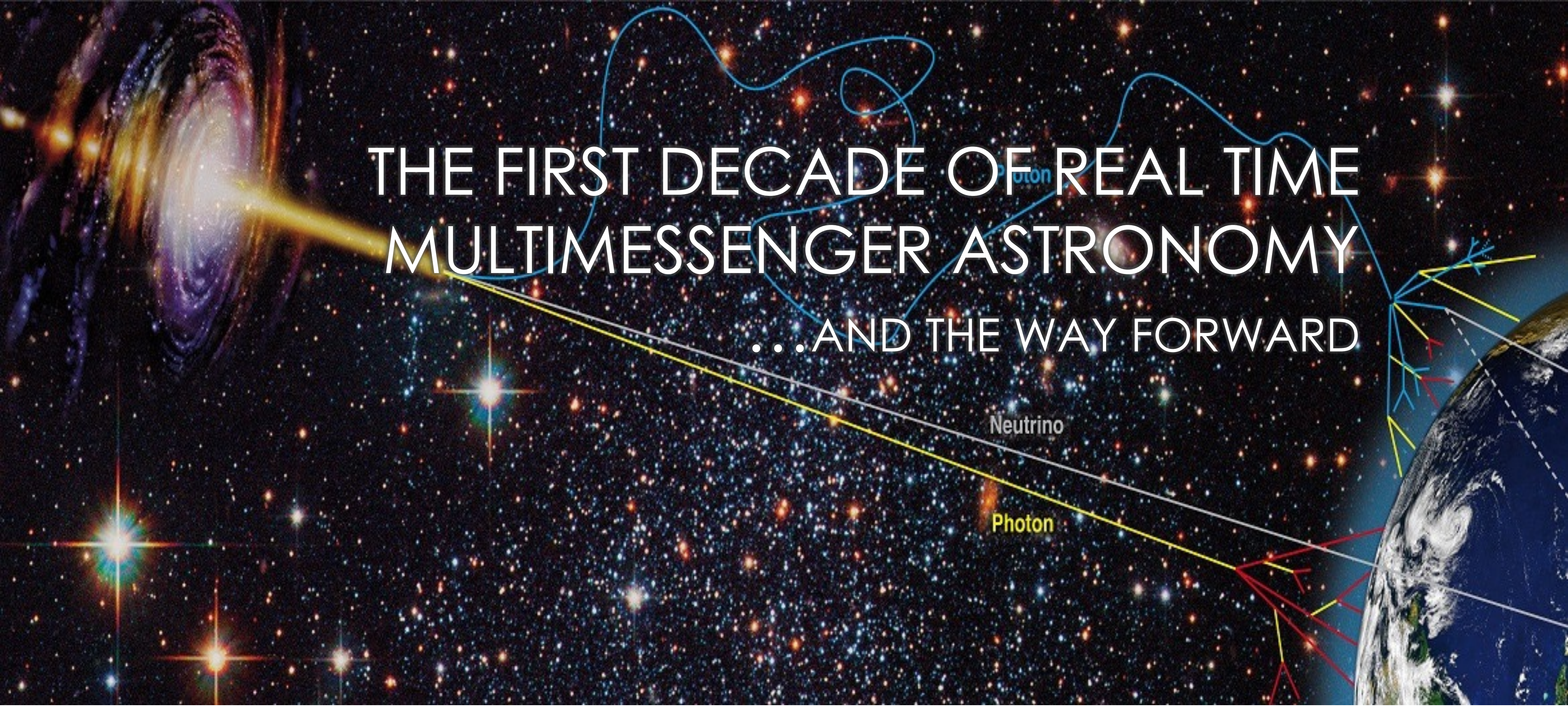
# THE FIRST DECADE OF REAL TIME MULTIMESSENGER ASTRONOMY

## …AND THE WAY FORWARD




14th December 2022

MOHAMED RAMEEZ

XXV DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM 2022, MOHALI

# Multi-messenger Astronomy

## Photons

>1 cm ~1 mm ~10 μm ~1 nm <0.1 nm


$10^{-6}$ eV $10^{-4}$ eV $10^{-1}$ eV ~1 KeV > 100 KeV

Pulsars, quasars, radio galaxies | The Big Bang (CMB) | Non thermal processes

## Cosmic Rays

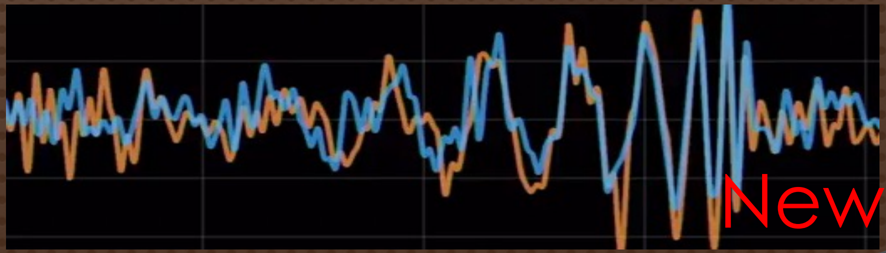
Electrons, protons, heavy nuclei : $10^{8}$ - $10^{20}$ eV – Origins unknown. Observed first by Victor Hess in 1912

## Gravitational Waves

Predicted by General relativity – Observed first in 2015

BH-BH merger ~410 Mpc away.

Now many events, including NS NS merger with EM counterpart



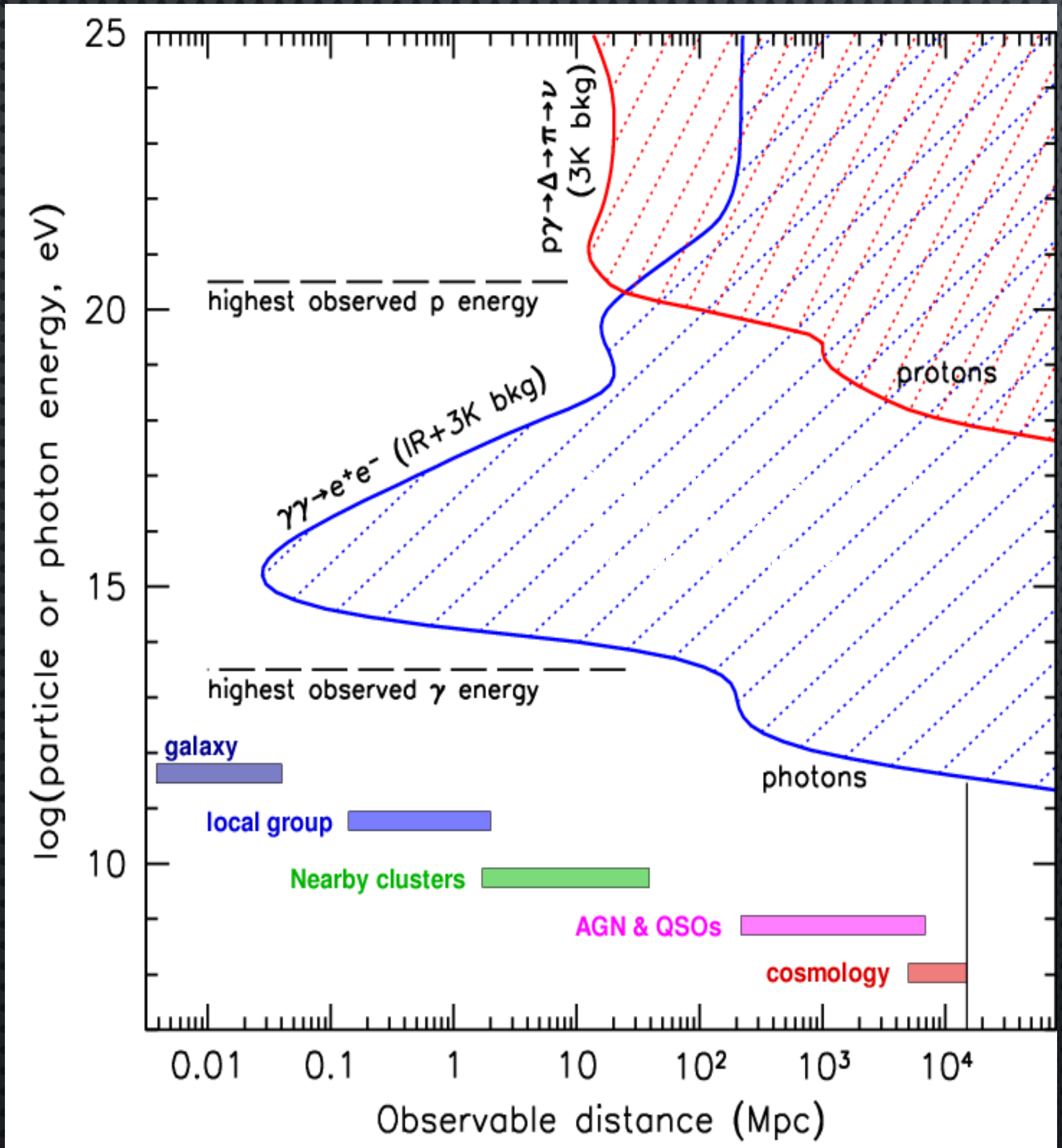

## Neutrinos

Proposed by Pauli in 1931, detected by Reines and Cowan in 1959, neutral, weakly interacting.

The Sun, SN1987 A – 10 MeV, TXS 0506+056, NGC 1068

Diffuse astrophysical flux >50 TeV

# The messenger horizon




γ-rays do not travel too far

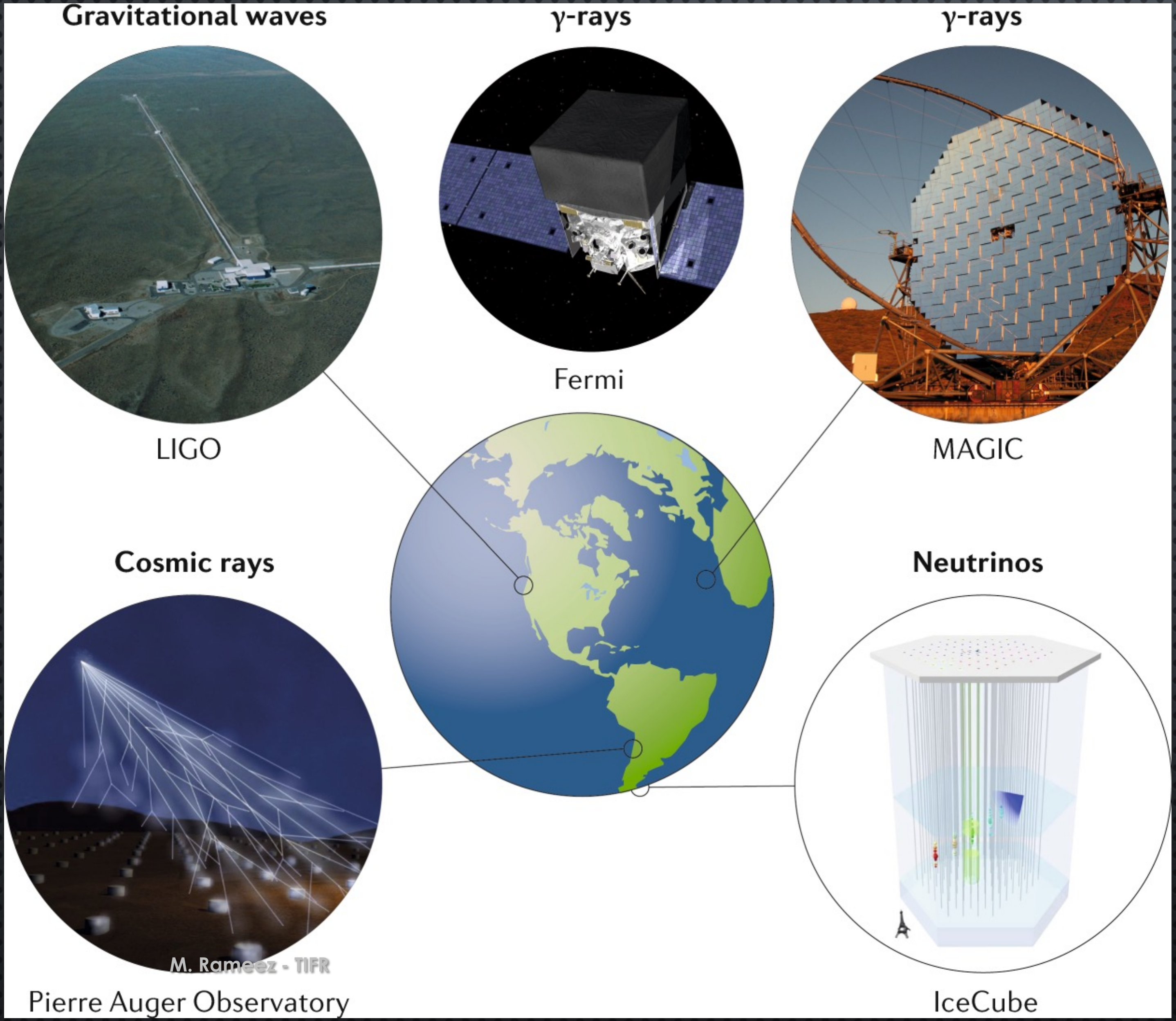
- 1 TeV : Closest AGNs

CRs cannot point back

- Deflection : few degrees at ~50 EeV
- Horizon ~100 MPc – interactions with CMB

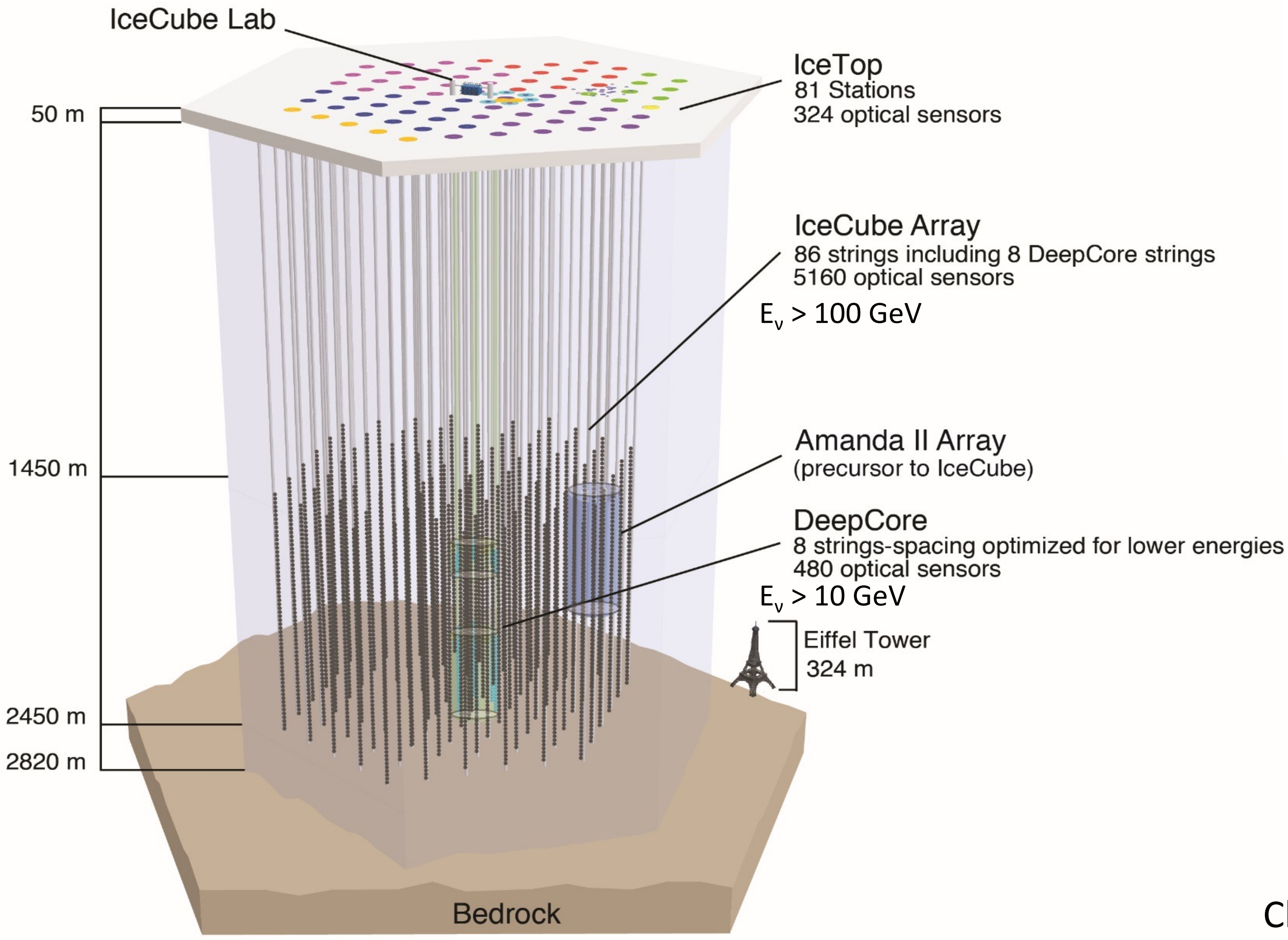
The neutrino - ideal messenger for the non thermal universe

- Neutral, undeflected
  - – can point back
- Interacts only weakly
  - – can travel Gpc distances
  - – hard to detect
- We hope to see
  - The sites of CR acceleration



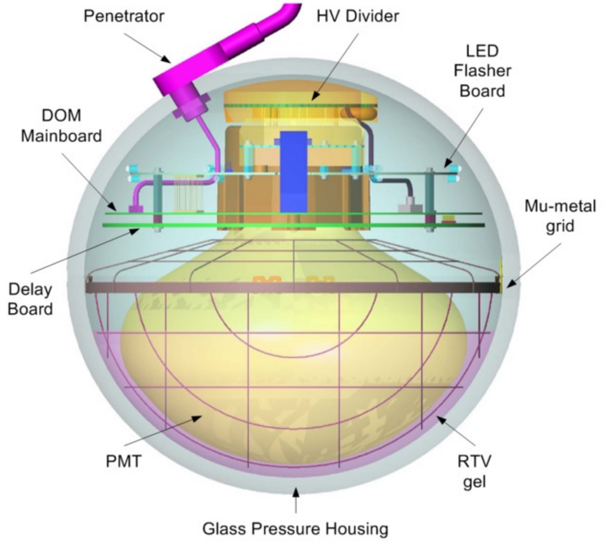

First decade of multimessenger astronomy

# The IceCube Neutrino Observatory

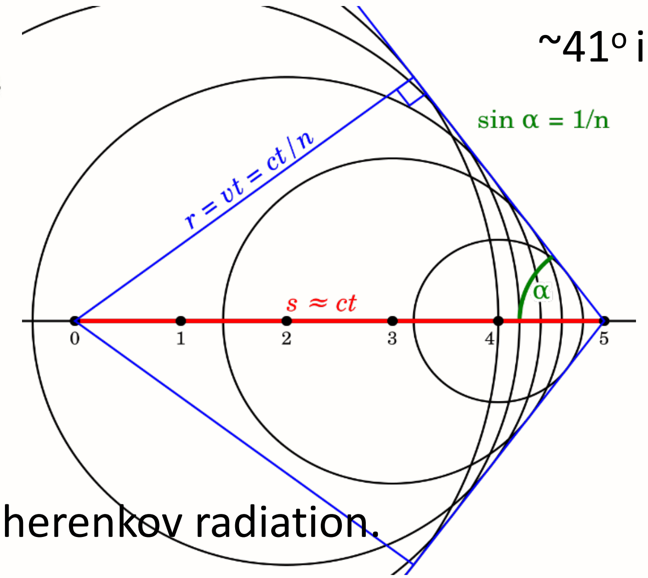



$E_\nu$ > 100 GeV

$E_\nu$ > 10 GeV

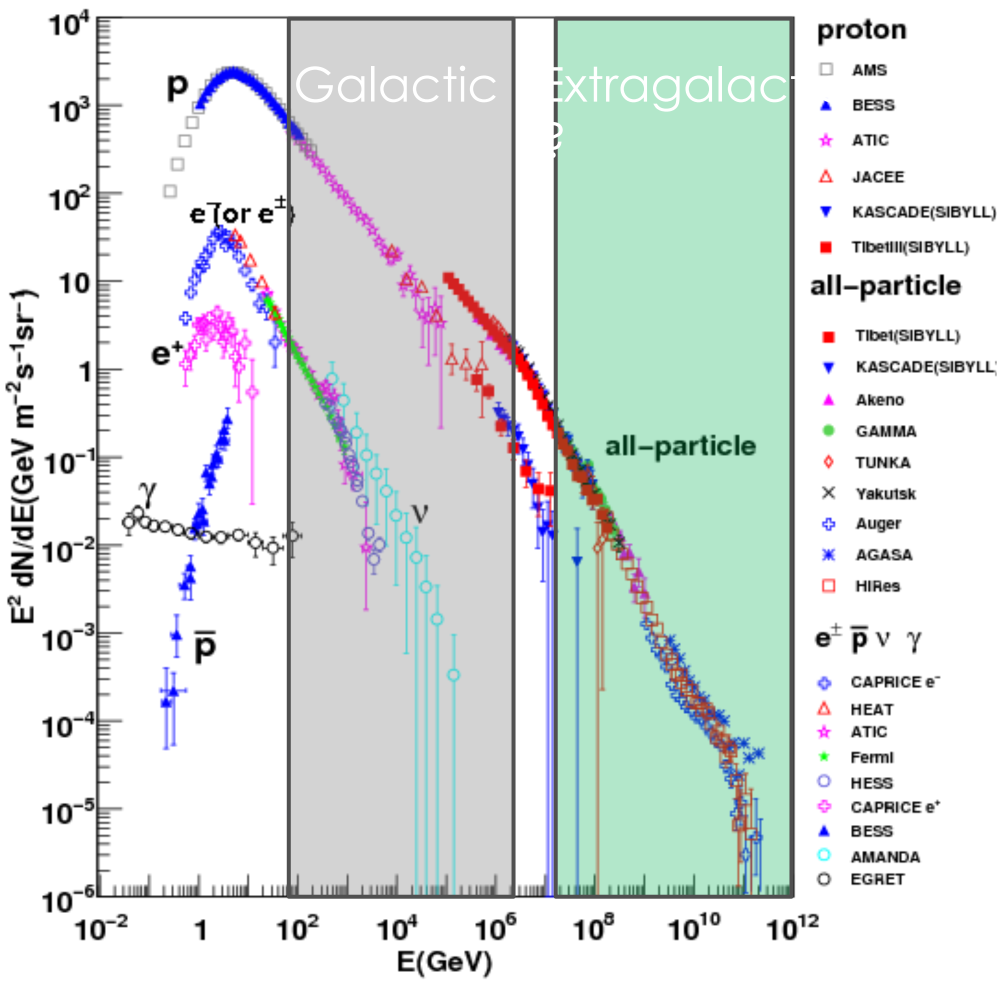


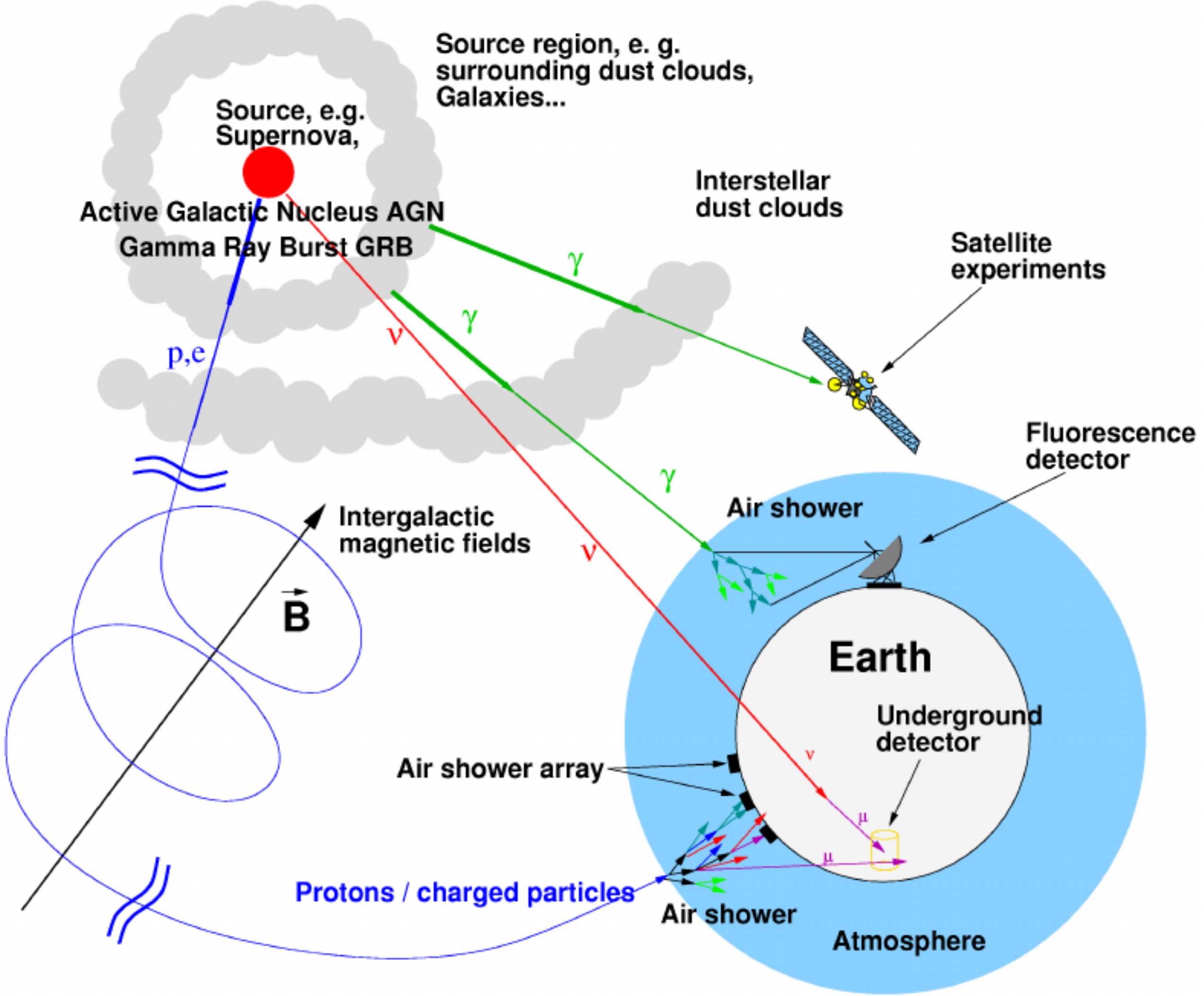

~41° in ice




Cherenkov radiation.

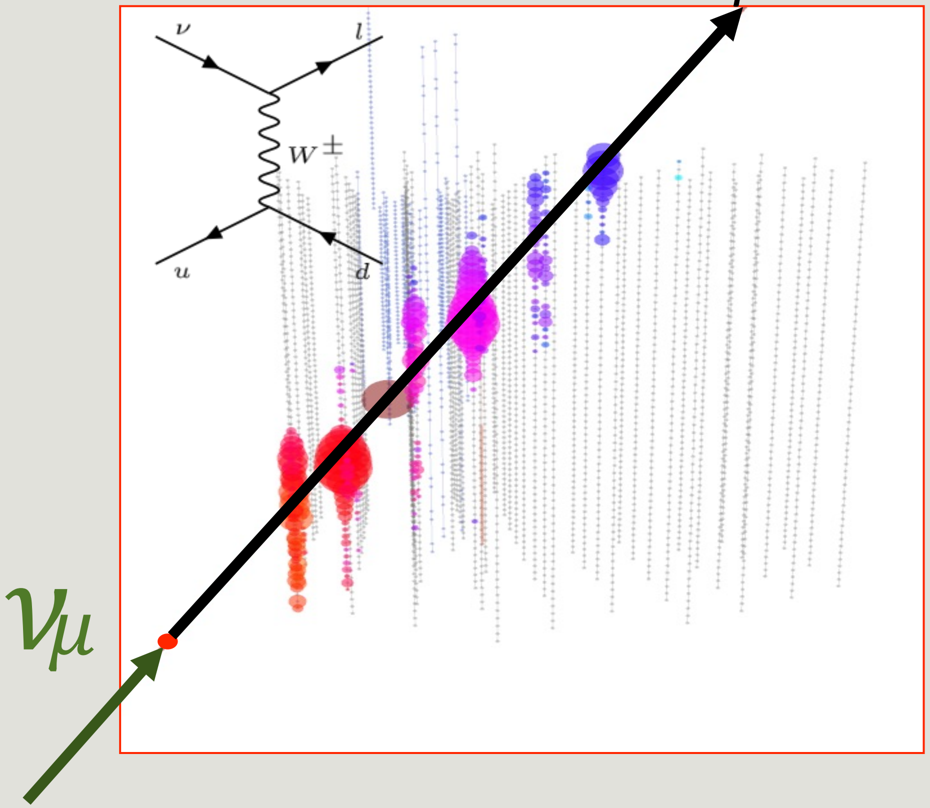
# WHY NEUTRINO ASTRONOMY?



# In-ice Signatures

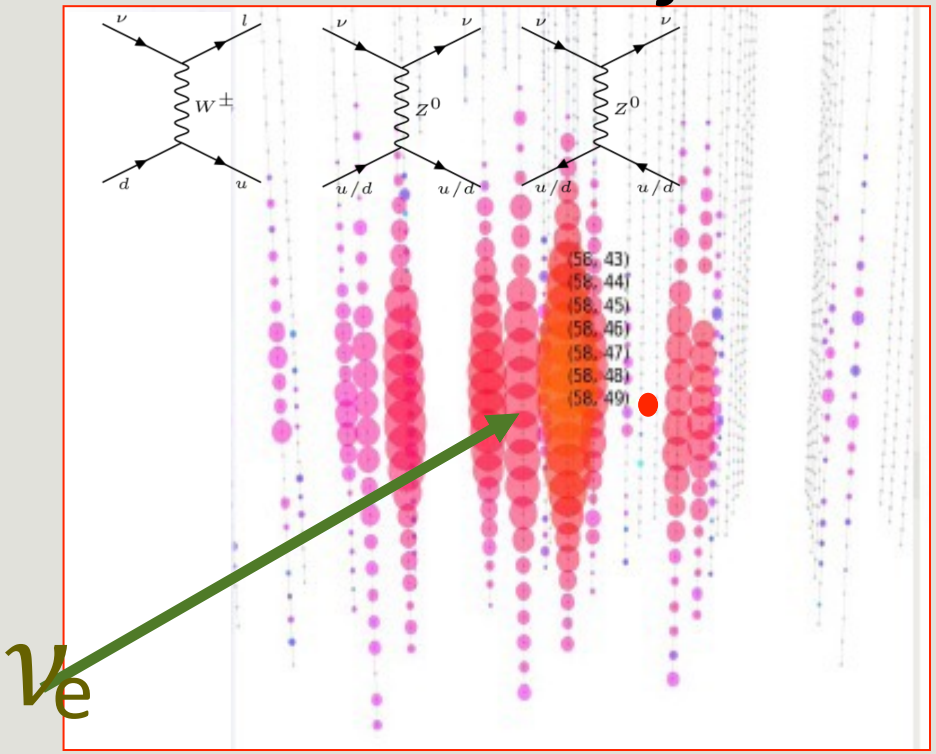
## *Muon tracks→ $\nu_\mu$ CC*




Good angular resolution: **Neutrino Astronomy**

- **(~0.6° at 10 TeV)**
- Vertex can be outside the detector: **Increased effective volume!**

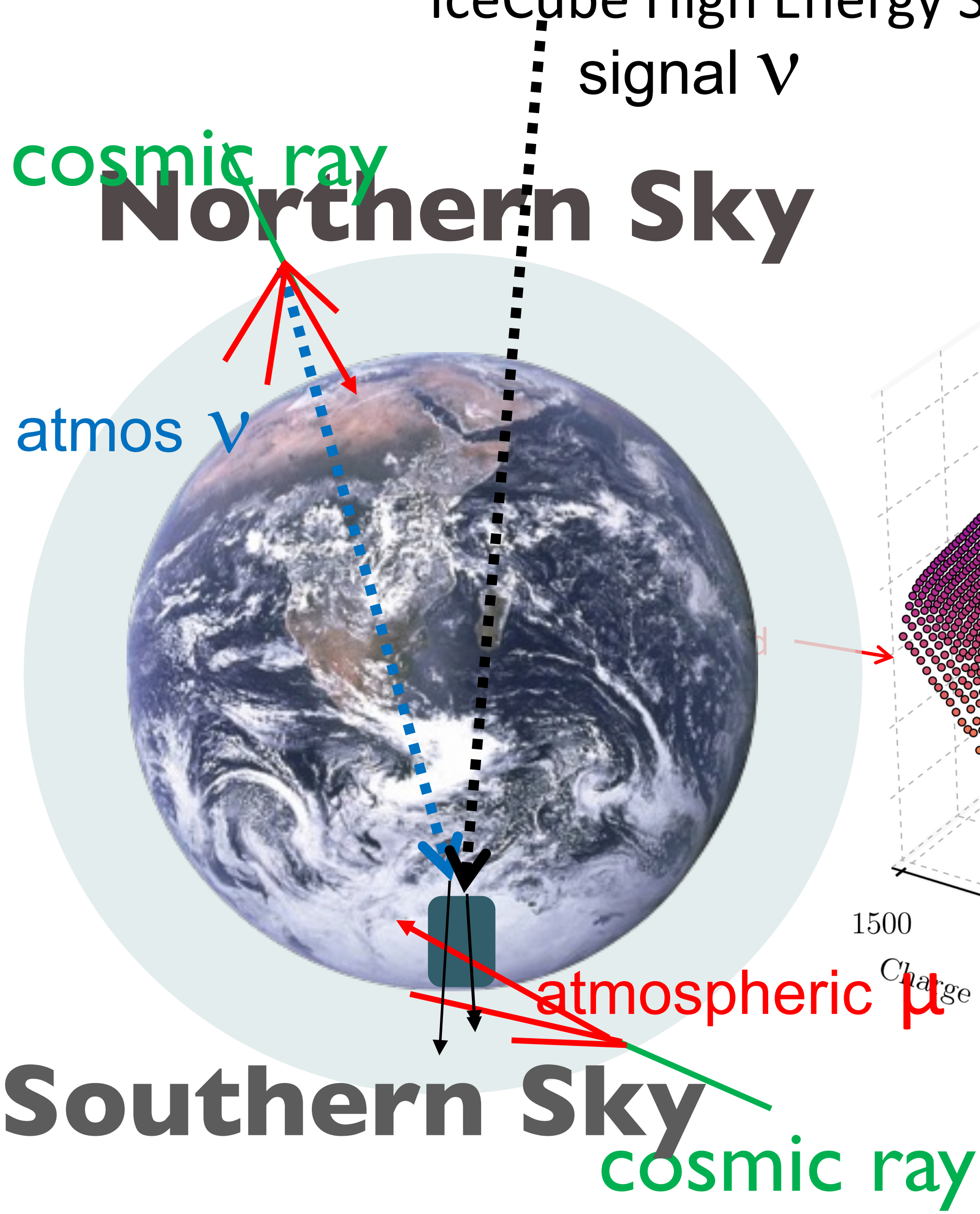
## *cascades → all flavors*

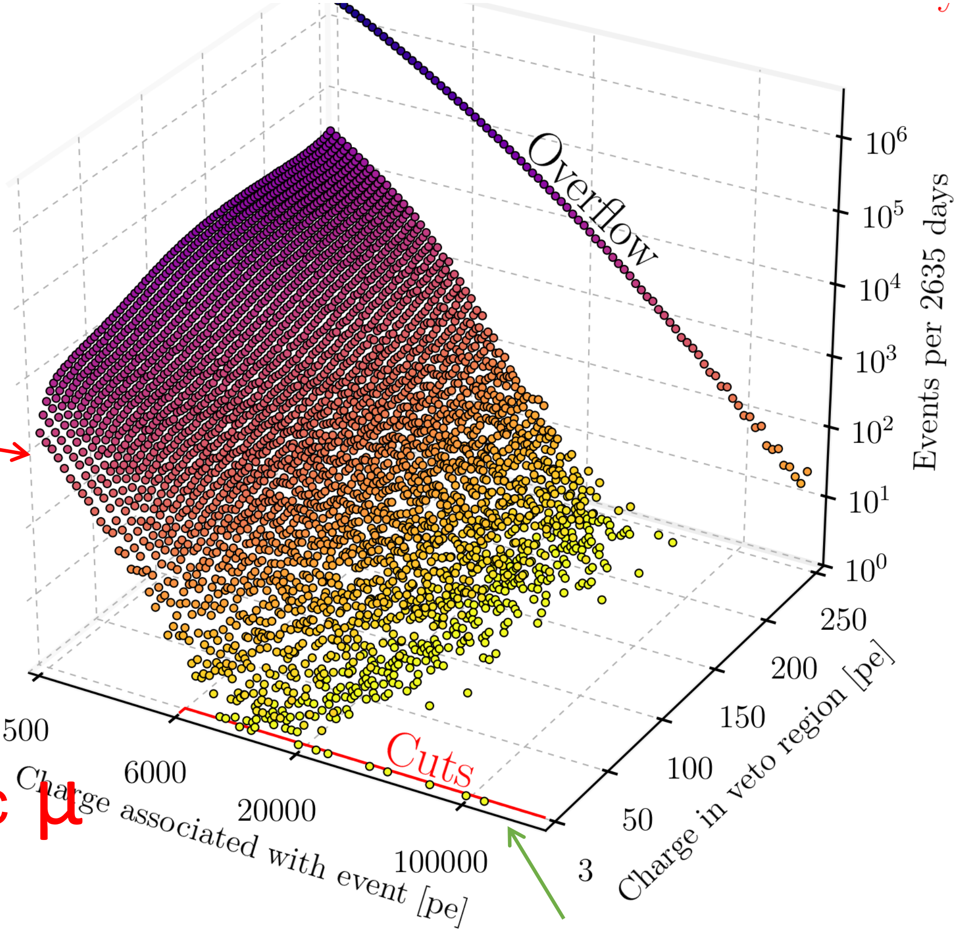


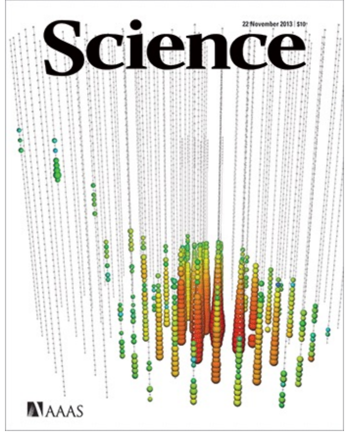

- $\nu_e$, $\nu_\tau$ and all-flavor neutral current
- Fully active calorimeter: **High energy resolution**
- Angular reconstruction above ~50 TeV

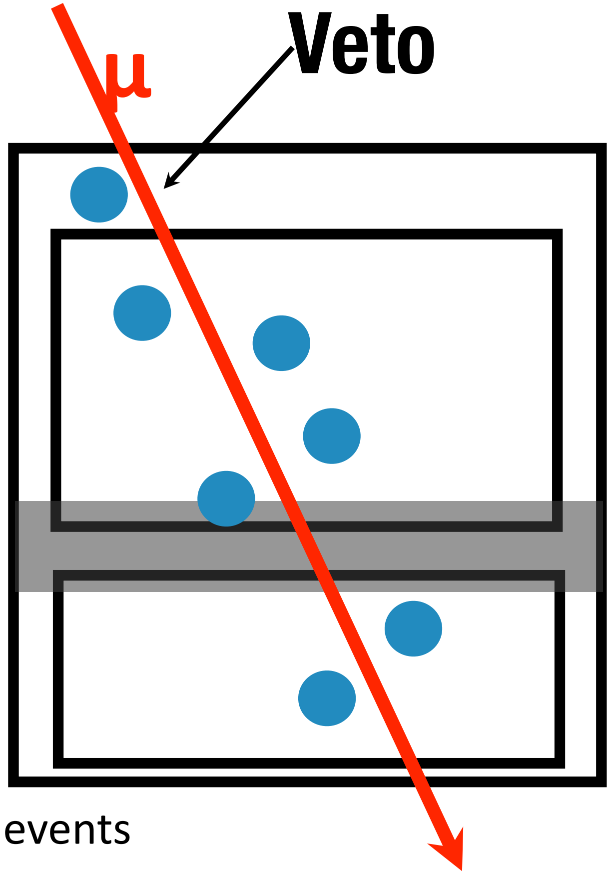
In both cases, $\nu$ and $\bar{\nu}$ are indistinguishable

# IceCube High Energy Starting Events : Neutrinos in a Haystack



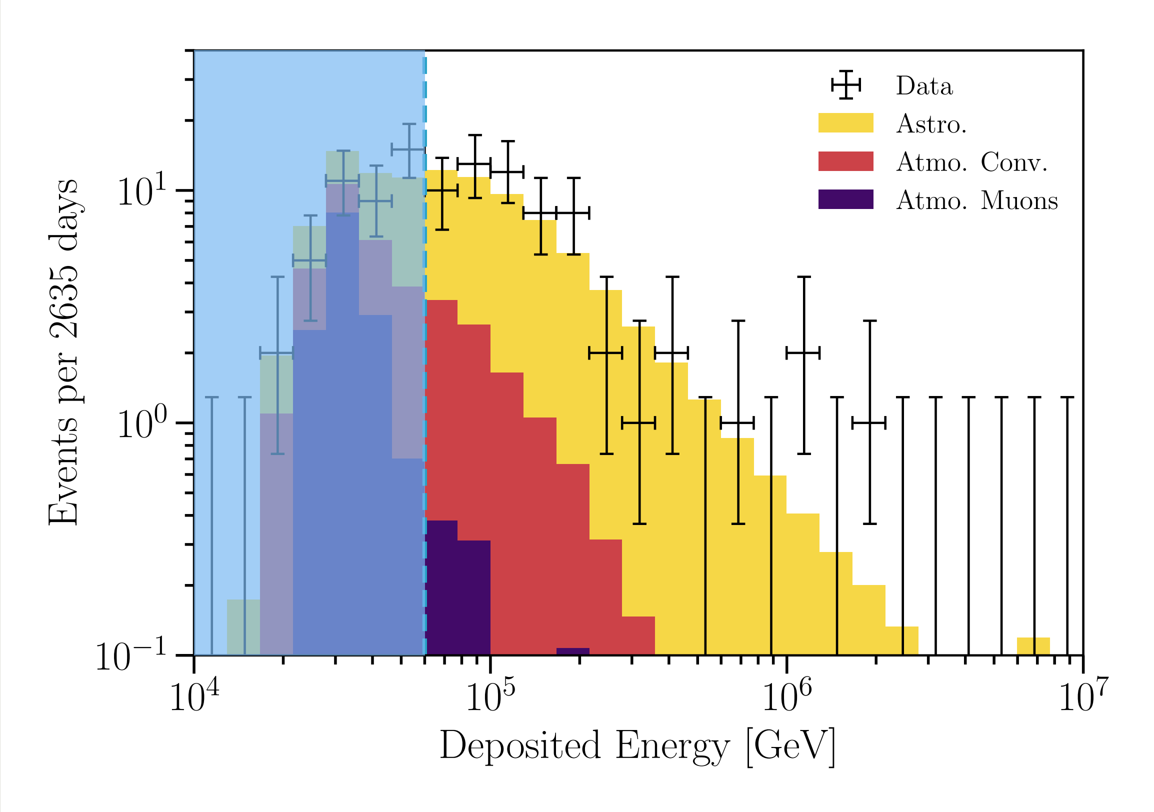



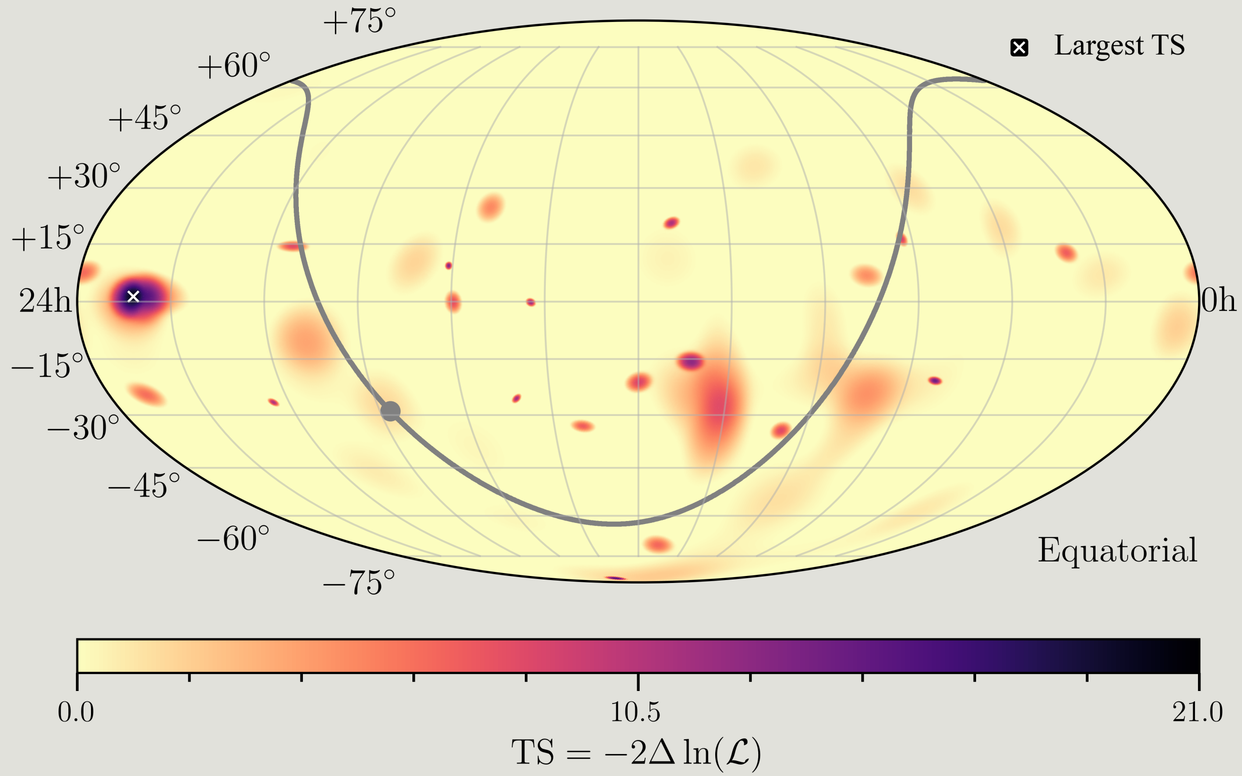

High Energy Starting events

# The IceCube astrophysical flux (7.5 years of data)




60 Events above 60 TeV

*Phys.Rev.D* 104 (2021) 022002



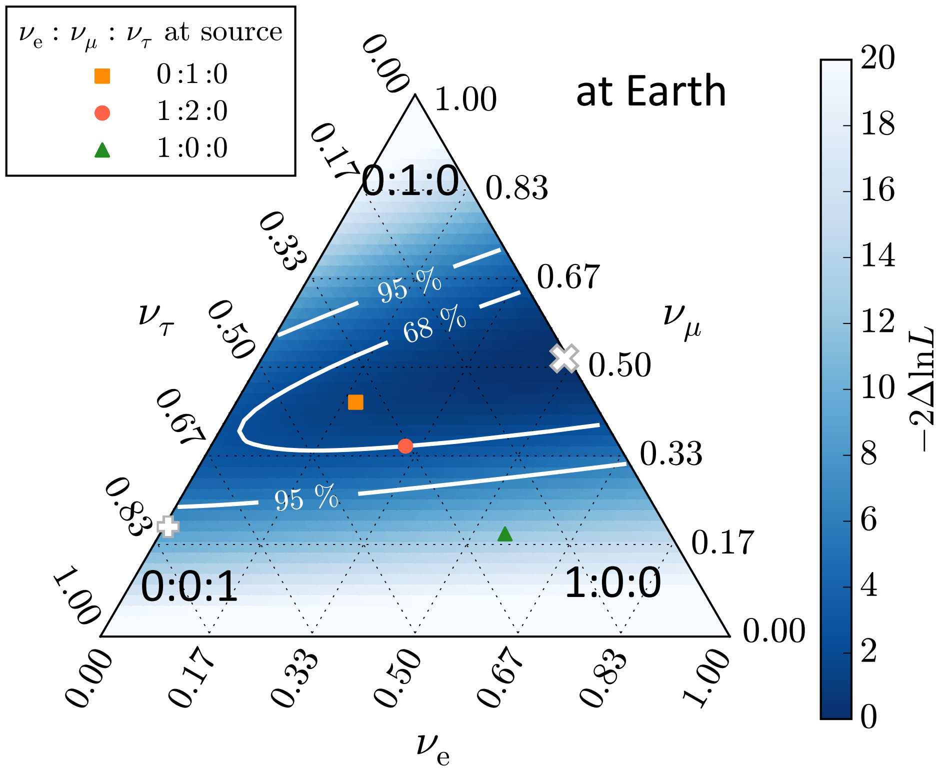

No statistically significant clustering
Corrected for trials

# Astrophysical neutrino flavour ratio

Muon damped

Standard $\pi$ production

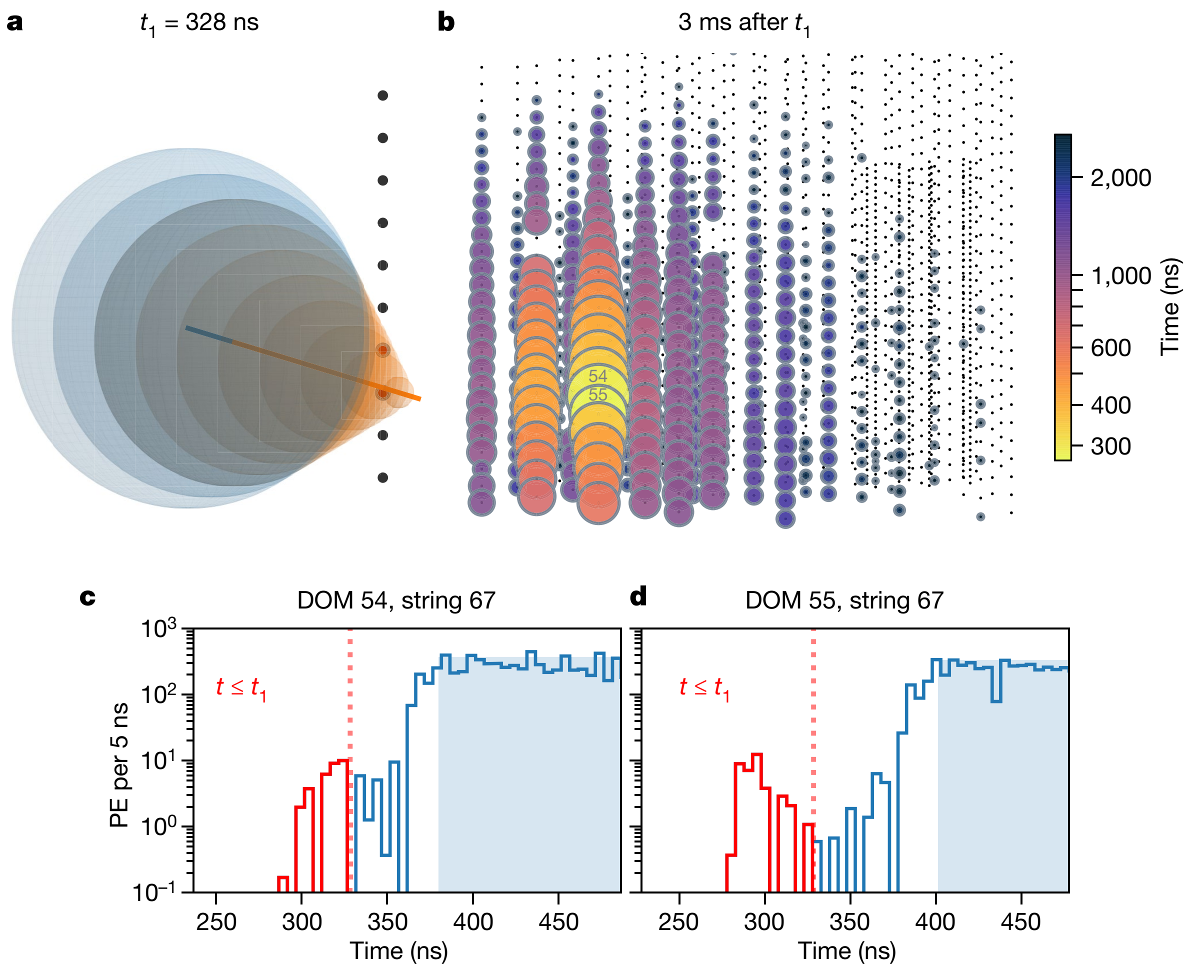
Neutron decay



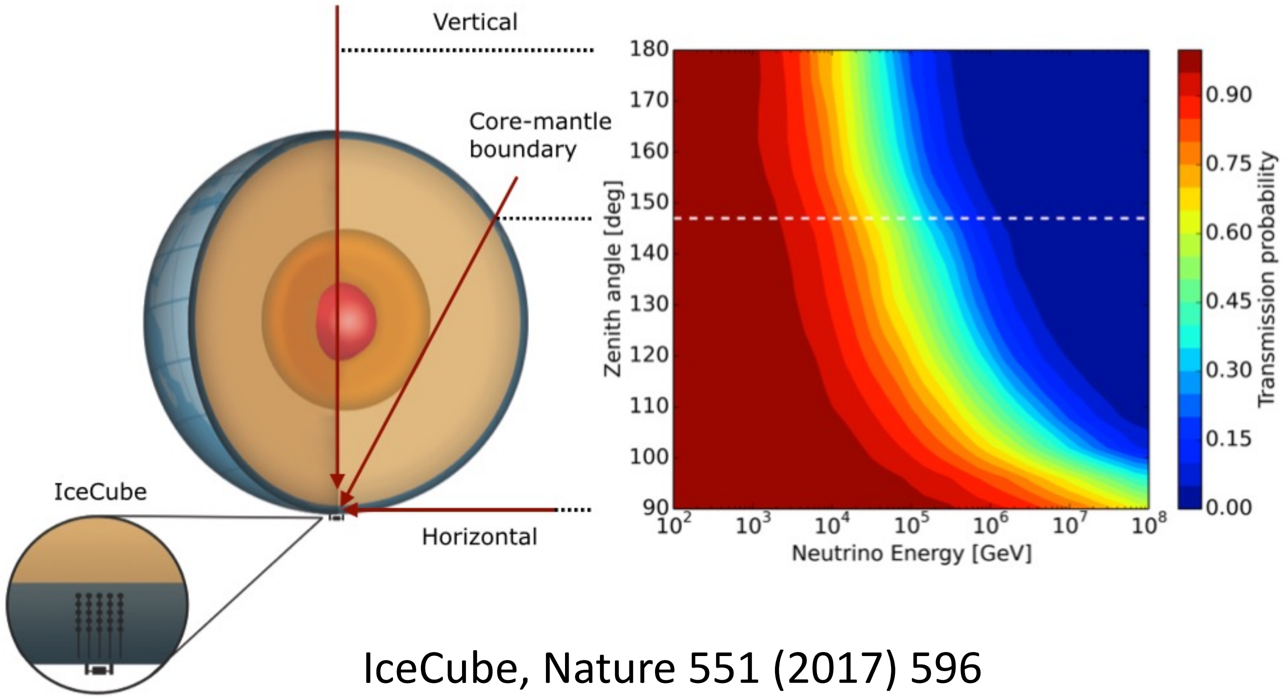

IceCube, ApJ 809:98 (2015)

IceCube, PRL 114, 171102 (2015)

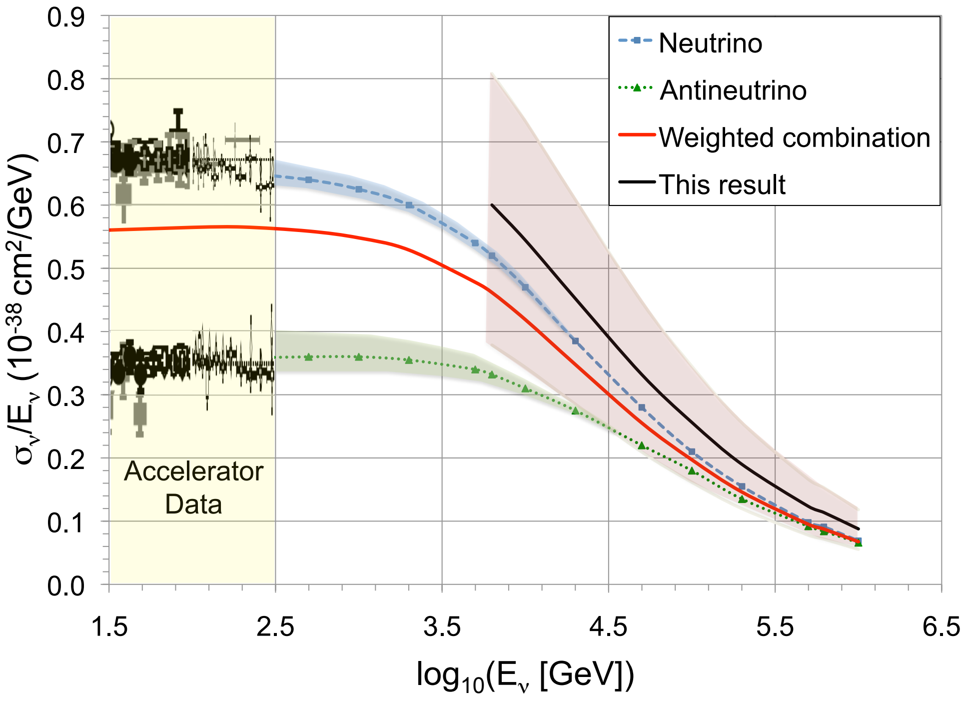
# Confirmation of Glashow resonance at 6.3 PeV



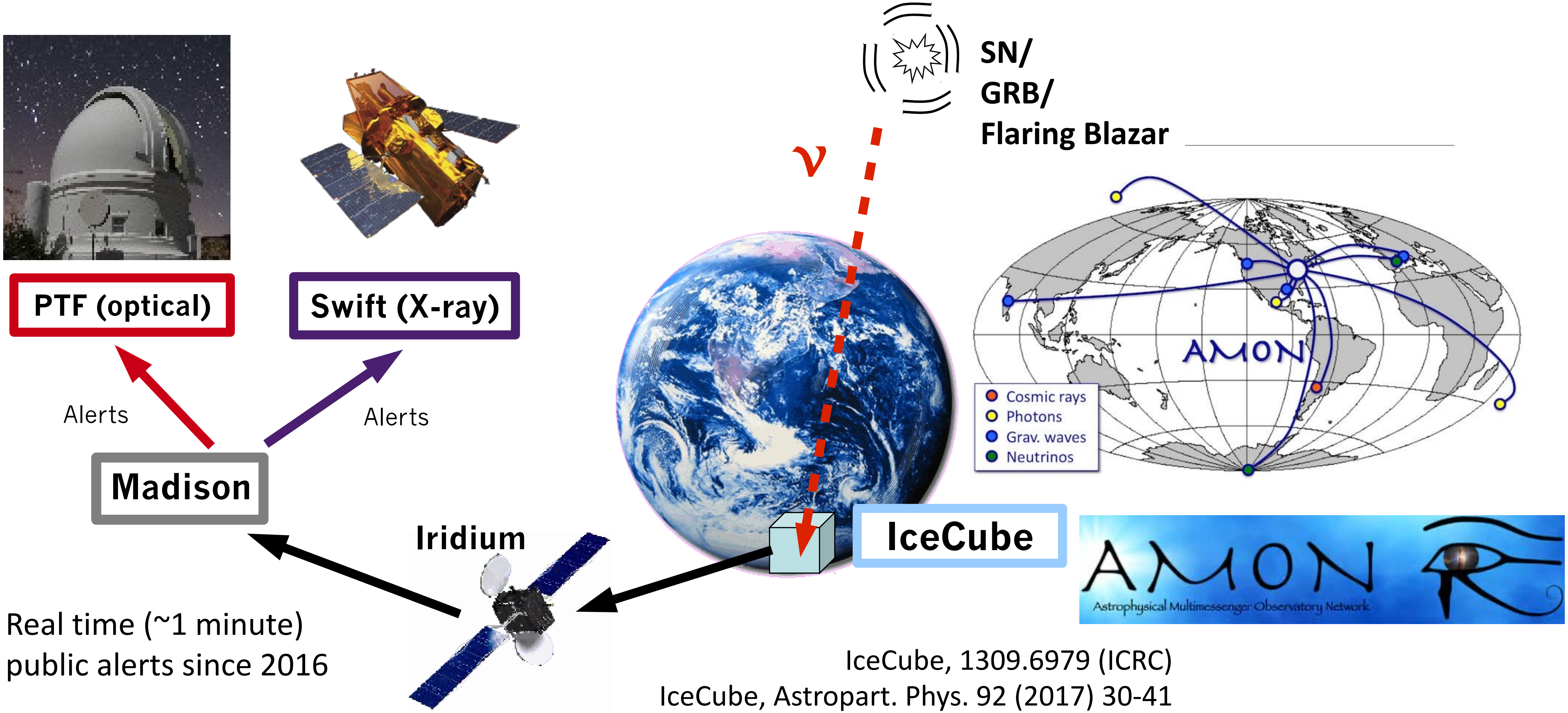
# Measurement of neutrino-nucleon cross section using Earth absorption




IceCube, Nature 551 (2017) 596



# Realtime Alerts from IceCube



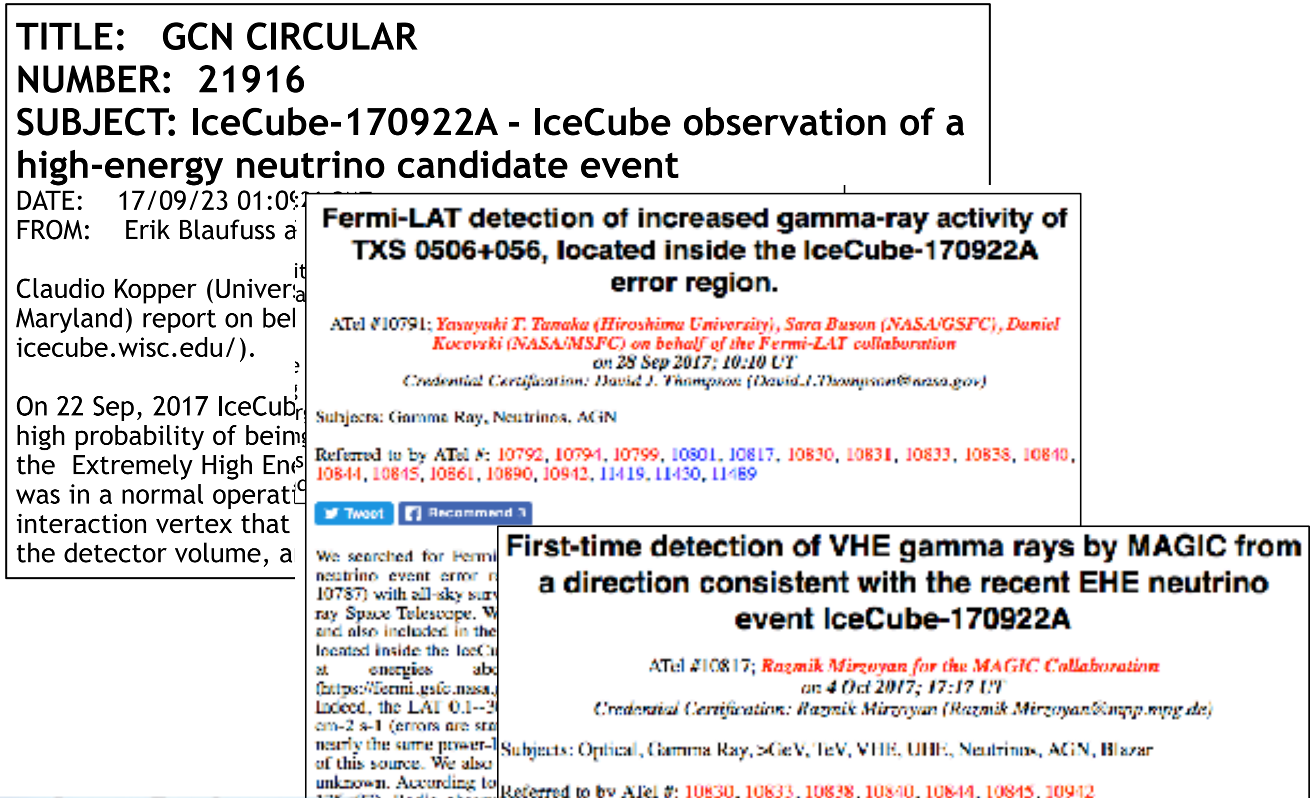

Real time (~1 minute)
public alerts since 2016

IceCube, 1309.6979 (ICRC)
IceCube, Astropart. Phys. 92 (2017) 30-41

# Multi-messenger alerts: TXS 0506+056

On September 22, 2017, IceCube issued a neutrino alert:

- A muon track event created by a ~290 TeV neutrino (IceCube-170922A)
- Found to be spatially coincident with a known blazar (TXS 0506+056) that was in a flaring state
- Blazar was also detected by the MAGIC air-Cherenkov telescope in the days after the alert, with γ-rays up to 400 GeV.
- This launched a very active multi-messenger follow-up campaign that included observations from radio to γ-rays.



TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09
FROM: Erik Blaufuss a

Claudio Kopper (Univer
Maryland) report on bel
icecube.wisc.edu/).

On 22 Sep, 2017 IceCub
high probability of bein
the Extremely High En
was in a normal operati
interaction vertex that
the detector volume, a

**Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.**

ATel #10791; Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration
on 28 Sep 2017; 10:10 UT

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

Tweet | Recommend

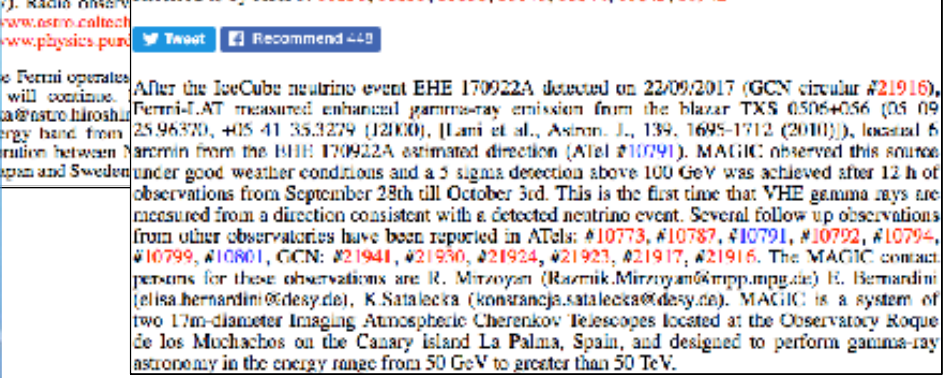
**First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A**

ATel #10817; Razmik Mirzoyan for the MAGIC Collaboration
on 4 Oct 2017; 17:17 UT

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend



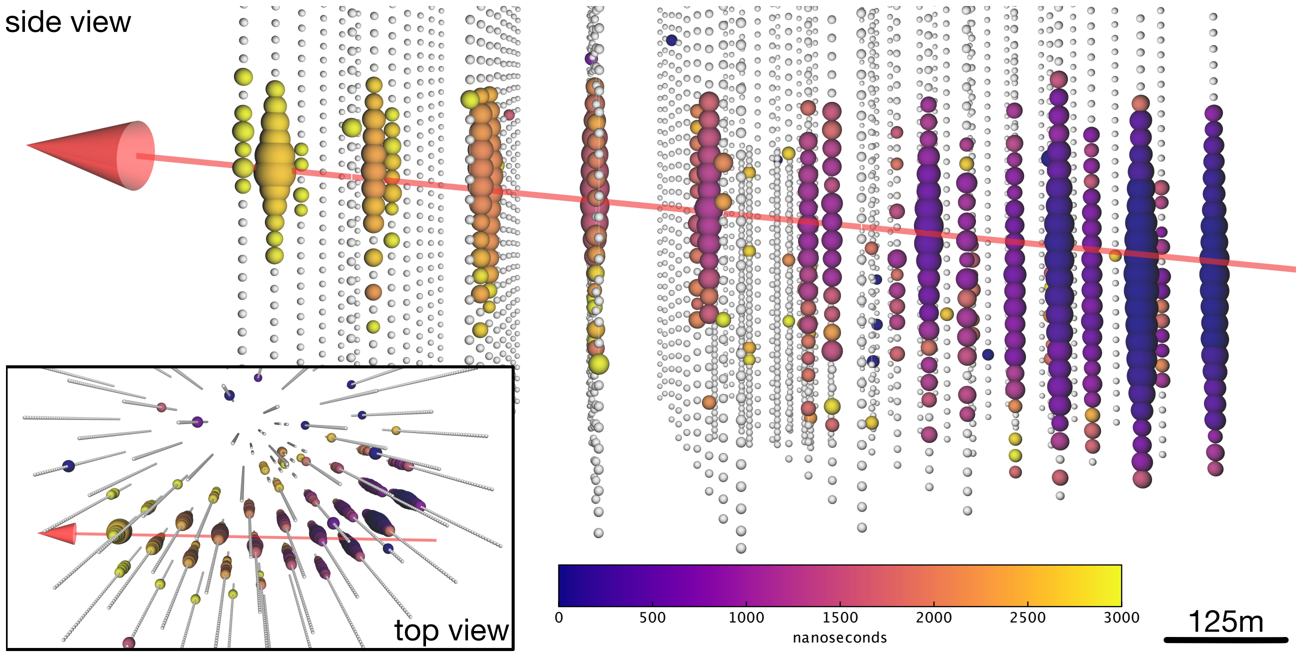
After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 ... MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K. Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

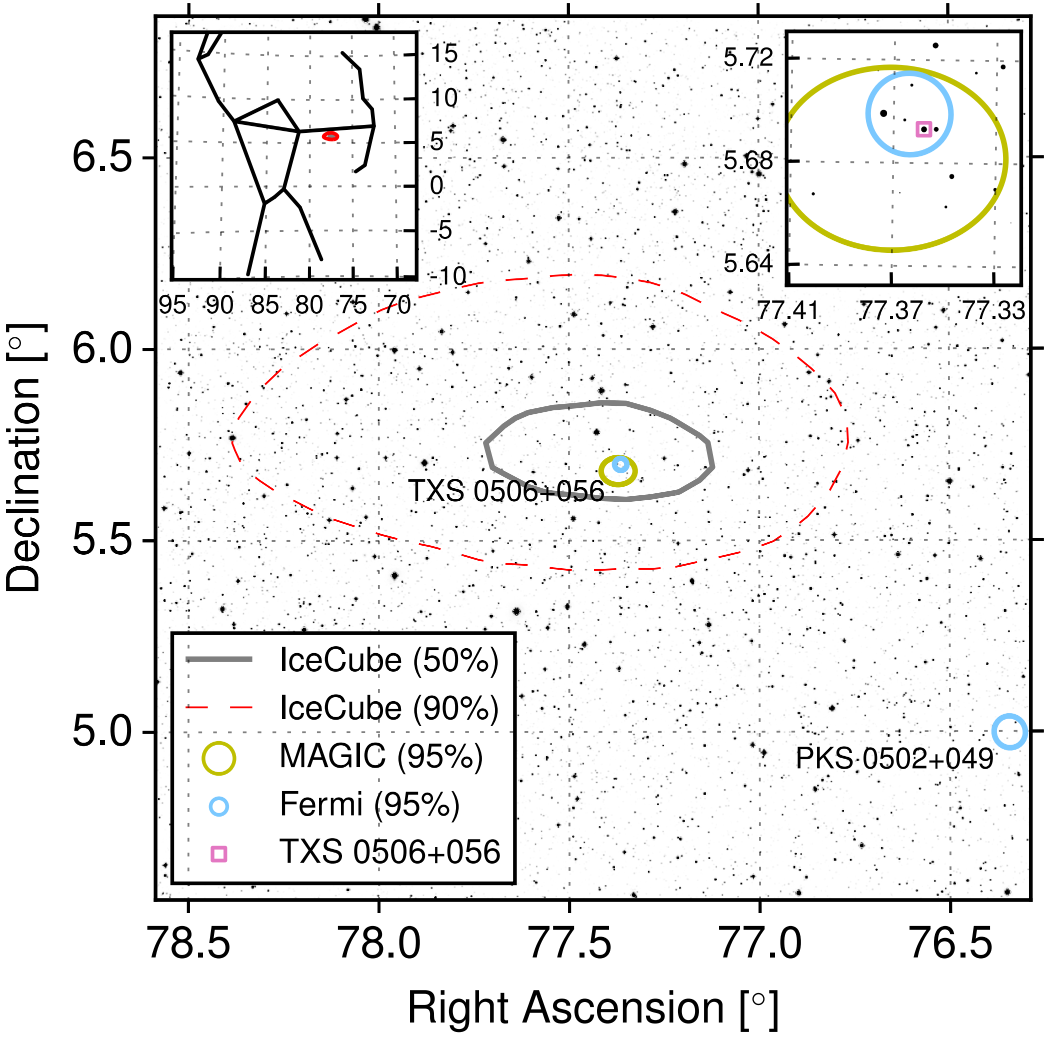

Recently published in Science:
IceCube Coll. et al., Science 361 (2018)

# Multi-messenger alerts: TXS 0506+056

Neutrino direction was well reconstructed

- Uncertainty of less than 1 sq. deg at 90% CL
- Positionally consistent with blazar TXS 0506+056
- ~290 TeV estimated neutrino energy



# Multi-messenger alerts: TXS 0506+056

At detection time of IceCube-170922A, very little was known about blazar TXS 0506+056.

As part of the large community follow-up effort, the redshift has been measured
$z = 0.3365 \pm 0.0010$ (Pianno, et al. ApJ **854** (2018) 2)

But how often does this happen by chance?

- 2257 cataloged extragalactic Fermi-LAT sources
- Light curves above 1 GeV in monthly bins
- Likelihood ratio test comparing random coincidence (null hypothesis) to correlation between gamma-ray flux and neutrino flux for several models
  - Energy flux, Flux variability, VHE detection/detectability
  - $4.1\sigma$ preference for correlated emission
- Trials corrected:
  - 9 previous alerts + 41 additional events that *would* have generated alerts, had they been operational
  - **$3.0\sigma$** preference for correlated emission

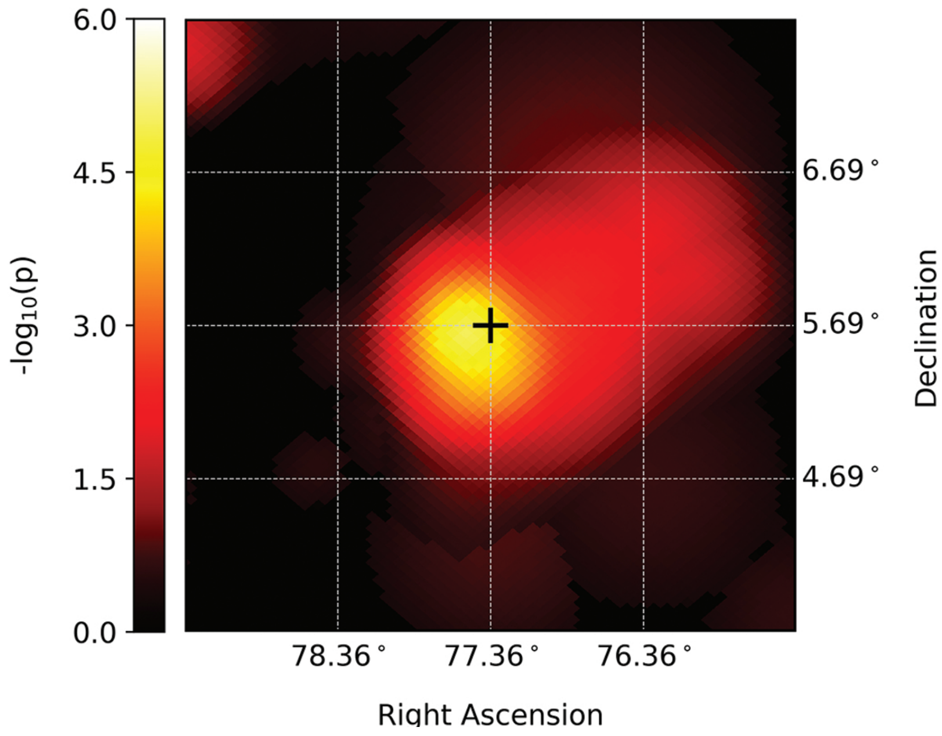
**Recently published in Science:**
**IceCube Coll. et al., Science 361 (2018)**

# IceCube Archival Data

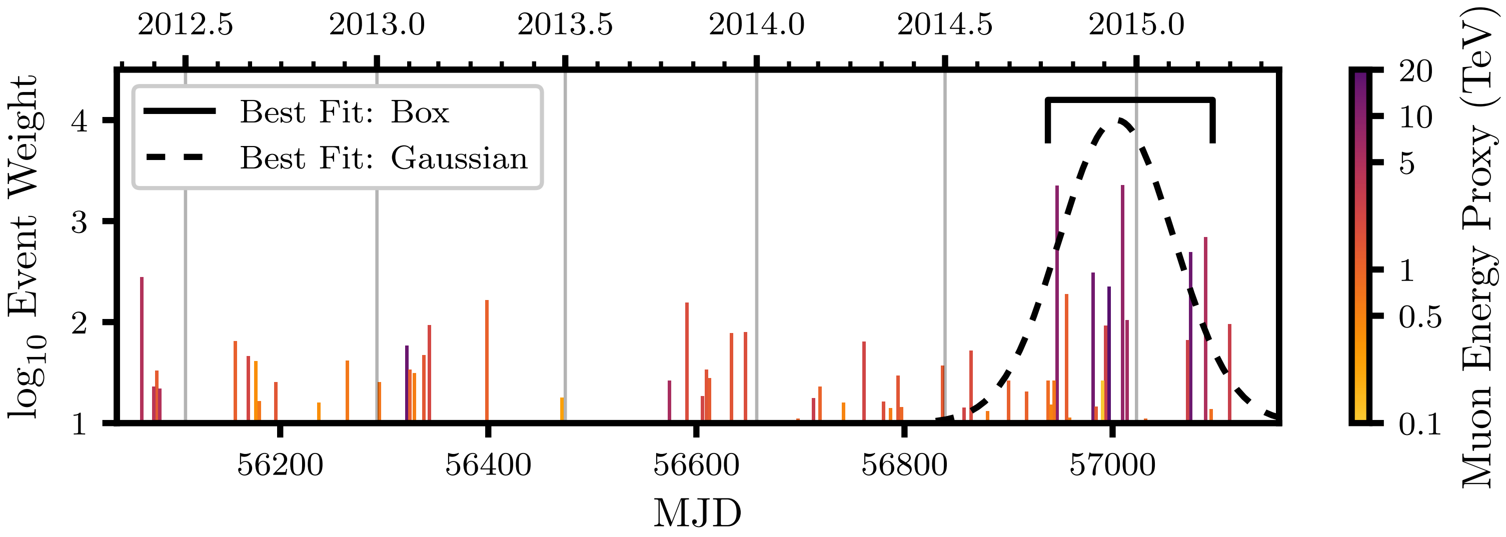
Evidence of time-dependent emissions is observed:

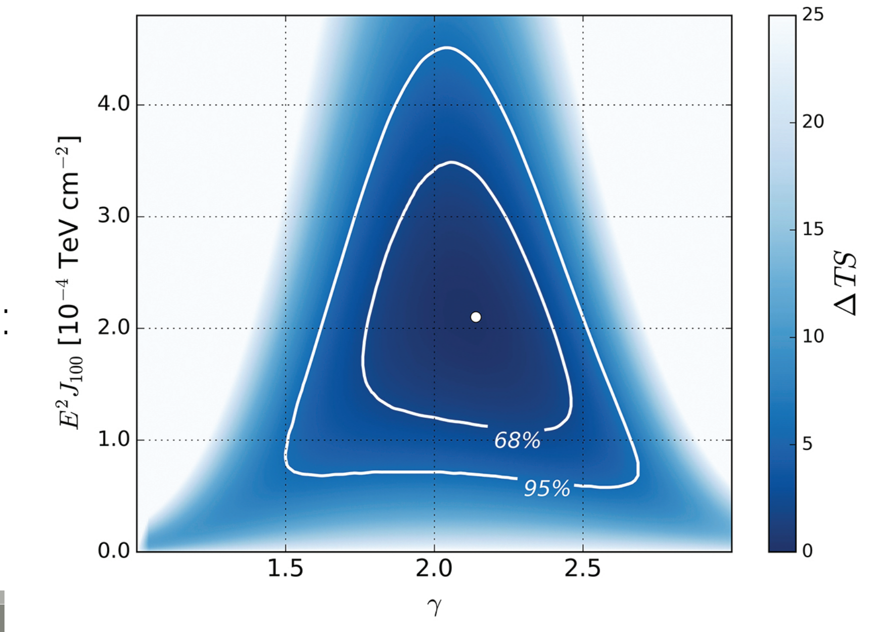
Independent of, and prior to neutrino alert

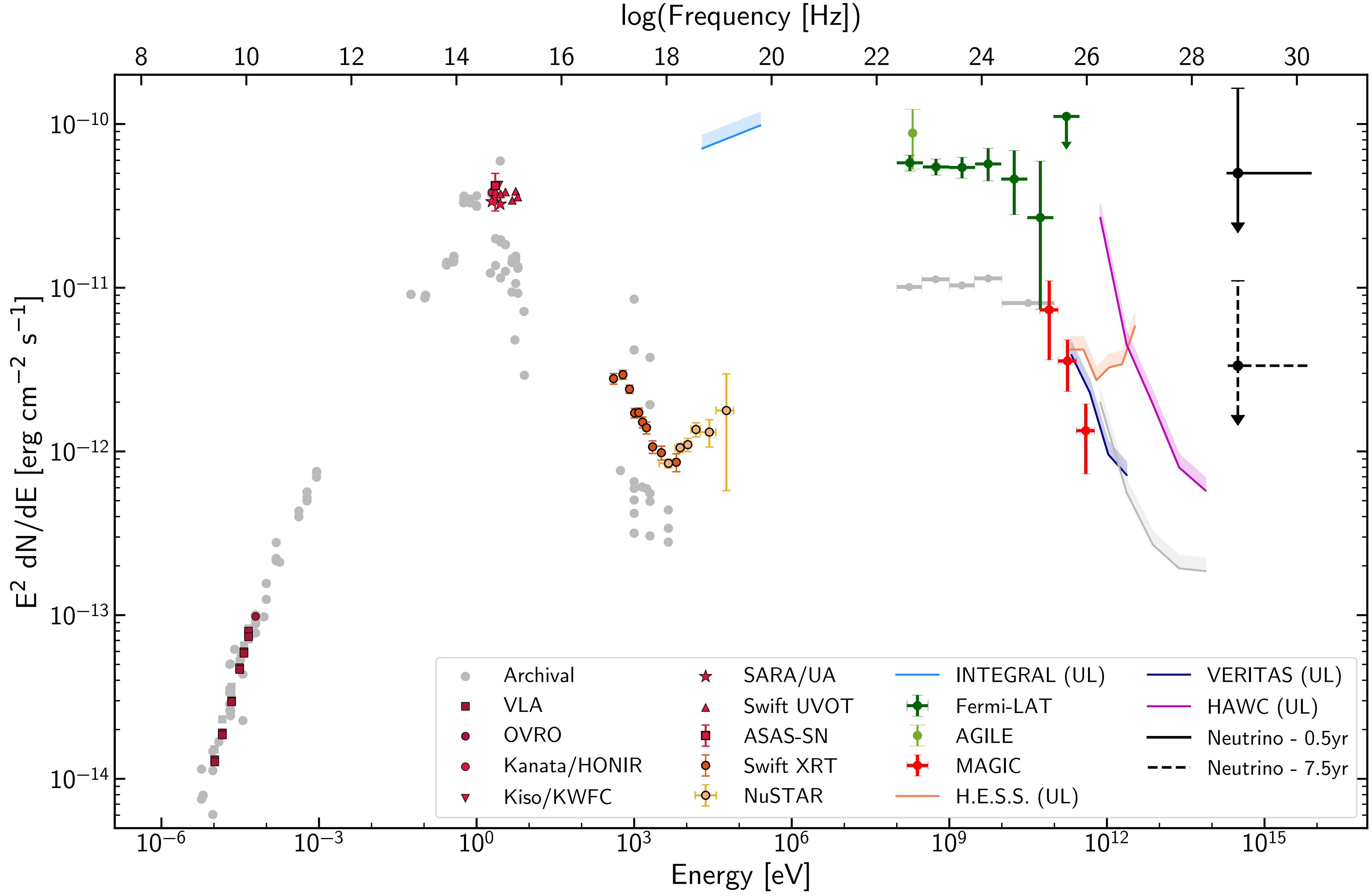
- September 2014 - March 2015
- 3.5σ excess over expected background
- 13 ± 5 events over background



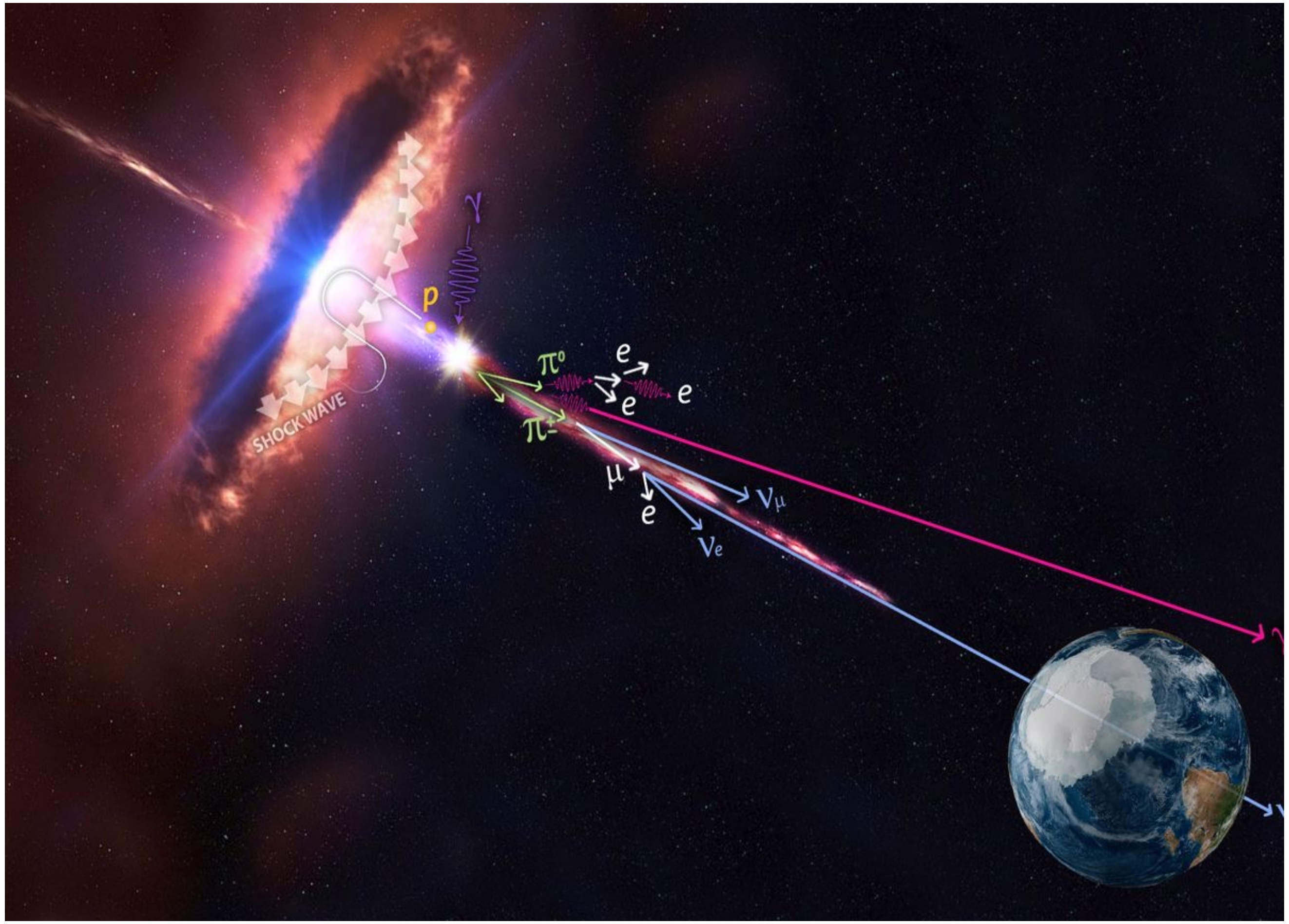

**IceCube Coll. Science 361 (2018) 147**




log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
E$^2$ dN/dE [erg cm$^{-2}$ s$^{-1}$]
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-6}$
$10^{-3}$
$10^{0}$
$10^{3}$
$10^{6}$
$10^{9}$
$10^{12}$
$10^{15}$
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

# Multi-messenger source: TXS 0506+056



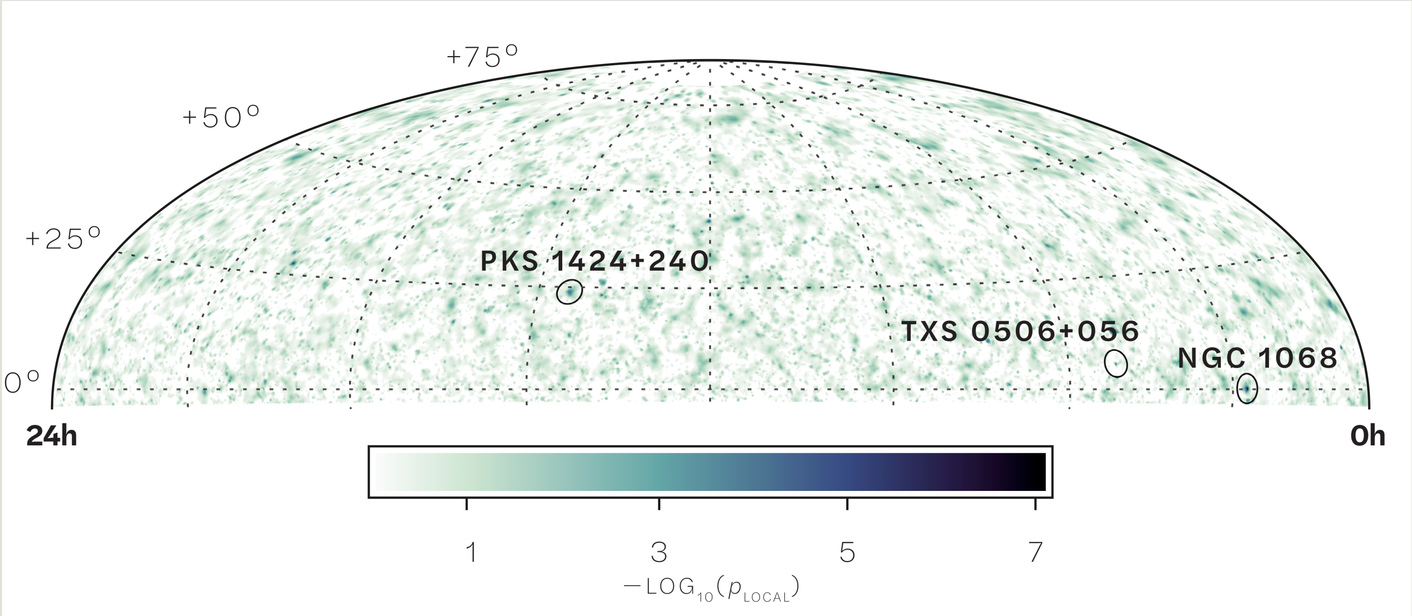

Two analyses provide evidence that TXS 0506+056 is the first of the long-sought sources of astrophysical neutrinos.

When both results are considered together, this provides evidence that blazars, especially TXS 0506+056, is a site of high-energy cosmic ray acceleration, and blazars are a potential source of a sizable fraction of the IceCube diffuse neutrino flux.

Many question still remain:

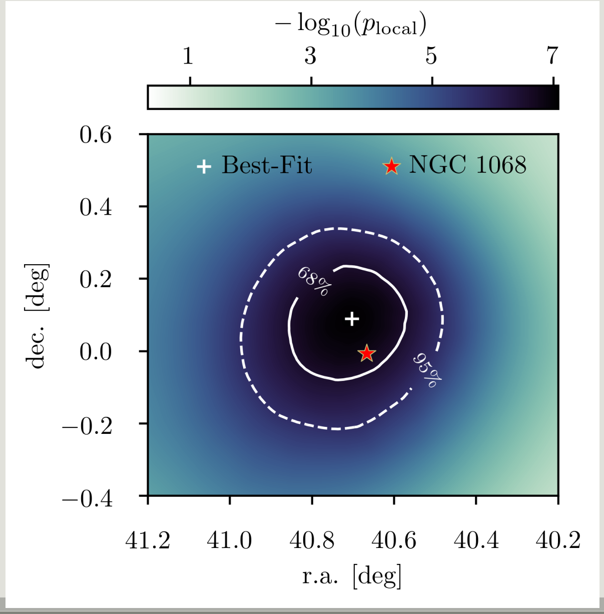
- Why TXS 0506+056?
  - A distant (4 Bly) and very luminous blazar • Why not closer blazars? (now solved)
- What other objects are out there like TXS 0506+056?
  - Ongoing investigations with partners to resolve
  - Continued alerts

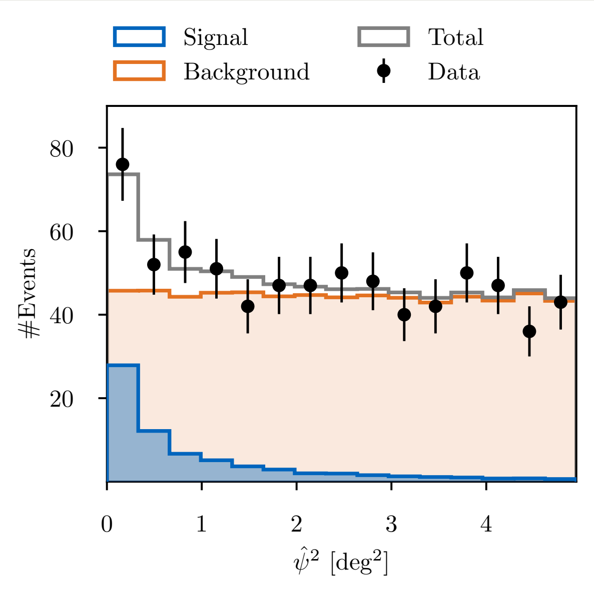
# NGC 1068

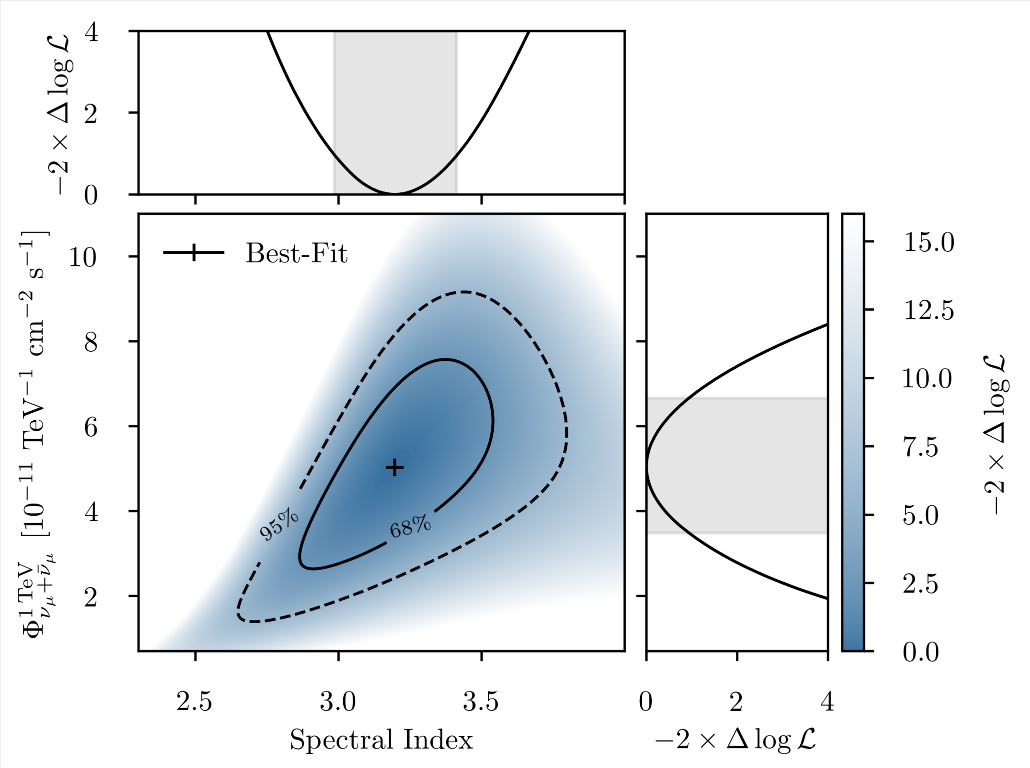



*Science* 378 (2022) 6619, 538-543

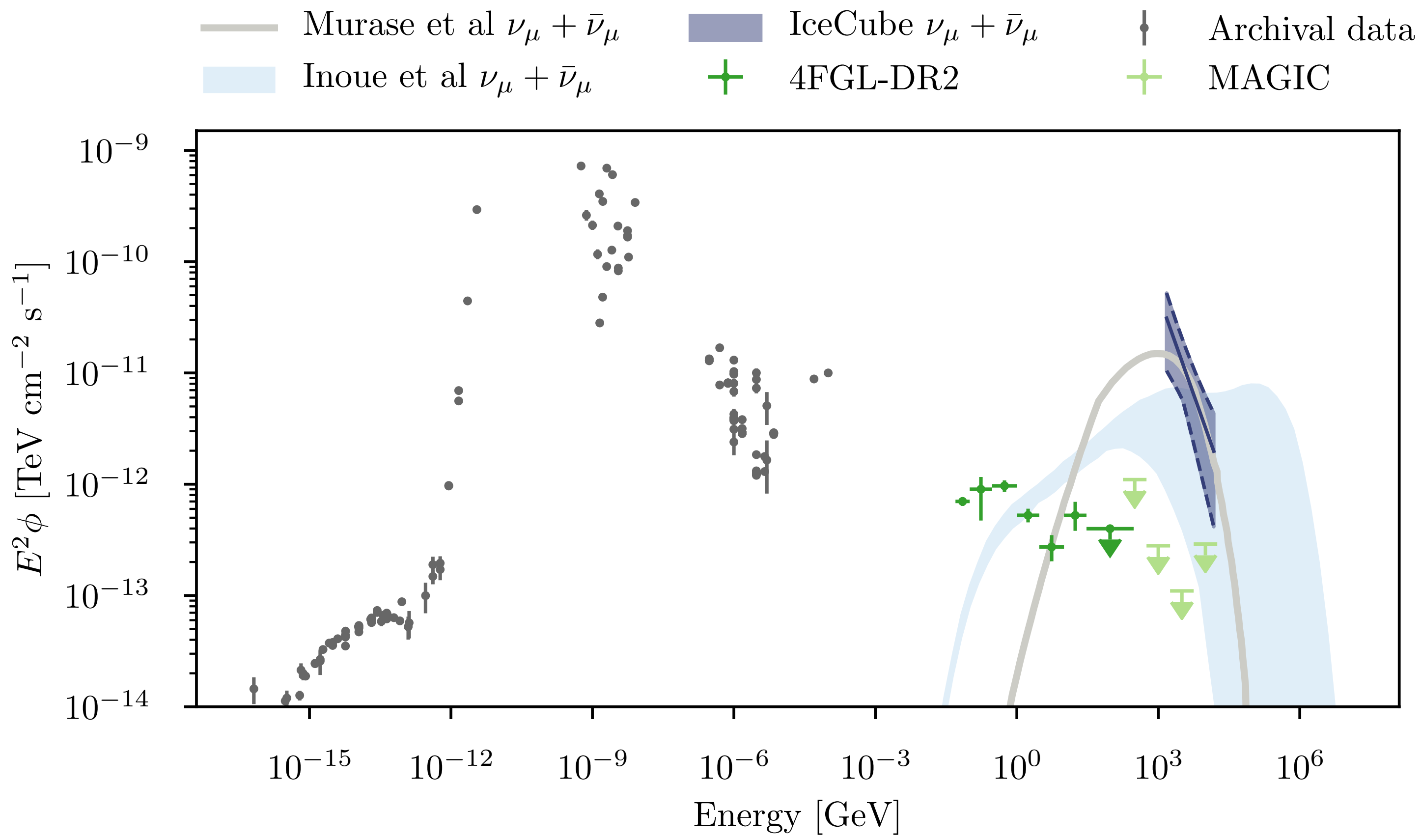
Trial factor reduced by looking only in the directions of 110 gamma ray sources

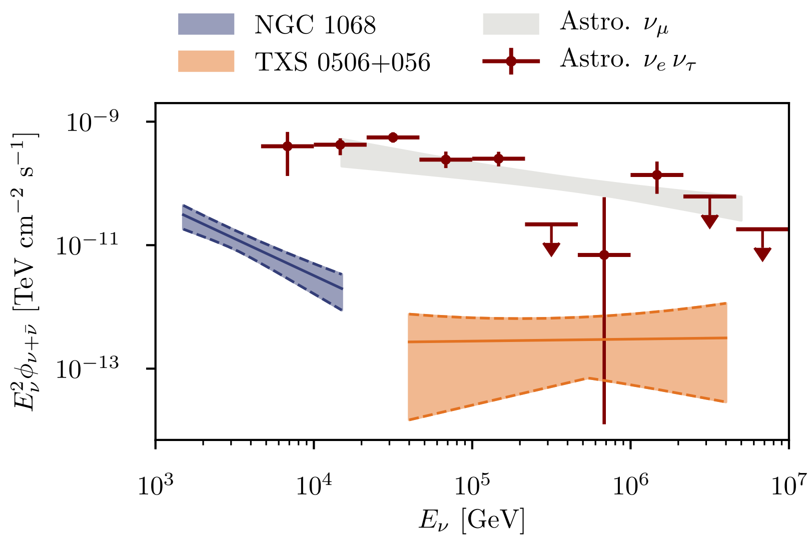


# Multimessenger phenomenology?

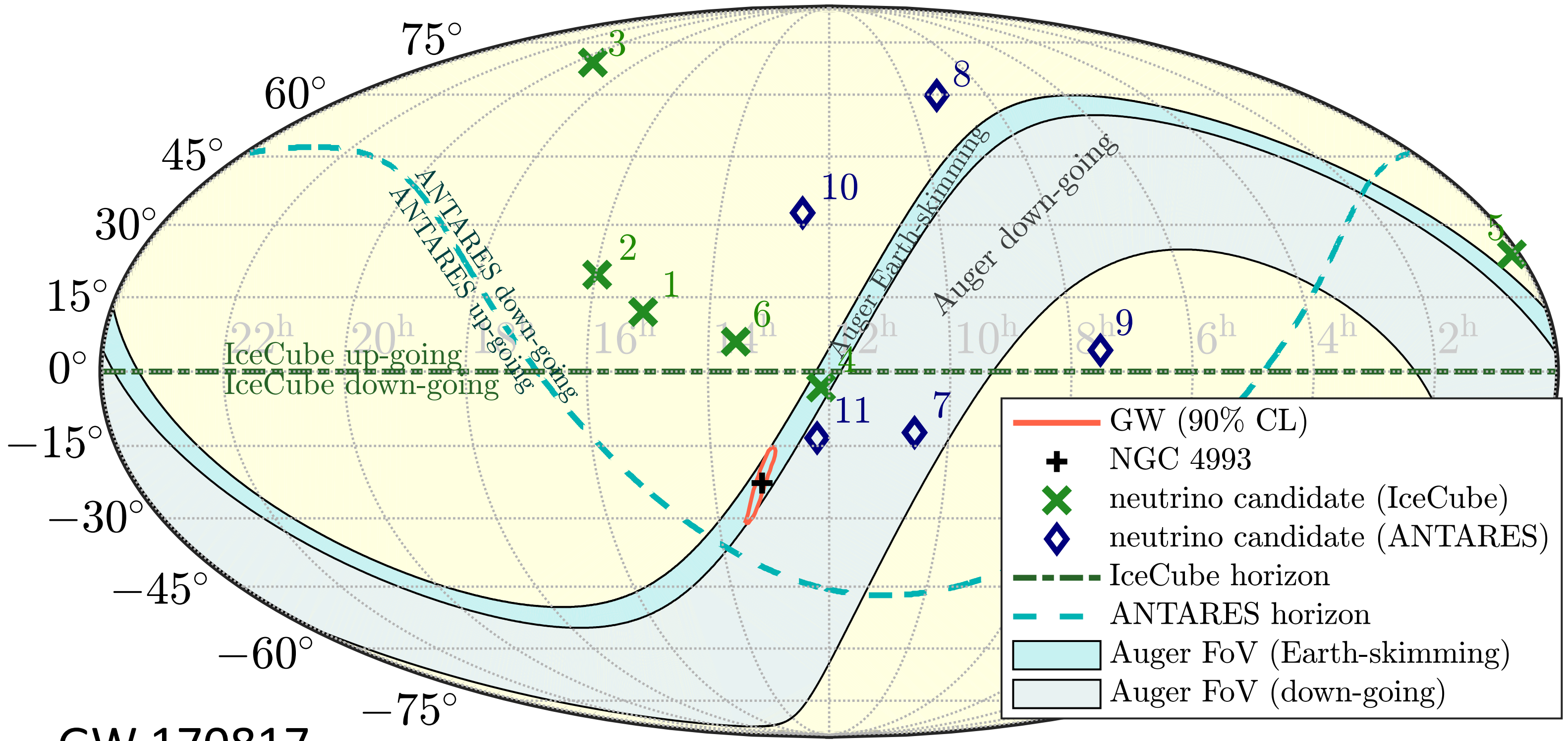


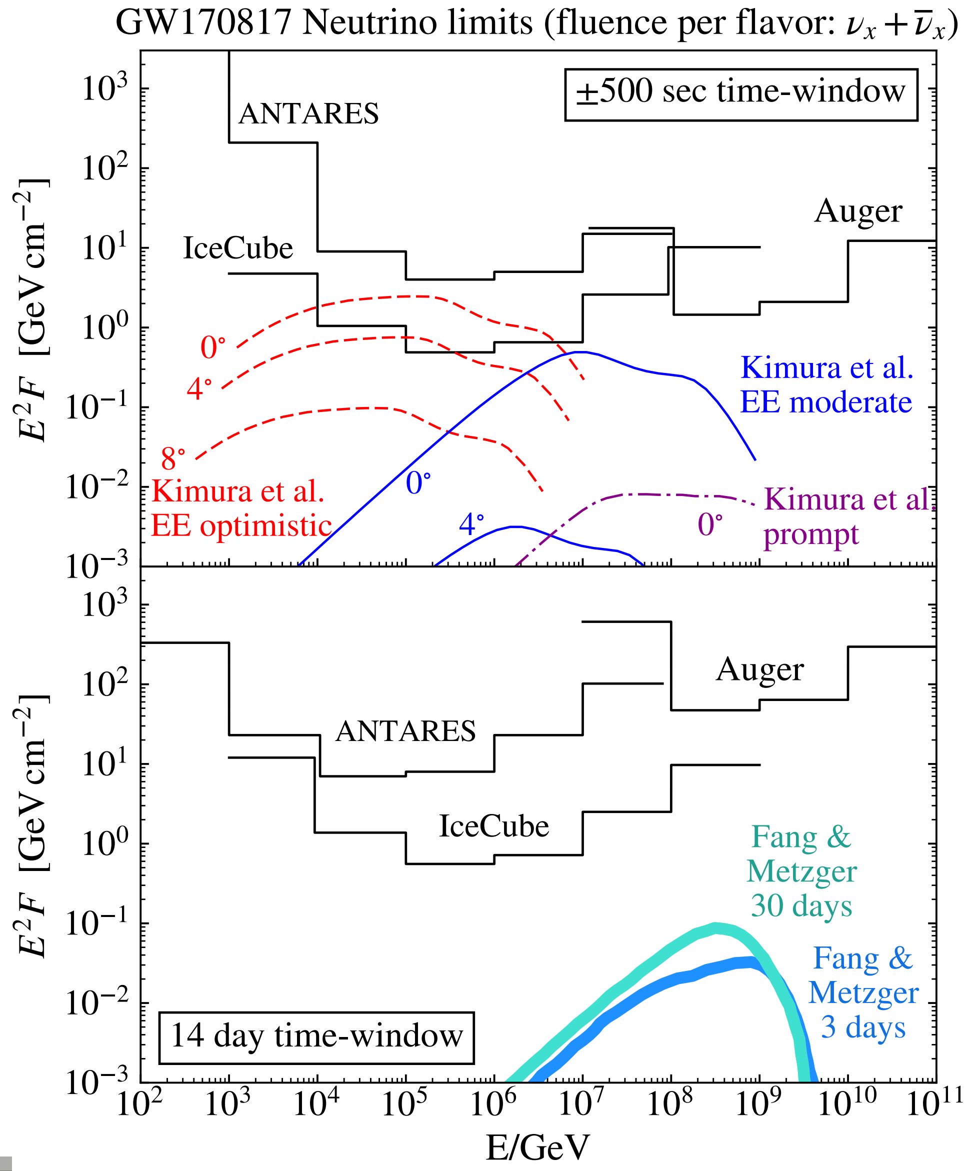

This field is ready to be disrupted

# Search for neutrinos in coincidence with gravitational waves

binary neutron star merger

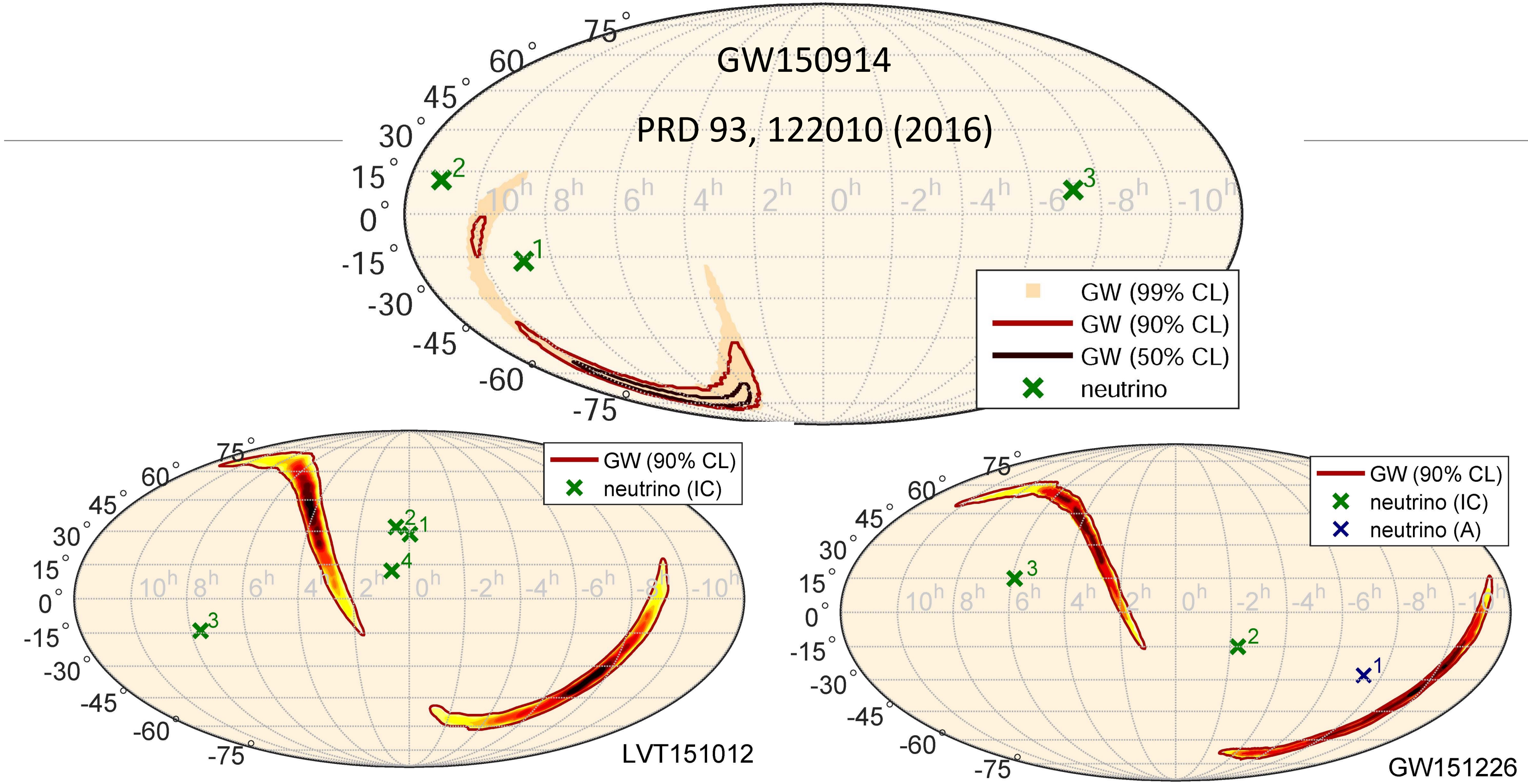



GW 170817




ANTARES, IceCube, Auger, LIGO/Virgo, ApJL 850:L35 (2017)
+ null results from binary black hole merger neutrino searches

# $\nu$ from GWs? (contd)

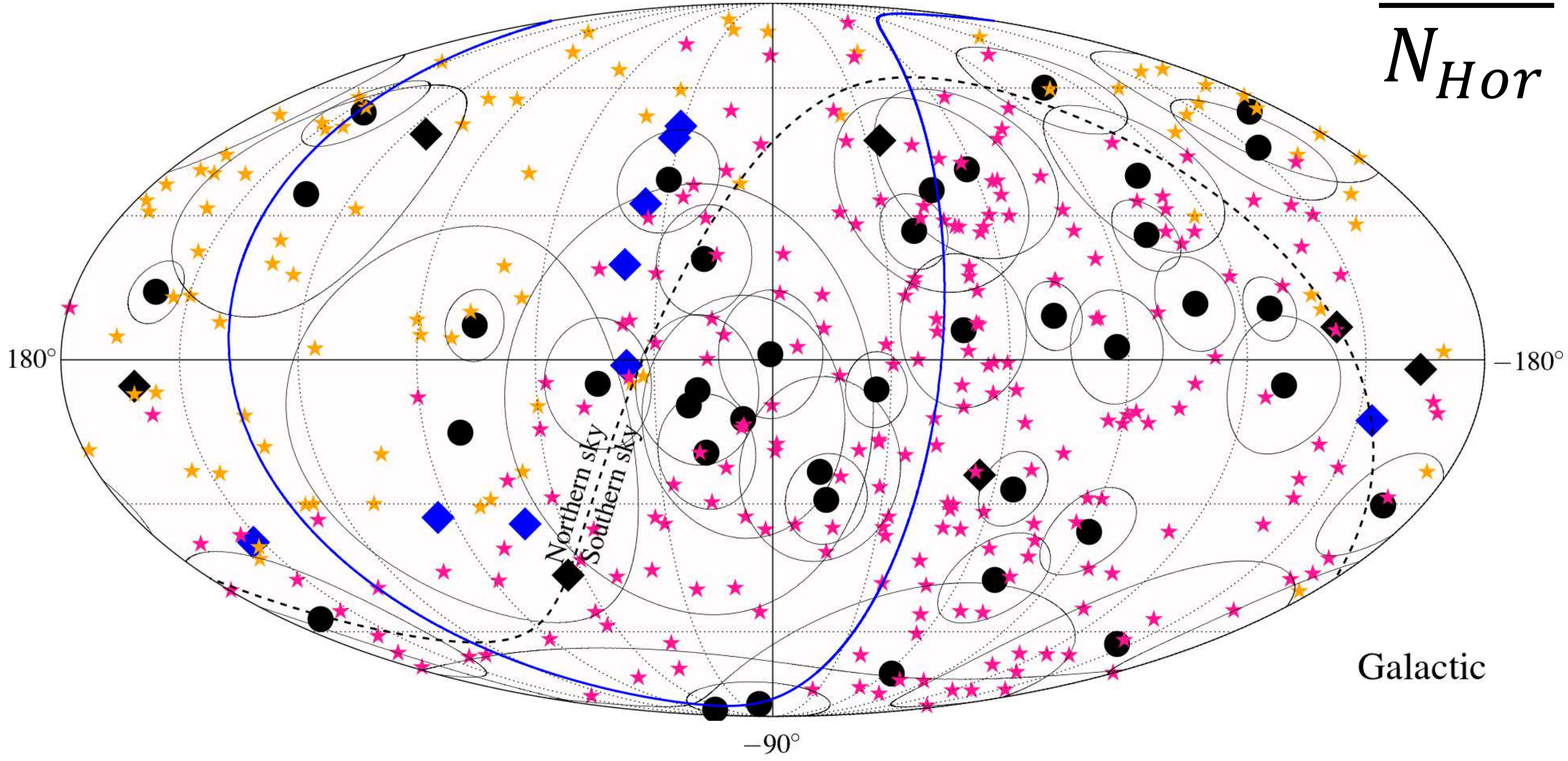



PRD 96, 022005 (2017)

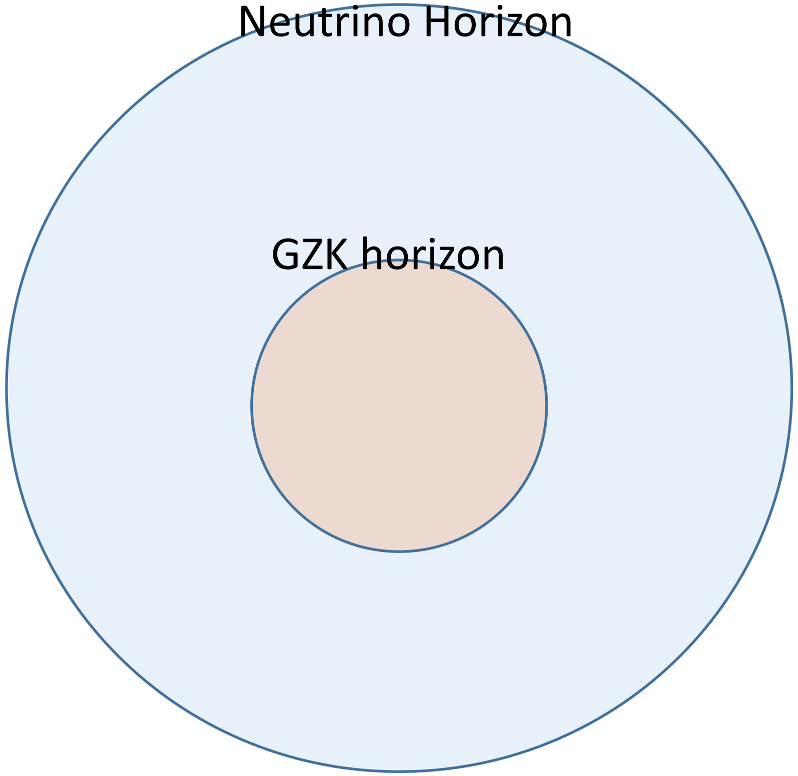
ANTARES, IceCube, LIGO/VIRGO

# Correlations with UHECR arrival directions?

JCAP01(2016)037

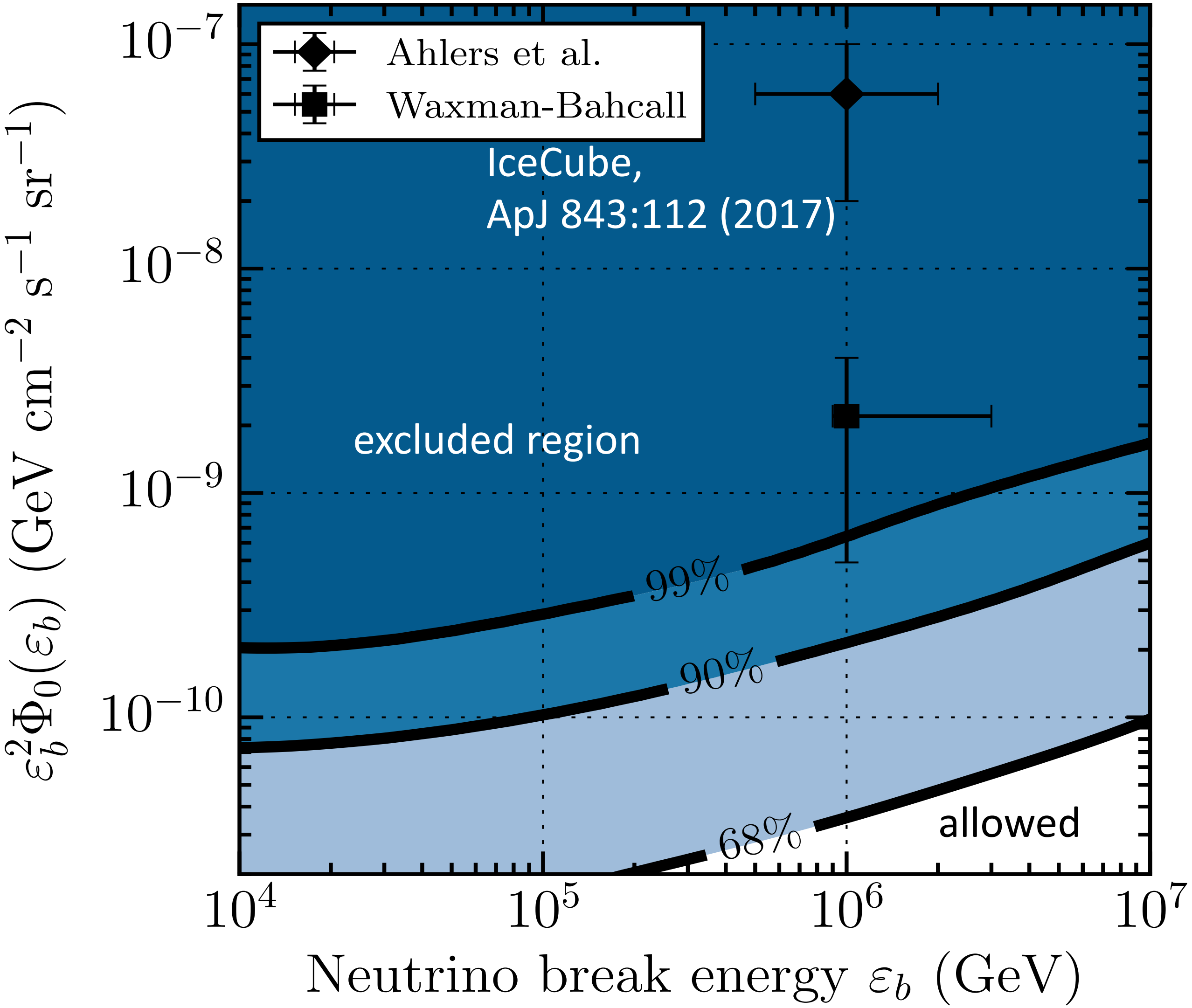



$$\frac{N_{GZK}}{N_{Hor}} < 5\%$$




No statistically significant correlation.

# Correlations with GRBs?

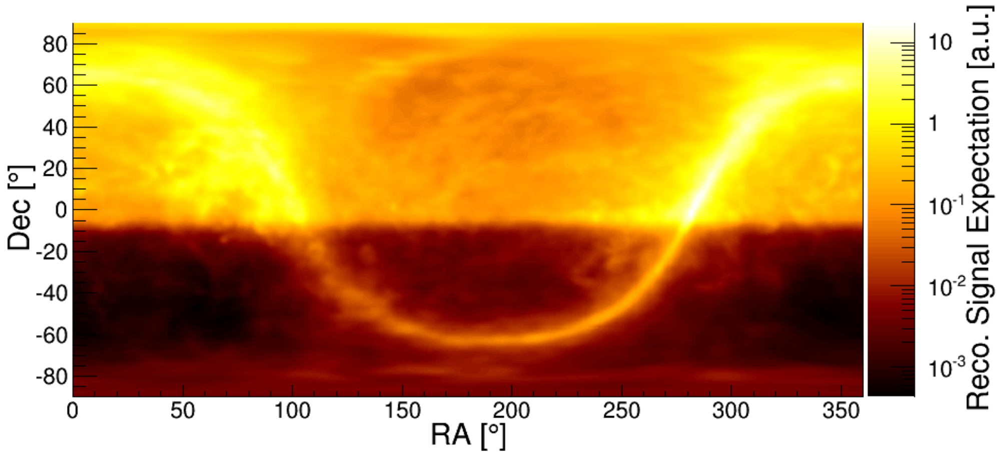



- No association with five years of muon neutrino track events
- Conclusion: <1% of astrophysical neutrino flux is produced by GRBs
- Non-detection rules out GRBs as the dominant source of UHE cosmic rays

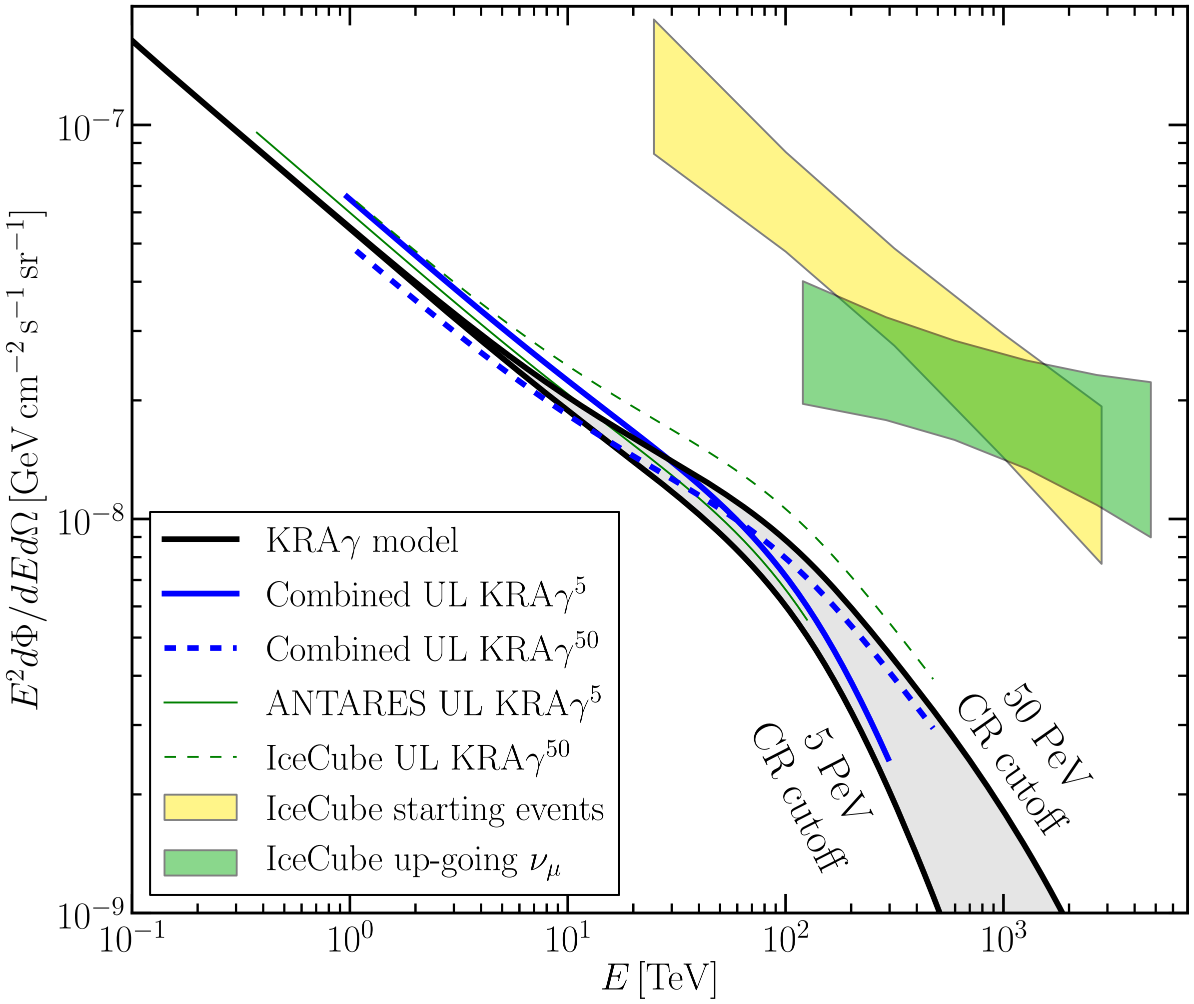
# A diffuse Galactic Component?

Realistic models are currently below the IC Sensitivity

*Astrophys.J.Lett.* 868 (2018) 2, L20




Diffuse spatial template from Fermi $\pi^0$ map, combined with IC effective area and angular resolution

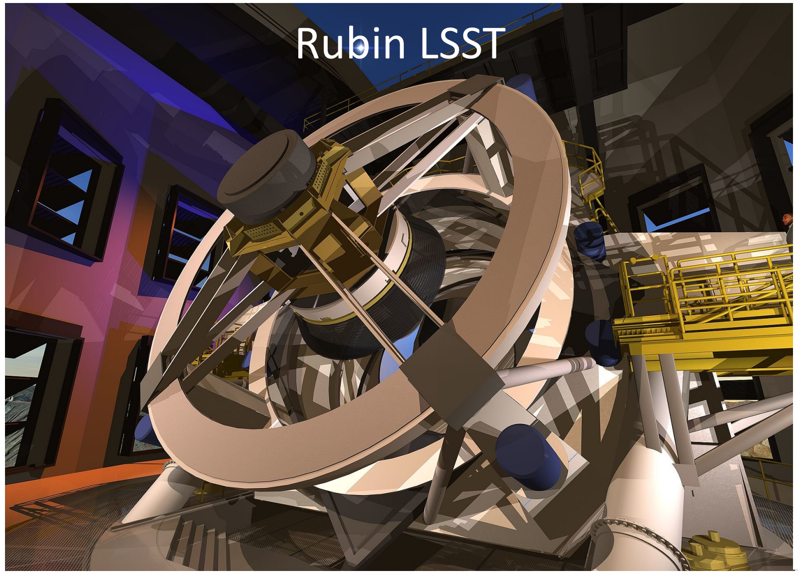


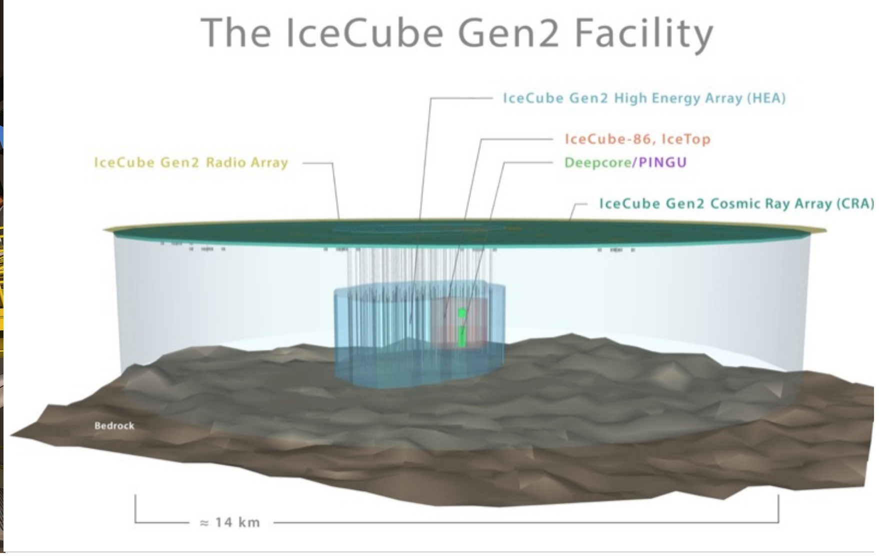
# The Future

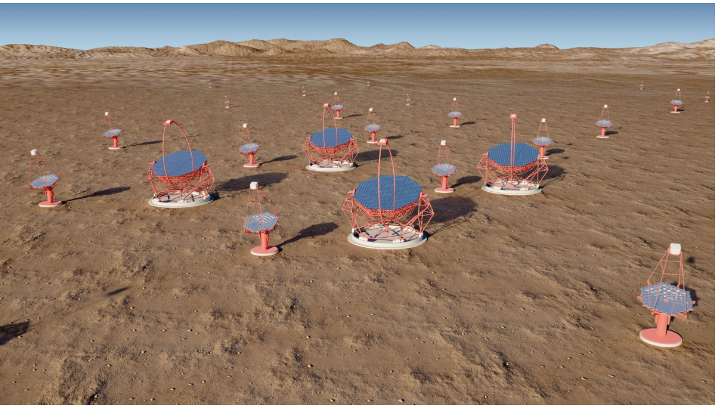
Transient factories

GRBs
SNe
Neutrinos
Gravitational waves
FRBs
Optical transients

We are about to be overwhelmed by data.
Great opportunity for citizen science and outreach

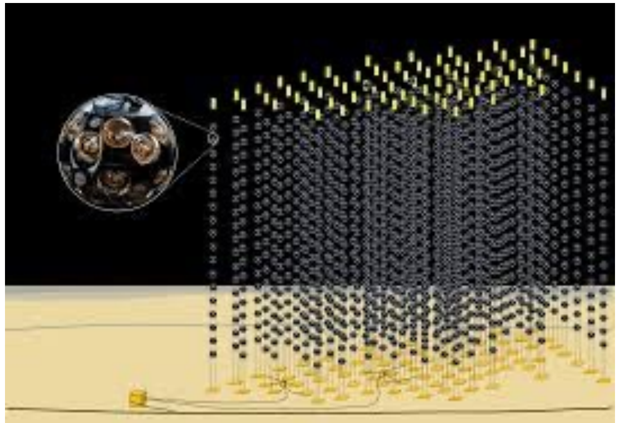


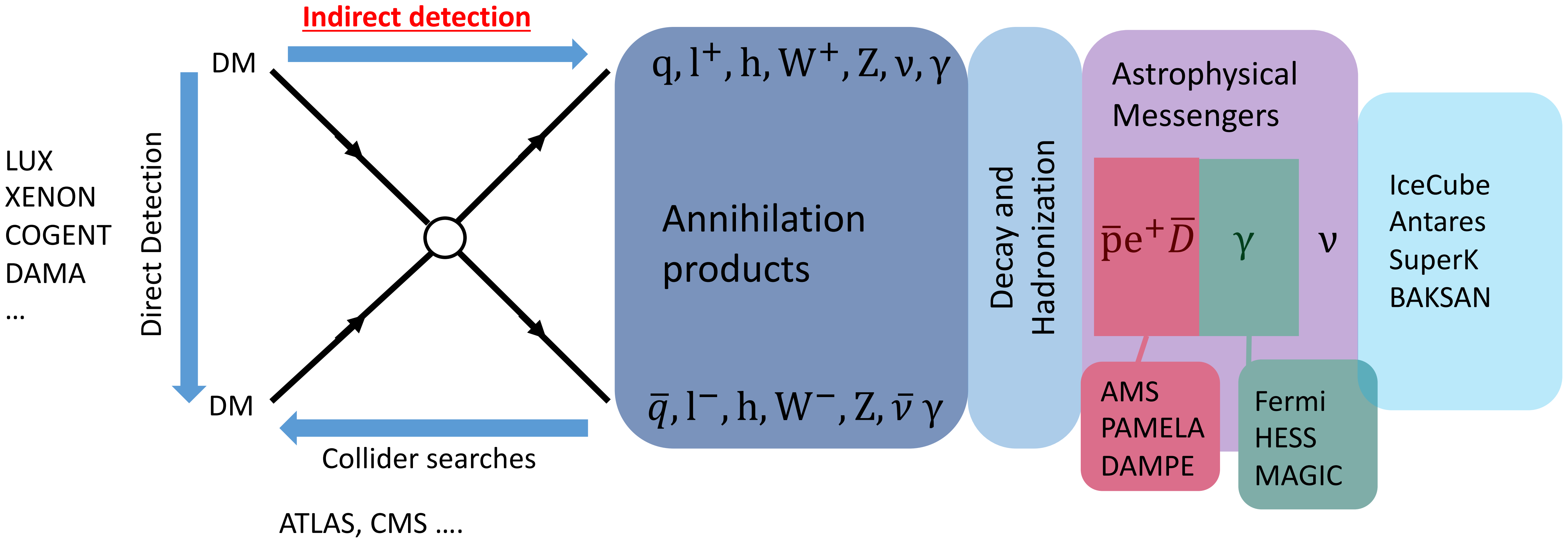



CTA

SKA



# Credible DM Detection *will need* multiple messengers



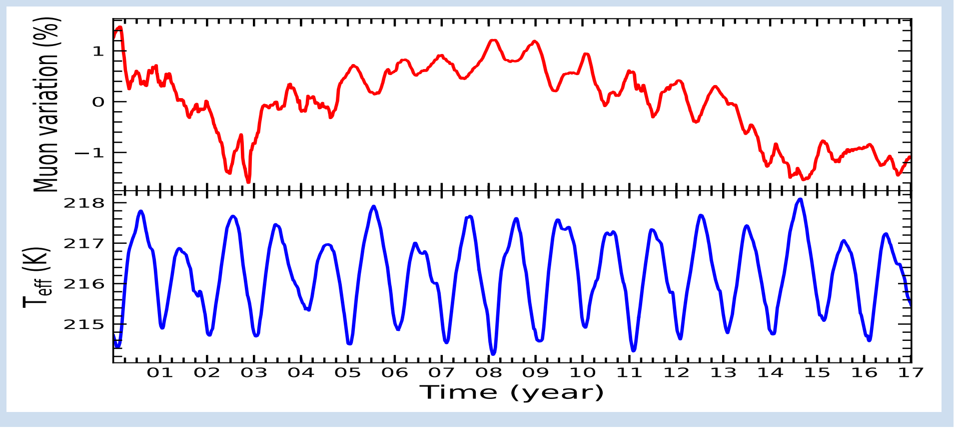

| | | |
|---|---|---|
| DM | annihilation rate | $\propto \rho^2$ |
| | decay rate | $\propto \rho$ |

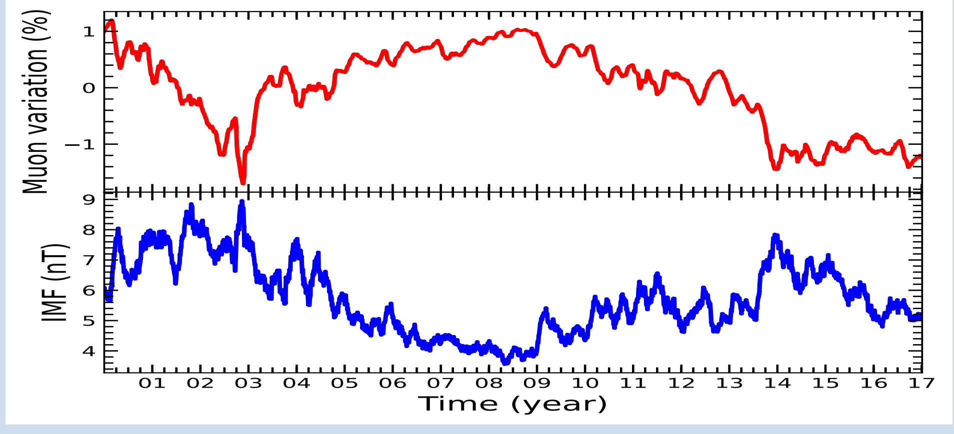
Fermi Galactic Centre Excess,
AMS $e^+/e^-$ excess etc inconclusive
Also DAMA, Cogent modulations

# What can we expect?

Surprising correlations, falsification of assumptions – keep an open mind

Short term




Posted-4 512

Developing atmospheric CR secondaries and in situ measurements of the IMF into an input for Earth-climate models

Long term

Galactic diffuse neutrinos? More confidence in our understanding of CR acceleration and diffusion models

Long shot

Anchordoqui *et. al. Phys.Rev.D* 72 (2005) 065019

Quantum gravity – neutrino flavour ratio from a multimessenger source

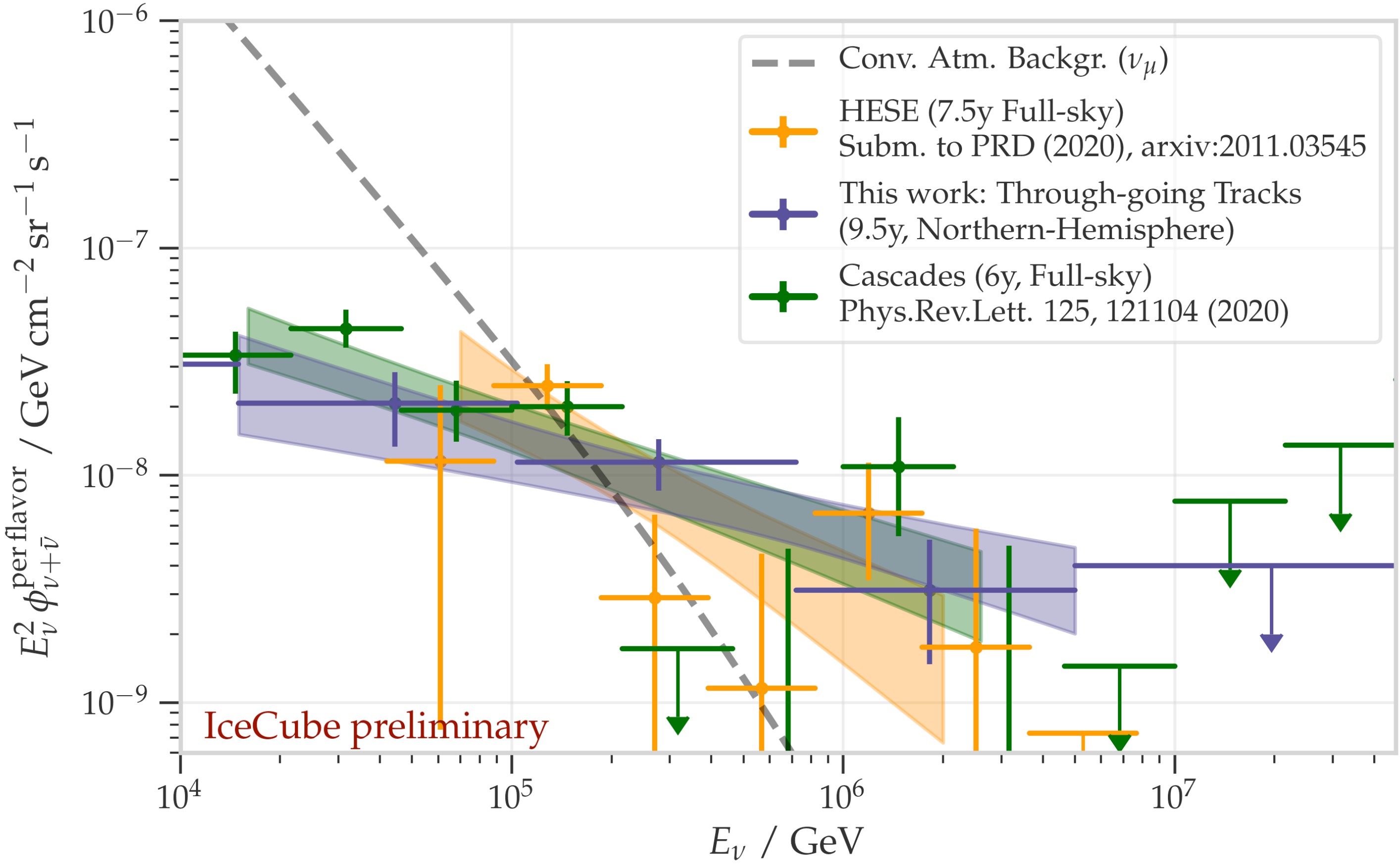
# Conclusions

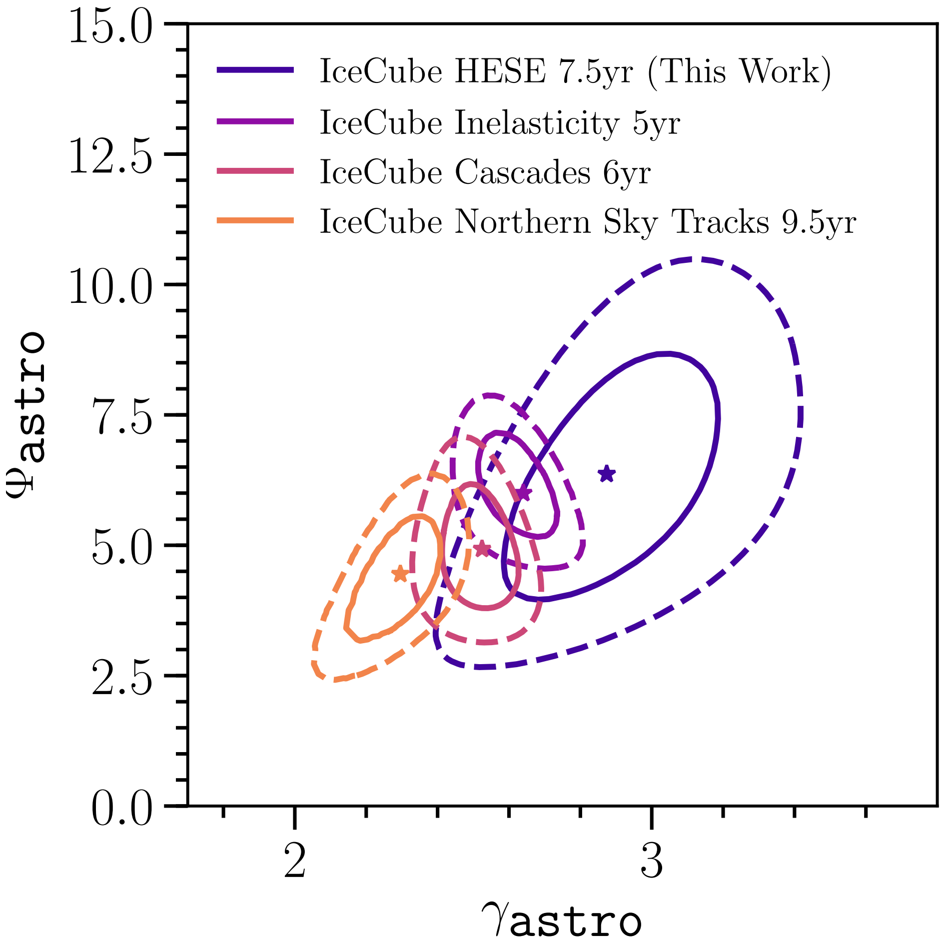
- Neutrinos and Gravitational waves are two astronomical messengers that have come of age in the last decade.
- Neutrinos – Diffuse flux, two high energy sources with EM counterparts
- GWs – 23 above 5 sigma
- Multimessenger phenomenology is nascent and needs fresh ideas
- Upcoming transient factories – great opportunity for citizen science and outreach

A revolution may be around the corner

# Backup

# Diffuse flux also discovered in other channels



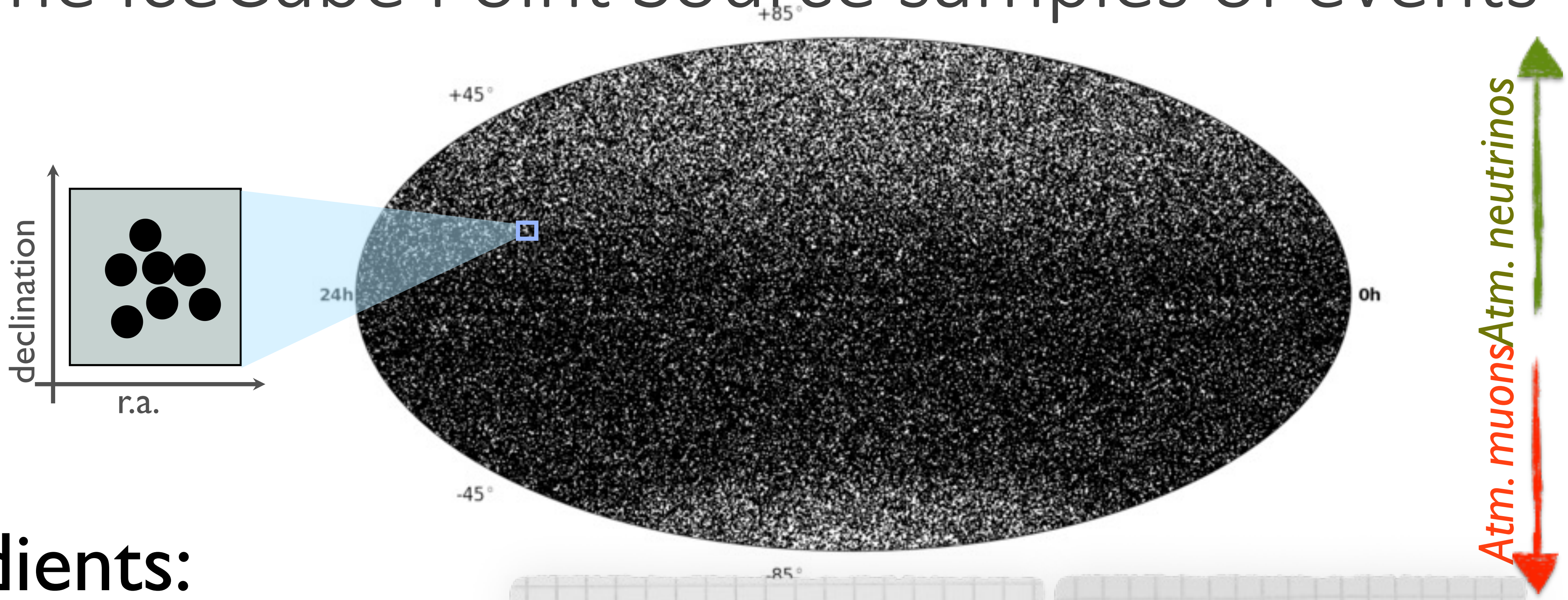



# The IceCube Point Source samples of events

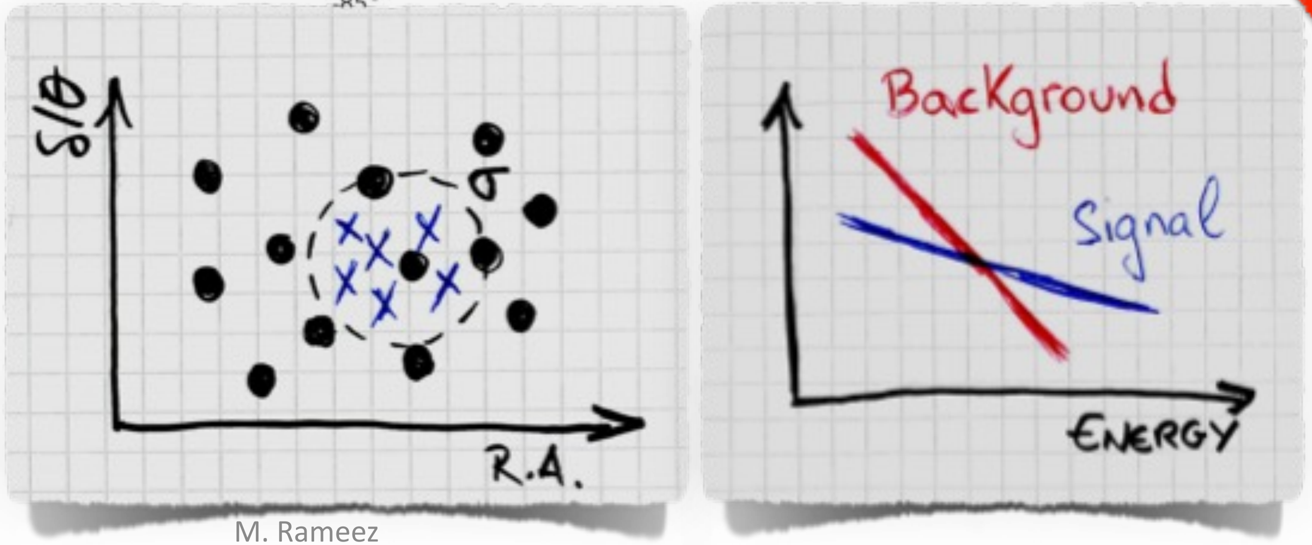
No Veto

Lower Energy Threshold

Tracks




# Ingredients:

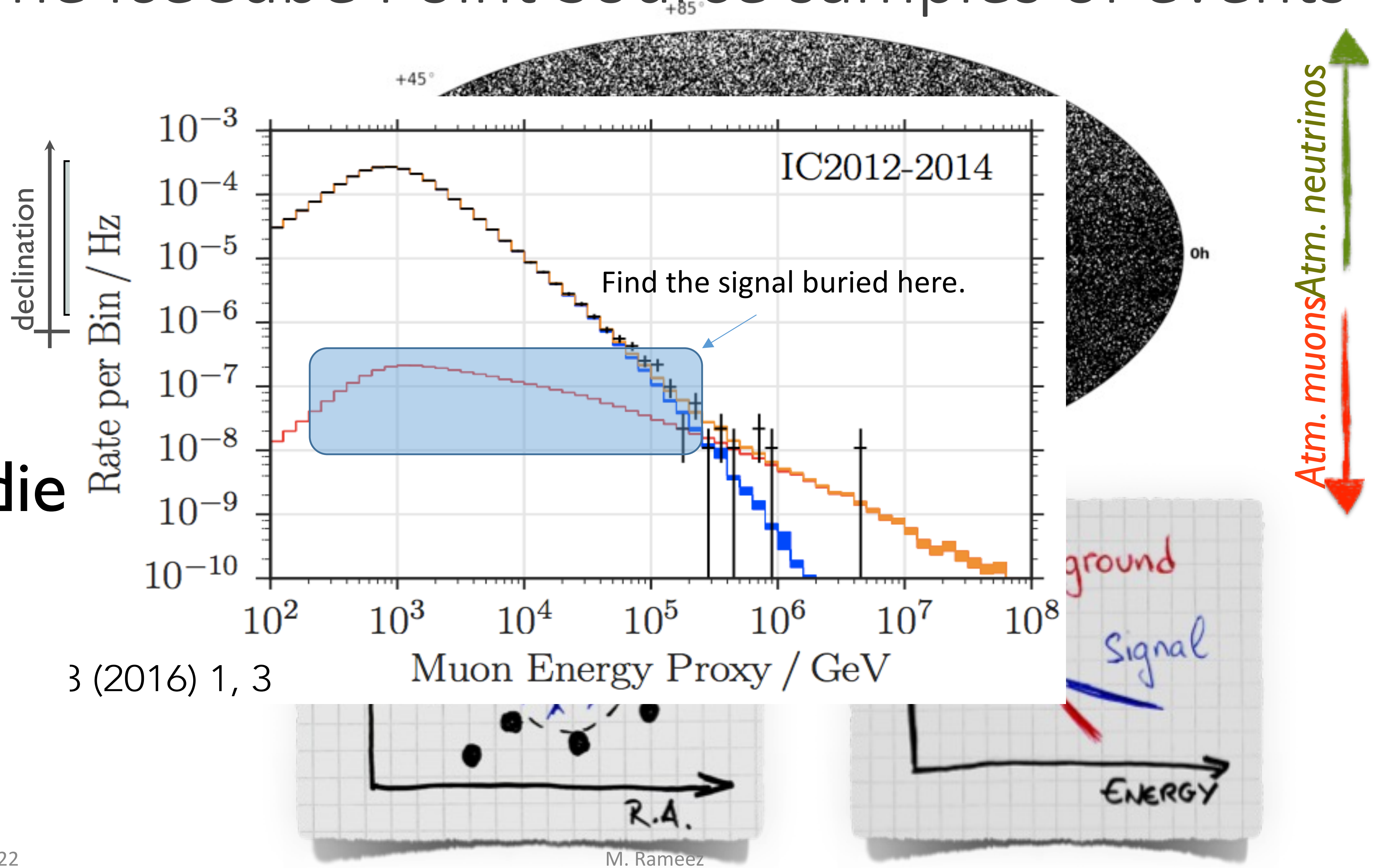


# The IceCube Point Source samples of events

No Veto

Lower
Energy
Threshold

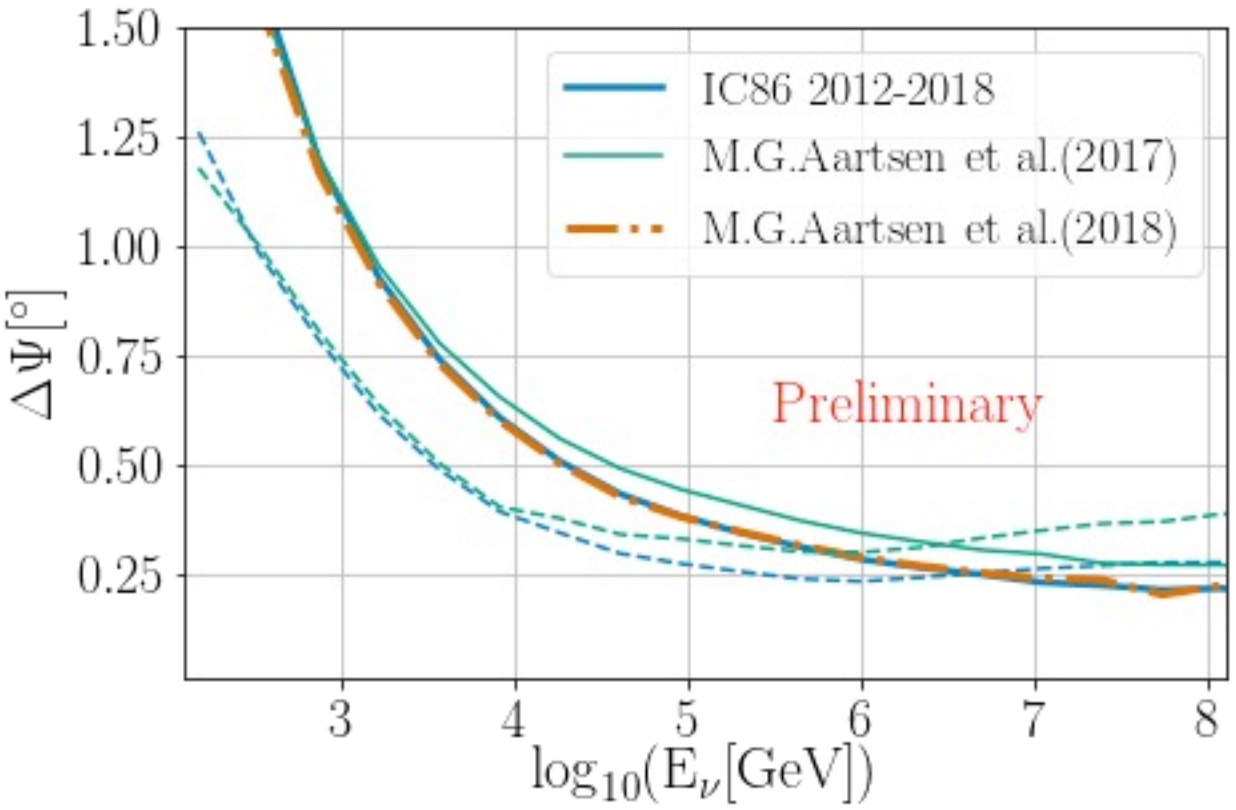
Tracks

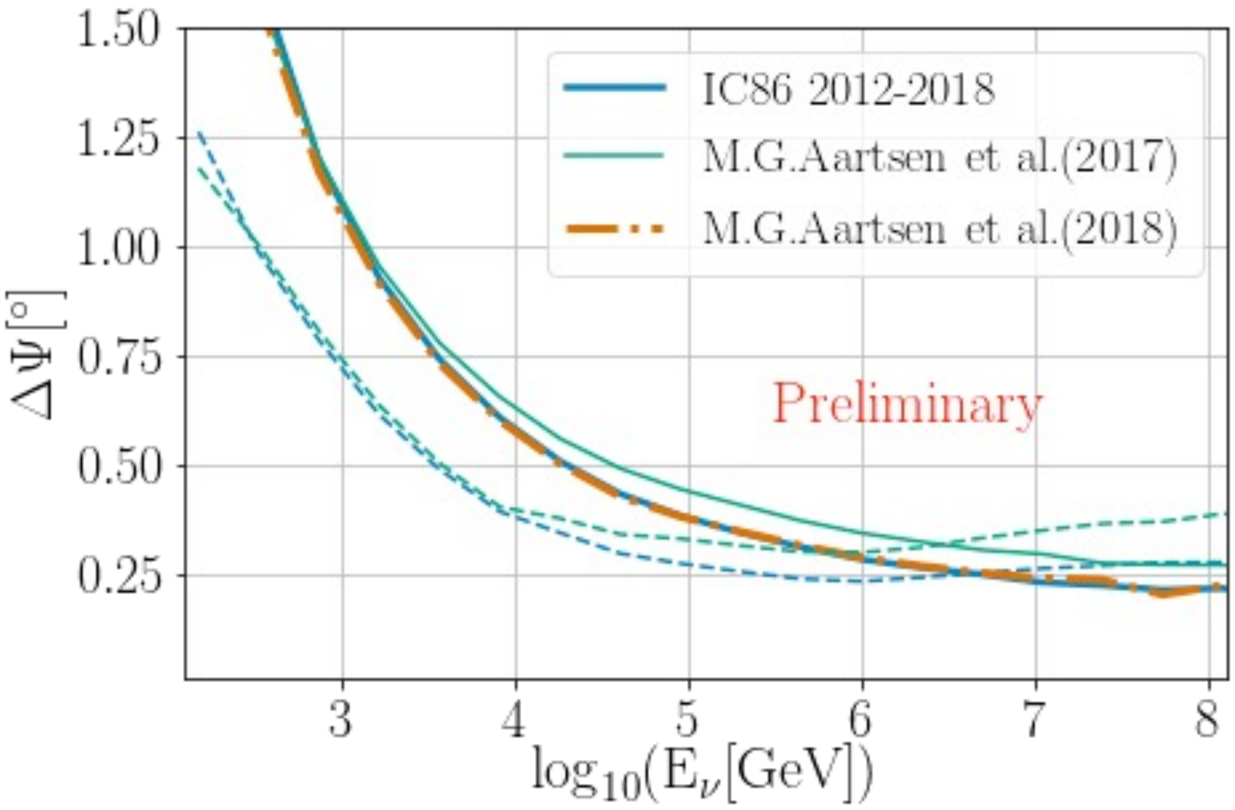



Ingredie

3 (2016) 1, 3

# The IceCube Point Source samples of events



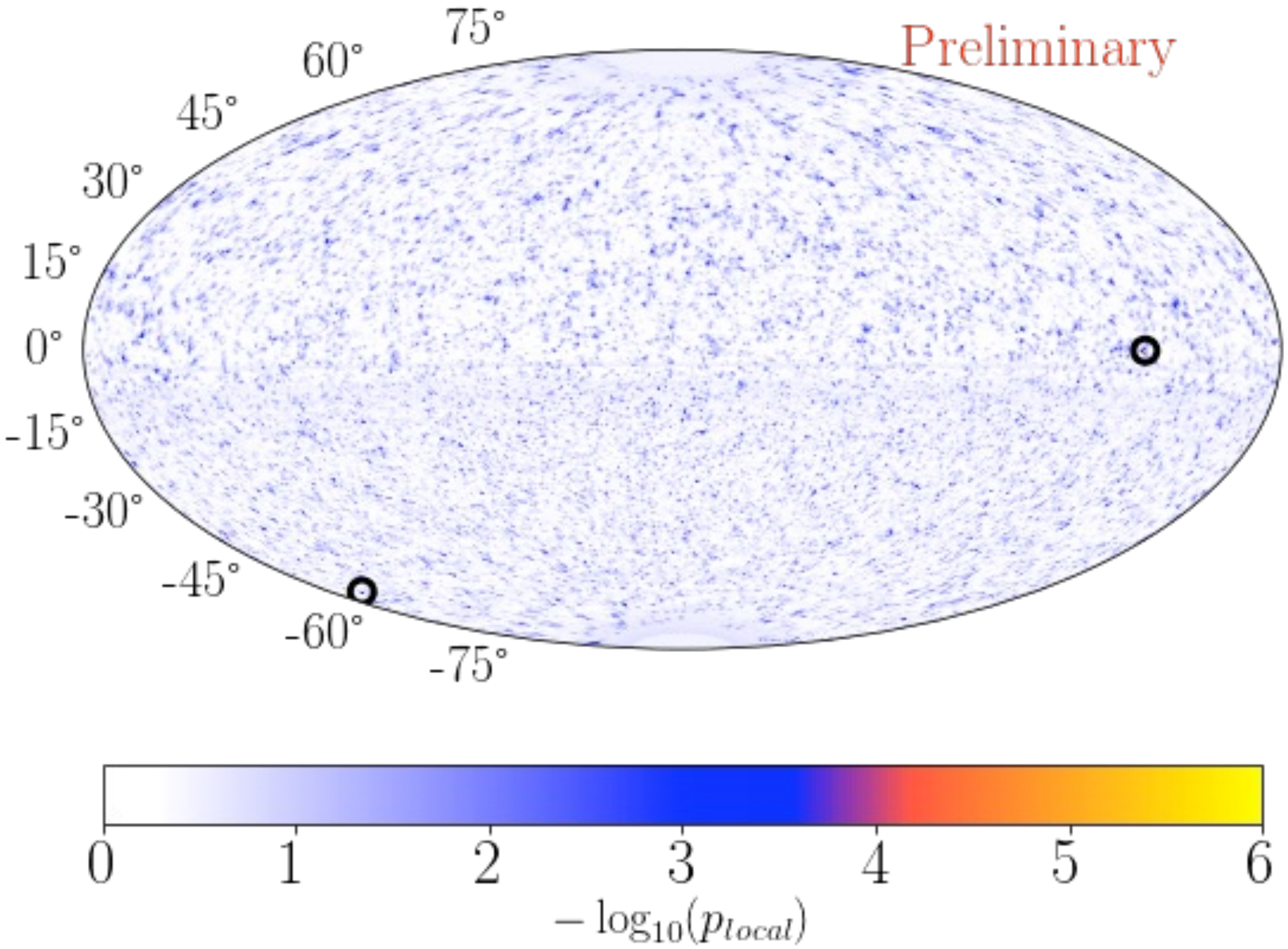




~600000 tracks, from IC40, 59, 79 and 86 (7 years of IceCube)

Northern sky: μ from $\nu_\mu + \bar{\nu}_\mu$ CC interactions

Southern sky: Atmospheric μ

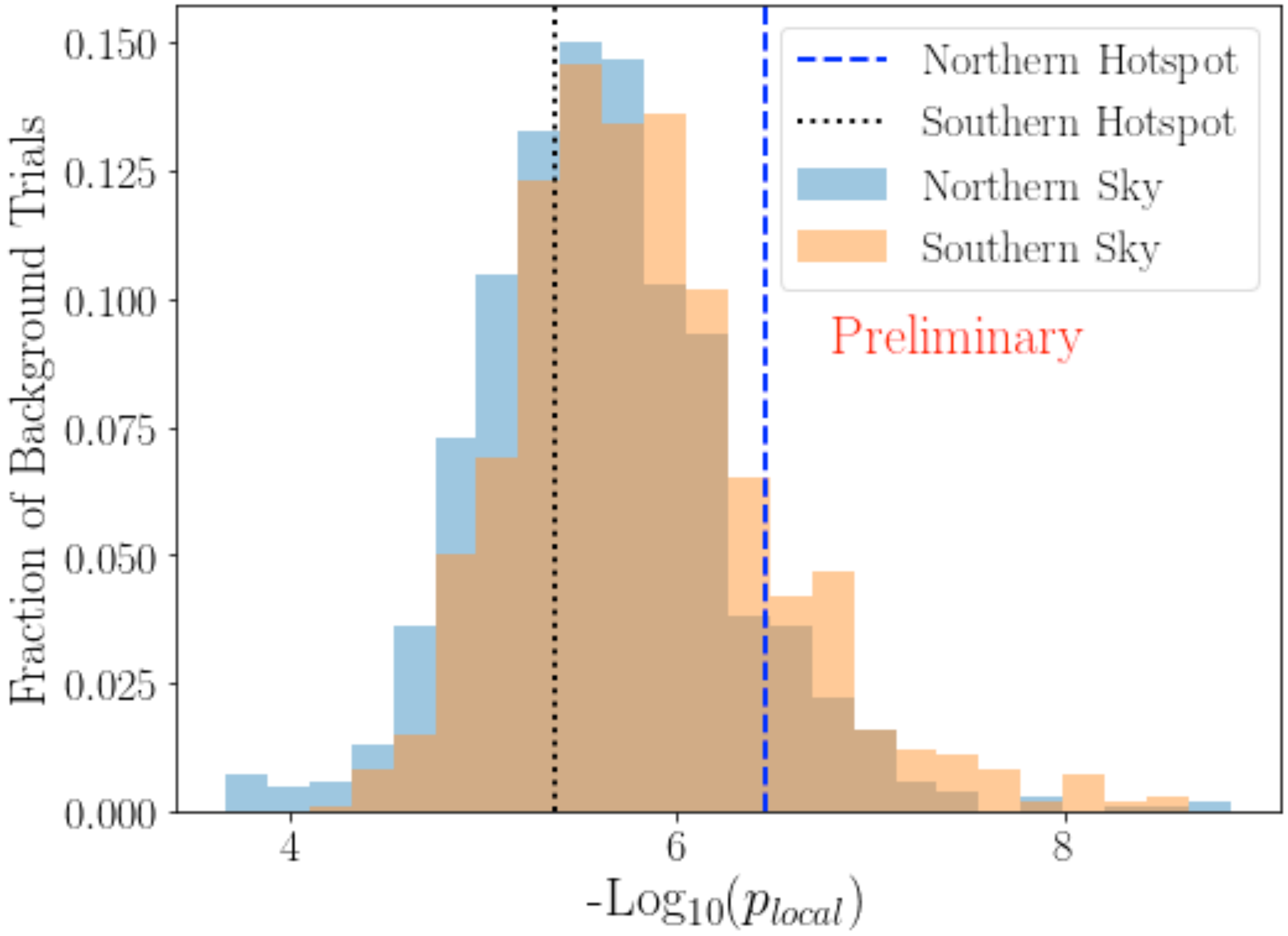
# All sky point source searches - 10 years




Northern sky p value : $10^{-6.45}$

Southern sky p value : $10^{-5.37}$

# All sky point source searches



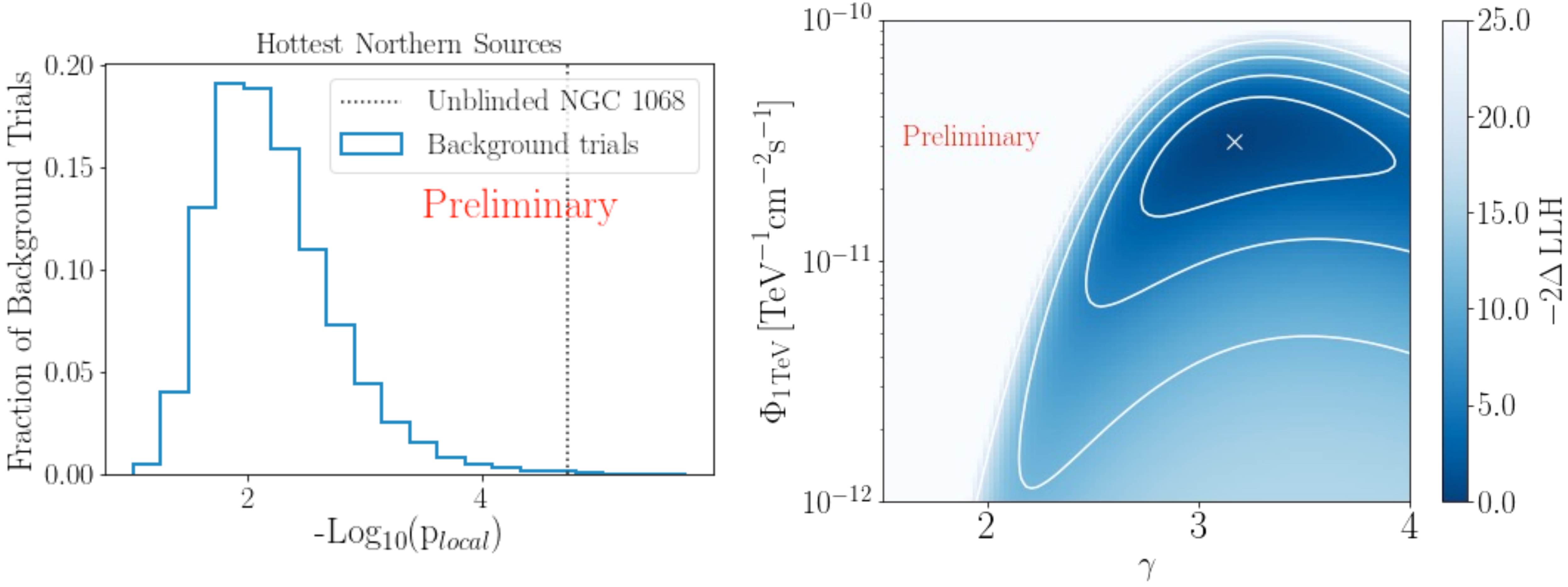

Northern sky p value : $10^{-6.45}$
Southern sky p value : $10^{-5.37}$

Post trials, p values of 0.099 and 0.75 respectively.

No statistically significant excess!

Compatible with the background only hypothesis.

# NGC 1068 as a candidate source (from a Catalogue search)



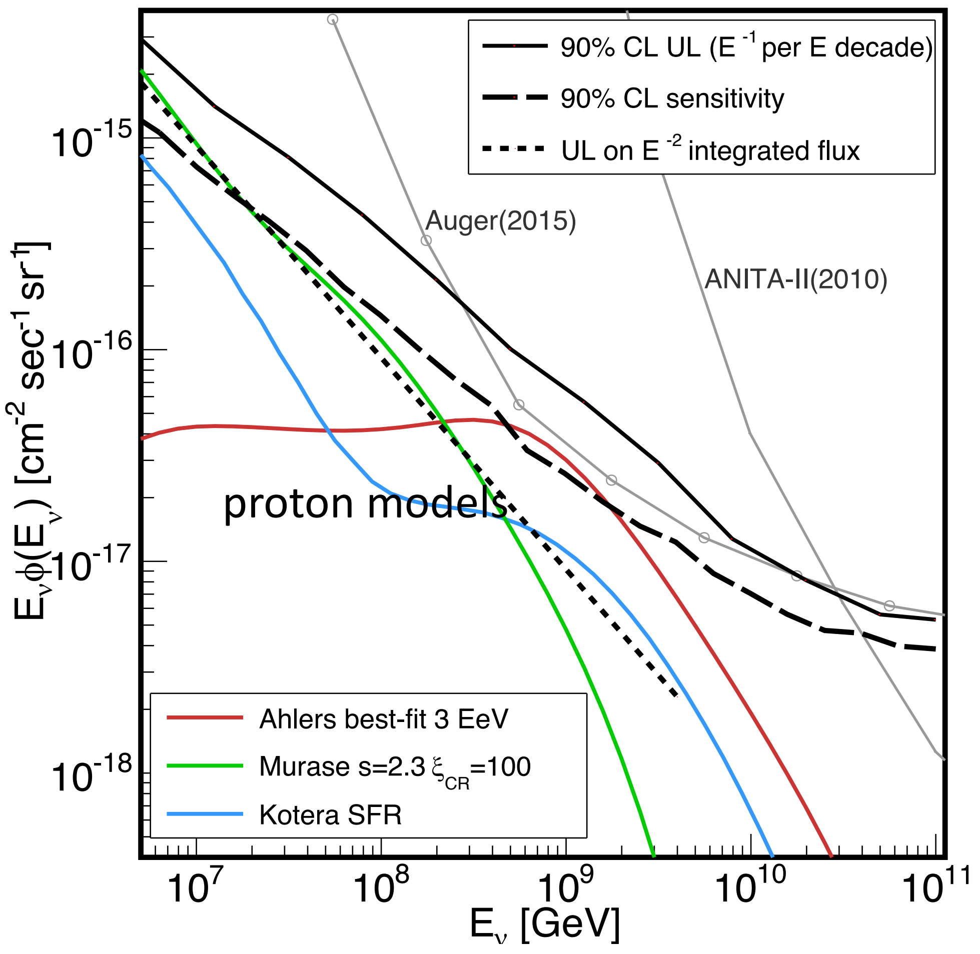

Only 2.9 sigma, accounting for trials.

# Cosmogenic (GZK) Neutrinos?

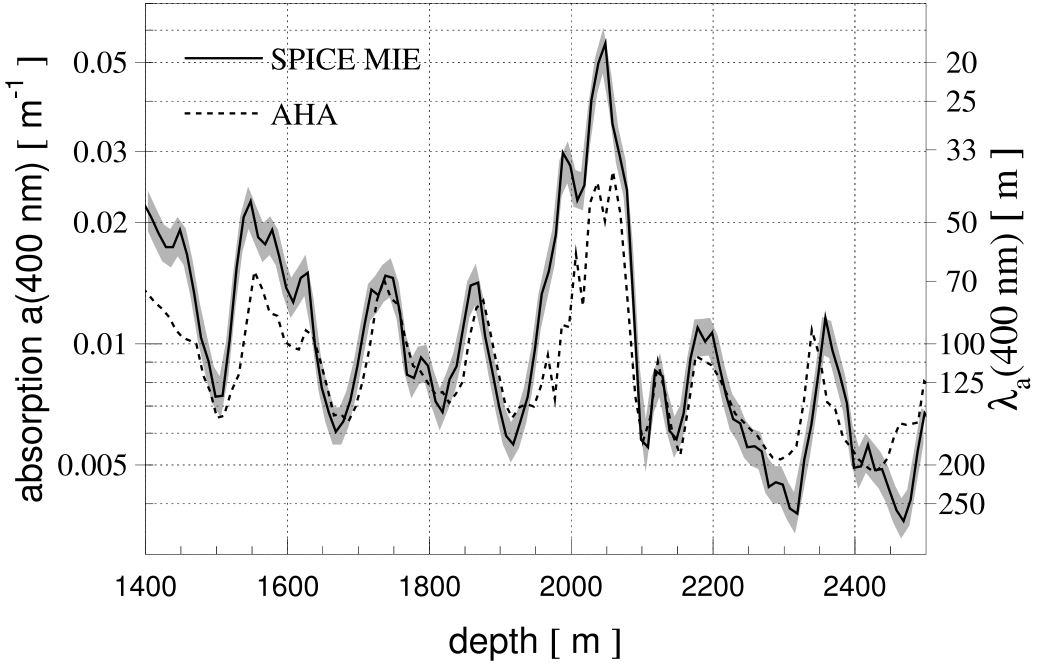
$$\gamma_{CMB} + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

No detection in 6 years of data

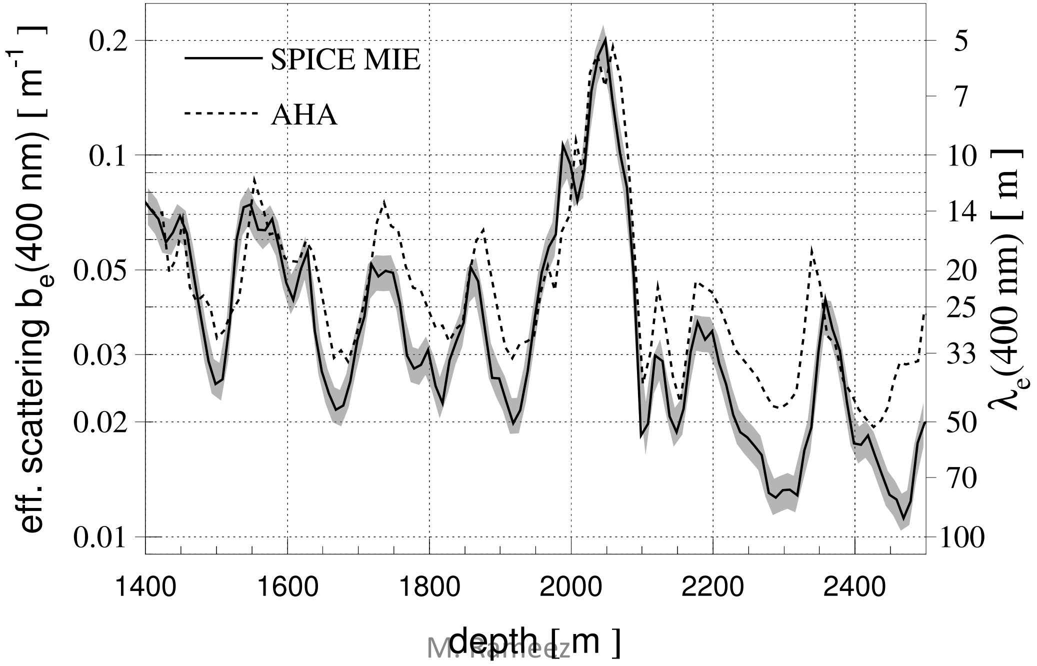
Favours heavier composition for UHECRs




IceCube, PRL 117, 241101 (2016)



SPICE MIE
AHA
absorption a(400 nm) [ m$^{-1}$ ]
0.05
0.03
0.02
0.01
0.005
$\lambda_a$(400 nm) [ m ]
20
25
33
50
70
100
125
200
250
1400
1600
1800
2000
2200
2400
depth [ m ]

SPICE MIE
AHA
eff. scattering $b_e$(400 nm) [ m$^{-1}$ ]
0.2
0.1
0.05
0.03
0.02
0.01
$\lambda_e$(400 nm) [ m ]
5
7
10
14
20
25
33
50
70
100
1400
1600
1800
2000
2200
2400
depth [ m ]

# Supernova Remnants (SNRs) and other Galactic Sources?

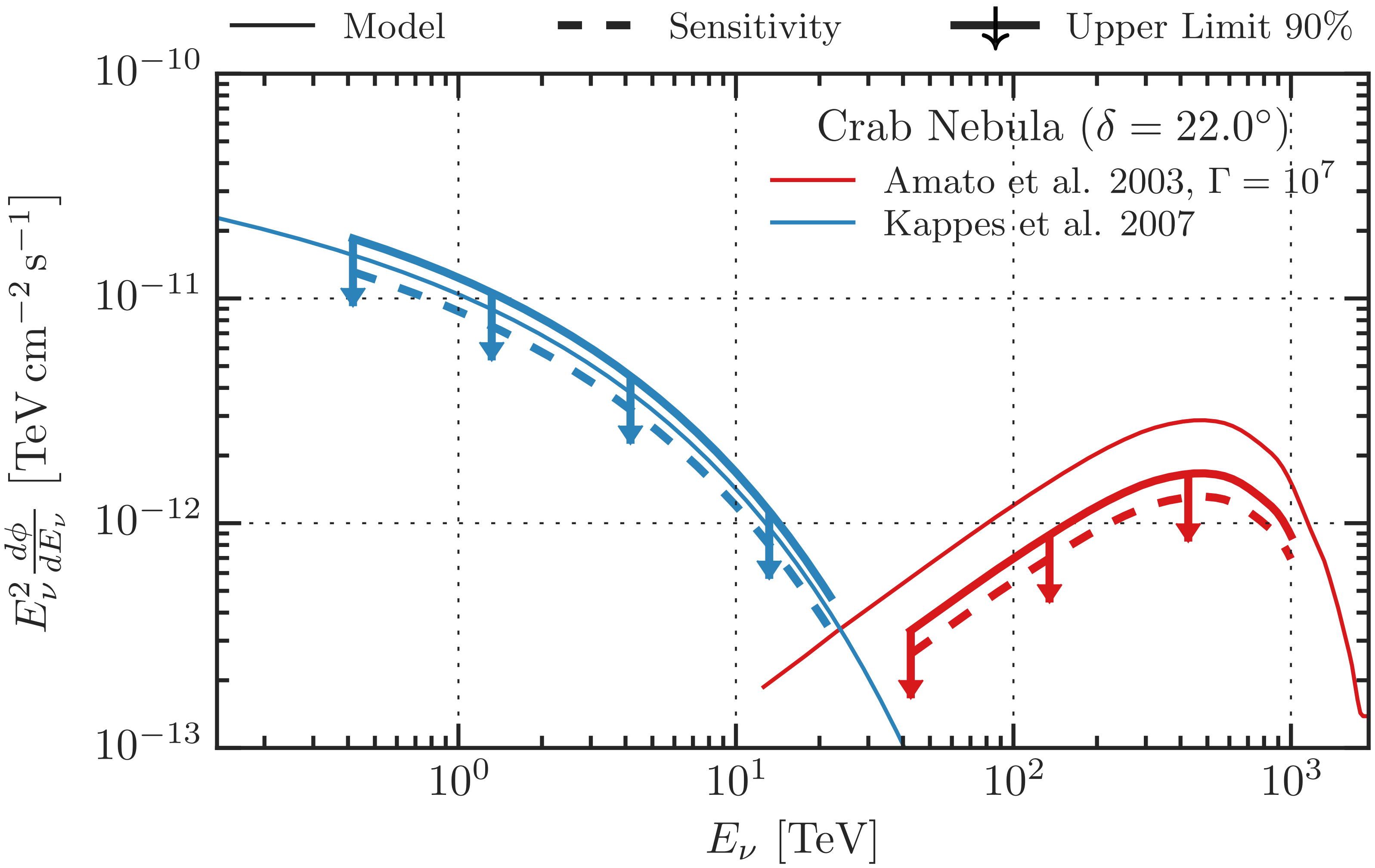
**Astrophys.J. 835 (2017) no.2, 151**

Supernovae – energy budget of Galactic CRs

Individual and Stacking searches for neutrinos from Galactic SNRs

Young SNRs and PWNs from SNRCat, HAWC hotspots

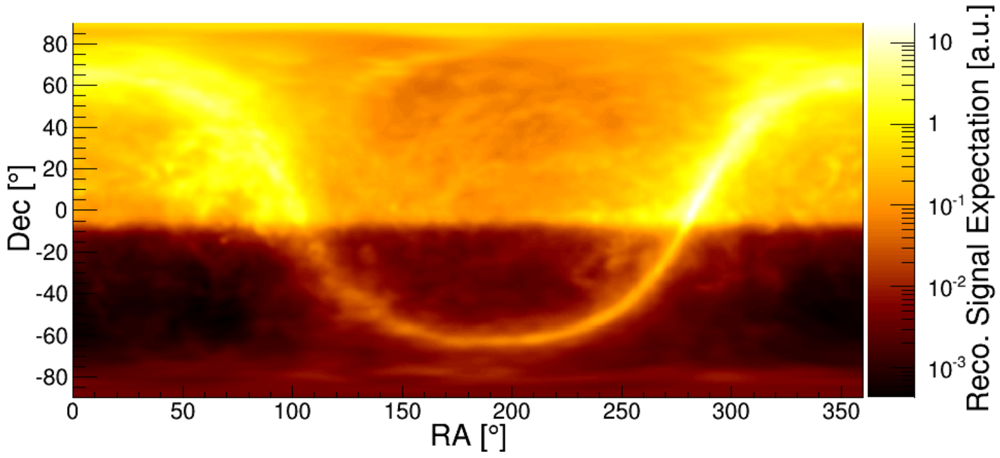
No significant excess. Optimistic models are being excluded



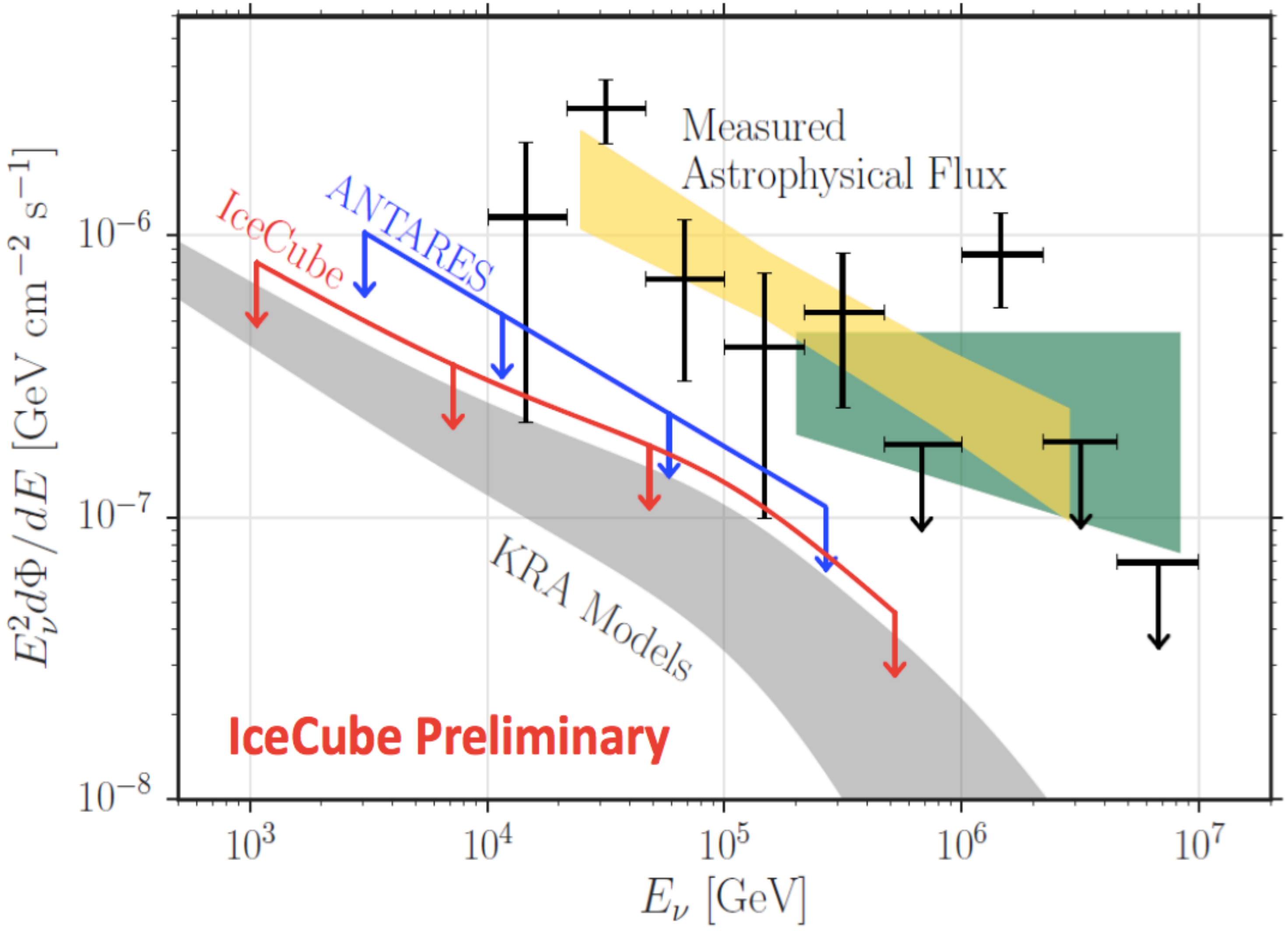
# A diffuse Galactic Component?

Realistic models are currently below the IC Sensitivity

The Astrophysical Journal Letters, 815:L25 (2015)




Diffuse spatial template from Fermi $\pi^0$ map, combined with IC effective area and angular resolution

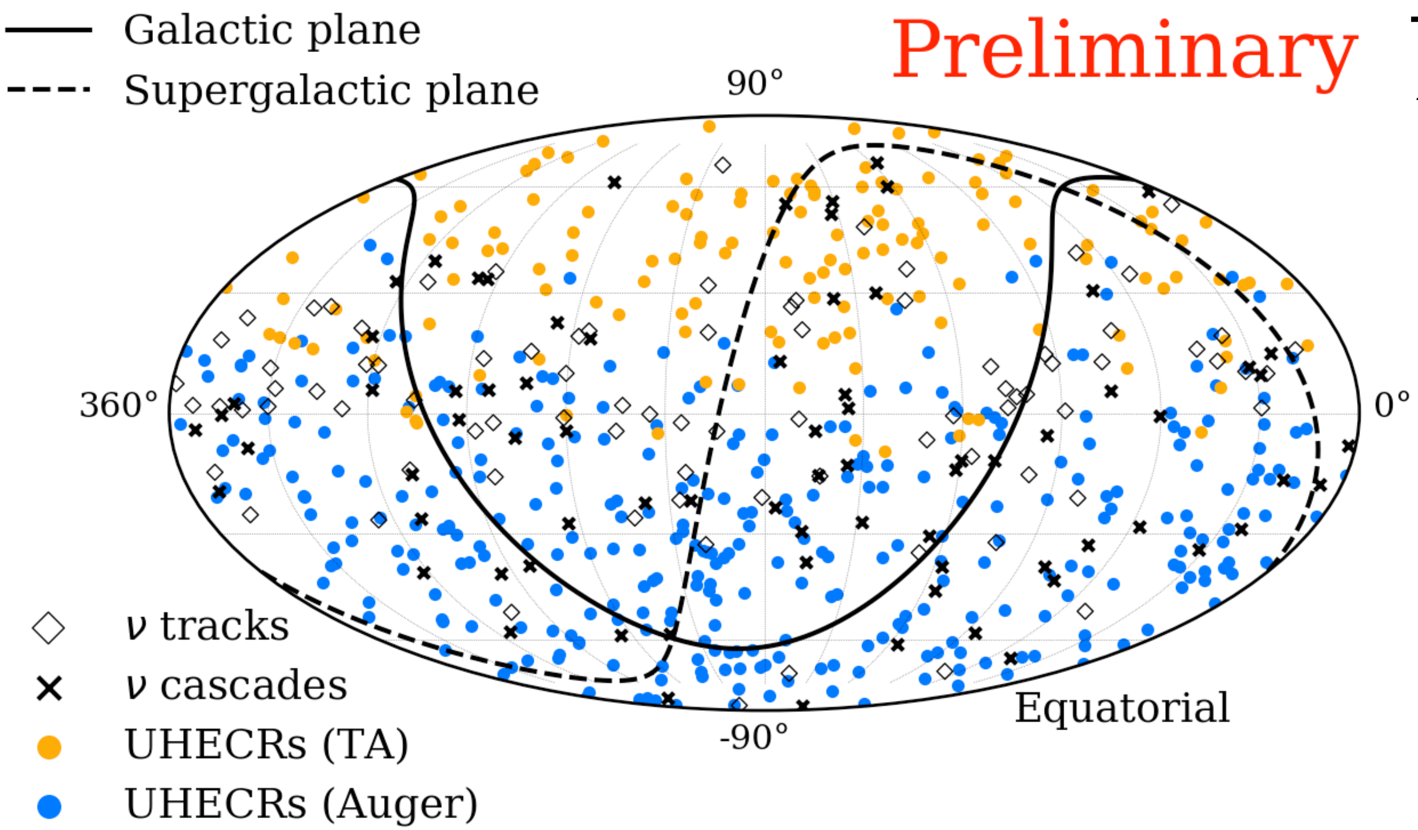


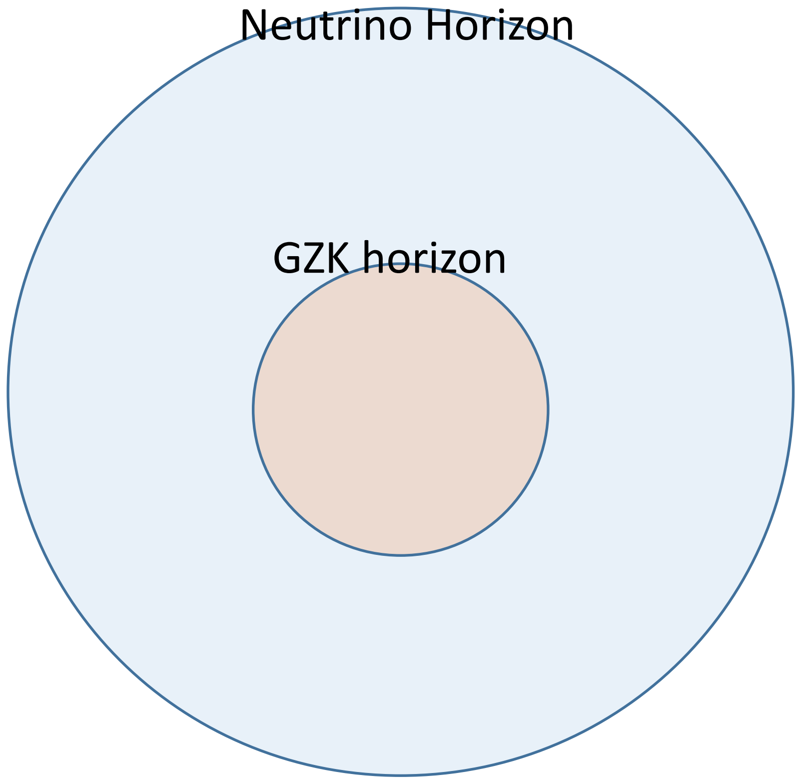
# Correlations with UHECR arrival directions?

JCAP01(2016)037

Preliminary

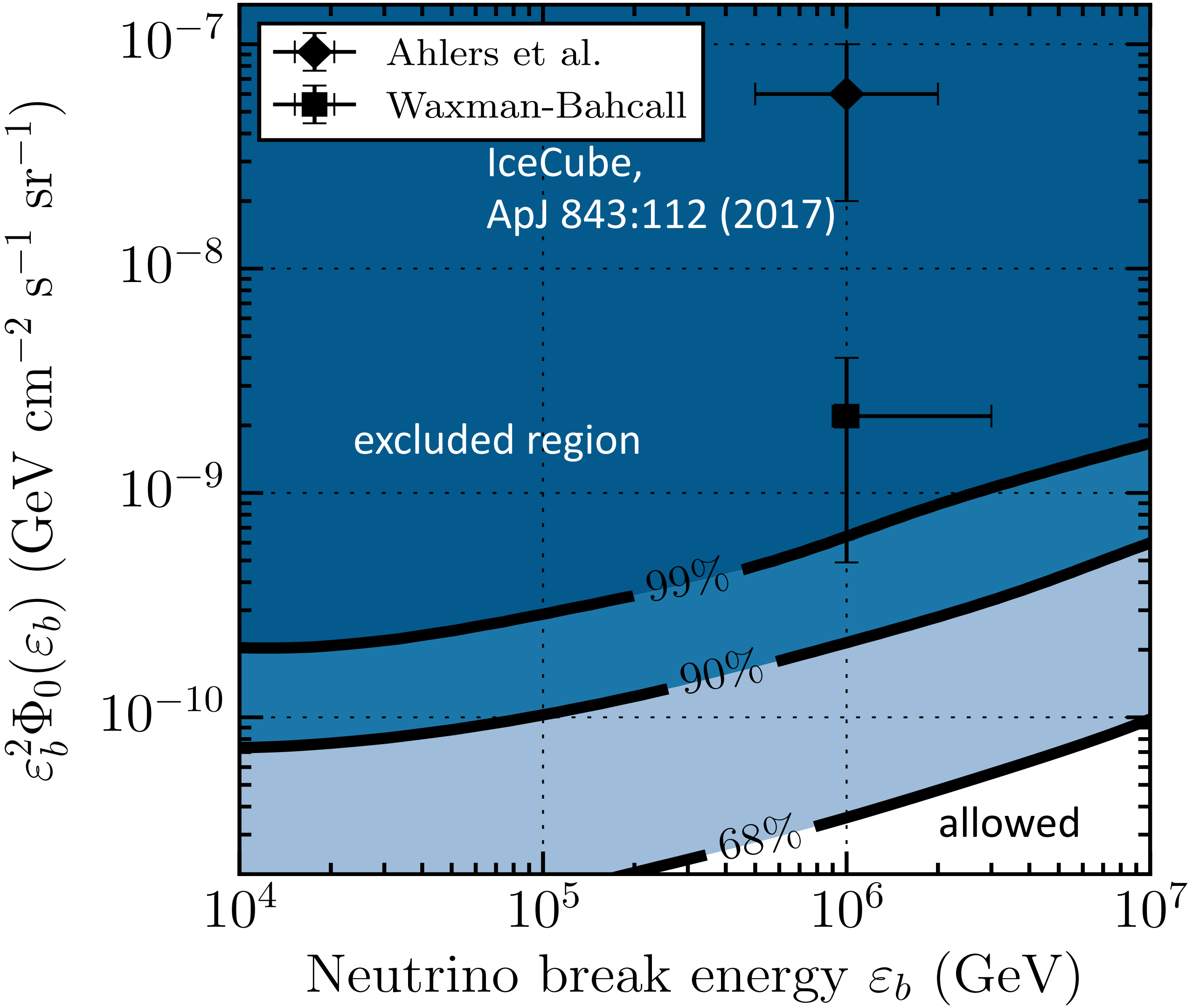
$$\frac{N_{GZK}}{N_{Hor}} < 5\%$$




No statistically significant excess.

# Correlations with GRBs?

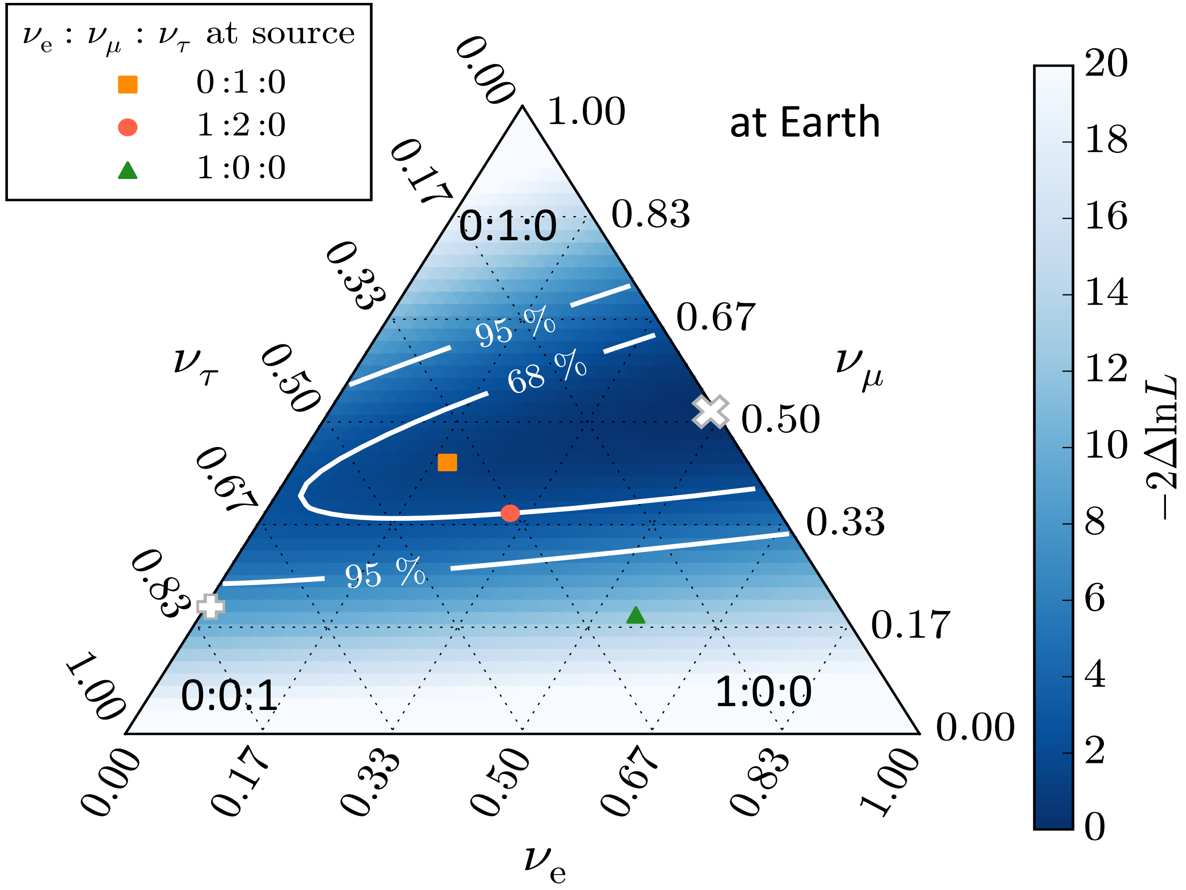



- No association with five years of muon neutrino track events
- Conclusion: <1% of astrophysical neutrino flux is produced by GRBs
- Non-detection rules out GRBs as the dominant source of UHE cosmic rays

# Astrophysical neutrino flavor ratio

Muon damped
Standard $\pi$ production
Neutron decay

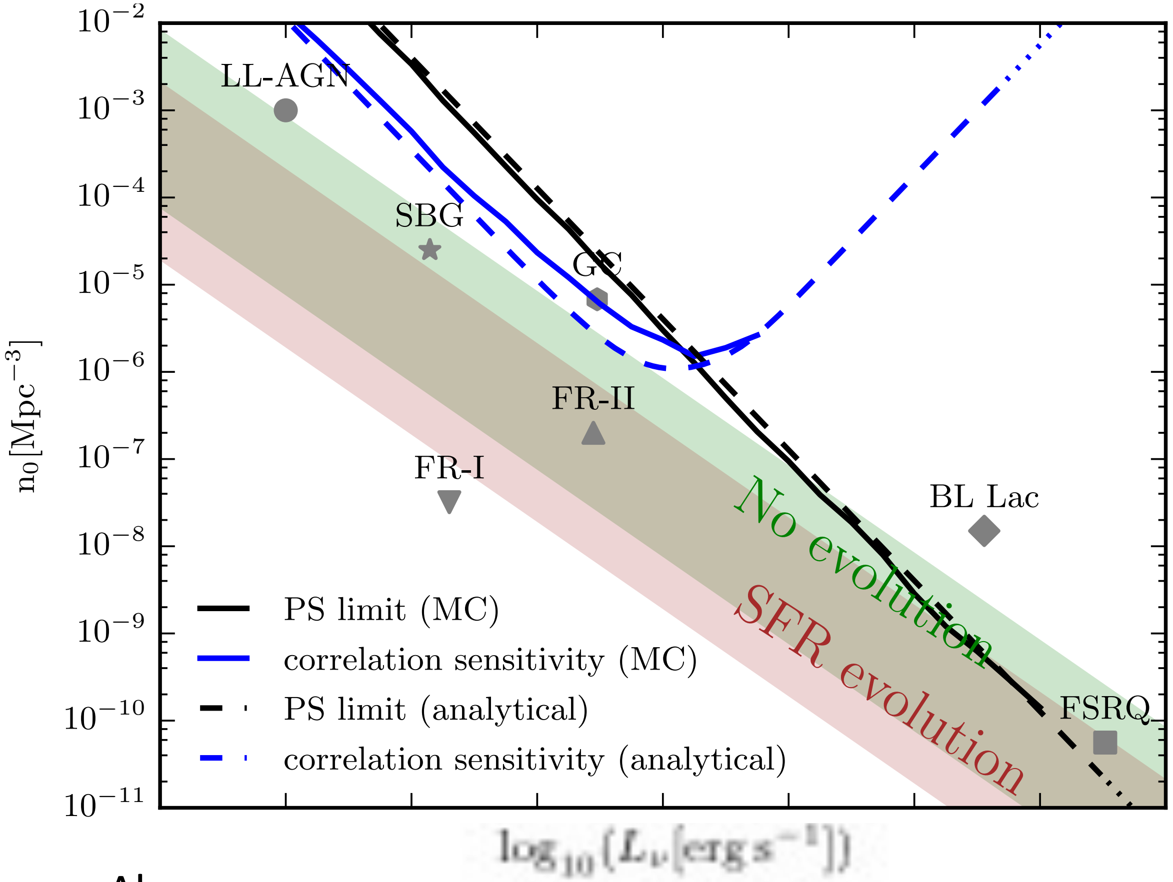
IceCube, ApJ 809:98 (2015)
IceCube, PRL 114, 171102 (2015)

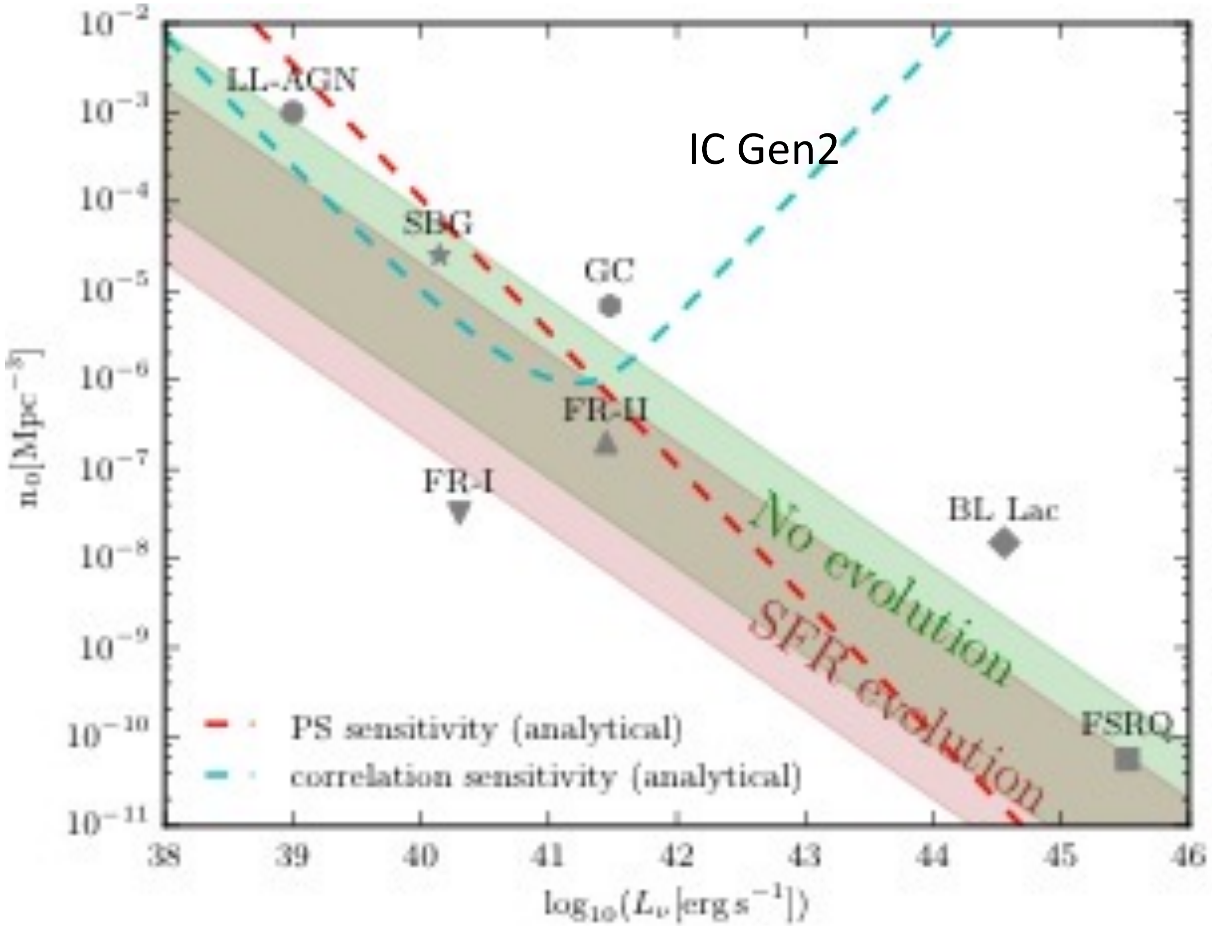



- Production of purely electron neutrinos at the sou
- “Muon damped”: muons lose energy to synchrotron radiation within/near source
- With future data, the *neutrino* flavor ratio can constrain *magnetic* field amplitude at source of astrophysical neutrinos / cosmic rays

How many standard candle sources?

Mertsch, Rameez and Tamborra 2017
**JCAP 1703 (2017) no.03, 011**




Also see,
Murase and Waxman 2016
**Phys.Rev. D94 (2016) no.10, 103006**