

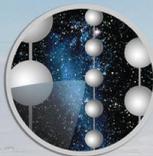
SEARCHING TRANSIENT NEUTRINO SOURCES WITH ICECUBE: STATUS AND RESULTS

THOMAS KINTSCHER (DESY)
FOR THE ICECUBE COLLABORATION

VERY HIGH ENERGY PHENOMENA
IN THE UNIVERSE
QUY NHON, VIETNAM
2018/08/16



Photo Credit: John Kelley



ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

50 m

Ice Top



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW-Madison



Amundsen-Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

1450 m

86 strings of DOMs,
set 125 meters apart



Digital Optical Module (DOM)

5,160 DOMs
deployed in the ice

2450 m

IceCube
detector

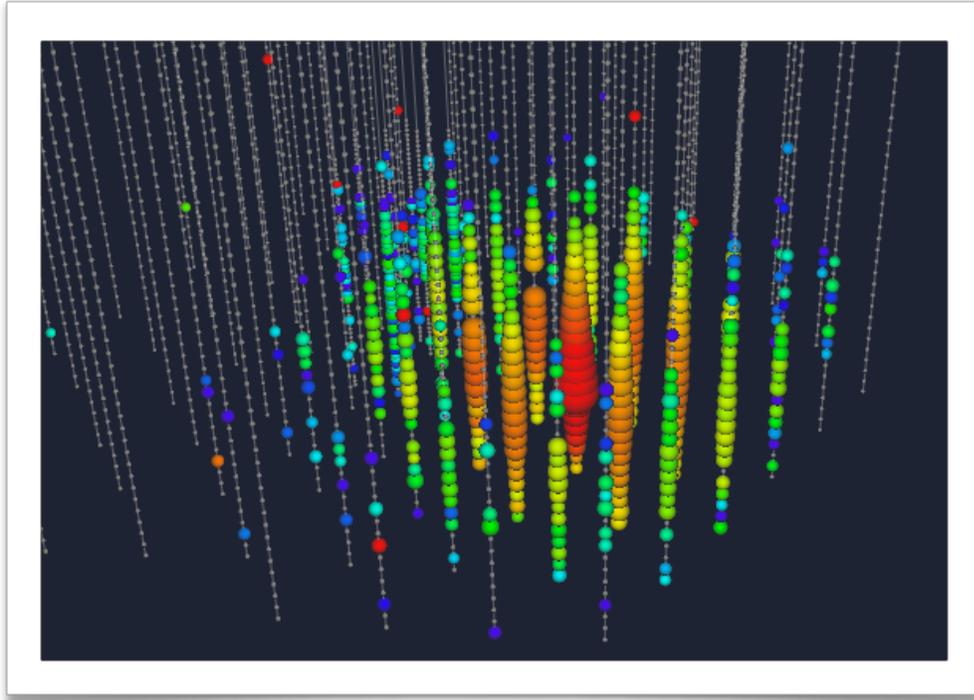
DeepCore

60 DOMs
on each
string

DOMs
are 17
meters
apart

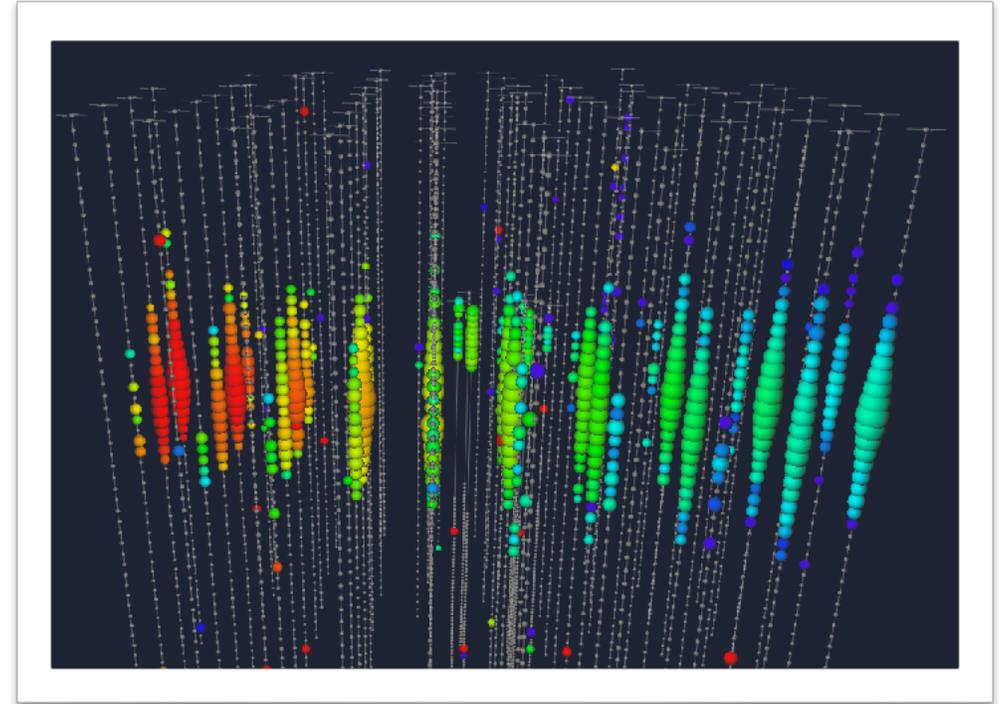
Antarctic bedrock

NEUTRINO SIGNATURES IN ICECUBE



“Showers” / “Cascades”

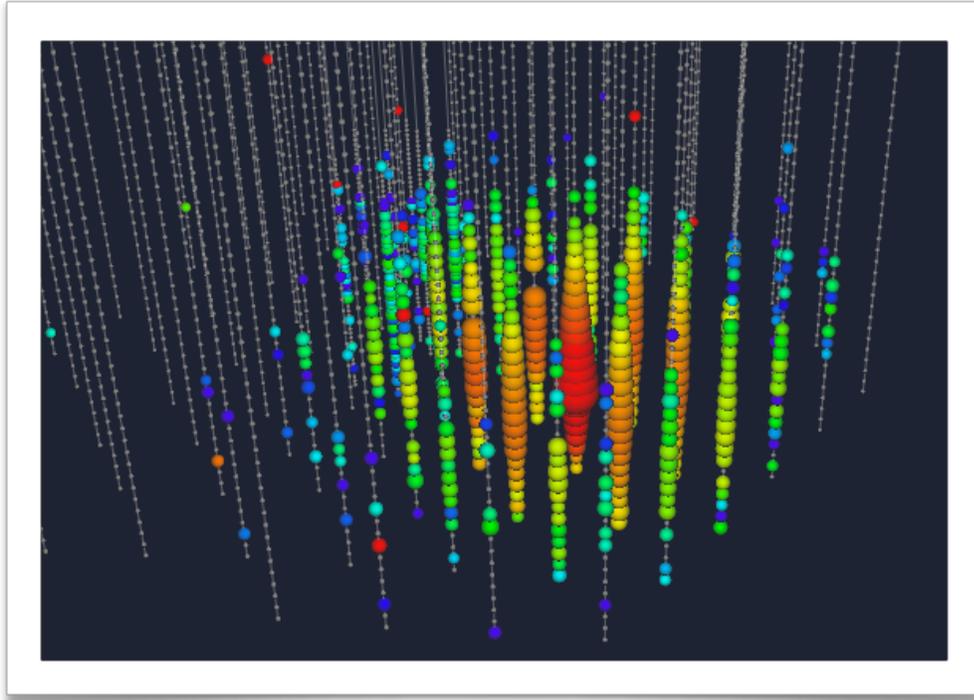
- ▶ Neutral-current $\nu_e/\nu_\mu/\nu_\tau$, charged-current ν_e
- ▶ Good energy resolution: $\sim 10\%$
- ▶ Angular resolution: $O(10 \text{ deg})$



“Tracks”

- ▶ Muons from **charged-current** ν_μ
- ▶ Energy resolution: $0.5 \cdot \log_{10} E$
- ▶ Good angular resolution: $< 1 \text{ deg}$

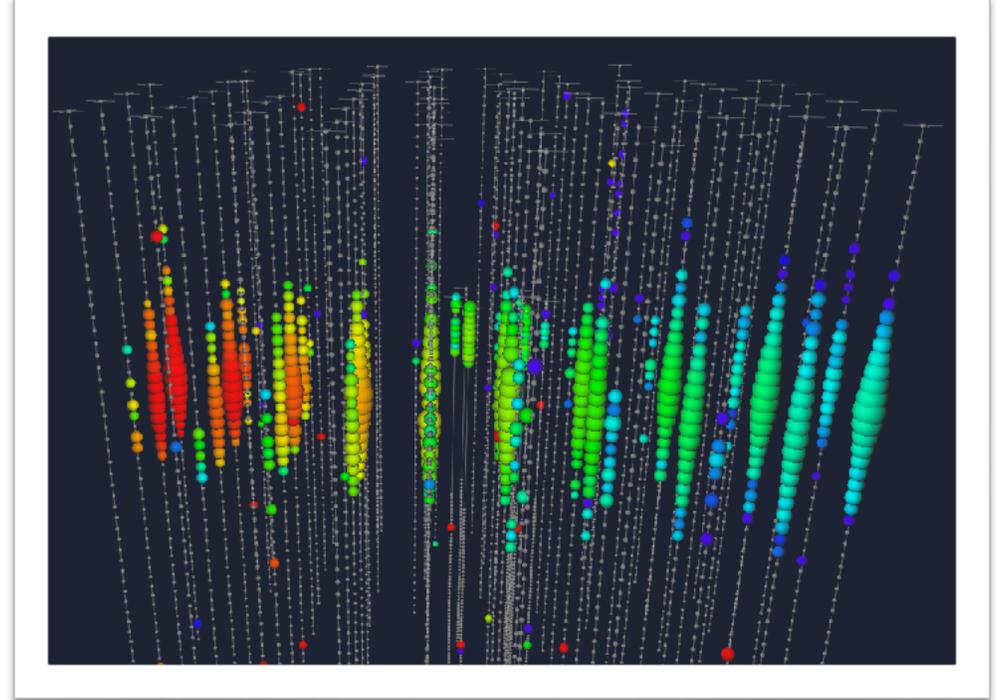
NEUTRINO SIGNATURES IN ICECUBE



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This talk!

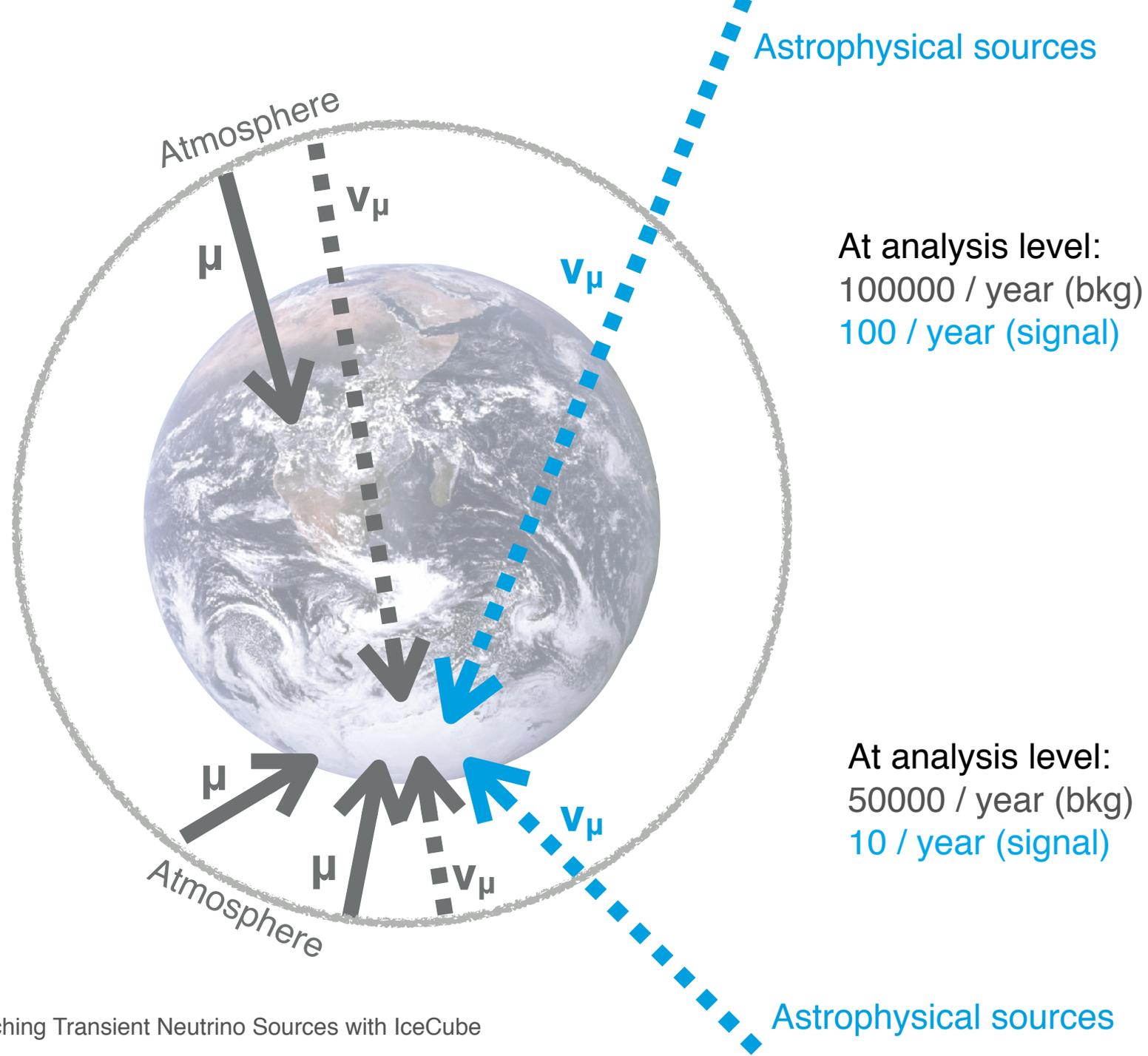


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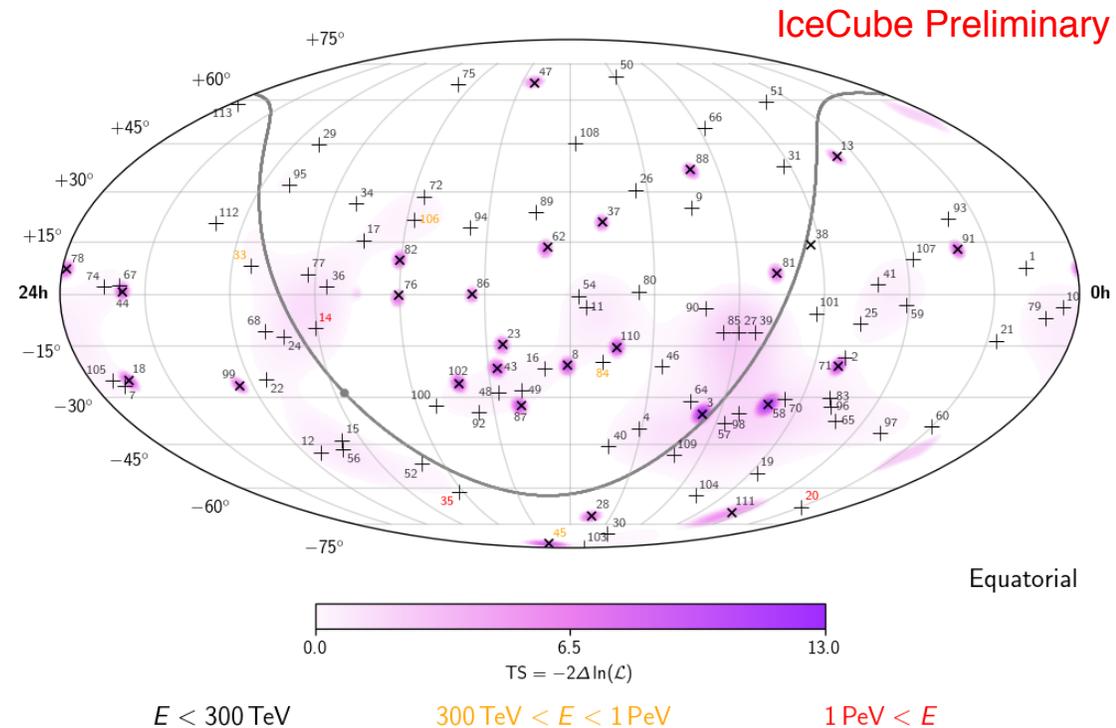
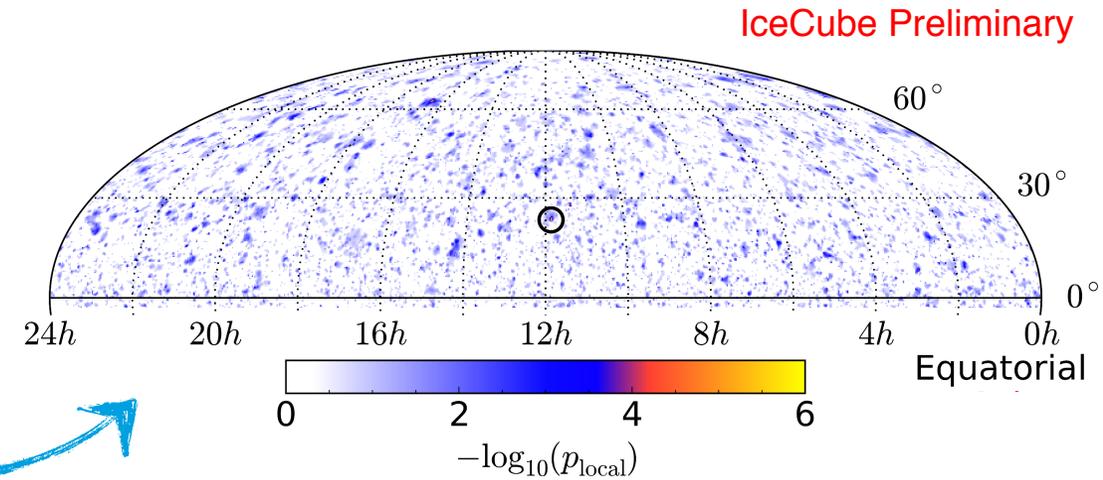
NEUTRINO ORIGINS

- ▶ Different backgrounds in different hemispheres
- ▶ Northern sky (“up-going”):
 - ▶ Cosmic ray-induced air showers
 - ▶ Muons absorbed, muon neutrinos reach IceCube
- ▶ Southern sky (“down-going”):
 - ▶ Both muons and muon-neutrinos reach IceCube
 - ▶ Enormous background of atmospheric muons/bundles

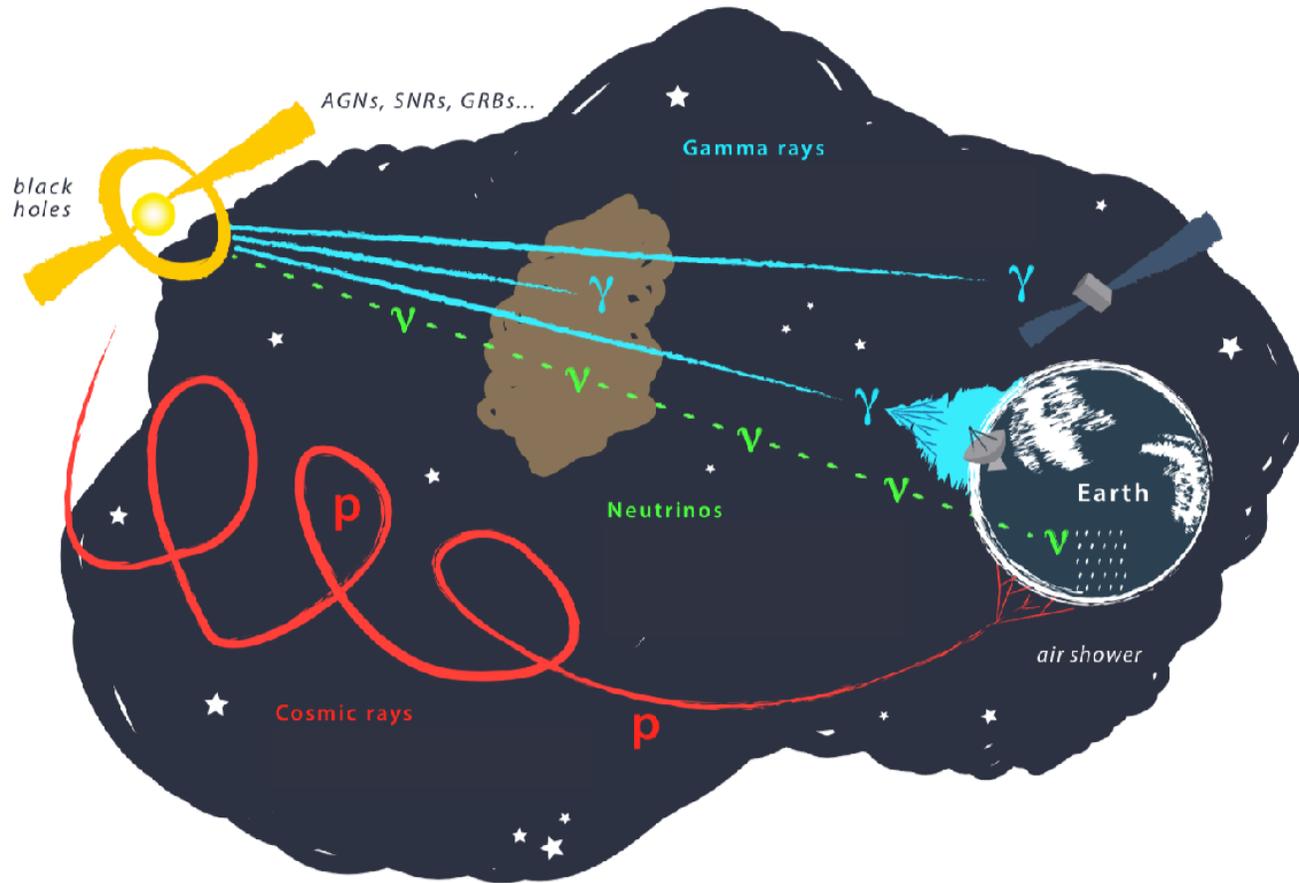


SEARCHING FOR POINT SOURCES

- ▶ Using 8 (7.5) years of IceCube data
- ▶ Time-independent clustering analyses (ApJ 835(2017)2)
 - ▶ Searching the origin of diffuse flux in the northern sky:
 - $p_{\text{local}} = 10^{-5.97}$ (pre-trial) = 29.9% (post-trial)
 - ▶ And for starting events (Neutrino'18):
 - $p = 81\%$ (post-trial)
 - ▶ Also no correlation with 74 tested sources
- ▶ Adding generic time-dependence: (TeVPA 2016)
 - ▶ Hottest spots
 - North: $p_{\text{local}} = 10^{-6.00}$ (pre) = 12.6% (post)
 - South: $p_{\text{local}} = 10^{-5.85}$ (pre) = 22.4% (post)



TESTING THE MULTI-MESSENGER CONNECTION

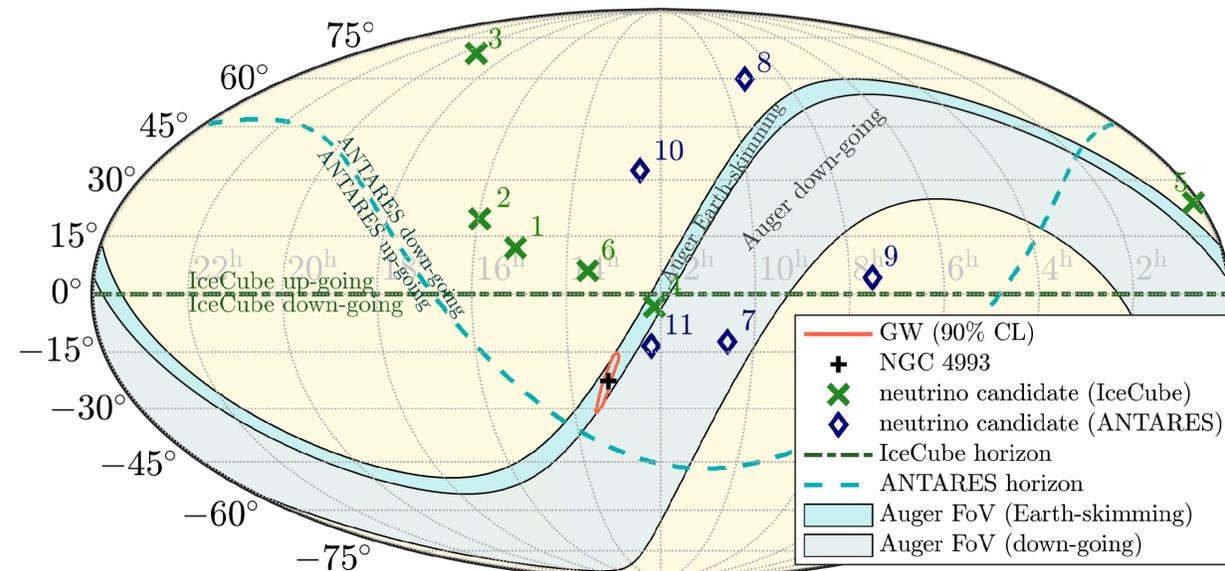


- ▶ Tested ν - γ correlation with variable Fermi-LAT Monitored Sources (TeVPA 2016):

North: PKS 0507+17, $p = 30\%$

South: PKS 2136-642, $p = 70\%$

- ▶ Tested ν -GW correlation, e.g. with GW170817:

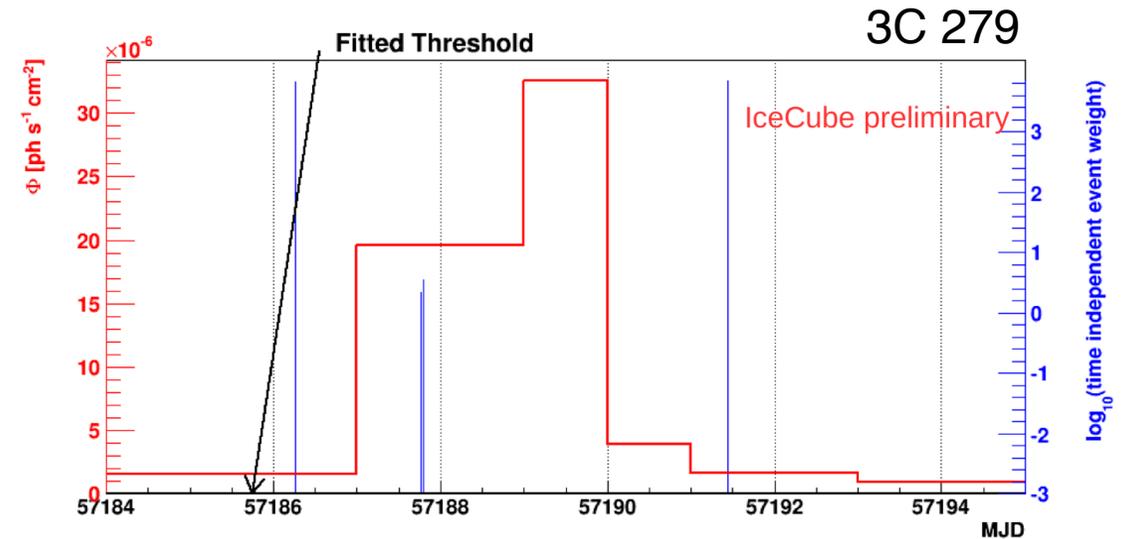
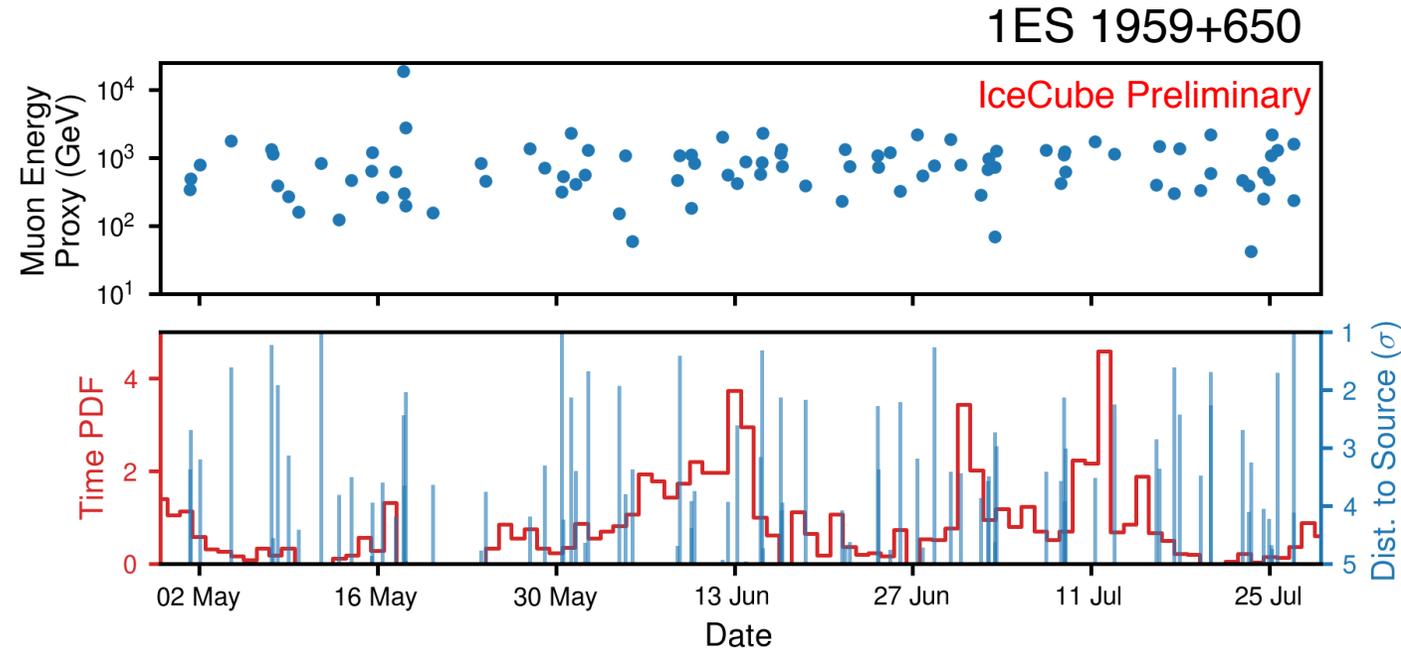


(ApJ Lett. 850)

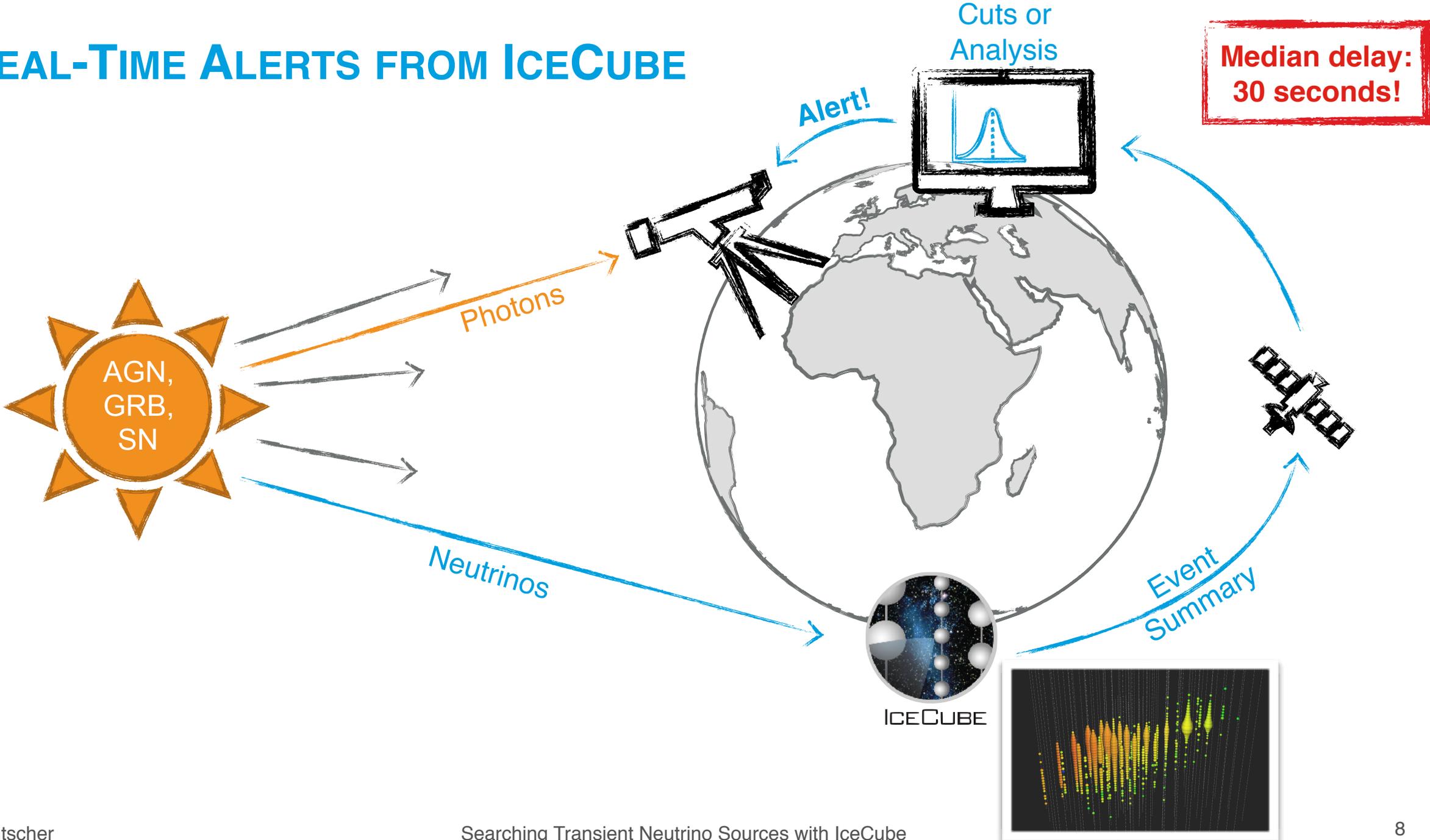
NEUTRINOS AND GAMMA-RAYS

- ▶ **1ES 1959+650**: HBL at $\delta=65$ deg, $z=0.048$
 - ▶ 2002: Orphan flare (3 ν in AMANDA)
 - ▶ 2016: Strong flare in VHE γ -rays
 - ▶ No excess in neutrinos; no correlation with gamma-rays ($p = 50\%$)

- ▶ **3C 279**: FSRQ at $\delta=-5.8$ deg, $z=0.536$
 - ▶ June 2015: Fermi-LAT flux exceeds 40x steady flux
 - ▶ No excess in neutrinos; no correlation with gamma-rays ($p = 19\%$)



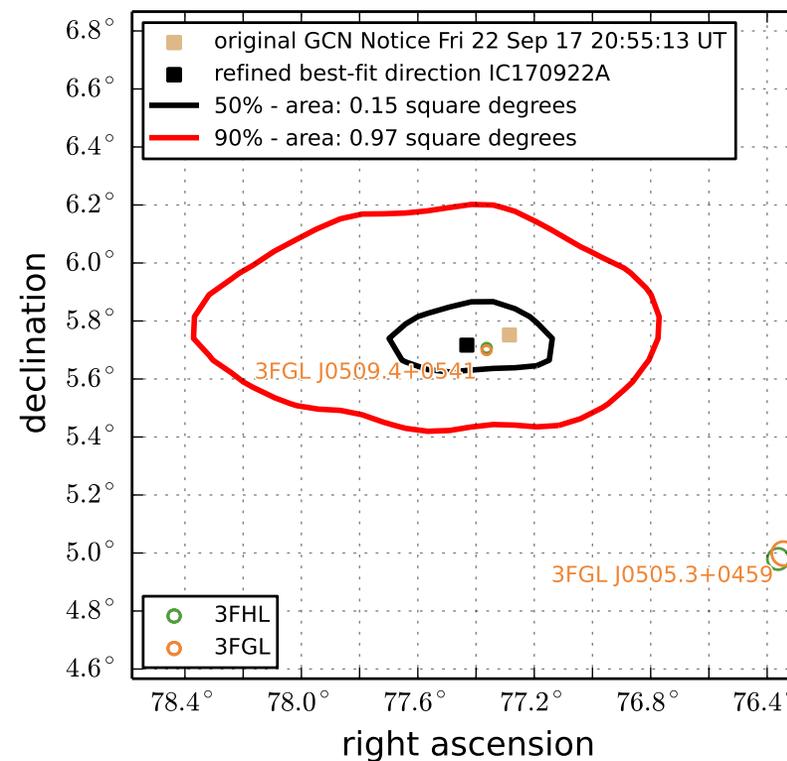
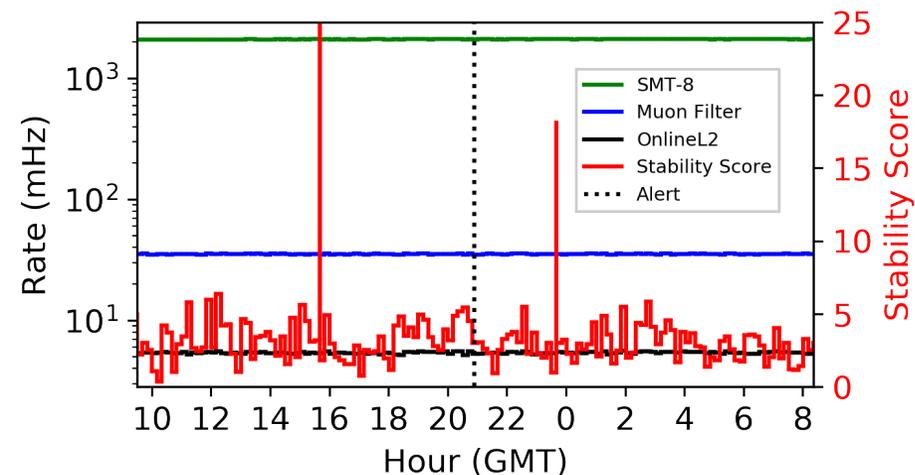
REAL-TIME ALERTS FROM ICECUBE



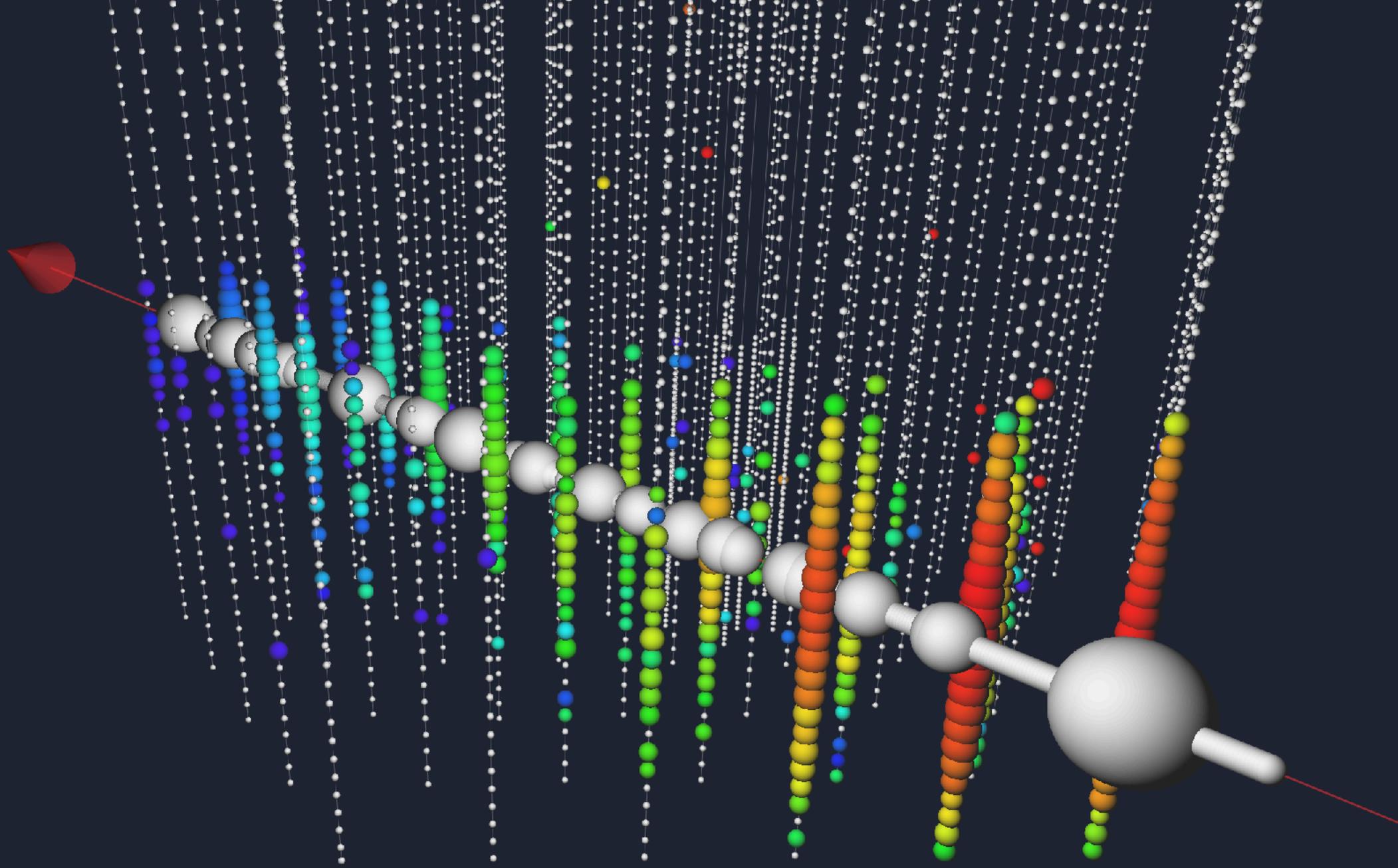
PRACTICAL EXAMPLE: THE ALERT IC170922A

ICECUBE-170922A: ALERT

- ▶ **Sept. 22nd, 2017**: EHE alert (Extreme High-Energy)
- ▶ Automated GCN Notice:
RA 77.29 deg / Dec. 5.75 deg
- ▶ After the event:
 - ✓ Visual inspection of the event
 - ✓ Detector stability checks
 - ✓ Refined angular reconstruction
- ▶ 4h later: GCN circular
 - ▶ RA 77.43 deg / Dec. 5.72 deg
 - ▶ 90% PSF containment: 0.9 deg

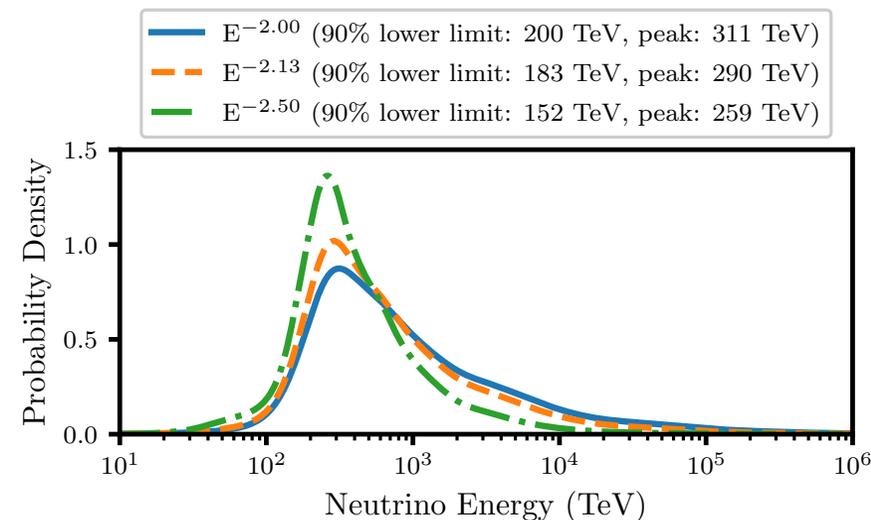
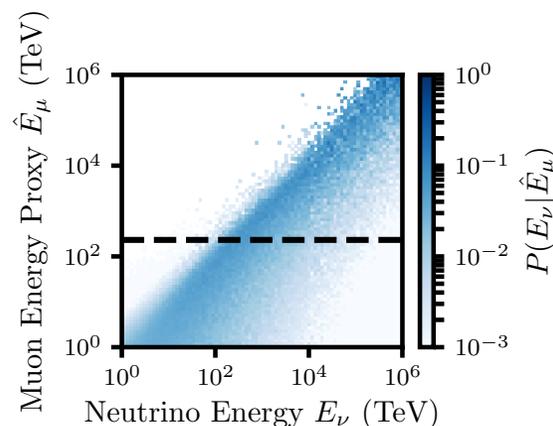


Event: 130033/50579430-6916977
Time: 2017-09-22 20:54:30 UTC
Duration: 22467.6 ns

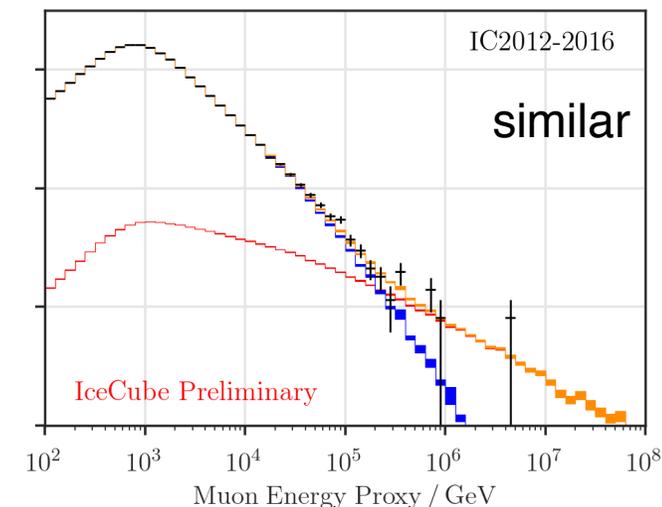


ICECUBE-170922A: SIGNAL PROBABILITY

- ▶ Energy estimate:
 - ▶ 5785 PE deposited (22 TeV)
 - ▶ 170 TeV muon energy at the detector
 - ▶ Most probable ν energy: 290 TeV

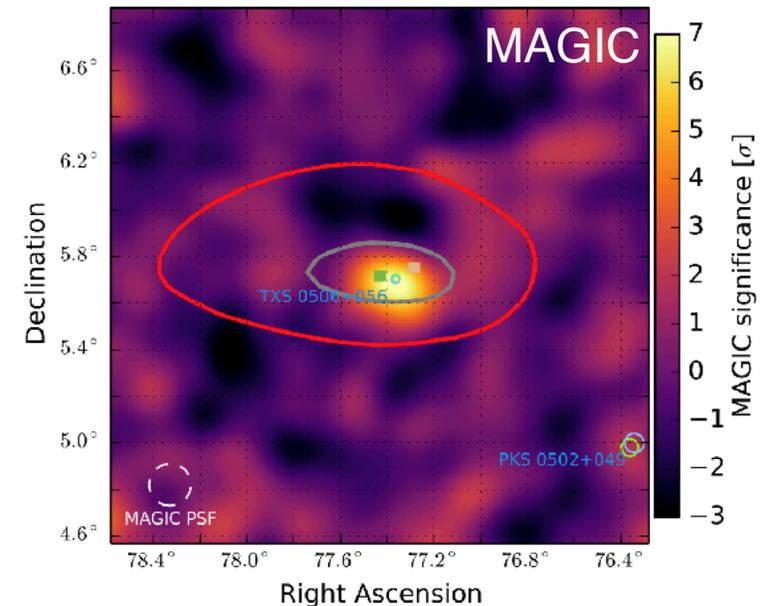
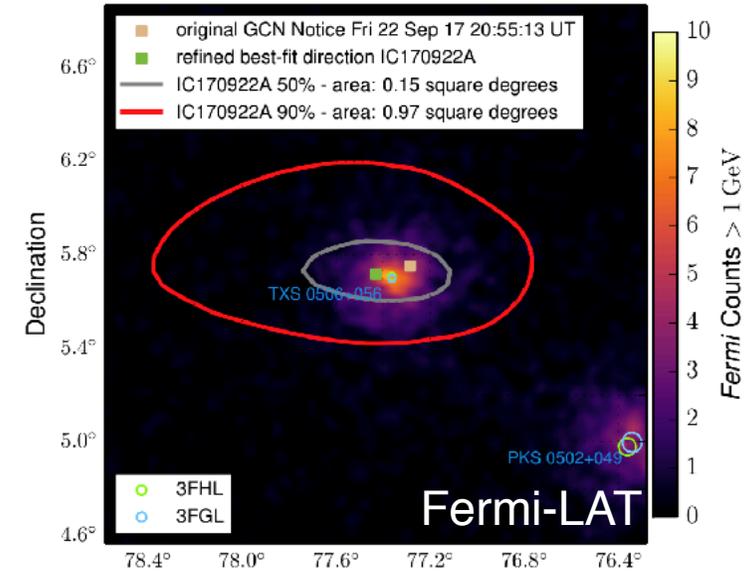


- ▶ Estimating “signalness”, given declination (5.7 deg) and energy
 - ▶ Signalness = $S / (S+B)$
 - ▶ Signal assumption: diffuse astrophysical flux ($E^{-2.13}$)
 - ▶ Dominant background: atmospheric neutrinos
- ▶ Probability for event to be of astrophysical origin: 56%



ICECUBE-170922A: ORIGIN?

- ▶ 3FHL source in the error circle: the blazar TXS 0506+056
- ▶ Fermi-LAT report of gamma-ray flare → plenty of follow-up observations
- ▶ MAGIC: VHE gamma-ray detection at 6.2σ (80 GeV — 400 GeV)
- ▶ **Chance coincidence? Disfavored at 3σ** , in each scenario where...
 - ▶ ... ν flux correlated to high energy γ -ray flux
 - ▶ ... ν flux correlated to high energy γ -ray flux variations
 - ▶ ... ν flux correlated to VHE γ -ray flux
 - ▶ Note: **a-posteriori** significance
 - ▶ Details on the calculation in M. Hayashida's talk

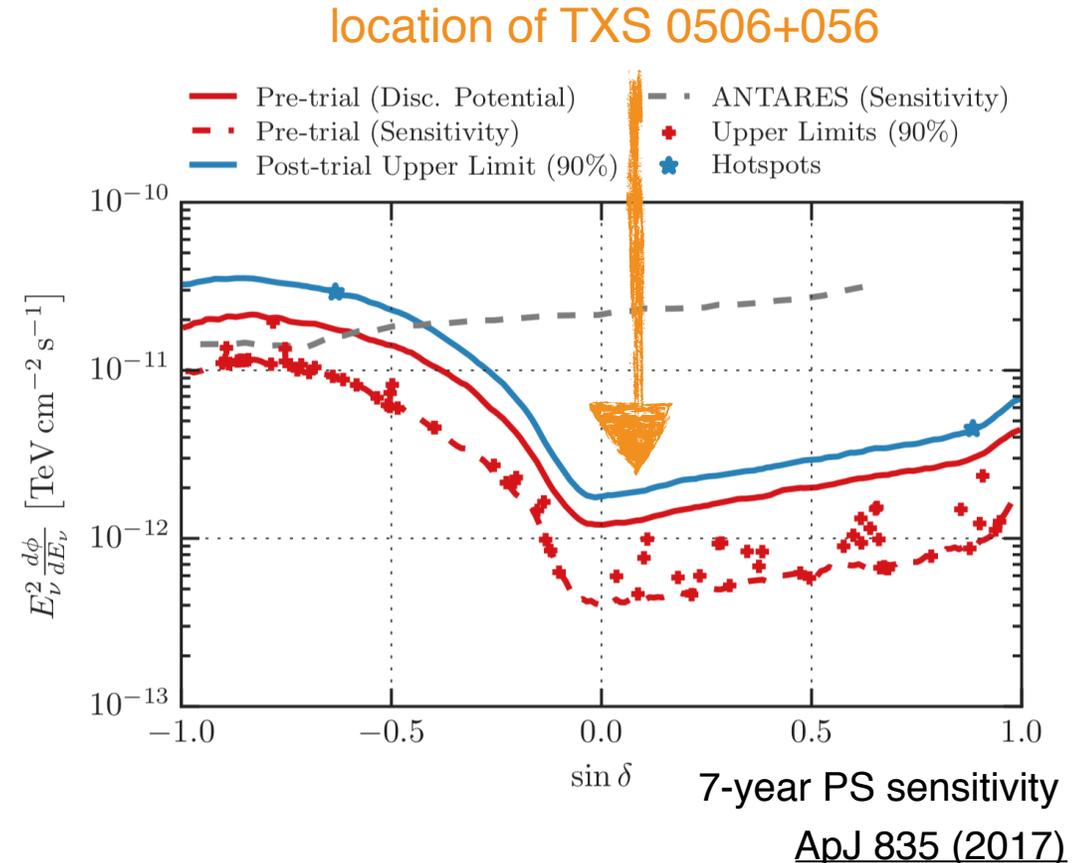


**ARCHIVAL SEARCH:
MORE NEUTRINO EMISSION FROM
TXS 0506+056?**

POINT SOURCE SEARCH

- ▶ Location of TXS 0506+056:
sweet spot of point source sensitivity
 - ▶ **Low earth absorption** for high-energy neutrinos
 - ▶ **Low atmospheric muon background**
- ▶ 9.5 years of archival data available:
 - ▶ From April 2008 (IC40)
 - ▶ Until Oct. 31st 2017
- ▶ Motivated by the alert and follow-up revelations:

**Has TXS 0506+056 been a source of neutrinos in the past?
(independent of the IC-170922 event)**

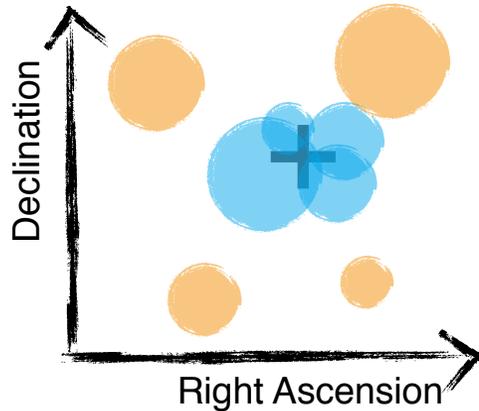


TIME-DEPENDENT POINT SOURCE SEARCH

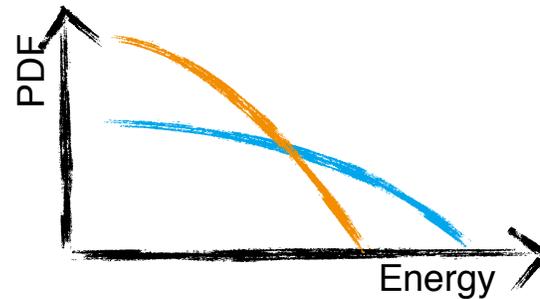
- ▶ Unbinned maximum-likelihood method:

$$\mathcal{L} = \prod_i^{\text{events}} \left[\frac{n}{N} S_i + \left(1 - \frac{n}{N}\right) B_i \right]$$

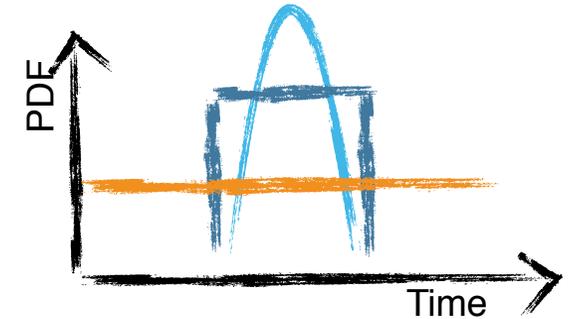
$$\text{TS} = -2 \log \left(\frac{\mathcal{L}(\hat{n}, \hat{\gamma})}{\mathcal{L}(n=0)} \right)$$



×



×



Spatial PDF

- ▶ Test compatibility with source location
- ▶ Use per-event angular uncertainty

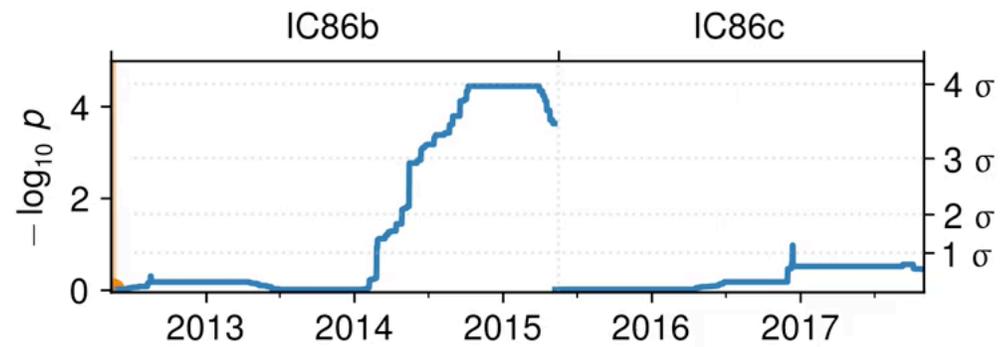
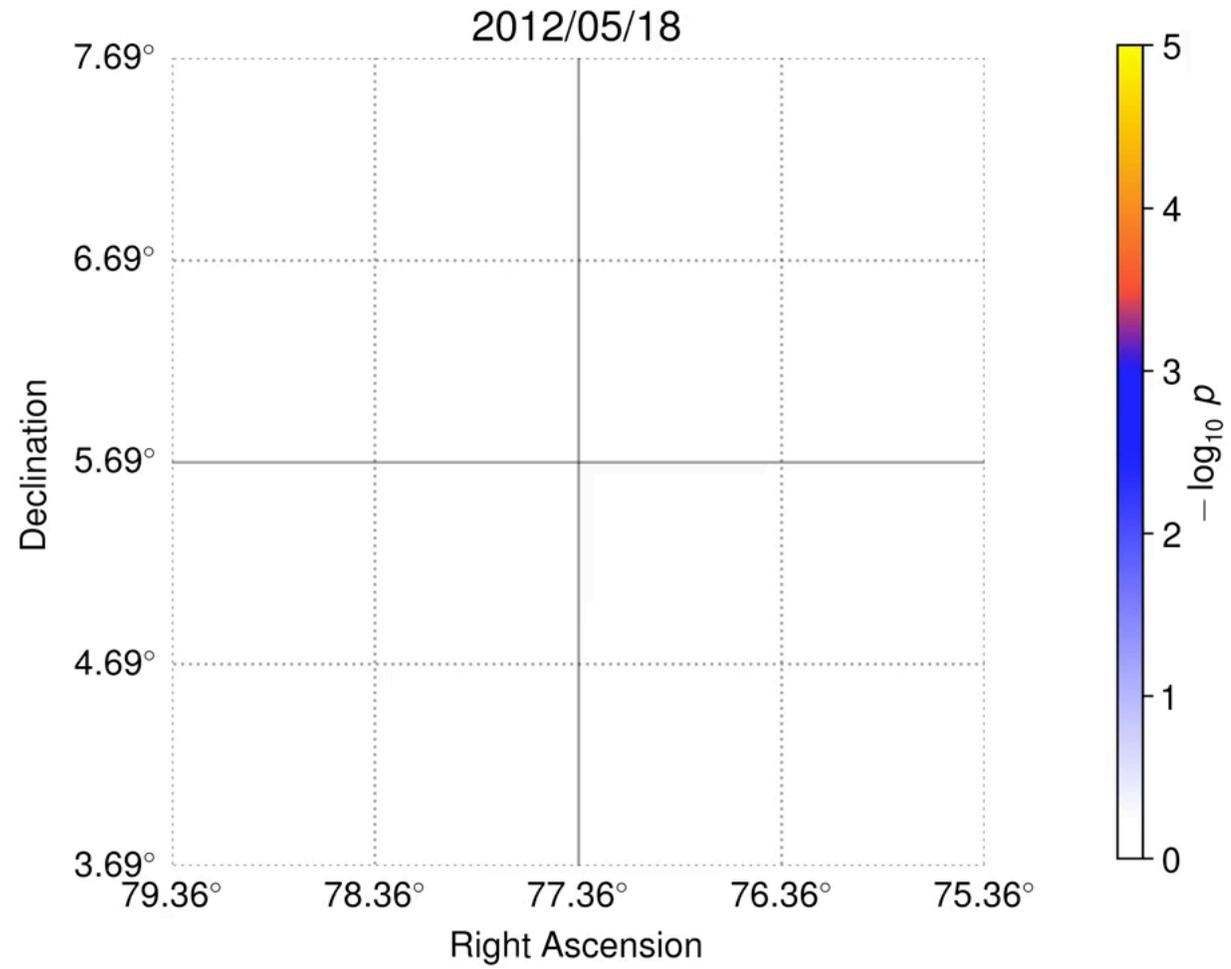
Energy PDF

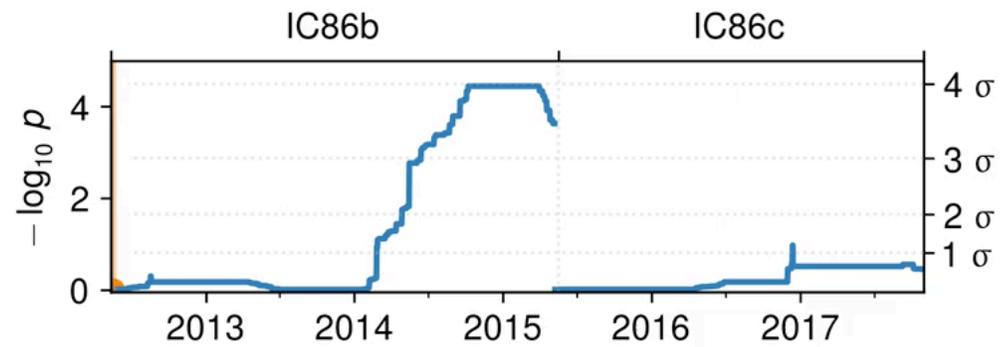
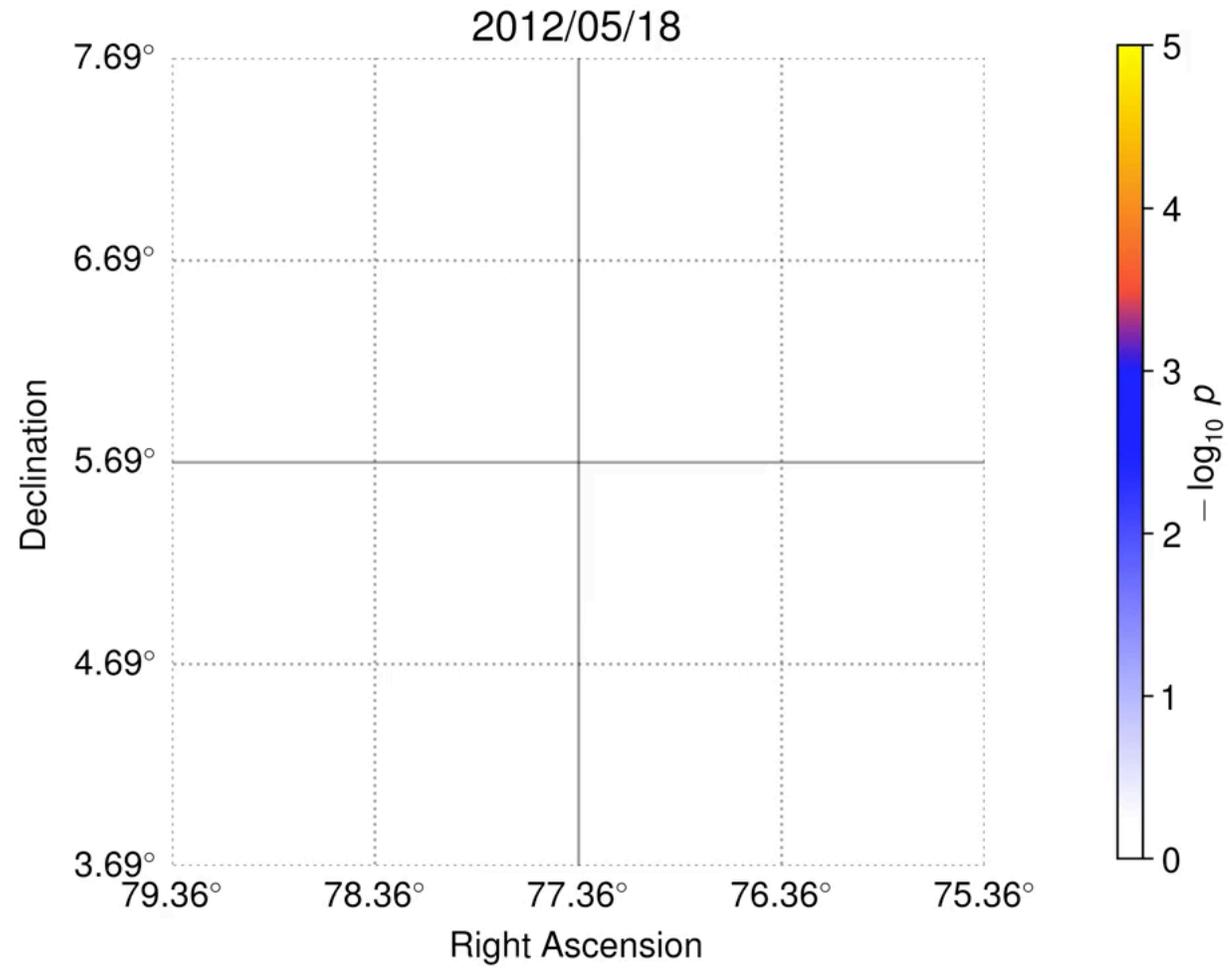
- ▶ Exploit different spectra of **signal** and **background**
- ▶ Use per-event energy estimate

Time PDF

- ▶ Clustering of **signal** over flat **background**
- ▶ Generic: Box or Gaussian

- ▶ Fit parameters: number of events and spectral index



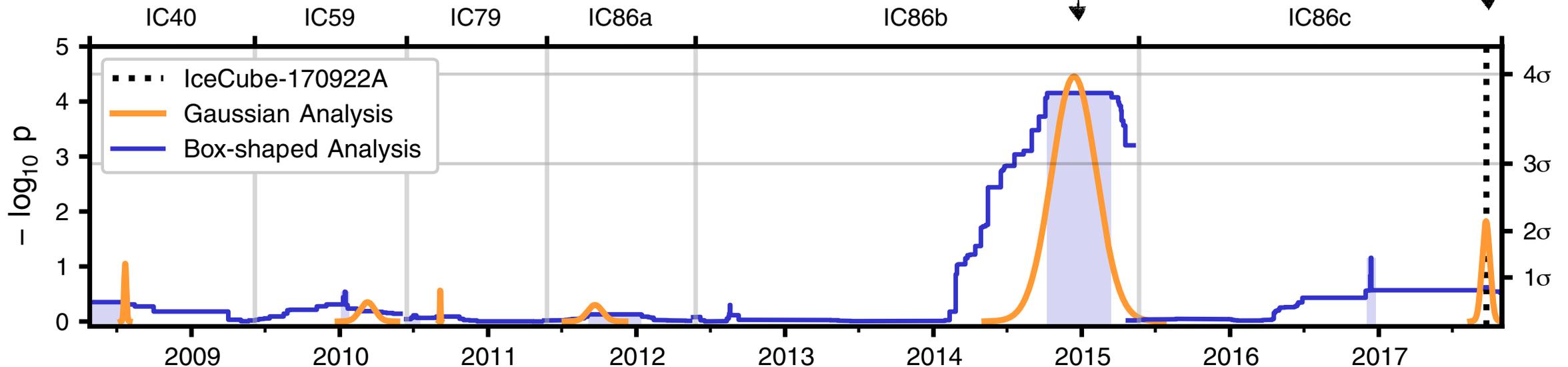


ICECUBE-170922A: ARCHIVAL ANALYSIS

- ▶ Search for neutrino emission prior to the alert using 9.5 years of archival data
- ▶ Compatible fit results between box-shaped and Gaussian time PDF
- ▶ Post-trial significance: **3.5 σ**

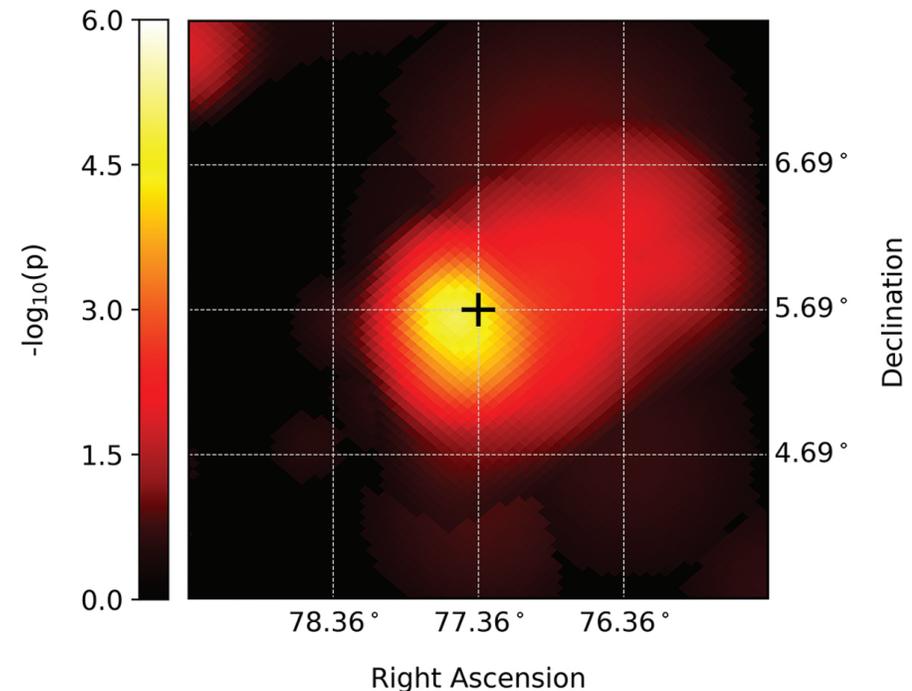
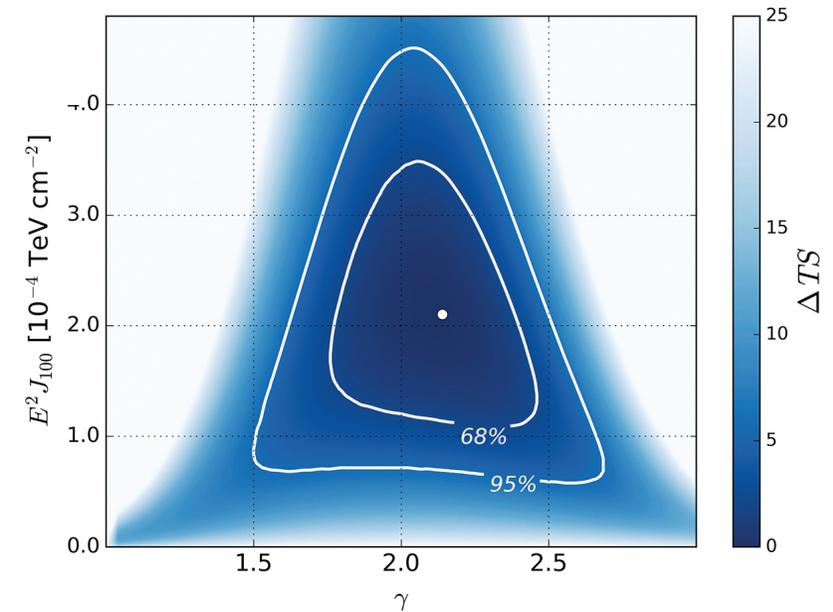
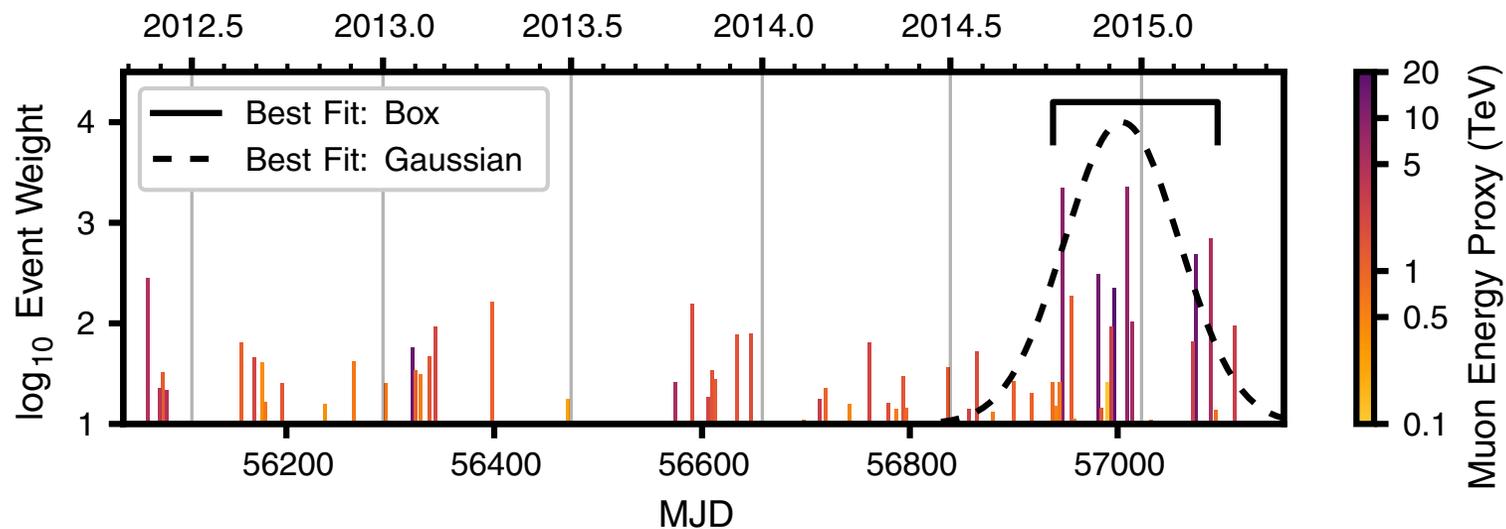
	Box	Gaussian
n_s	14	13
γ	2.2	2.1
Duration	158 days	110 days
Time Window	2014-10-07 2015-03-15	centered at 2014-12-13
Significance	$7 \cdot 10^{-5}$ (3.5σ)	$3 \cdot 10^{-5}$ (3.7σ)

No cluster of neutrinos around the alert



ICECUBE-170922A: ARCHIVAL ANALYSIS

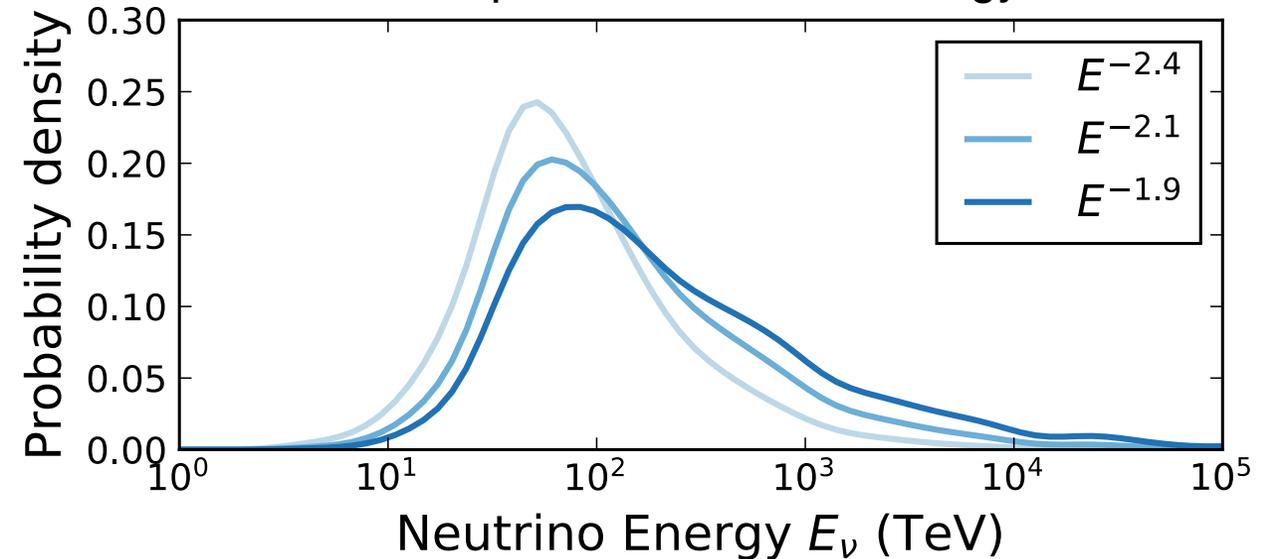
- ▶ Comparing with time-*independent* analysis of 9.5 years:
 - ▶ $\gamma = 2.1$, $p = 0.9\%$ (2.3σ) excl. the trigger
- ▶ The hottest spot in this region, clearly separated from PKS 0502+049 (2 deg away)
- ▶ Compatible with previous result: ([ApJ 835\(1\), 2017](#))
Fermi-2LAC blazar contribution to astrophys. ν flux $< 27\%$



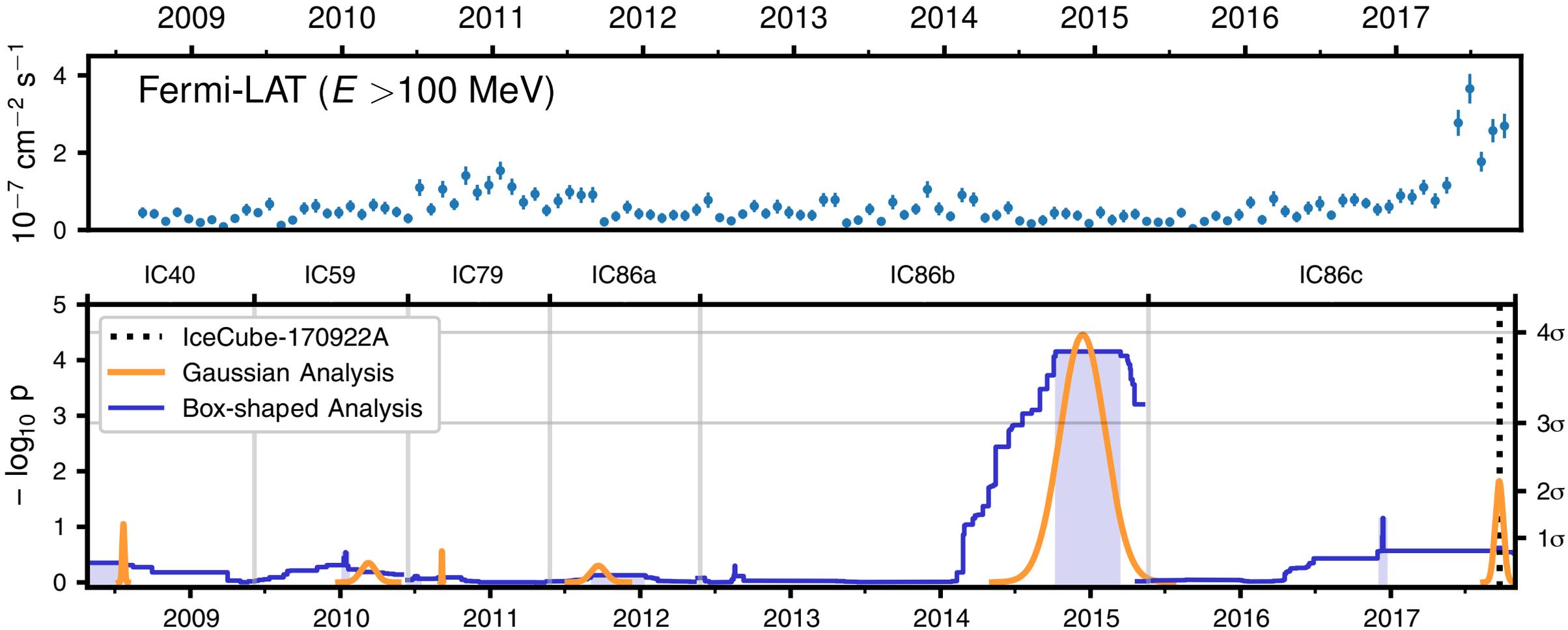
A NEUTRINO SOURCE?

- ▶ Excess due to **number of events and energies**
- ▶ Event energies comprising the flare:
 - ~10 TeV muon energy
 - ~50 TeV neutrino energy
- ▶ Isotropic ν luminosity > isotropic γ luminosity
(1.2×10^{47} erg s $^{-1}$) (0.3×10^{47} erg s $^{-1}$)
(32 TeV — 3.6 PeV) (100 MeV — 100 GeV)
- ▶ **Bright object in gamma-rays**
 - ▶ 3rd Fermi AGN catalog: among 50 brightest objects
 - ▶ Previously unknown redshift → now: order of magnitude more luminous than e.g. 1ES 1959+650!
- ▶ Located at **favorable declination** for IceCube
- ▶ Average time-integrated neutrino flux \cong 1 high-energy alert in same time frame

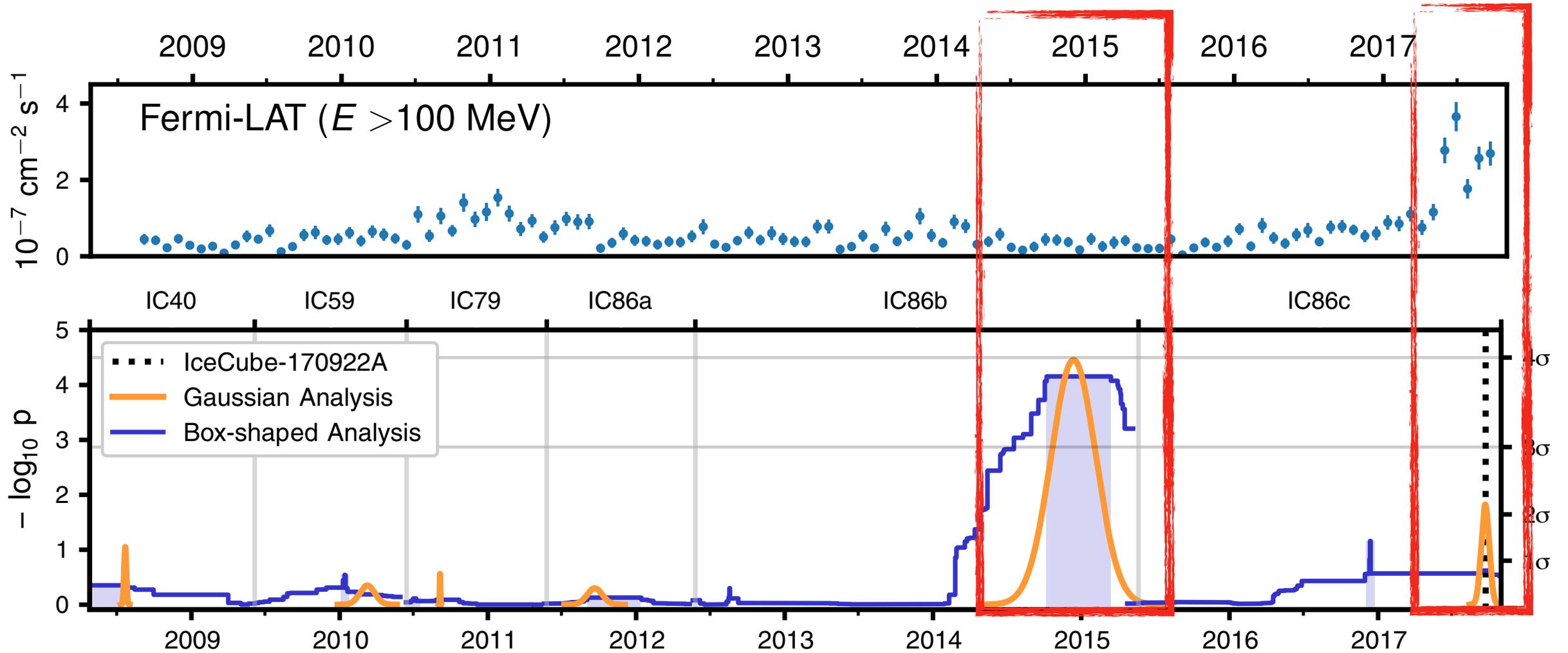
Example: 10 TeV muon energy estimate



ICECUBE-170922A: NEUTRINOS AND PHOTONS



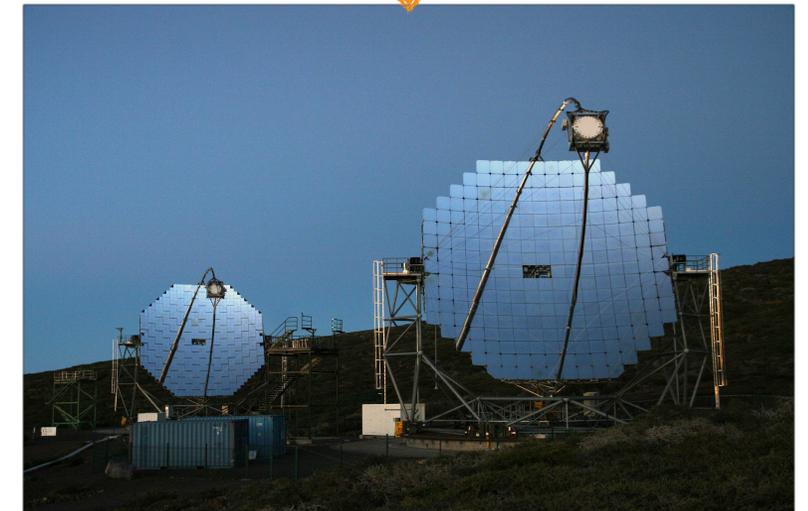
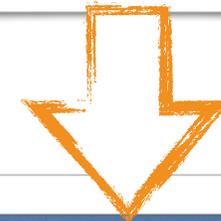
ICECUBE-170922A: NEUTRINOS AND PHOTONS



OUTLOOK

- ▶ Upcoming improvements to IceCube's alert system:
 - ▶ One **high-energy alert** stream
 - ▶ Combining starting and through-going tracks with 50% signal-ness
 - ▶ Improved event selections: doubling the rate of through-going tracks (~8/year) at same signalness
 - ▶ Searching for **neutrino clusters in real-time** (same as for TXS!):
 - ▶ Monitoring known, variable FERMI sources (3FGL/3FHL) for excess in neutrinos
 - ▶ Alerting IACTs: MAGIC, VERITAS, H.E.S.S.
 - ▶ Unbiased all-sky monitoring in preparation (→ public alerts)

```
////////////////////////////////////  
TITLE:          GCN/AMON NOTICE  
NOTICE_DATE:    Mon 23 Apr 18 02:29:12 UT  
NOTICE_TYPE:    AMON ICECUBE  
RUN_NUM:        130949  
EVENT_NUM:      71165249  
SRC_RA:          294.8820d {+19h 39m 32s} (J2000),  
                294.8324d {+19h 39m 20s} (current),  
                295.0135d {+19h 40m 03s} (1950)  
SRC_DEC:         +71.9530d {+71d 57' 11"} (J2000),  
                +71.9958d {+71d 59' 45"} (current),  
                +71.8356d {+71d 50' 08"} (1950)  
SRC_ERROR:       534.00 [arcmin radius, stat+sys, 90%]  
SRC_ERROR50:     96.00 [arcmin radius, stat+sys, 50%]  
DISCOVERY_DATE: 18231 TJD; 113 DOY; 18/04/23 (YY  
DISCOVERY_TIME: 8920 SOD {02:28:40.98} UT  
REVISION:        0  
N_EVENTS:        1 [number of neutrinos]
```



SUMMARY

- ▶ Astrophysical neutrinos → ongoing **hunt for sources!**
- ▶ IceCube's real-time capabilities:
 - ▶ Trigger **follow-up observations** and **collect** contemporaneous **multi-messenger data**
 - ▶ Search strategies:
 - ▶ Single, most-energetic neutrino events
 - ▶ Clustering of neutrinos in space and time
 - ▶ Monitor known source candidates
 - ▶ Chase unknown ones
- ▶ **Evidence for TXS 0506+056 as a neutrino source:** this may be just the beginning!
 - ▶ Afternoon talks: multi-wavelength campaign (Masaaki Hayashida) and interpretation (Shan Gao)

