IceCube recent results

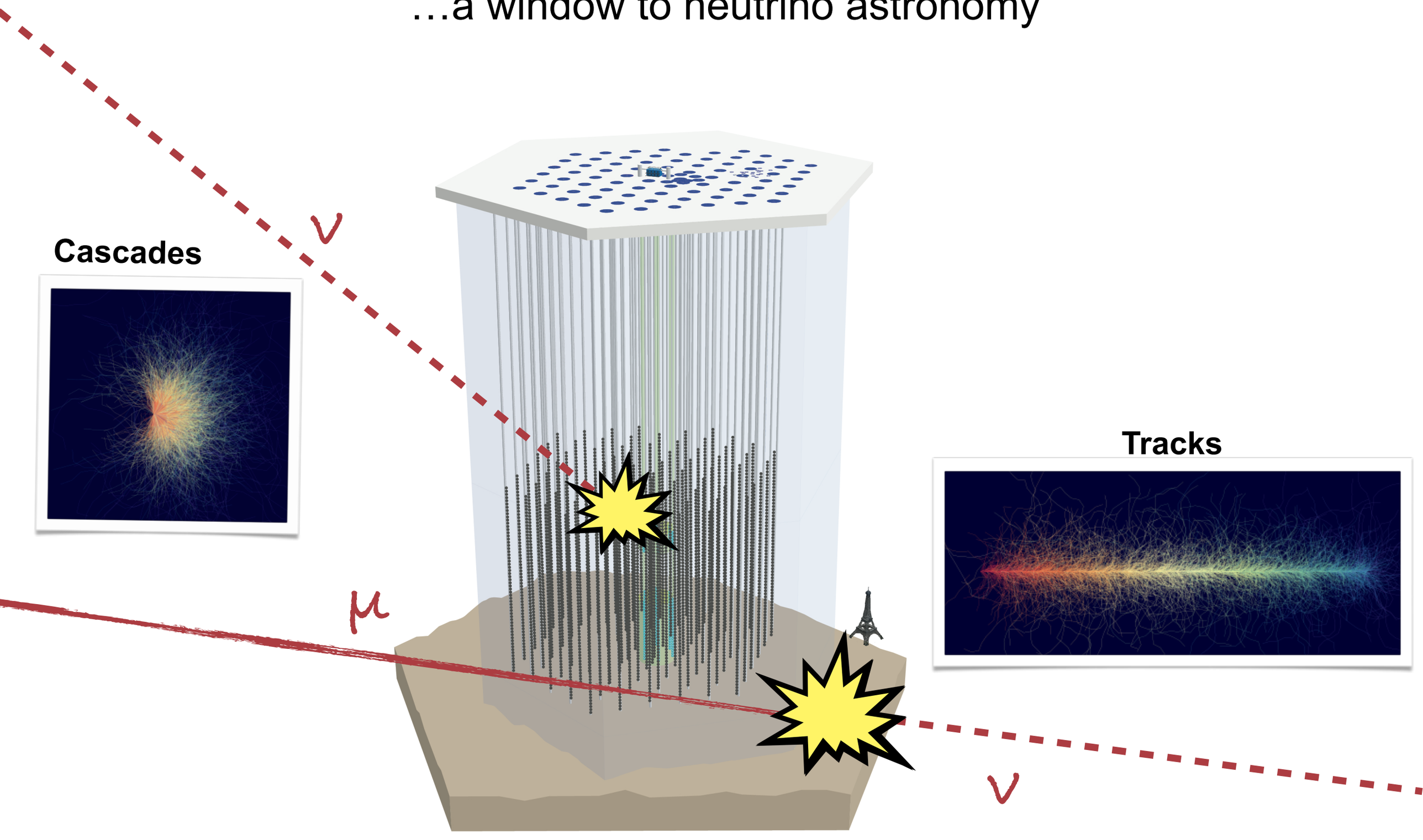
...or why we need the multi-messenger astronomy

Fermi Lat Collaboration Meeting
Pisa, 15th of March, 2018

Theo Glauch
IceCube Collaboration

The IceCube Neutrino Observatory

…a window to neutrino astronomy



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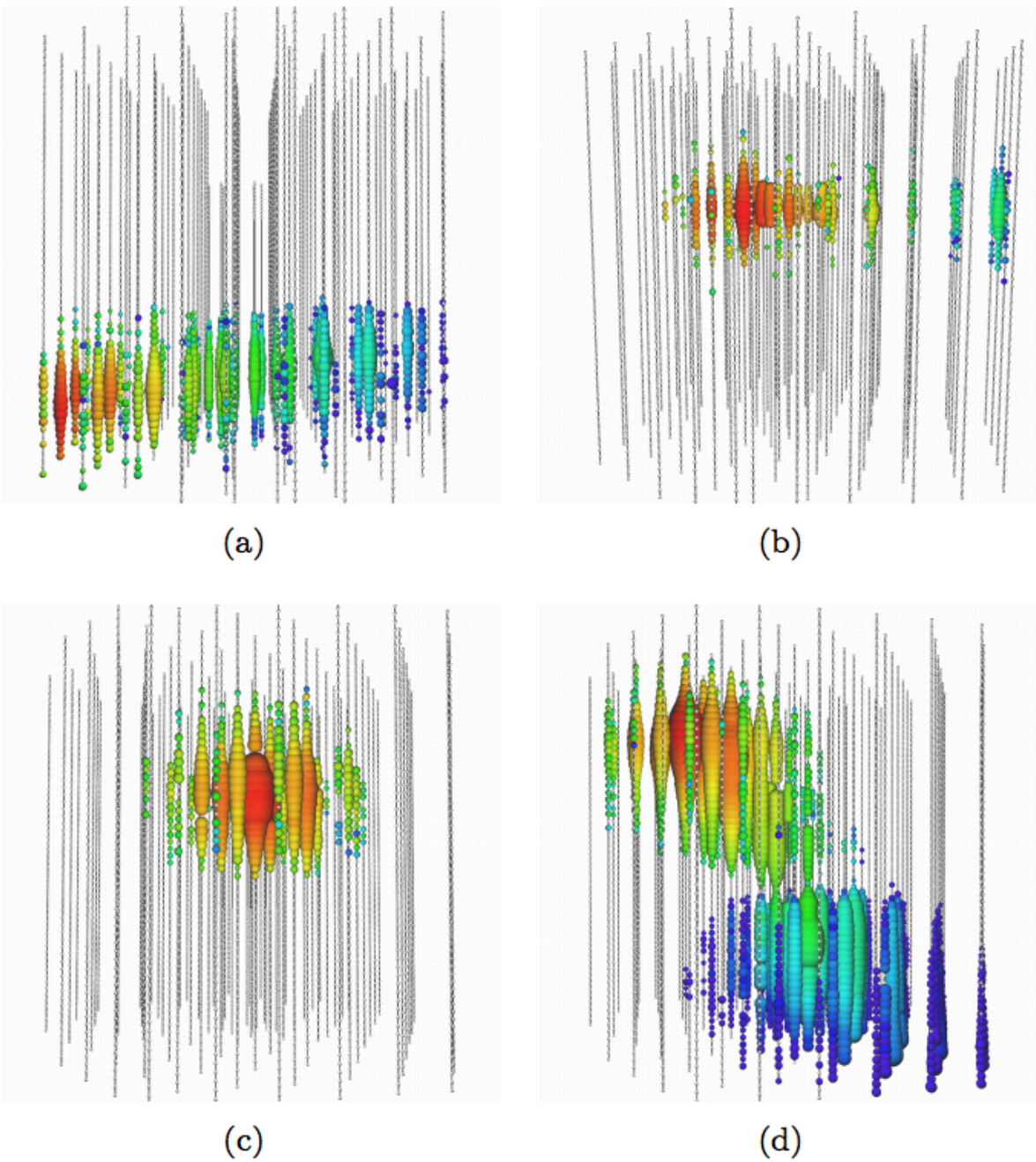
Fermi Collaboration Meeting, Pisa, March 2018

The Important Data Samples

…two ways to look at the sky



Through-Going Muon Sample (a)

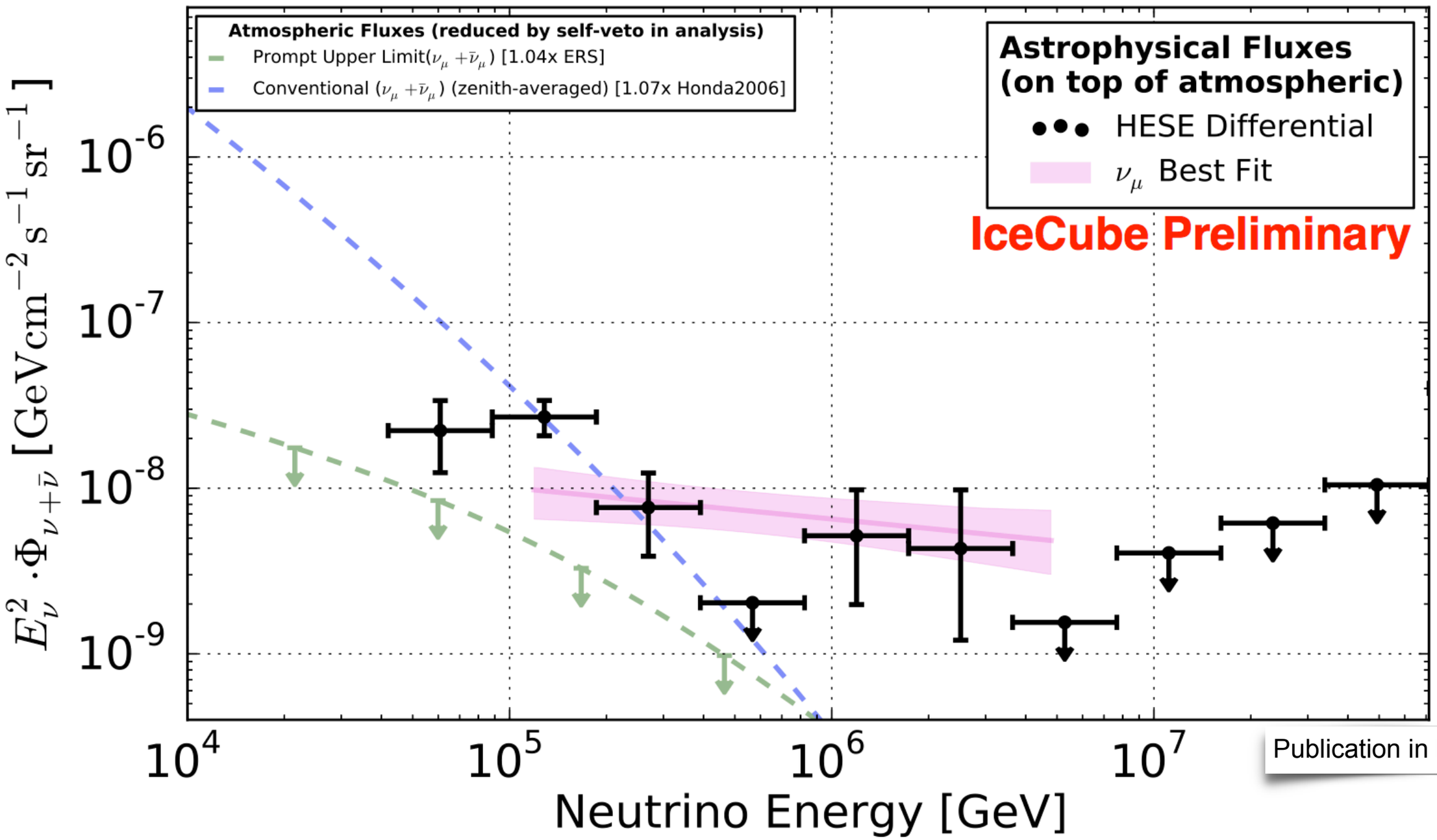
- Bad Energy Resolution
- Angular Resolution ~0.5 deg @ 100TeV
- Good statistics due to large effective detect volume (~80 astro. neutrinos per year)
- Only Northern Hemisphere (δ >-5°)

High Energy Starting Events (b), (c)

- Good Energy Resolution
- Angular Resolution: ~10 deg (Cascades)
- Low Statistics (around 12 events/year)
- All-Sky
- All Flavour

The good news

…there is clear evidence for a flux of astrophysical neutrinos



Publication in Preparation

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Fermi Collaboration Meeting, Pisa, March 2018

The IceCube Neutrino Sky

…8yr time-integrated search for point-sources

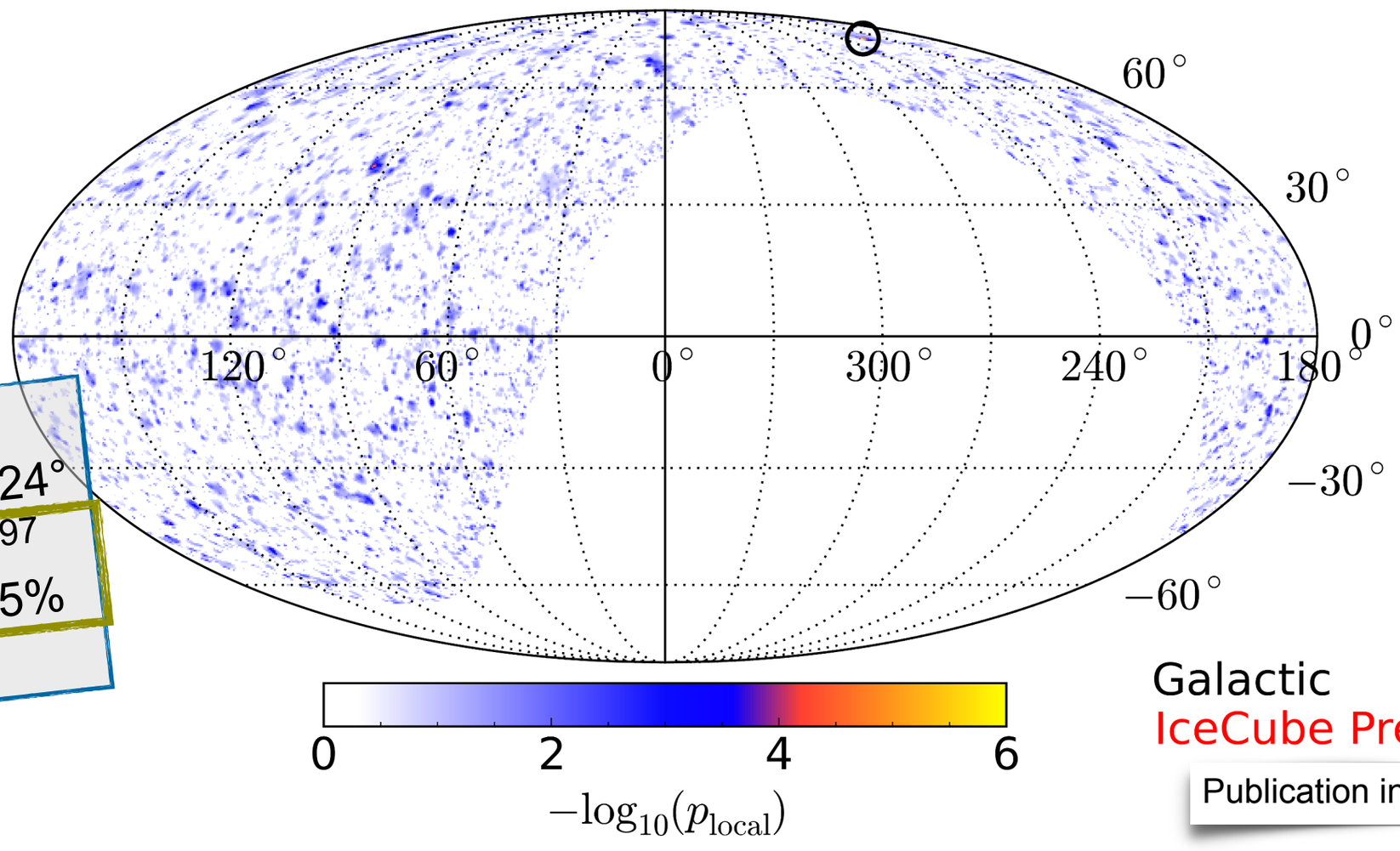
- **Look for a clustering of (high-energy) events at each spot in the sky**

Signal Likelihood

$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\mathbf{x}_s - \mathbf{x}_i|}{2\sigma_i^2}\right) \times \mathcal{E}_s(E_i, \sin\delta_i; \gamma)$$

Background Likelihood

$$\mathcal{B}_i = \frac{\mathcal{P}_B(\sin\delta_i)}{2\pi} \times \mathcal{E}_s(E_i, \sin\delta_i)$$



Hottest Spot:
RA: 177.89°, DEC: 23.24°
Pre-Trial p-value: $10^{-5.97}$
Post-Trial p-value: 26.5%

Galactic
IceCube Preliminary

Publication in Preparation

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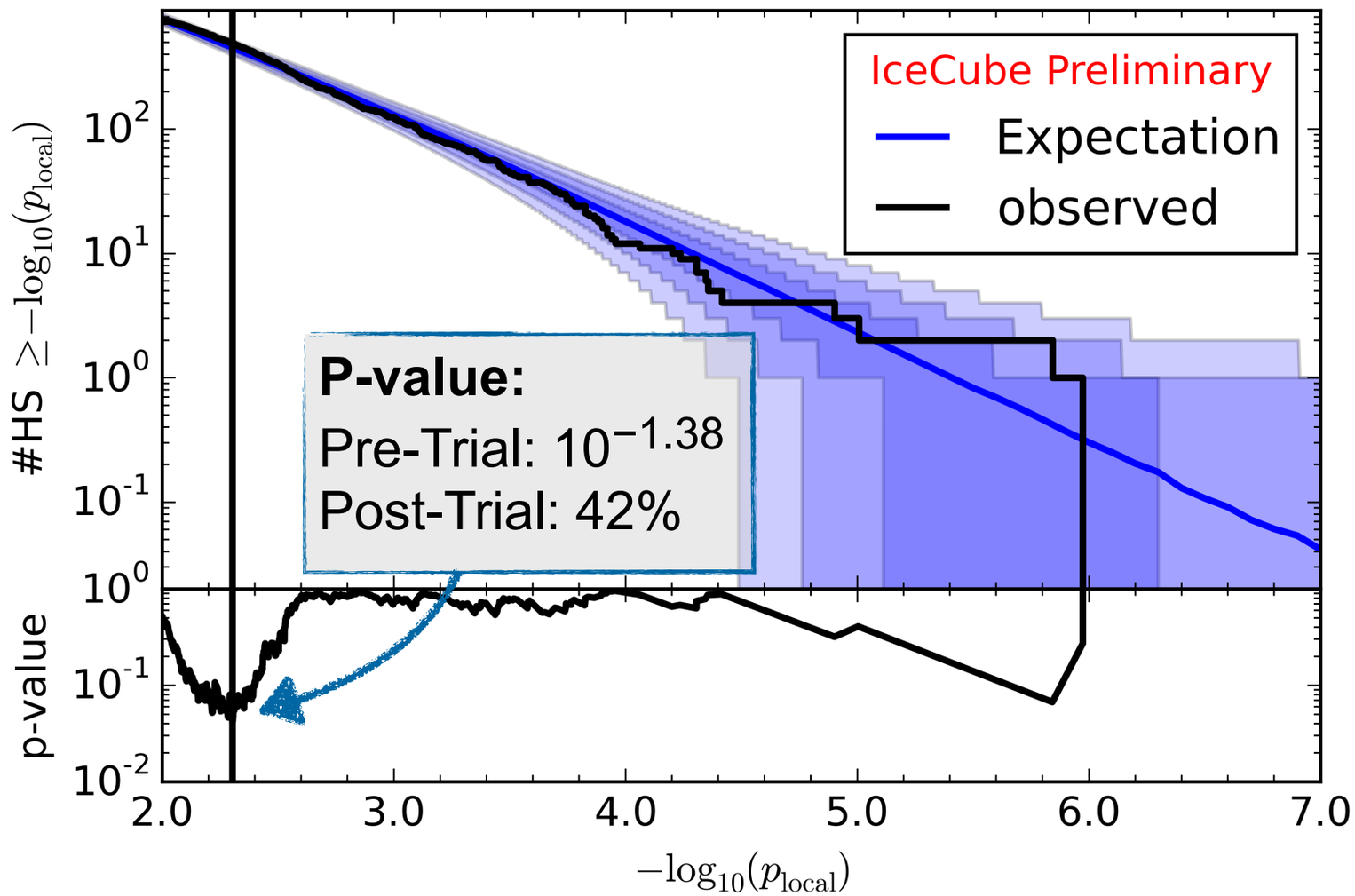
The IceCube Neutrino Sky

…a population of weak sources?

- **Count the number of hotspots above a certain p-value threshold**



Publication in Preparation

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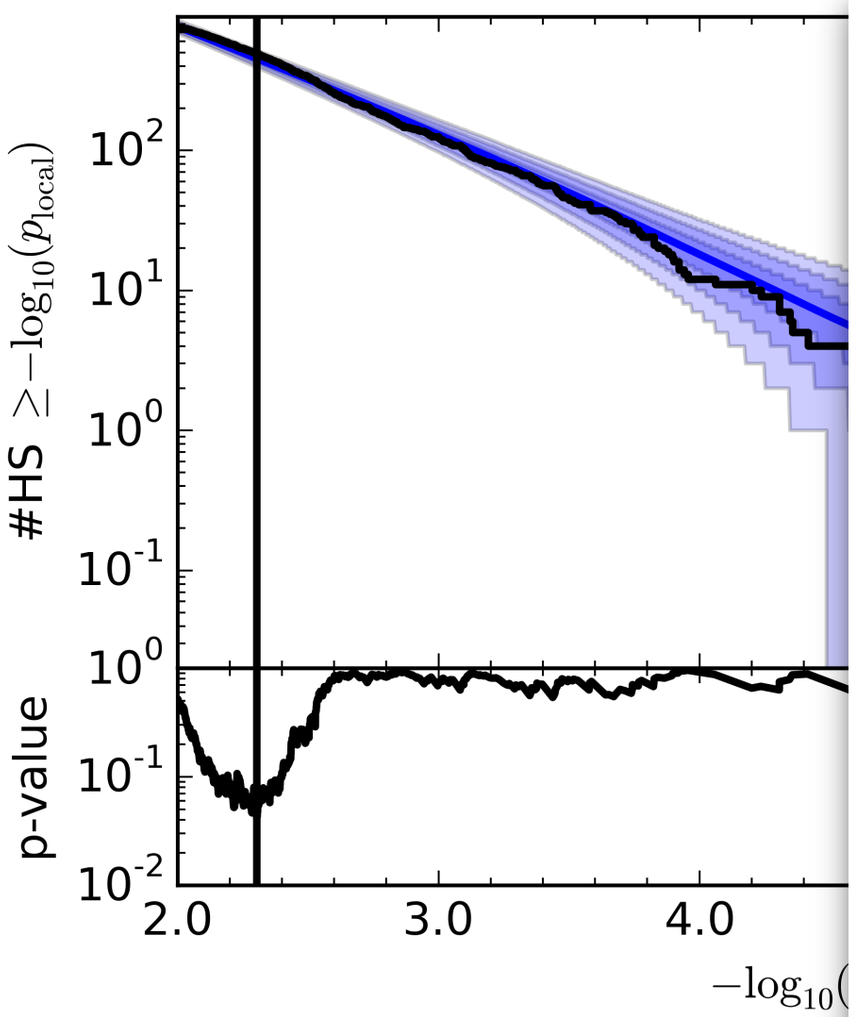
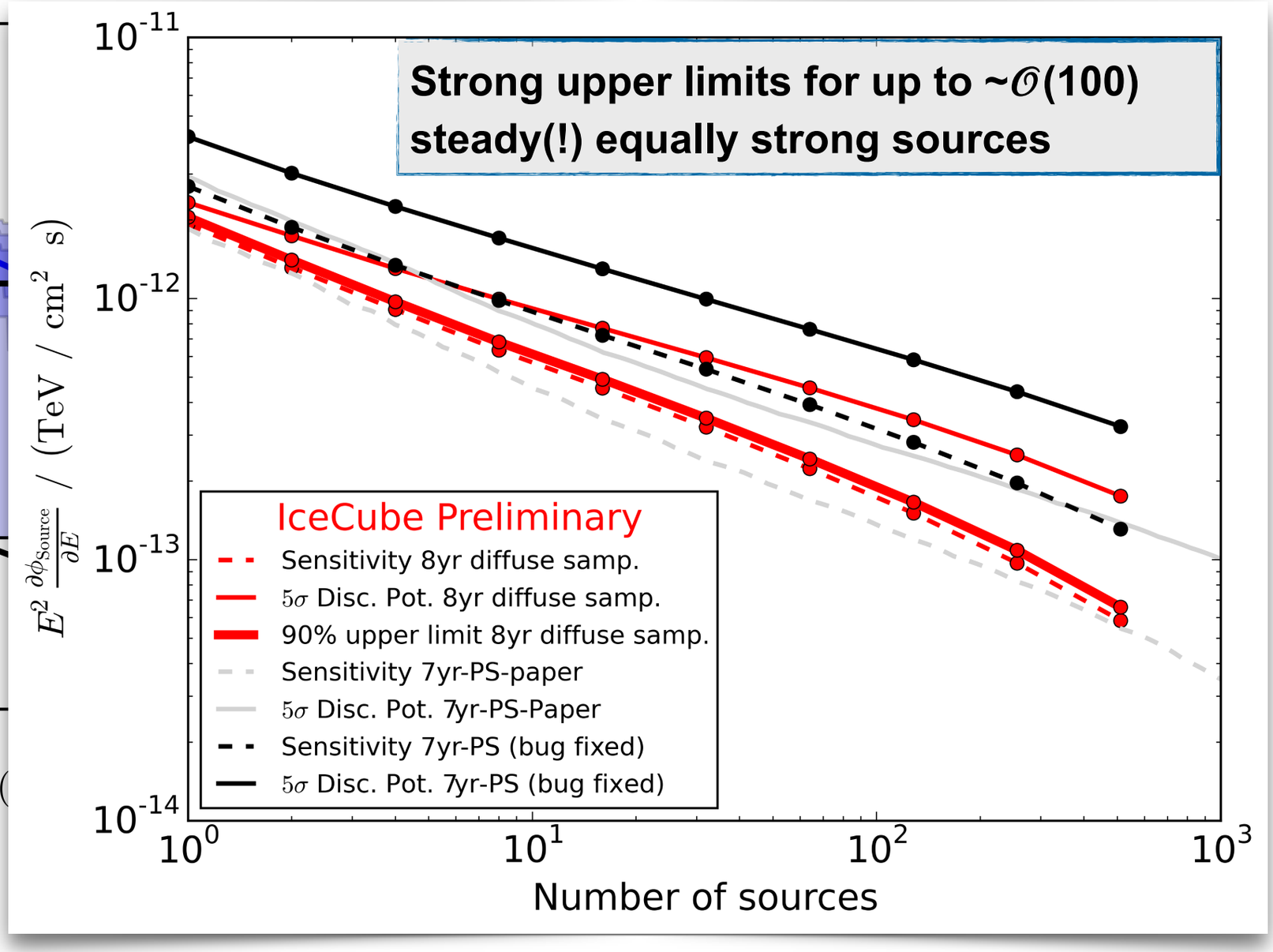
The IceCube Neutrino Sky

…a population of weak sources?

- **Count the number of sources above a certain p-value threshold**



Publication in Preparation



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The IceCube Neutrino Sky

…searching source catalogs

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A predefined source list

Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
3C 273	FSRQ	187.28	2.05	0.4285	-0.3705	0.0000	$2.72 \cdot 10^{-10}$
SS433	XB/mqso	287.96	4.98	0.8455	-8.0055	0.0000	$2.71 \cdot 10^{-10}$
HESS J0632+057	XB/mqso	98.24	5.81	0.5017	-0.7603	0.0000	$2.82 \cdot 10^{-10}$
MGRO J1908+06	NI	286.99	6.27	0.0088	4.7933	2.8153	$7.62 \cdot 10^{-10}$
PKS 1502+106	FSRQ	226.10	10.52	0.3931	-0.1770	0.0000	[illegible]
M87	SRG	187.71	12.39	[illegible]			
PKS 0528+134	[illegible]						
3C4[illegible]							
PKS[illegible]					[illegible]	0.0000	$3.33 \cdot 10^{-10}$
Gem[illegible]	PWN	98.48	17.77	0.7950	-4.7785	0.0000	$3.41 \cdot 10^{-10}$
1ES 0229+200	BL Lac	38.20	20.29	0.6257	-1.6867	0.0000	$3.41 \cdot 10^{-10}$
Crab Nebula	PWN	83.63	22.01	0.3213	-0.0197	0.0000	$4.74 \cdot 10^{-10}$
IC443	SNR	94.18	22.53	0.9620	-16.4154	0.0000	$3.63 \cdot 10^{-10}$
W Comae	BL Lac	185.38	28.23	0.5961	-1.0769	0.0000	$3.88 \cdot 10^{-10}$
3C 123.0	SRG	69.27	29.67	0.9056	-8.2916	0.0000	$4.11 \cdot 10^{-10}$
Cyg X-1	XB/mqso	299.59	35.20	0.6170	-1.0639	0.0000	$4.31 \cdot 10^{-10}$
MGRO J2019+37	PWN	305.22	36.83	0.9784	-17.6070	0.0000	$4.54 \cdot 10^{-10}$
4C 38.41	FSRQ	248.81	38.13	0.0080	5.0893	7.6911	$1.27 \cdot 10^{-09}$
Mrk 421	BL Lac	166.11	38.21	[illegible]			
Mrk 501	[illegible]						
Cyg[illegible]							
Cyg[illegible]					[illegible]	4.3301	$8.20 \cdot 10^{-10}$
Cyg[illegible]	SNR	308.09	41.23	0.1706	0.2554	2.8184	$7.64 \cdot 10^{-10}$
NGC 1275	SRG	49.95	41.51	0.2447	0.0230	0.4985	$6.96 \cdot 10^{-10}$
BL Lac	BL Lac	330.68	42.28	0.5378	-0.4766	0.0000	$4.78 \cdot 10^{-10}$
H 1426+428	BL Lac	217.14	42.67	0.7587	-2.5100	0.0000	$4.86 \cdot 10^{-10}$
3C66A	BL Lac	35.67	43.04	0.4265	-0.1089	0.0000	$5.44 \cdot 10^{-10}$

The most significant sources have a post-trial p-value of ~25%

Publication in Preparation

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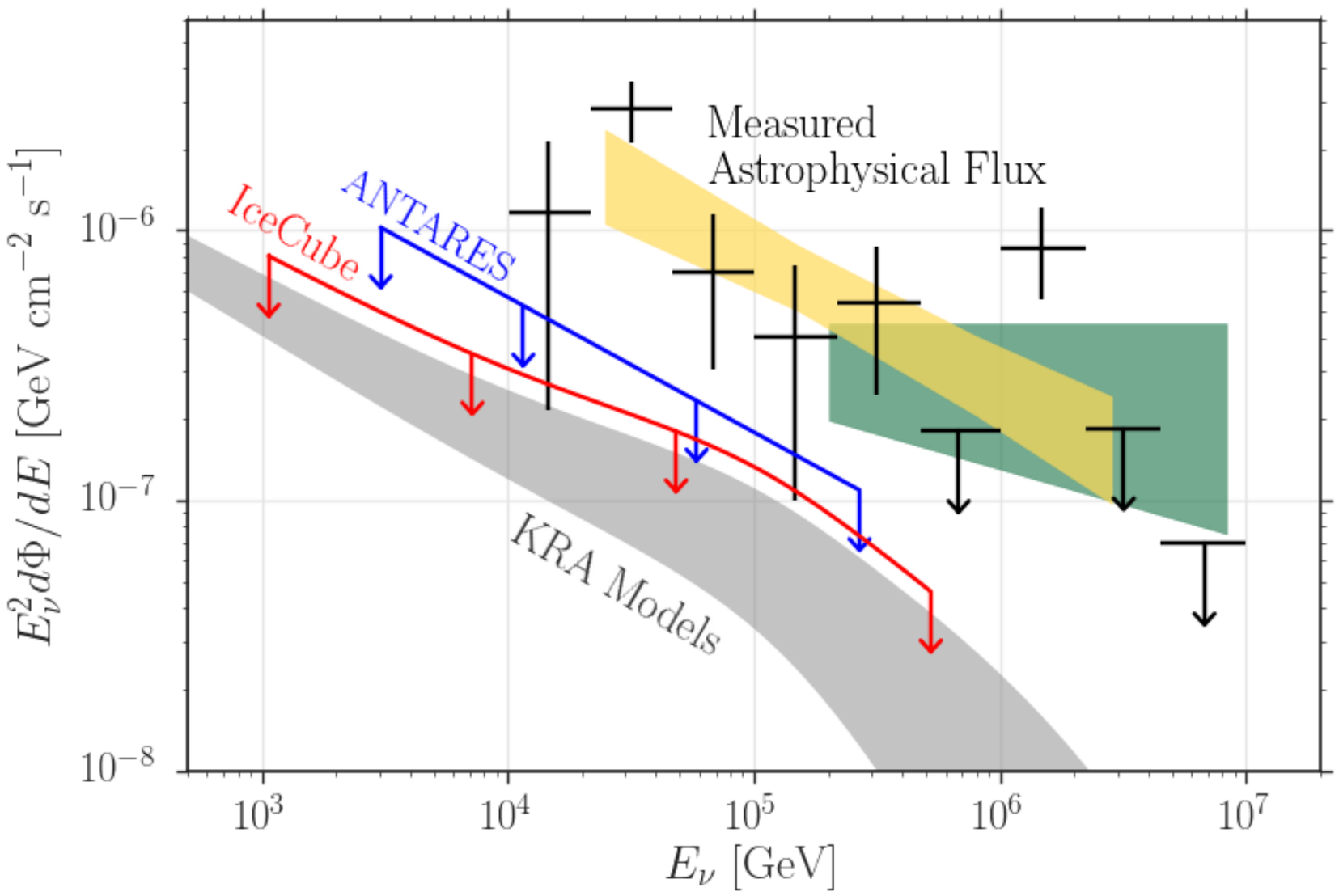
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

The IceCube Neutrino Sky

…diffuse emission from the galactic plane

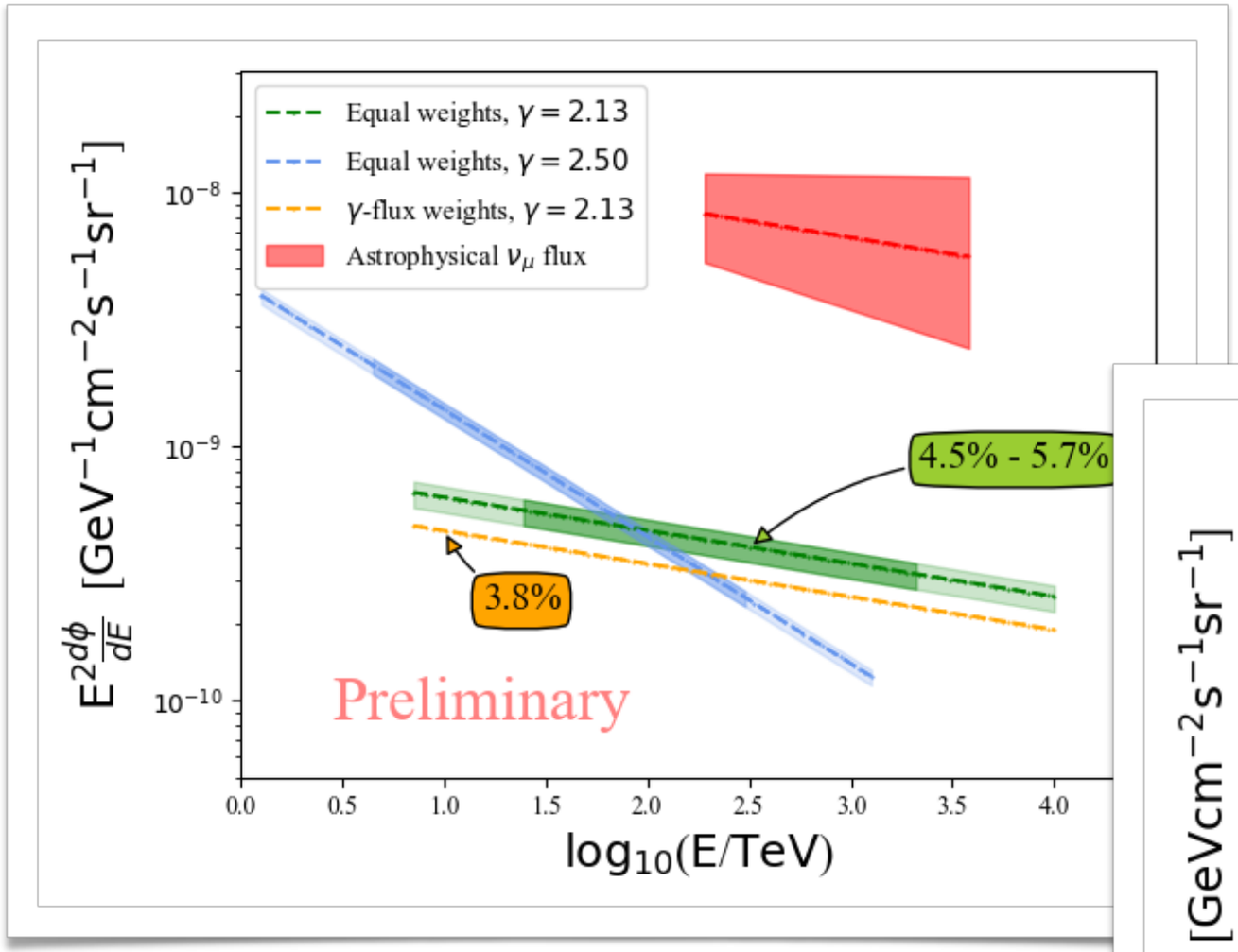
- Search for a neutrino flux from the interaction of Galactic cosmic-rays with the ambient interstellar gas
- Assume cosmic-ray flux with cut-off at 5, 50 PeV (KRA Model)
- Galactic contribution is limited to **~14%** of the diffuse neutrino flux for an $E^{-2.5}$ spectrum



Published in
PoS(ICRC2017)1011

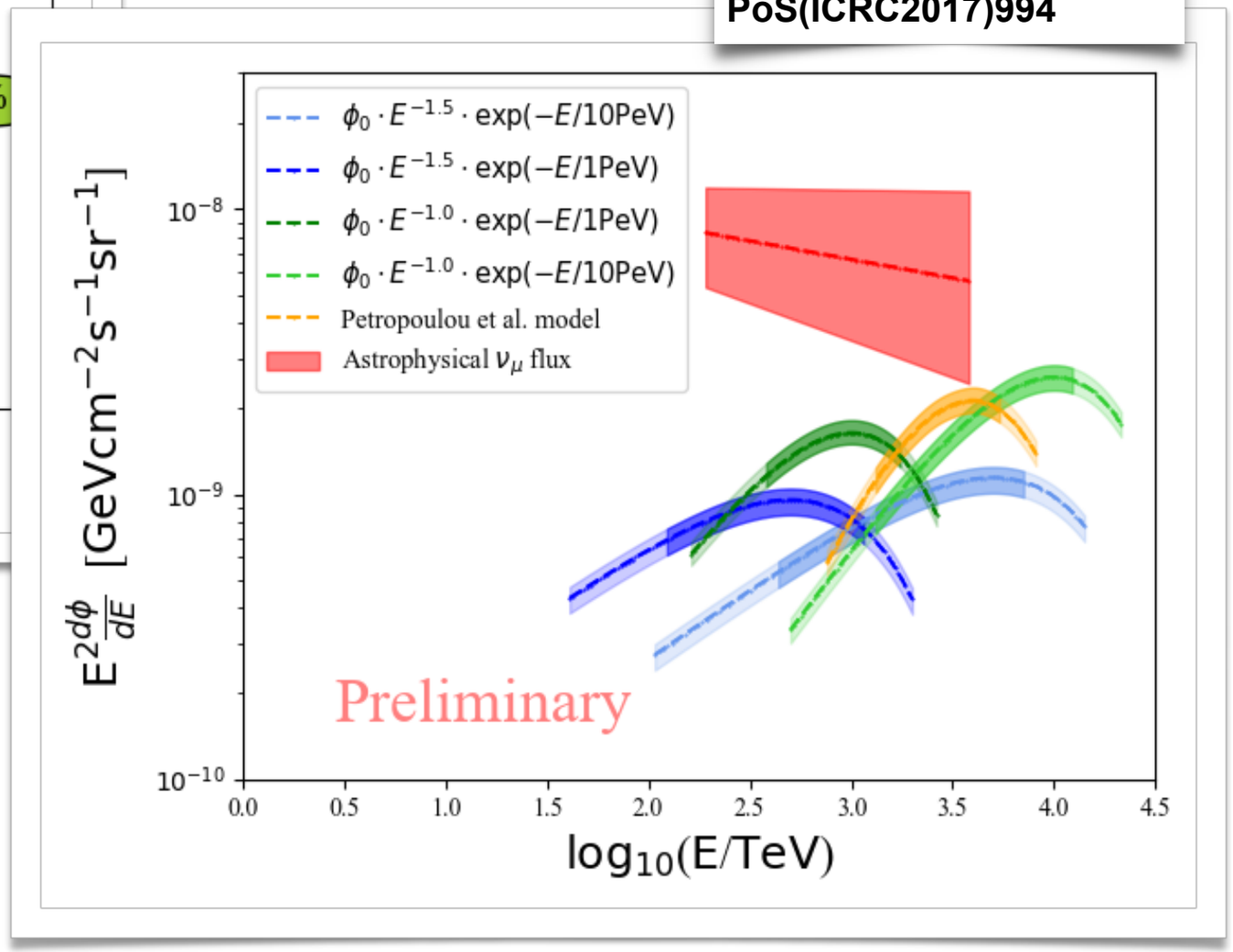
The IceCube Neutrino Sky

…a significant Blazar component?



Use a sample of 2FGL identified blazer positions to search for an cumulative (*stacked*) neutrino emission

Published in **PoS(ICRC2017)994**



Precise limit depends strongly on the assumed spectral shape!

Blazars contribute 80% to the gamma-ray background but less than 30% to the diffuse neutrino flux

Summary I

- We have evidence for an astrophysical neutrino signal in various detection channels
- **Until now, <u>no source</u> or <u>source class</u> of astrophysical neutrinos has been identified**
- A search for a population of up to ~500 *steady, equally strong* sources has shown no significant excess
- Strong limits have been placed on the contribution from most promising candidate source classes

Neutrinos <u>alone</u> might not give us the answer about their origin…

Multi-Messenger Searches

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- **Archival (Offline) Analysis**
  - Use a model derived from one or several Multi-Messenger Observations
  - Build a statistical test which weights the neutrino sources according to the model assumption
  - Look for weak neutrino signal from entire source population
  - PRO: sensitive to weak sources and able to test specific physic scenarios
  - CON: Result is strongly model dependent, possible incompleteness of the multi-wavenglength data

- **Realtime Analysis**
  - Use special neutrino events (or clusterings) in order to trigger follow-up observations in a broad wavelength band
  - Is able to detect classes of transient (and unknown) source
  - Identification of the source through electro-magnetic counterpart
  - PRO: transient sources will not be missed, unexpected counterparts can be found, collecting time-synchronized data
  - CON: technically challenging to run analysis in real-time

IceCube Realtime Streams

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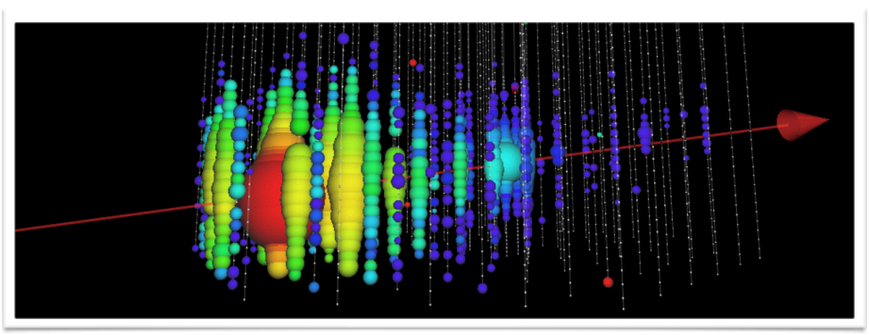
TUM

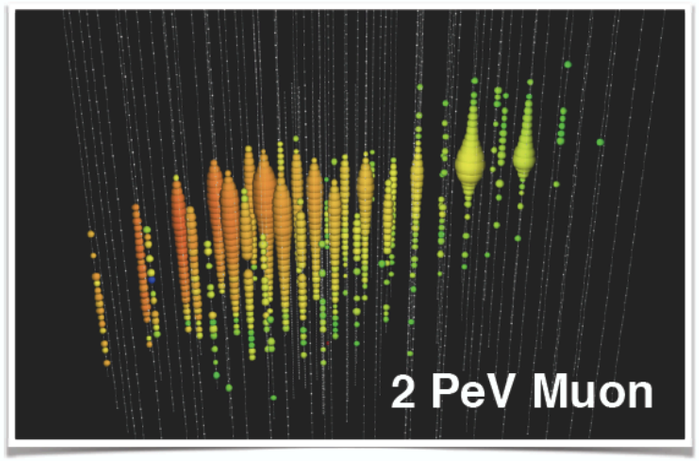
HESE-Stream

- Starting Tracks with high energies
- Starting tracks with Q > 6000 P.E.
- Expensive reconstruction (revised alerts after few h)
- ~ 3.5 events/year



EHE-Stream

- Through-going muon tracks with extremely-high energies
- Combination of charge and zenith cut ⟶ high purity
- 4-6 events/year



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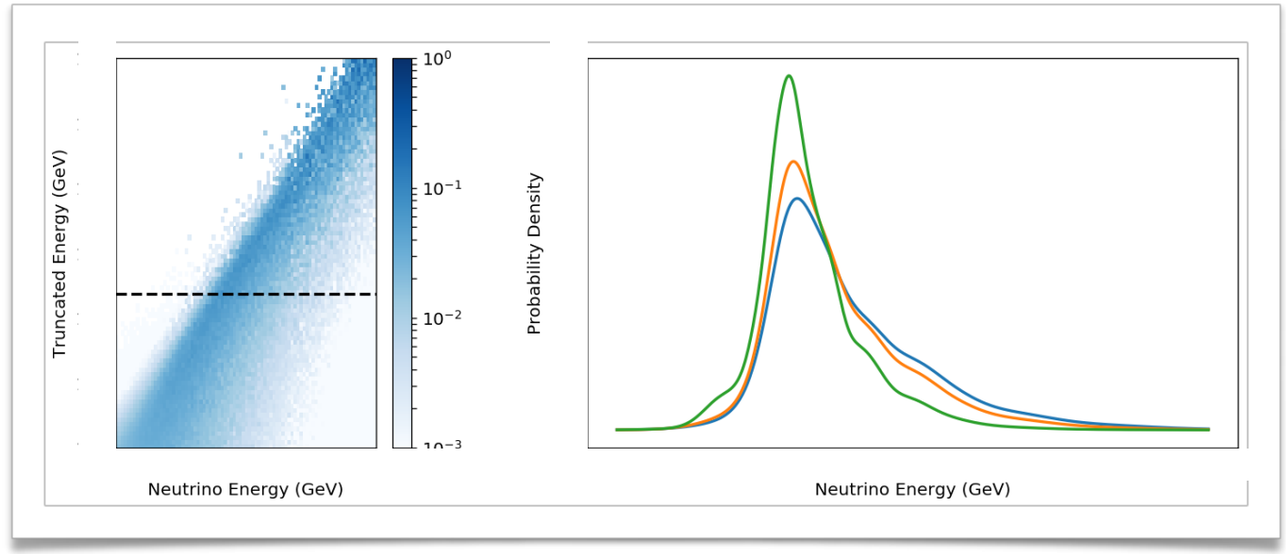
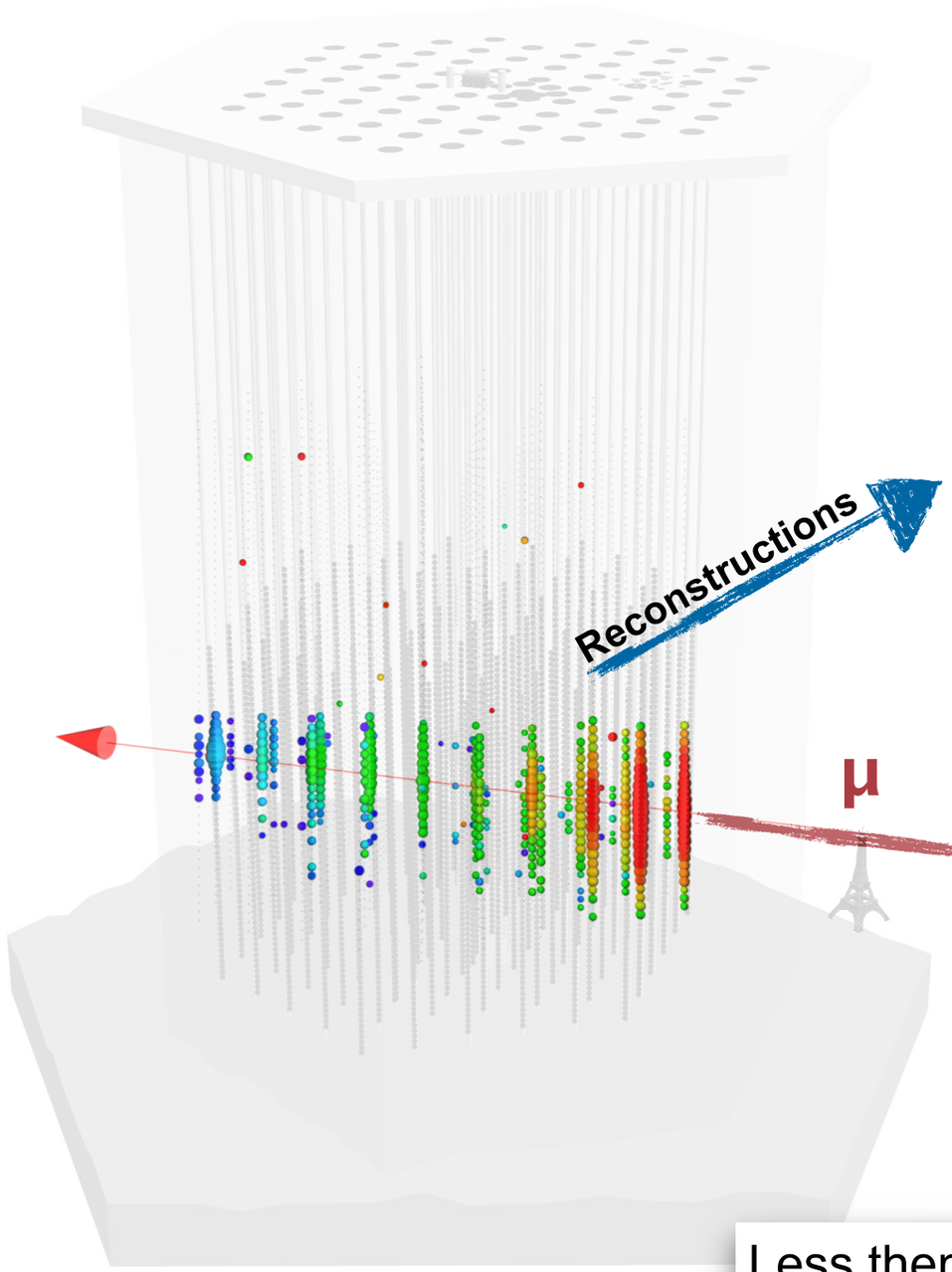
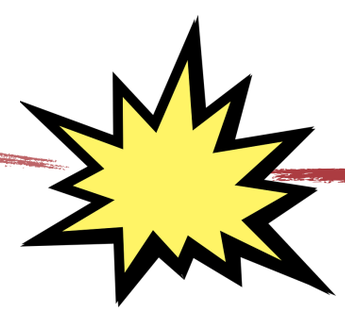
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

The few very special ones

…EHE Event IC170922







ν

AMON

IC170922A:

Passed EHE Alert Filter

Neutrino Energy: 120 TeV
(90% Lower Limit)

RA: 77.28, DEC: 5.75

Signalness: ~57%

Less then **0.1 degrees** away from the event location a known Blazar TXS 0506+056 was identified.

The few very special ones

…EHE Event IC170922

43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

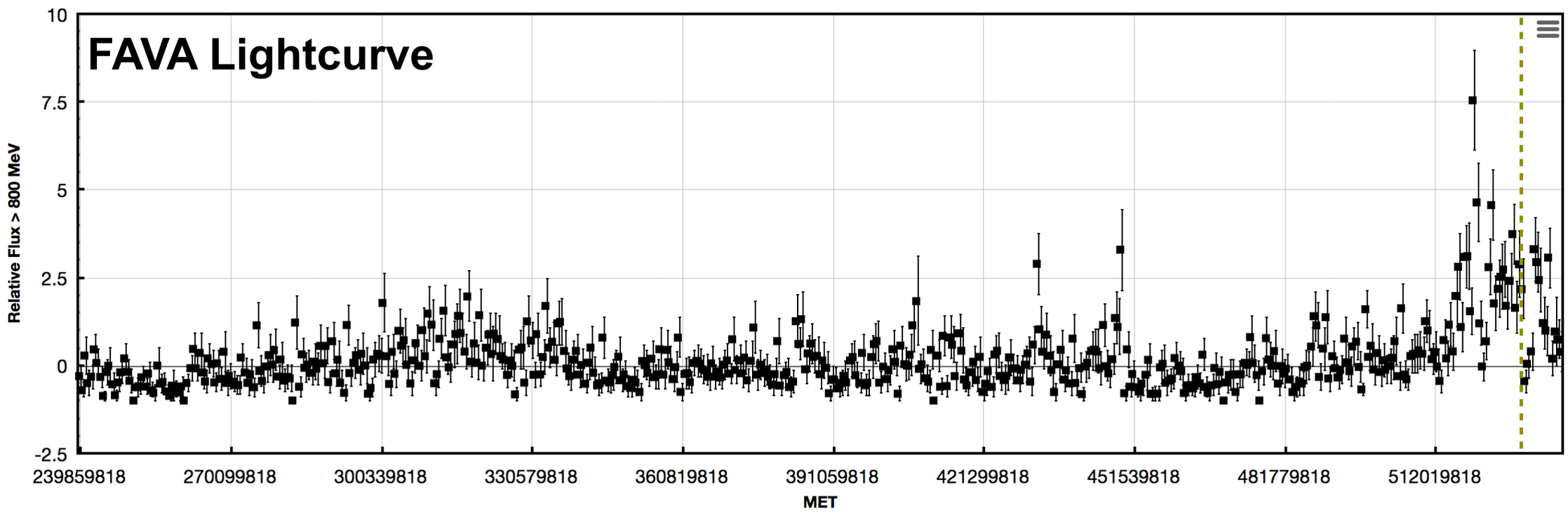

Theo Glauch
Fermi Collaboration Meeting, Pisa, March 2018

The few very special ones

…EHE Event IC170922A

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)



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The few very special ones

…EHE Event IC170922A

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube

ATel #1079

Further Swift-XRT observations of IceCube 170922A

ATel #10792; P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:
on 28 Sep 2017; 11:57 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

First observation: ~3h after the neutrino trigger, 9 sources identified

Second observation: Additional observational time, hint for spectral evolution?

The few very special ones

…EHE Event IC170922A

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

…bservations of IceCube 170922A

…Kennea (PSU), D. B. Fox (PSU), …FC) report on behalf of

…c.uk)

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson (OSU), T. W.-S. Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)*

on ***28 Sep 2017; 18:00 UT***

Credential Certification: Krzysztof Stanek (stanek.32@osu.edu)

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The few very special ones

…EHE Event IC170922A

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

Swift-XRT observations of IceCube 170922A

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

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)

5 sigma detection above 100 GeV was achieved after 12 h of observations from Sept. 28th till Oct. 3rd

The few very special ones

…EHE Event IC170922A

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

ASAS-SN optical light curve

Swift-XRT observations of 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)

The redshift of the BL Lac object TXS 0506+056

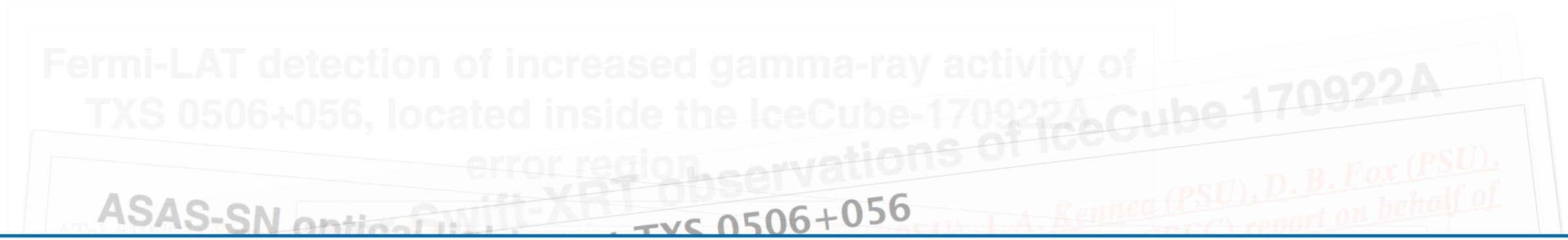
Simona Paiano, Renato Falomo, Aldo Treves, Riccardo Scarpa

(Submitted on 6 Feb 2018)

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 \AA, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW ~ 0.1 \AA) emission lines that we identify with [O II] 3727 \AA, [O III] 5007 \AA, and [N II] 6583 \AA, yielding the redshift z = 0.3365±0.0010.

The few very special ones

…EHE Event IC170922A



Open Questions

- What is the chance probability? → Fermi-LAT all-sky data are crucial
- Are there more (low-energy) neutrinos from this source?
- Can we model the multi-wavelength data in a consistent way?

Yesterday night…

Fermi-LAT detection of enhanced gamma-ray activity and hard spectrum of TXS 0506+056, located inside the IceCube-170922A error region

ATel #11419; ***Roopesh Ojha (NASA/GSFC/UMBC), and Janeth Valverde (LLR/Ecole Polytechnique) on behalf of the Fermi Large Area Telescope Collaboration***
*on **14 Mar 2018; 20:16 UT***
Credential Certification: Roopesh Ojha (Roopesh.Ojha@gmail.com)

Summary

2013

"In summary, it may be too early to speculate."

Francis Halzen

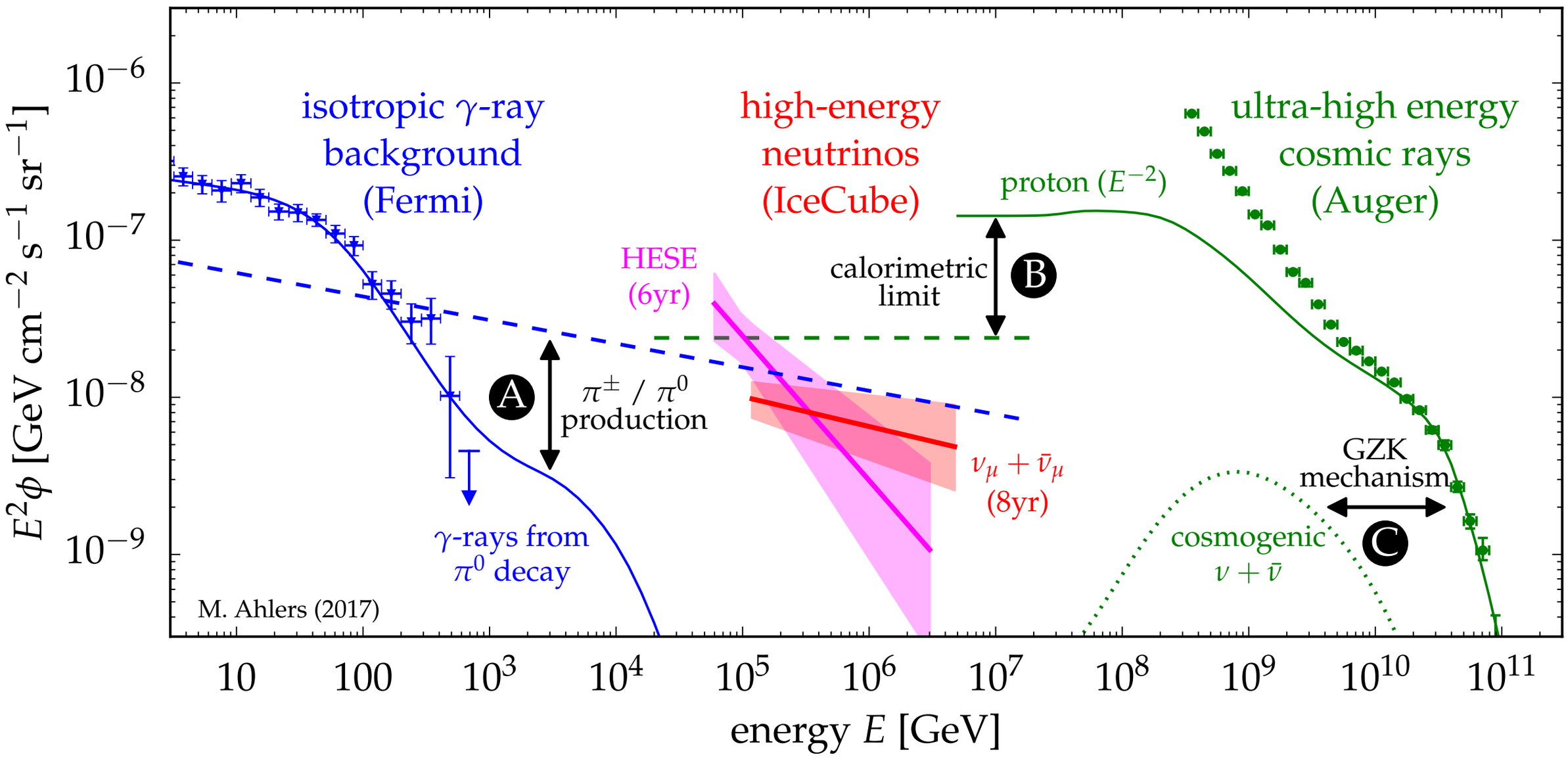
2018

- Evidence for an astrophysical neutrino flux
- Yet, no neutrino source has been identified
- …but we are on the way, *speculation is welcome*

Backup

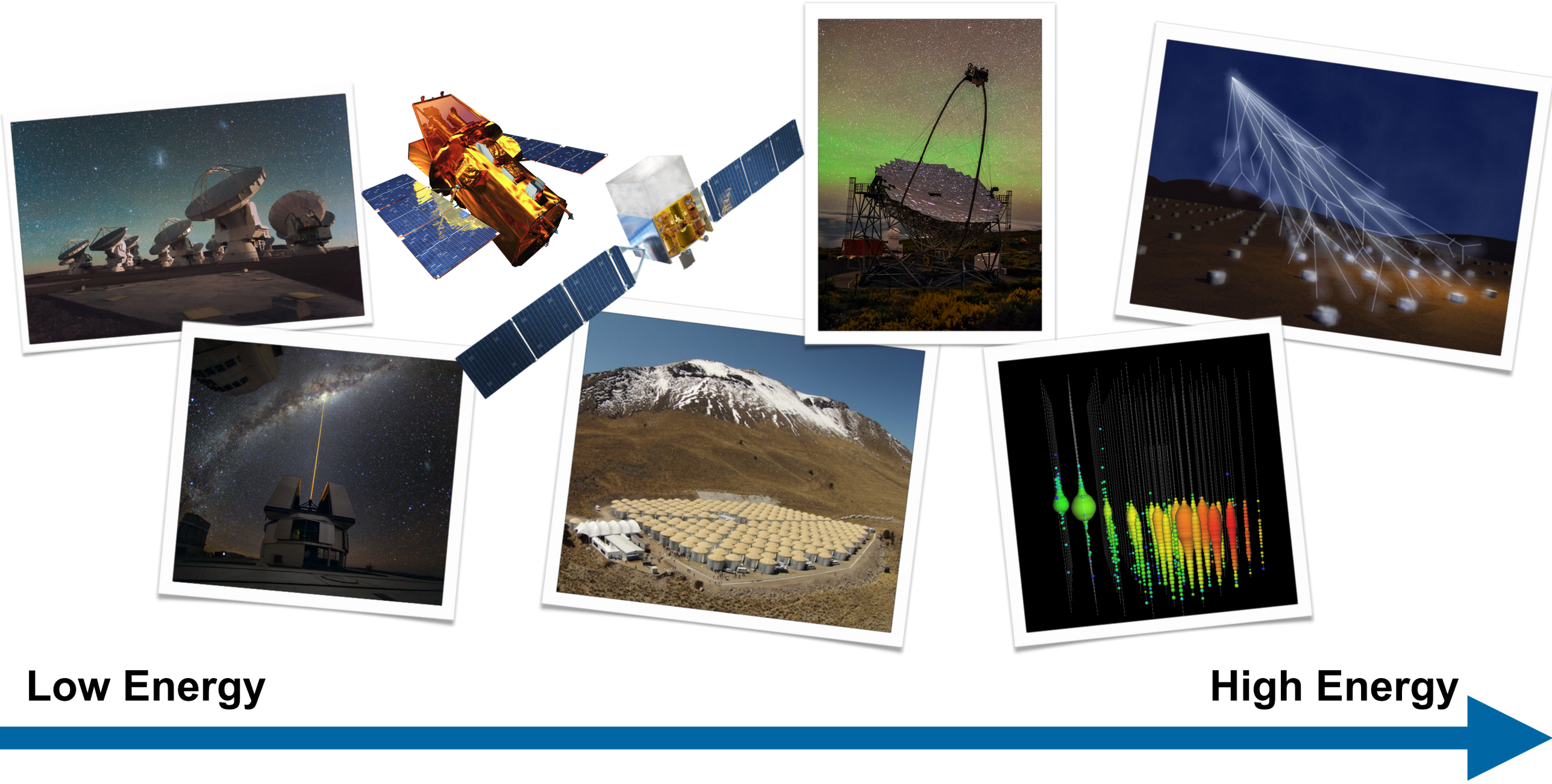
Neutrino Astronomy

…in the context of cosmic radiation



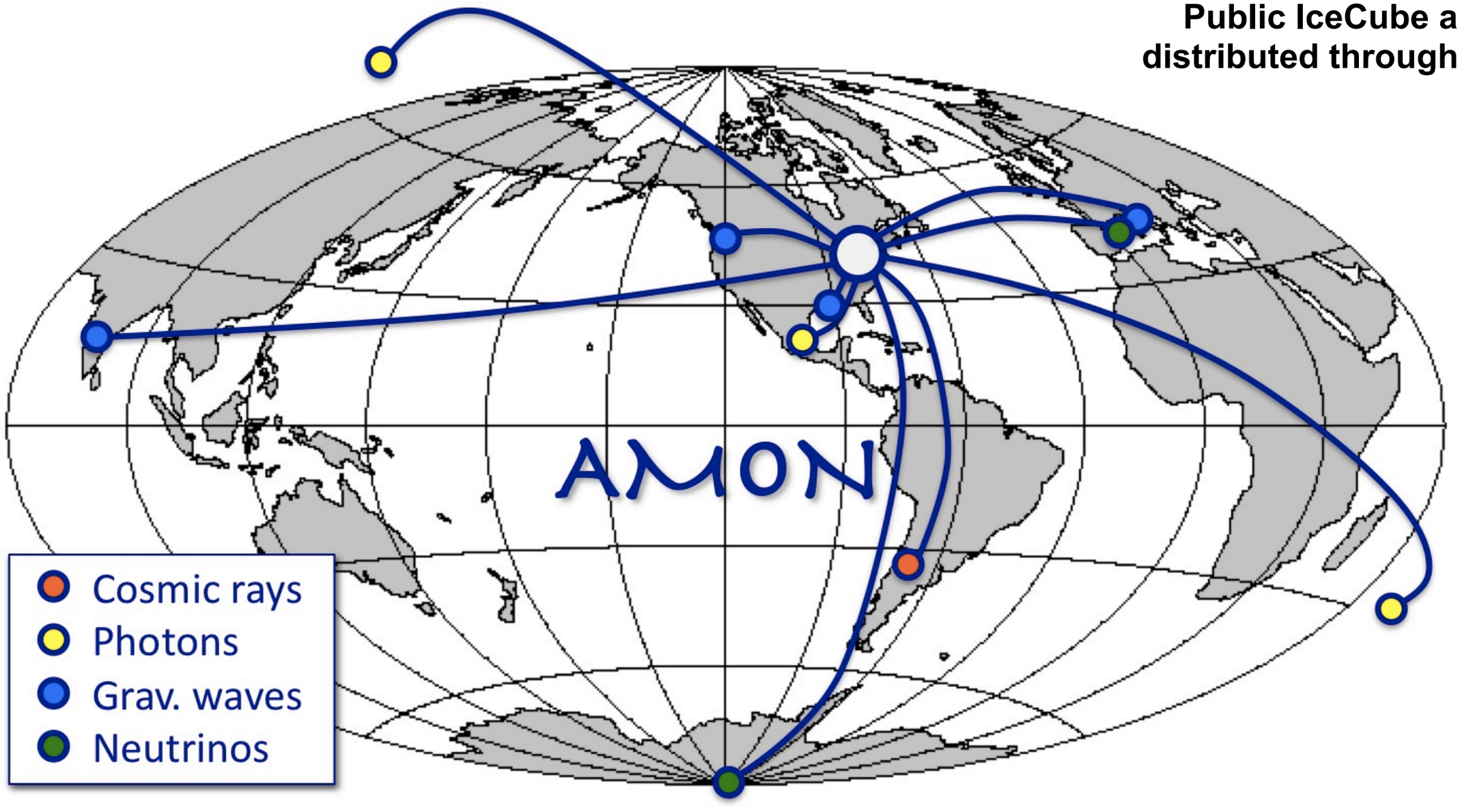
The Multi-Messenger Era

…gigantic amount of information over a large energy range



Astrophysical Multimessenger Observatory Network

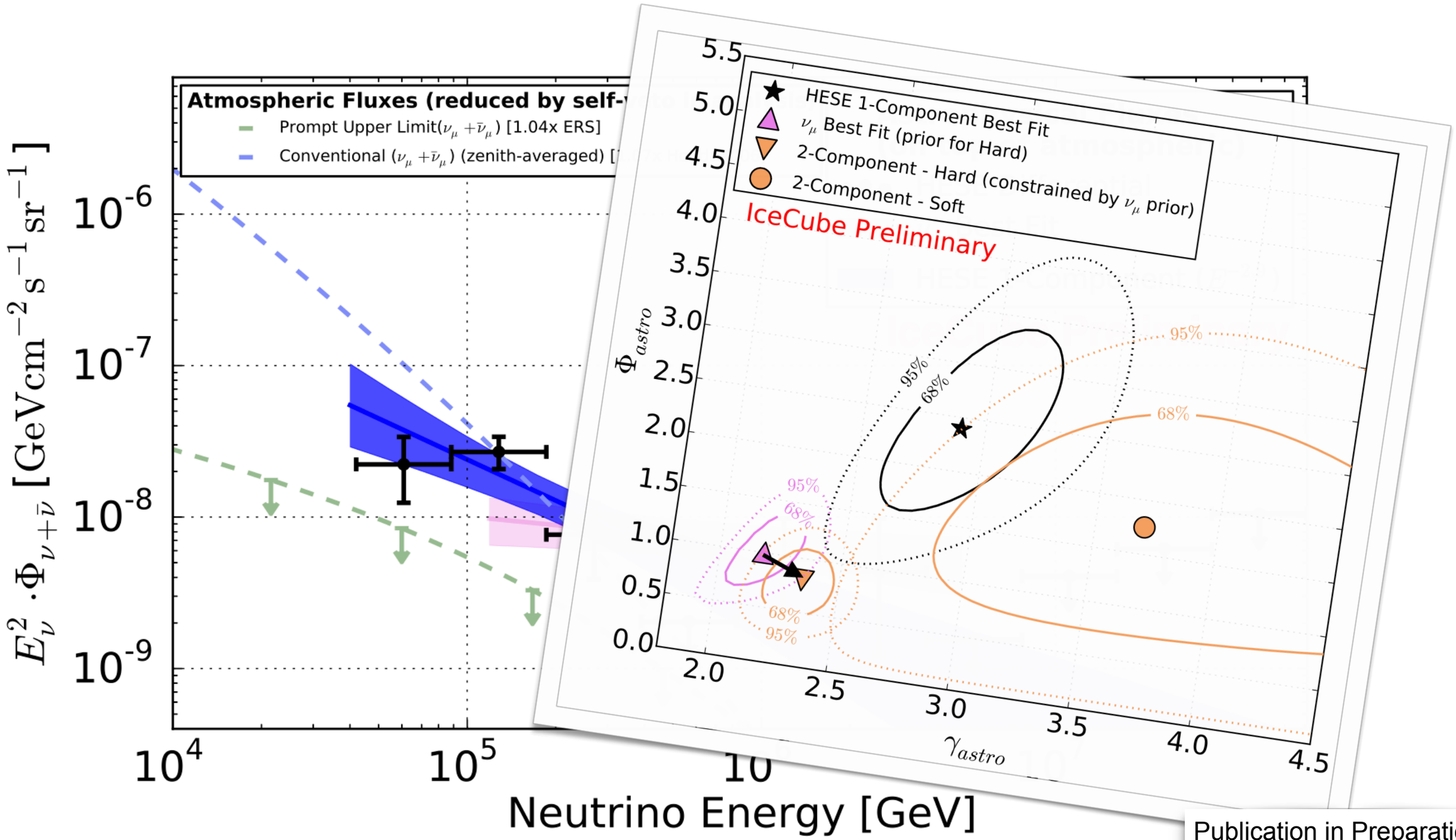
Public IceCube alerts distributed through AMON



http://sites.psu.edu/amon/
Keivani, et al., PoS(ICRC2017) 629

Single Powerlaw?

…fitting with a second component not yet conclusive



Publication in Preparation

Theo Glauch
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