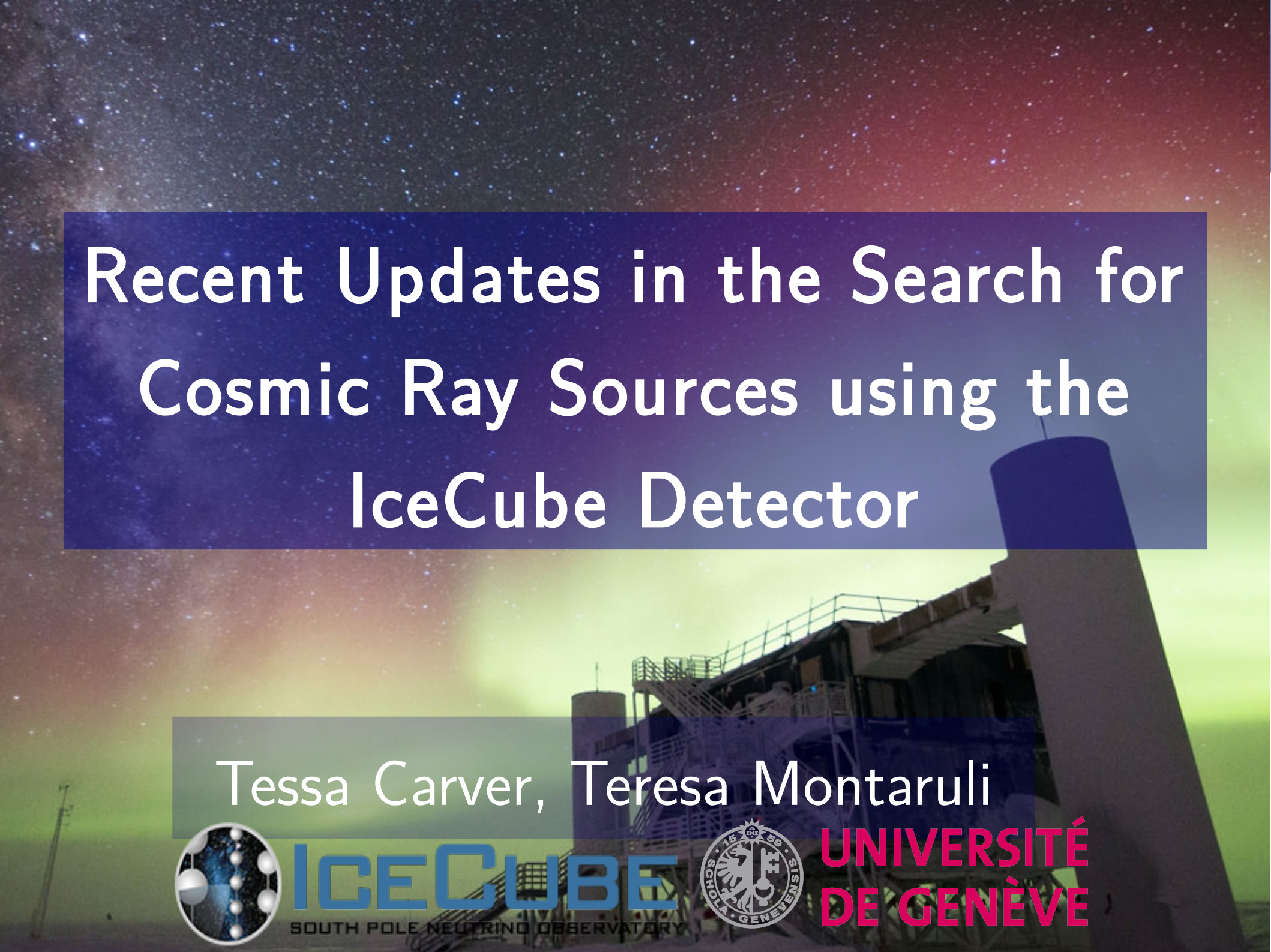


Recent Updates in the Search for Cosmic Ray Sources using the IceCube Detector

Tessa Carver, Teresa Montaruli

IceCube SOUTH POLE NEUTRINO OBSERVATORY

UNIVERSITÉ DE GENÈVE

Current Extraterrestrial Observations

- Observations using **Photons** :

  → Lowest Energy range ~ eV :

  examples : CMB

  → Highest energy Gamma Ray ~ 100TeV

  examples : Active Galactic Nuclei, Supernova Remnants, Starburst Galaxies etc

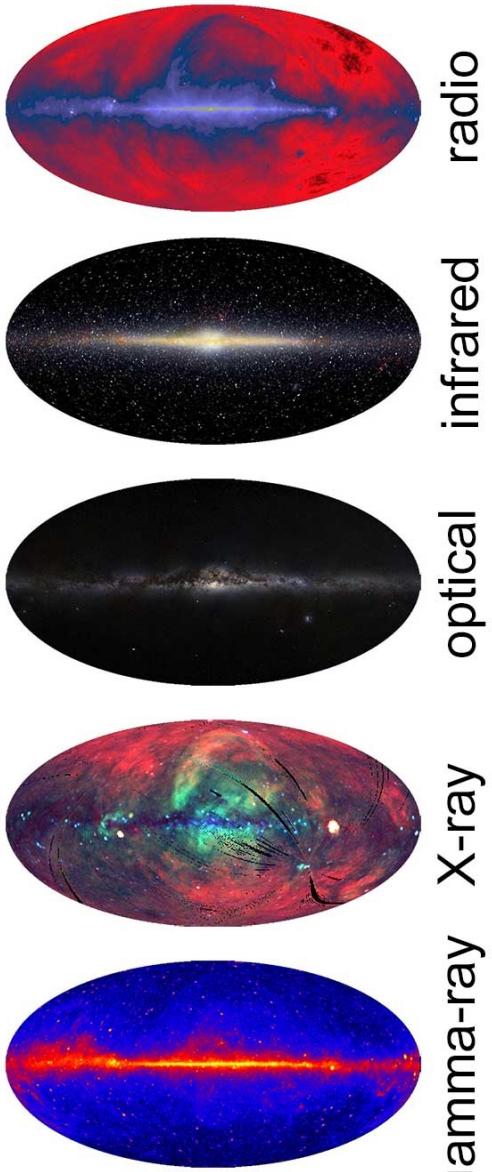
- Aside from photons **other messenger particles** are also observed:

  → CR : TA, Pierre Auger

  → GW : LIGO, Virgo

  → Neutrino : Antares, IceCube

  Information is combined from these messengers to discover the sources of Cosmic Rays which are currently unkown.



https://imagine.gsfc.nasa.gov/science/toolbox/multiwavelength1.html

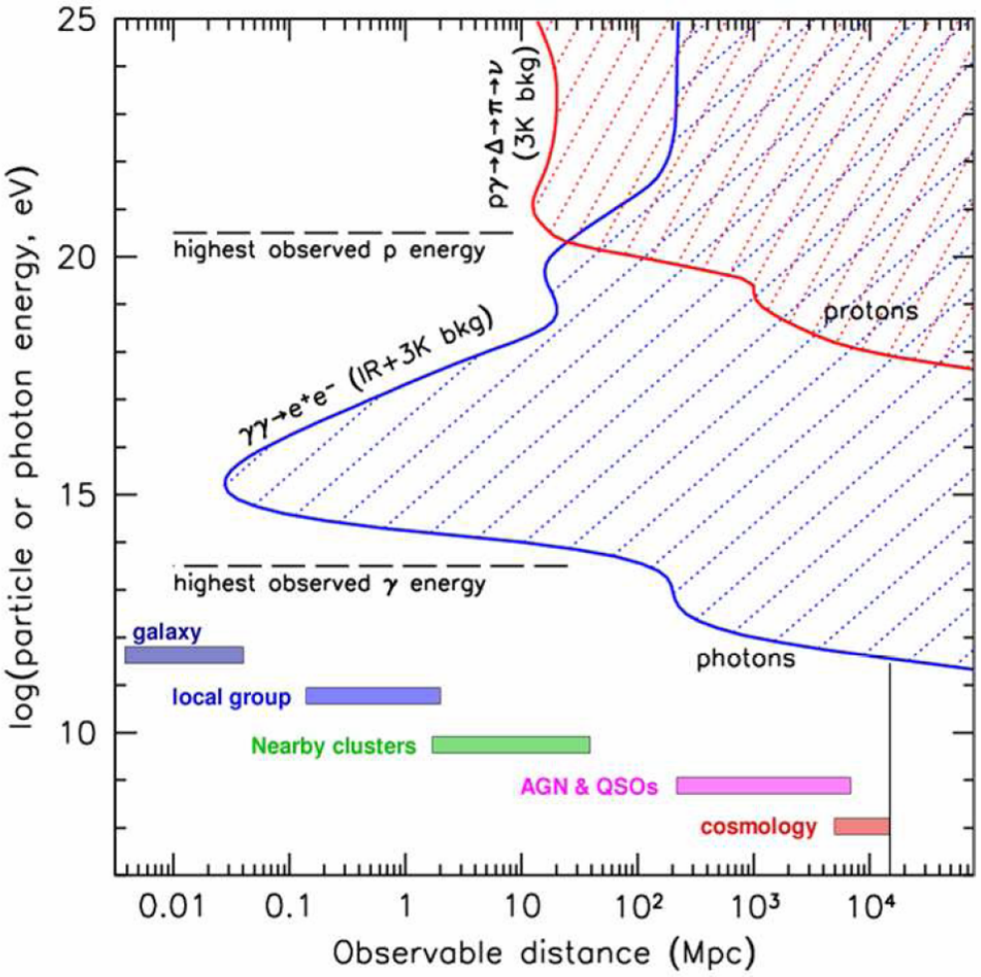
Messenger Particles

- **Protons / Cosmic Rays** : directly from the astrophysical sources.
- **Photons** : produced by CR interactions : Leptonic and Hadronic
- **Neutrinos** : produced only by Hadronic CR interactions.

Hadronic Interactions :

$$pp \Rightarrow \pi^0 \Rightarrow \gamma\,\gamma$$

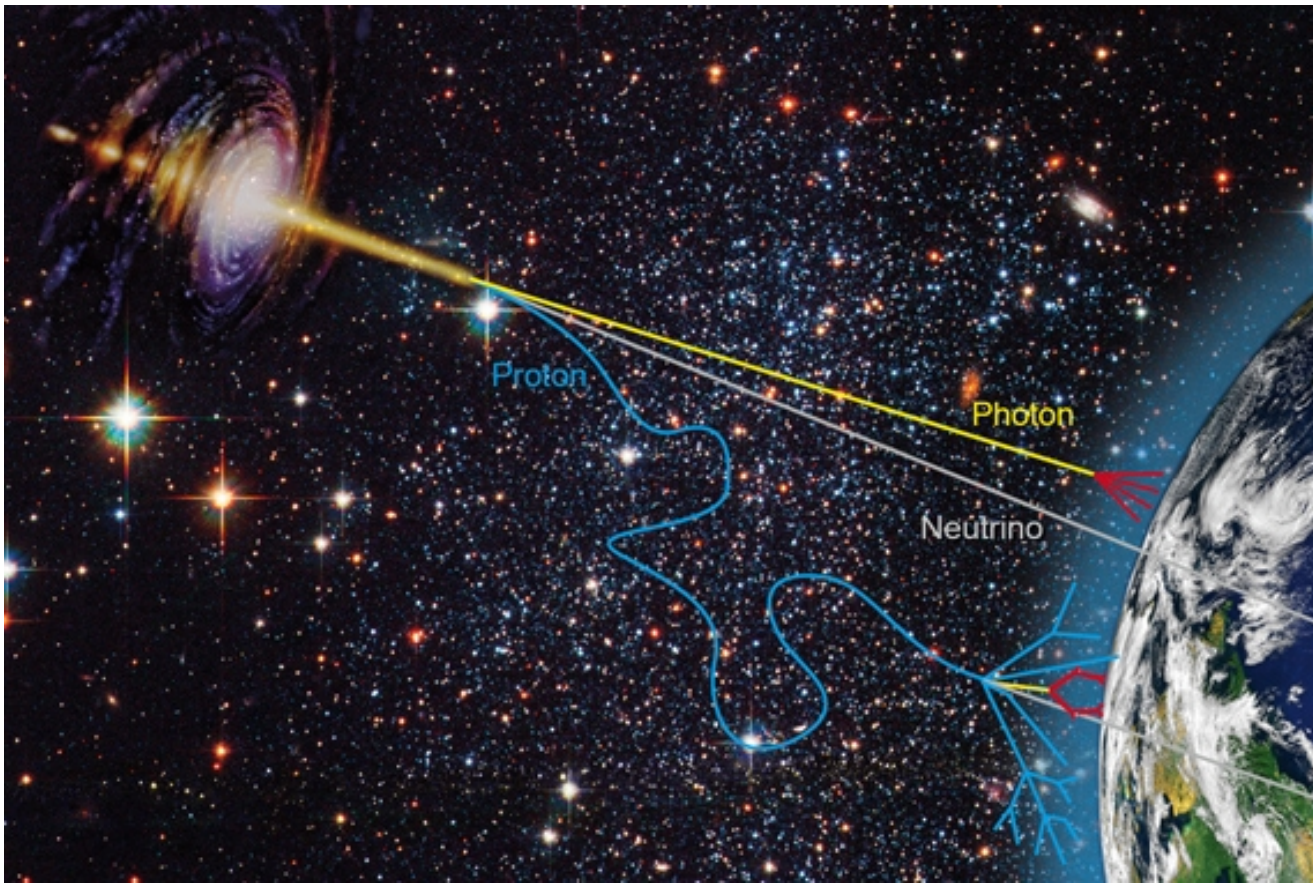
$$pp \Rightarrow \pi^{\pm 1} \Rightarrow \mu^{\pm 1} + \nu_\mu$$



Pointing with Neutrinos

Other messenger particles are attenuated and/or **deviated** on their journey towards the earth.

Neutrinos travel unimpeded accross the universe so they can point **directly towards the source**.



Schematic view of the intergalactic trajectories of ultra-high energy protons, photons, and neutrinos.
Image credit: DESY/Zeuthen

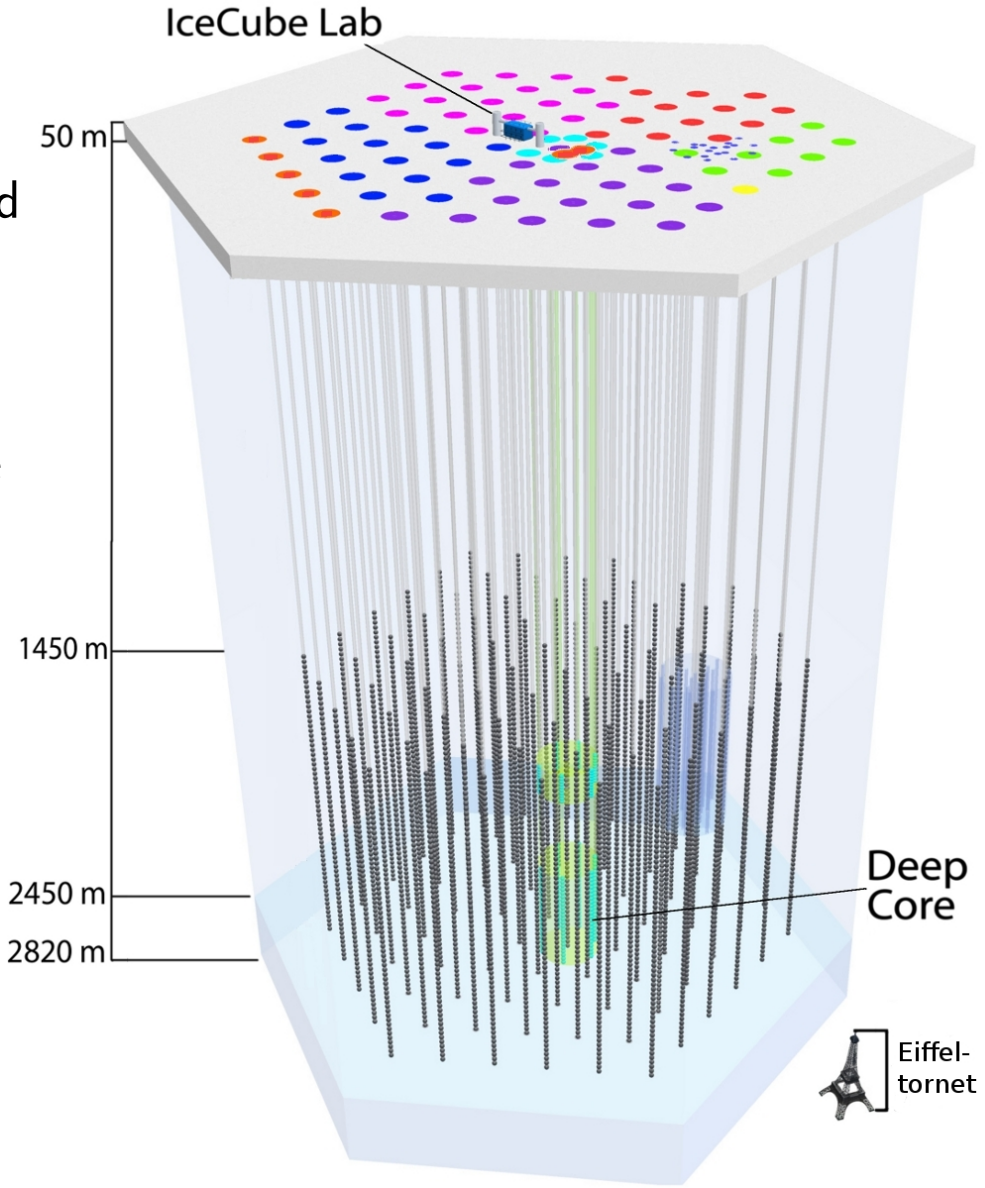
IceCube Detector

What Do We Detect ?

- Neutrinos interact in the ice producing charged leptons.
- Charged leptons then induce Cherenkov radiation during their propagation through the ice.

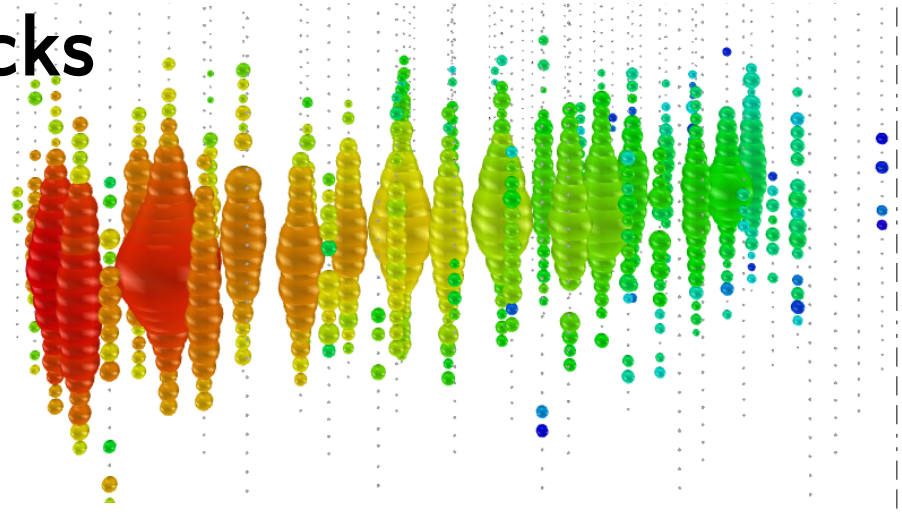
How ?

- 86 strings in cubic Km of Antarctic Ice over 1Km below the surface.
- Each string contains 60 Digital Optical Modules (DOMs) for observing Cherenkov Radiation in the ice.



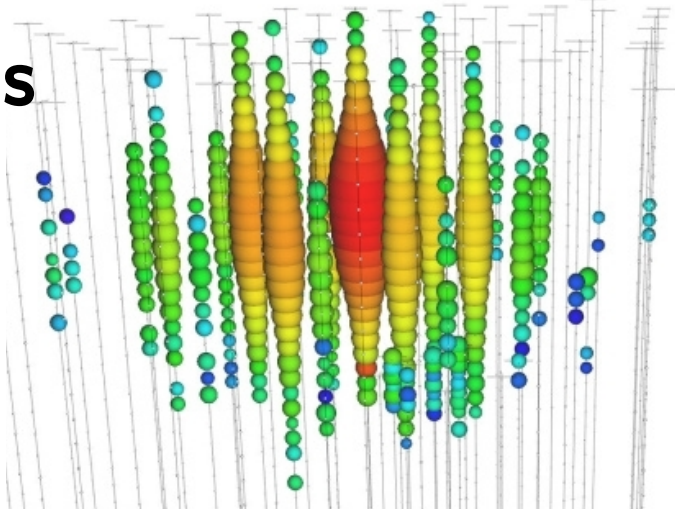
IceCube Events

Tracks



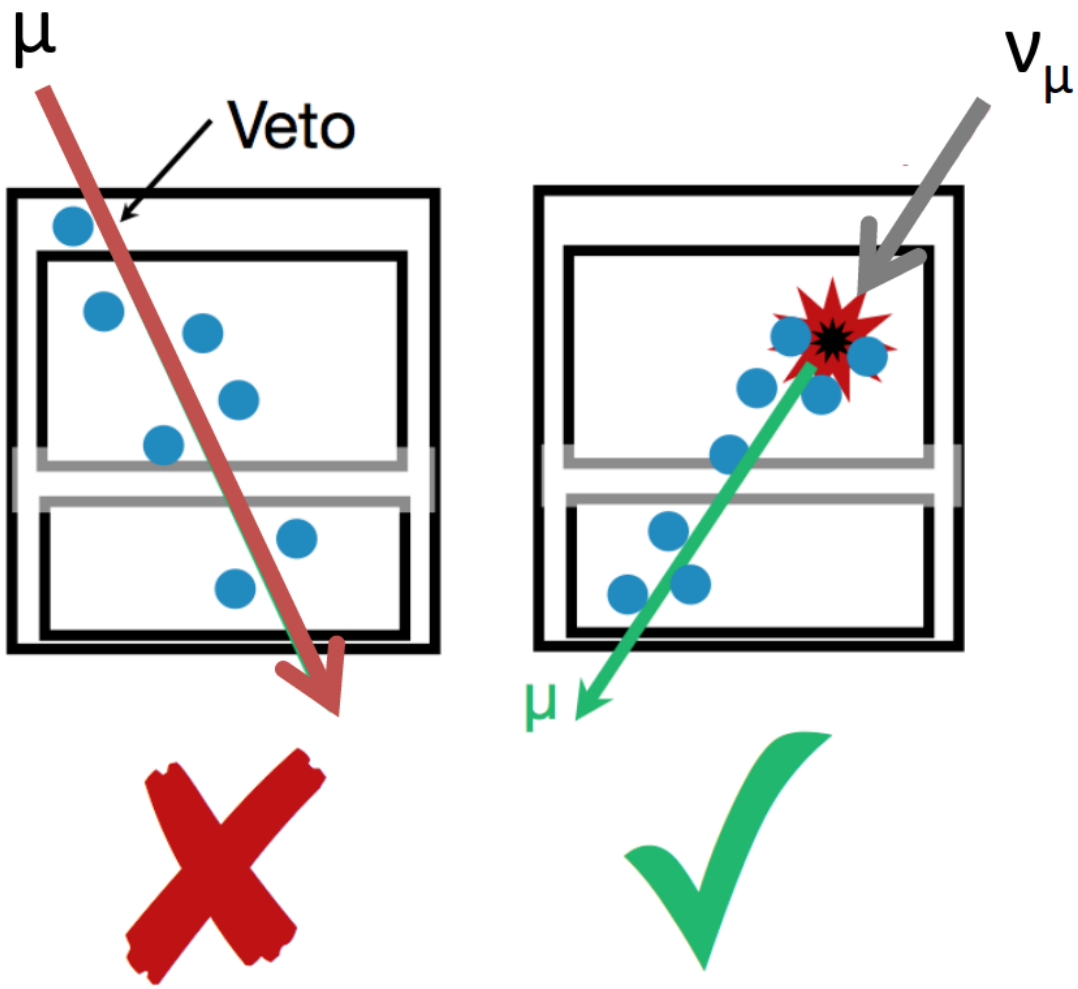
- High Energy Muons propagate in the ice.
- From: Atmospheric Muons, and Charged Current ν_μ interactions.
- Angular Resolution $\sim 1^\circ$
- Poor Energy resolution

Cascades



- Shower of charged particles in the ice
- From: ν_τ, ν_e and Neutral Current ν_μ interactions.
- Angular Resolution $\sim 10^\circ$
- Good Energy Resolution

High Energy Starting Events



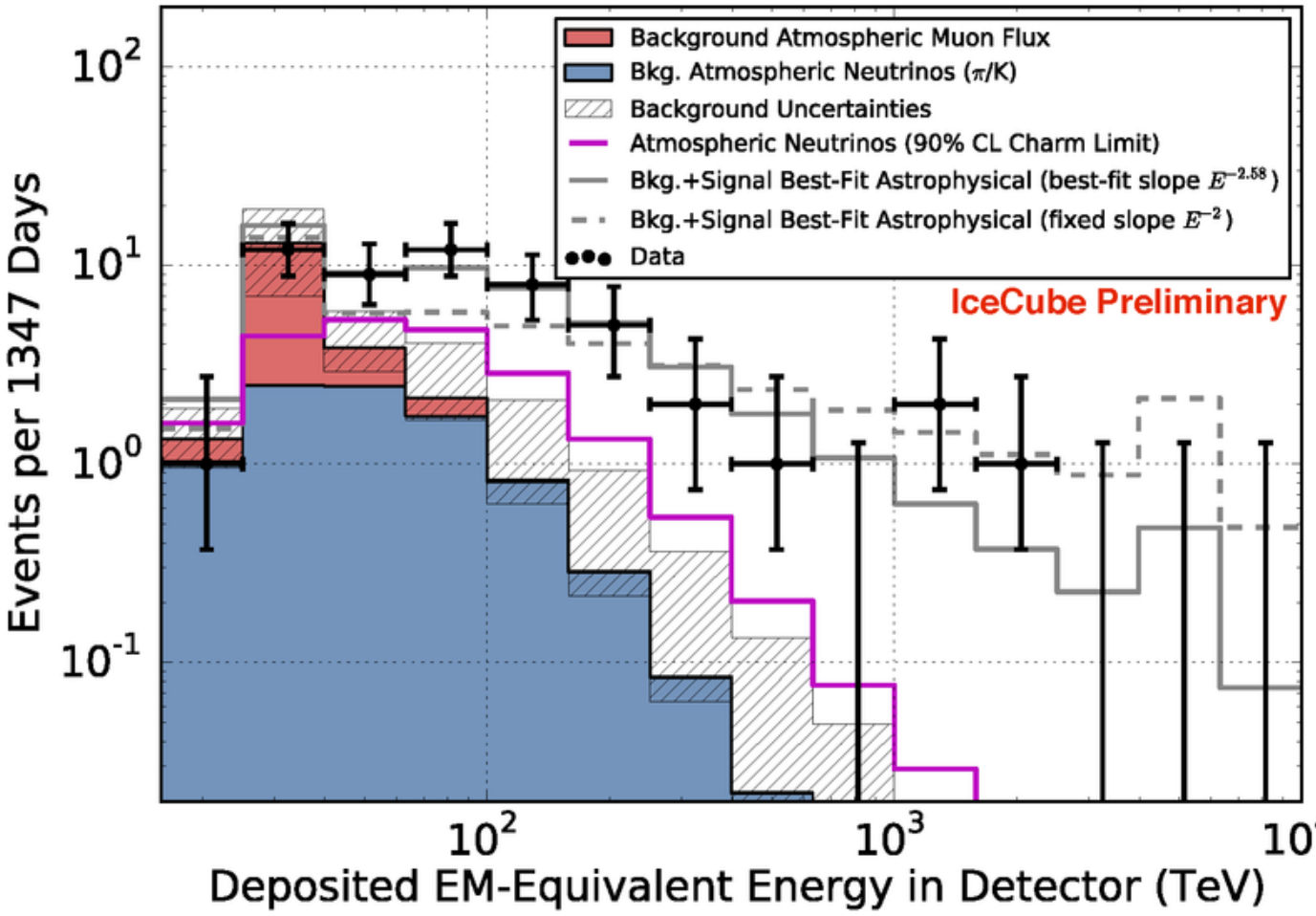
Massively reduce Muon background by demanding only events that start inside detector.

Also increase purity by strict energy threshold of 6000 photoelectrons observed. (approx 30TeV)

There is also an ***active veto*** which eliminates starting events in coincidence with muon tracks to remove obvious atmospheric ν_μ

HESE flux

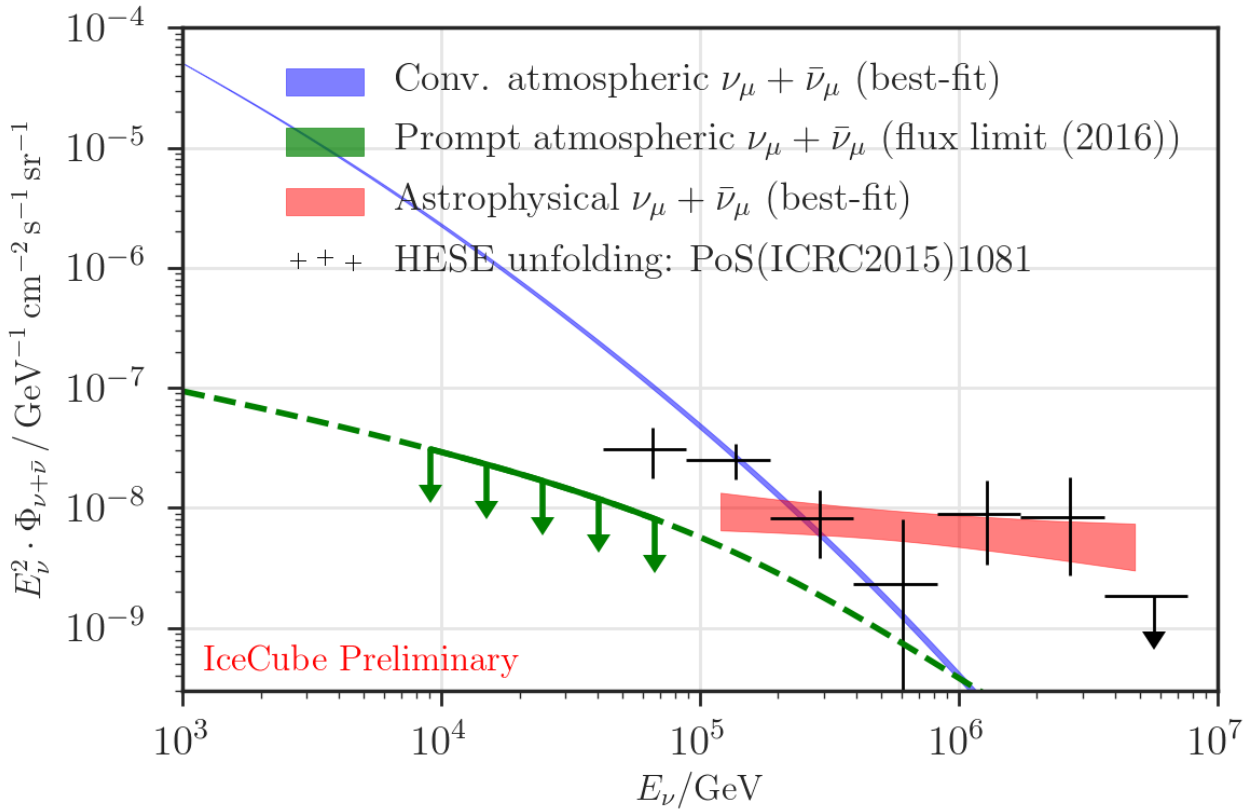
- IceCube was the first to observe an Astrophysical Neutrino Flux :



54 events were observed (PoS(ICRC2015)1081) with 20±6 expected from atmosphere depositing $>$ 30TeV in the detector.

An unbroken power law fit points to a spectral index of -2.58±0.25

Diffuse Flux



Updated 8 year Diffuse Muon Neutrino Sample

→ Looser cuts applied

→ Only high quality track events

A fit is constructed for :

→ atmospheric,

→ astrophysical

→ prompt

Components of the neutrino spectrum

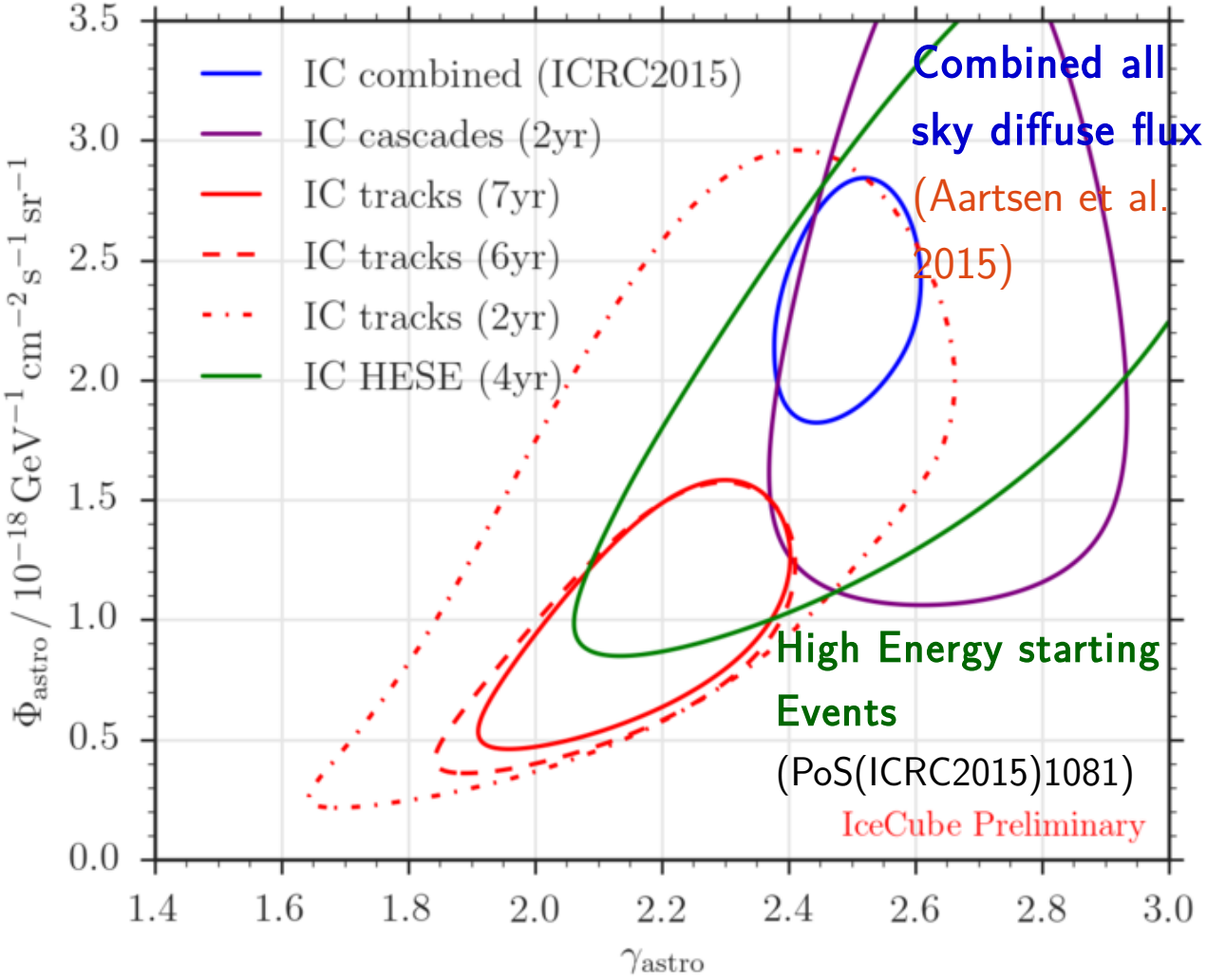
Astrophysical fit :

$$\Phi_{\nu+\bar{\nu}} = 1.01^{+0.26}_{-0.23} \times \left[\frac{E_\nu}{100\,TeV}\right]^{-2.19\pm0.10}$$

In units of :

$10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$

Spectral Fit Comparisons

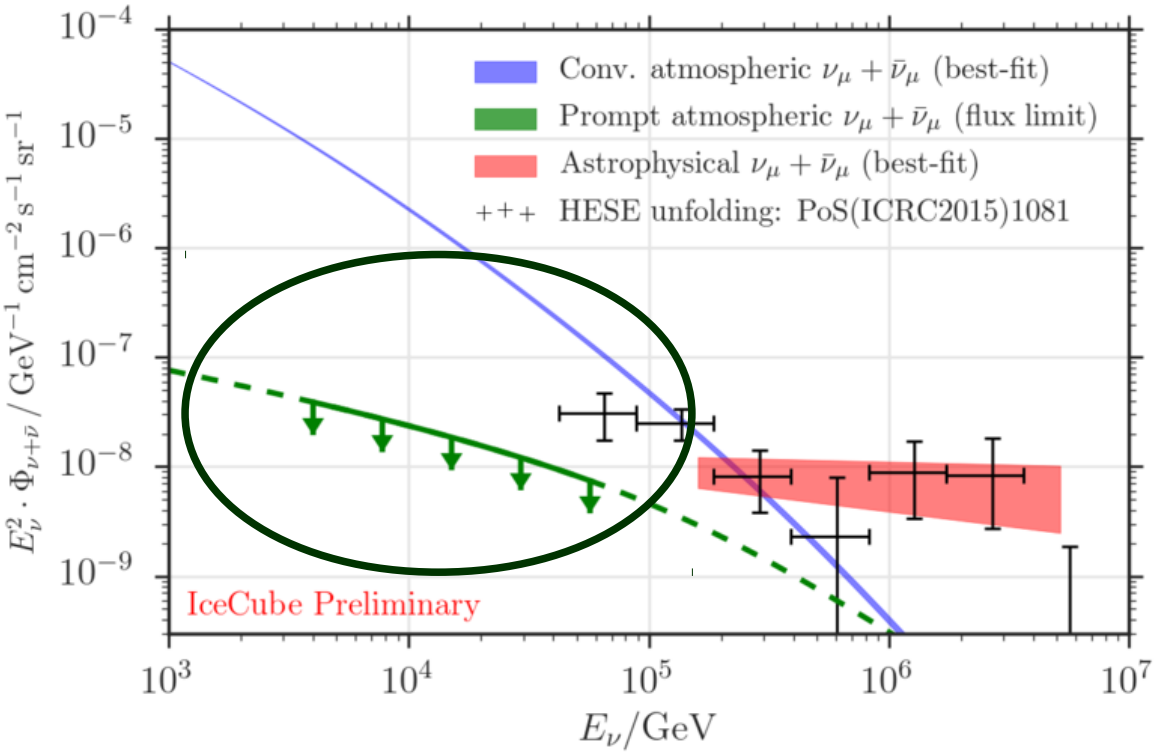


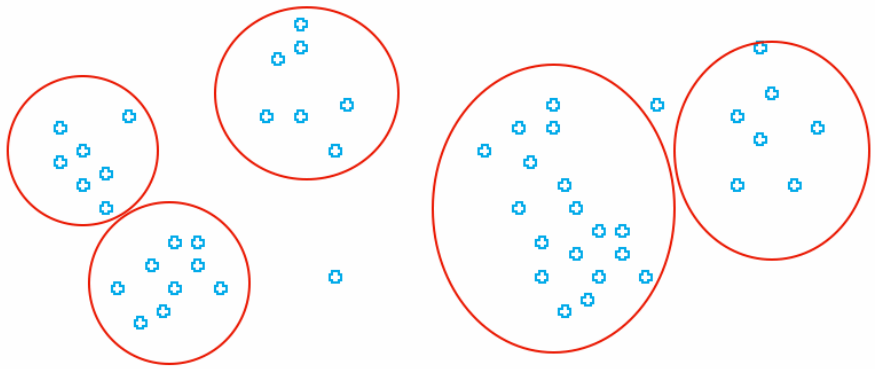
Combined results → $E^{-2.5}$ for a simple unbroken power-law spectrum.

Regions here show 90% C.L.

Tension in results could be variations due to factors such as a break in the flux or a prompt component

Where do they come from ?



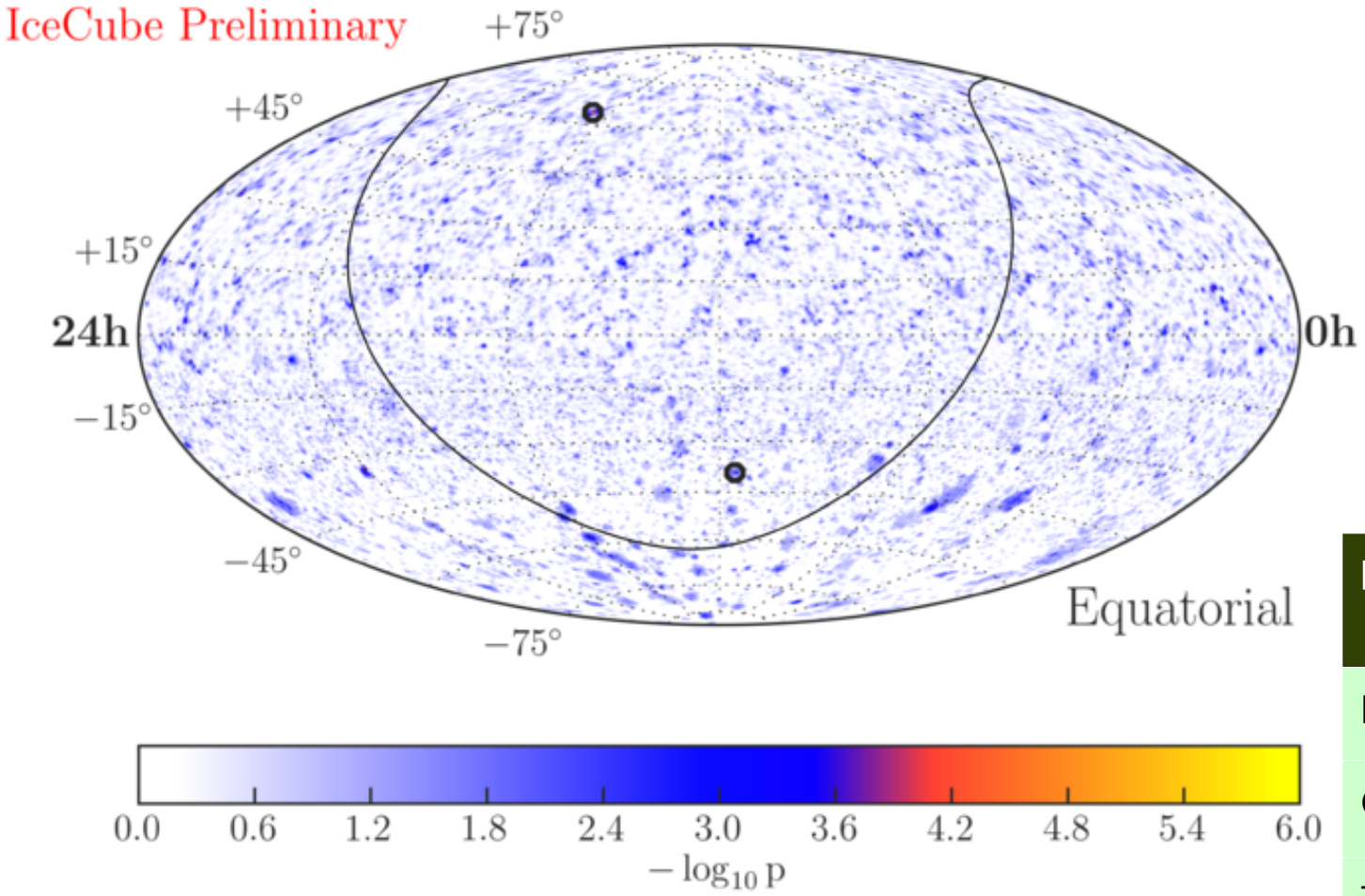


- If we loosen cuts to allow more signal the data becomes dominated by atmospheric events.
- However, we expect :

  → *Clustered* signal (in space and/or time)

  → *Uniform* Background
- Searching for clustering takes advantage of all the signal that is currently *hidden* amongst background

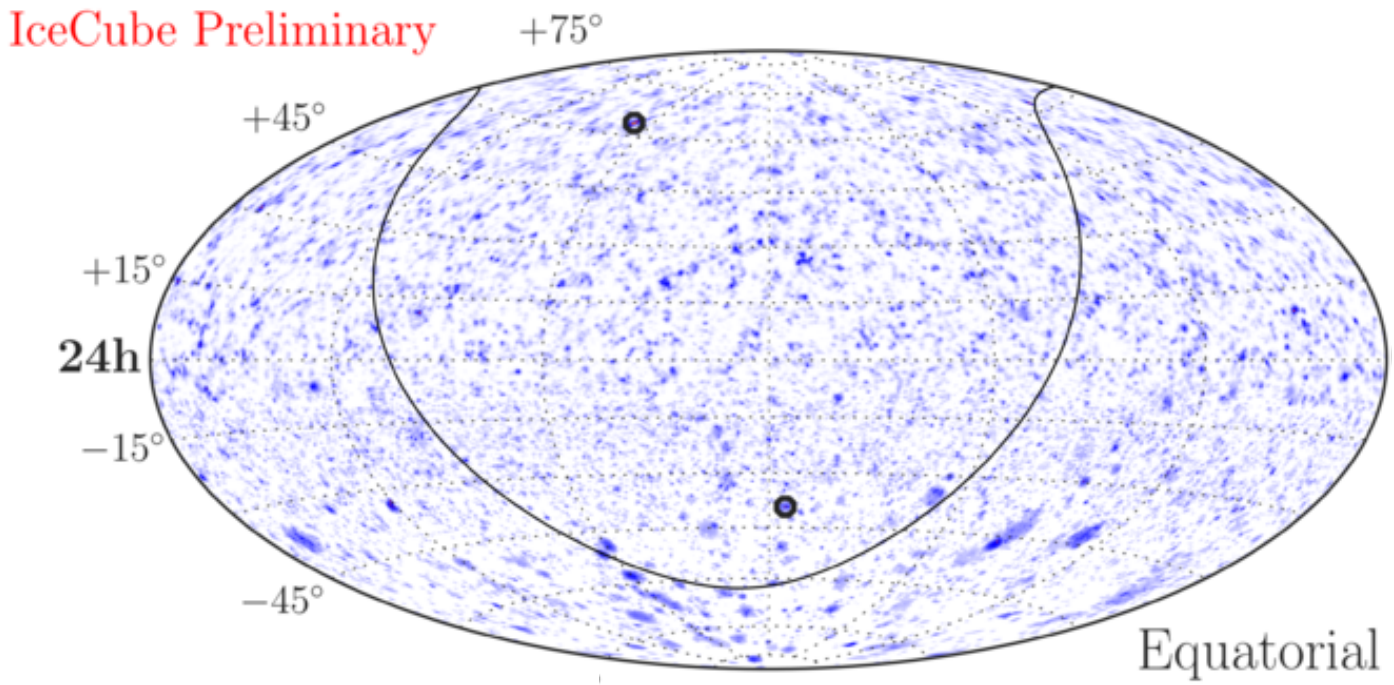
7 year Time Integrated All Sky Scan

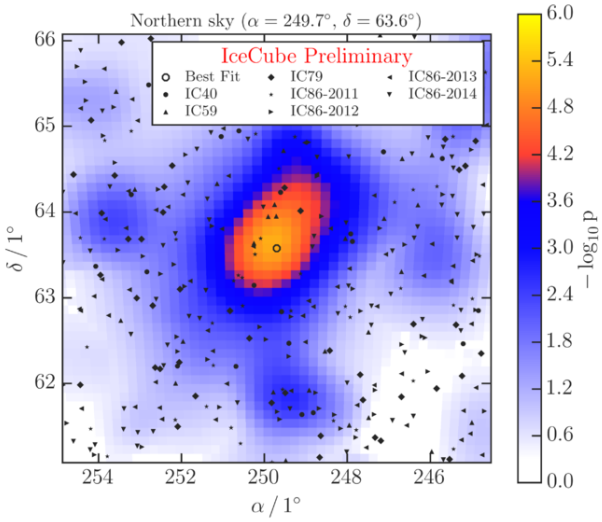


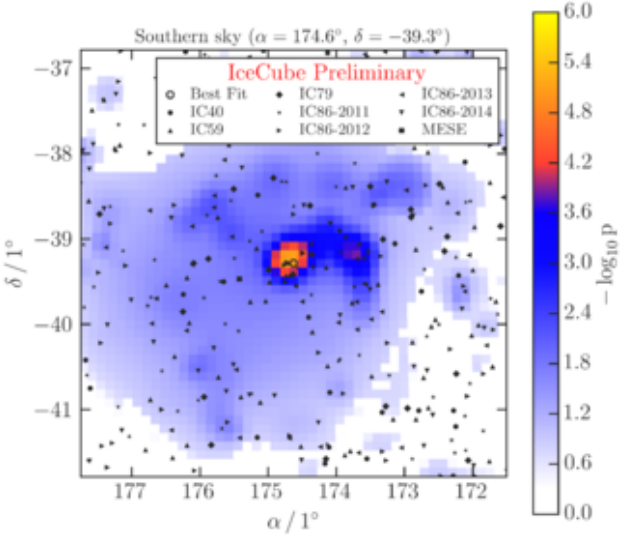
Using event selection starting from ~ 1 TeV

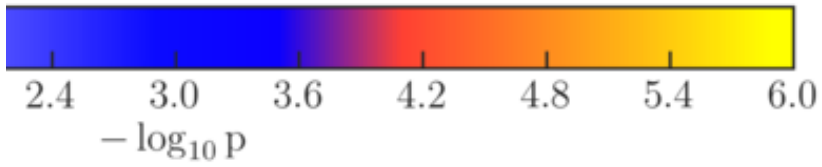
Hemisphere	North	South
N sources	27.22	15.54
Gamma	1.95	2.84
Test Statistic	18.99	20.26
Post Trial P	44 %	39 %

7 year Time Integrated All Sky Scan



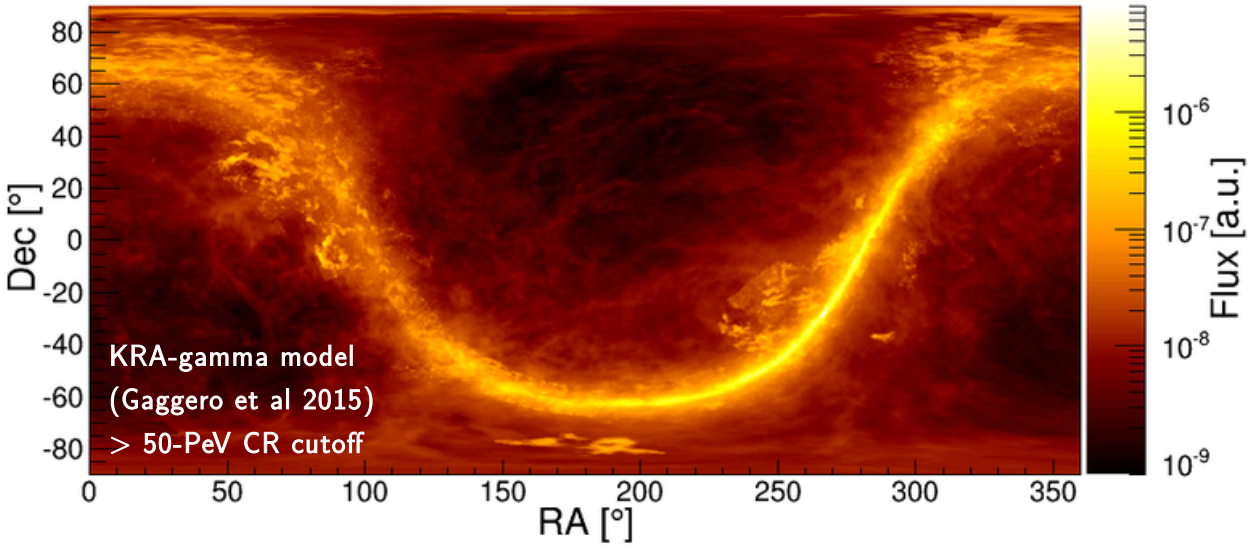




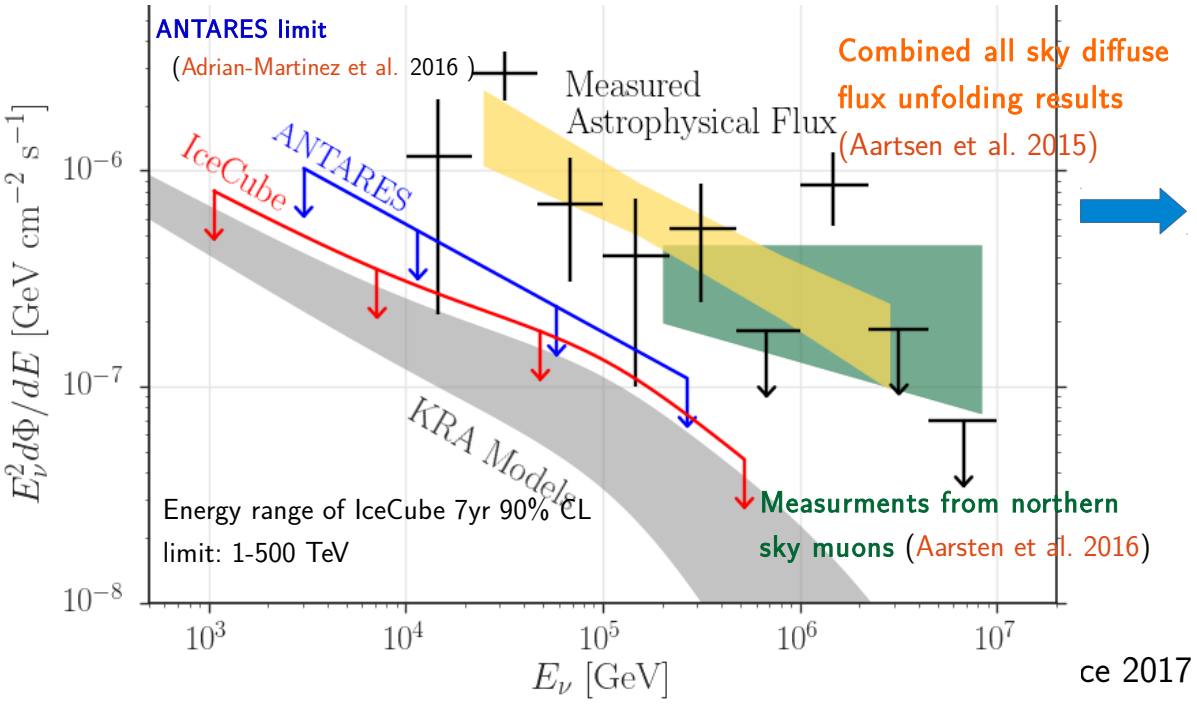


Hemisphere	North	South
N sources	27.22	15.54
Gamma	1.95	2.84
Test Statistic	18.99	20.26
Post Trial P	44 %	39 %

Galactic Plane Correlation



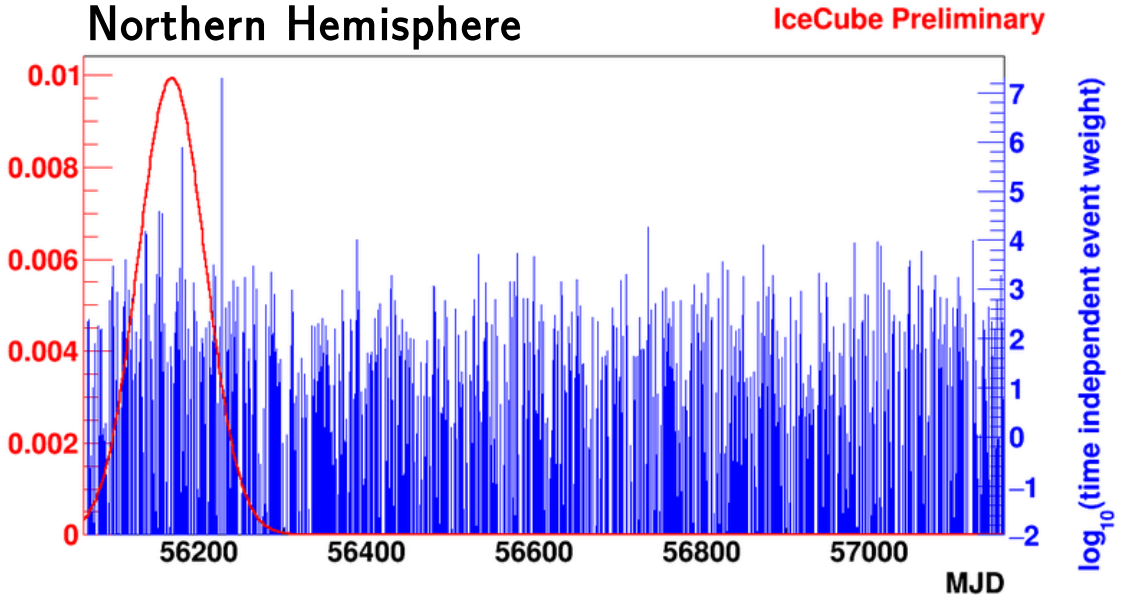
Multiple models of the Galactic plane used as a template for the source signal.

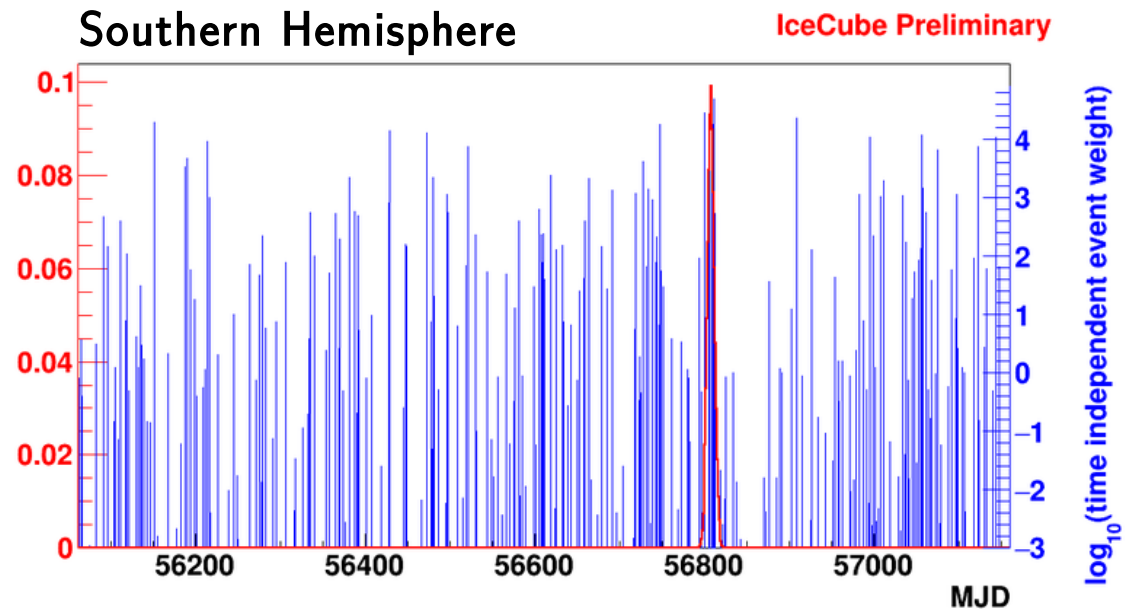


Maximum of 14% of the isotropic diffuse neutrino emission comes from the galactic plane for the case of the Fermi-LAT template with an $E^{-2.5}$ power law.

ce 2017

Time Dependent - Untriggered





- Look for clustering in **time** as well as space :

  → add time variable to the likelihood.

- Plots show :

  → **Gaussian best fit** compared to

  → **IceCube events**

  as a function of time.

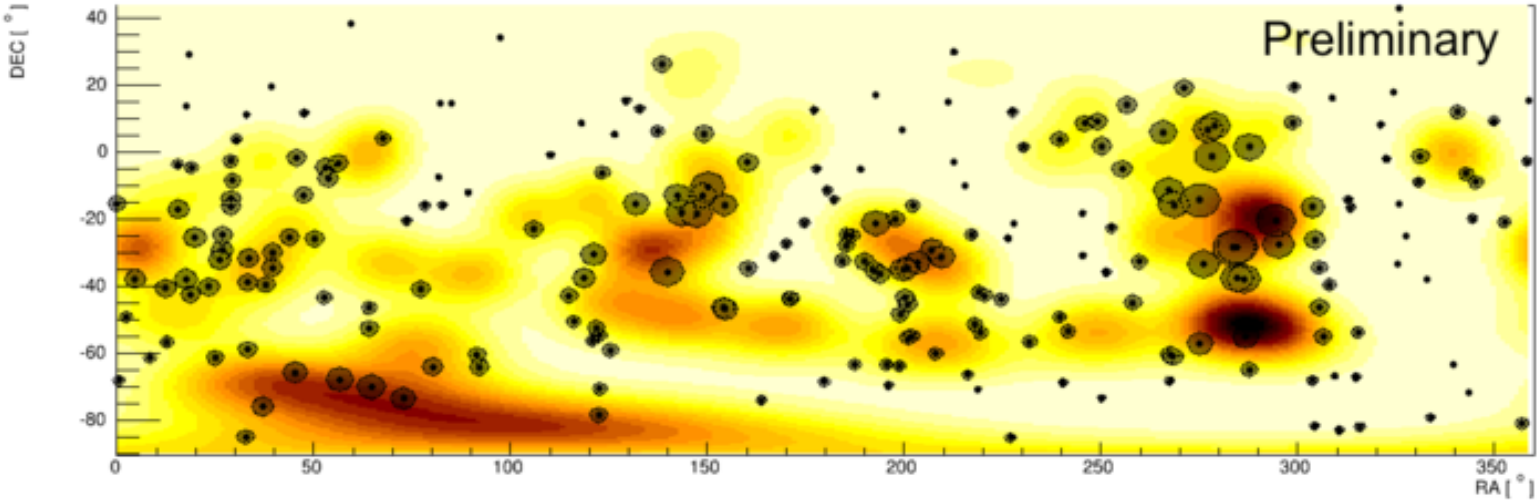
	North	South
Ra (°)	170.35	89.45
Dec (°)	27.95	-35.95
Best fit N° Signal Events	11.08	7.46
Best-fit mean date	28.8.2012	31.5.2014
Best-fit time width (days)	40.0	4.01
Post Trial P	**12.6**	**22.4**

Ultra High Energy Cosmic Rays

- Unbinned analysis to test correlation of 6 years of Icecube Tracks & Cascades with UHECRs assuming deflection angles of : 3°,6°, and 9°

CR events Above ~50EeV	Telescope Array : **109**	Pierre Auger Observatory : **231**
IceCube events	Tracks : **49**	Cascades : **58**

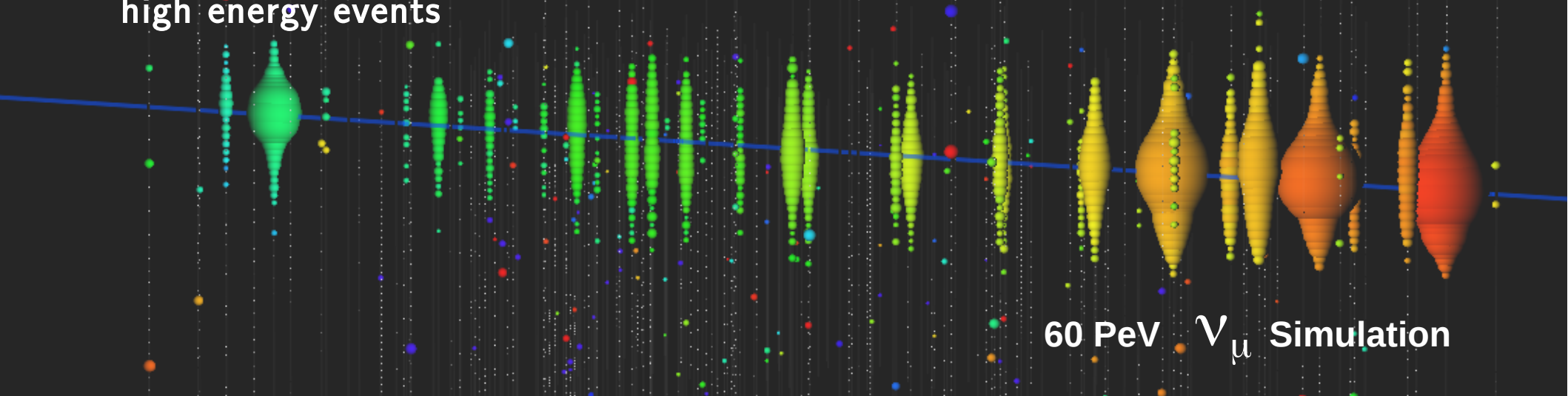
➡ Most significant result found for Cascades assuming 6° deflection.
With the addition of 2 years of HESE events this **significance has fallen from 3σ→ 2σ**



- Neutrino signal PDF with **PAO events**
- Consistent results seen from an independent analysis using the same data.

Summary & Outlook

- We observe an astrophysical neutrino flux
- We are still searching for sources of this flux and more information on the spectral properties.
- Source searches look for clustering in space and time or correlations with sources and events observed by other telescopes.
- We now have alerts that send track details to other telescopes to catch transient sources in real time.
- We plan to upgrade to IceCube in the future expanding the effective area for high energy events



Thank you !

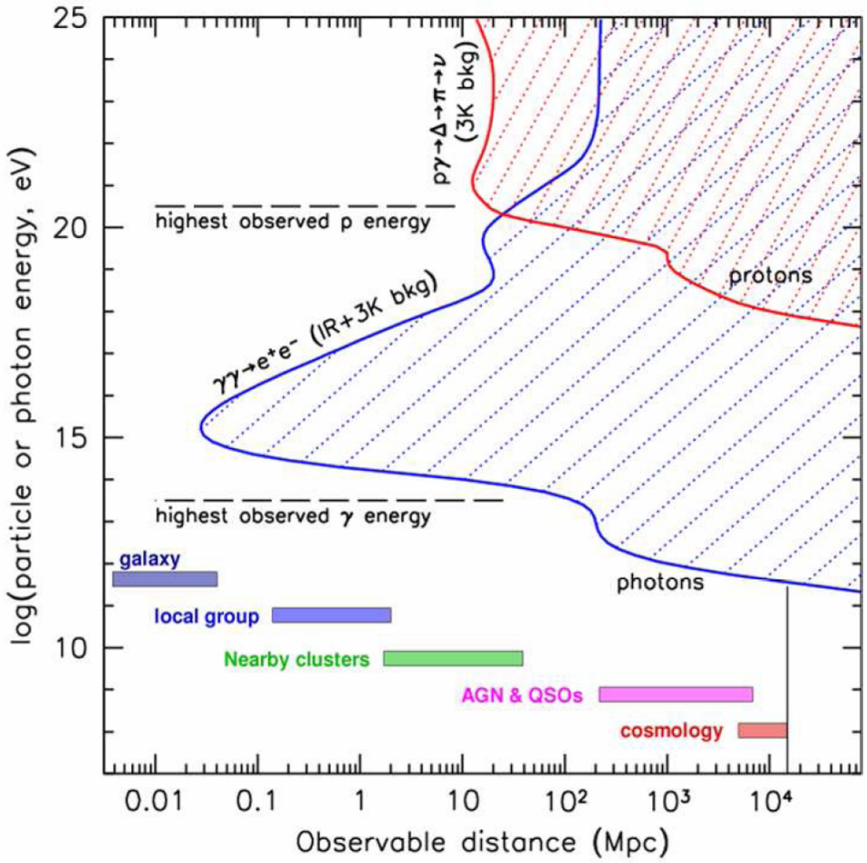
Backup

Messenger Particles

- **Protons / Cosmic Rays** : directly from the astrophysical sources.
- **Photons** : produced by CR interactions : Leptonic and Hadronic
- **Neutrinos** : produced only by Hadronic CR interactions.

Hadronic Interactions :

$$pp \Rightarrow \pi^0 \Rightarrow \gamma\,\gamma$$
$$pp \Rightarrow \pi^{\pm 1} \Rightarrow \mu^{\pm 1} + \nu_\mu$$



- Above certain energies the universe becomes opaque at far distances to photons and protons but not to neutrinos.
- Neutrinos have a horizon comparable to the dimension of the universe and thus can provide unequivocal evidence that sources accelerate matter and thus CRs.

Real Time Alerts

- Working with other telescopes to identify flaring objects in real time.
- There are multiple analyses or alerts triggered by IceCube events which allow coincidences between IceCube and other telescopes to be investigated :

  $\rightarrow$HESE/EHE Alerts : Events over a certain energy threshold are quickly reconstructed to a high level and their properties sent to The Astrophysics Multimessenger Observatory Network.

  $\rightarrow$ Optical Follow Up : Triggered by multiple IceCube events within 100s in the northern hemisphere targeting SN or GRB transients. Information sent to PTF, SWIFT and XRT

  $\rightarrow$ Gamma Follow Up : Triggered by neutrino bursts over a period of up to 3 weeks from a selection of known AGNs. Information sent to Magic and Veritas.

7 year Time Integrated Catalog Search

Type	Source	α	δ	p-Value	n_S	γ	B_{1°	Φ
BL Lac	PKS 0537-441	84.71	-44.09	—	0.0	—	45.7	—
BL Lac	PKS 2155-304	329.72	-30.23	—	0.0	—	52.6	—
BL Lac	PKS 0235+164	39.66	16.62	0.27	12.2	3.4	72.0	0.76
BL Lac	1ES 0229+200	38.20	20.29	0.13	13.9	4.0	66.6	0.98
BL Lac	W Comae	185.38	28.23	—	0.0	—	60.8	—
BL Lac	Mrk 421	166.11	38.21	0.25	3.2	1.9	53.1	0.97
BL Lac	Mrk 501	253.47	39.76	0.17	13.5	4.0	52.0	1.16
BL Lac	BL Lac	330.68	42.28	—	0.0	—	50.4	—
BL Lac	H 1426+428	217.14	42.67	—	0.0	—	50.9	—
BL Lac	3C66A	35.67	43.04	—	0.0	—	50.9	—
BL Lac	1ES 2344+514	356.77	51.70	—	0.0	—	46.3	—
BL Lac	1ES 1959+650	300.00	65.15	0.032[†]	15.3	3.2	42.8	2.27
BL Lac	S5 0716+71	110.47	71.34	—	0.0	—	38.4	—
FSRQ	PKS 1454-354	224.36	-35.65	0.088	3.9	2.4	49.1	9.54
FSRQ	PKS 1622-297	246.53	-29.86	0.049	5.2	2.3	52.7	9.04
FSRQ	QSO 1730-130	263.26	-13.08	—	0.0	—	49.8	—
FSRQ	PKS 1406-076	212.24	-7.87	0.010[†]	12.8	2.8	50.5	1.93
FSRQ	QSO 2022-077	306.42	-7.64	0.28	0.9	1.6	50.5	0.95
FSRQ	3C279	194.05	-5.79	—	0.0	—	54.3	—
FSRQ	3C 273	187.28	2.05	0.13	14.7	3.2	76.4	0.75
FSRQ	PKS 1502+106	226.10	10.49	0.37	4.1	2.6	73.7	0.60
FSRQ	PKS 0528+134	82.73	13.53	0.32	7.4	4.0	73.0	0.68
FSRQ	3C 454.3	343.49	16.15	0.19	2.4	1.8	72.3	0.85
FSRQ	4C 38.41	248.81	38.13	0.16	5.9	2.4	53.2	1.15
GC	Sgr A*	266.42	-29.01	—	0.0	—	52.2	—
NI	MGRO J1908+06	286.98	6.27	0.043	5.0	2.1	74.9	0.96
PWN	Geminga	98.48	17.77	—	0.0	—	69.3	—
PWN	Crab Nebula	83.63	22.01	0.23	11.4	4.0	67.0	0.86
PWN	MGRO J2019+37	305.22	36.83	0.27	8.7	4.0	53.2	0.99
SFR	Cyg OB2	308.30	41.32	0.26	7.9	4.0	50.6	1.09
SNR	IC443	94.21	22.50	0.28	7.7	4.0	66.0	0.80

Section of results from the Catalog Search

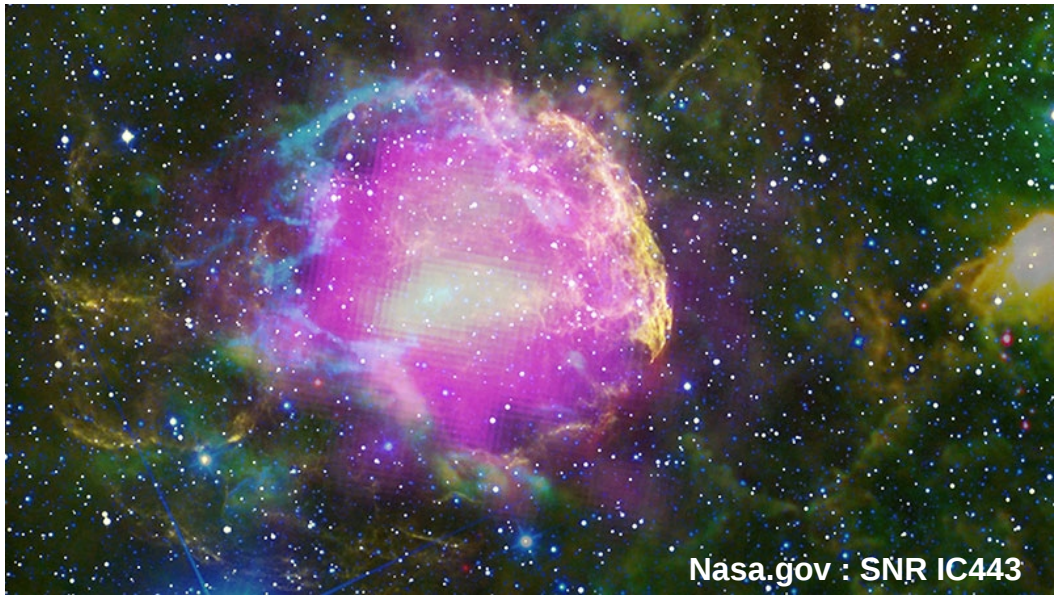
Hottest spot in the northern hemisphere : post-trial p-value yields 67 %

Hottest spot in the southern hemisphere : post-trial p-value yields 8.3 %

Galactic source in the Cygnus Region iseen by Milagro and HAWC and included in Stacking searches

Stacking Searches

- In the absence of a strong enough Source signal to be observed individually, a collection of similar sources can be *Stacked* to obtain a single p-value.
- Current Stacking Catalogs include :
  - → HAWC Inner Galaxy
  - → Milagro 6
  - → Starburst Galaxies
  - → Young Galactic Supernova Remnants



- Most significant pretrial p-value 25 % for Young Supernova Remnants with a fit spectral index of $E^{-3.95}$
- Milagro 6 results strongly disfavours flux models with spectrum of E^{-2} exponential cut-off at 300 TeV. Halzen et al. (2008)