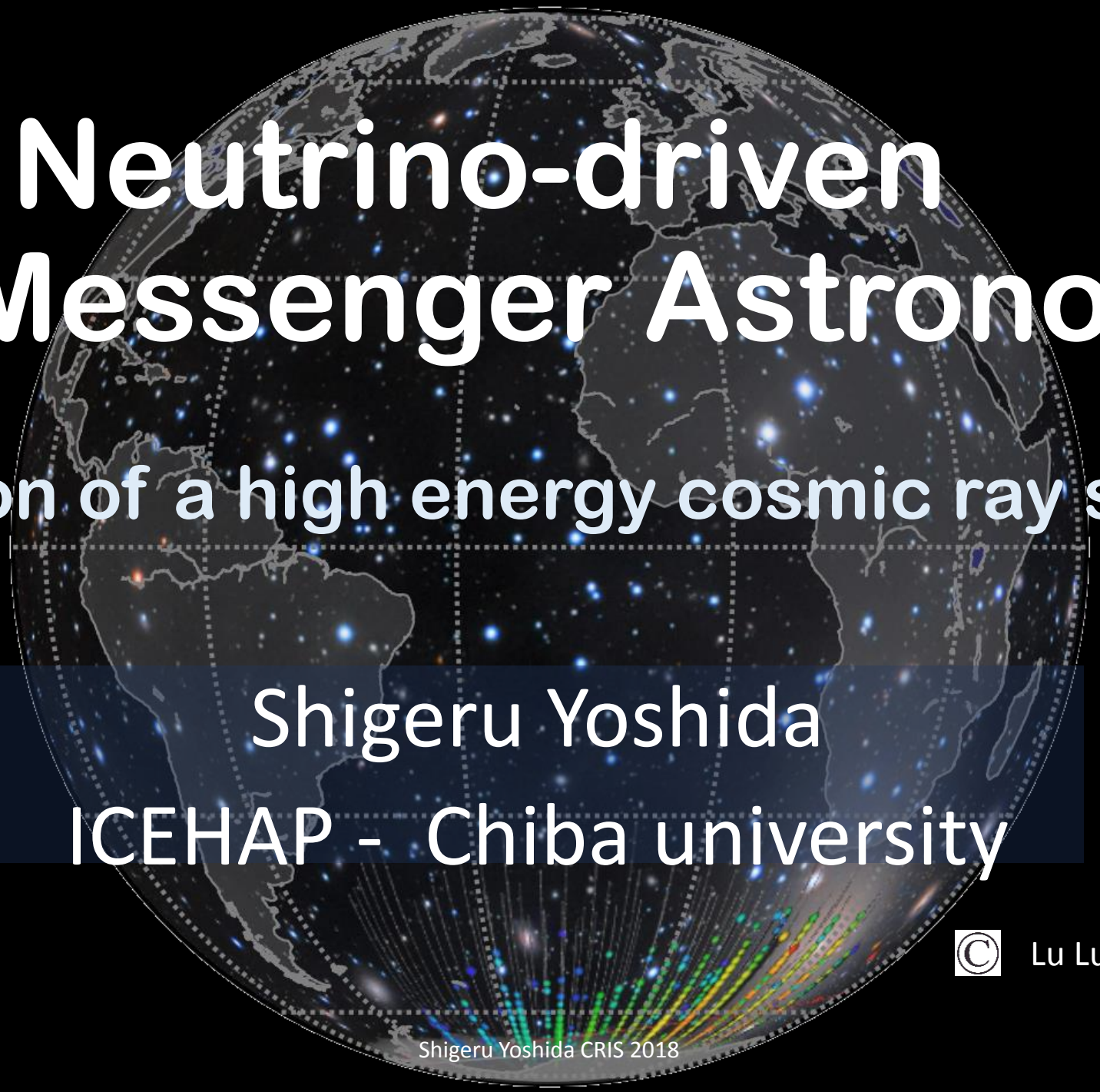
Neutrino-driven Milti-Messenger Astronomy

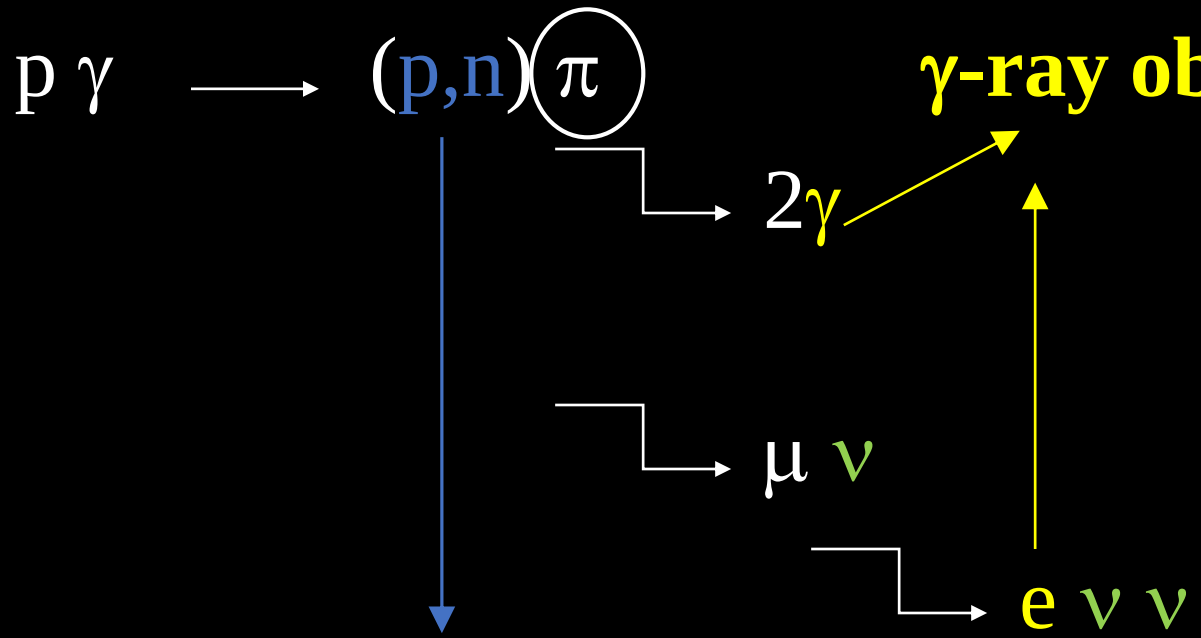
Detection of a high energy cosmic ray source

Shigeru Yoshida
ICEHAP - Chiba university

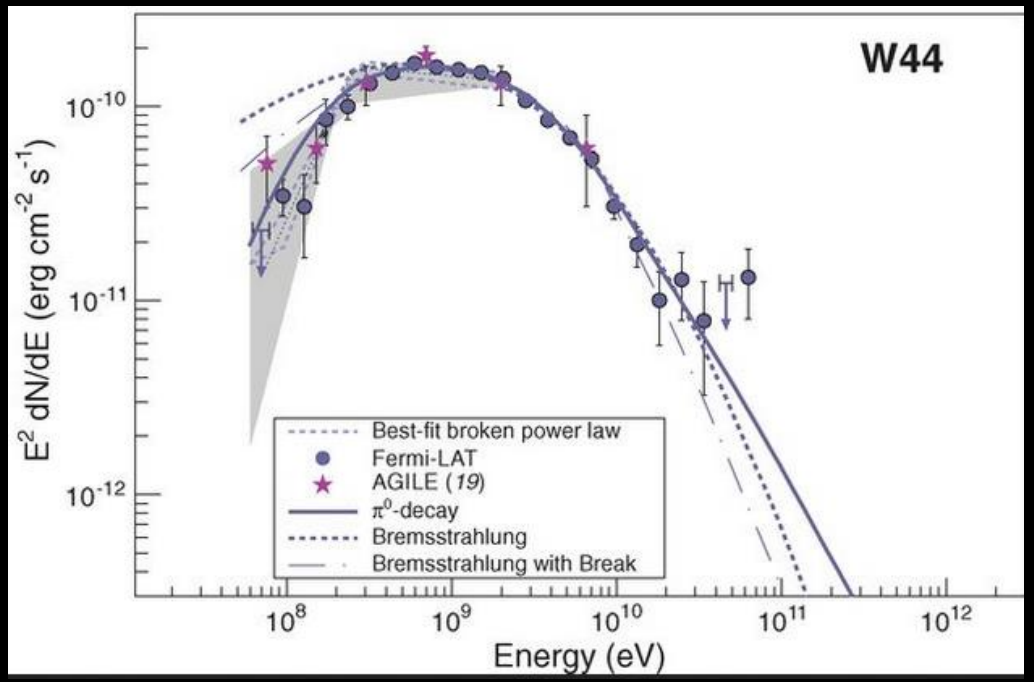


© Lu Lu

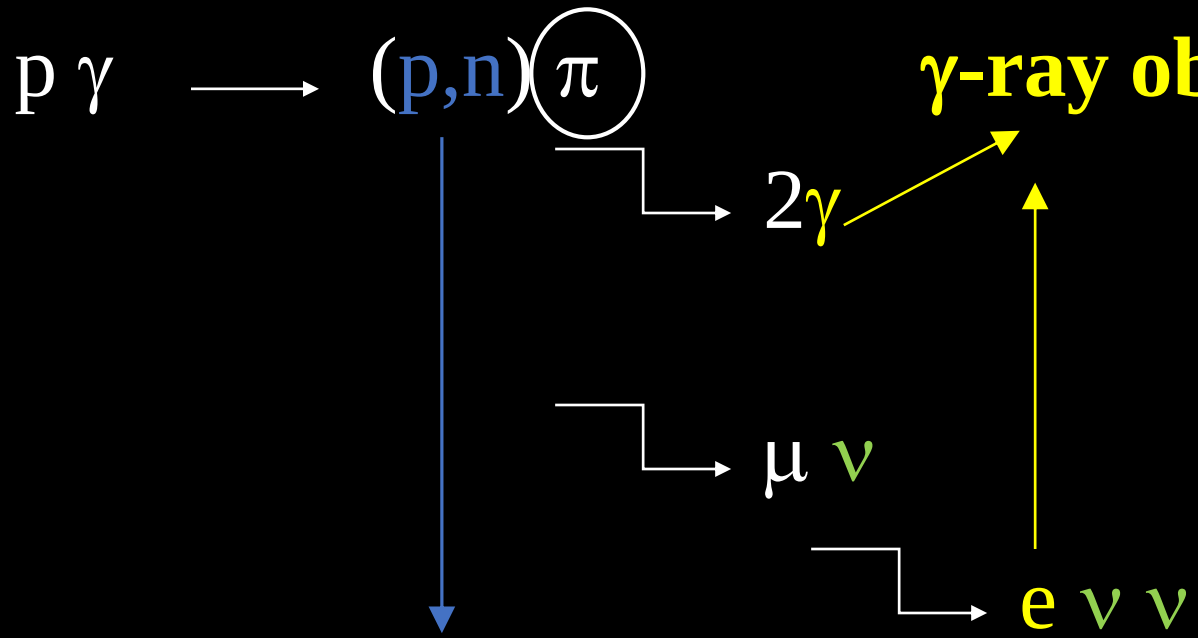
Multi-Messenger framework



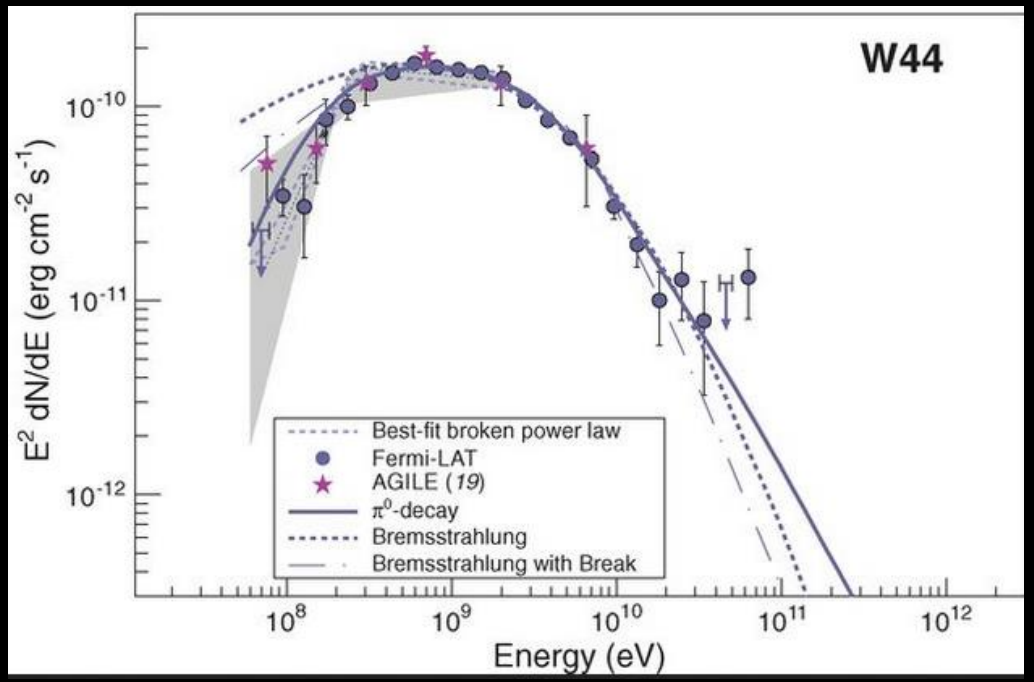
Fermi-LAT collaboration, Science **339**, 807 (2013)



Multi-Messenger framework

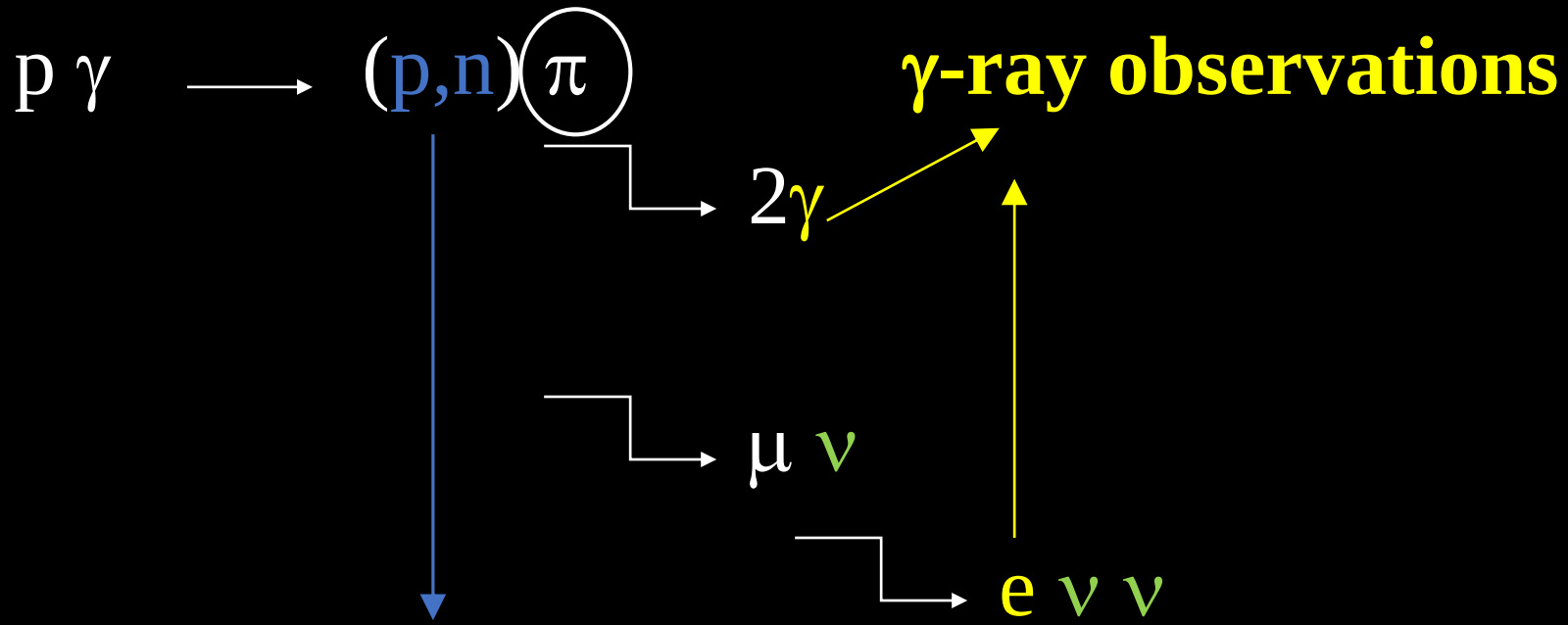


Fermi-LAT collaboration, Science **339**, 807 (2013)



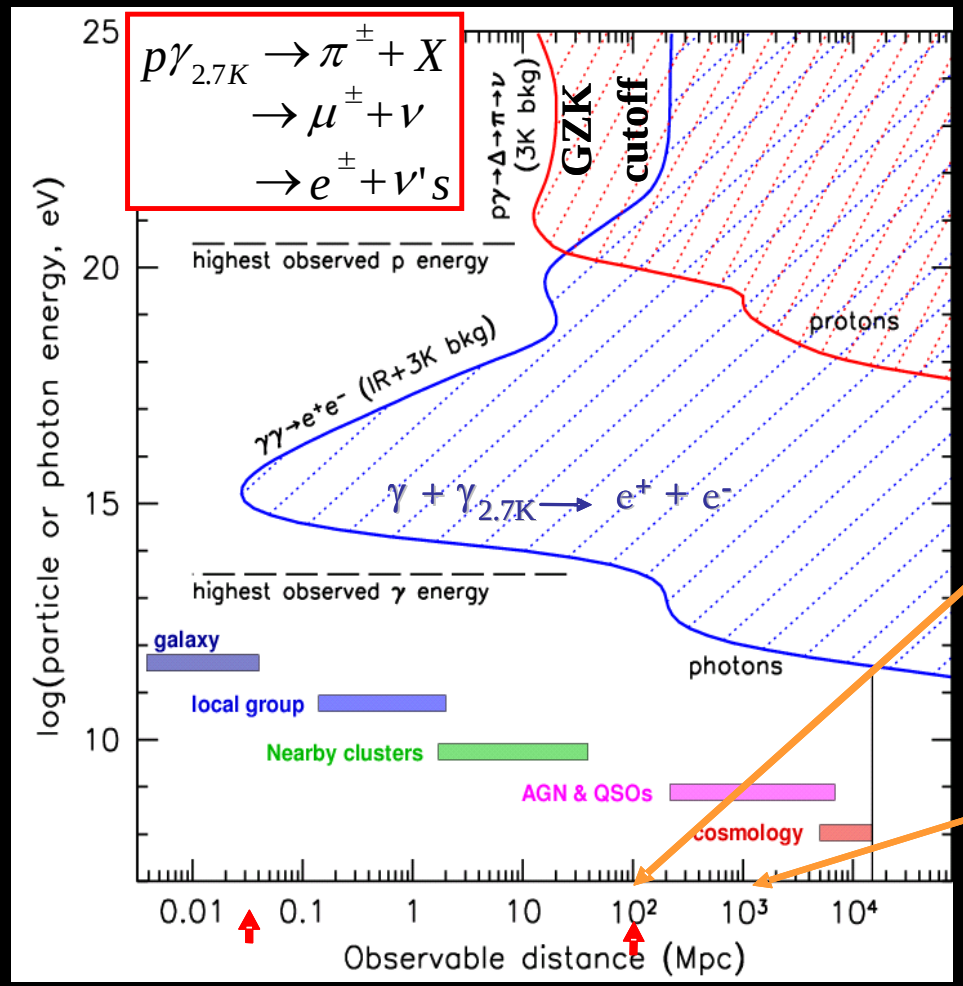
But eZ → eγZ (Bremsstrahlung)
eγ → eγ (inverse Compton)
could produce γ-ray

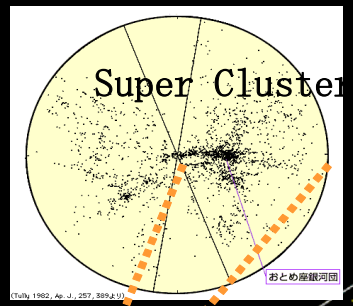
Multi-Messenger framework

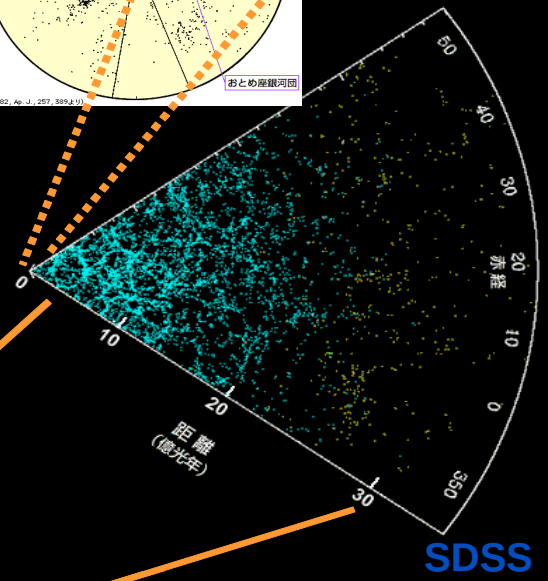


ν observations
||
The smoking gun

Why ν is so powerful to explore high energy universe?







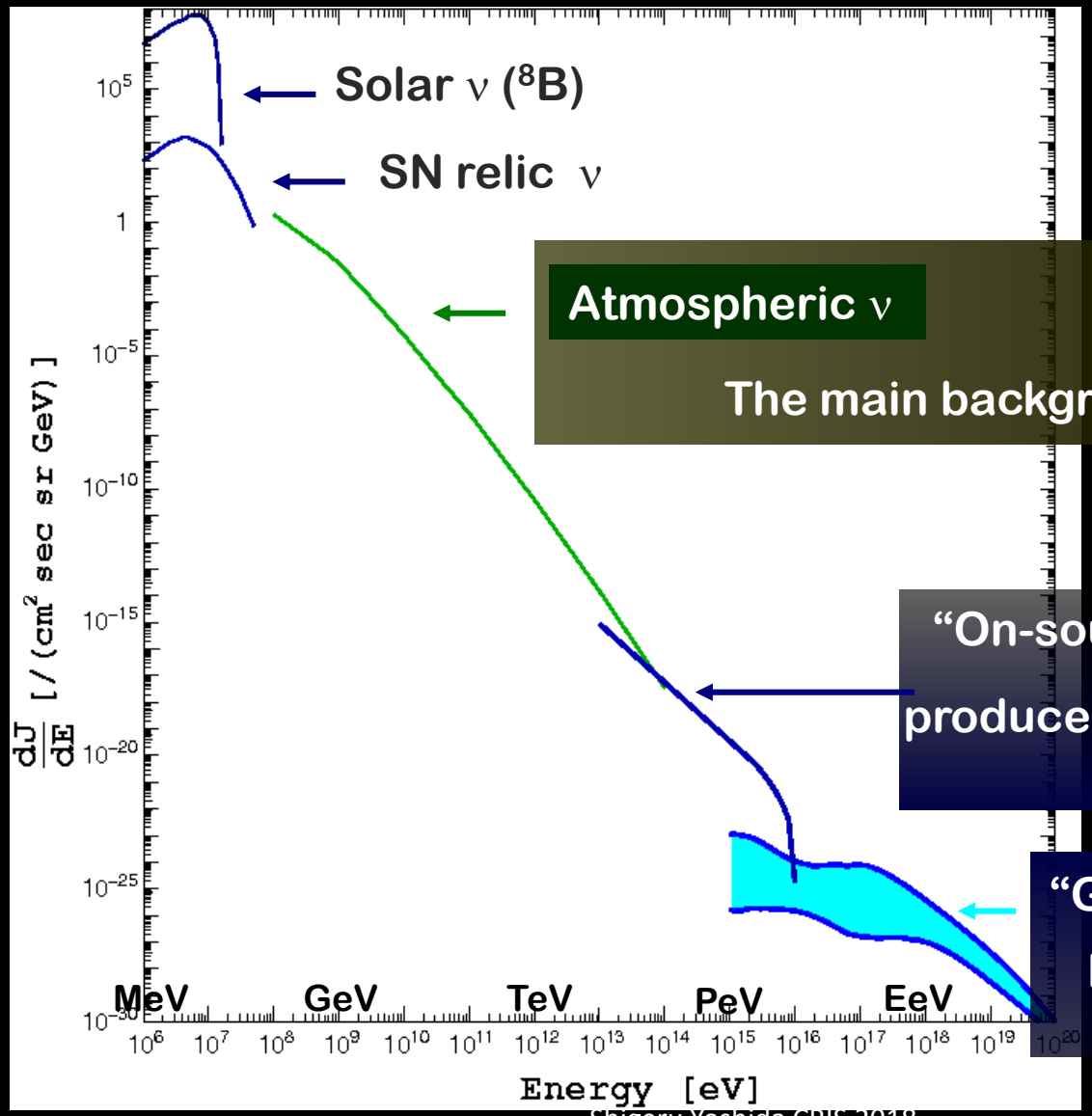
Distant Young Universe

Our Galaxy

Super Cluster

The Neutrino Flux: overview

CHIBA UNIVERSITY

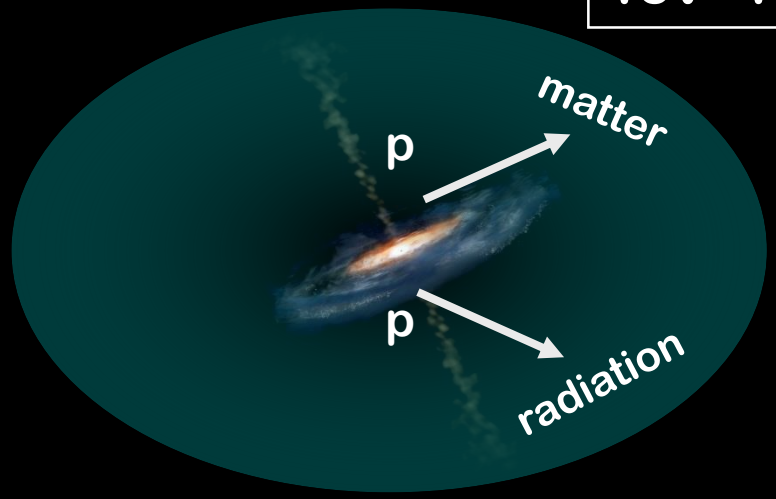


The Cosmic Neutrinos
Production Mechanisms

CHIBA UNIVERSITY

"On-source" ν

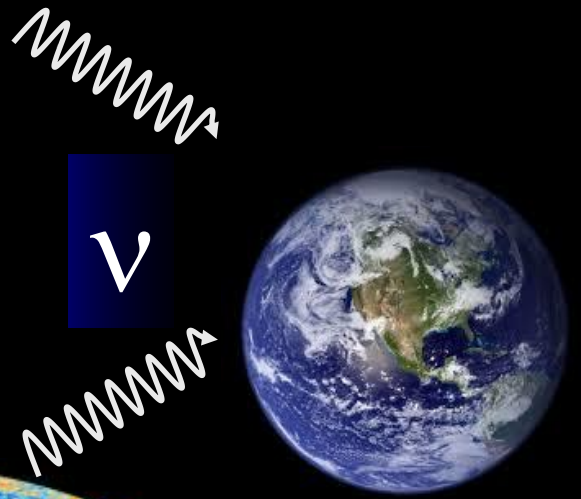
TeV - PeV



$pp \rightarrow \pi \rightarrow \nu$

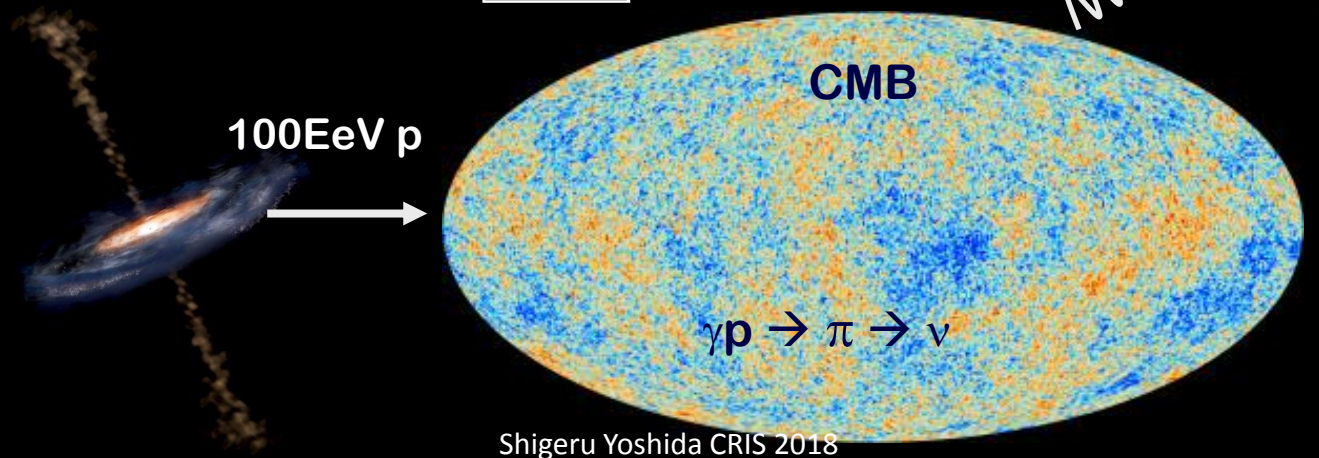
$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production



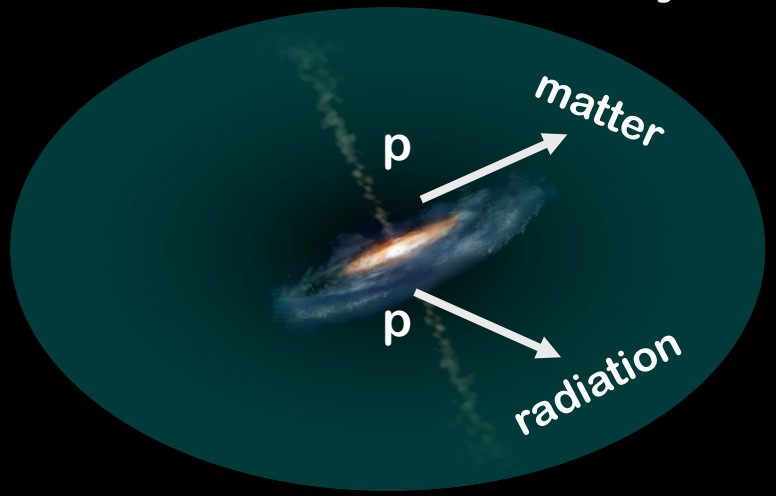
"GZK" cosmogenic ν

EeV



How can we identify cosmic ray sources via neutrino detection?

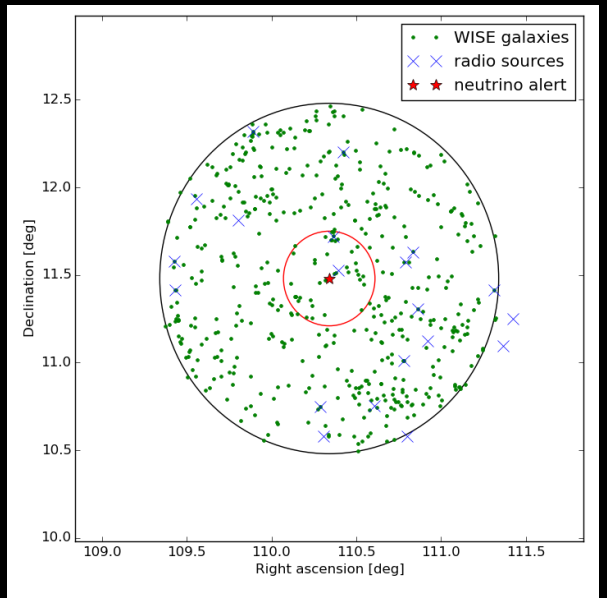
Neutrinos from a cosmic ray source



$pp \rightarrow \pi \rightarrow \nu$

$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production



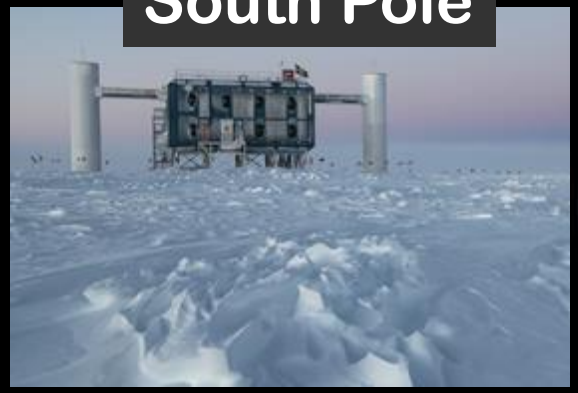
Astronomical objects within the direction of 3PeV ν detected in 2014

Which one is Cosmic Pevatron ??

We need *Timing coincidence* !
(Remember the GRB tale!)

Realtime Multi-Messenger

South Pole



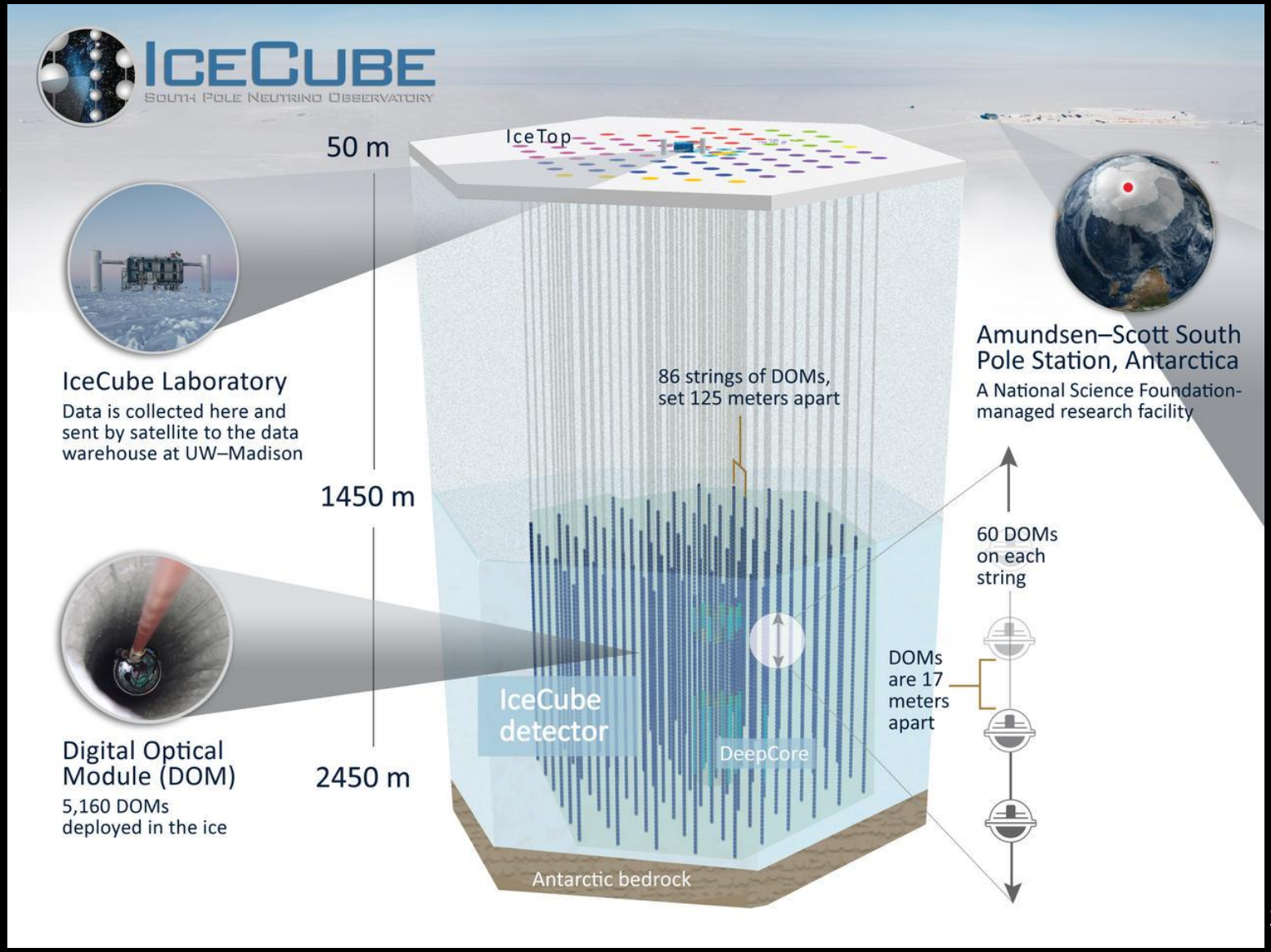
Northern Hemisphere

WIPAC
Wisconsin IceCube Particle Astrophysics Center

GCN-TAN

IceCube Neutrino Observatory

IceCube Highlight → Justin's talk tomorrow!



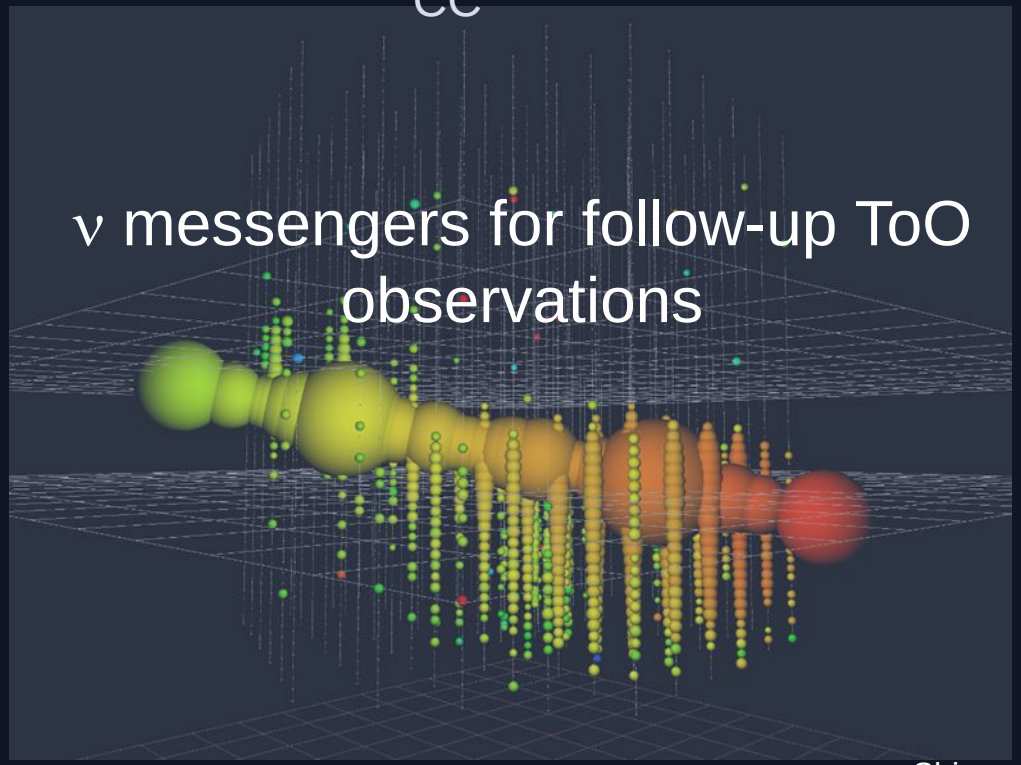
IceCube Event Topology

Track

Angular resolution
~ 0.5 degree

$\nu_\mu \xrightarrow[CC]{} \mu$

$\nu_\tau \xrightarrow[CC]{} \tau$ (only at ultra-high energies)

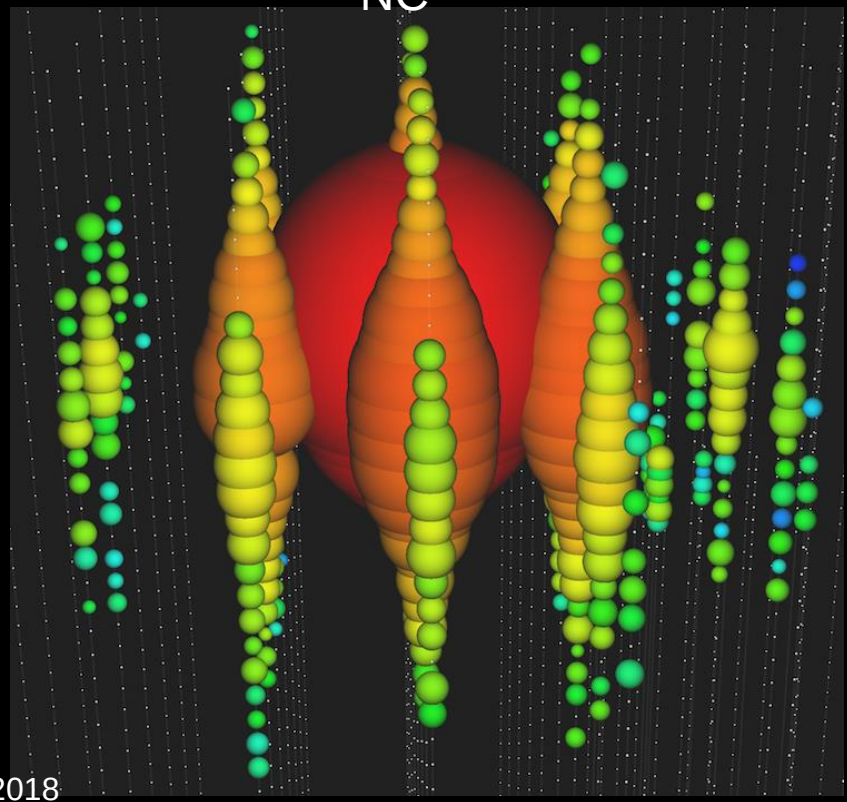


Cascade (shower)

Angular resolution
~ 15 degree

$\nu_e \xrightarrow[CC]{} e + X$

$\nu_x \xrightarrow[NC]{} x + X$ x=e, μ, τ



IceCube Realtime Analysis Chain

Deliver of public alerts via GCN

High cosmic ν purity samples.
Launched in 2016!

veto-based HESE

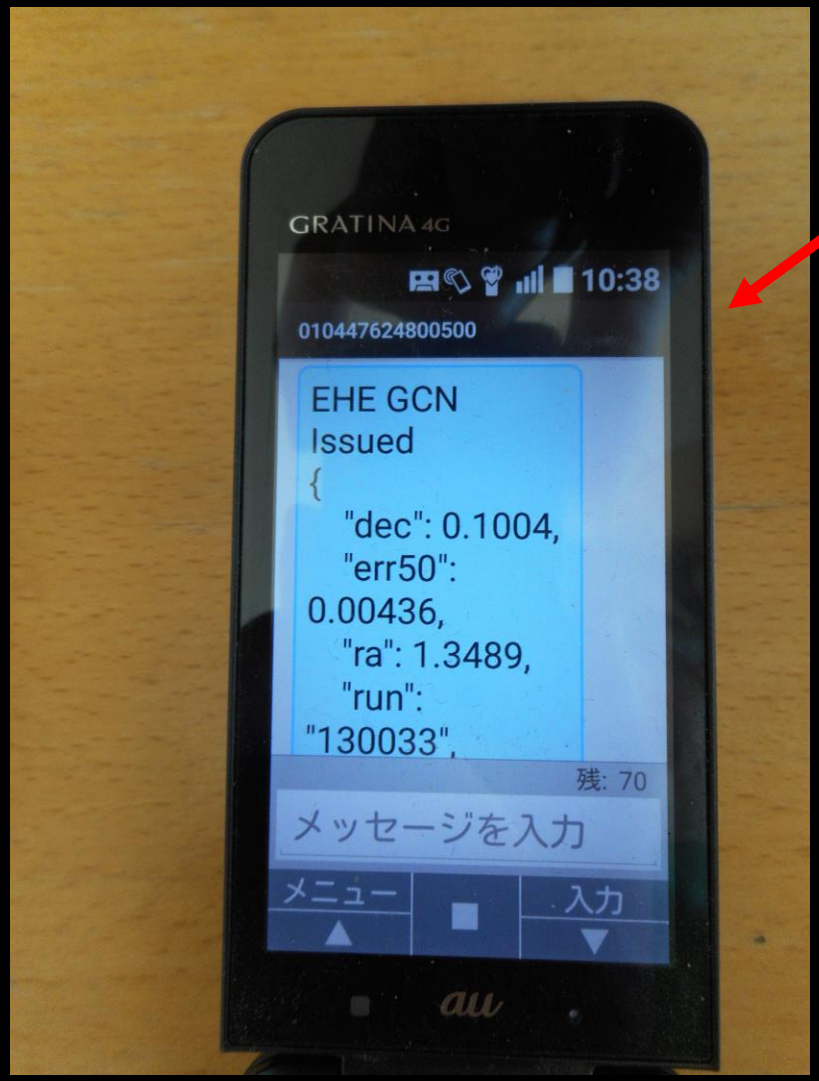
all neutrino flavor sensitive
high chance of real cosmic neutrino signals
angular resolutions so-so

EHE (Ultra-High Energies)

all neutrino flavor sensitive
high chance of real cosmic neutrino signals
good angular resolutions
signal flux highly uncertain

The breakthrough event detected in this channel

And the story began here



SMS notice
pinged my (non-smart) cellphone

5:55 am, Saturday, September 23, JST

the greatest wakeup call I've ever had in Saturday morning

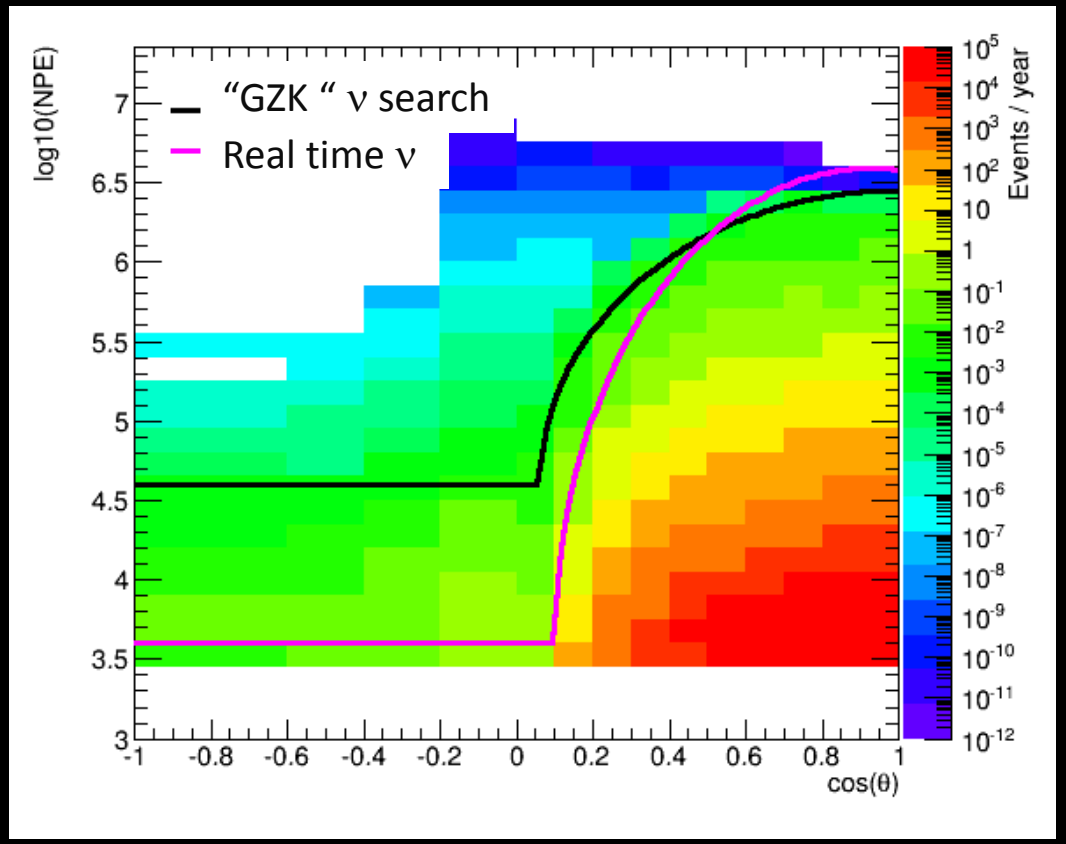
Event selections for EHE real time stream

Inspired by the IceCube's GZK/cosmogenic ν search

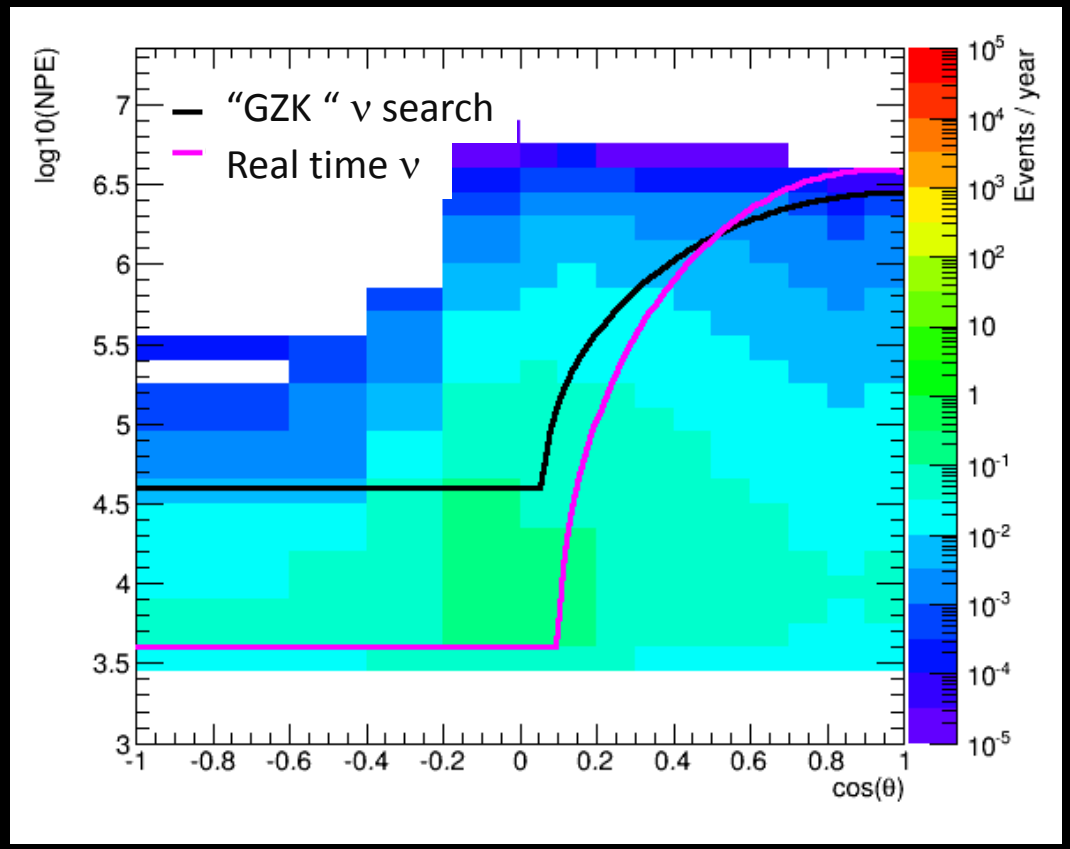
Relaxed cuts on NPE-cos(zenith) plane for track-like EHE sample

(χ^2 EHE trackfit < 80)

Atmospheric BG



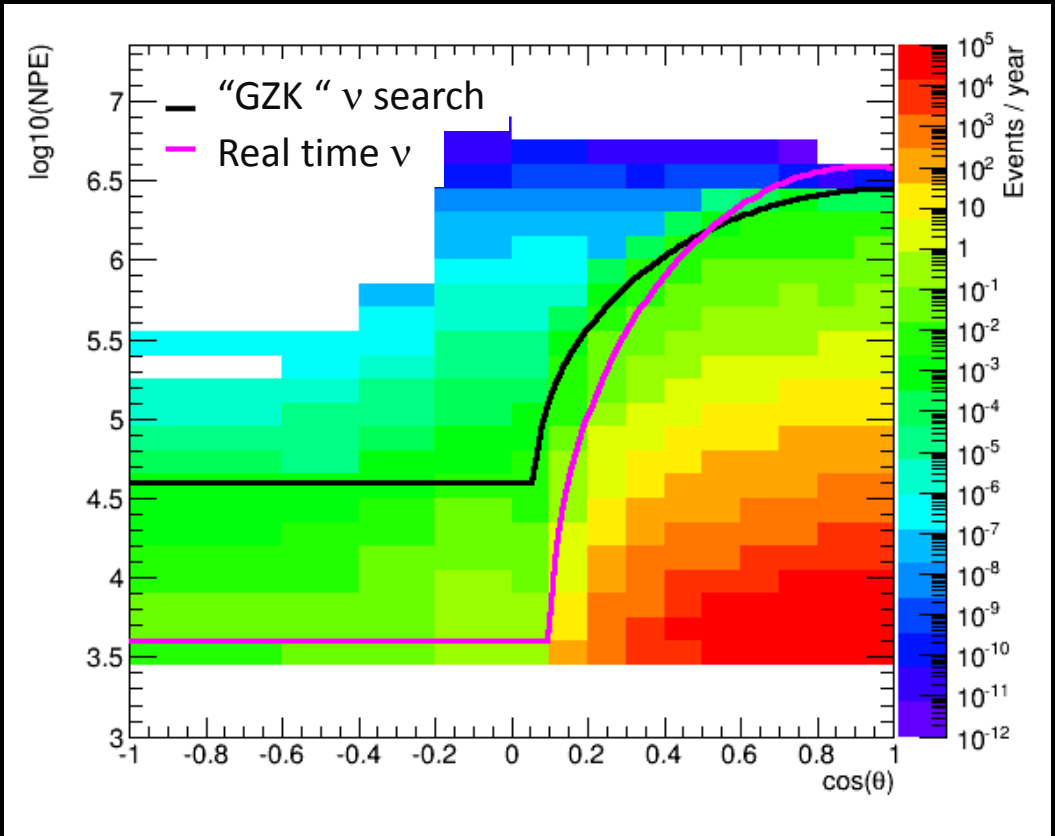
E^{-2} signal



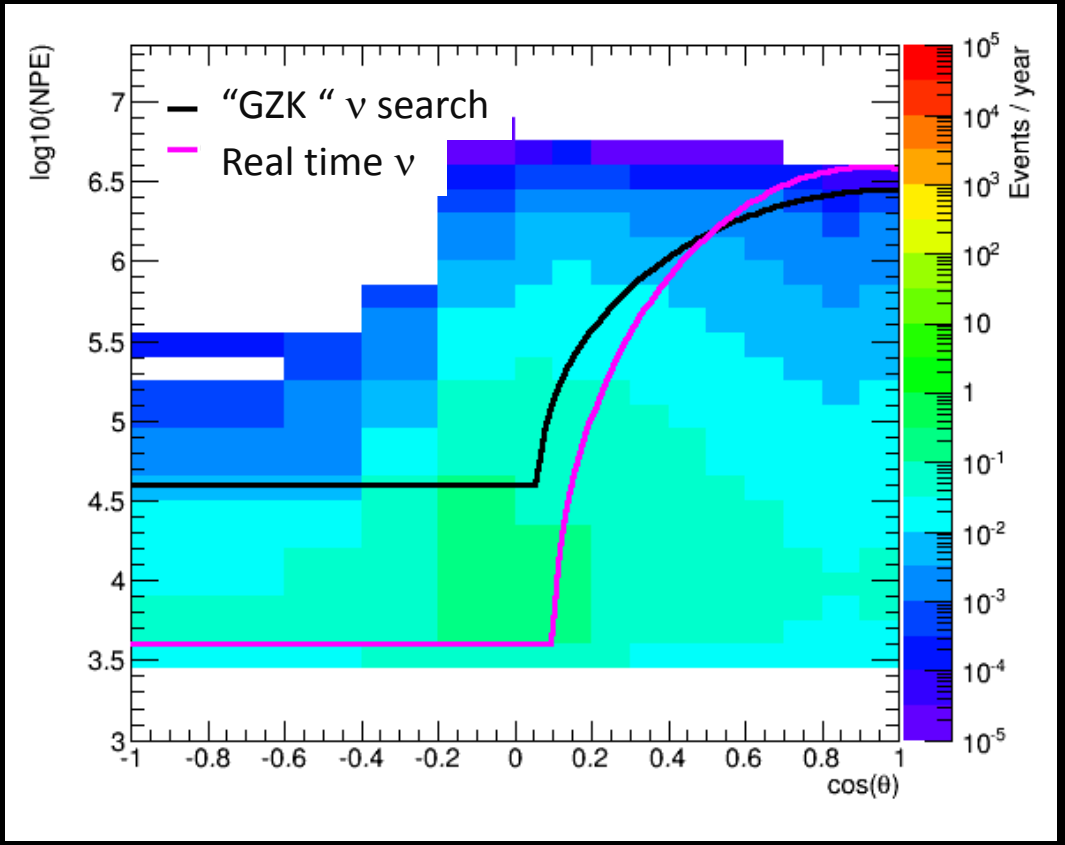
IceCube 170922A

NPE 5,786 cos(zenith) -0.13

Atmospheric BG



E^{-2} signal

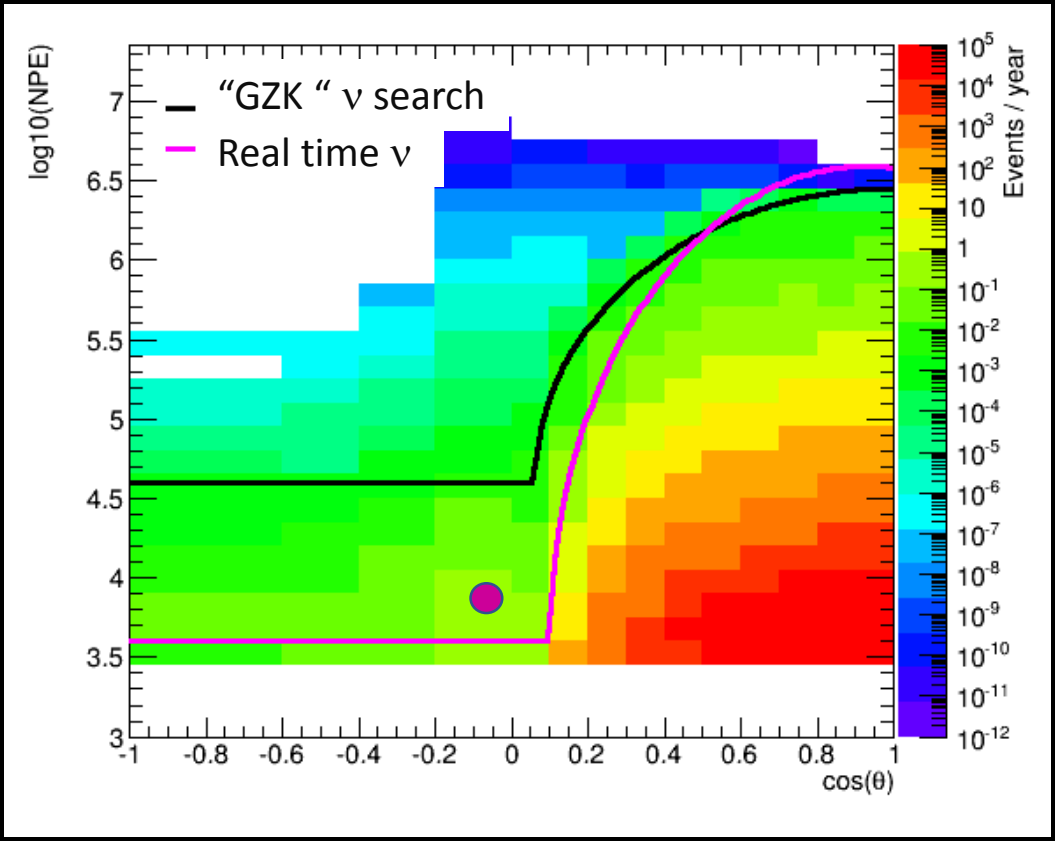


IceCube 170922A

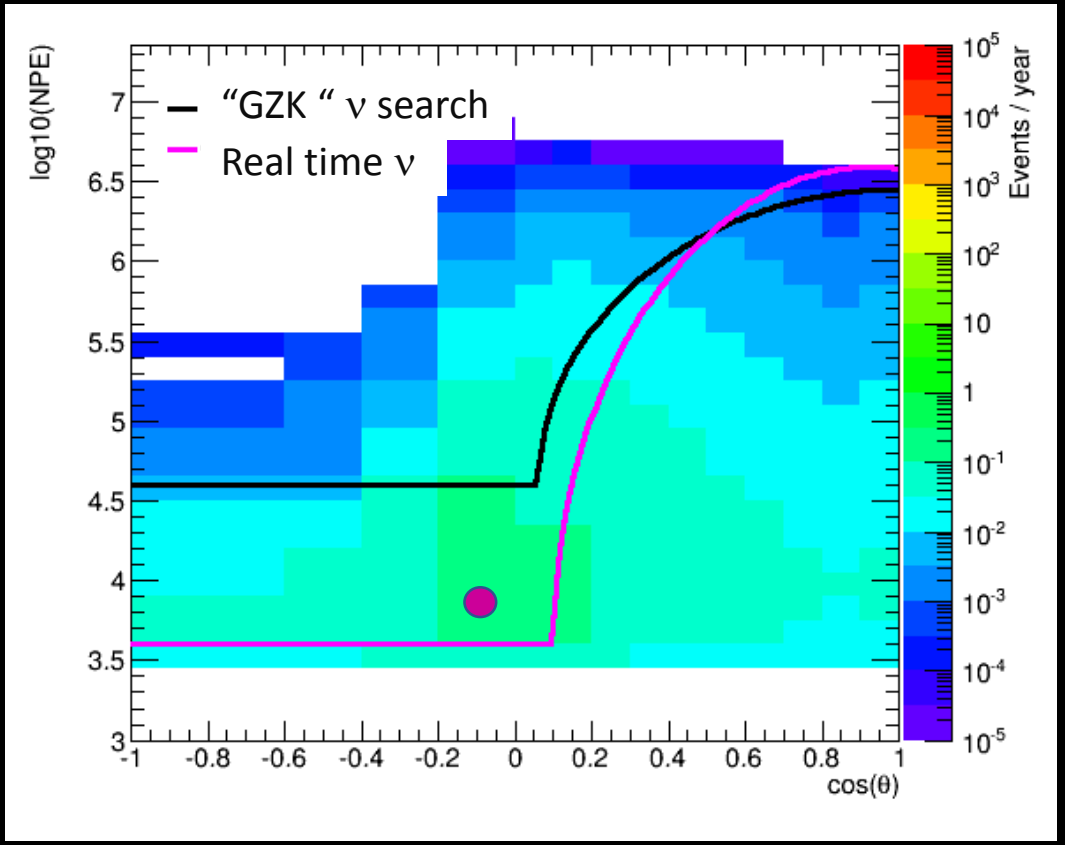
NPE 5,786 cos(zenith) -0.13

right on the “sweat spot” signalness : 56.5 %

Atmospheric BG



E^{-2} signal

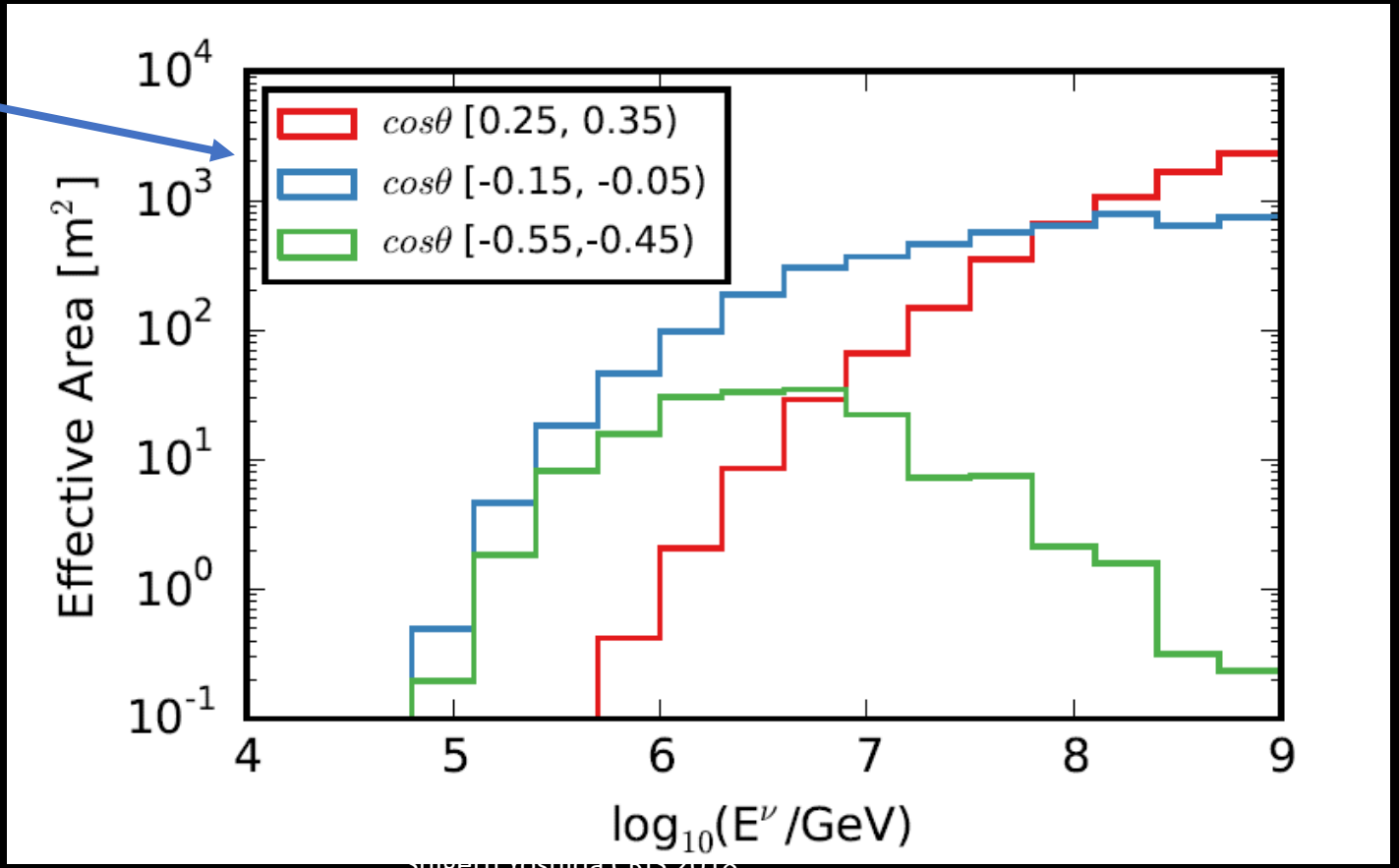


ν detection effective area

$$N = T \int d\Omega \int dE_\nu \phi_\nu(E_\nu)\, A_\nu(E_\nu)$$

# of events | time | solid angle | ν flux | ν effective area

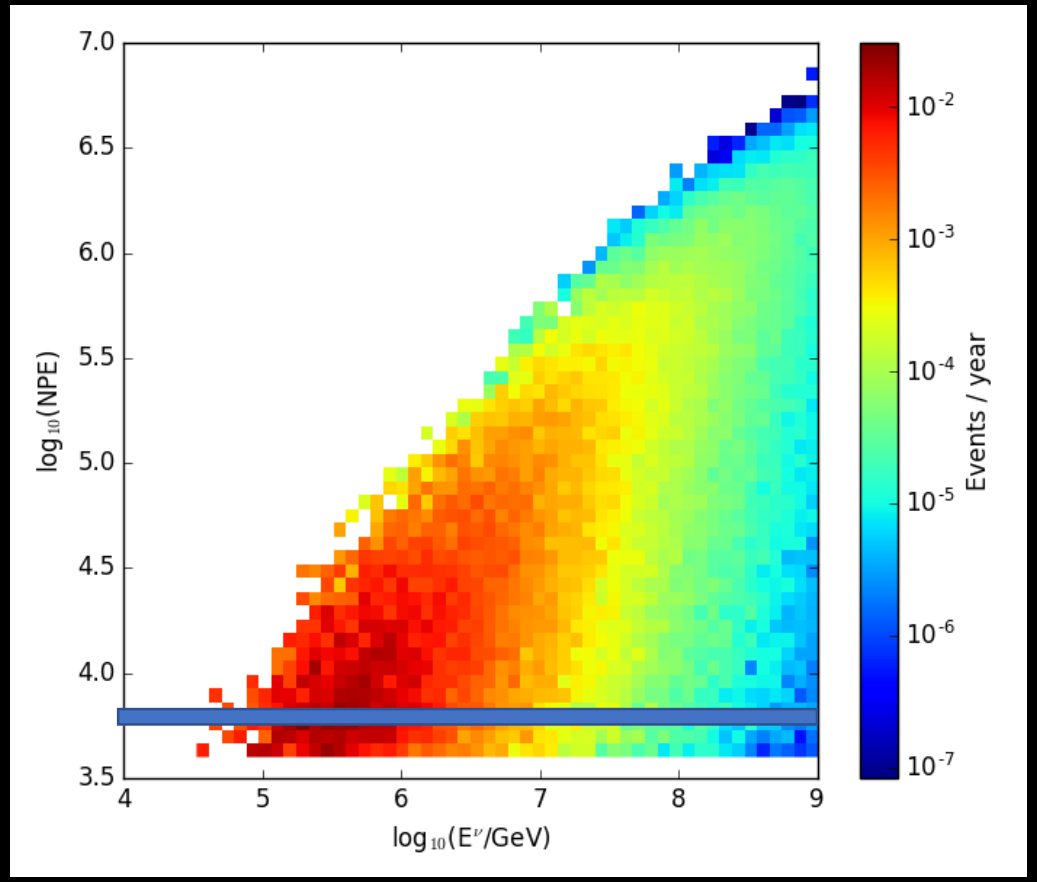
Zenith bin of this ν event



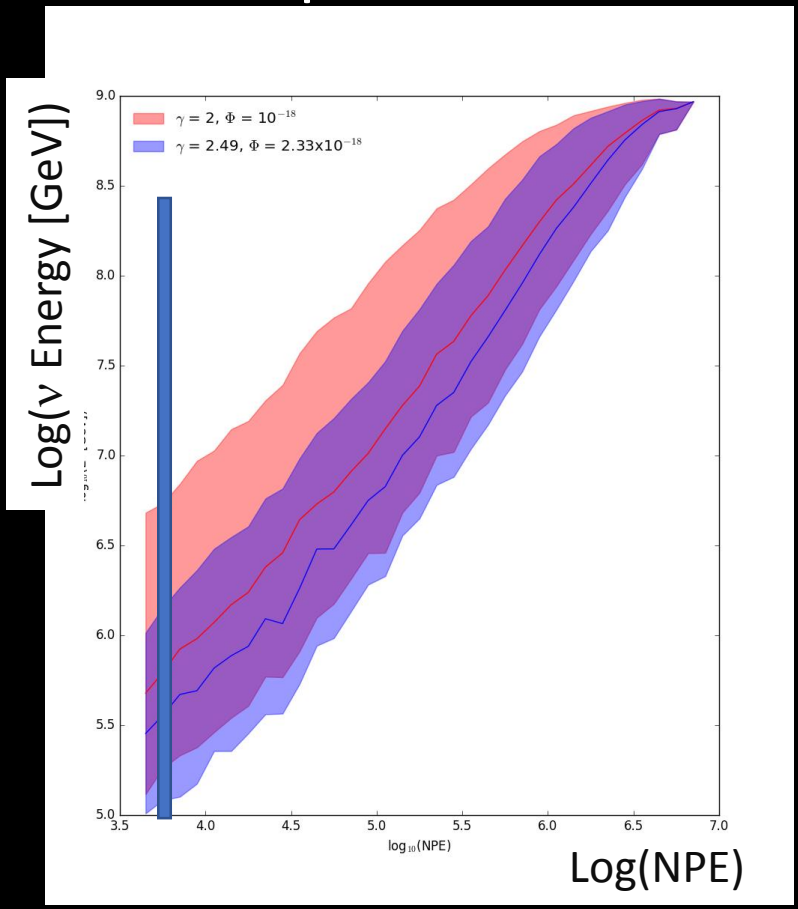
Neutrino Energy ?

Initial estimate reported in the GCN: 120 TeV

ν Energy Vs NPE ($E^{-2.5}$)



profile



Neutrino Energy Flux

$$N = T \int d\Omega \int dE_\nu \phi_\nu(E_\nu)\, A_\nu(E_\nu)$$

$$\phi_\nu(E_\nu) \sim {E_\nu}^{-2}$$

$$L_\nu = \int_{200TeV}^{7.5PeV} dE_\nu \phi_\upsilon(E_\upsilon) E_\nu$$

$$= \frac{N}{T \int dE_\nu\, {E_\nu}^{-2} A_\nu(E_\nu)} \ln \frac{7.5PeV}{200TeV}$$

$$\cong 1.8 \times 10^{-10} \left(\frac{T}{6month}\right)^{-1} erg\ cm^{-2}\ s^{-1}$$

Summary of the follow-up observations

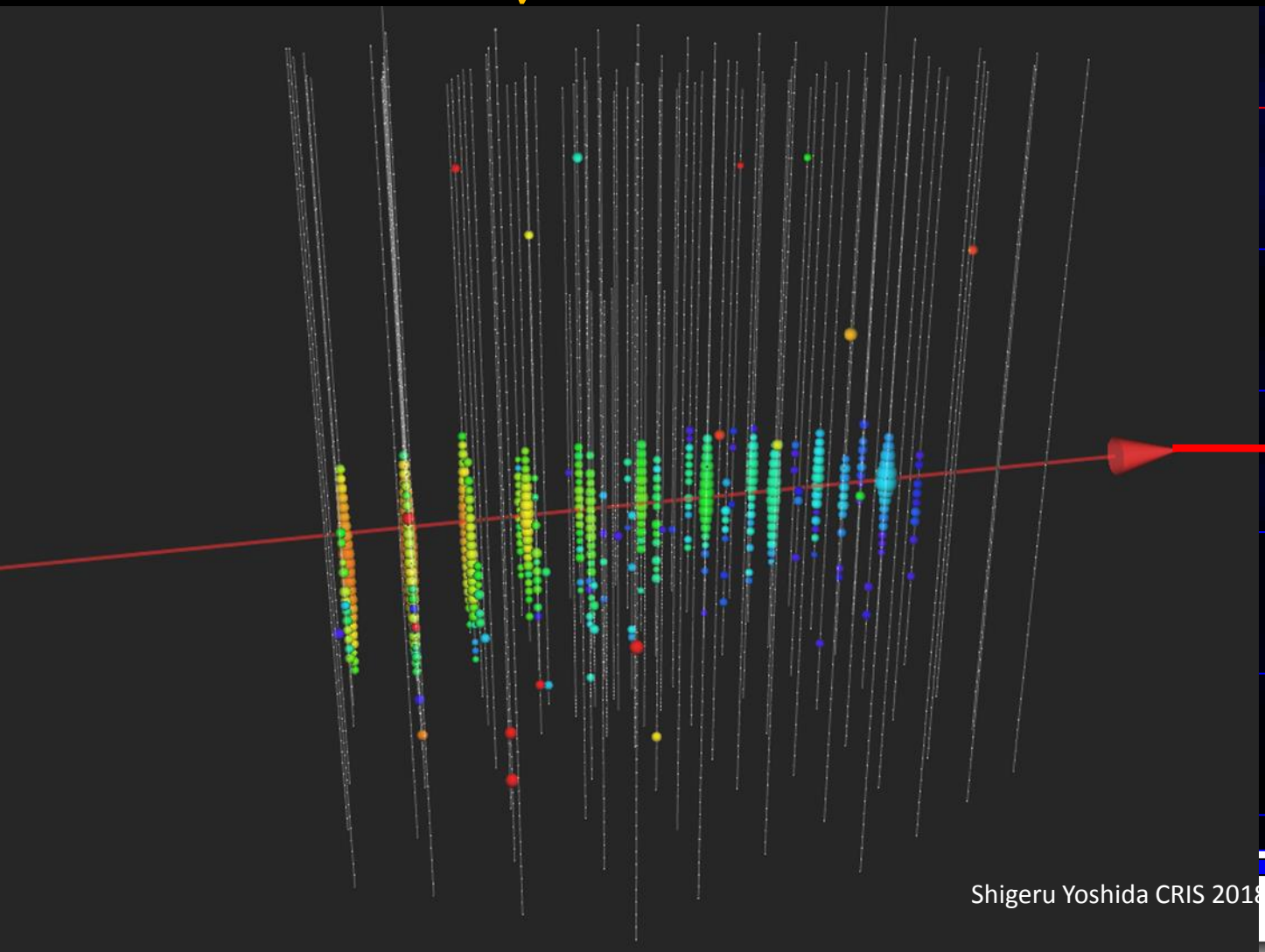
Observatory	Observation Time	Detection	Source	Comments
Fermi-LAT	Sept 15-27	✓	TXS 0506+056 / 3FGL J0509.4+0541 / 3FHL J0509.4+0542	Flaring >800 MeV
Swift-XRT	Sept 28 00:09-22:42 UT Sept 27 18:52 UT, 5 ks Sept 30 – Oct 7, 2 ks	✓	1SXPS J050925.9+054134	Spectral softening/evolution
Liverpool	Sept 28, 900 s	✓	TXS 0506+056 (PMN J0509+0541)	Typical BL Lac spectrum "Bluer when brighter"
ASAS-SN	-50 days	✓	TXS 0506+056	~0.5 mag in V-band
AGILE	Sept 18 12:00 UT + 3 days ±6 days	✓	< 1° from 3FGL J0509.4+0541	Excess > 100 MeV
H.E.S.S.	Sept 28 01:05 UT, 1 hr Sept 24 03:10 UT, 1 hr	×		Set 90% CL UL on ν fluence
HAWC	Sept 15 09:04 UT - Sept 19 14:41 UT Sept 21 08:41 UT to Sept 27 14:10 UT	×		At T0, this location was not in HAWC's fov
ANTARES	±1 hr and ±1 day of T0	×		Set 90% CL UL on ν fluence
INTEGRAL	±300 s of T0	×		Set 3σ UL
IC multi-day	Sept 15 00:00 UT – Sept 29 00:00 UT	×		
VERITRAS	Sept 28, 1 hr + Sept 28-39, 5.5 hrs	×		~200 GeV

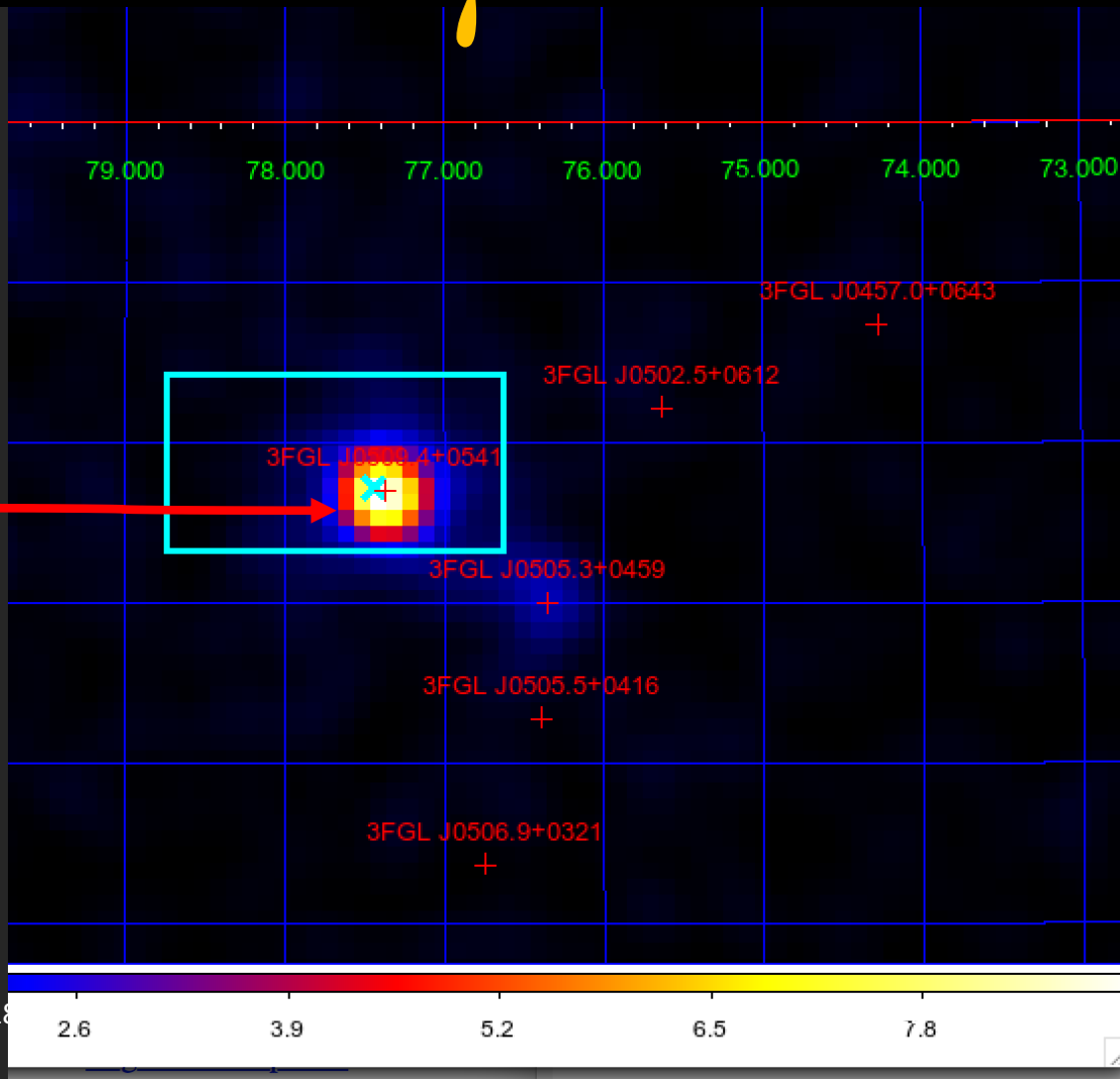
And many more!

and this is what happened

ν

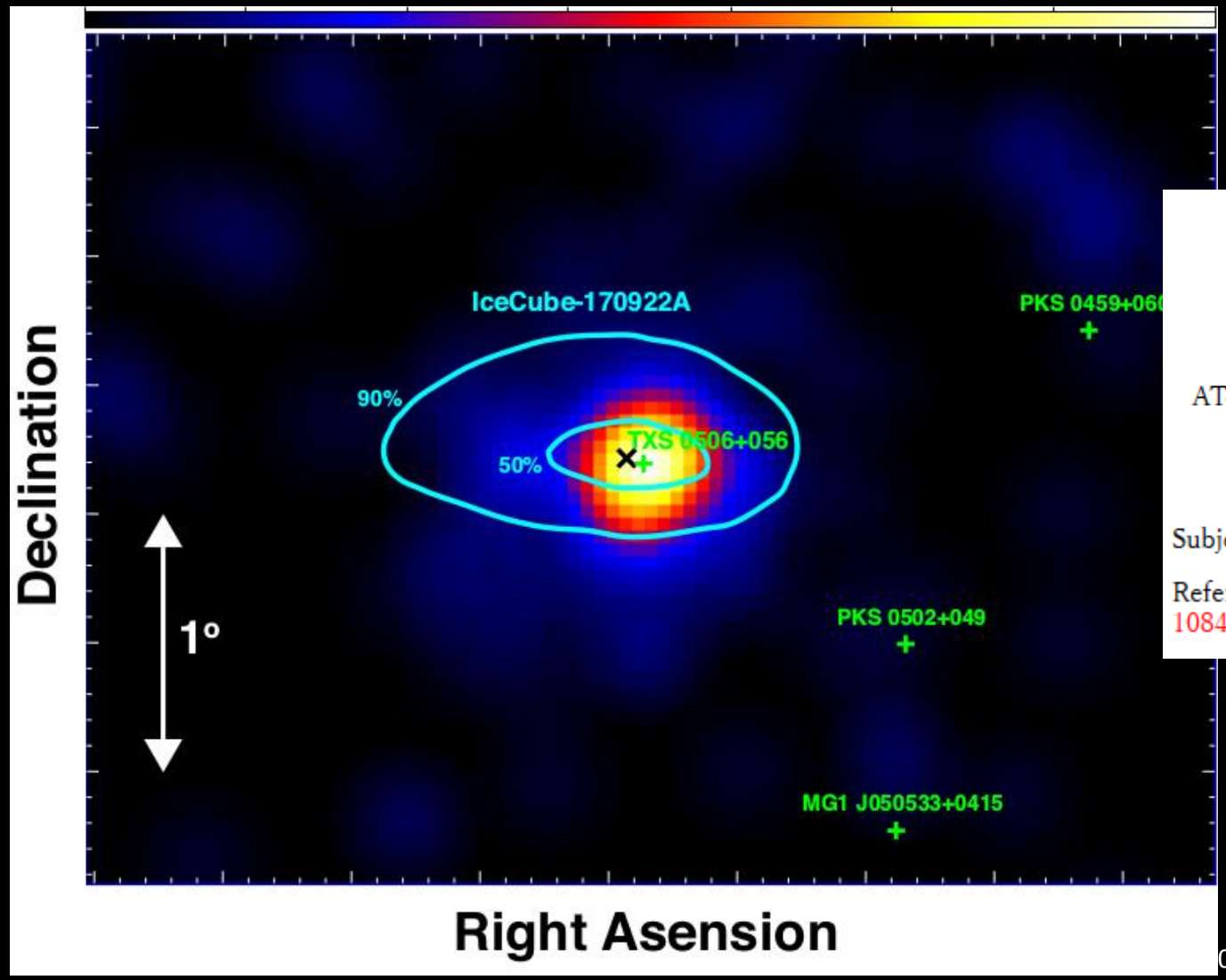
γ





Fermi Blazar TXS 0506+56

Right on top of IceCube 170922A



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
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

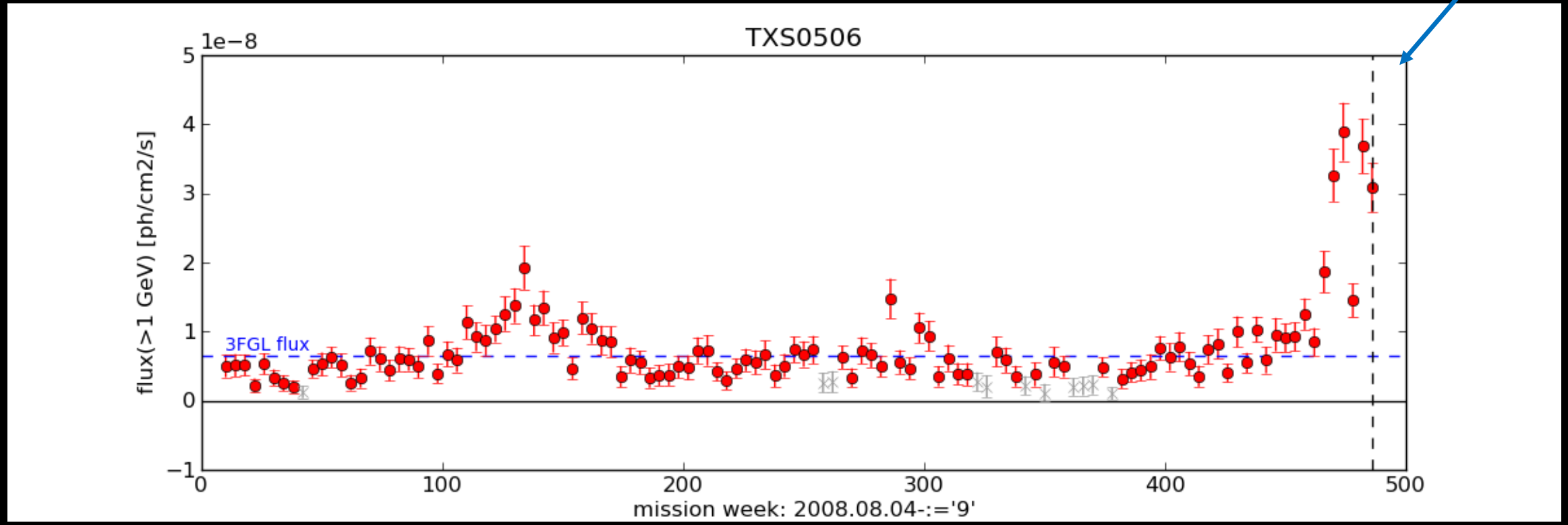
Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

Fermi Blazar TXS 0506+56

IceCube 170922A

E>1GeV

9 years



Made By public tool FAVAI

VHE γ detection by MAGIC

E > 100 GeV

~5σ detection

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
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

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

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

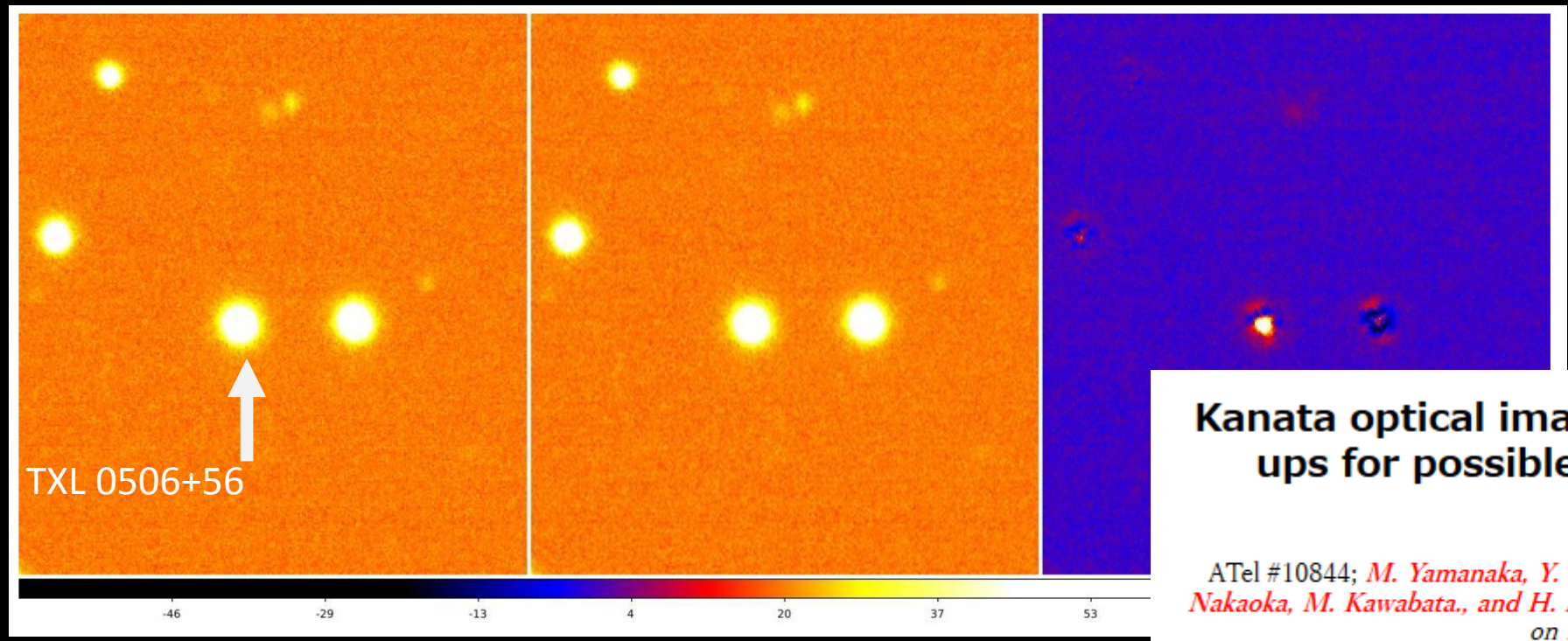
Tweet Recommend 448

Optical follow-up

Kanata's follow-up

1.5 m dish at Hiroshima, Japan

September 23 | September 24 | Residual



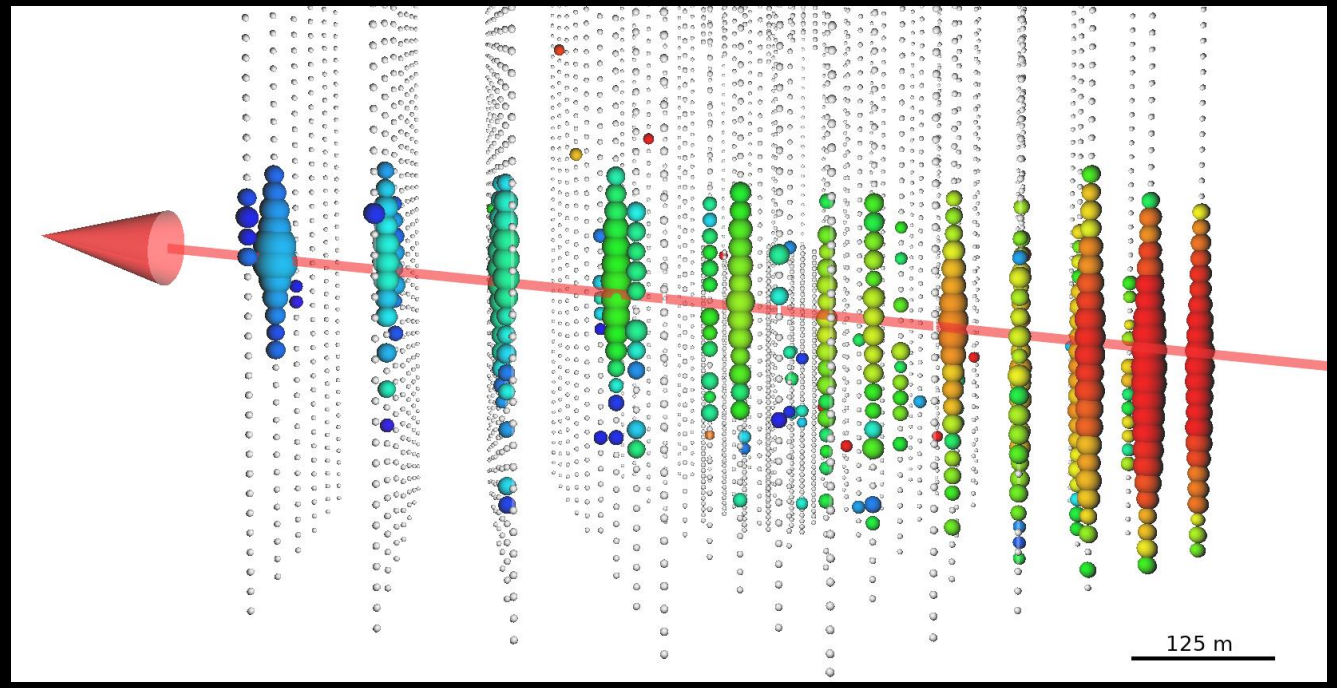
Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056

ATel #10844; *M. Yamanaka, Y. T. Tanaka, H. Mori, K. S. Kawabata, Y. Utsumi, T. Nakaoka, M. Kawabata., and H. Nagashima on behalf of Kanata and OISTER teams.*
on 12 Oct 2017; 15:50 UT
Distributed as an Instant Email Notice Transients
Credential Certification: Masayuki Yamanaka (masyamanaka@hiroshima-u.ac.jp)

Subjects: Infra-Red, Optical, Blazar, Transient

Referred to by ATel #: 10861, 11430, 11489

Stay tuned NEXT MONTH



No Blazars as major sources

Blazar stacking analysis

THE CONTRIBUTION OF *FERMI*-2LAC BLAZARS TO DIFFUSE TEV–PEV NEUTRINO FLUX

M. G. Aartsen[1], K. Abraham[2], M. Ackermann[3], J. Adams[4], J. A. Aguilar[5], M. Ahlers[6], M. Ahrens[7], D. Altmann[8], K. Andeen[9], T. Anderson[10]

Show full author list

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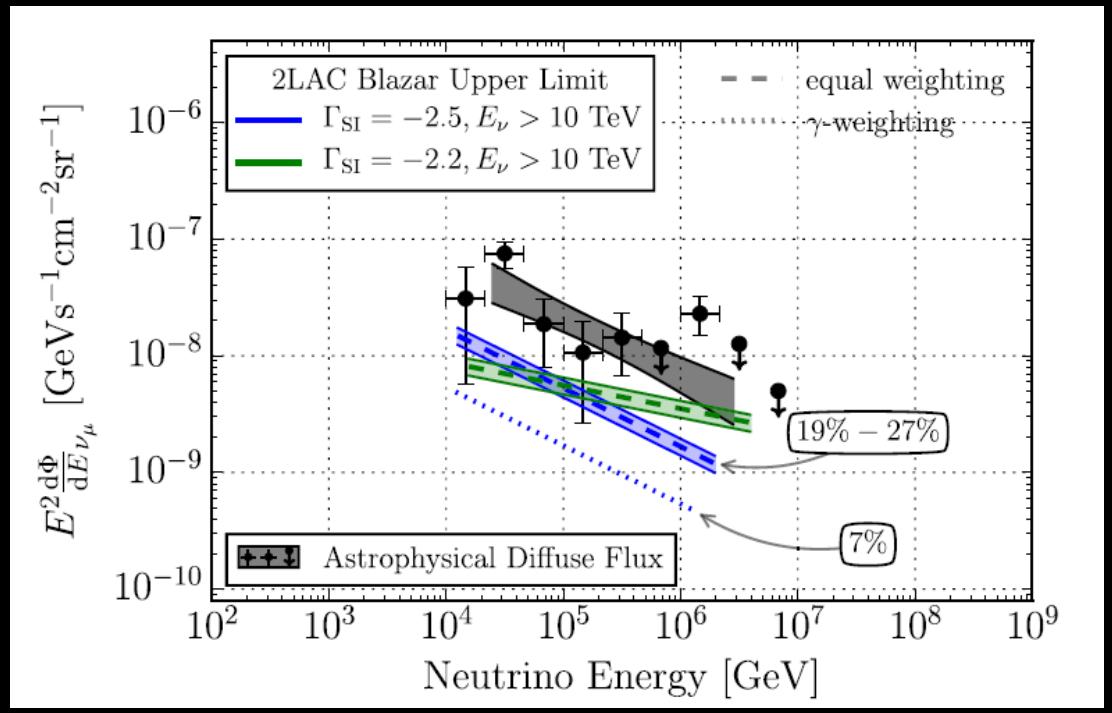
The Astrophysical Journal, Volume 835, Number 1

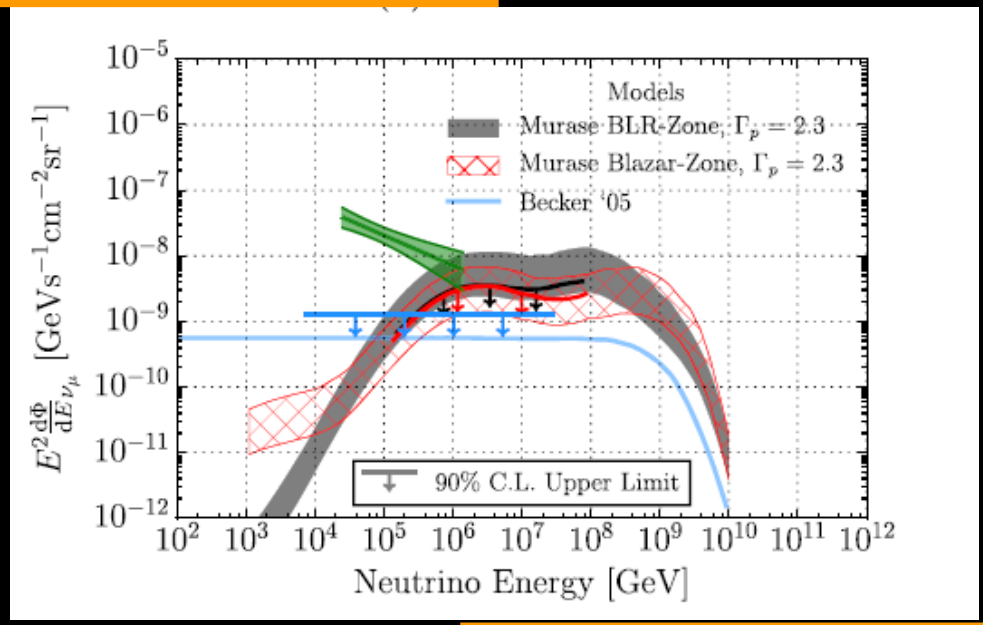


Search for a cumulative ν excess from 862 2LAC blazars

Model dependent constraints on Blazars

TeV PeV EeV

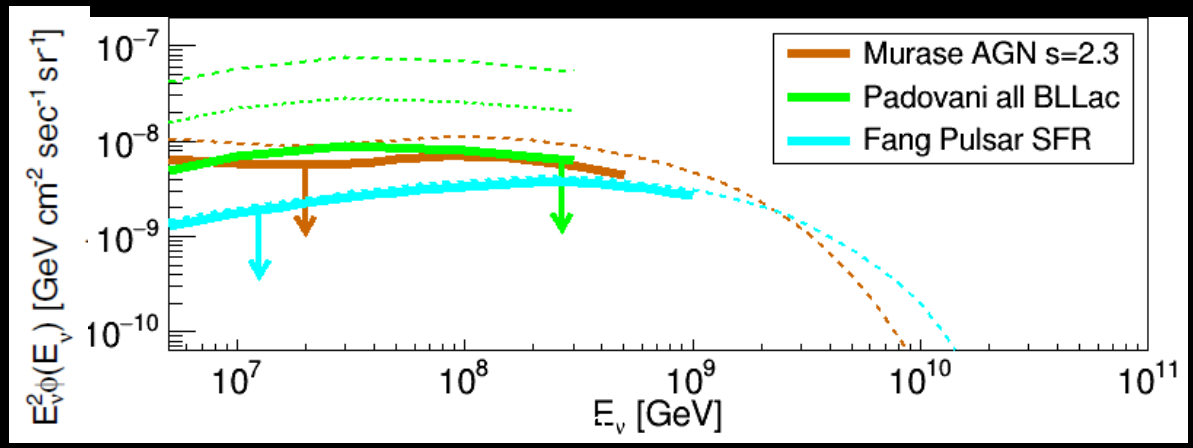
IceCube Collaboration
ApJ 835 no.1 45 (2017)



ν_μ only

TeV PeV EeV

IceCube Collaboration
PRL 117 241101 (2016)



all flavor sum

Another big question

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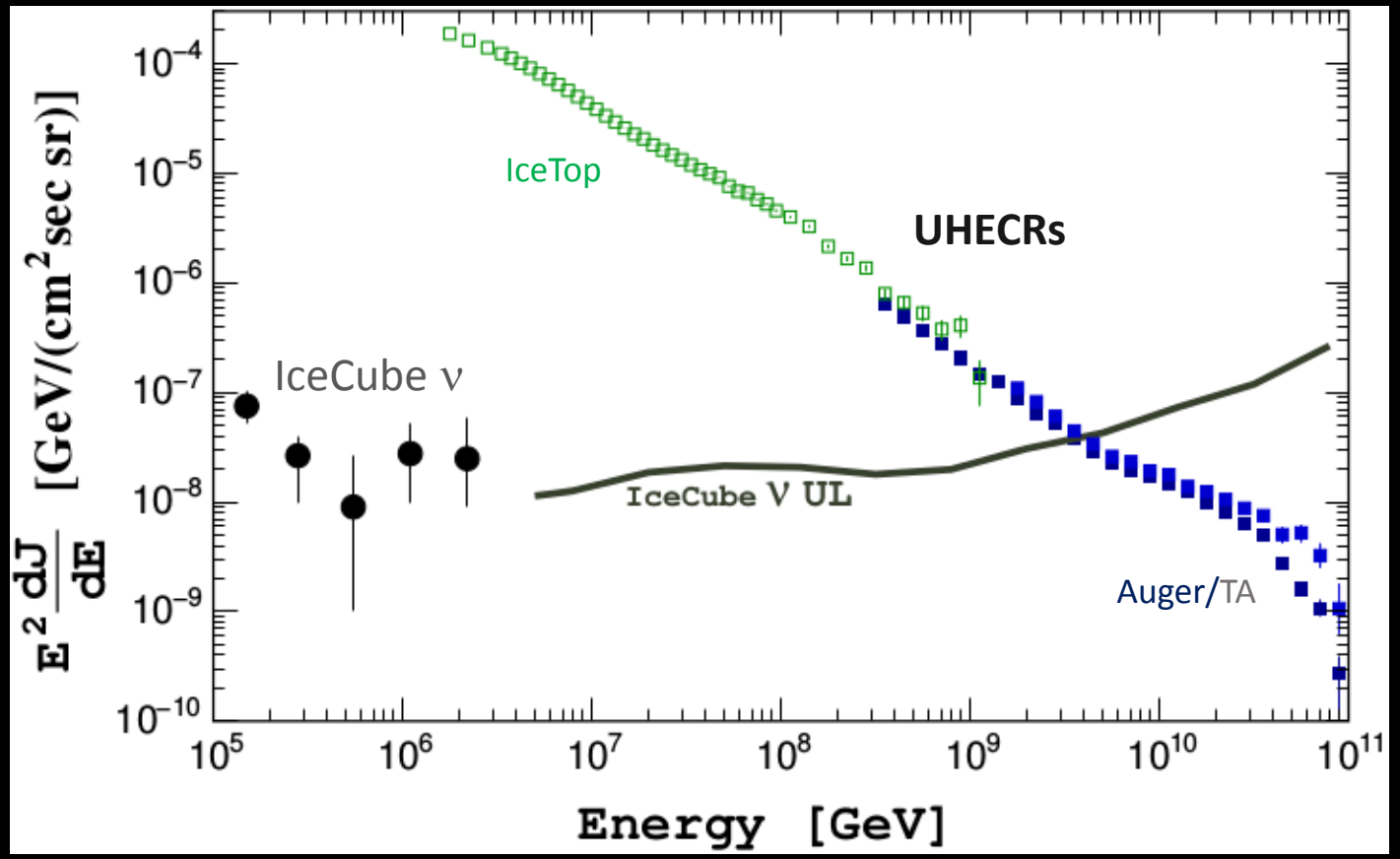
The (yet-unknown) UHECR sources are also the origin of IceCube TeV ν?



Energy flux

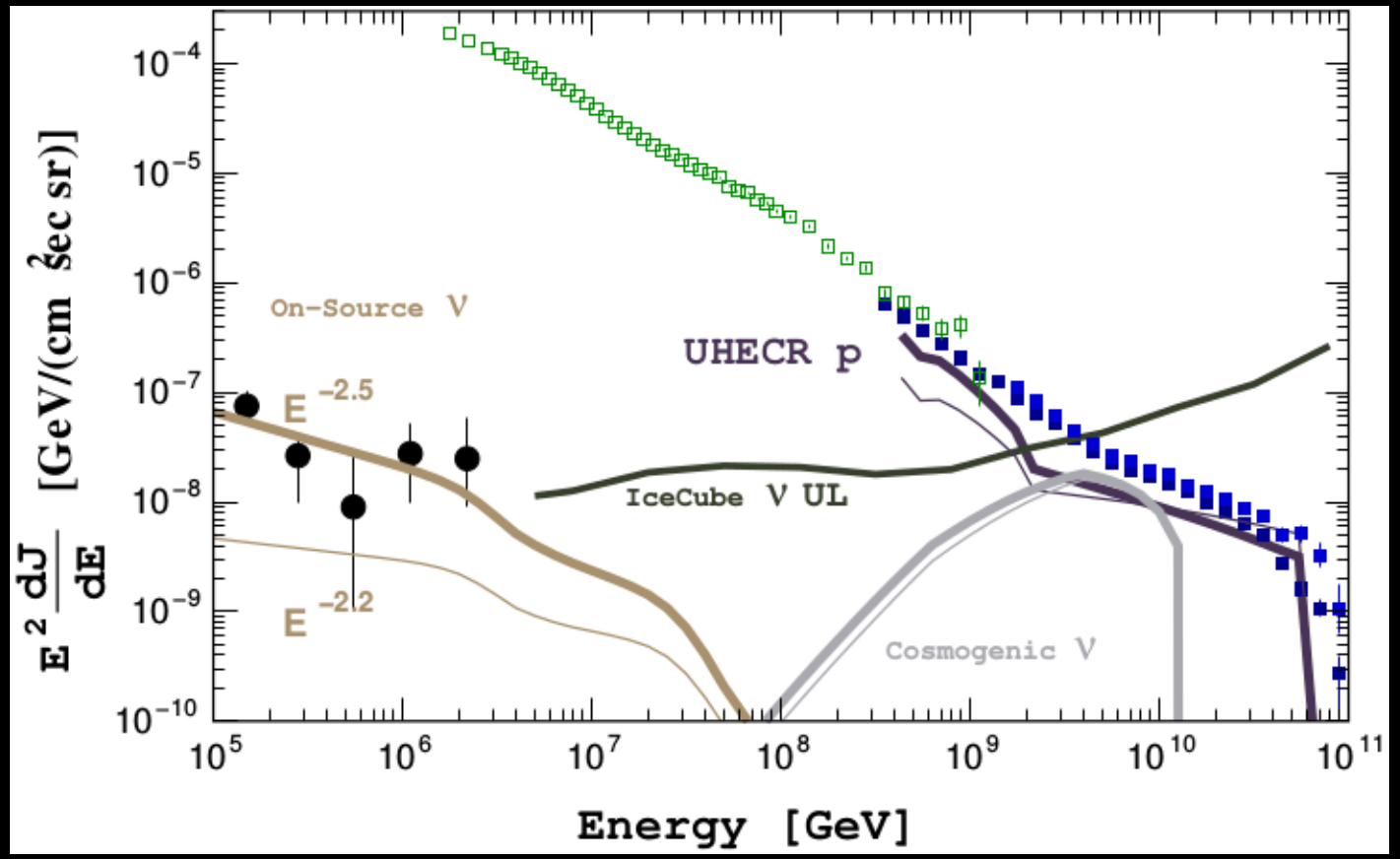
IceCube ν ~ UHECRs

Is this just a coincidence?

UHECR-IceCube ν Unified Model

CHIBA UNIVERSITY

The (yet-unknown) UHECR sources are also the origin of IceCube TeV ν?



A genetic analytical model

- Optical Depth 0.1
- SFR-like evolution

Can be consistent with UHECR data and ν UL at higher energies

taking the formula from

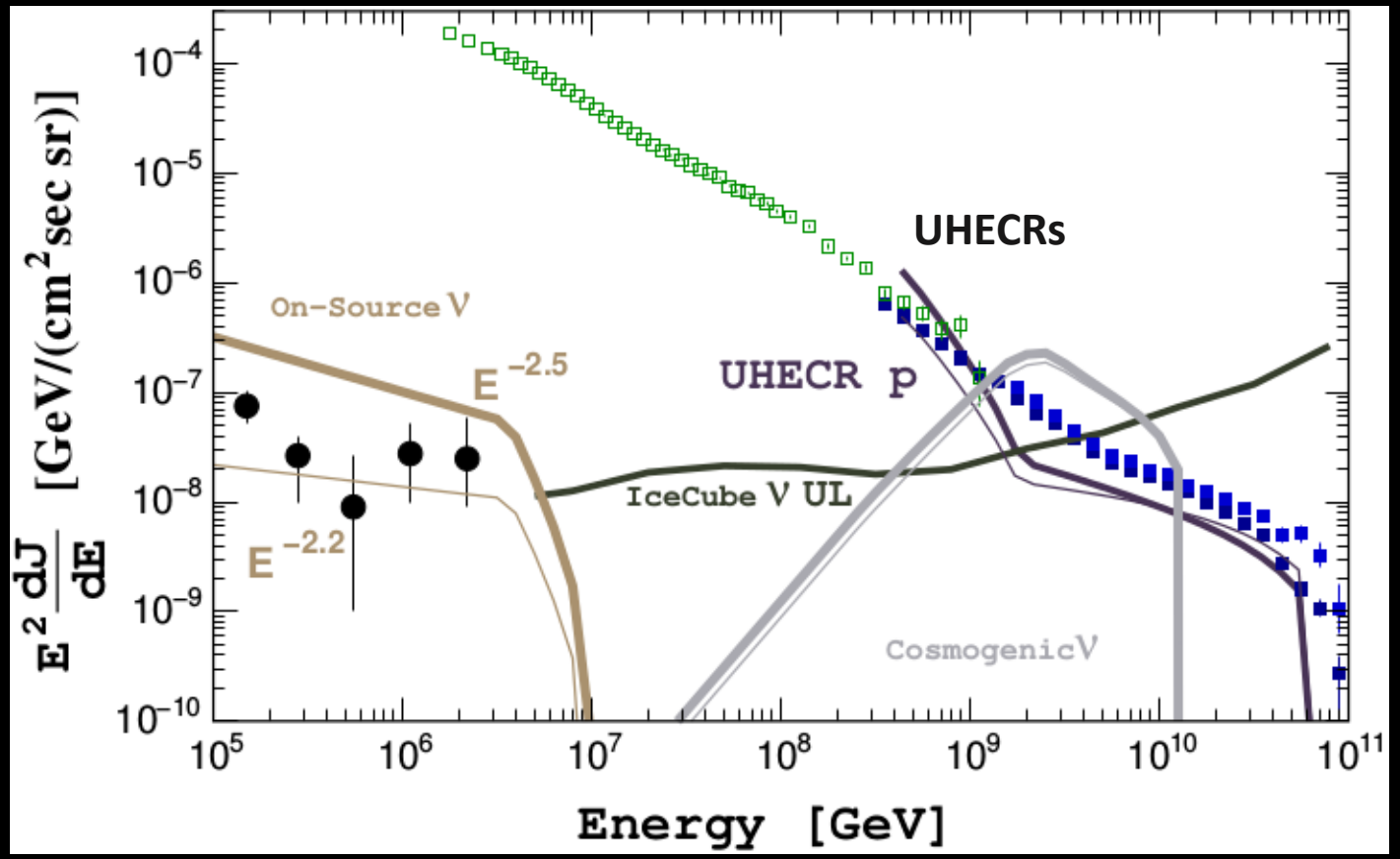
Yoshida & Takami PRD 2014

Yoshida & Ishihara PRD 2012

UHECR-IceCube ν Unified Model

CHIBA UNIVERSITY

The (yet-unknown) UHECR sources are also the origin of IceCube TeV ν?



A genetic analytical model

- Optical Depth 0.1
- FSRQ-like evolution

Inconsistent with
ν UL at higher energies

taking the formula from

Yoshida & Takami PRD 2014

Yoshida & Ishihara PRD 2012

Tracing *history* of the particle emissions with ν flux

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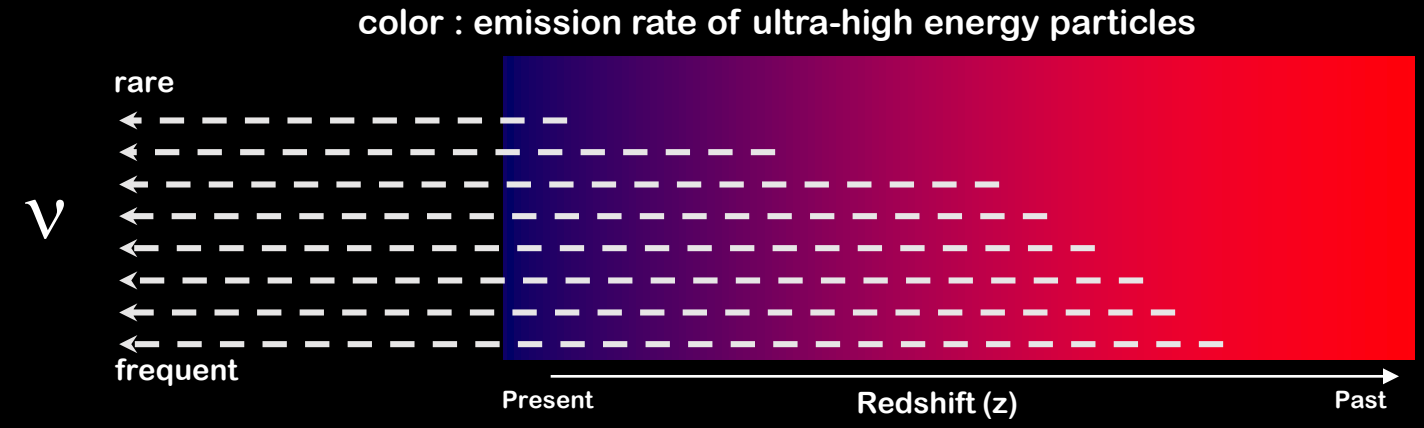
Intensity gets higher if the emission is more active in the past

because ν beams are penetrating over cosmological distances

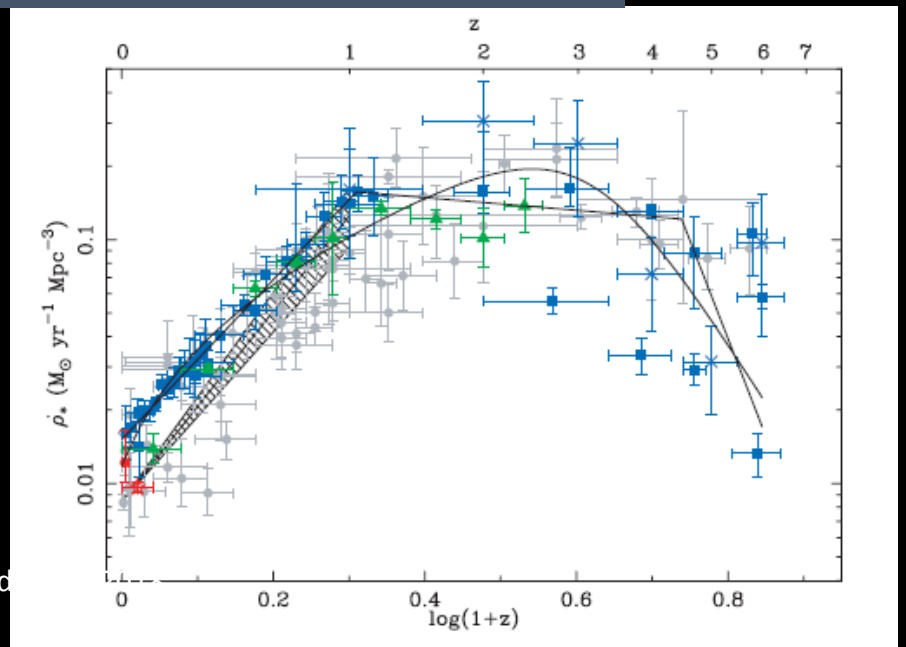


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→



The spectral emission rate

$\rho(z) \sim (1+z)^m$

m= 0 : No evolution

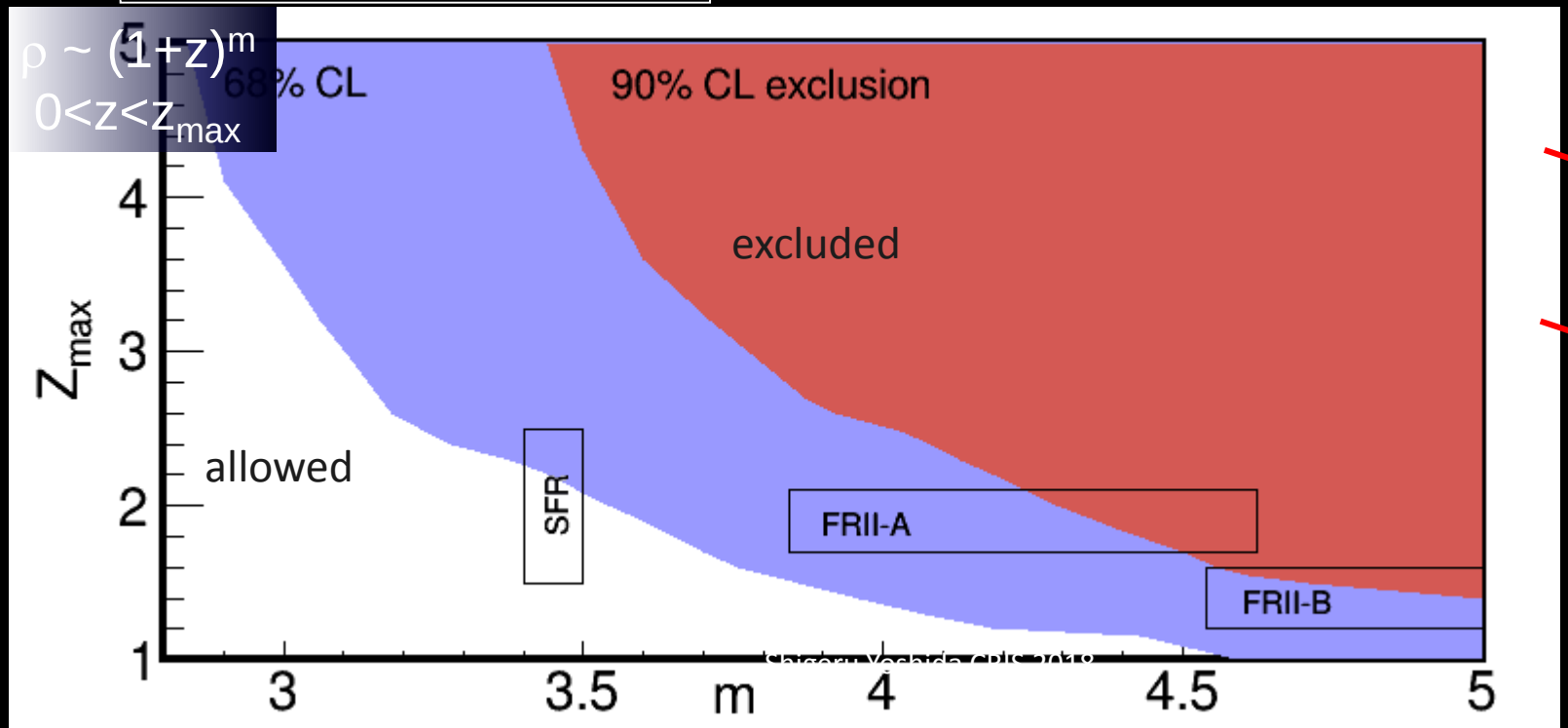
TeV PeV EeV

The Constraints on evolution (emission history) of UHE cosmic ray sources

IceCube collaboration
Phys.Rev.Lett.**117** 241101(2016) errutum **119** 259902 (2017)

UHECR source is cosmologically LESS evolved

Any sources with evolution compatible or stronger than star formation rate are disfavored



FRII (FSRQs)

GRBs

UHECR-IceCube ν Unified Model

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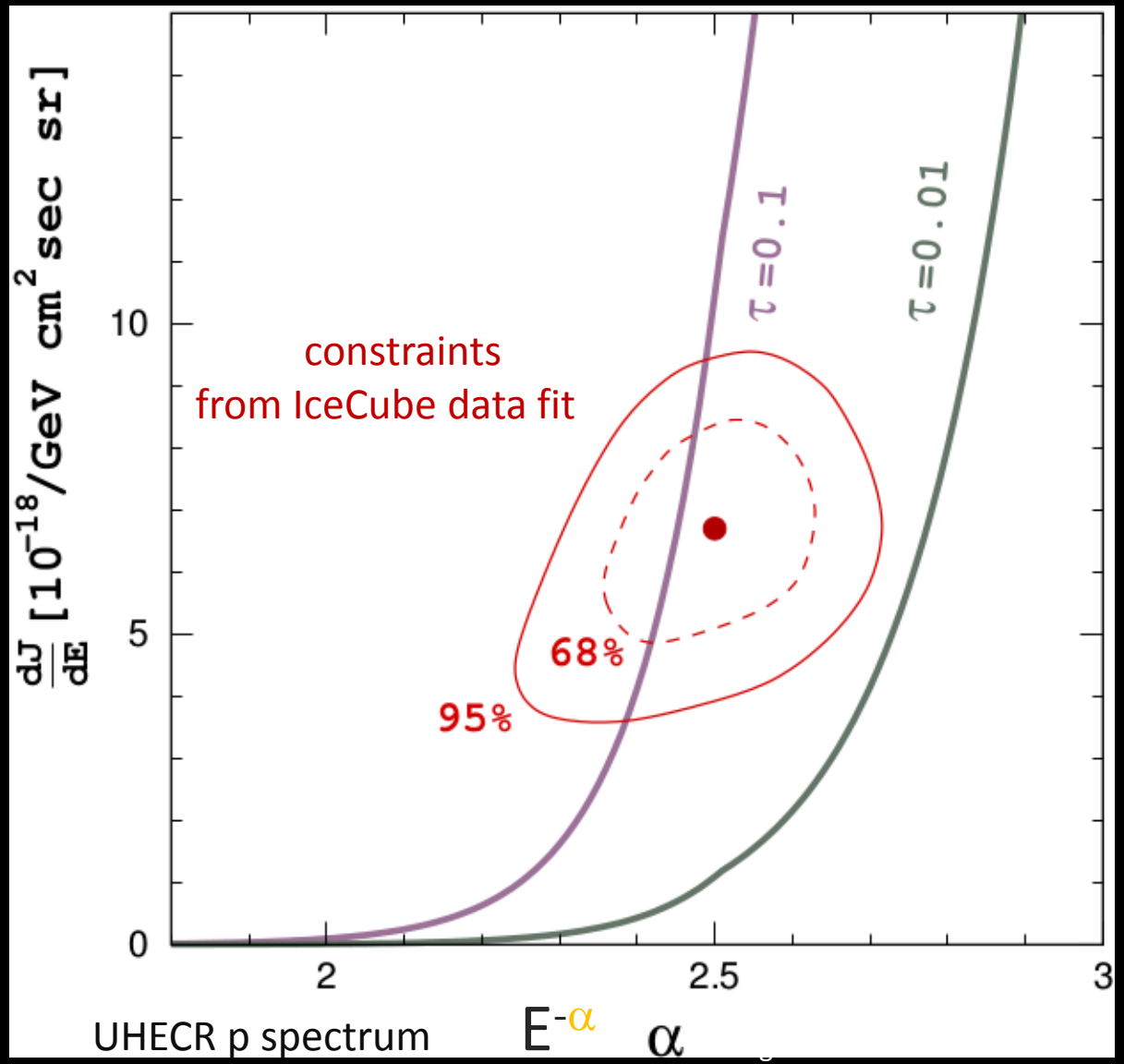

prediction from the unified model

There are not many astronomical objects to meet these criteria

Optical depth> 0.01 if soft spectrum

Optical depth~ 1 if hard spectrum

evolution weaker or compatible to SFR

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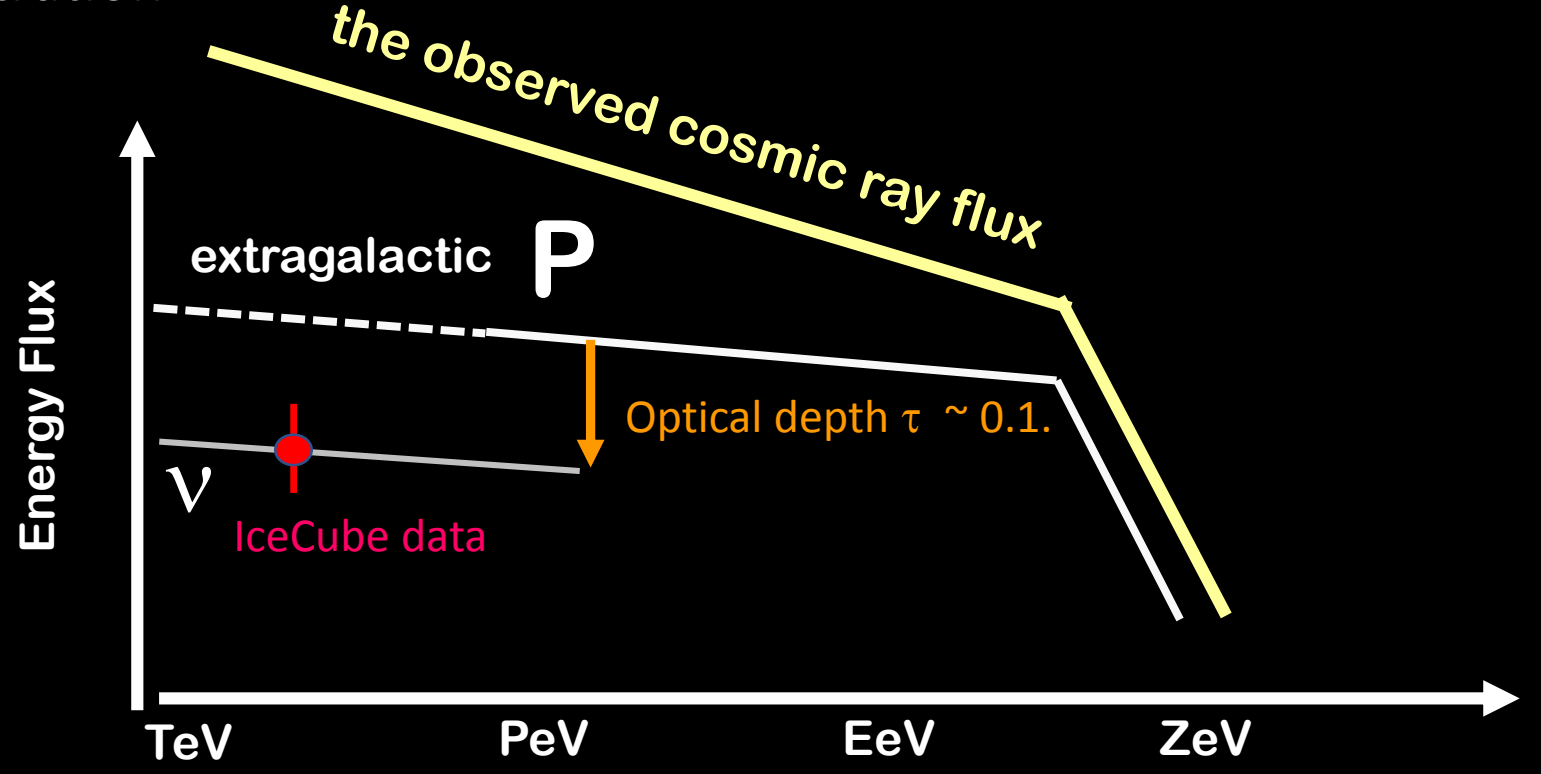
Connections between the observed TeV-PeV ν flux and UHECRs

Schematic Illustration



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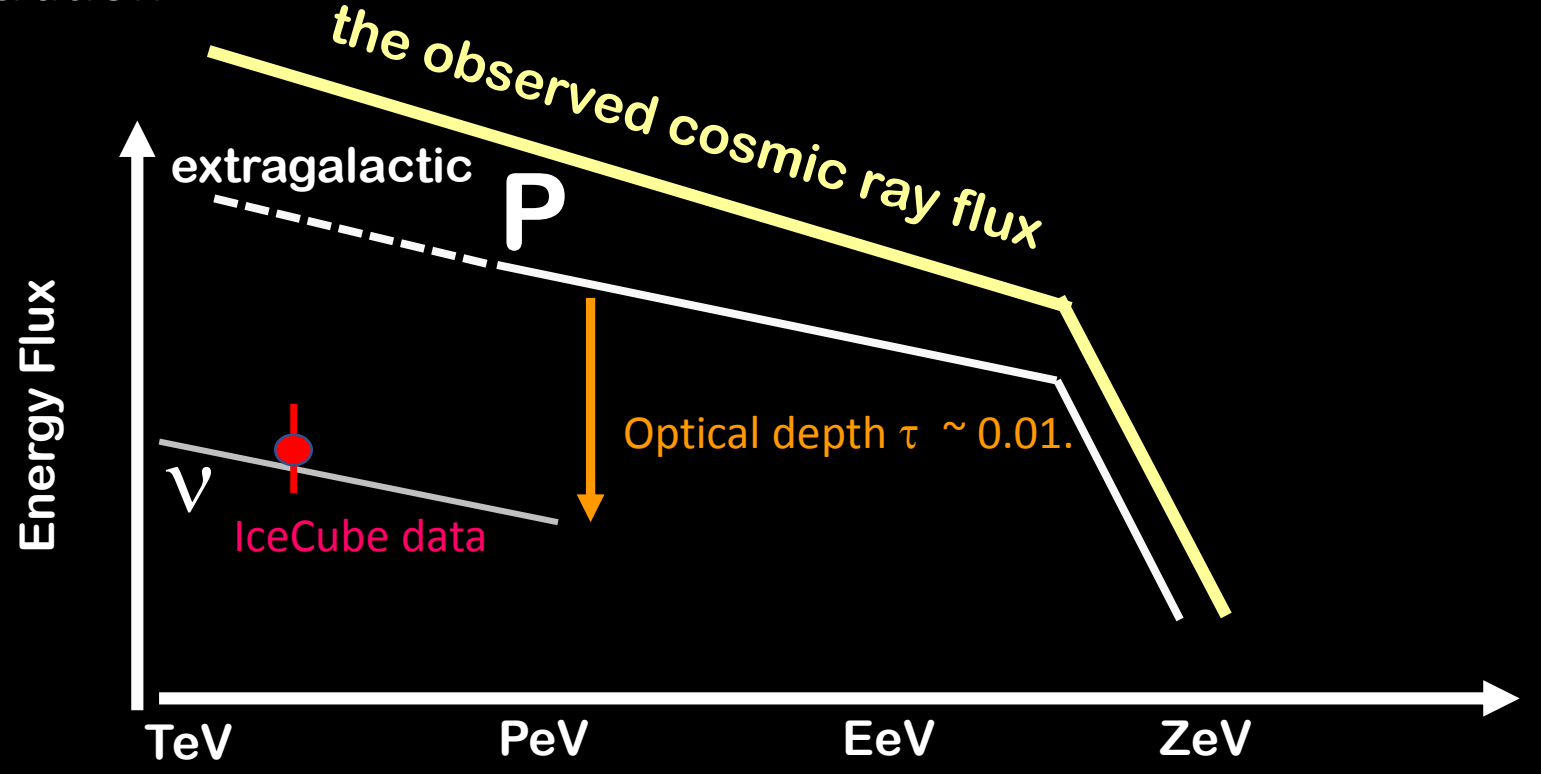
Connections between the observed TeV-PeV ν flux and UHECRs

Schematic Illustration



UHECR-IceCube ν Unified Model

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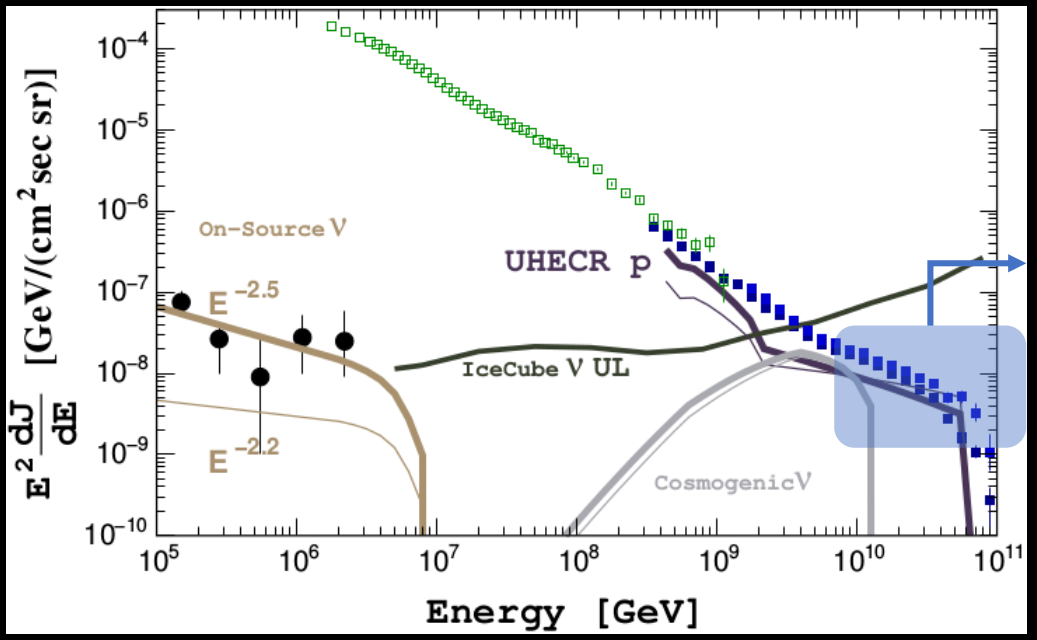
Energetics requirements



Source luminosity with SFR-like evolution

	$E^{-2.2}$	$E^{-2.5}$
E>10 EeV	~4×10^{44} erg/Mpc^3 yr	~2×10^{44} erg/Mpc^3 yr
extrapolate ↓		
E>10 PeV	~2×10^{48} erg/Mpc^3 yr	~6×10^{48} erg/Mpc^3 yr

c.f. GRB L_γ ~ 10^{44} erg/Mpc^3 yr FSRQ L_γ ~ 10^{46} erg/Mpc^3 yr

UHECR-IceCube ν Unified Model

genetic requirements to UHECR sources

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cosmological evolution compatible or weaker than star formation rate

IceCube bounds on GZK ν

Fermi extra-galactic diffuse γ-ray bound

optical depth $\tau >\sim 0.01$ if $E^{-2.6}$, $\tau>0.1$ if $E^{-2.3}$ or harder

IceCube TeV-PeV ν flux

c.f. GRB internal shock $\tau\sim0.1$, afterglow $O(10^{-3})$, BL Lac $O(10^{-6})$

Energy luminosity $O(10^{48})$ erg/Mpc^3 yr @ E>10 PeV

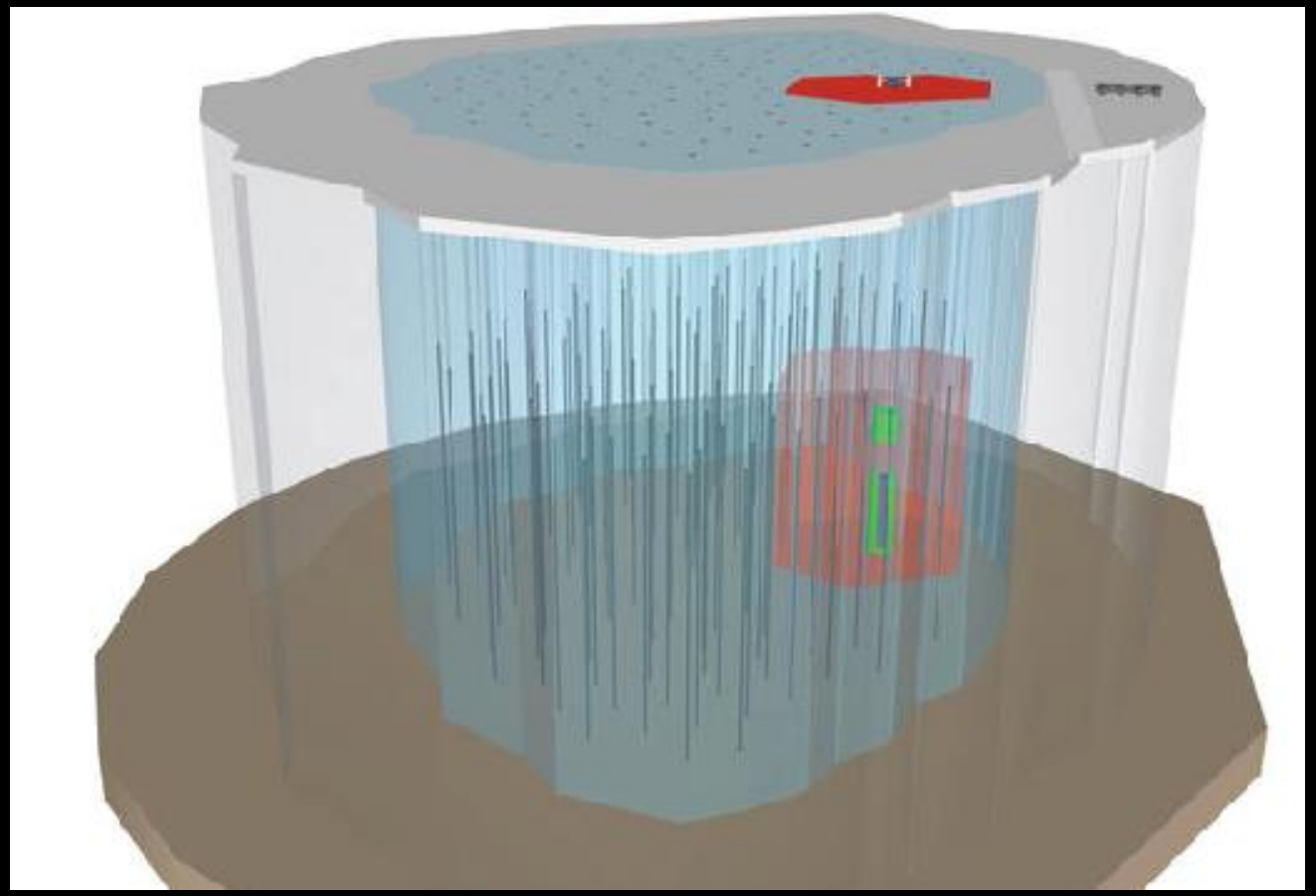
extrapolated from UHECR luminosity

BL Lac, GRB internal shocks, FSRQs all unlikely

A *major class* of (UHE) cosmic ray sources is yet unknown

The solution

IceCube-Gen2



IceCube-Gen2
the staging strategy

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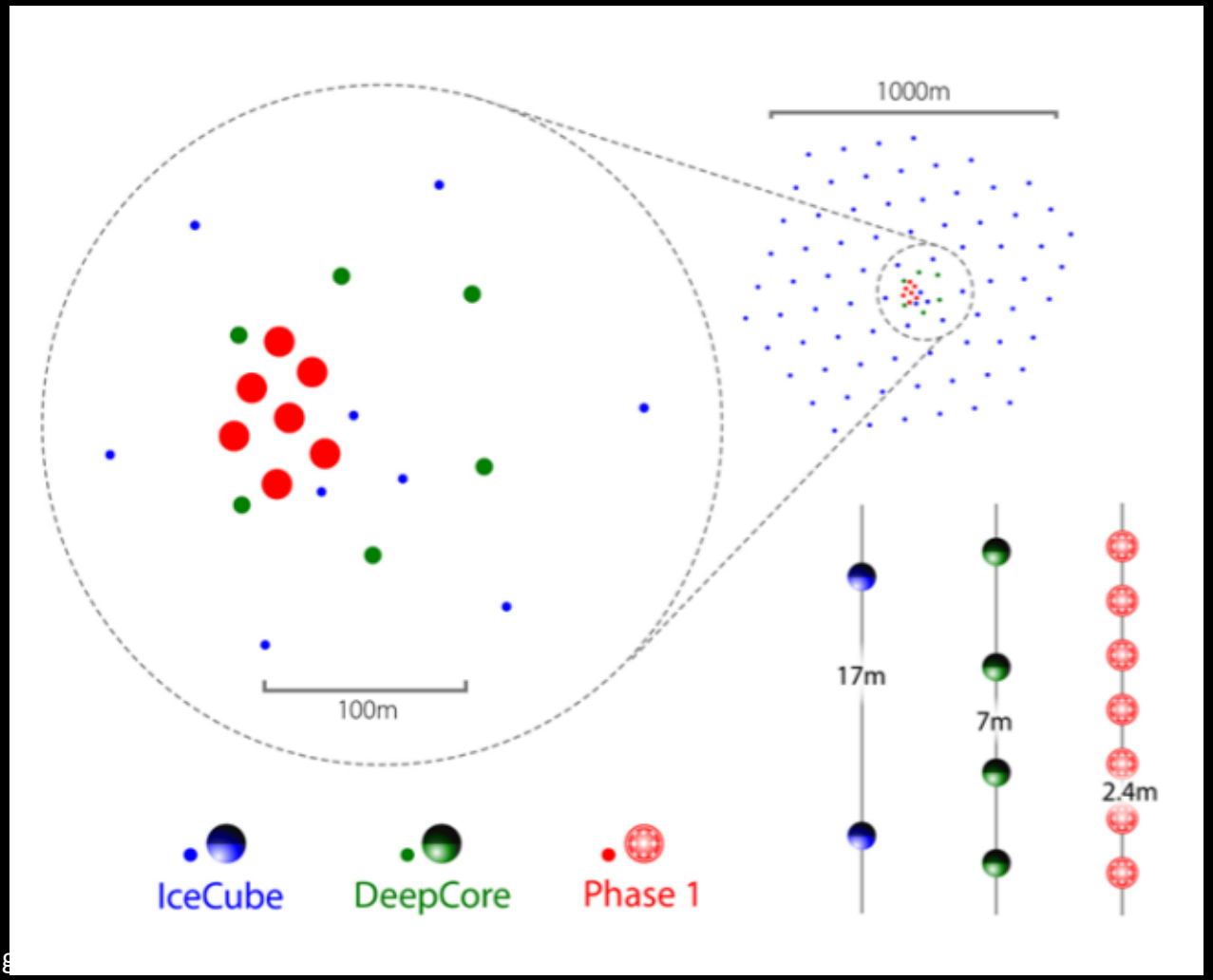
IceCube-Gen2 Phase1

towards precise measurements
of ice's optical characteristics



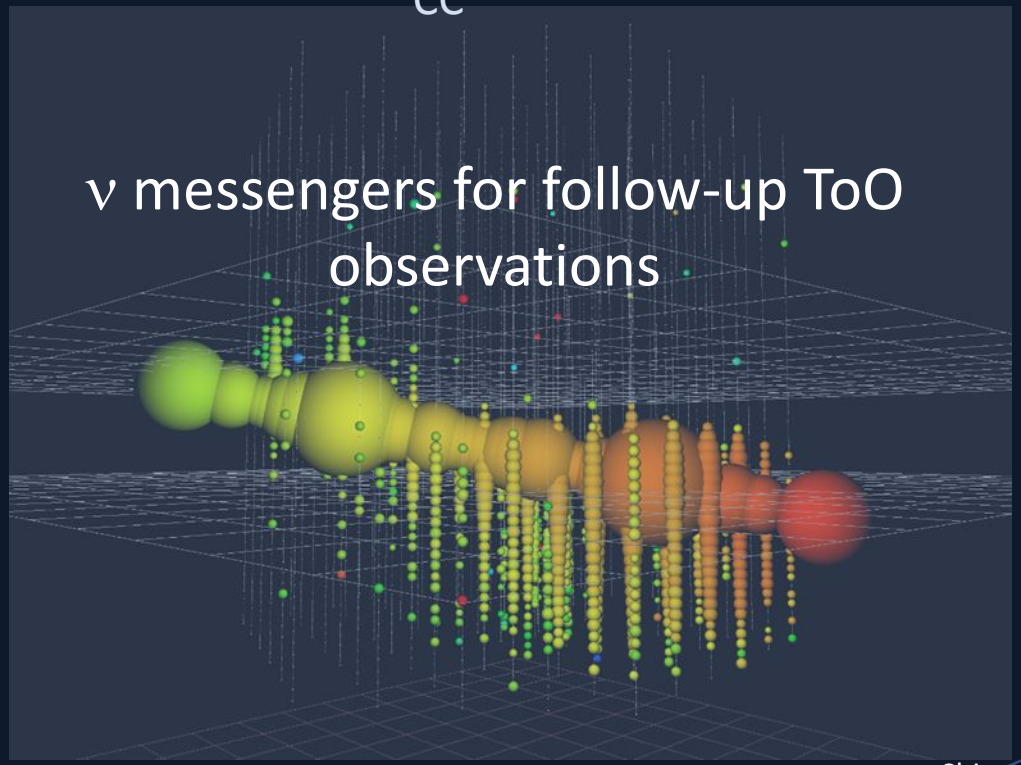
IceCube Event Topology

Track

Angular resolution
~ 0.5 degree

$\nu_\mu \xrightarrow[CC]{} \mu$

$\nu_\tau \xrightarrow[CC]{} \tau$ (only at ultra-high energies)



ν messengers for follow-up ToO observations

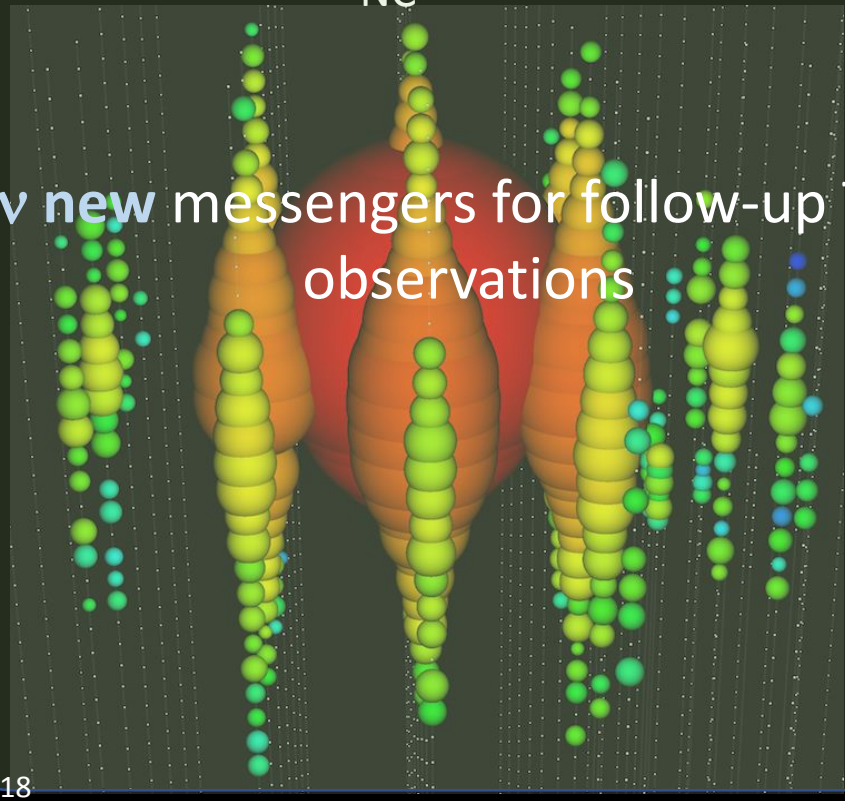
Cascade (shower)

Angular resolution
~ 4 degree

$\nu_e \xrightarrow[CC]{} e + X$

$\nu_x \xrightarrow[NC]{} x + X$

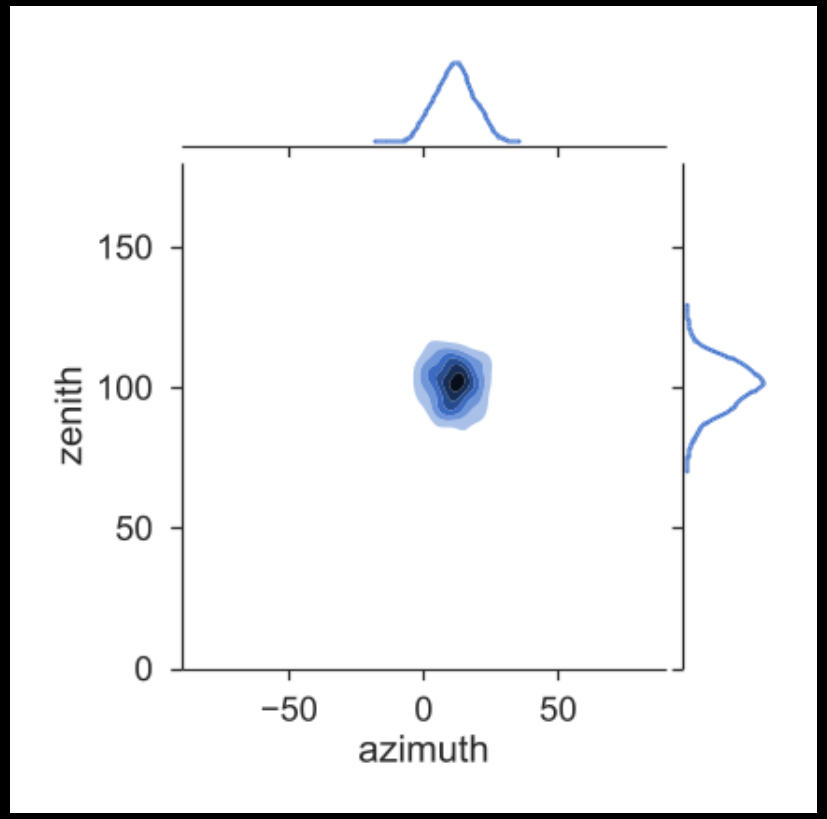
x=e, μ, τ



ν **new** messengers for follow-up ToO observations

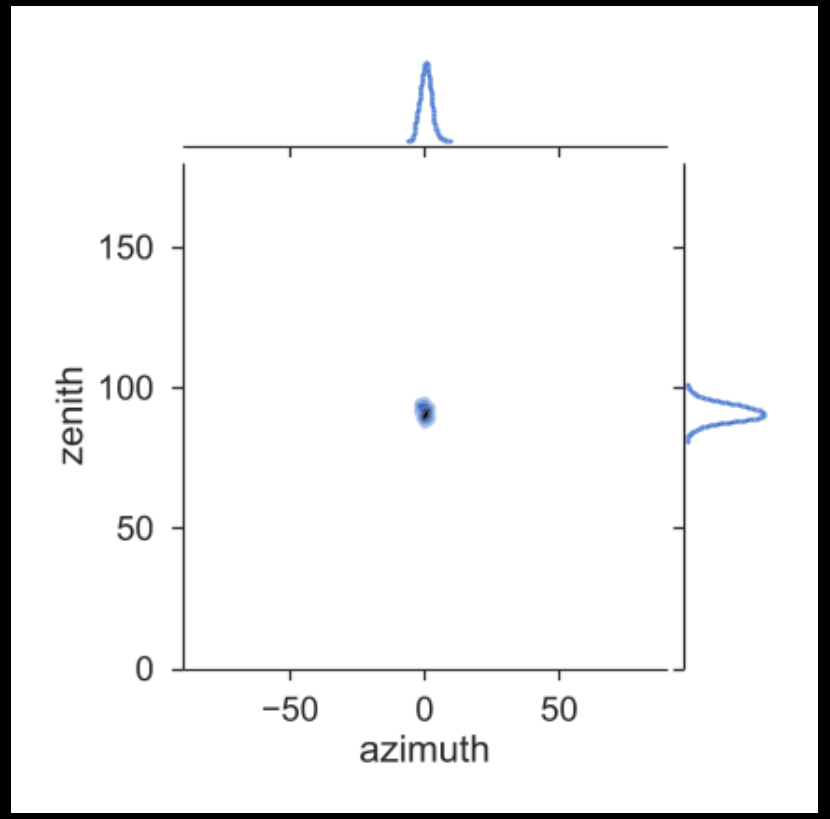
Improving the angular resolutions of ν-induced *shower* events for multi-messenger astronomy

The present – 15 degree error



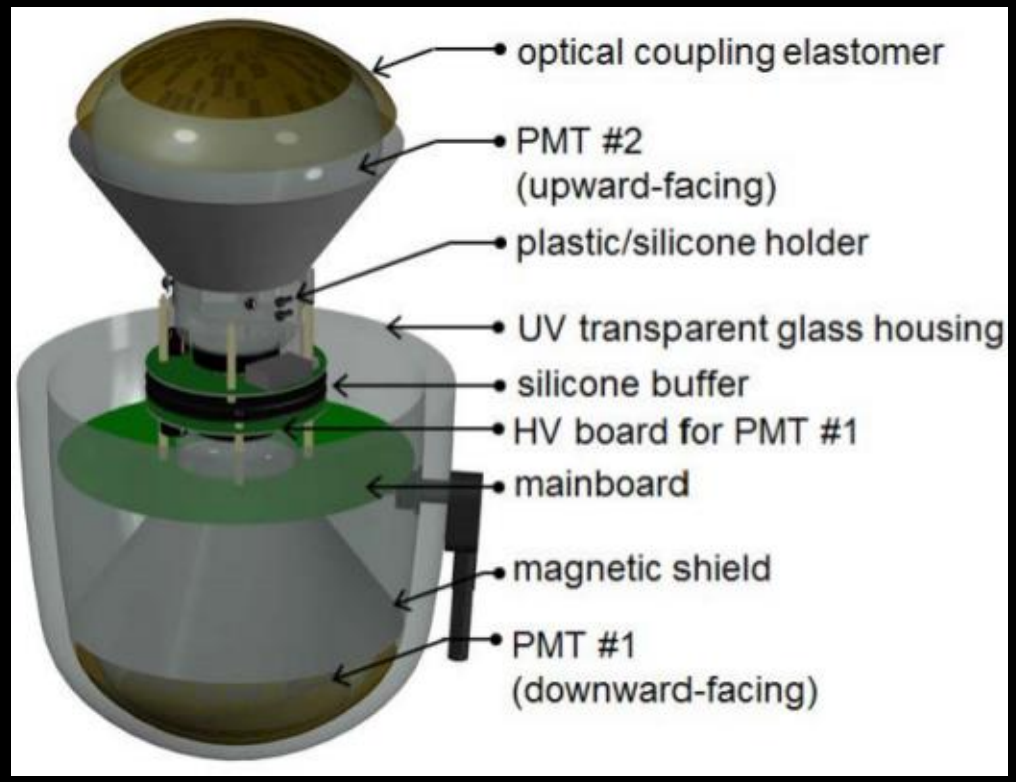
With better understandings of **C light scattering**

Yes we can! 4 degree error



D-Egg detectors map out Ice

D-Egg schematics



D-Egg prototypes

IceCube upgrading coming soon

We are hiring two postdocs

Contact me if you are interested