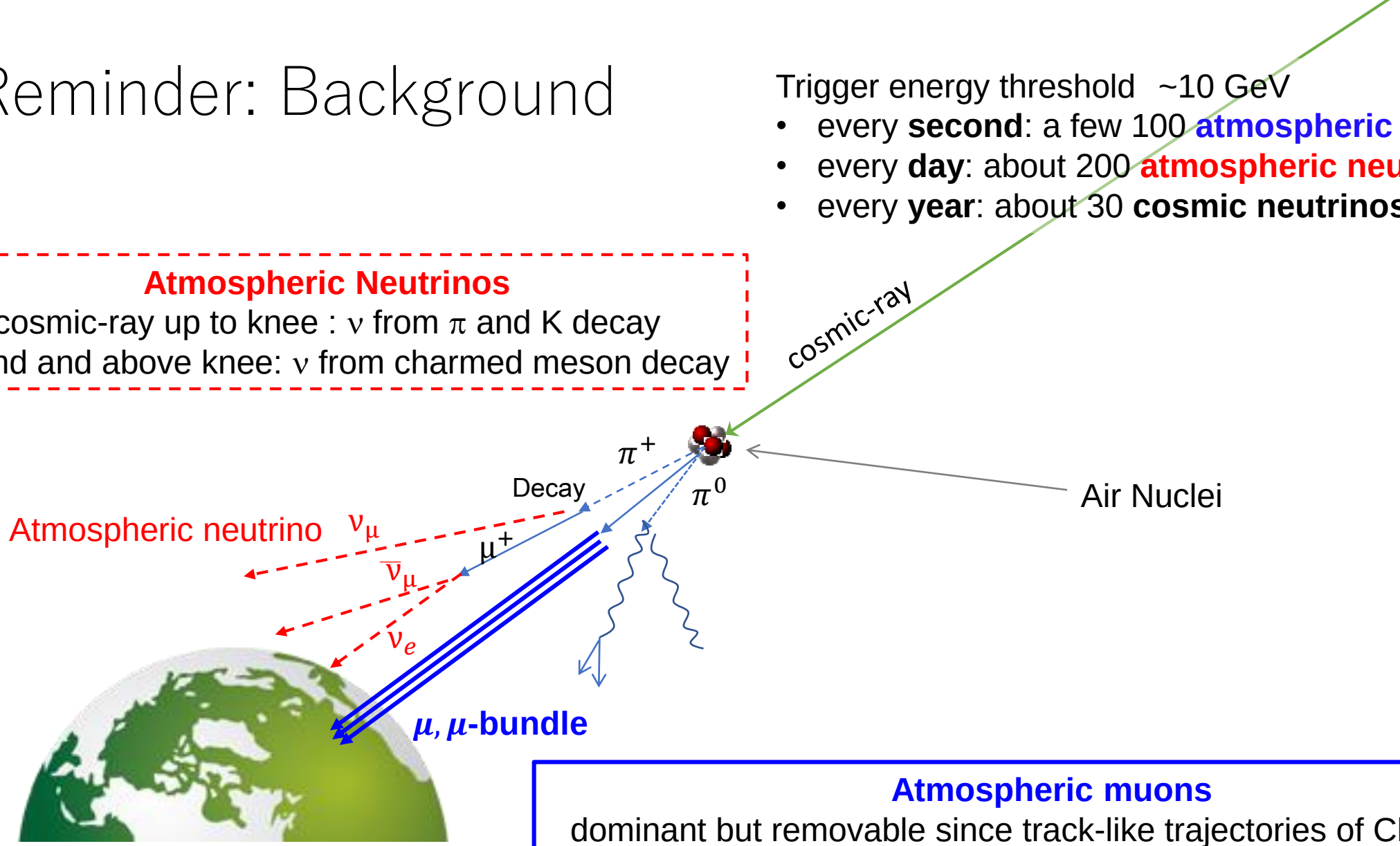
ν

Reminder: Background

Trigger energy threshold ~10 GeV

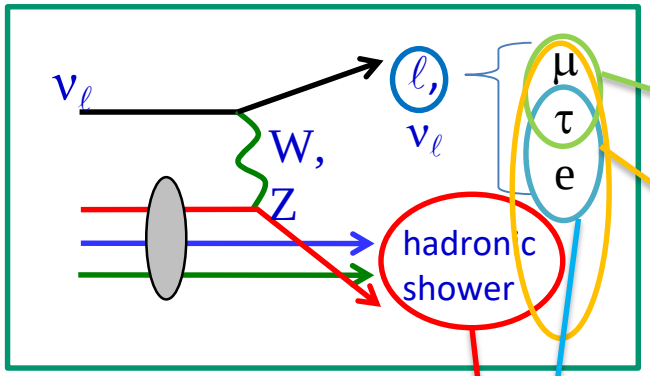
- every **second**: a few 100 **atmospheric muons**
- every **day**: about 200 **atmospheric neutrinos**
- every **year**: about 30 **cosmic neutrinos**

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

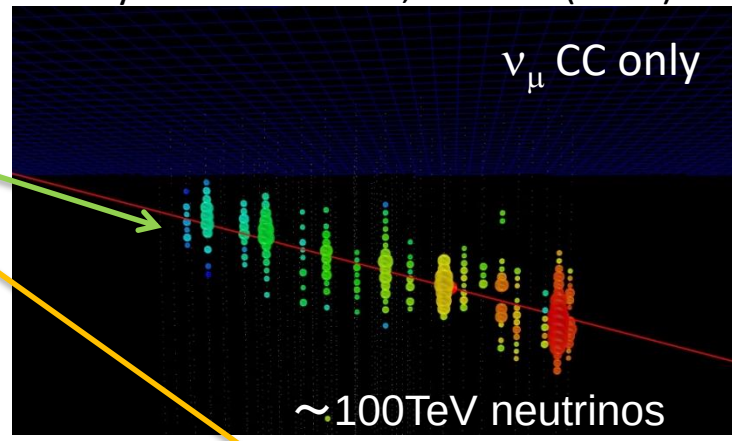


Atmospheric muons
dominant but removable since track-like trajectories of Cherenkov photons and its directions is able to be reliably reconstructed

High energy neutrino signal channels



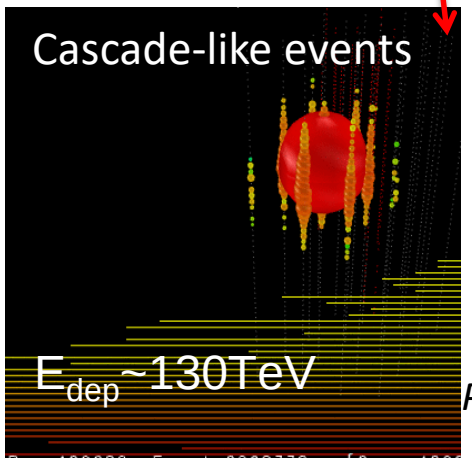
Phys. Rev. Lett. 115, 081102 (2015)



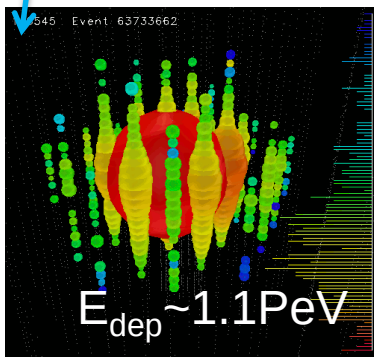
Upward going track event sensitive to CC muon neutrino interaction

HESE
>60TeV

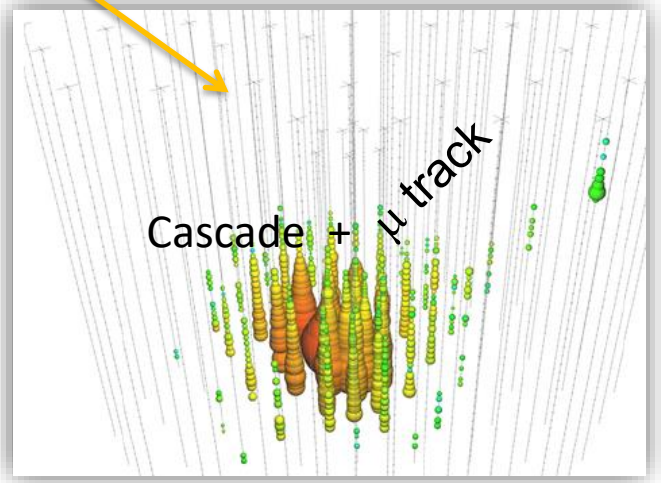
Starting event inside detector sensitive to all flavor CC/NC



Phys. Rev. D 84, 072001 (2011)

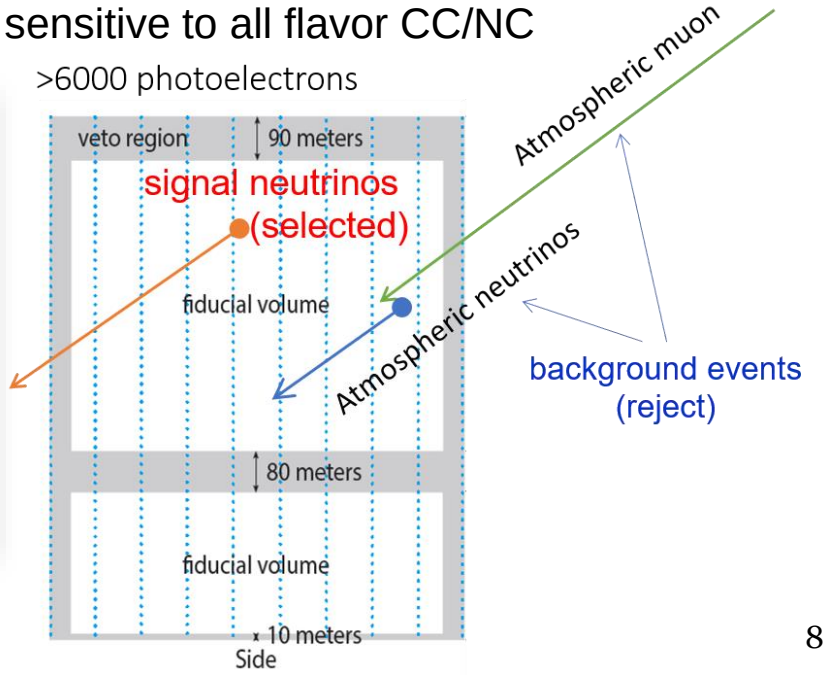


PRL 111 (2013) 021103

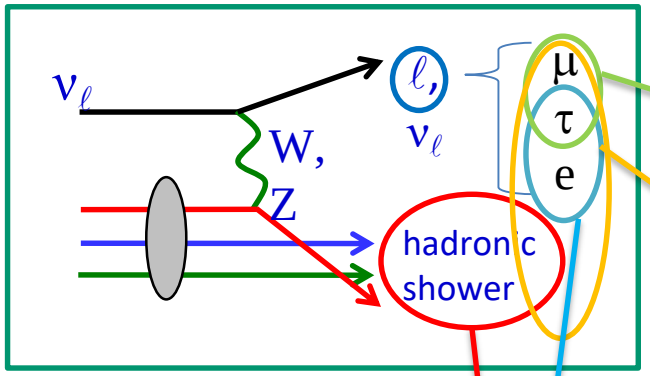


Science 22 Vol. 342 (2013)
PRL 113, 101101 (2014)

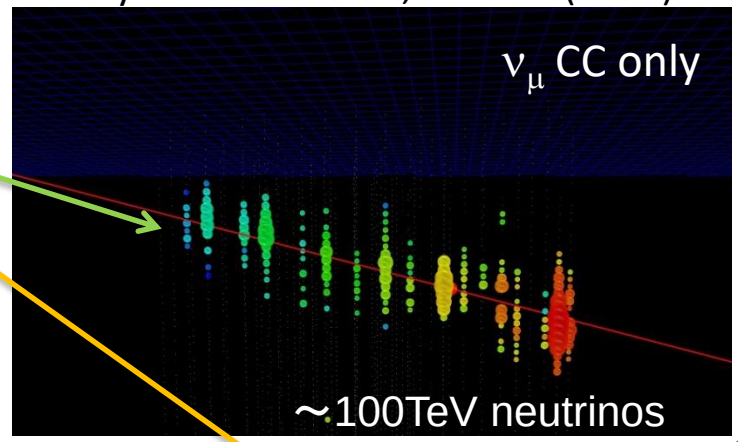
>6000 photoelectrons



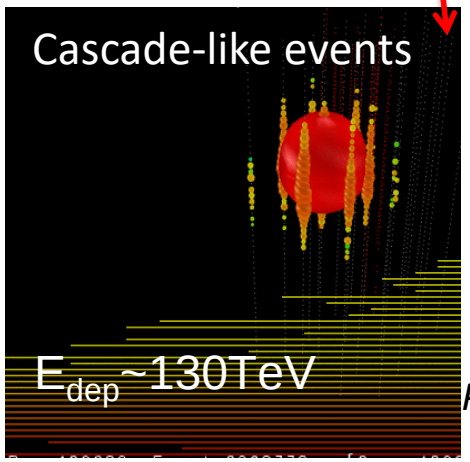
Extremly-High energy neutrino signal

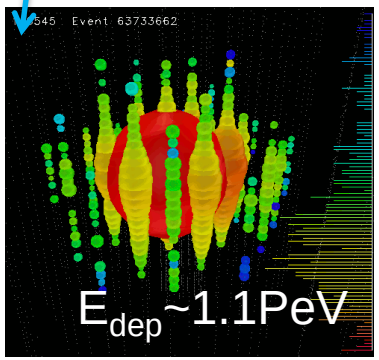


Phys. Rev. Lett. 115, 081102 (2015)



Upward going track event sensitive to CC muon neutrino interaction





PRL 111 (2013) 021103

Phys. Rev. D 84, 072001 (2011)

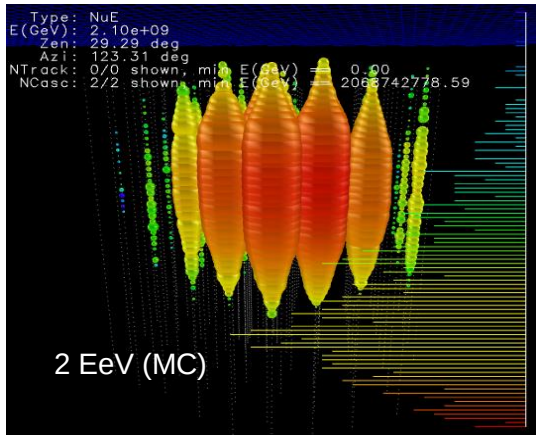
EHE

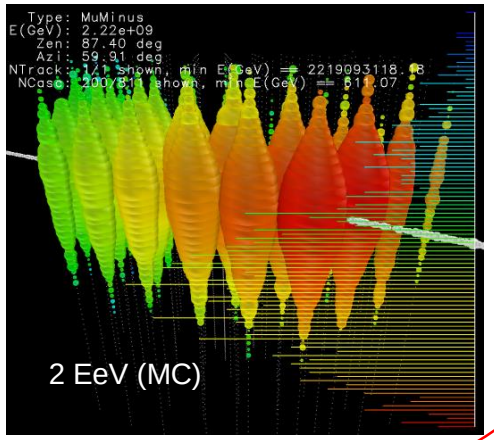
>PeV-10PeV

Calorimetrical selection of high brightness events

EHE signals: All flavors

elongated cascades and highly stochastic tracks

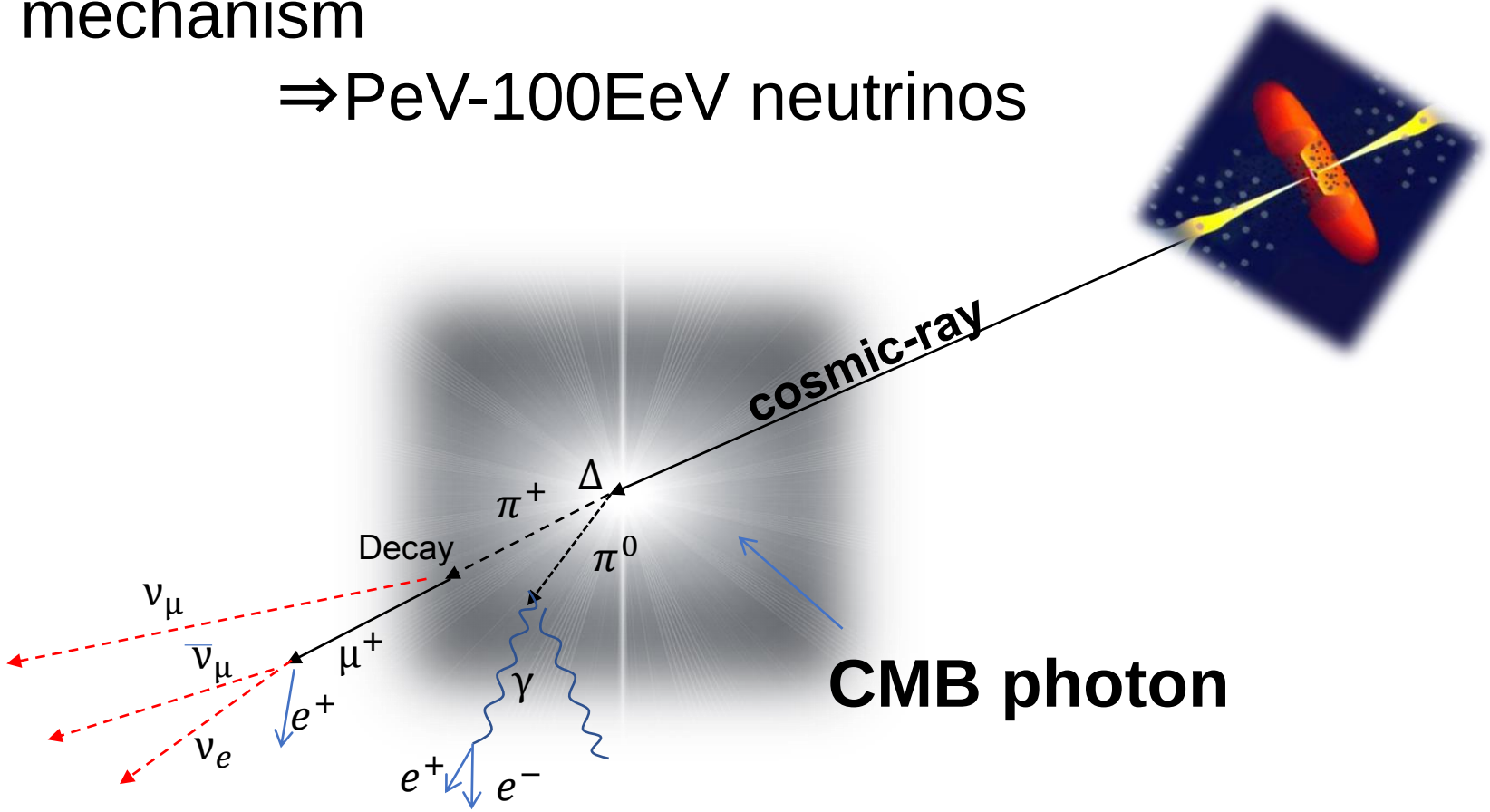




Cosmogenic neutrinos

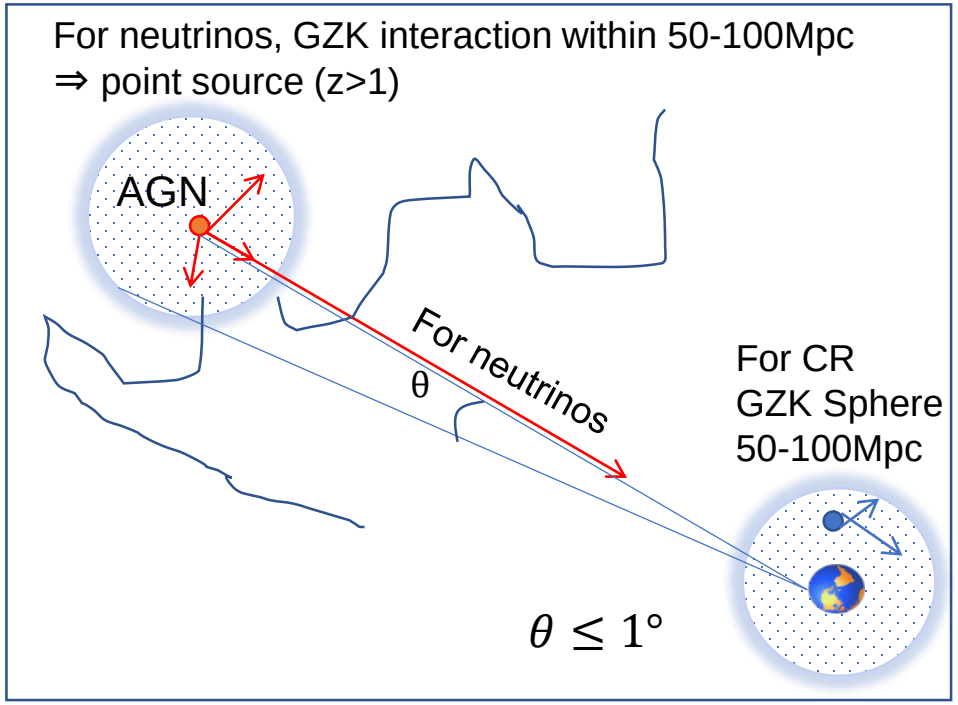
Induced by the off-source (<50Mpc) interactions of UH cosmic-rays (>$10^{19.5}$eV) and CMB photons via GZK (Greisen-Zatsepin-Kuzmin) mechanism

⇒PeV-100EeV neutrinos

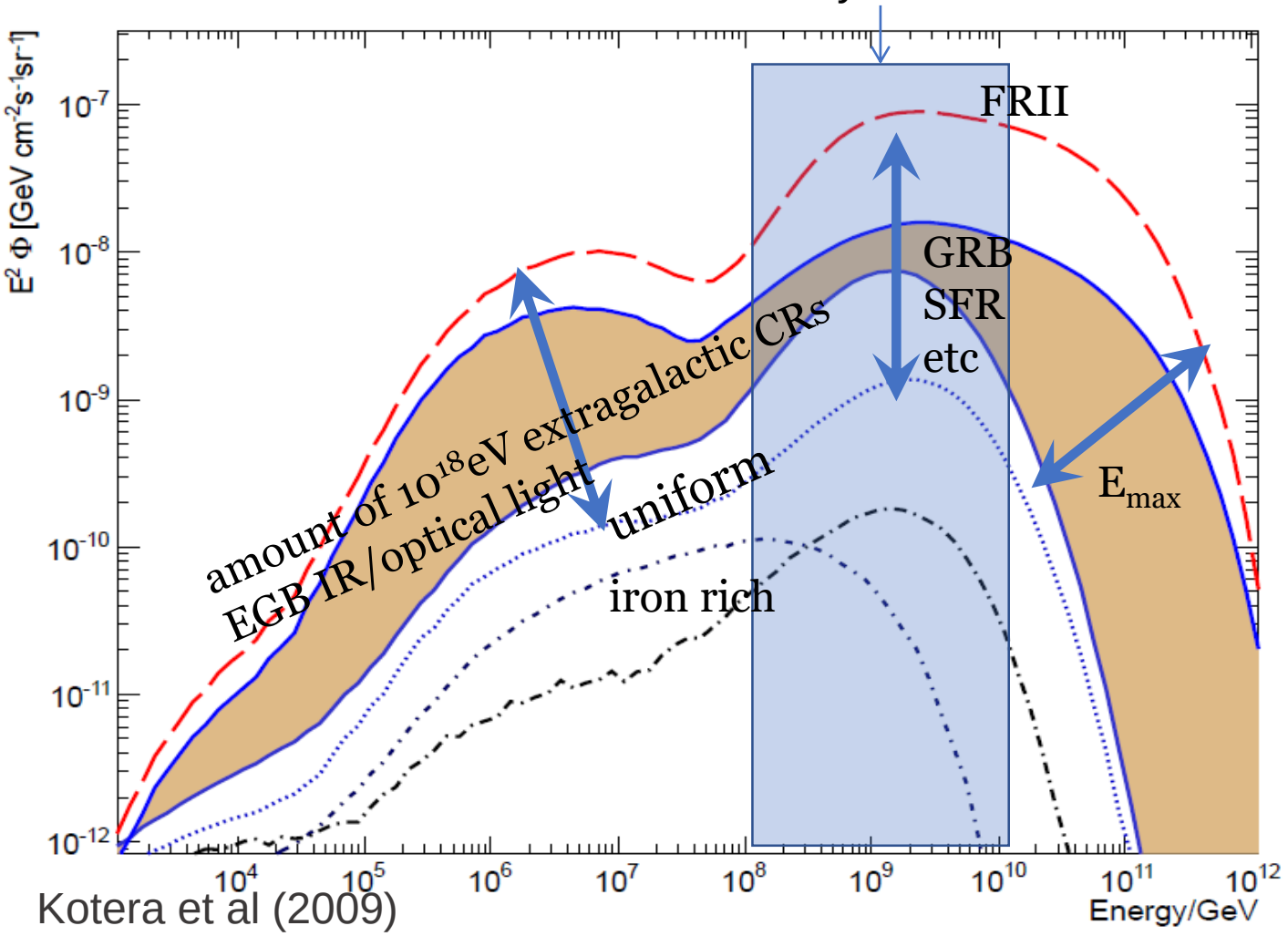


EHE Neutrinos tell us about the hidden Universe

Location of the UHE cosmic-ray sources



IceCube's event rates ⇒ cosmic-ray source evolutions



Kotera et al (2009)

Constraints on UHECR source parameters

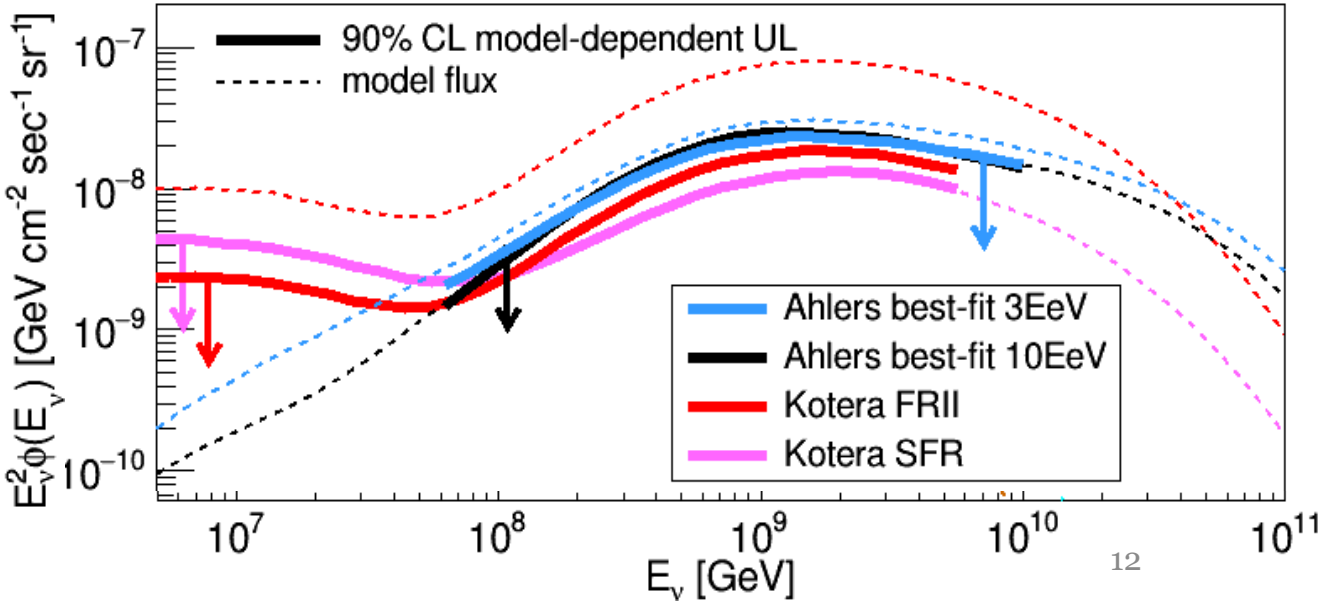
Non detection of >10PeV events in 7 years of IceCube data constraints on cosmological evolution parameters of UHECR sources

model predictions cosmogenic neutrinos:
7 year rates (IceCube)

ν Model	Event rate per livetime	p-value	MRF
Kotera *et al.* SFR	$3.6^{+0.5}_{-0.8}$	$6.0^{+2.9}_{-1.0}\%$	1.04
Kotera *et al.* FRII	$14.7^{+2.2}_{-2.7}$	$<0.1\%$	0.23
Aloisio *et al.* SFR	$4.8^{+0.7}_{-0.9}$	$3.2^{+2.8}_{-0.7}\%$	0.80
Aloisio *et al.* FRII	$24.7^{+3.6}_{-4.6}$	$<0.1\%$	0.15

- UHECR sources evolve more slowly than SFR assuming proton composition
- Otherwise limits on proton component of UHECR flux

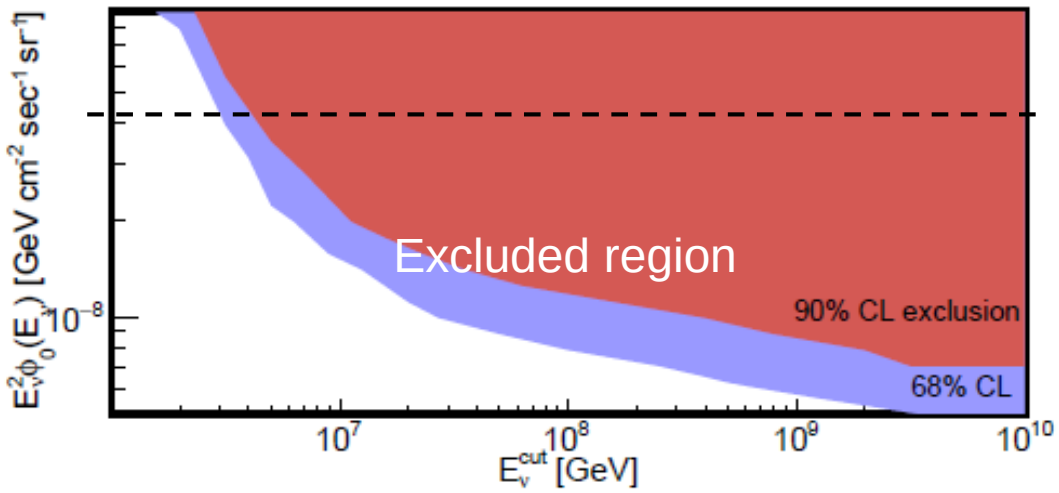
Phys. Rev. Lett. 117, 241101 (2016); Erratum Phys. Rev. Lett. 119, 259902 (2017)



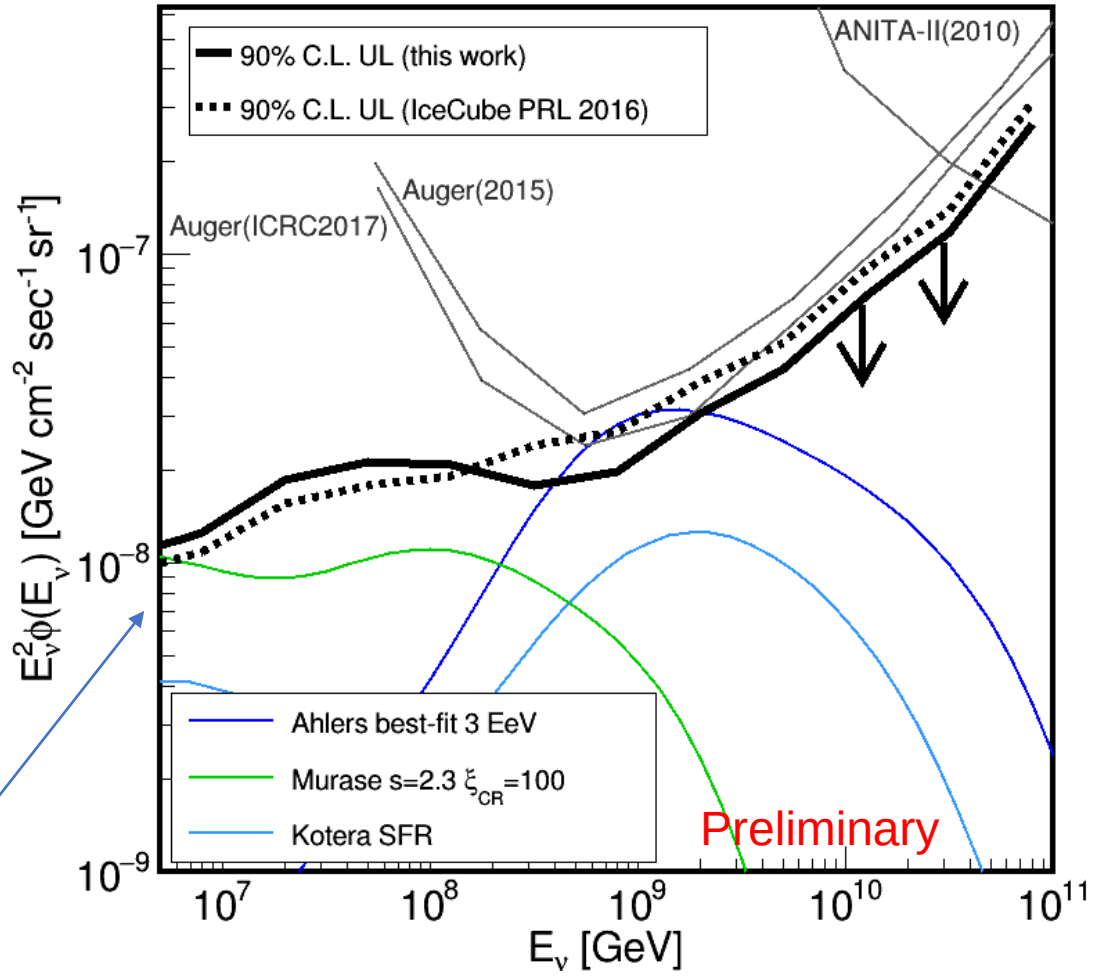
Limits on neutrino flux above 10PeV

Constraints on UHE astrophysical power-law (E^{-2}) flux

UHECR source may produce detectable fluxes above 10 PeV but it could be different origin from the TeV-PeV flux



The latest differential limits above 10PeV
Proceedings of ICRC2017 PoS (ICRC2017)975

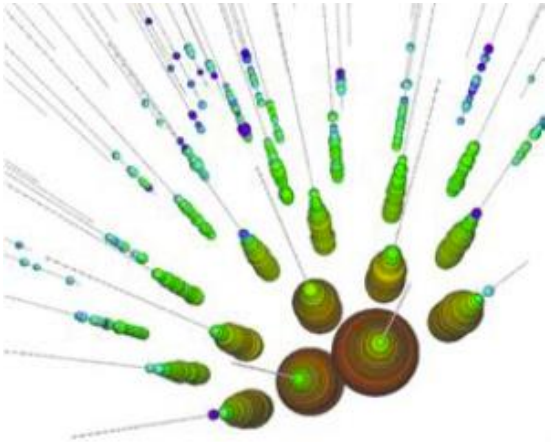


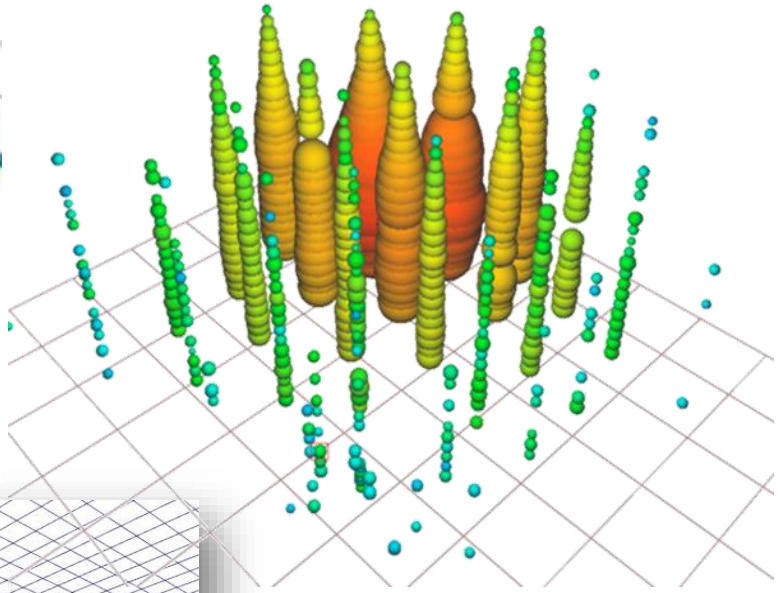
- Two events with a few PeV energy deposits found, but they were not consistent with cosmogenic origin

Neutrino events above PeV（=10^{15}eV）

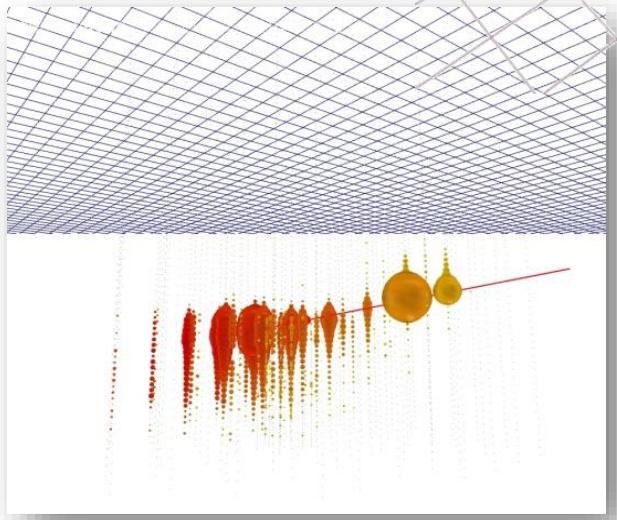
- 9 year data based extremely-high energy neutrino analysis
- two events observed

ICRC2017, TeVPA2017





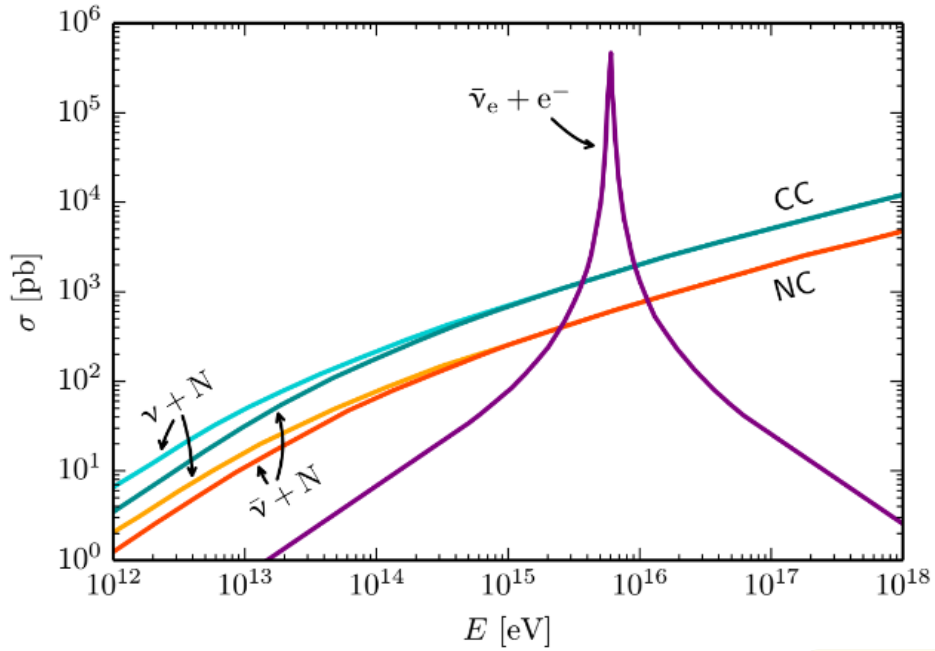
particle shower event
2016 data
reconstructed energy deposit **6.0±0.3 PeV**
number of photoelectrons　200,000pe（the brightest to date）



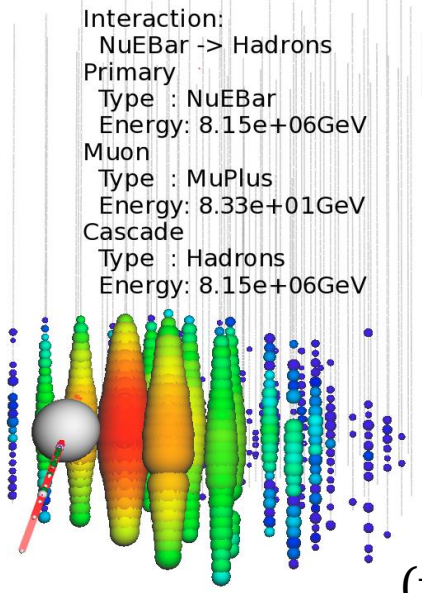
A upward-going track with the highest energy deposit
2014 data
reconstructed energy deposits　**2.6±0.3 PeV**
number of photo electrons　130,000pe

ATEL #7856
The Astronomer‘s Telegram

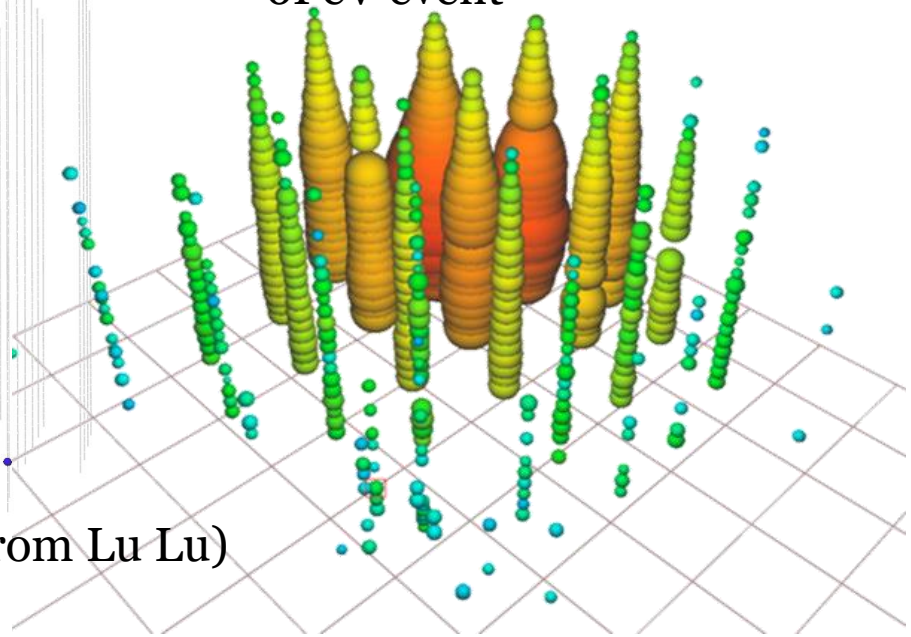
Glashow Resonance?



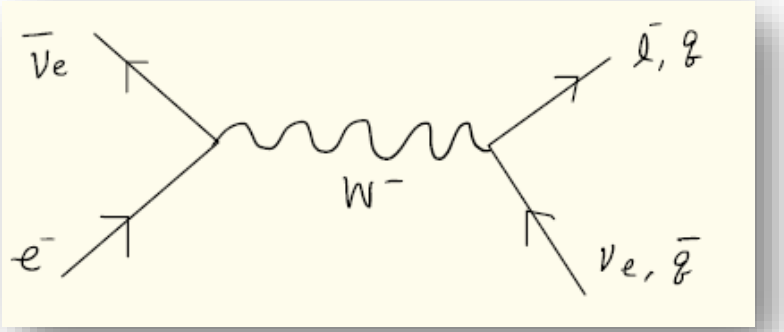
simulation



6PeV event



(from Lu Lu)

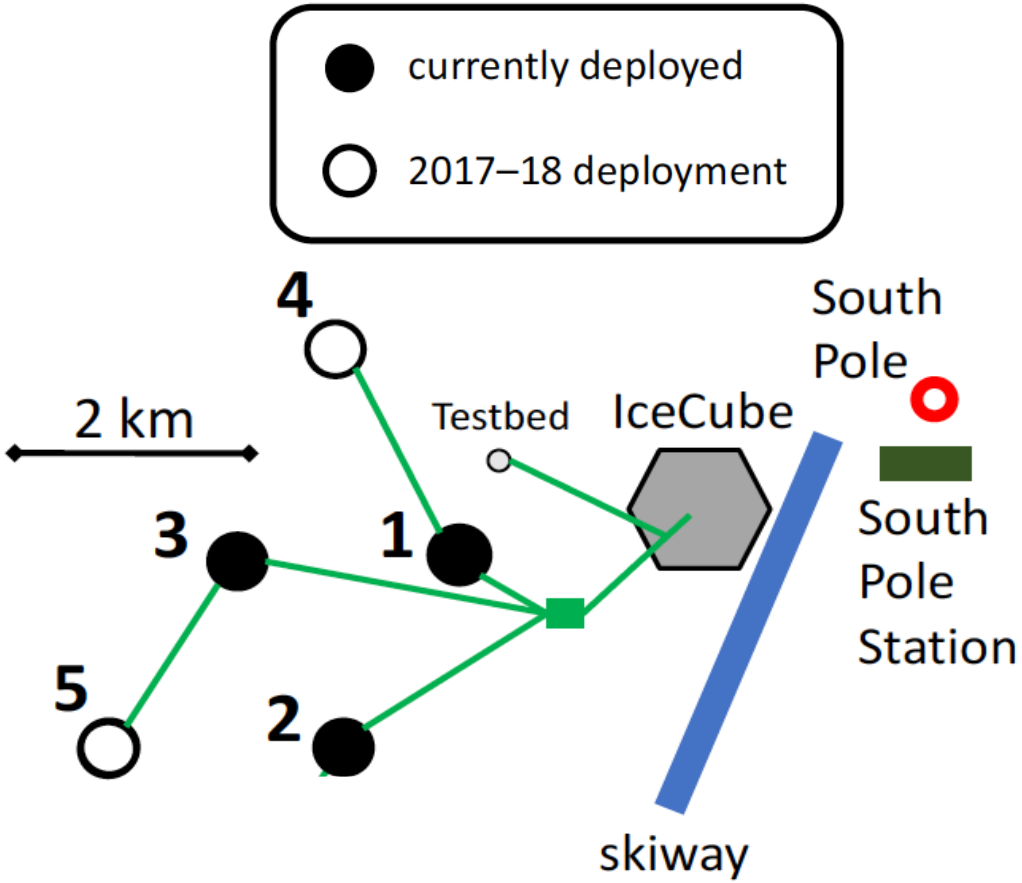


W^- Decay modes	Fraction (Γ_i/Γ_{tot})
$e^- \bar{\nu}_e$	10.8%
$\mu^- \bar{\nu}_\mu$	10.6%
$\tau^- \bar{\nu}_\tau$	11.3%
hadrons	67.6%

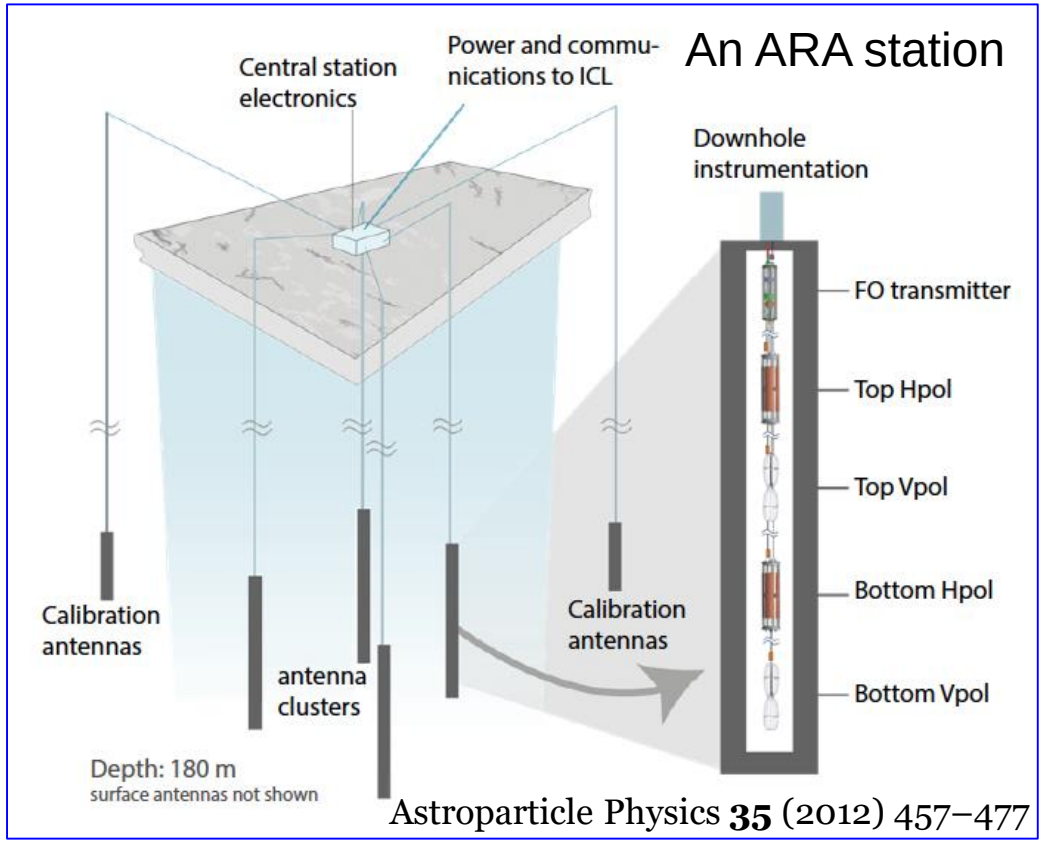
systematics studies on going....

The next move on cosmogenic ν detection: ARA

- Successful deployment of already data taking 5 stations next to IceCube!!



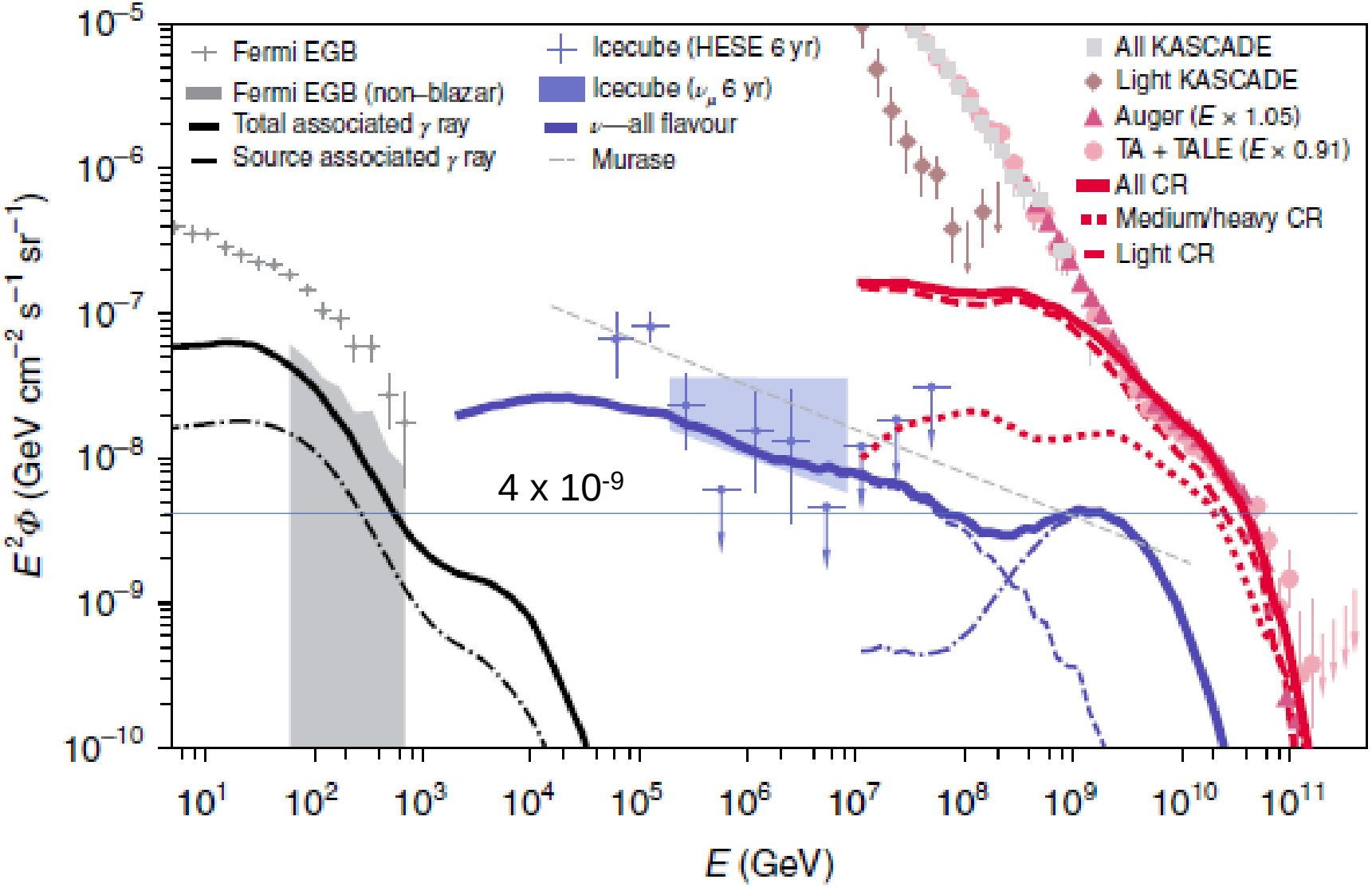
- Sensitivity will be comparable to IceCube @ 10^{18} eV
- A combined analysis will double the effective detection volume of cosmogenic ν at the South Pole
- On-going effort to lower energy threshold toward PeV by "phased array" of antennas



Astroparticle Physics **35** (2012) 457–477

Possible near future target model

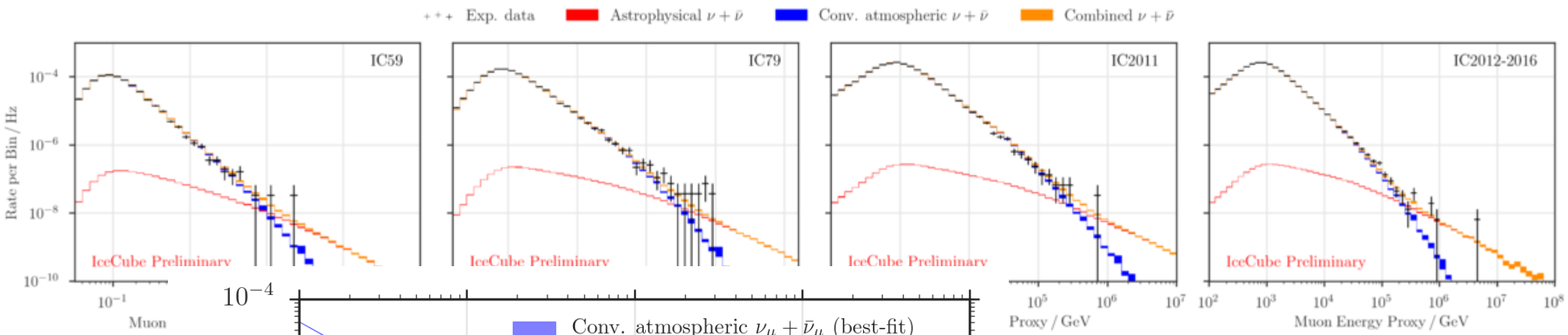
Fang and Murase Nature Phys (2018)

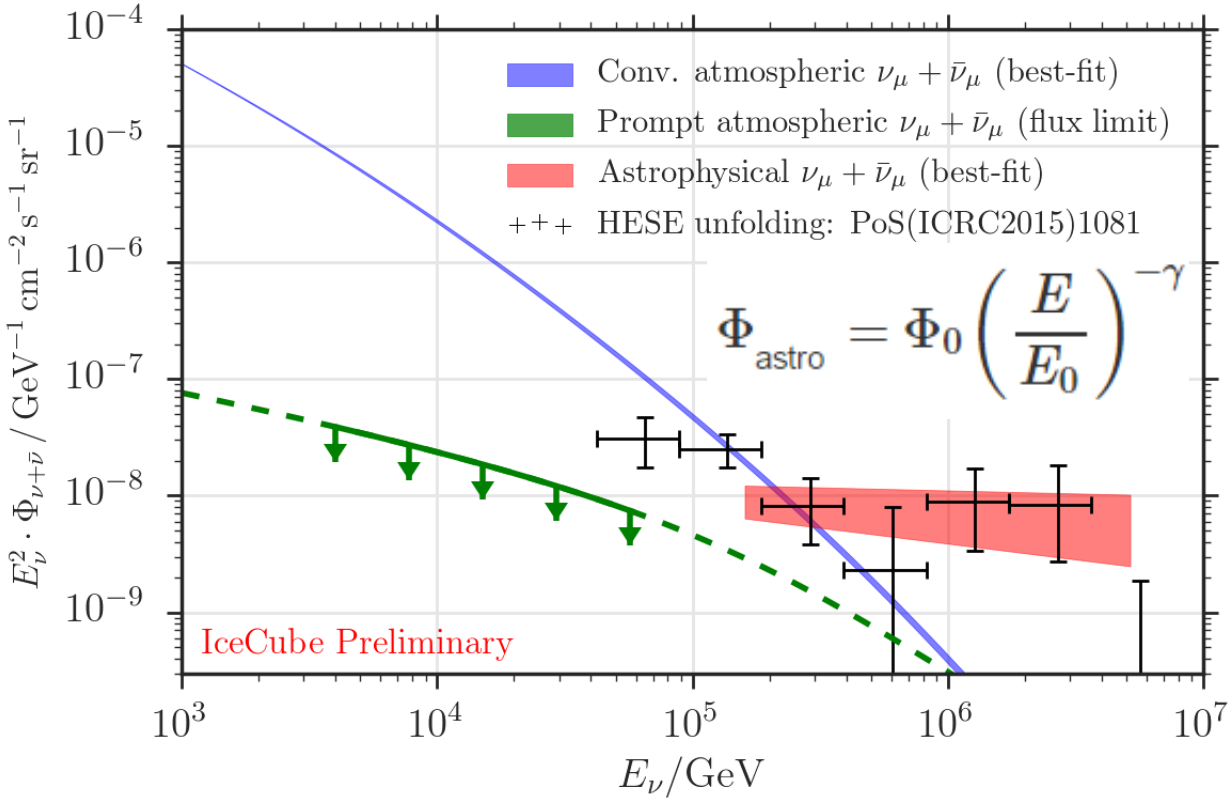


AGN in the large scale cluster model: consistent with Auger composition, Kascade-Grande light composition, fermi EGB fluxes
...and IceCube neutrino flux

A factor of ∼two better sensitivity than the current IceCube sensitivity allow us to reach

HE neutrino flux with upward-going muons



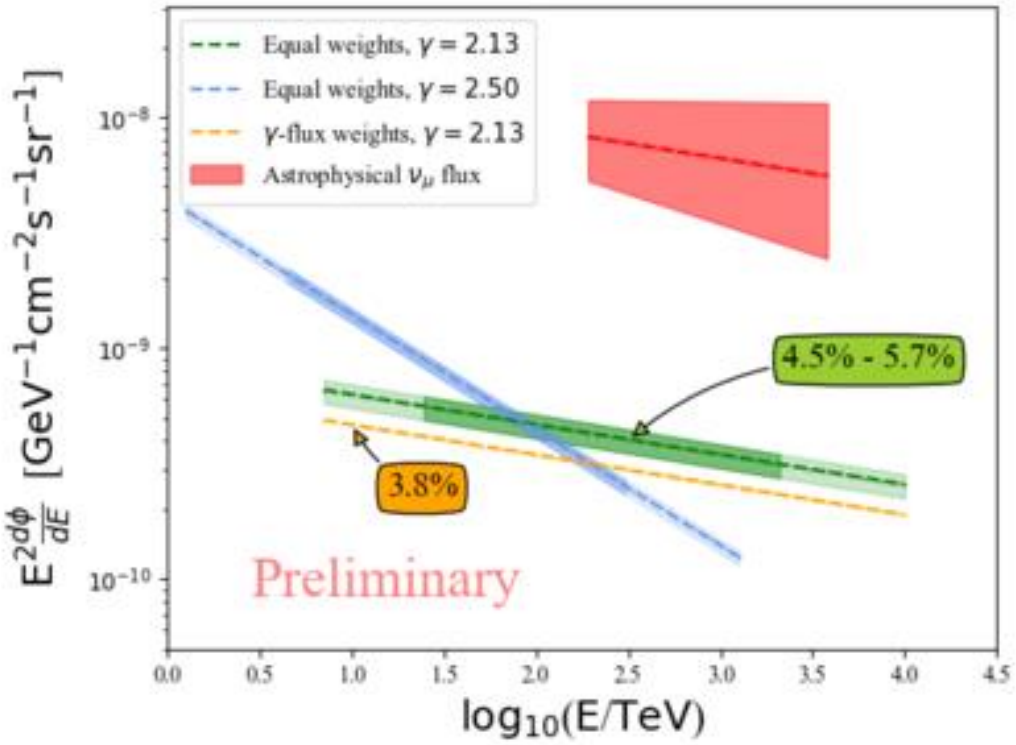


- 2 year sample
  - γ=2.2±0.2 PRL **115**, 081102 (2015)
- 6 year sample ApJ **833** 3 (2016)
  - γ=2.13±0.13
- 7 year sample
  - γ= 2.16±0.11
- 8 year sample ICRC(2017)
  - γ= 2.19±0.10

Constraints on «γ-bright» source models

AGN Blazer spacial correlation

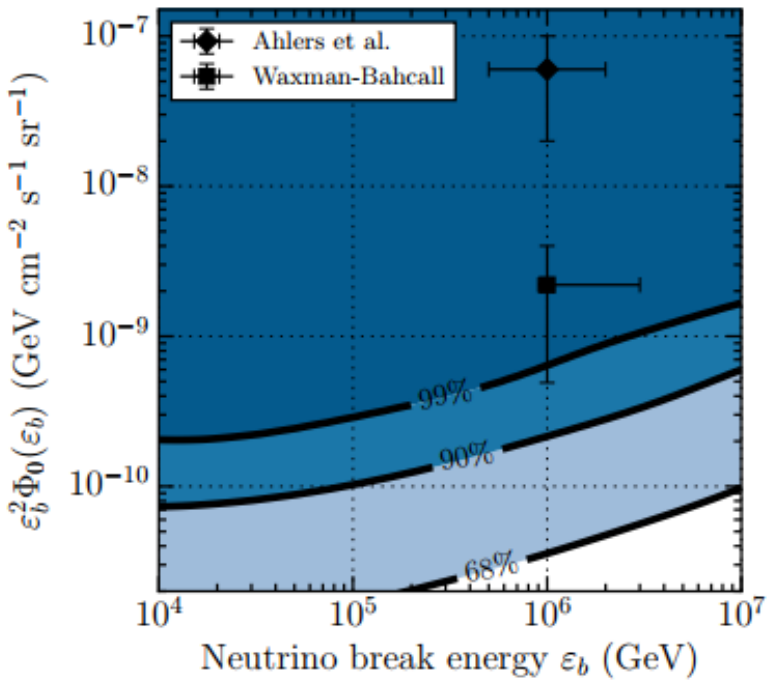
- The equal-weighting upper limit results in a **maximally4.5%-5.7% contribution** of the total Fermi blazar sample to the astrophysical neutrino flux – no continuous emission from blazar?



GRB time/space correlation

contribute **no more than 1%** of the observed diffuse flux

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

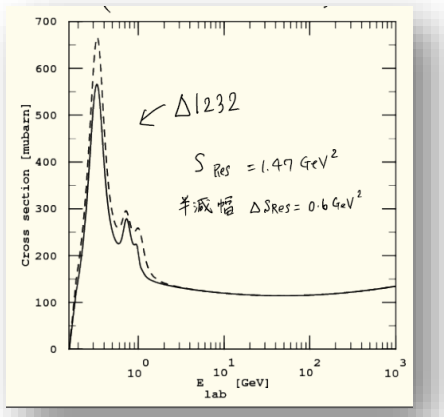


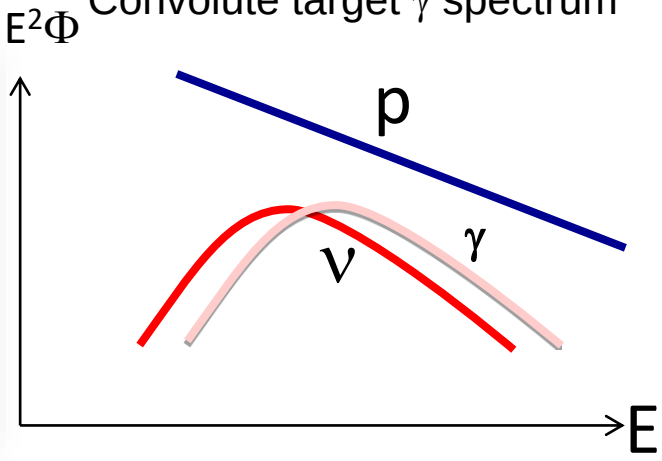
pp or pγ ?

$$\pi^0 \rightarrow 2\gamma_{VHE}$$

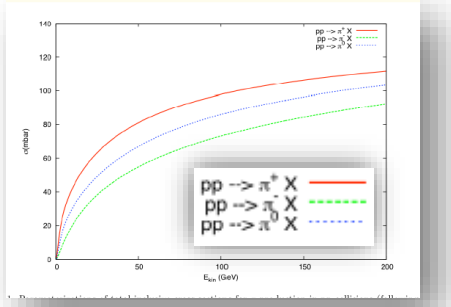
$\varepsilon'_p\, \varepsilon'_\gamma \sim 0.16\ \mathrm{GeV}^2$

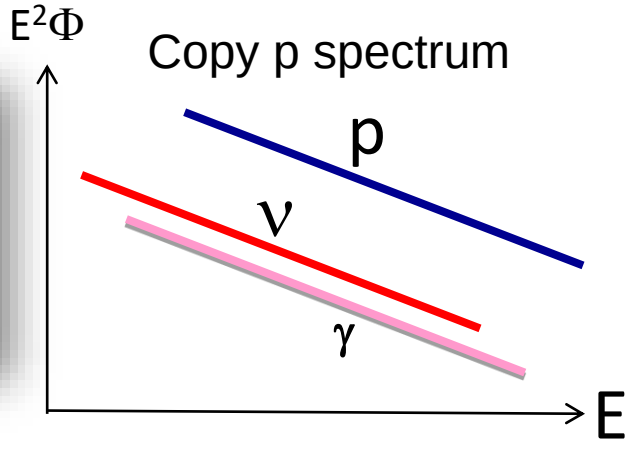
Convolute target γ spectrum





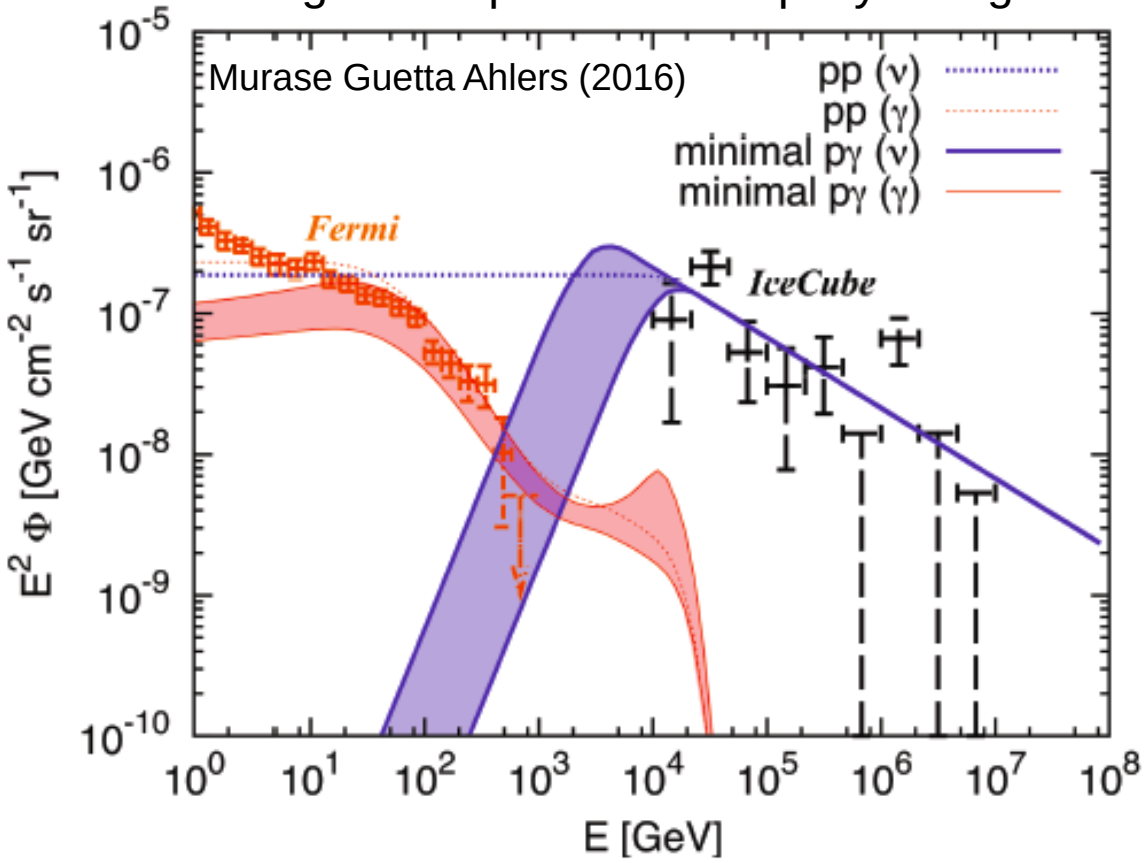
Copy p spectrum





$$\gamma_{VHE} + \gamma_{EBL,\,CMB} \rightarrow e^+ + e^-$$

These pairs inverse-Compton with CMB, boosting them up to sub-TeV γ-ray energies



sub-TeV γ-ray also includes contributions from cosmogenic gamma-ray and on-source neutrino production

Neutrino online alert

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

Iridium satellites

Before 2016 April, the system was up but only background dominant alert channels existed

New and public online channel with signal efficiency of >30-50%

Flare and exposure in the universe

high energy ν

ν

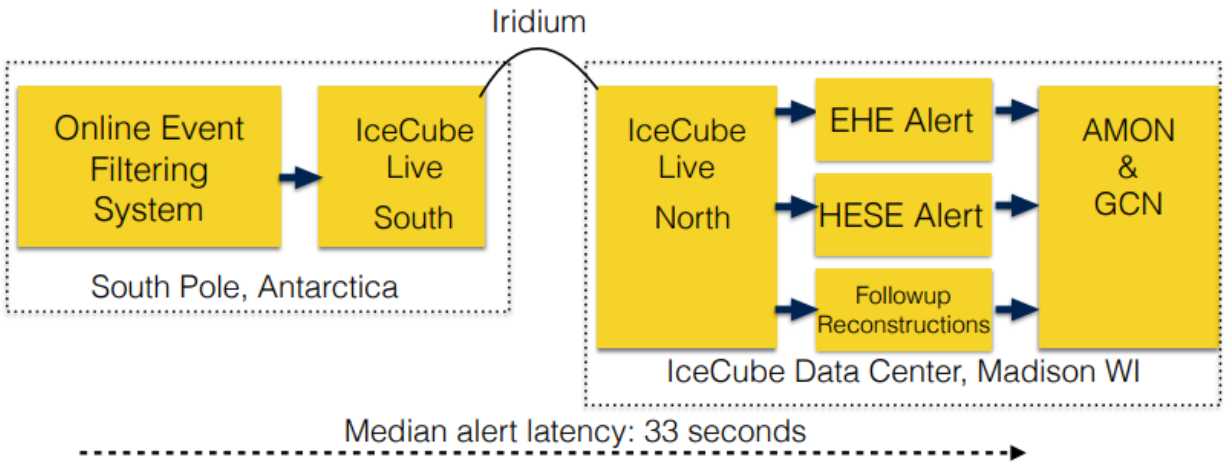
Alert!

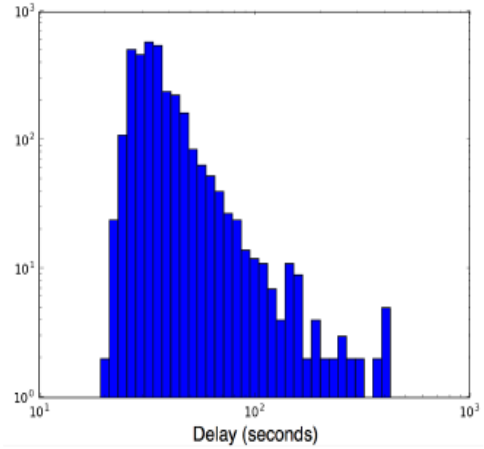
photon and GW

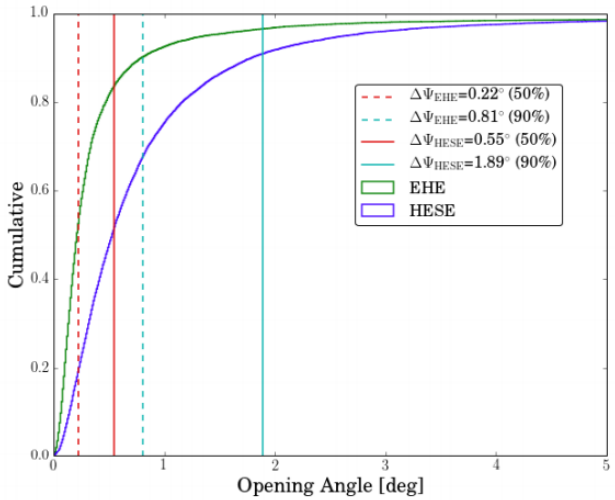
Latency time: a few minutes

"The IceCube realtime alert system", IceCube Collaboration (M. G. Aartsen et al), Astroparticle Physics, 92, 30–41,(2017)

« Public » aleart channels







Alert	Event type	Coverage	thres E [TeV]	Median Ang Res [deg]	Alert rate Sig+BG/yr
EHE	through going ν_μ track	All sky	~100	0.25	~ 2+2
HESE	starting ν_μ track in detector volume	All sky	~60	~1.6	~ 1+3 (could be worse with less track-like events)

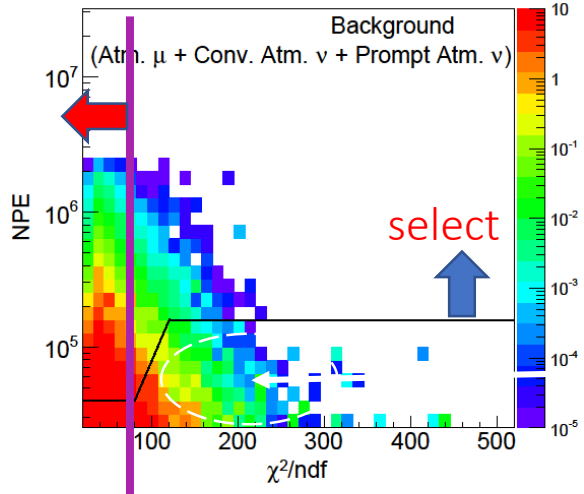
Private alerts for specific telescopes: low energy threshold, more background rates

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 event selection

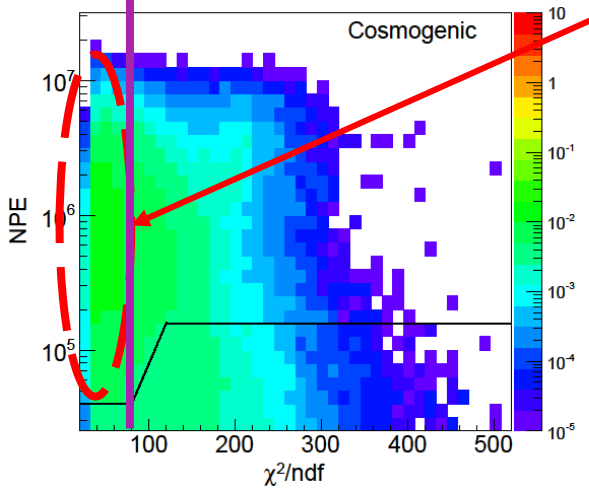
track hypothesis chi2

track-like ⟷ sphere-like



Atmospheric BG

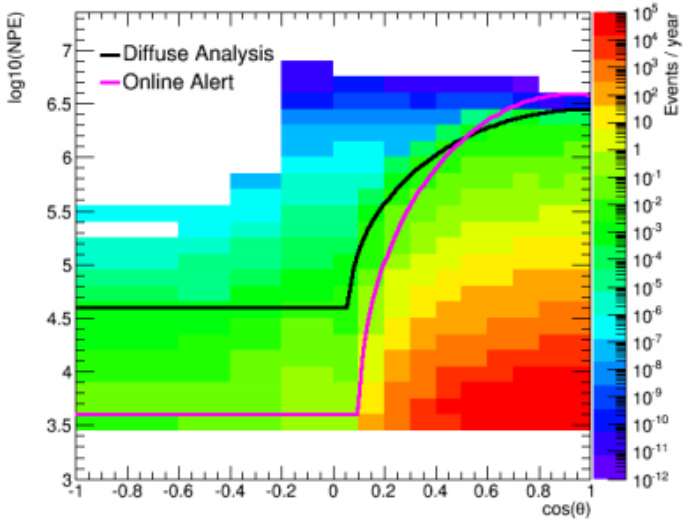
Good angular resolution



Cosmic Signal

zenith angle dependent log of brightness

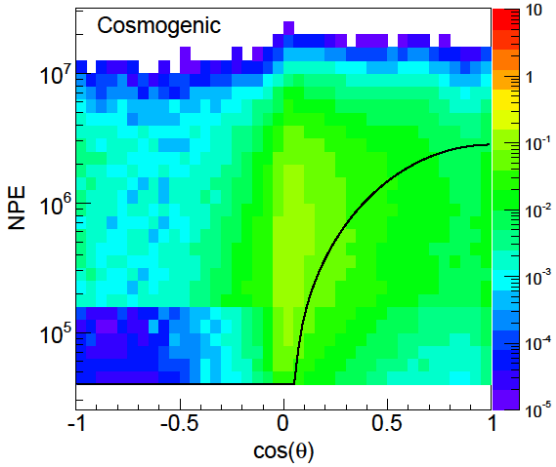
upward-going ⟷ downward-going

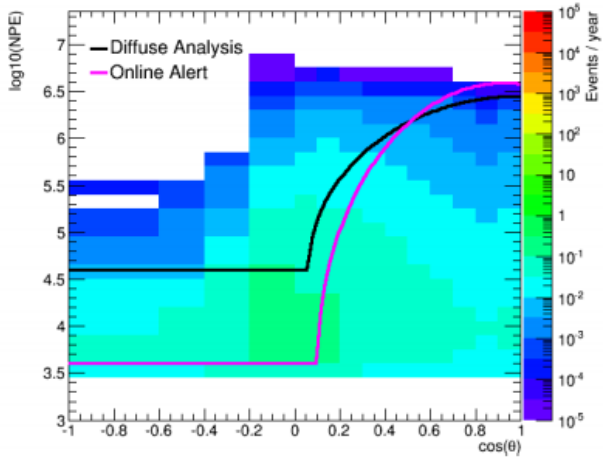


Sample	Events / year
Atmospheric muon	0.52
Conv. Atmos. ν_μ	1.20
Prompt Atmos. ν_μ	0.19
Total Background	1.91
Astro. ν_μ (E^{-2})	4.09
Astro. ν_μ ($E^{-2.49}$)	2.48

EHE >10PeV

HE >100TeV





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

« Public » aleart history

- April 2016 - 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
50579430_130033	17/09/22	18:39:39.21	77.2853	+5.7517	14.99	0.56507
80305071_129307	17/03/21	07:32:20.69	98.3268	-14.4861	19.48	0.2801
80127519_128906	16/12/10	20:06:40.31	46.5799	+14.9800	60.00	0.49023
26552458_128311	16/08/06	12:21:33.00	122.7980	-0.7331	6.67	0.28016
6888376_128290	16/07/31	01:55:04.00	214.5440	-0.3347	20.99	0.84879

same event

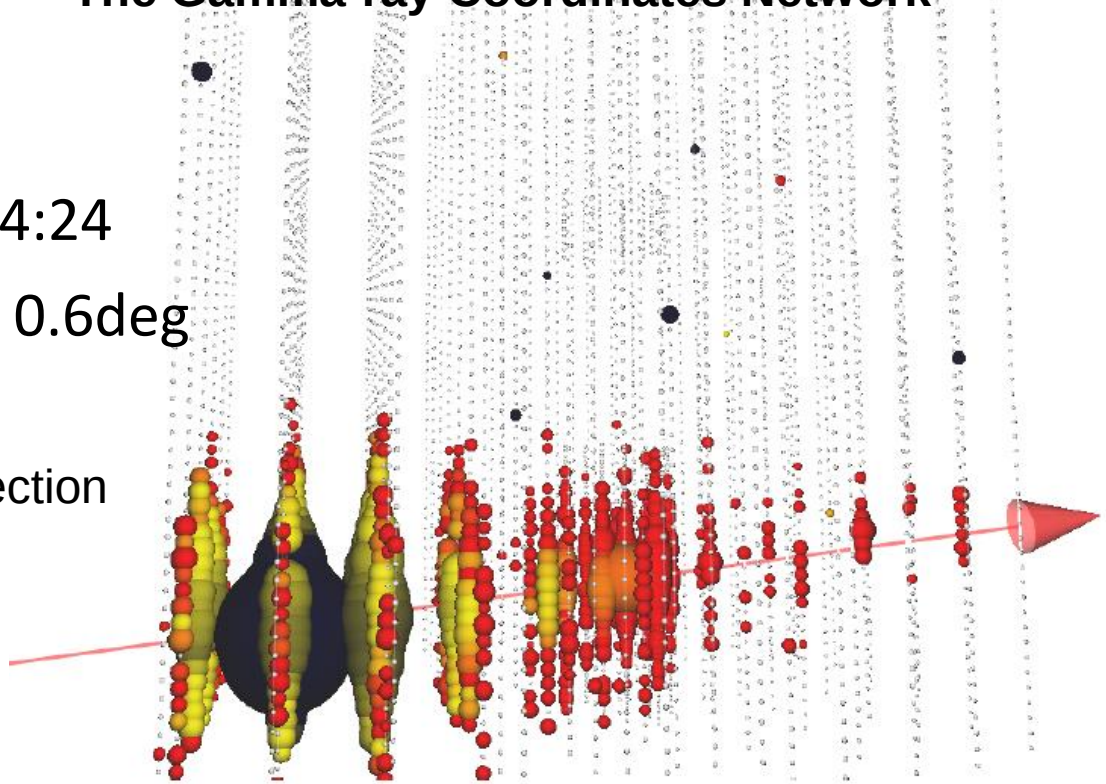
AMON ICECUBE_HESE EVENTS – Since April 2016 archived at https://gcn.gsfc.nasa.gov/amon_hese_events.html

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
56068624_130126	17/10/15	1:34:30.06	162.5790	-15.8611	73.79	13906.14	0.51
32674593_129474	17/05/06	12:36:55.80	221.6750	-26.0359	73.79	8685.07	0.35
65274589_129281	17/03/12	13:49:39.83	304.7300	-26.2380	73.79	8858.64	0.78
38561326_128672	16/11/03	09:07:31.12	40.8252	+12.5592	66.00	7546.05	0.30
58537957_128340	16/08/14	21:45:54.00	199.3100	-32.0165	89.39	10431.02	0.12
6888376_128290	16/07/31	01:55:04.00	215.1090	-0.4581	73.79	15814.74	0.91
67093193_127853	16/04/27	05:52:32.00	240.5683	+9.3417	35.99	18883.62	0.92

The first GCN notice: HESE-160427A

- Event occurred at 27th April 2016 at **05:52:32**
- First notice sent on 27th April 2016 at **05:53:53**
- Revised coordinates sent at 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**

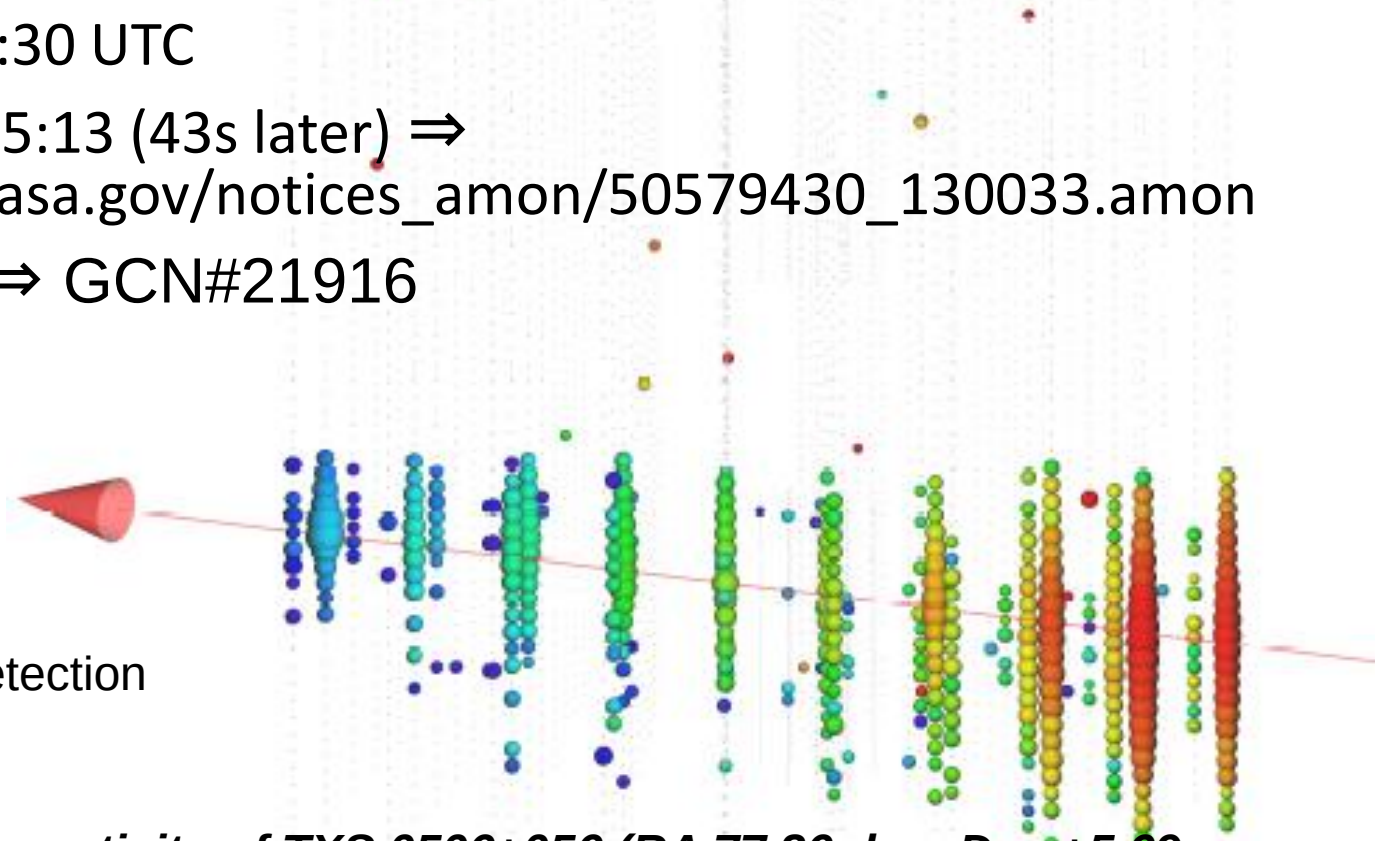
The Gamma-ray Coordinates Network



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

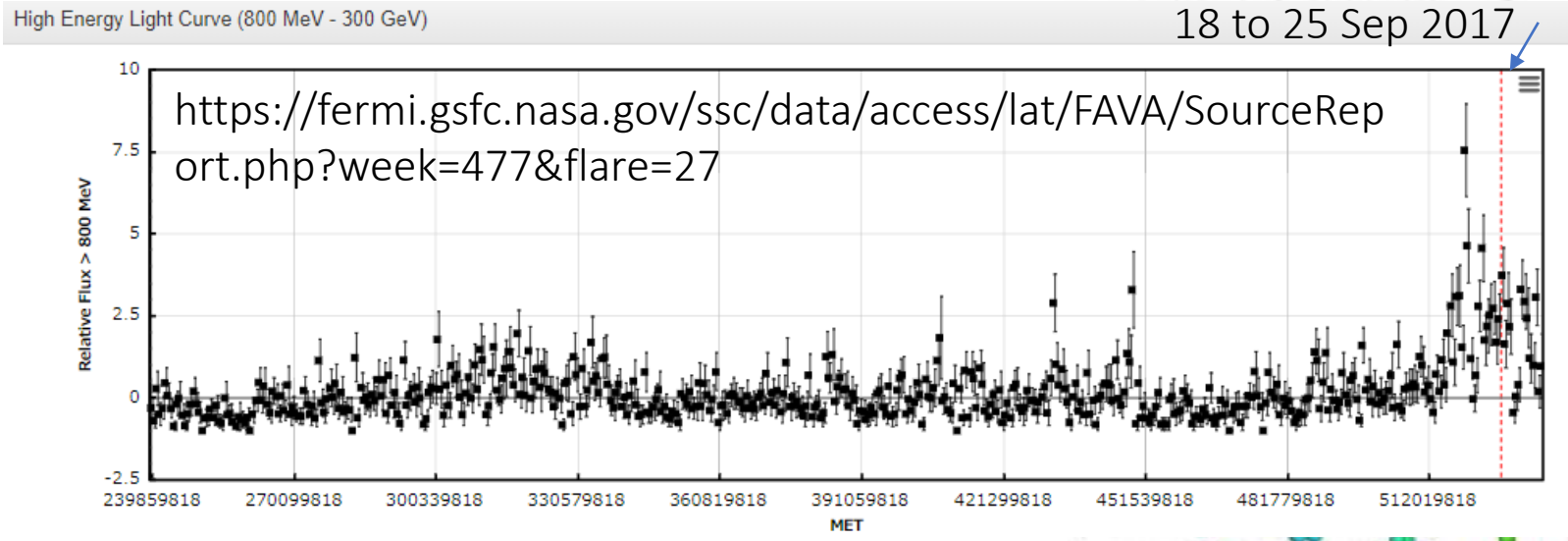
- Event occurred at 22nd Sept 2017 20:54:30 UTC
- First notice sent on 22nd Sept 2017 20:55:13 (43s later) ⇒ https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon
- Revised coordinates sent 4 hours later ⇒ GCN#21916
- Event direction RA $77.43^{+0.95}_{-0.65}$deg,

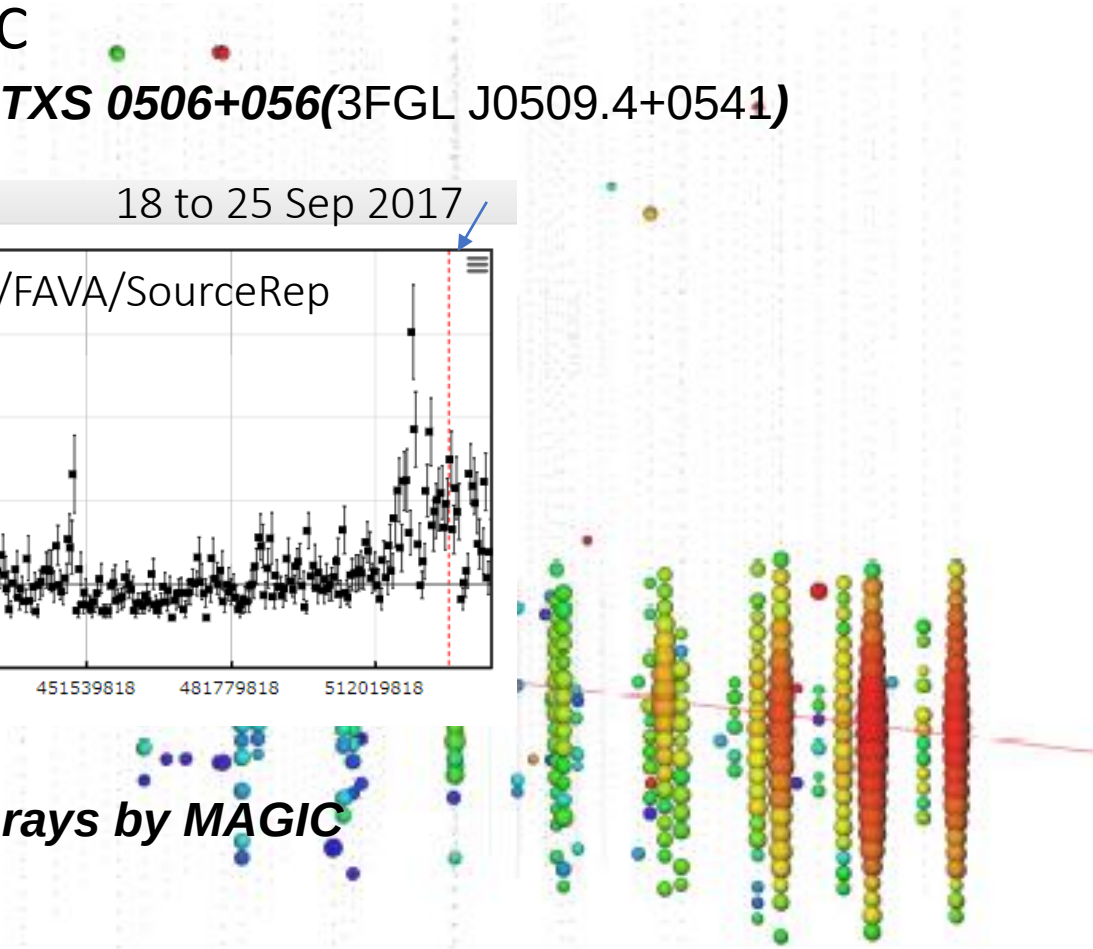
  Dec $+5.72^{+0.50}_{-0.30}$ deg, 90%CL
- Follow-up responses
  - GCN 21917 - Integral - No detection
  - GCN 21923/Atel 10773 - ANTARES - No detection
  - GCN 21924 - HAWK - no detection
  - GCN 21930 - SWIFT XRT - 9 x-ray emitters
  - ***ATel 10791 - Fermi - increased gamma-ray activity of TXS 0506+056 (RA 77.36 deg, Dec +5.69 deg)***
  - ATel 10787 - H.E.S.S. – no detection
  - ***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



The recent most hot alert: **EHE-170922A**

- Event occurred at 22nd Sept 2017 at 20:54:30 UTC
  - ***ATel 10791 - Fermi - increased gamma-ray activity of TXS 0506+056(***3FGL J0509.4+0541***)***





  - ***ATel 10817 – The First-time detection of VHE gamma rays by MAGIC***

MAGIC observed this source under good weather conditions for 12 h of observations from September 28th till October 3rd.
...and a 5 sigma detection above 100 GeV was achieved!

The first time measurement of VHE gamma-ray from a direction consistent with a detected neutrino event

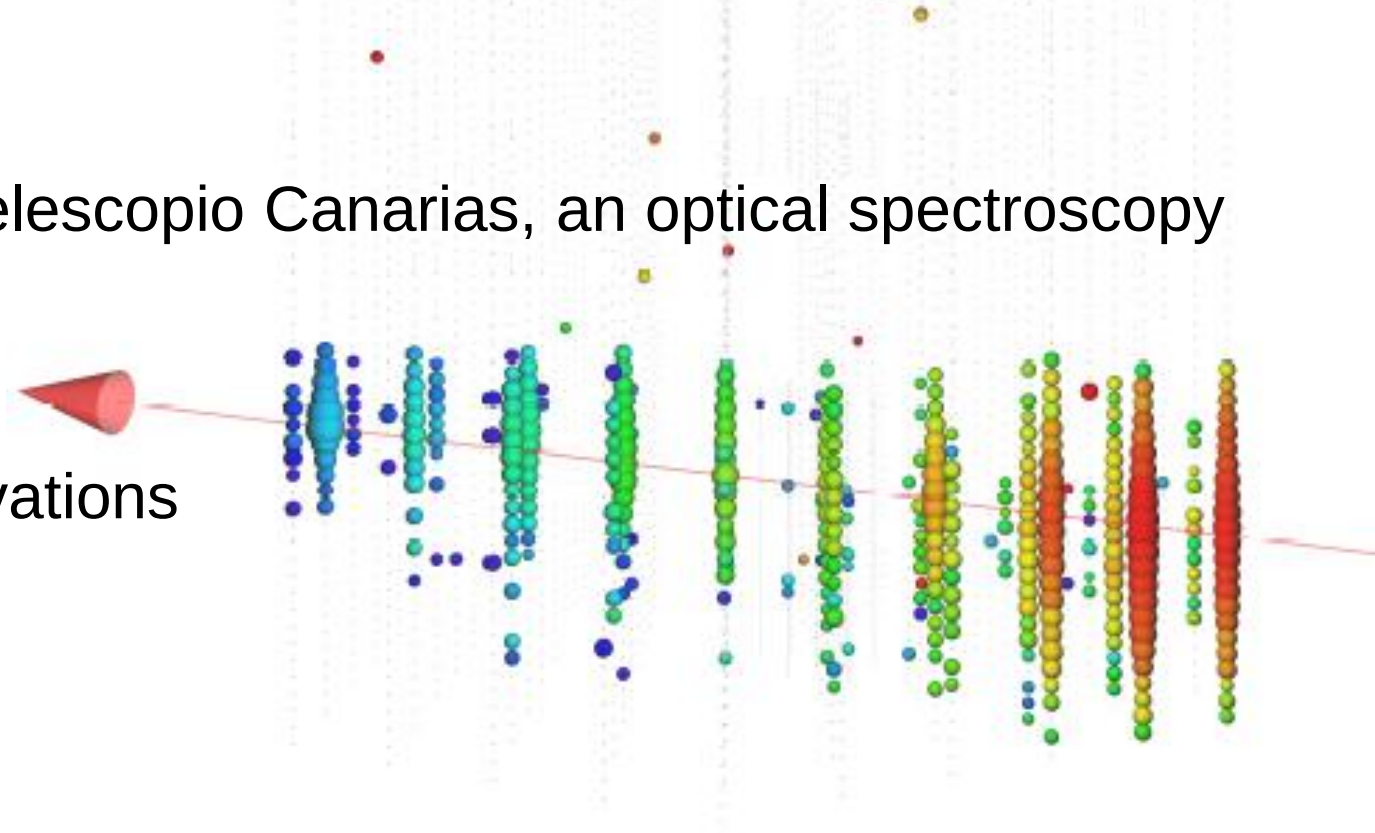
The recent most hot object: ***TXS 0506+056***

- ***Distance to TXS 0506+056?***

Paiano et al. (2018):the 10.4m Gran Telescopio Canarias, an optical spectroscopy

⇒ z = 0.3365 +/- 0.0010

consistent with VHE gamma-ray observations



Summary

- Cosmogenic neutrino search with 7+2 years of IceCube data
- *Stringent upper limits on neutrino above 10 PeV* with an interesting *event at 6 PeV*
- Constraints on source parameters
  - Proton dominant UHECR sources with cosmological evolution equal to or stronger than SFR disfavored - UL on proton components
- Quick and robust event selections for diffuse analyses – HESE and EHE – lead to on-ice "real time" *semi*-automated event alert system with high signal-likeness – with ~8 events/year rate
- The first association with the wide wavelength flaring AGN which is also VHE gamma-ray emitting object