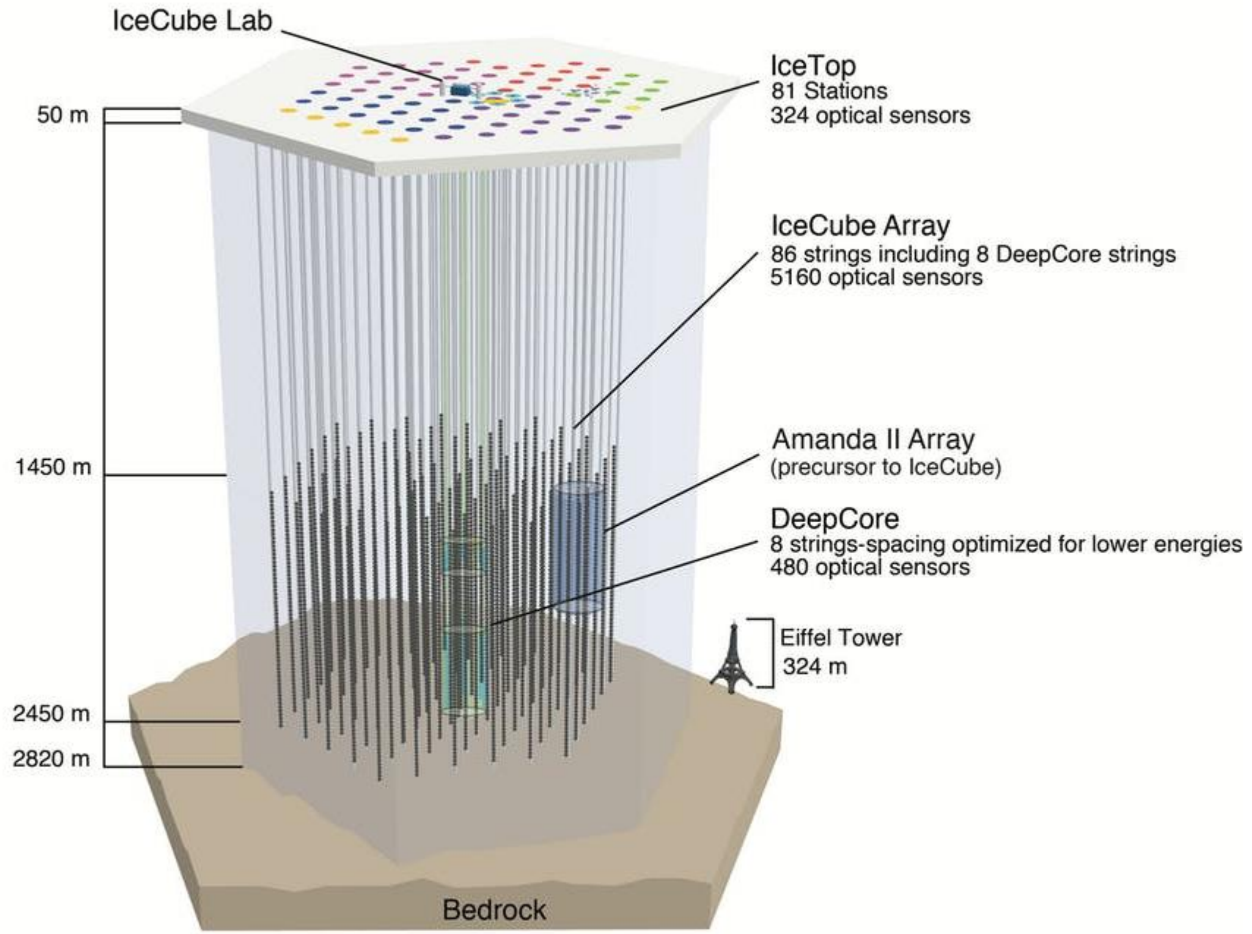

Ota Chou,1936

REAL-TIME @ICECUBE

Lu Lu for the IceCube Collaboration
Chiba University

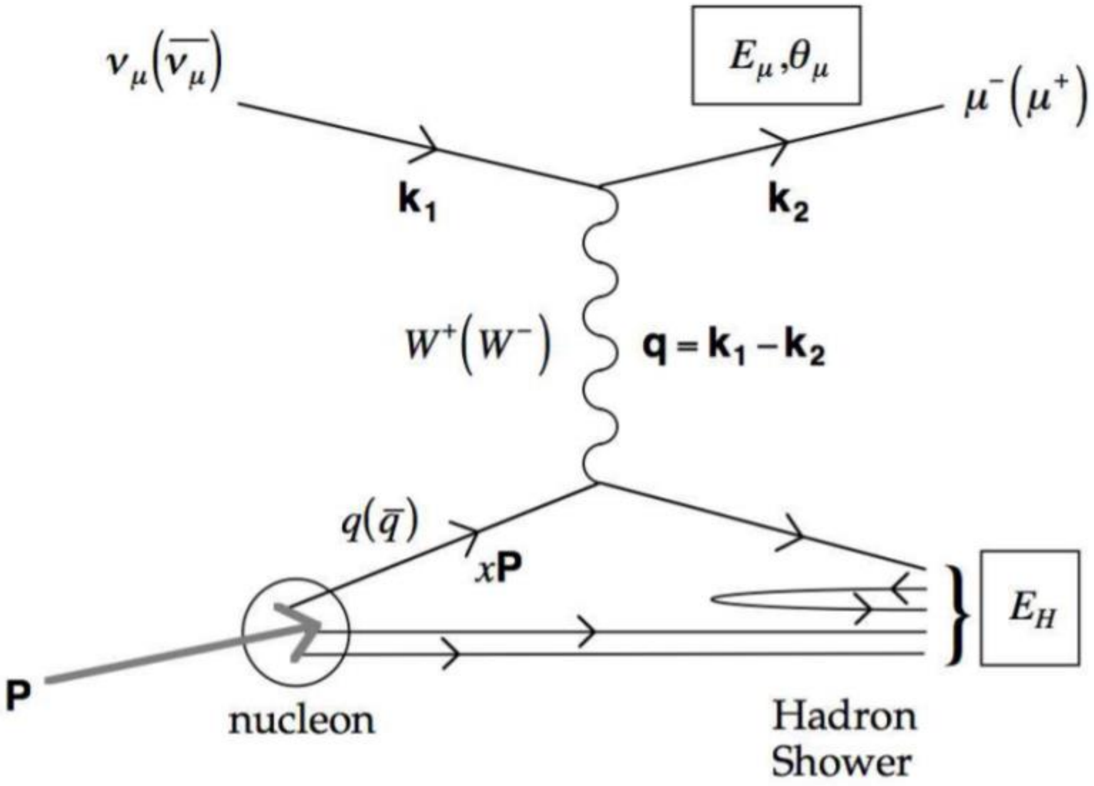
THE ICECUBE NEUTRINO OBSERVATORY



Cherenkov detector in ice, 4pi acceptance

NEUTRINO DETECTION IN DEEP ICE

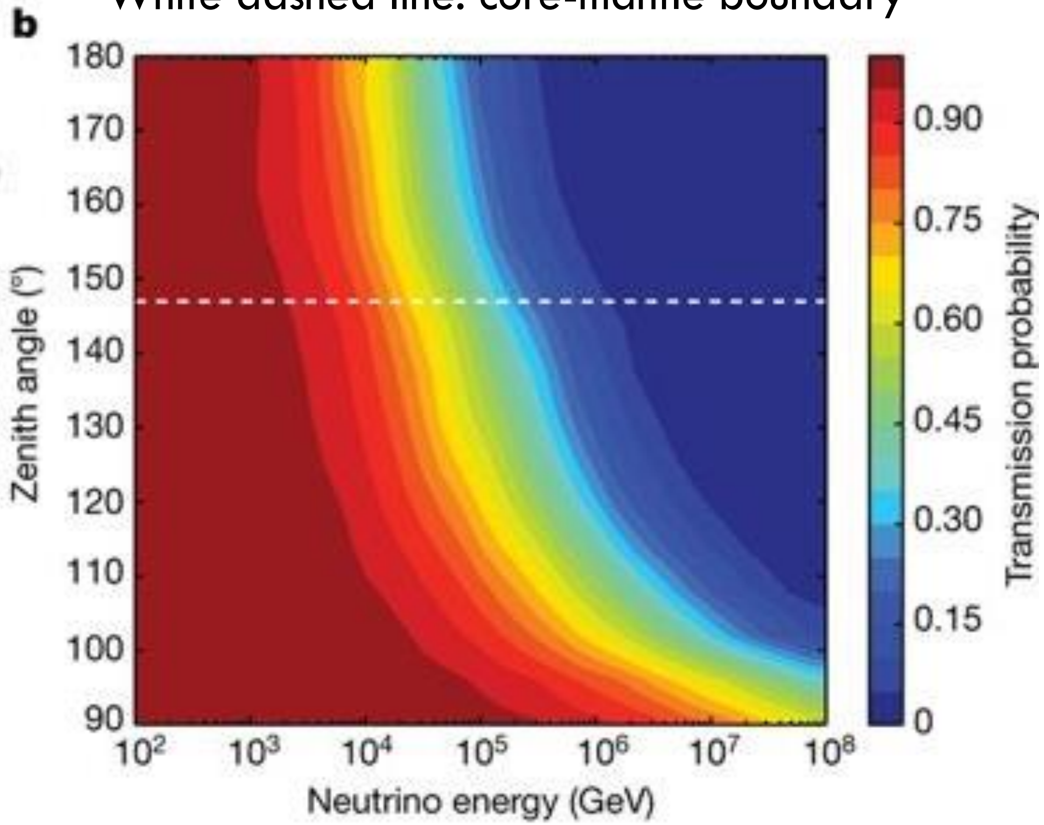
Atmospheric nu:
background for astro;
signal for low-energy



Rev. Mod. Phys. 84, 1307

deep-inelastic scattering (DIS) off nucleons in ice

White dashed line: core-mantle boundary



Nature volume551, page 596–600

Highest energy events expected
horizontal/down-going from southern sky

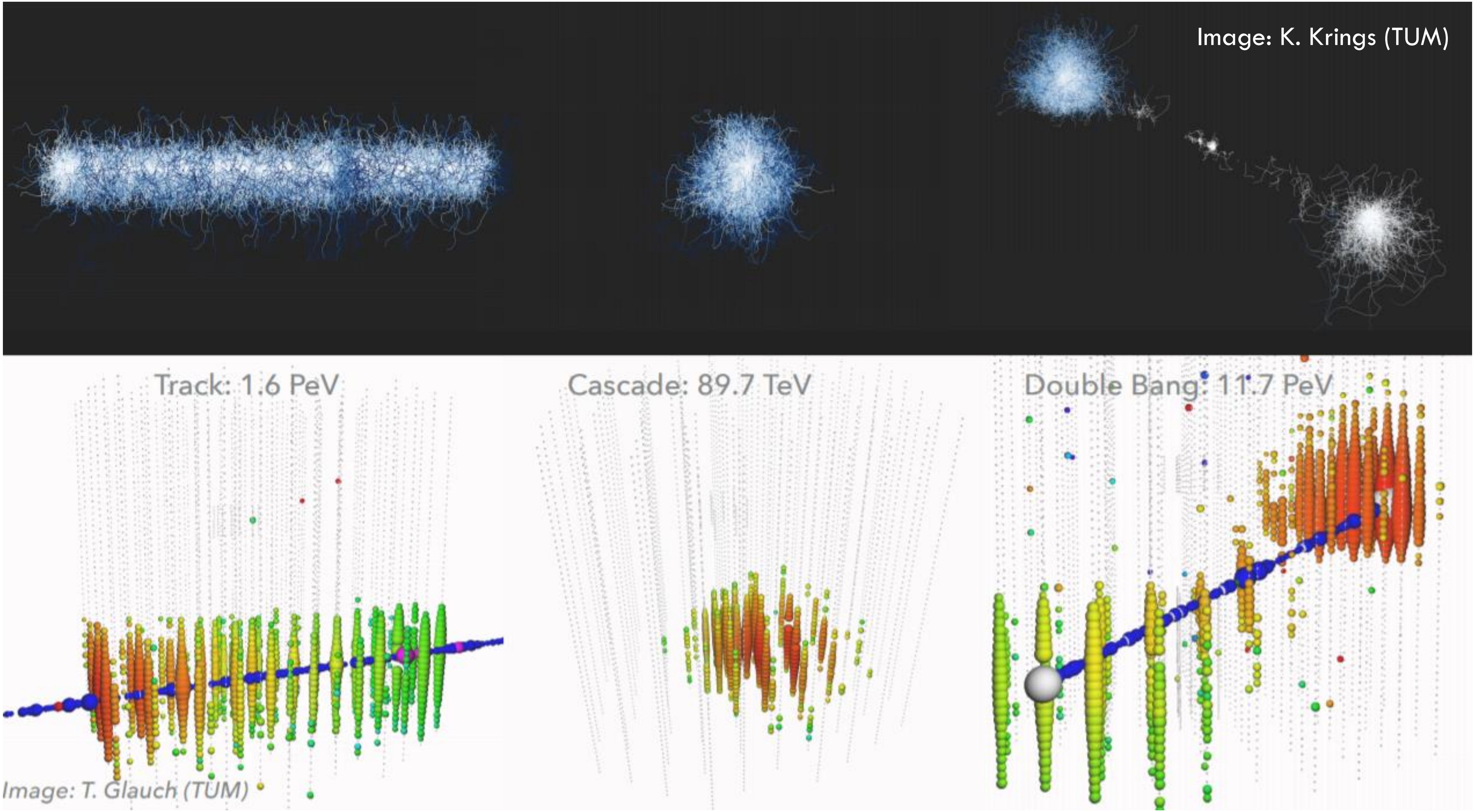
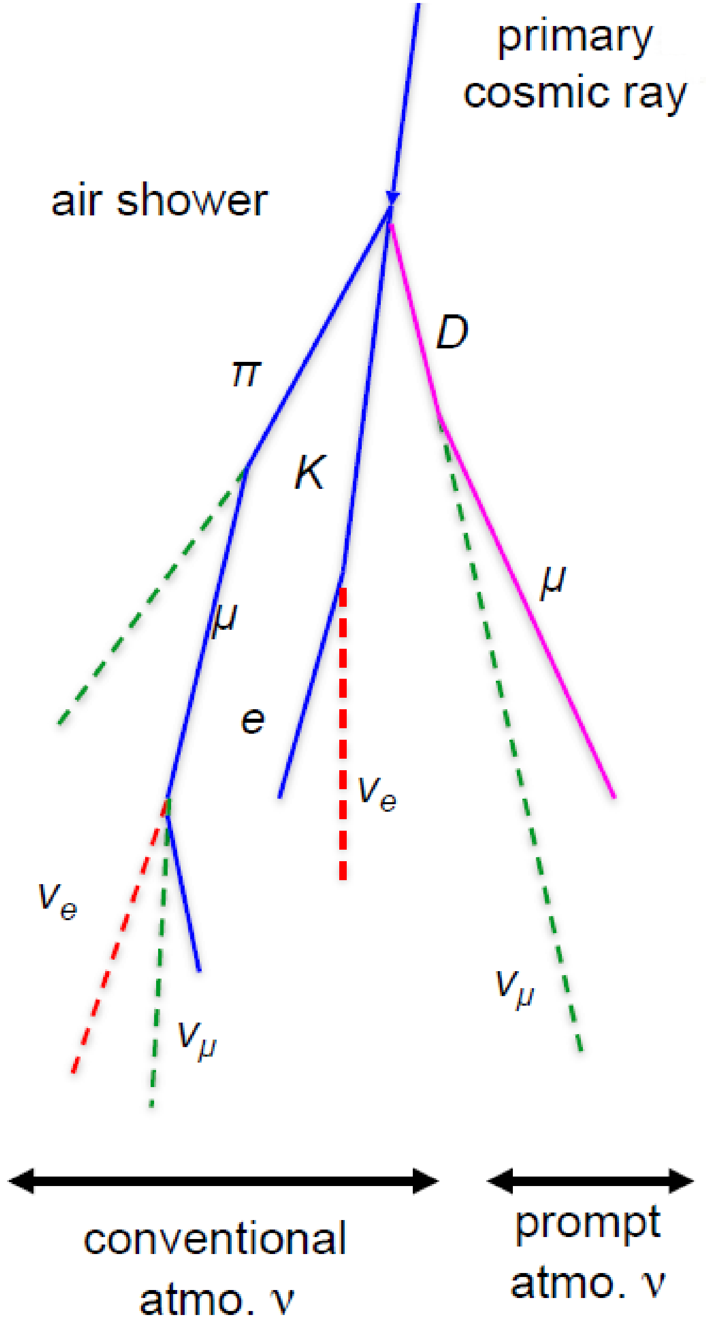
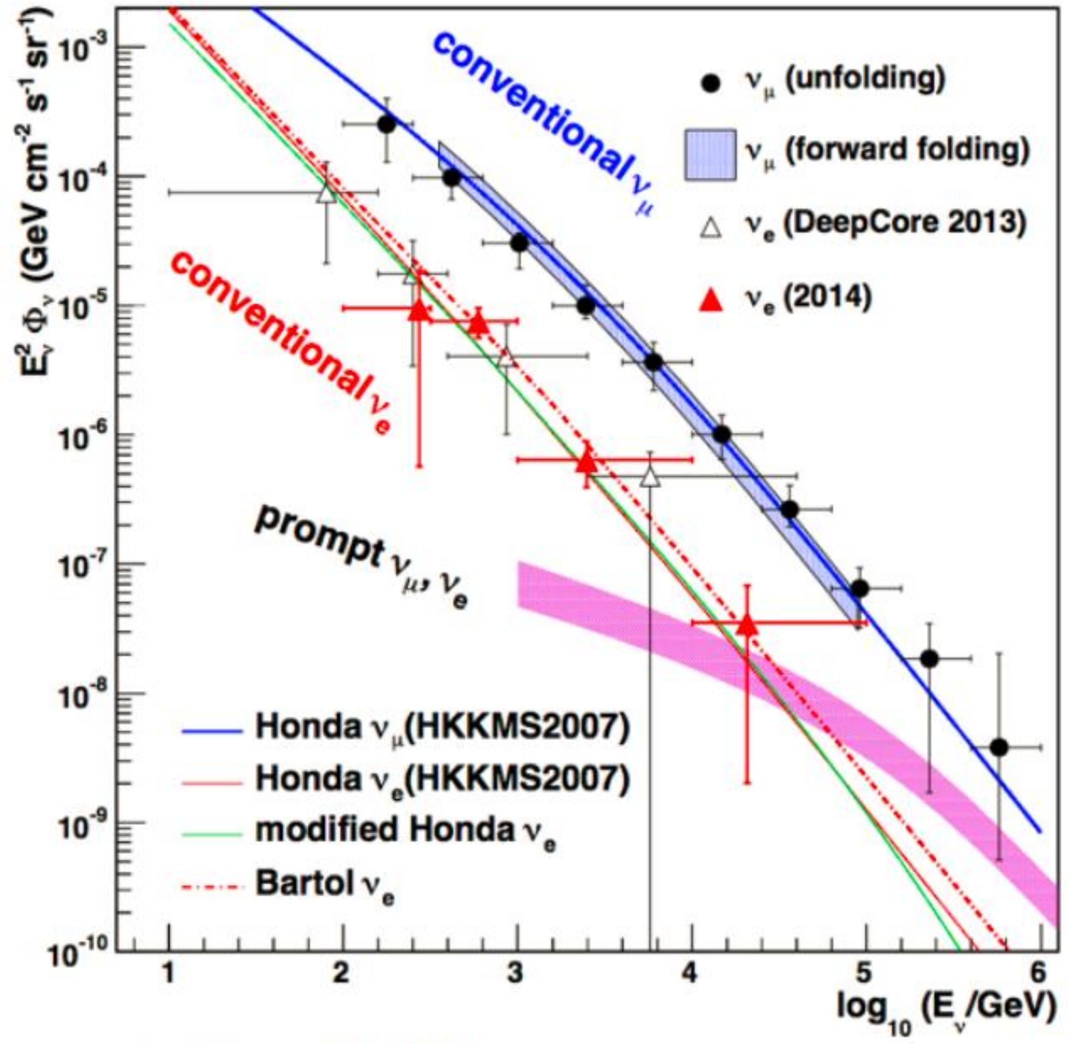


Image: K. Krings (TUM)
Track: 1.6 PeV
Cascade: 89.7 TeV
Double Bang: 11.7 PeV
Image: T. Glauch (TUM)

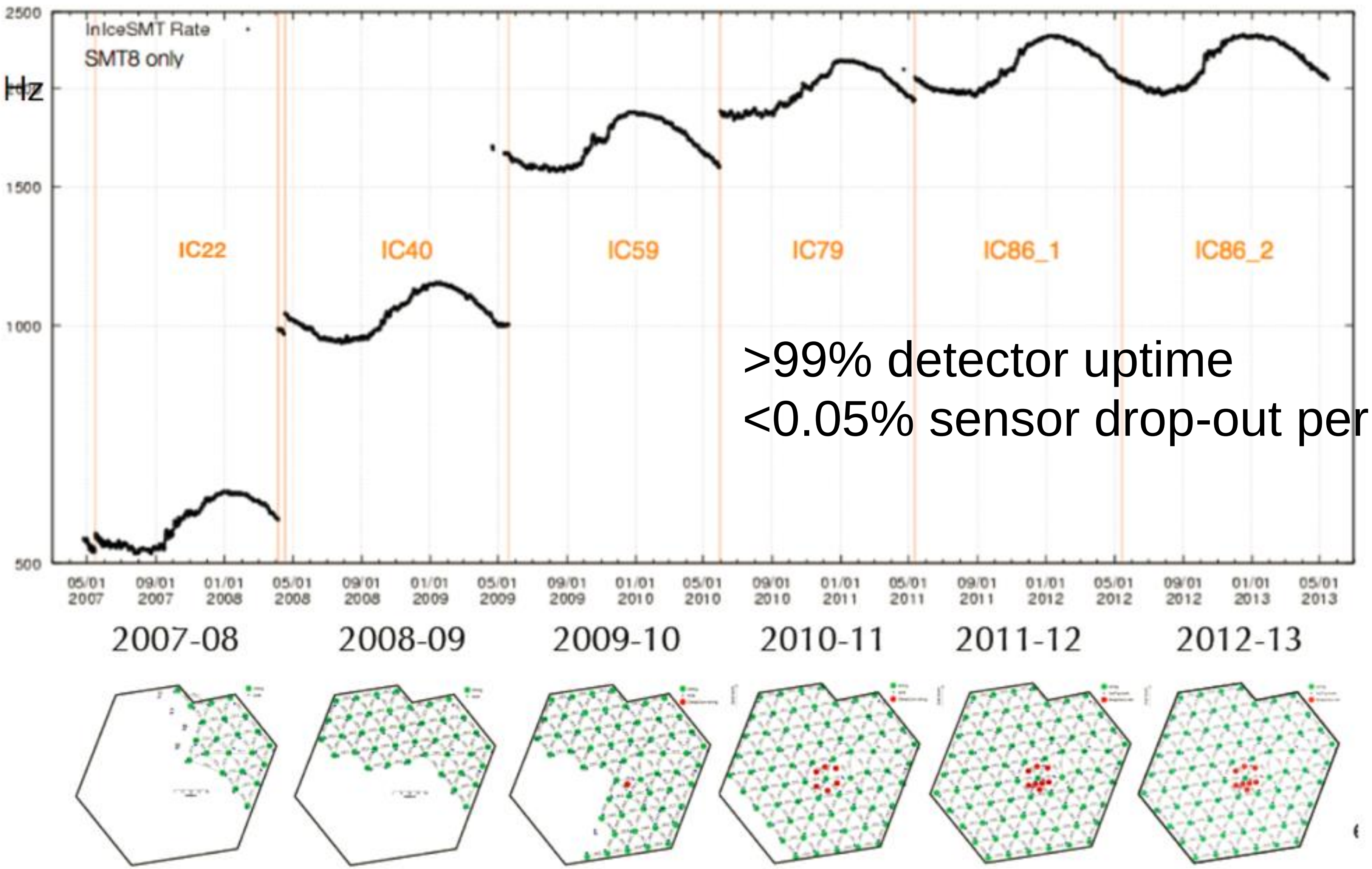
- Conventional: parent pion/kaon
- Prompt: parent/grandparent particles contain charm quark, short lifetime





IceCube, PRD2015

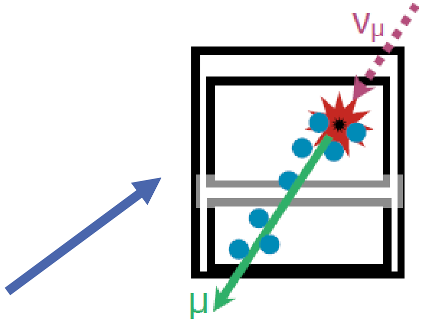
REAL-TIME DETECTION: SIGNAL PURITY (2.5KHZ)



>99% detector uptime

<0.05% sensor drop-out per year

IceCube real-time stream (current)



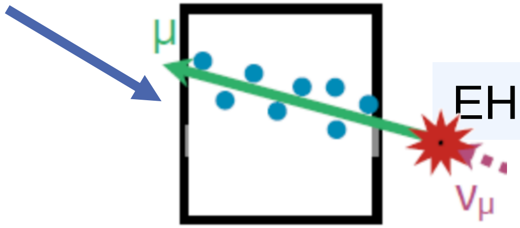
veto-based
HESE

all neutrino flavor sensitive

high chance of real cosmic neutrino signals

angular resolutions so-so

High cosmic ν purity samples.
Launched in 2016!



EHE (Ultra-High Energies)

all neutrino flavor sensitive

high chance of real cosmic neutrino signals

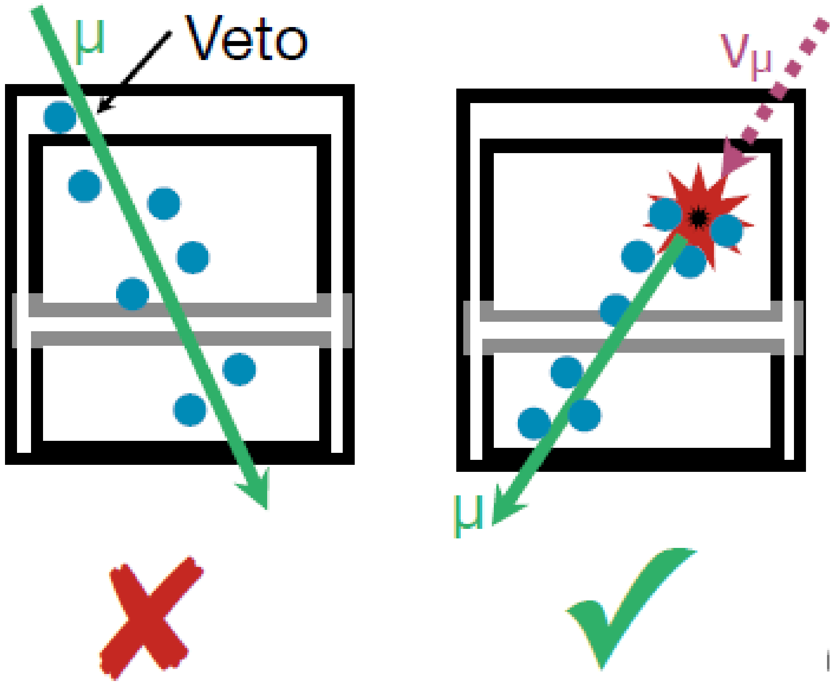
good angular resolutions

signal flux highly uncertain

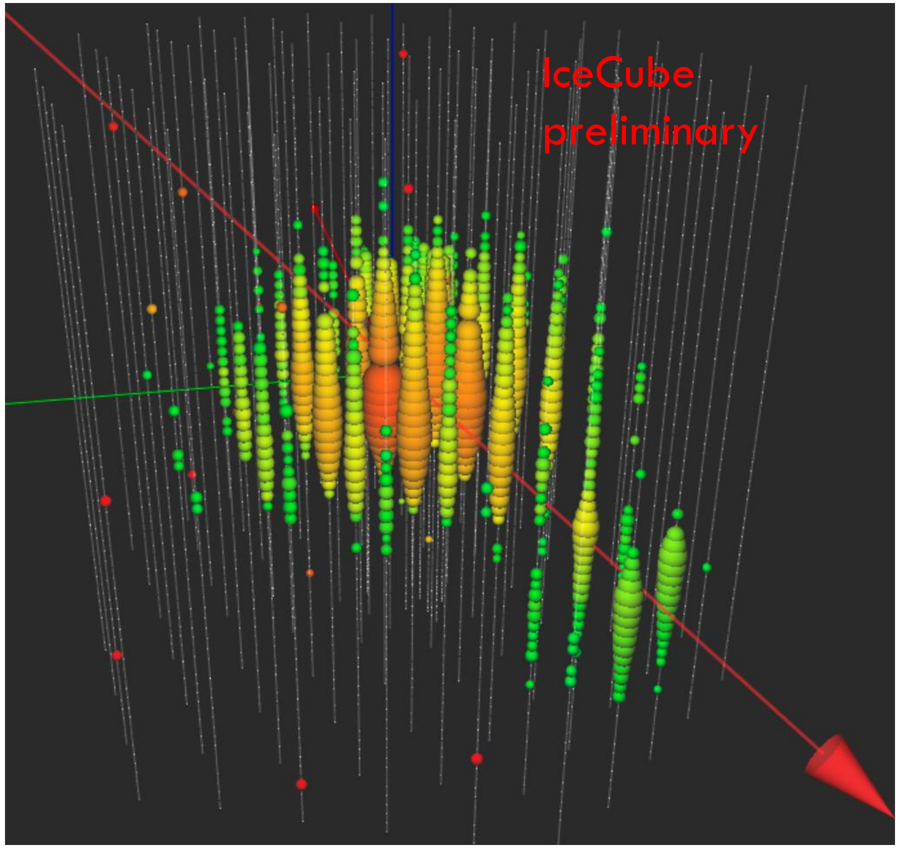
event by event alert

REAL-TIME DETECTION: SIGNAL SELECTIONS

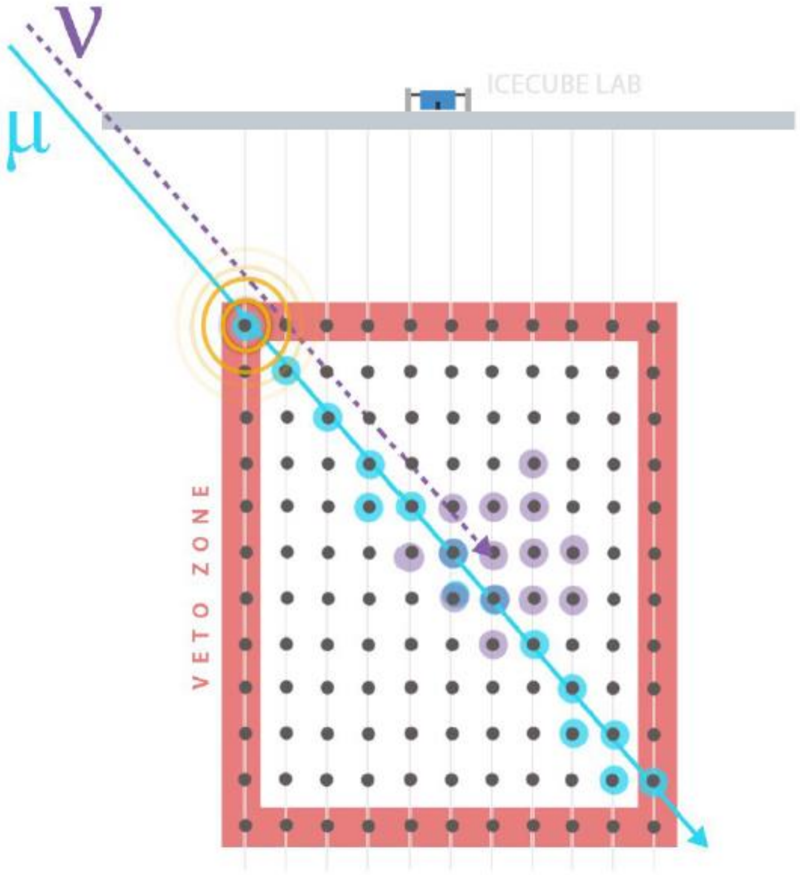
HESE: high-energy starting tracks

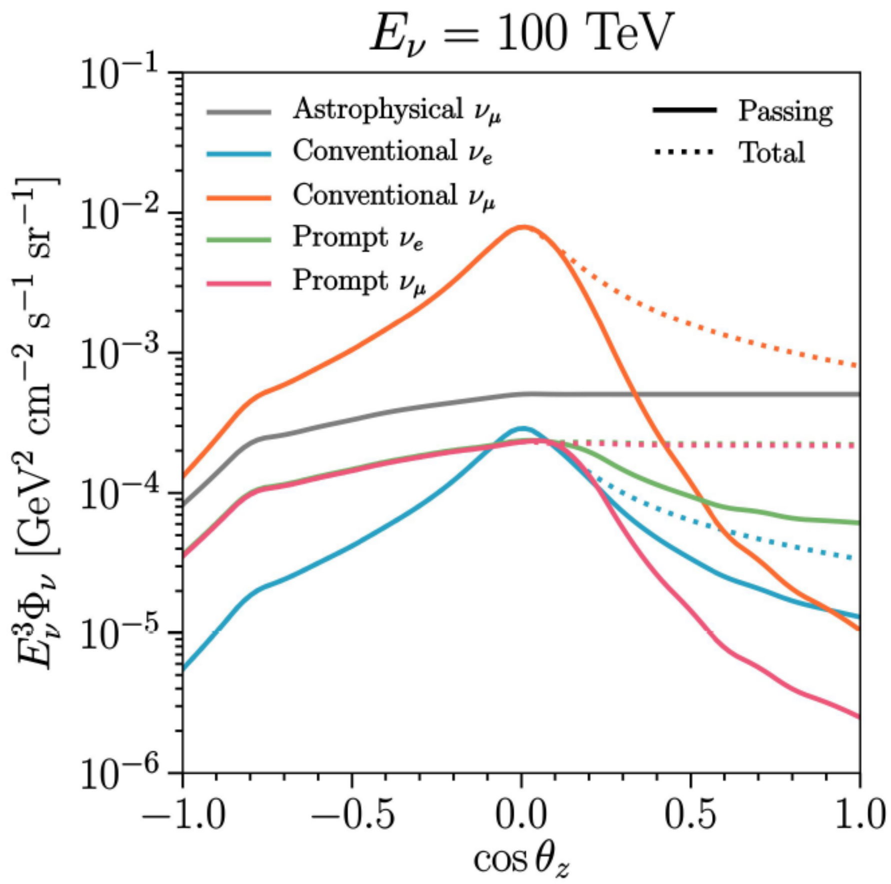


IC190331A
Neutrino energy ~10 PeV



SELF-VETO: INCREASE SIGNAL PURITY





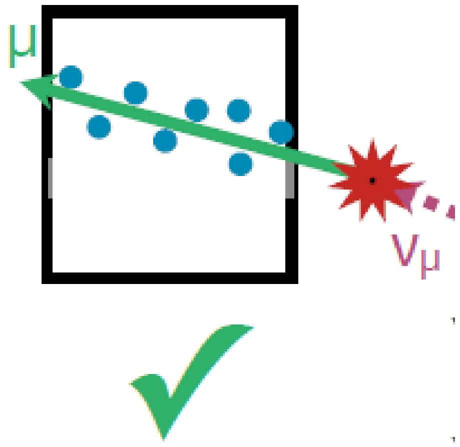
Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
Arguelles., Palomares-Ruiz, AS, Wille, Yuan
JCAP 1807 (2018) no.07, 047

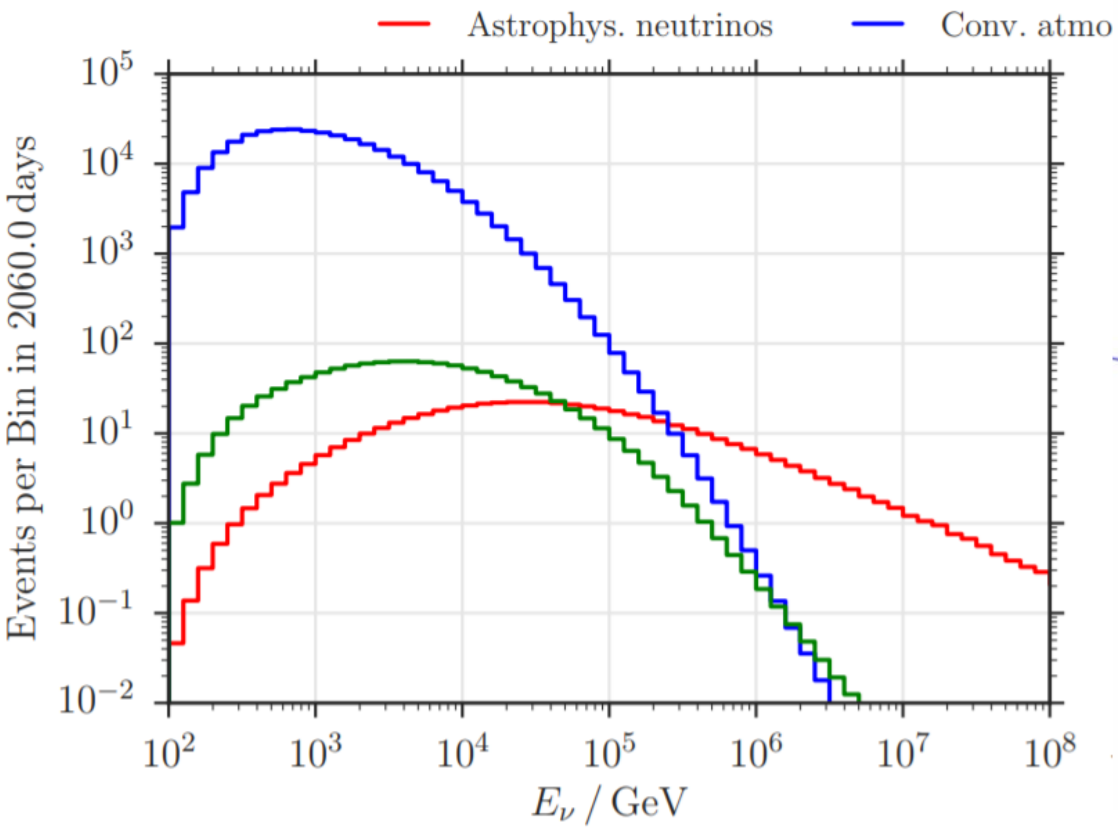
THROUGH-GOING MUONS

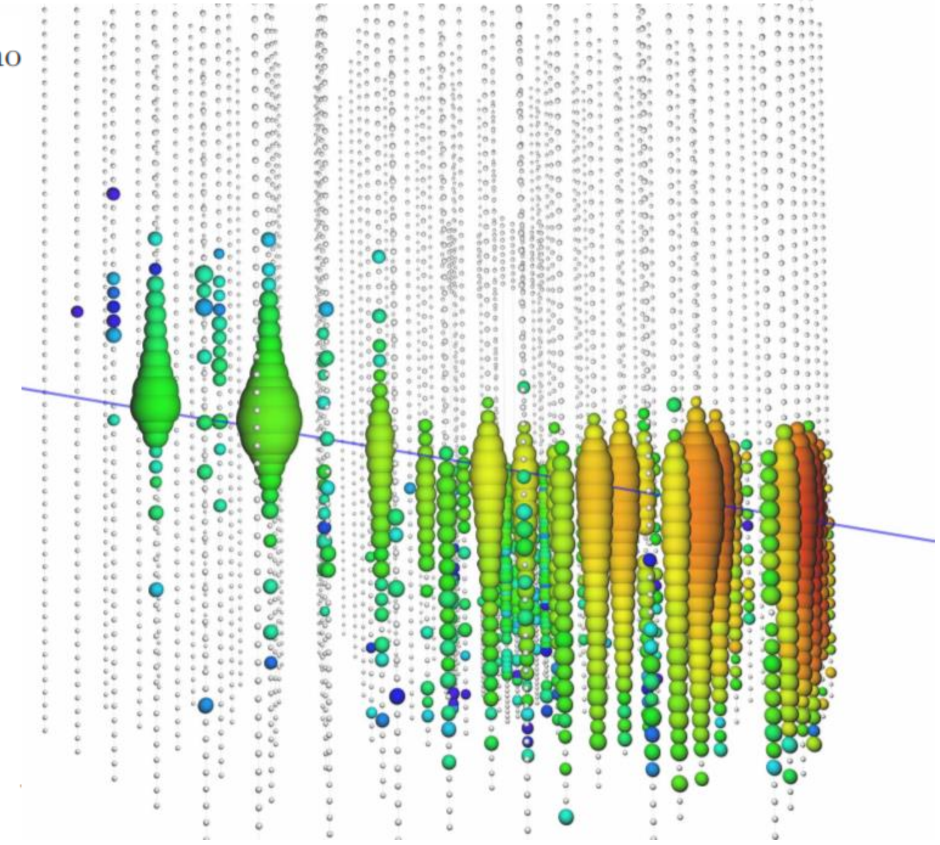
Sample	Events / year
Atmospheric muon	0.52
Conv. Atmos. ν_μ	1.20
Prompt Atmos. ν_μ	0.19
Total Background	1.91
Astro. ν_μ (E^{-2})	4.09
Astro. ν_μ ($E^{-2.49}$)	2.48

EHE: extreme high-energy

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



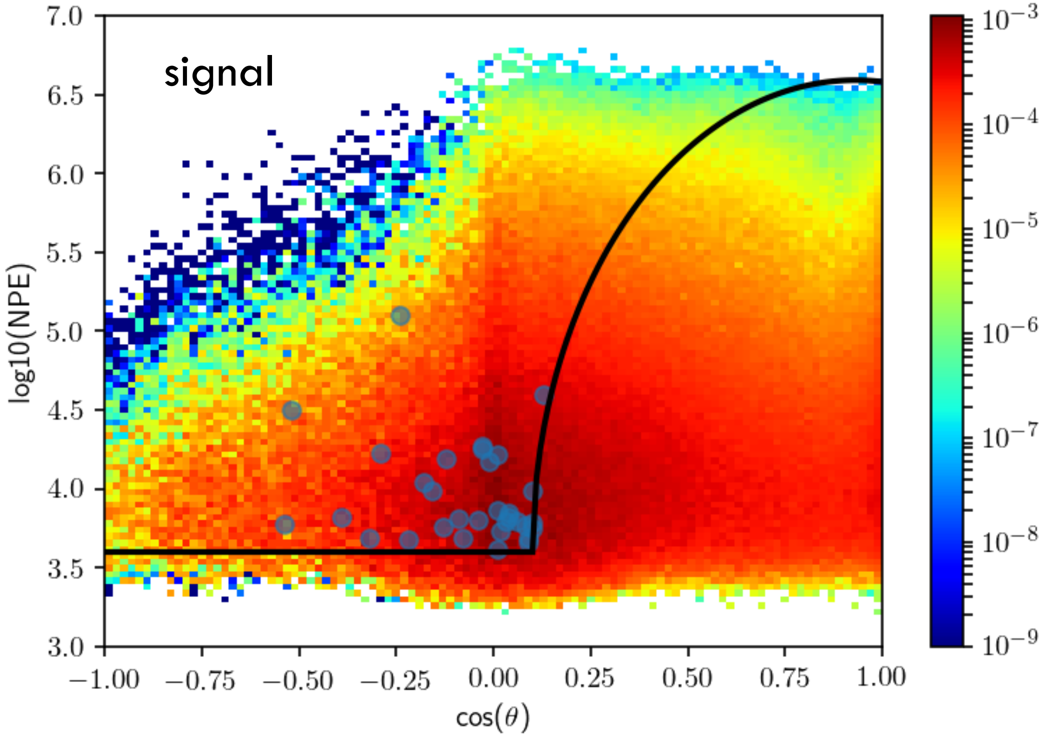


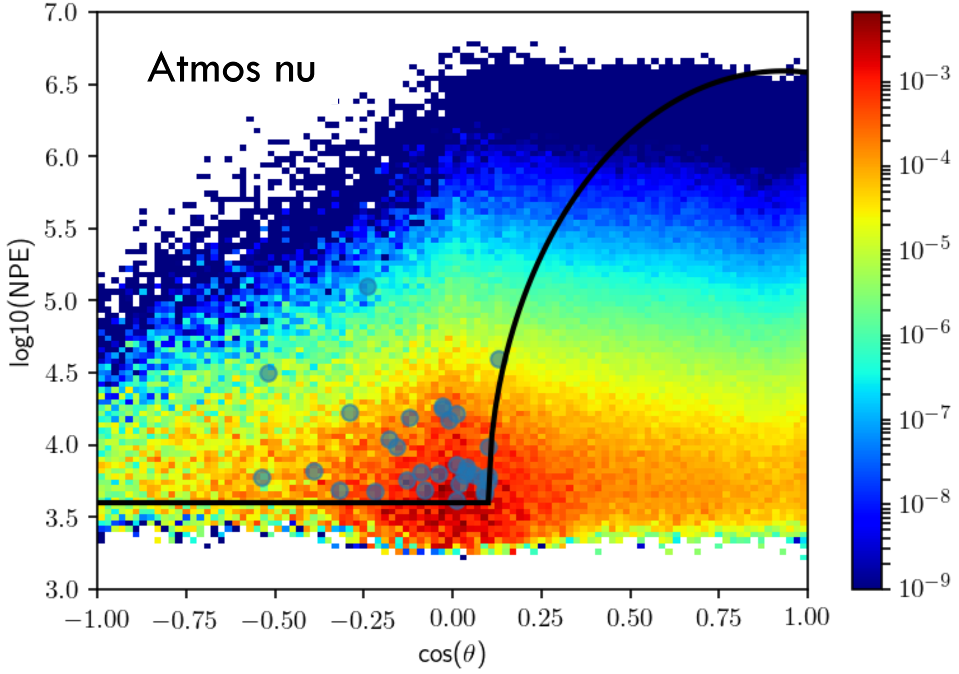


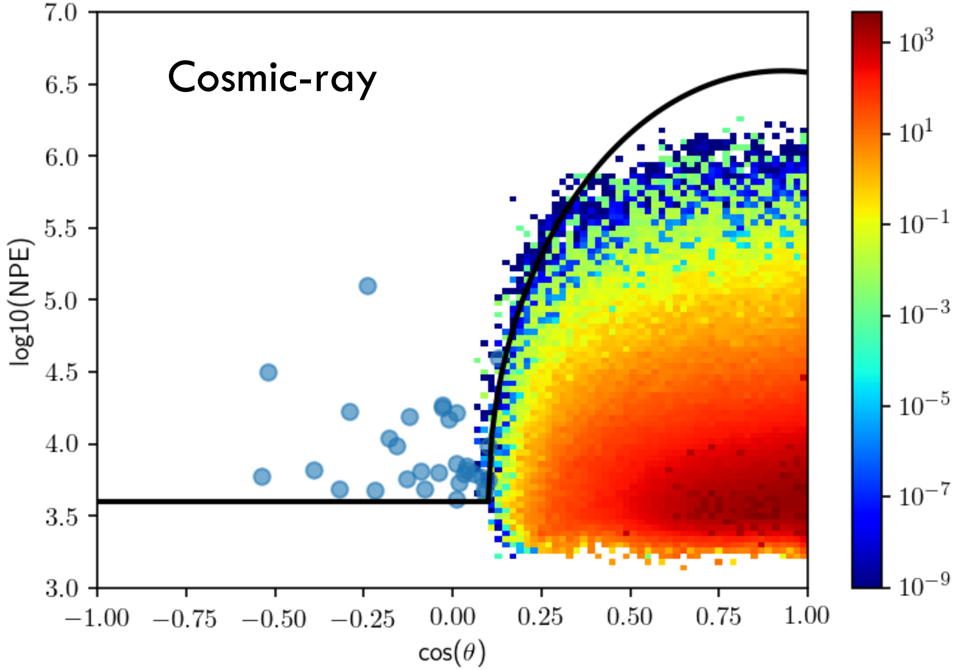
EHE SELECTION

Signal:background=1:1

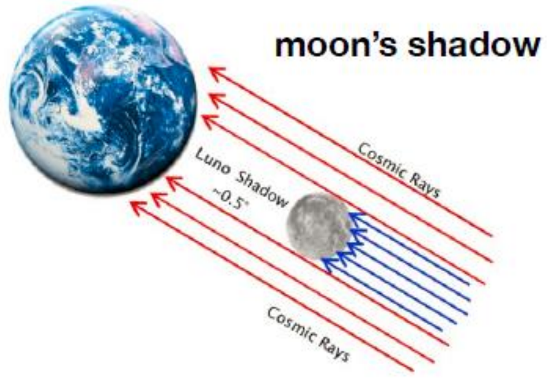
Optimised for PeVs



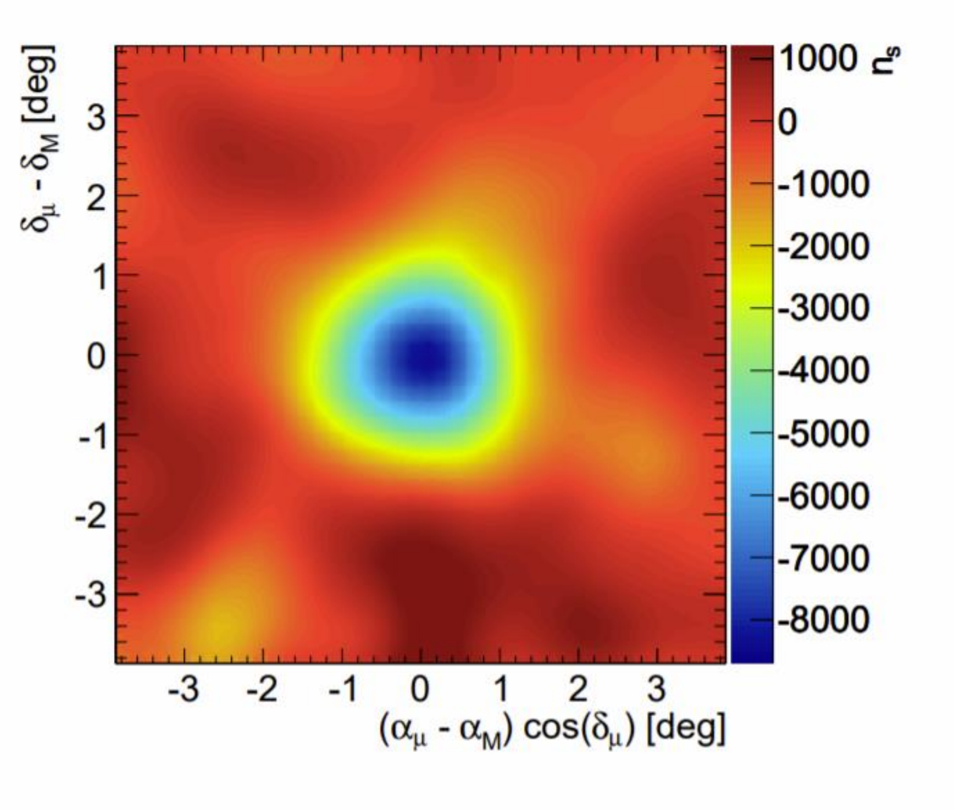


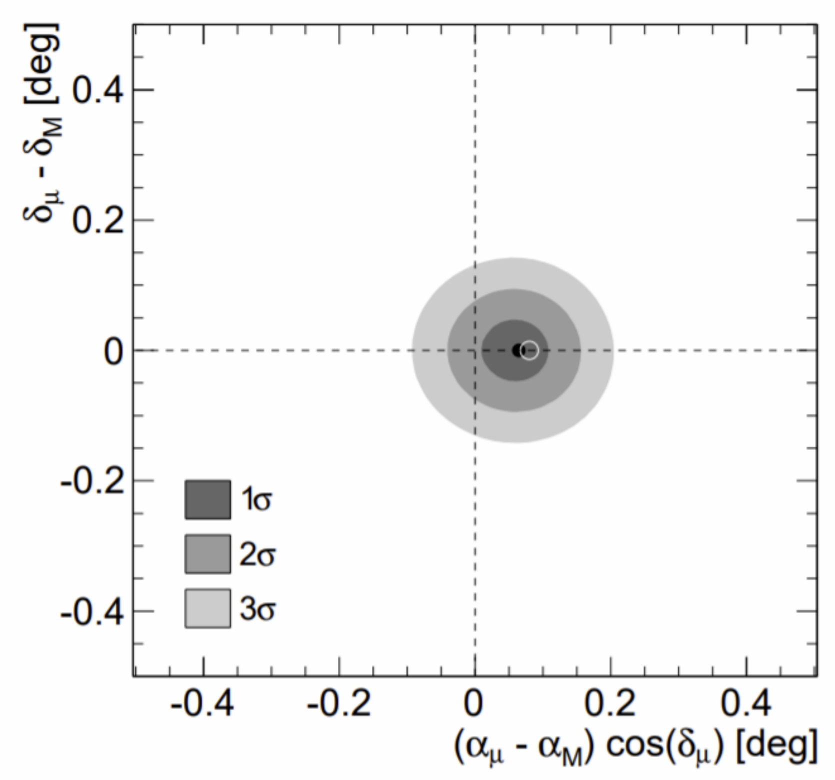


REAL-TIME DETECTION: DIRECTION RESOLUTION



TeV cosmic-ray muon tracks -> pointing accuracy to 0.2 deg





https://arxiv.org/pdf/1305.6811.pdf

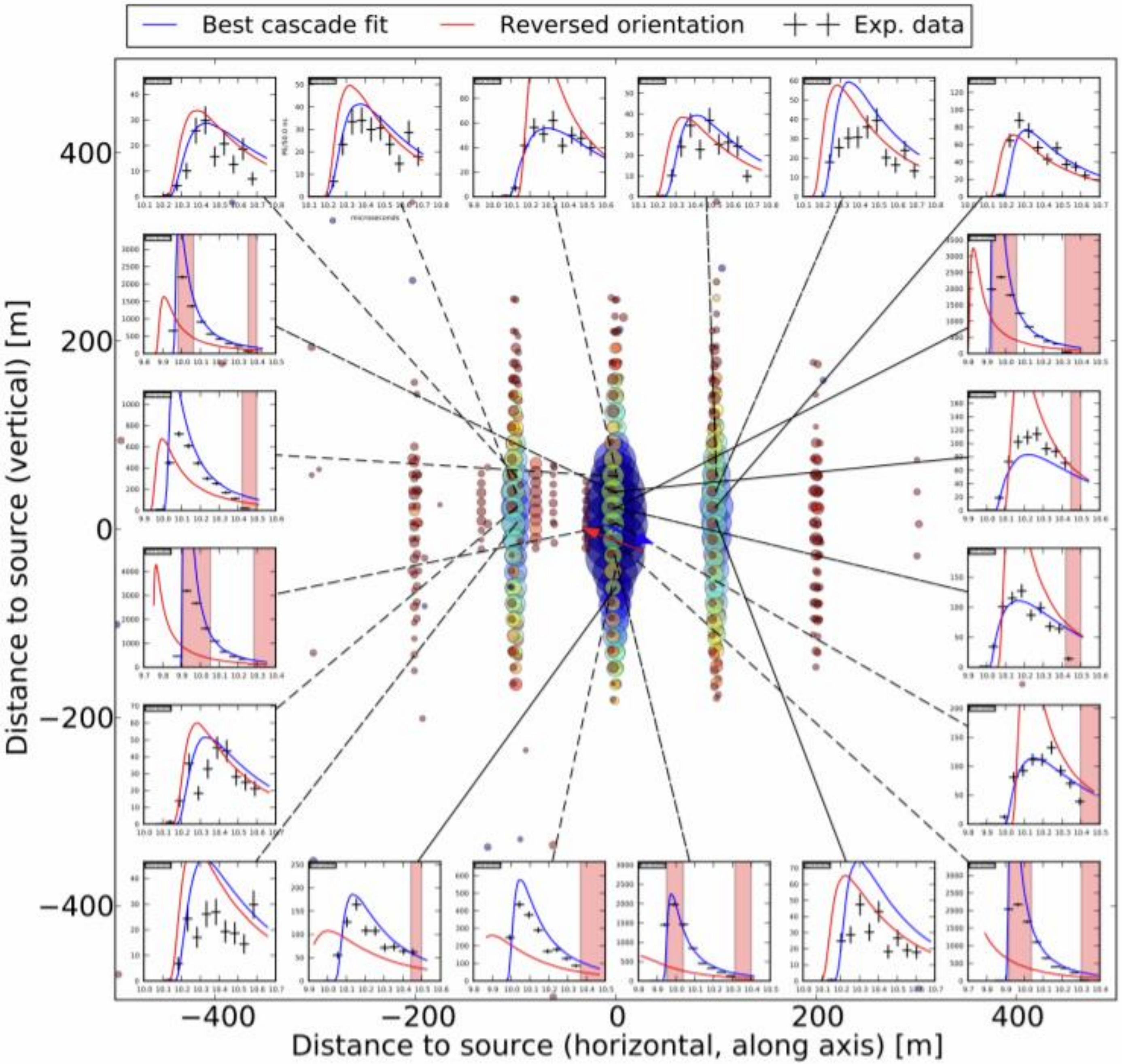
DIRECTION RECONSTRUCTION

1. GCN notice (initial alert): maximum likelihood fits using spline tables for ice.

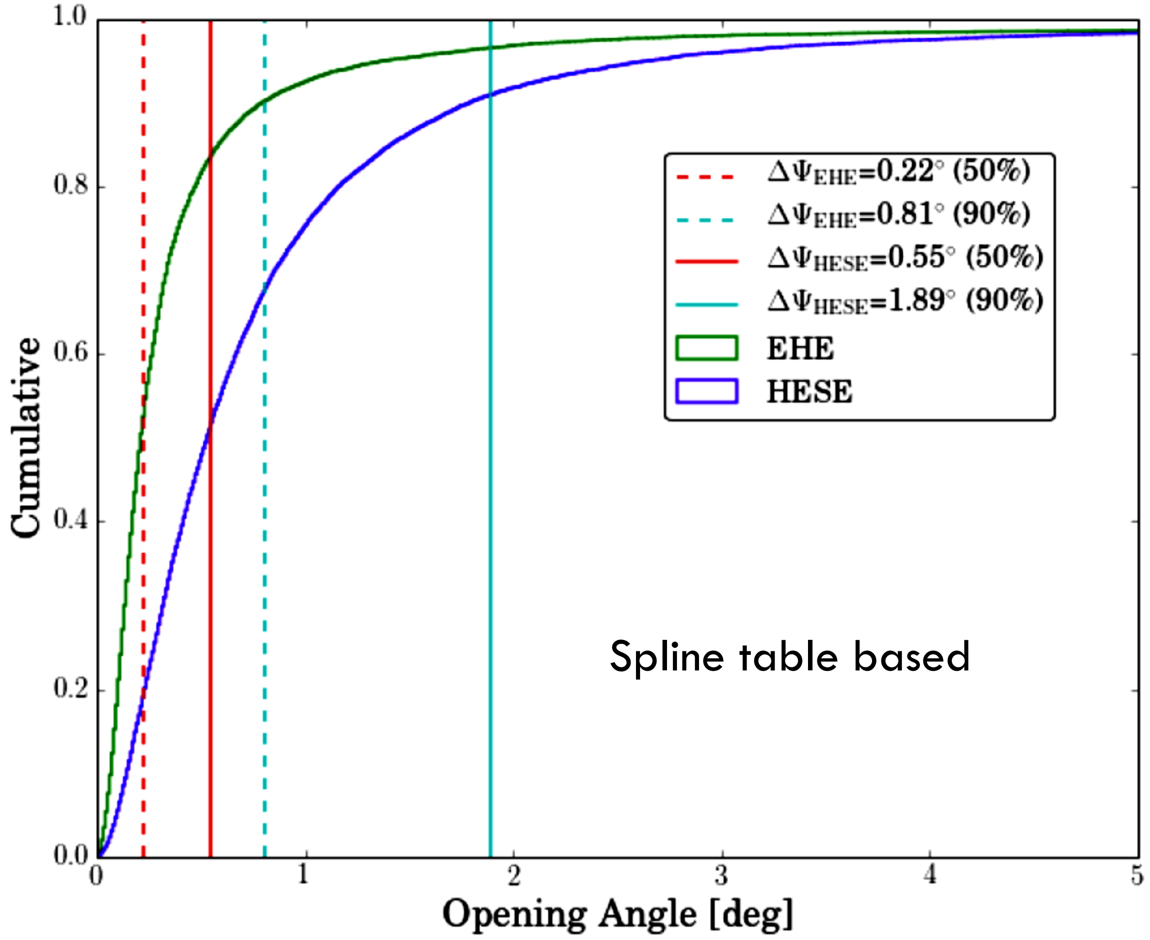
2. GCN circular: skymap scans. Useful to catch up local minimums and provide more reliable error contours. Takes a few hours or less.

3. direct-fit: GPU based resimulation. Bayesian and can include ice systematics without tables. Takes days.

Bert “Panopticon” plot

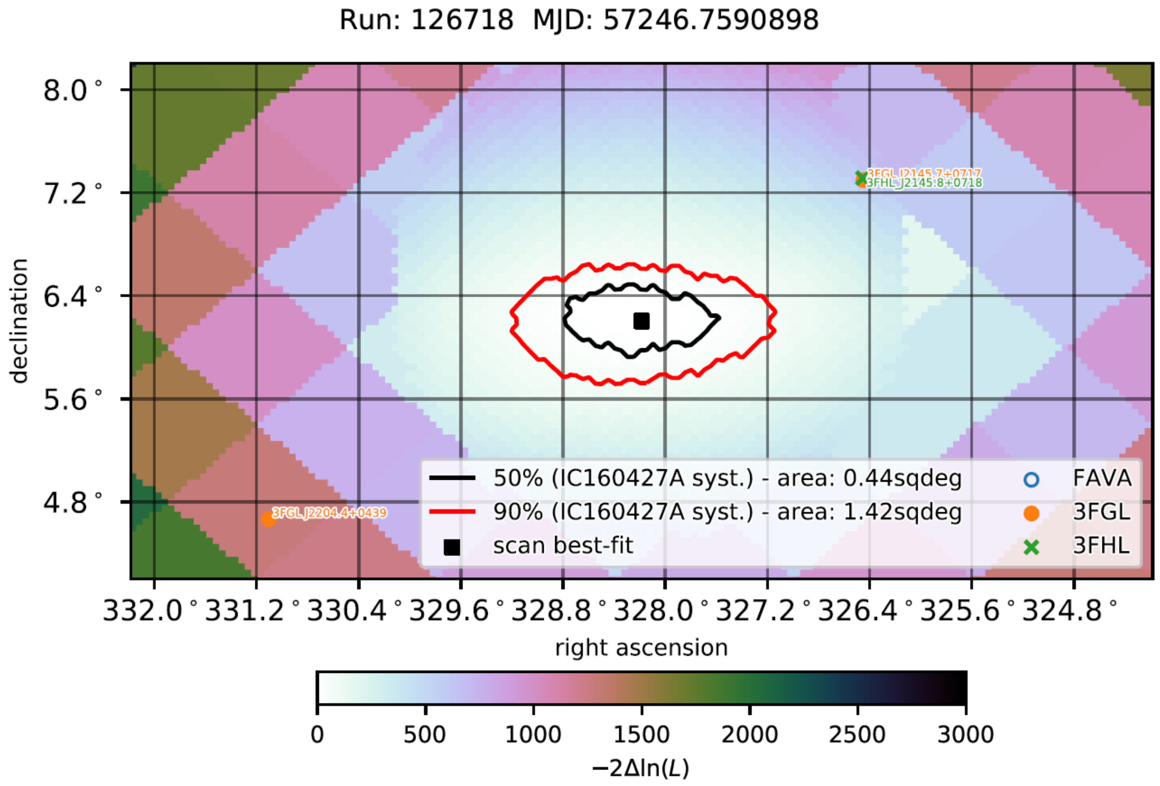


ANGULAR RESOLUTION



Sky map scan

A typical EHE alert (historical)

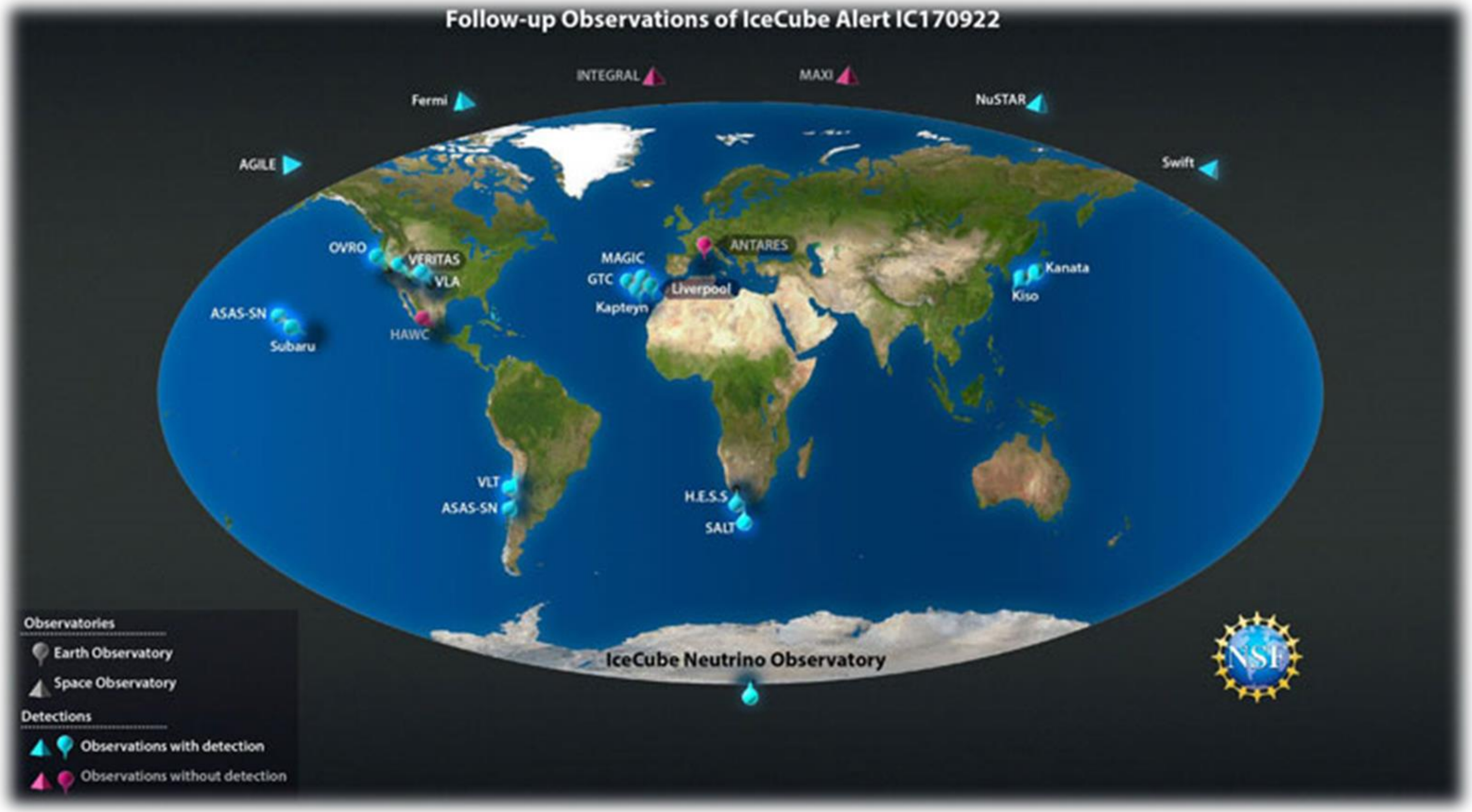


IC170922A

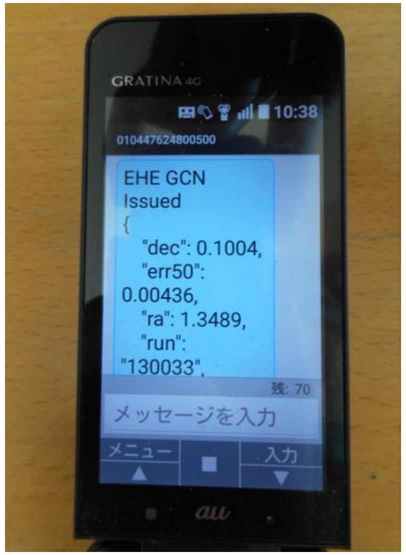
2017/09/22

EHE alert stream

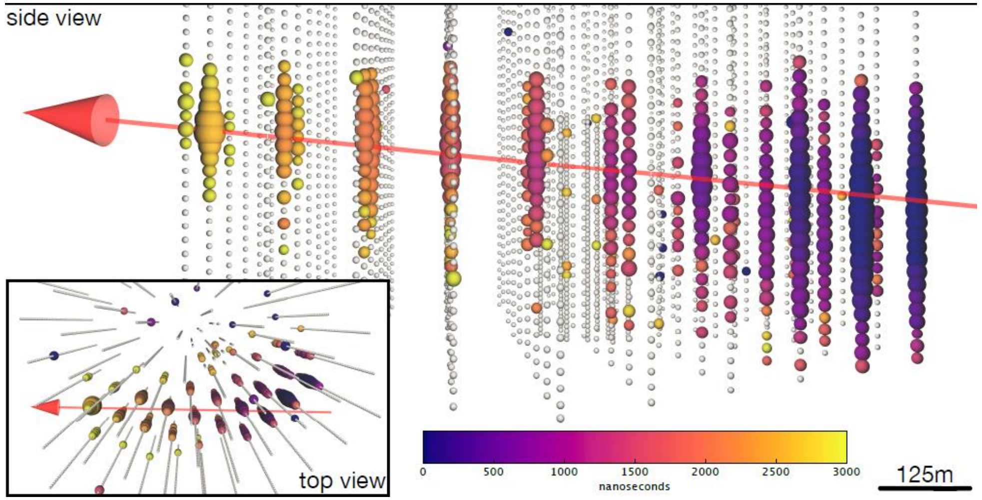
Japan time (JST)
2017. 09. 23. 5:55 am
土曜日

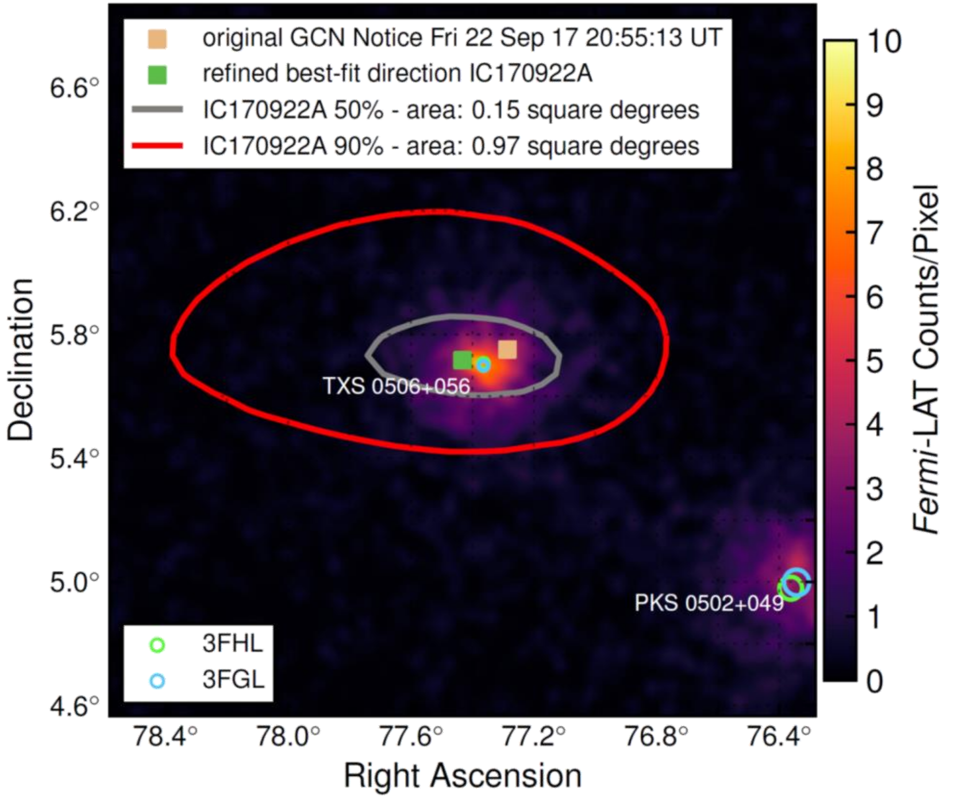


Alert sent in 43 seconds

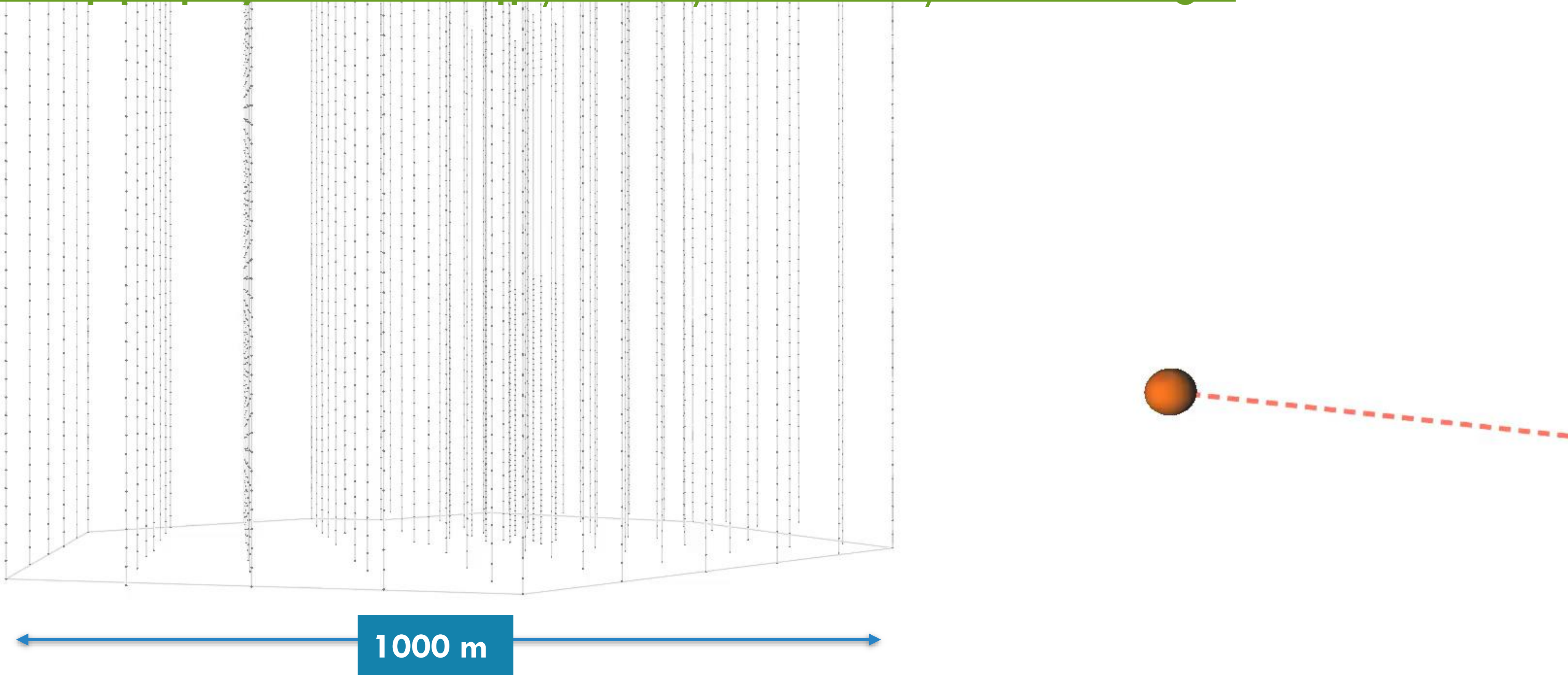


170922A





http://www.ppl.phys.chiba-u.jp/~lulu/170922/170922.gif

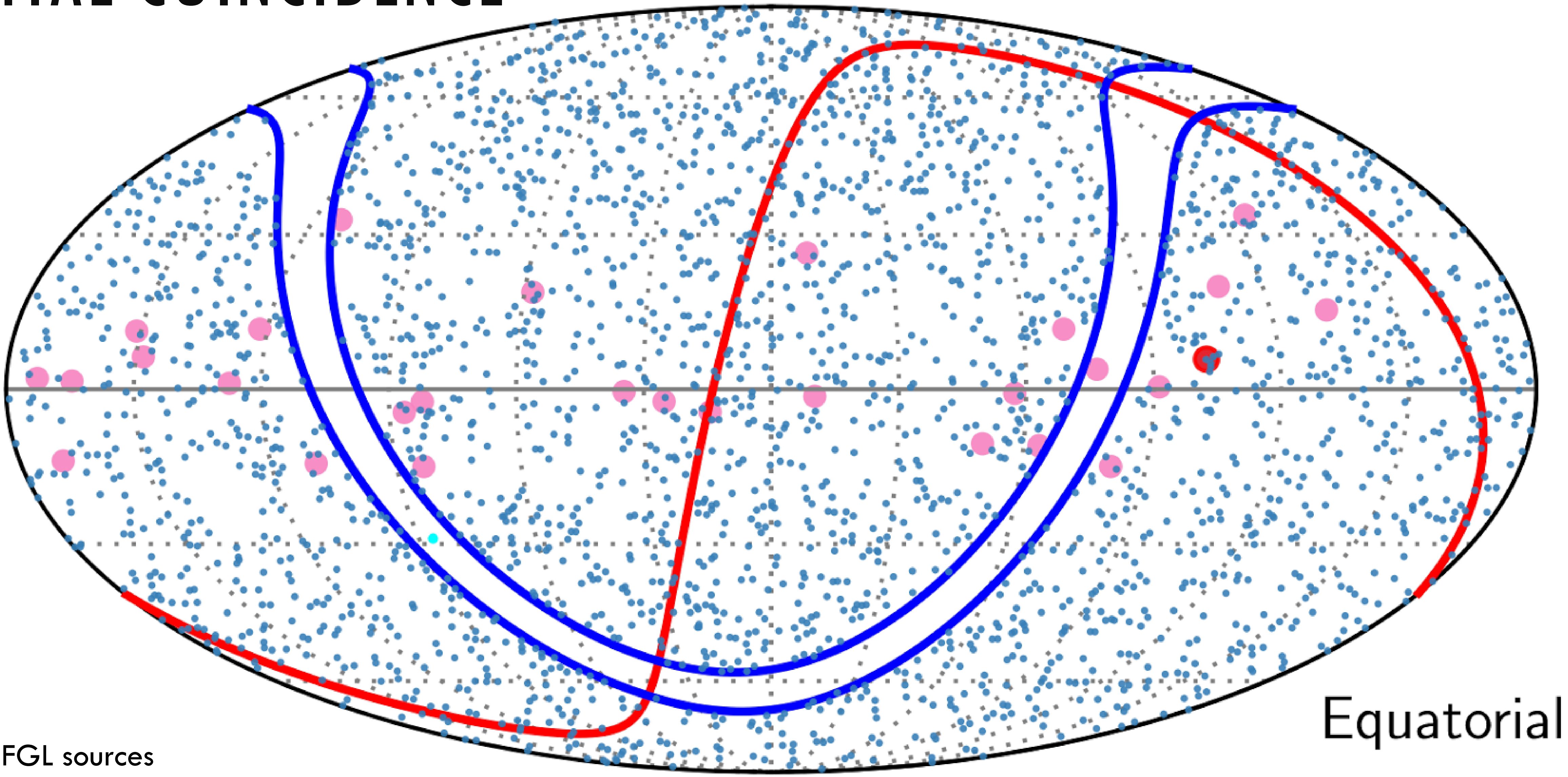


ニュートリノ反応から出る光

290 TeV energy originated from direction of TXS 0506+056

The movie is a simulation for photon path inside of ice

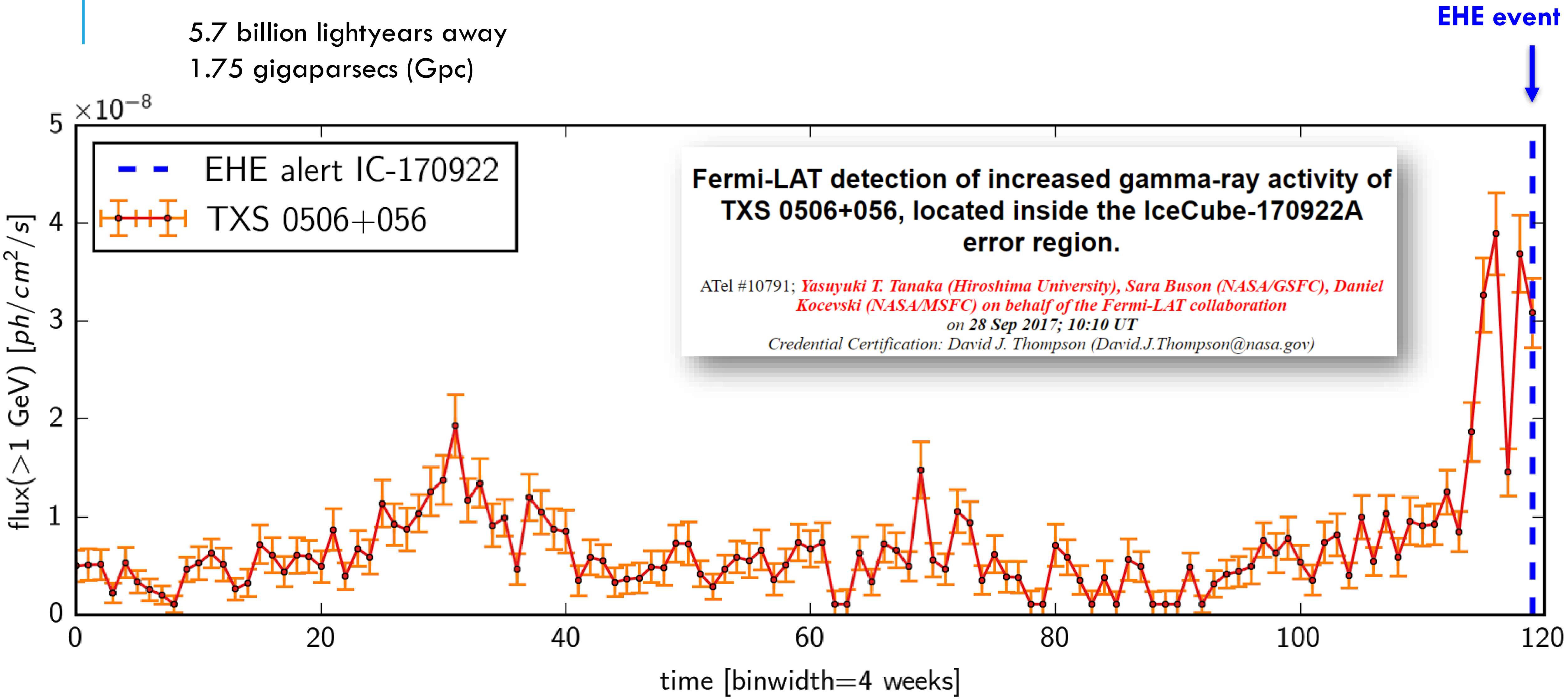
‘SPATIAL COINCIDENCE’



3 FGL sources
Historical EHE events

'TIME COINCIDENCE' : LIGHT CURVE OF TXS 0506+056

5.7 billion lightyears away
1.75 gigaparsecs (Gpc)



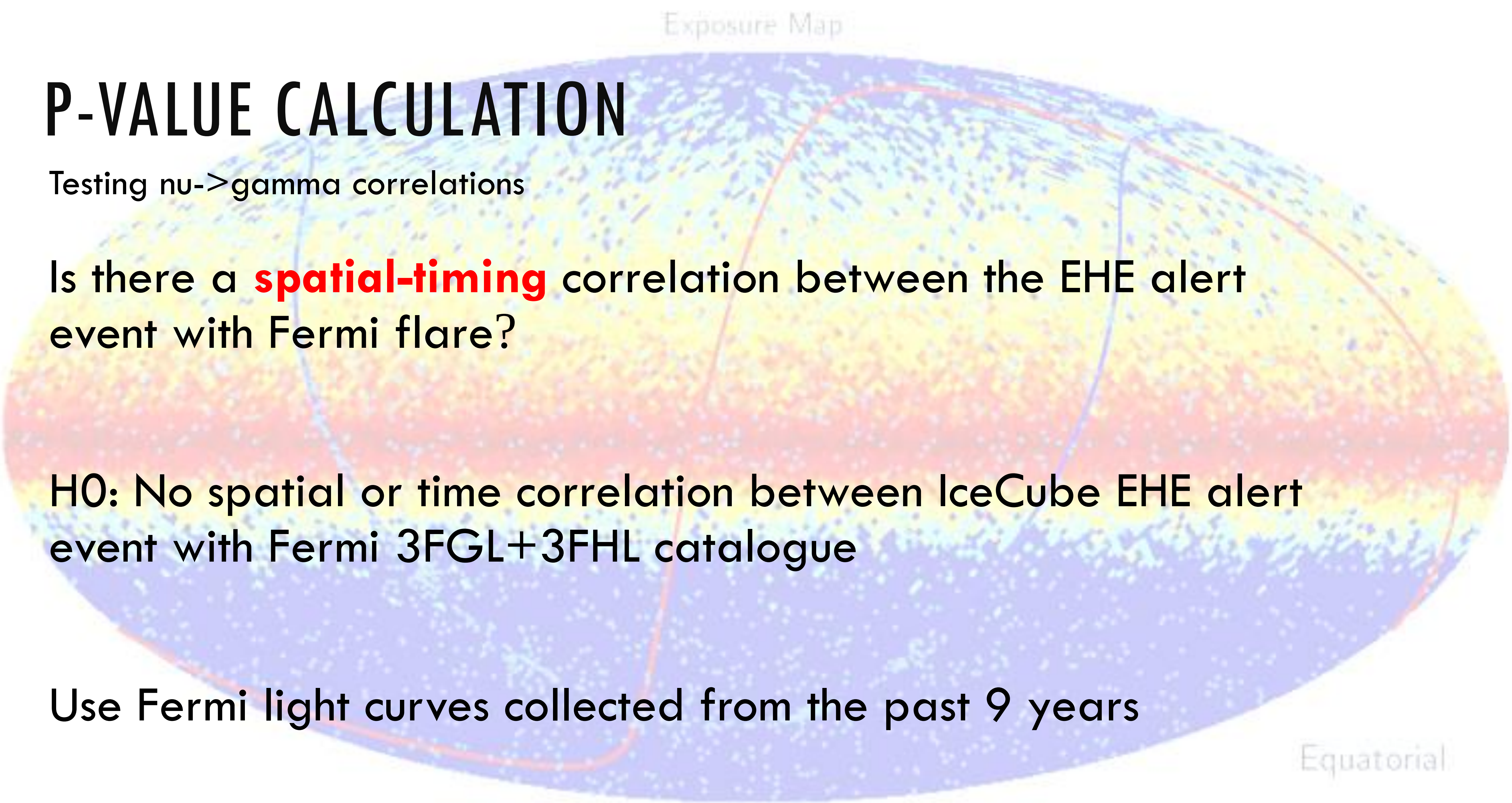
P-VALUE CALCULATION

Testing nu->gamma correlations

Is there a **spatial-timing** correlation between the EHE alert event with Fermi flare?

H0: No spatial or time correlation between IceCube EHE alert event with Fermi 3FGL+3FHL catalogue

Use Fermi light curves collected from the past 9 years



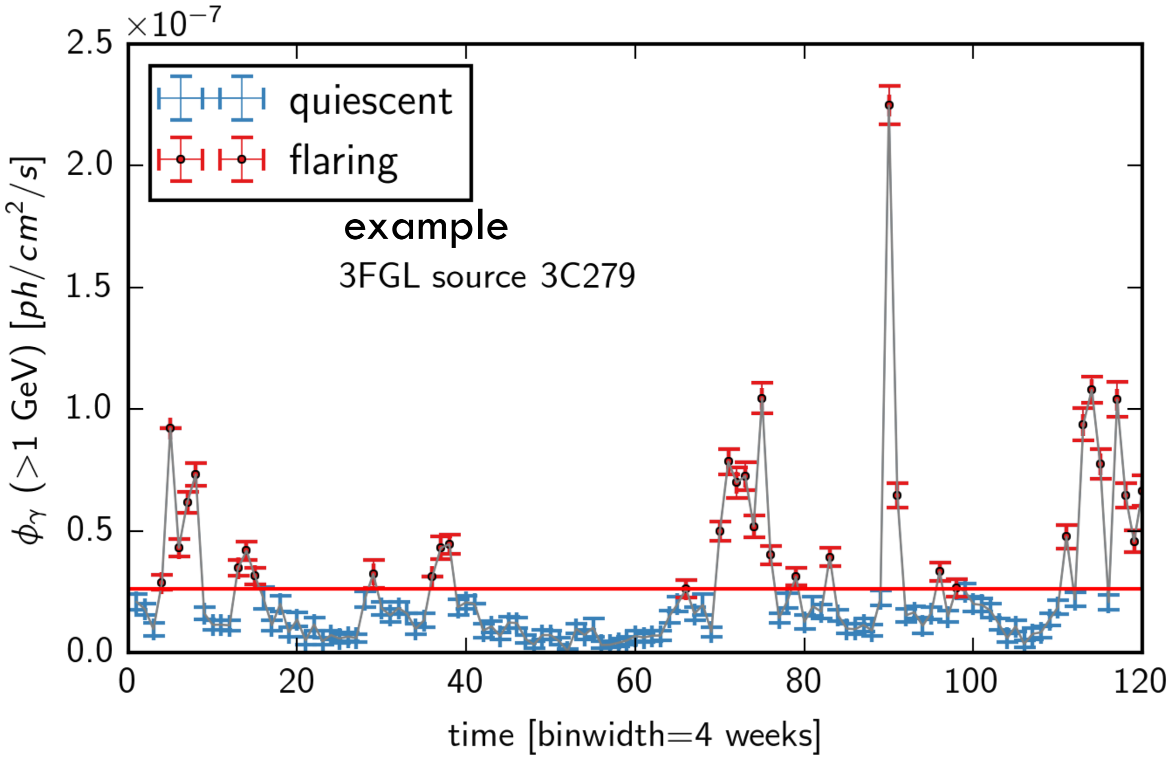
P-VALUE CALCULATION

How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

$$\mathcal{L}_{\text{flux}} \propto I_\gamma(t) / \langle I_\gamma \rangle$$

Hypo 1: ν detection scales to ***variations*** in γ flux of the source, regardless of γ luminosity



P-VALUE CALCULATION

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$$\mathcal{L}_{\text{flux}} \propto I_\gamma(t) / \langle I_\gamma \rangle$$

Hypo 1: ν detection scales to ***variations*** in γ flux of the source, regardless of γ luminosity

$$\mathcal{L}_{\text{flux}} \propto \frac{\phi_E(t)}{\sum_s^{N_s} \sum_i^{N_t} \phi_E(t_i)}$$

Hypo 2: ν detection scales linearly to γ energy flux. Brighter γ source more likely

P-VALUE CALCULATION

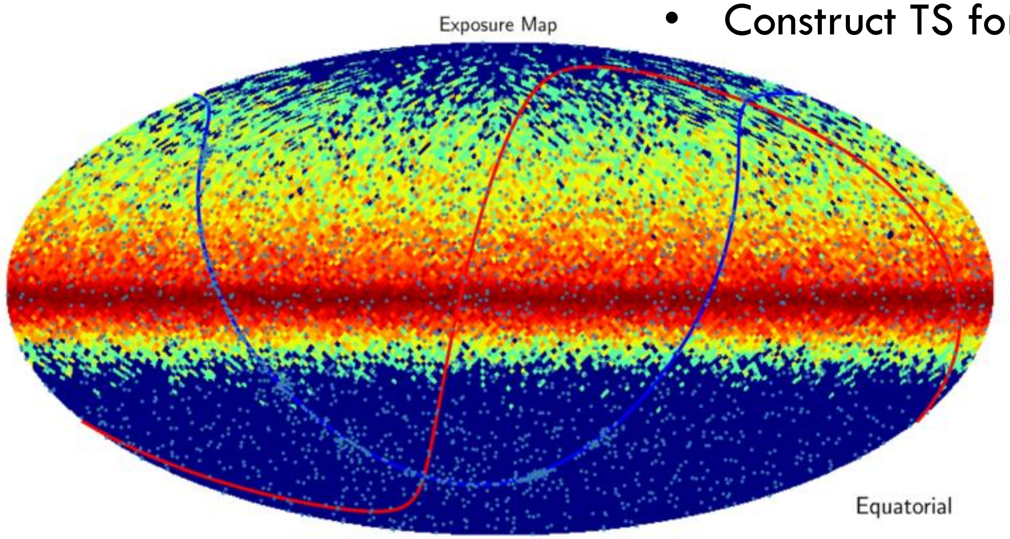
How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

Scales with variations of γ flux of the source

Or

Scales with γ energy flux, the brightness of the source



Pseudo experiments

- Randomly sample time t (flat pdf)
- Randomly sample DEC according to event selection pdf
- Randomly sample RA
- Construct TS for H0

WHAT WE LEARNED FROM THE TXS EXERCISE

1. Need of having a priori p-value calculations
2. More alerts are needed → New alerts (almost online)

The 'high-energy neutrino' alert from IceCube:

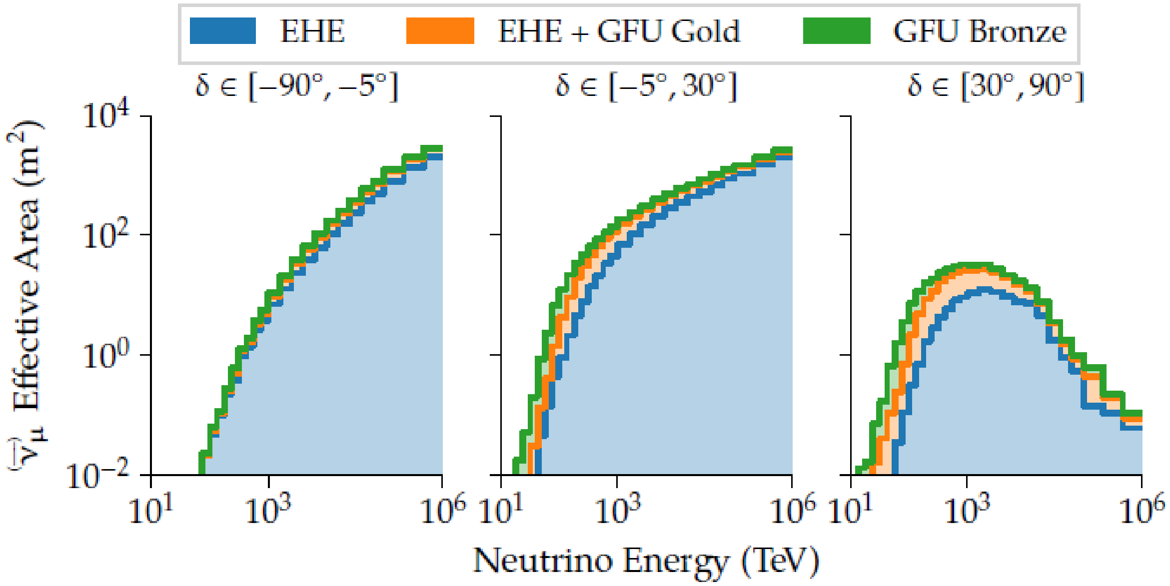
EHE selection is based on charge -> ice property not uniform across all depth

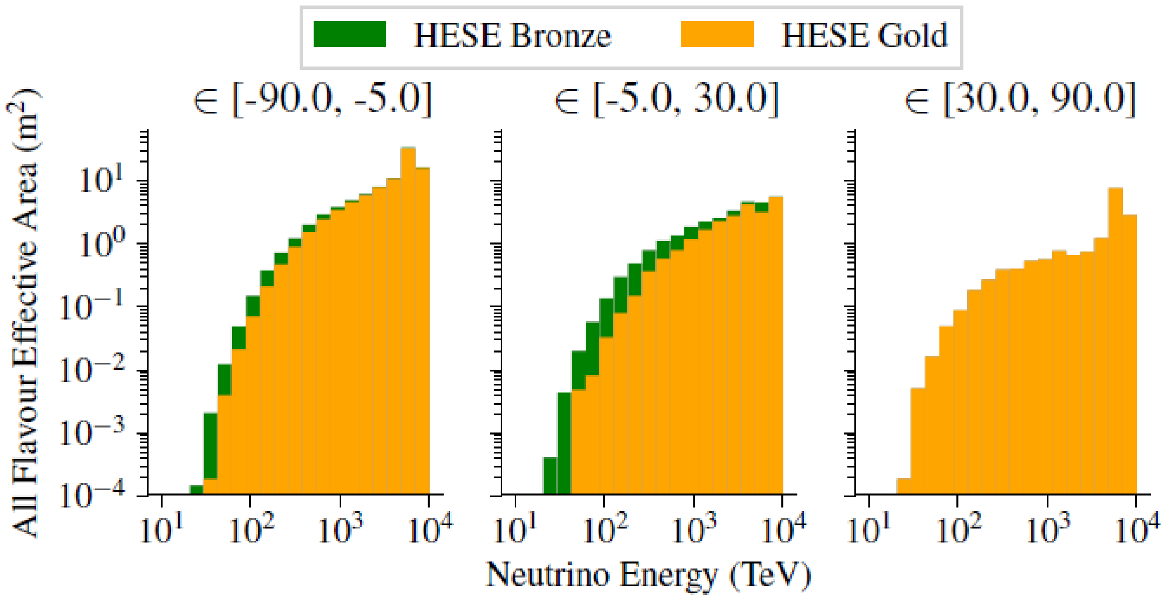
TYPE	POS_ERROR [radius]	TIME SINCE TRIGGER	COMMENTS	
AMON_ICECUBE_HESE	2-9deg	0.5-3 min	Direction of a single hi-energy neutrino	ACTIVE
AMON_ICECUBE_EHE	0.2-0.8deg	0.5-3 min	Direction of a single extremely hi-energy neutrino	ACTIVE
AMON_ICECUBE_COINC	1-3deg	0.5-3 min	Temporal/spatial coinc between IceCube neutrinos	NOT YET PUBLIC
ICECUBE_TRACK_GOLD	0.2-0.75deg	0.5-1 min	Hi-energy single neutrinos directions	SOON TO BE PUBLIC
ICECUBE_TRACK_BRONZE	0.2-0.75deg	0.5-1 min	Hi-energy single neutrinos directions	SOON TO BE PUBLIC
HAWC_BURST_MONITOR	0.4-0.8deg	0.5-1 min	HAWC alert of GRB-like events	SOON TO BE PUBLIC

EVENT RATES

X2 EHE in near future

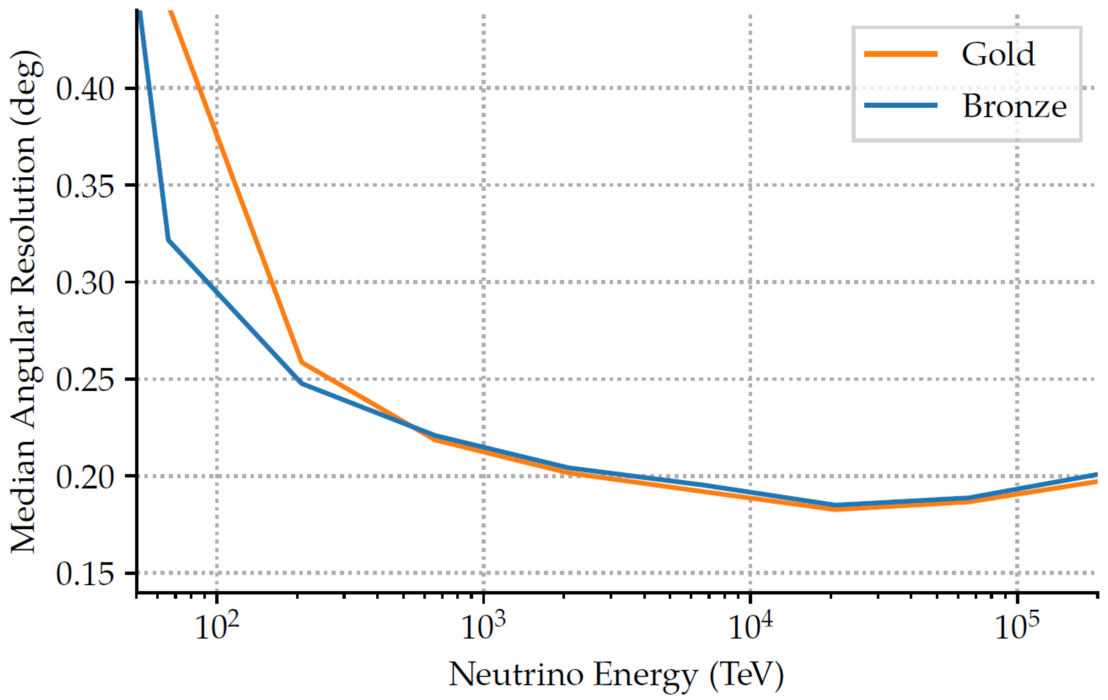
	Gold events	Bronze Events
Signal ($E^{-2.19}$)	6.6 (Total) 5.1 (GFU) 0.5 (HESE) 2.1 (EHE)	8.4 (Total) 7.6 (GFU) 0.8 (HESE)
Atmospheric Backgrounds	6.1 (Total) 4.7 (GFU) 0.4 (HESE) 1.9 (EHE)	19.8 (Total) 18.5 (GFU) 1.3 (HESE)
Observed historical rate	9.9 (Total) 7.8 (GFU) 1.1 (HESE) 4.3 (EHE)	28.2 (Total) 26.2 (GFU) 2.0 (HESE)



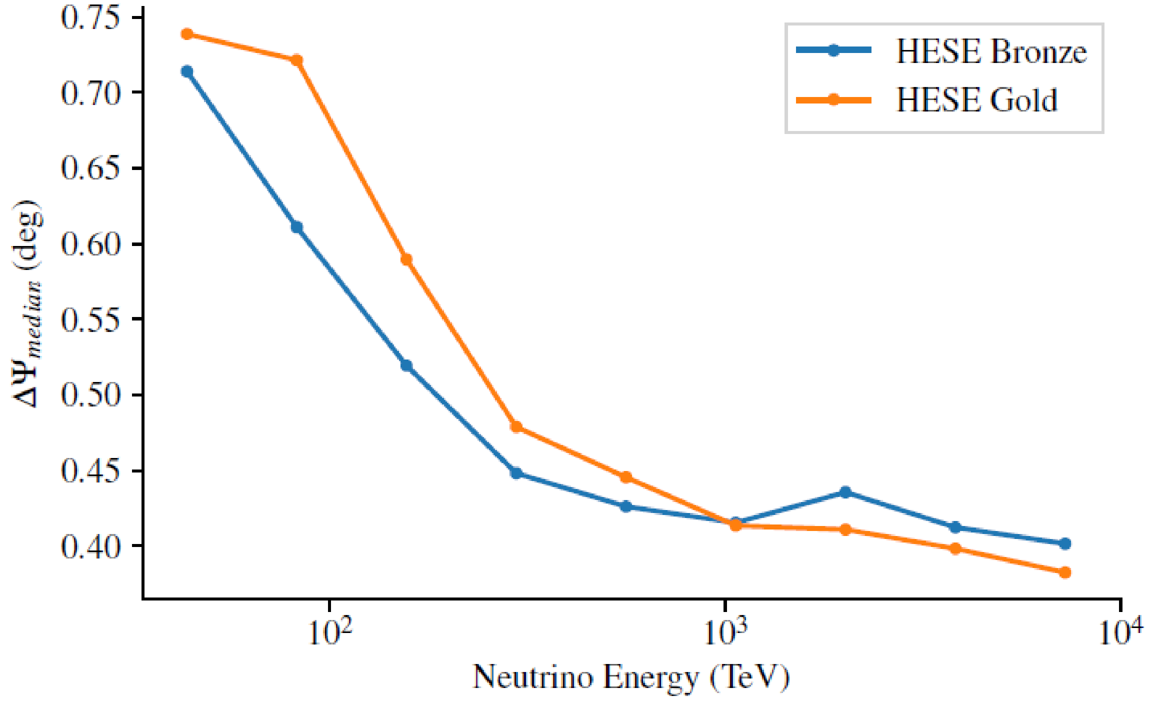


ANGULAR RESOLUTION OF GOLD/BRONZE

GFU/EHE: through-going tracks



HESE: removed cascade/short-tracks



An example gold alert GCN Notice is listed below:

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Tue 16 Apr 19 15:22:51 UT
NOTICE_TYPE:      GOLD ICECUBE ASTROPHYSICAL
RUN_NUM:          132446
EVENT_NUM:        59759967
SRC_RA:           239.2334d {+15h 56m 56s} (J2000),
                  241.7055d {+16h 06m 49s} (current),
                  233.3180d {+15h 33m 16s} (1950)
SRC_DEC:          -87.5694d {-87d 34' 09"} (J2000),
                  -87.6224d {-87d 37' 20"} (current),
                  -87.4141d {-87d 24' 50"} (1950)
SRC_ERROR90:      36.55 [arcmin radius, stat, 90% containment]
SRC_ERROR50:      14.24 [arcmin radius, stat, 50% containment]
DISCOVERY_DATE:   18589 TJD;   106 DOY;   19/04/16 (yy/mm/dd)
DISCOVERY_TIME:   55341 SOD {15:22:21.08} UT
REVISION:         0
ENERGY:           1.8867e+03 [TeV]
SIGNALNESS:       0.5643 [dn]
FAR:              2.5605 [yr^-1]
STREAM:           24
SUN_POSTN:         24.45d {+01h 37m 47s}  +10.17d {+10d 10' 11"}
SUN_DIST:         102.06 [deg]   Sun_angle= 9.5 [hr] (West of Sun)
MOON_POSTN:       170.58d {+11h 22m 19s}   +8.65d {+08d 39' 06"}
MOON_DIST:         97.88 [deg]
GAL_COORDS:       304.88,-25.44 [deg] galactic lon,lat of the event
ECL_COORDS:       267.12,-64.44 [deg] ecliptic lon,lat of the event
COMMENTS:         IceCube Gold Event.
```

An example bronze alert GCN Notice is listed below:

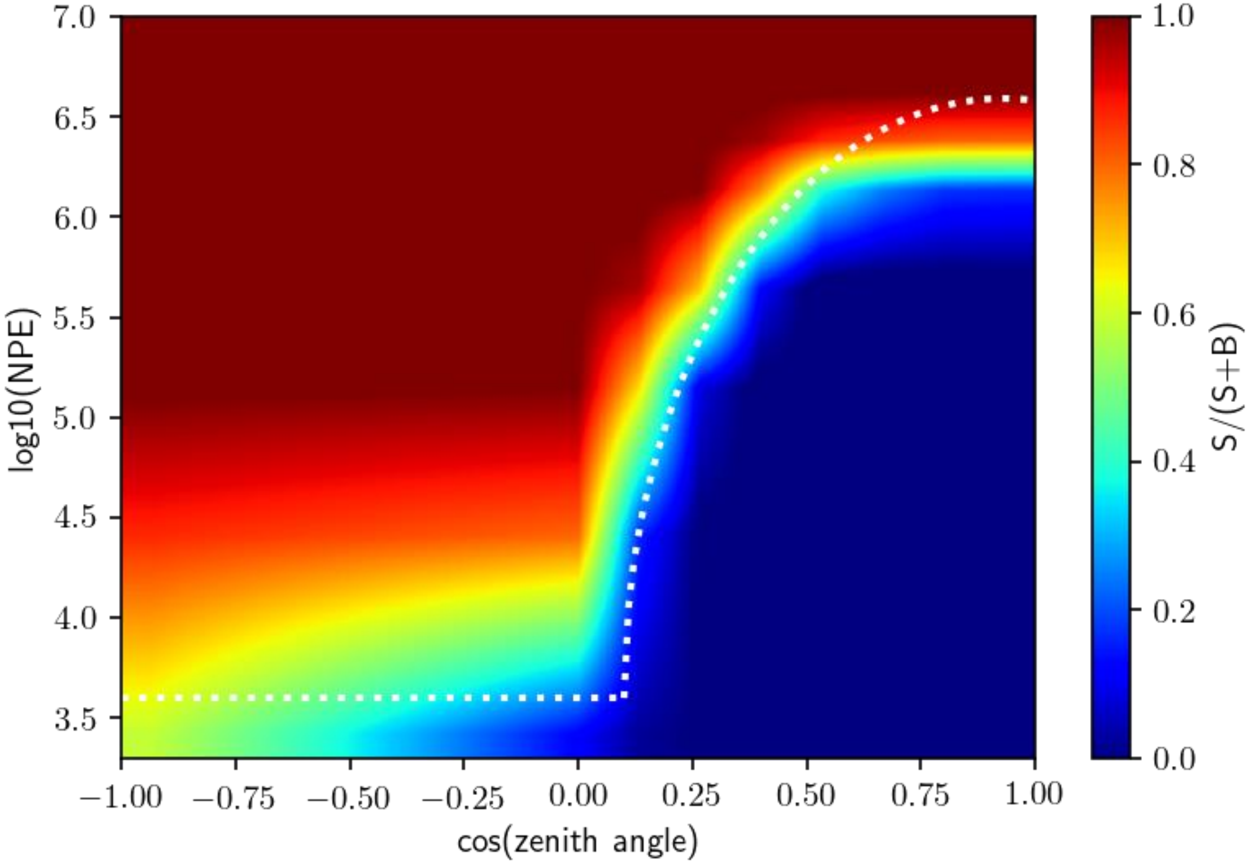
What to look out for:

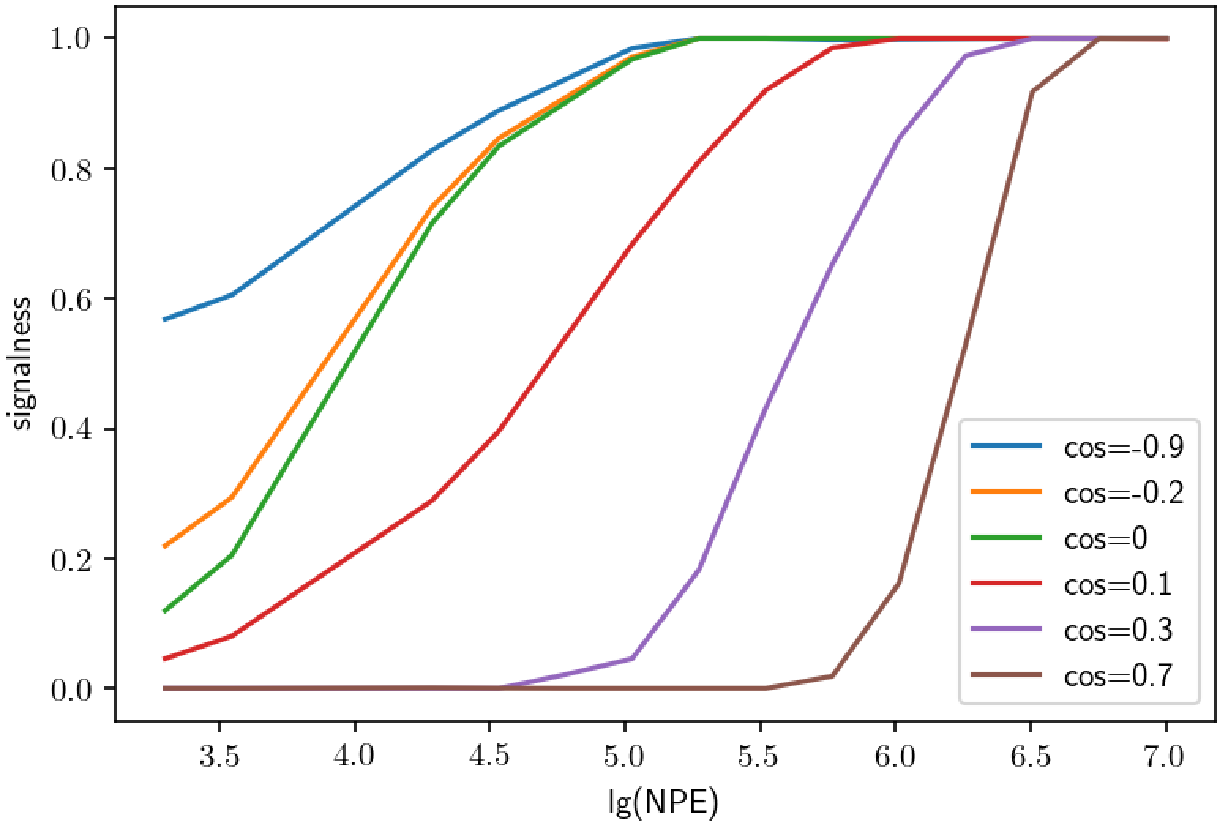
1. Energy (most-likely neutrino energy, only median, no uncertainty)
2. Signalness (signal/tot)
3. FAR (false alarm rate)

SIGNALNESS

Gold: >=0.5
Bronze: 0.3-0.5

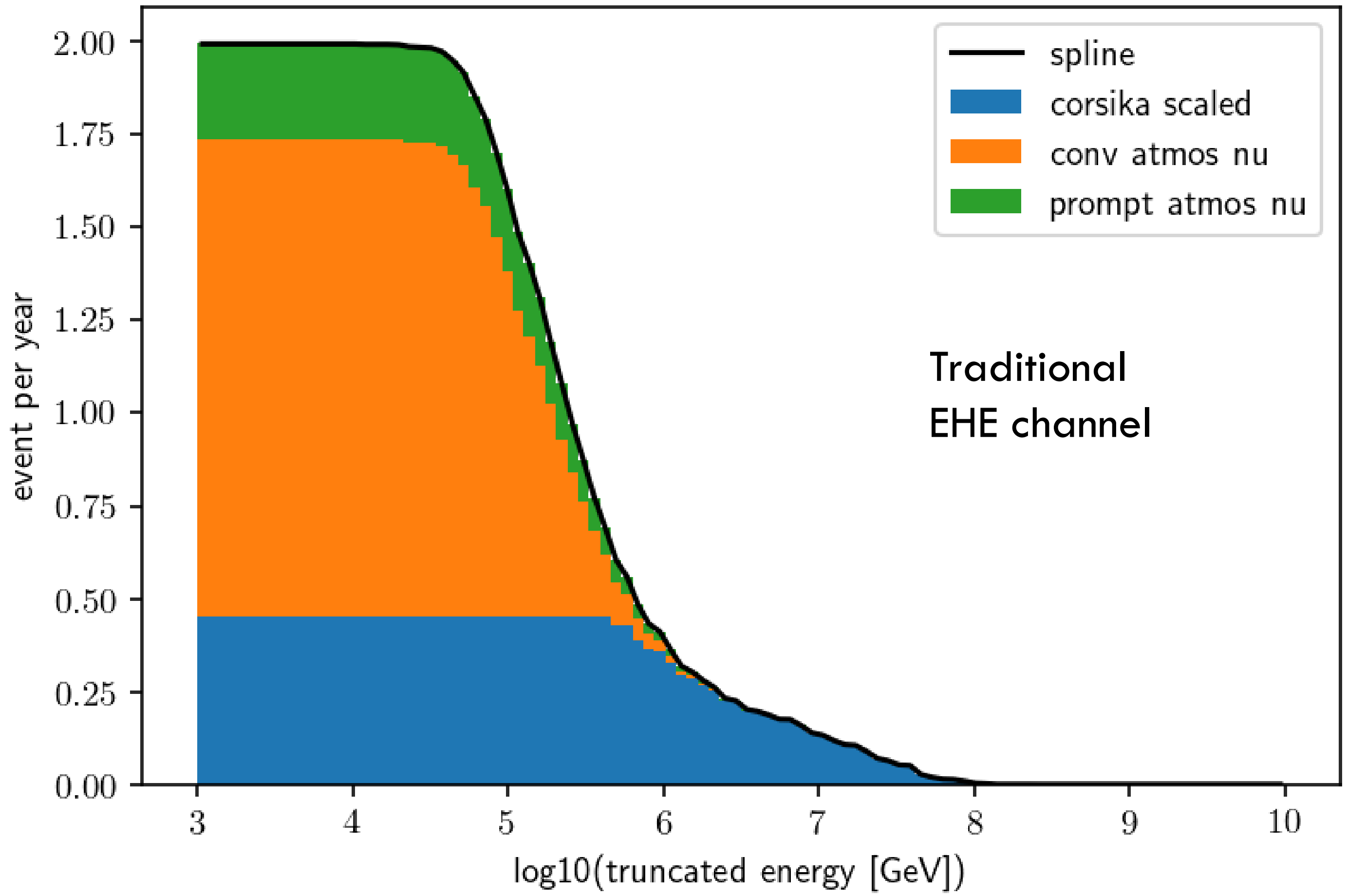
$$\text{Signalness} = \frac{N_{signal}}{N_{signal} + N_{background}}$$





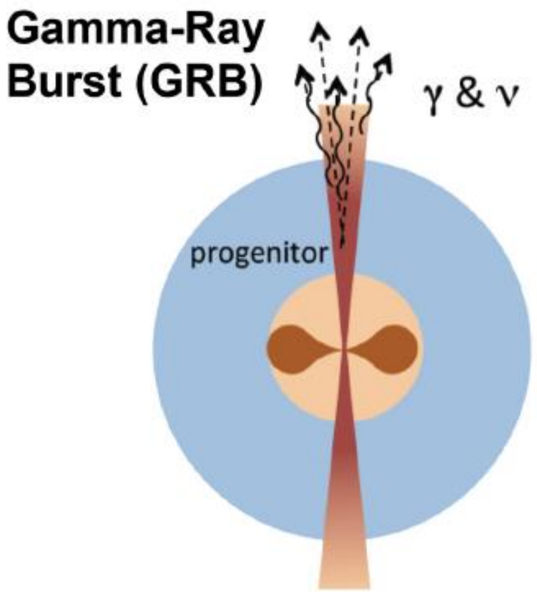
FAR (FALSE ALARM RATE)

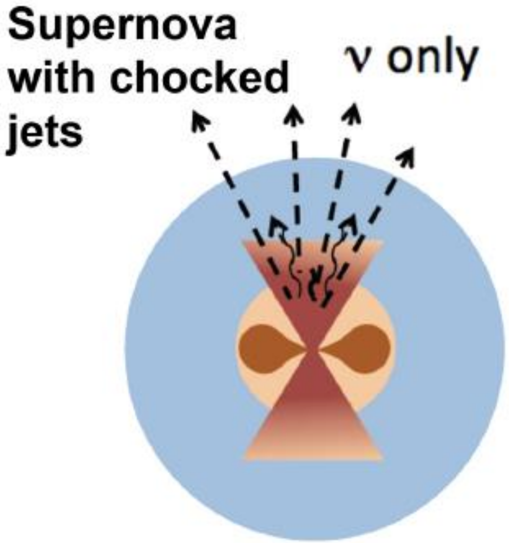
Background year expectation for
'event like this'   E>Eref

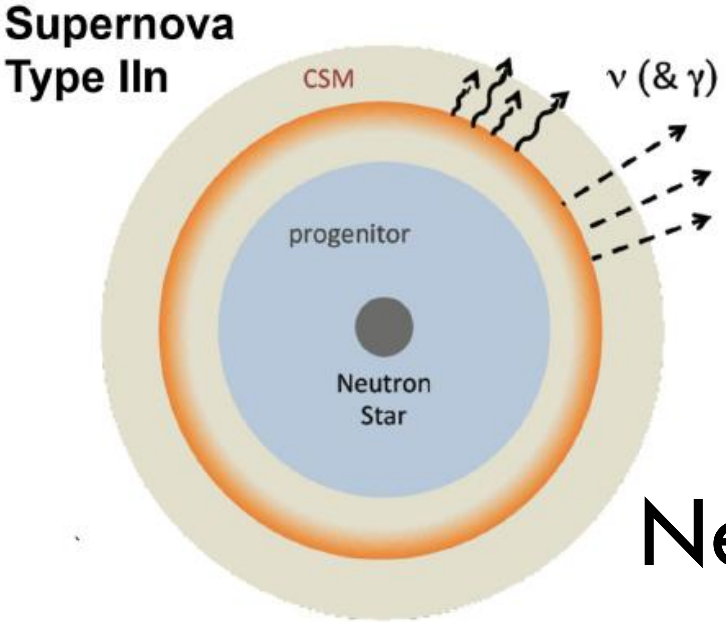


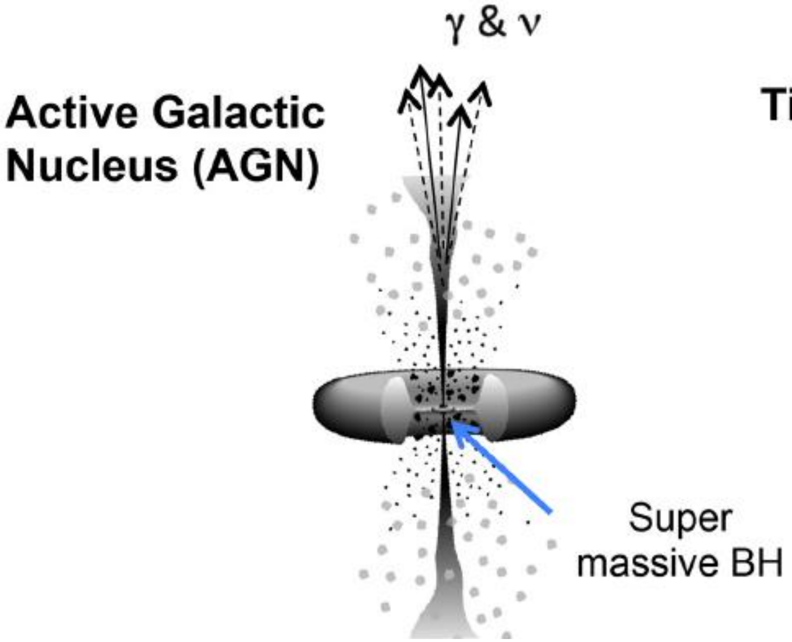
FAR, signalness are designed to guide multimessenger followups, not for statistical significance calculations

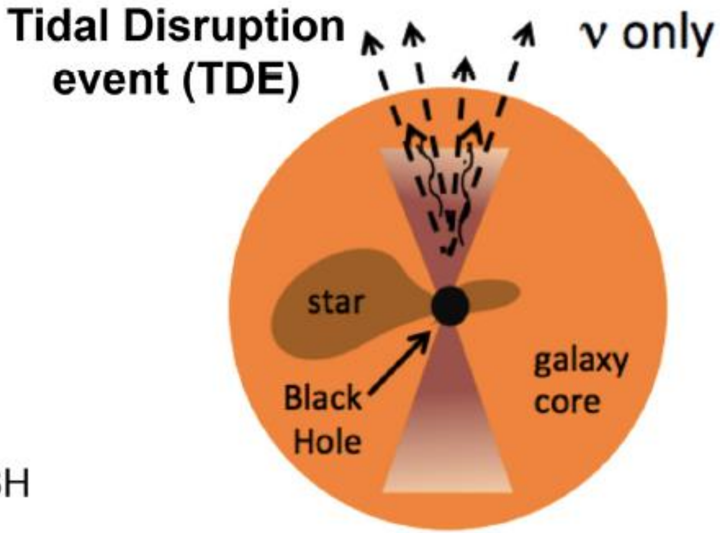
(e.g. spectrum shape dependencies)







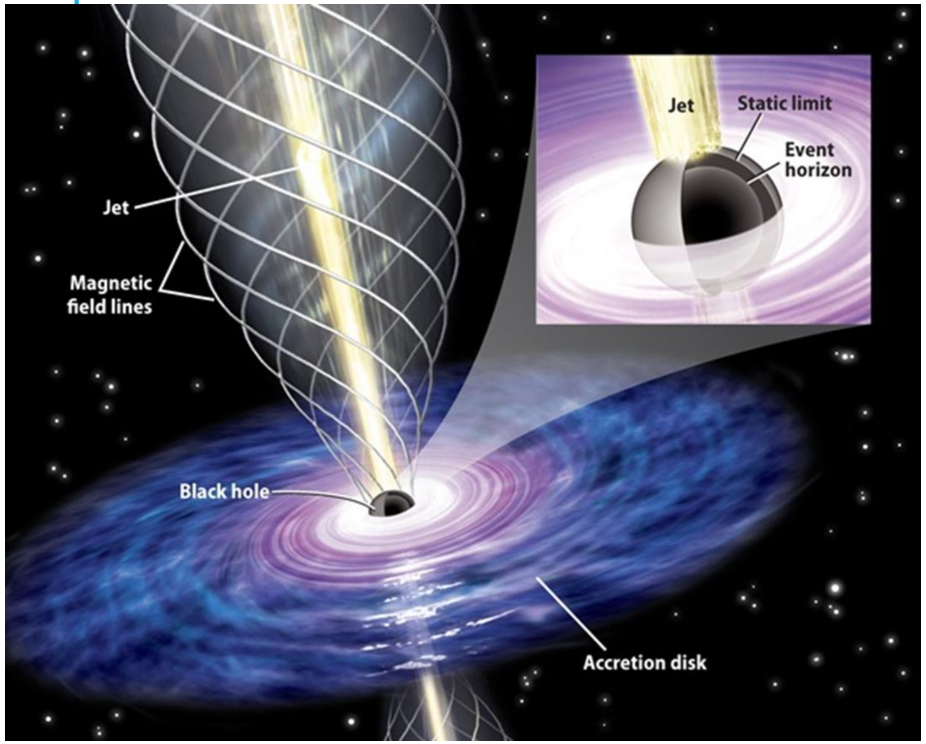


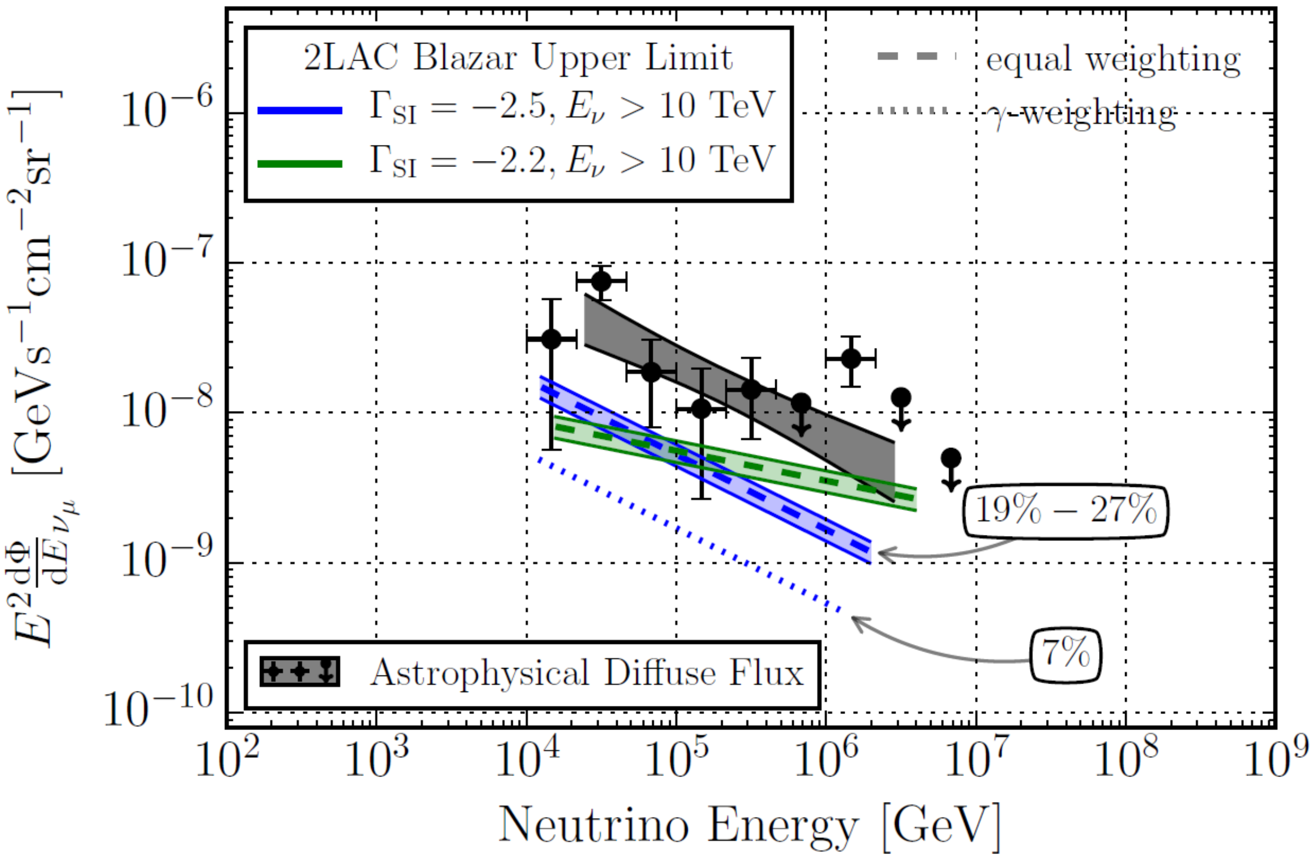


Neutrino clustering follow-ups

- Optical/X-ray Follow-Up: upgoing multiplets within 100 seconds and 3.5 degrees of angular separation
- Gamma-Ray Follow-Up: searches target sources from a predefined source catalog of 3 weeks window
- Low energy supernova bursts detection.

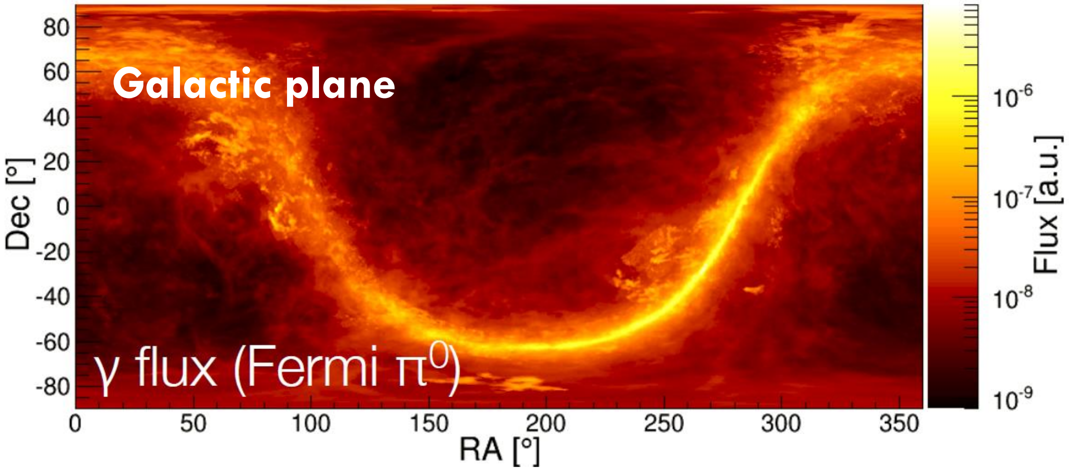
CORRELATIONS WITH BLAZARS





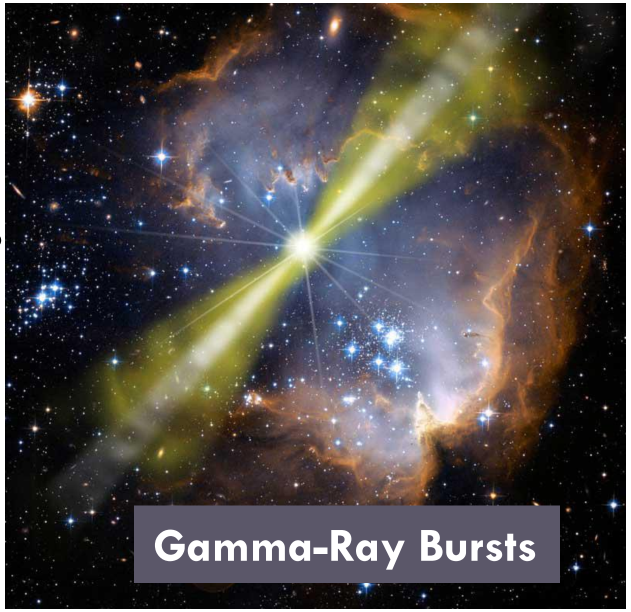
86% Fermi diffuse photons are from blazars
highly variable EM emission
IceCube time-integrated stacking analysis

IceCube, ApJ vol. 835, no. 1, p. 45 (2017)
862 gamma-ray blazars with 3 years of IceCube neutrino data found that **< 30%** (6-27%) of the neutrino flux originates in blazars



IceCube, Astrophys.J. 849 (2017) 67
<16% of $E^{-2.5}$ flux above 1 TeV

Not LLGRB or choked jet



Icecube, Astrophys.J. 824 (2016) no.2, 115
Short duration -> low background
No neutrinos observed in coincidence with GRBs
Prompt emission from GRBs can produce **<1%** of observed neutrino flux

Bechtol K et al. 2017 Astrophys. J. 836 47
86% Fermi diffuse photons are from blazars
<30% (at 100 TeV) diffuse nu flux
Applies to pp optical thin sources

QUESTION TO AUDIENCES

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

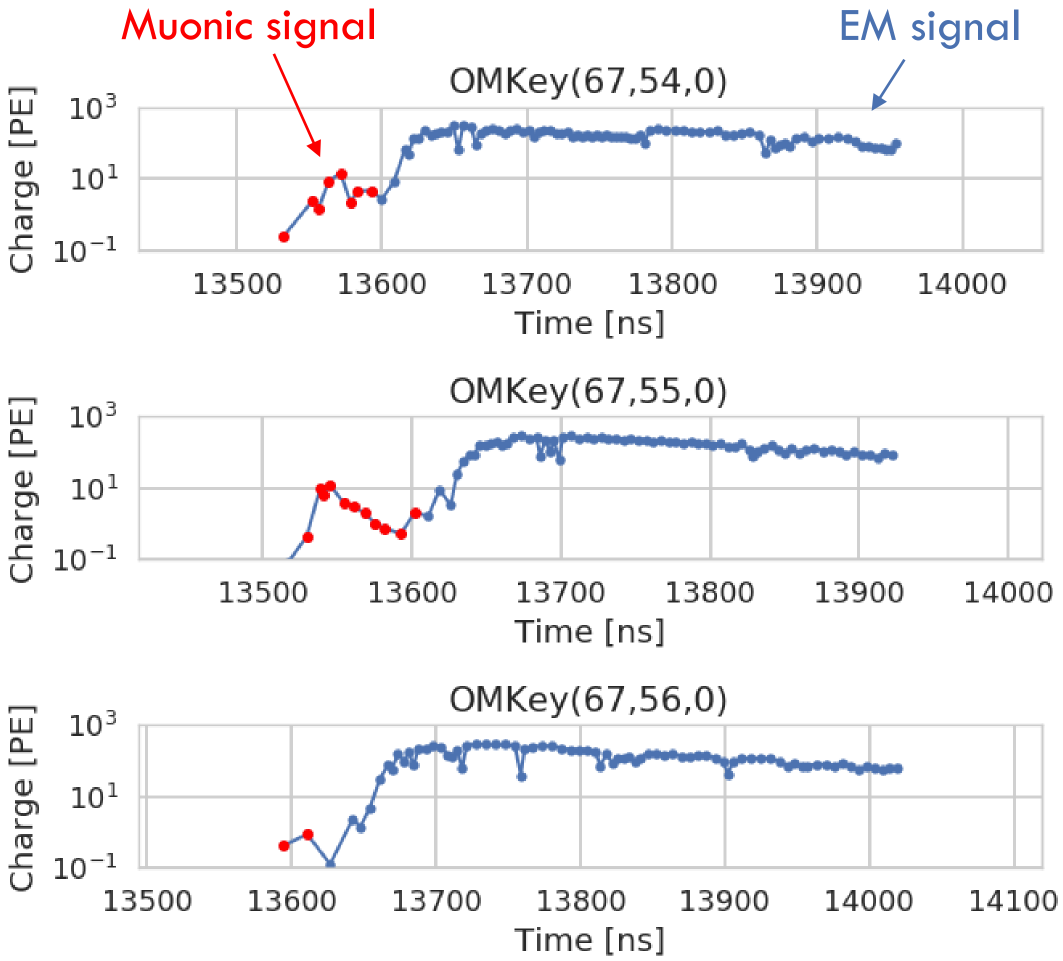
1. Moving towards to including optical/x-ray source catalogues -> should we include prior of energy dependent neutrino expectation based on source type, SED

2. sub threshold alerts with cascades? For instruments with large f.o.v. could be interesting. But need to define significance calculation

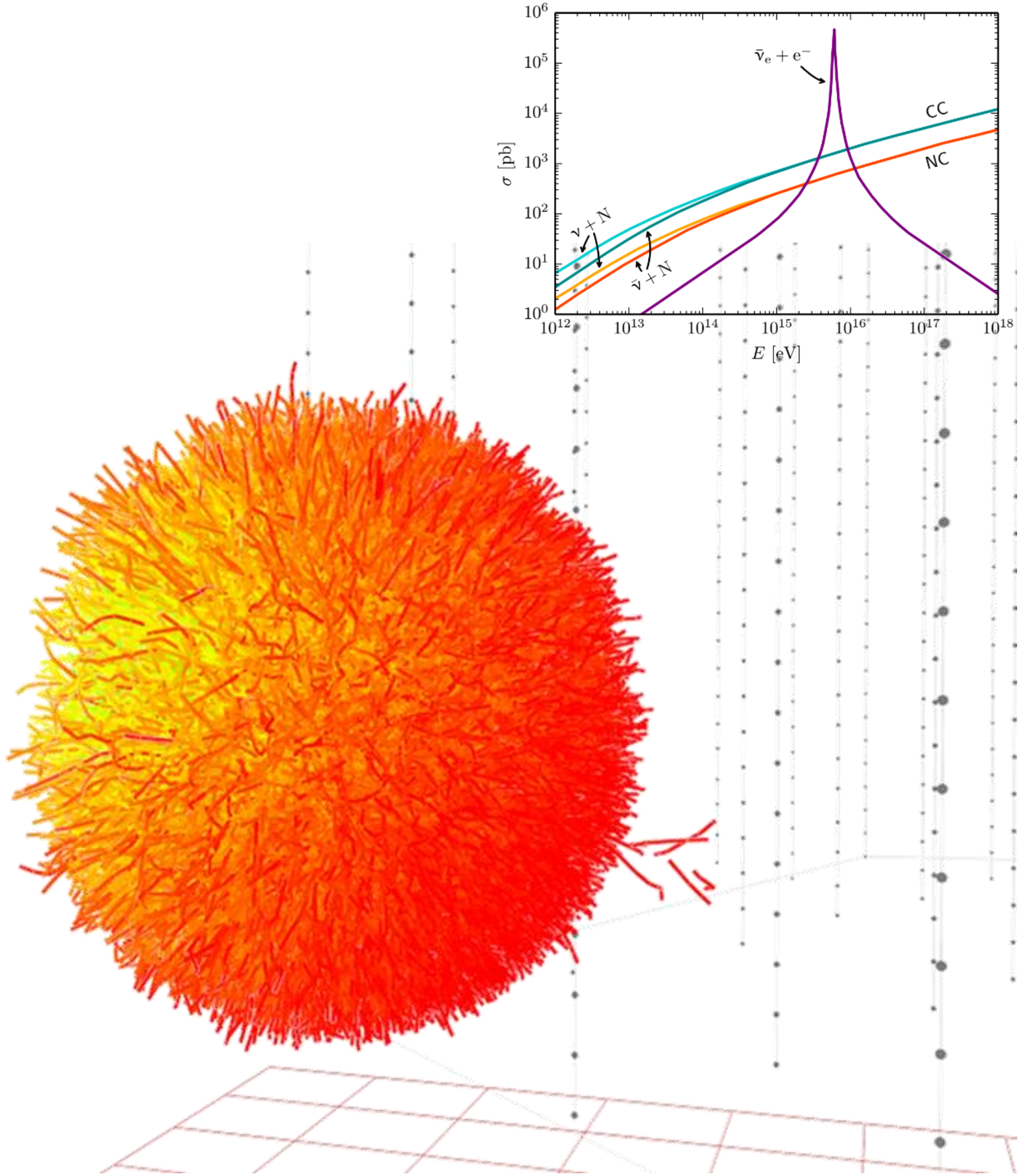
cascade-like events (~10 deg resolution but good energy reconstruction)

3. other methods to remove background. E.g. doublets but also open southern sky. Can we take into prior of dt, dE and open northern sky?

EARLY MUONS IN DATA



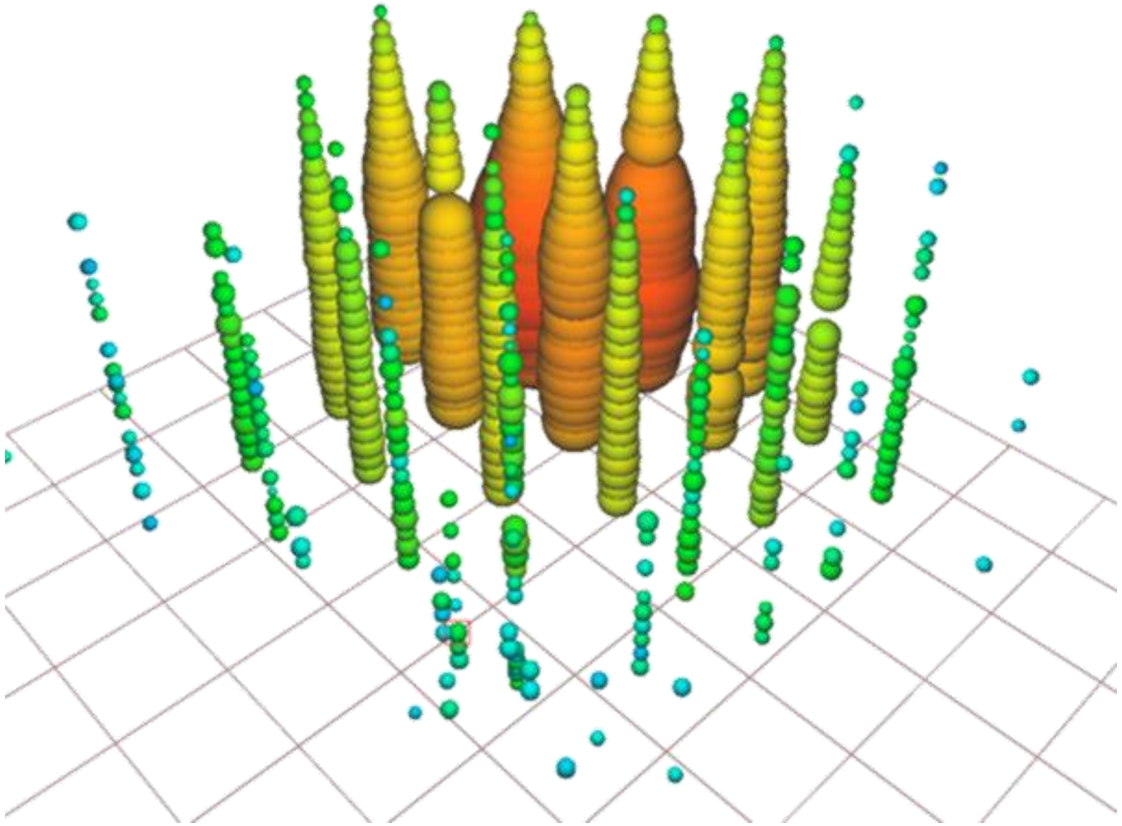
IceCube has 3.3 ns timing resolution!

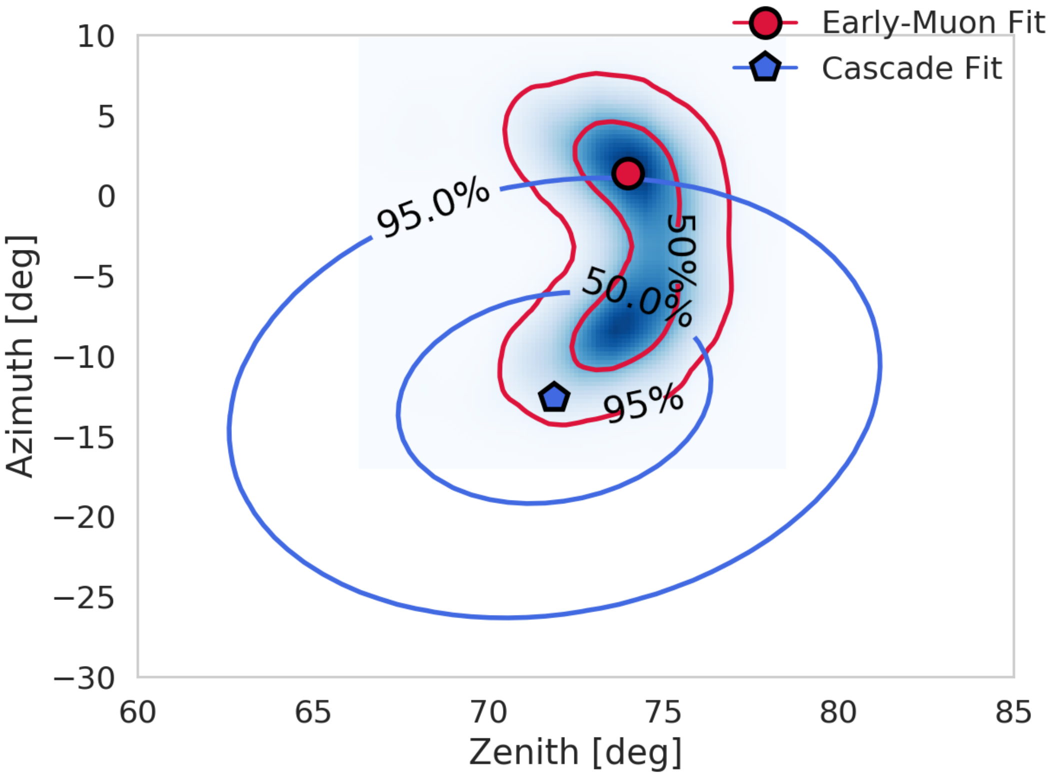


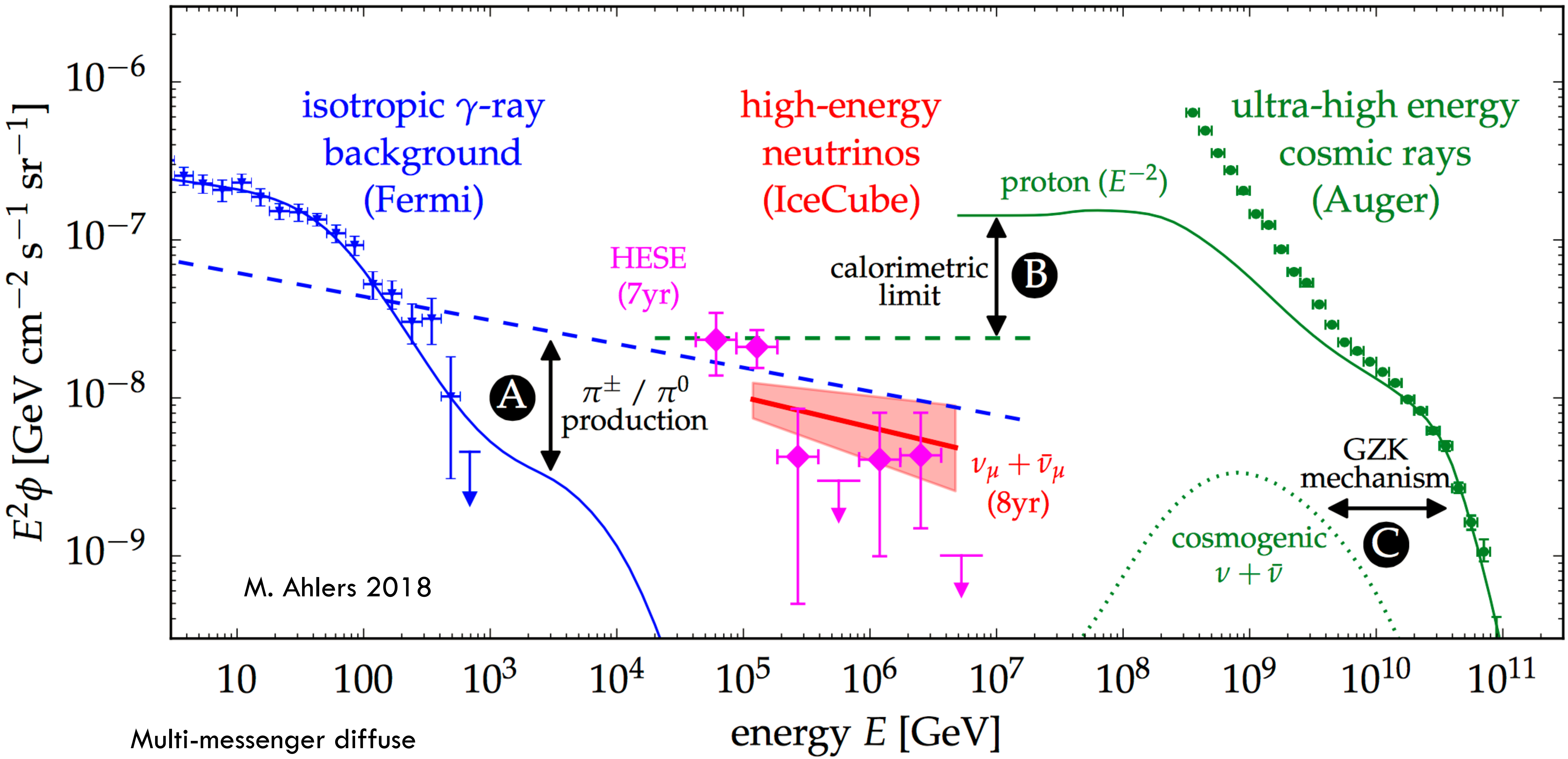
GLASHOW CHANNEL: HOW TO FIND COUNTER PARTS FOR LARGE ERROR REGION

Hadronic cascade with good angular resolution
Highest deposit energy event
Glashow candidate

e.g. include prior on nuebar fraction of source search







Multi-messenger diffuse

Dark neutrino source at <100 TeV?

Need more data!

CONCLUSION

The origins of IceCube neutrinos are still largely unknown. Are the sources related to UHE? It’s a rewarding puzzle.

Clues from

- diffuse neutrino measurements [spectra shape, flavour ratio, nuebar ratio]
- Point source [catalogue stacking, time dependent]
- Real-time. [TXS, non-blazars with X-ray/optical?]

We can explore dedicated event selections for instance doublets with energy prior to open southern sky. => discussion session backup

Time-dependent analysis
Transient alerts!