HIGHLIGHTS FROM

ICECUBE

J. A. Aguilar on behalf IceCube

ULB iihe

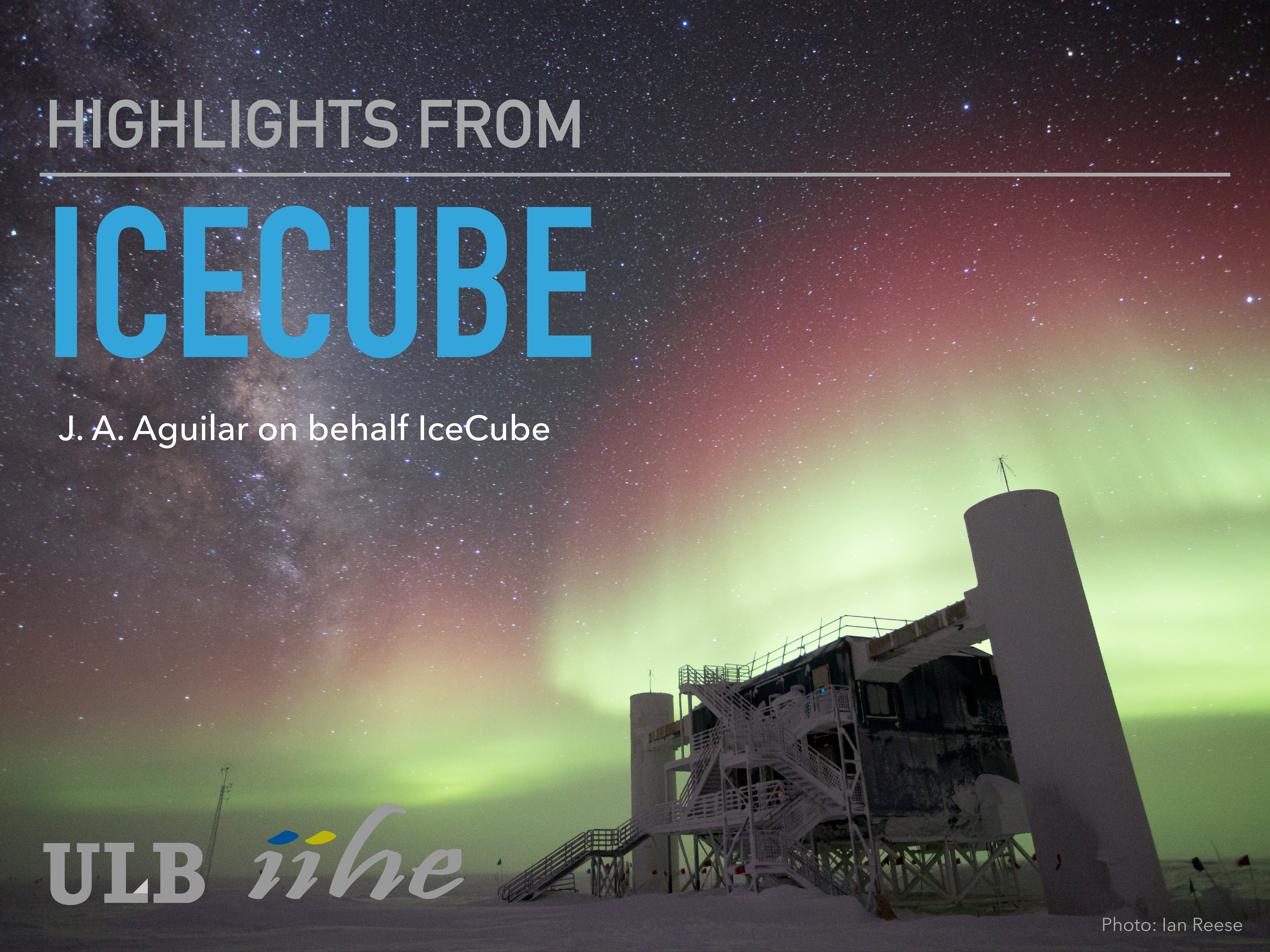


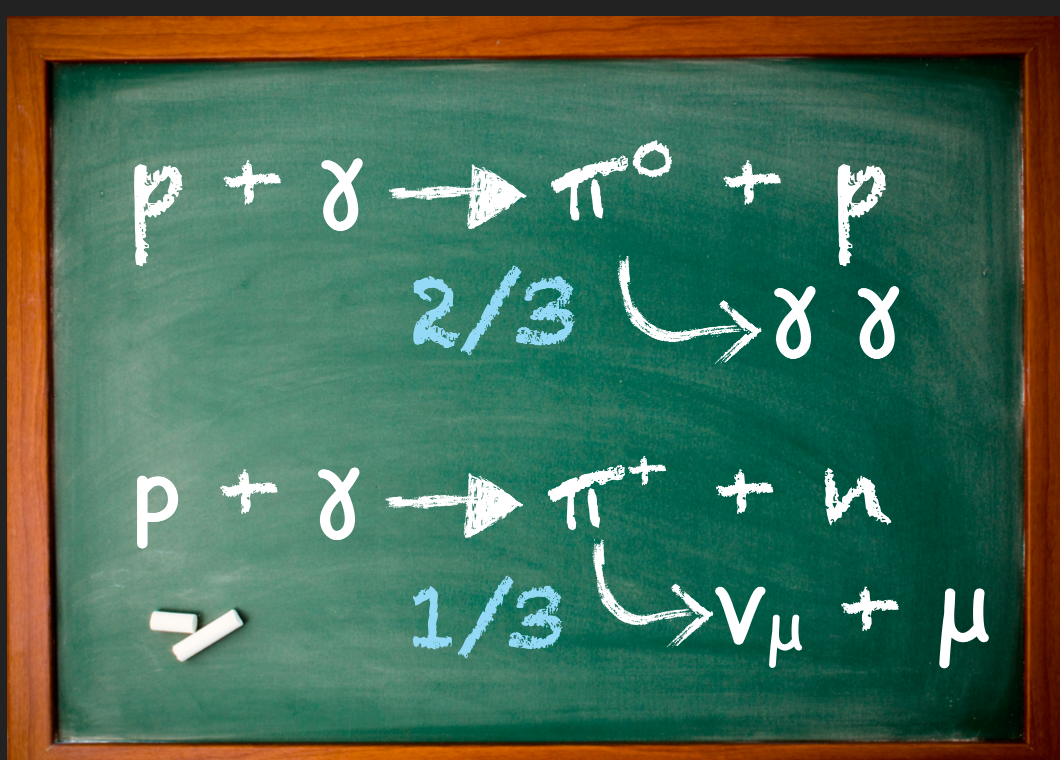
Photo: Ian Reese

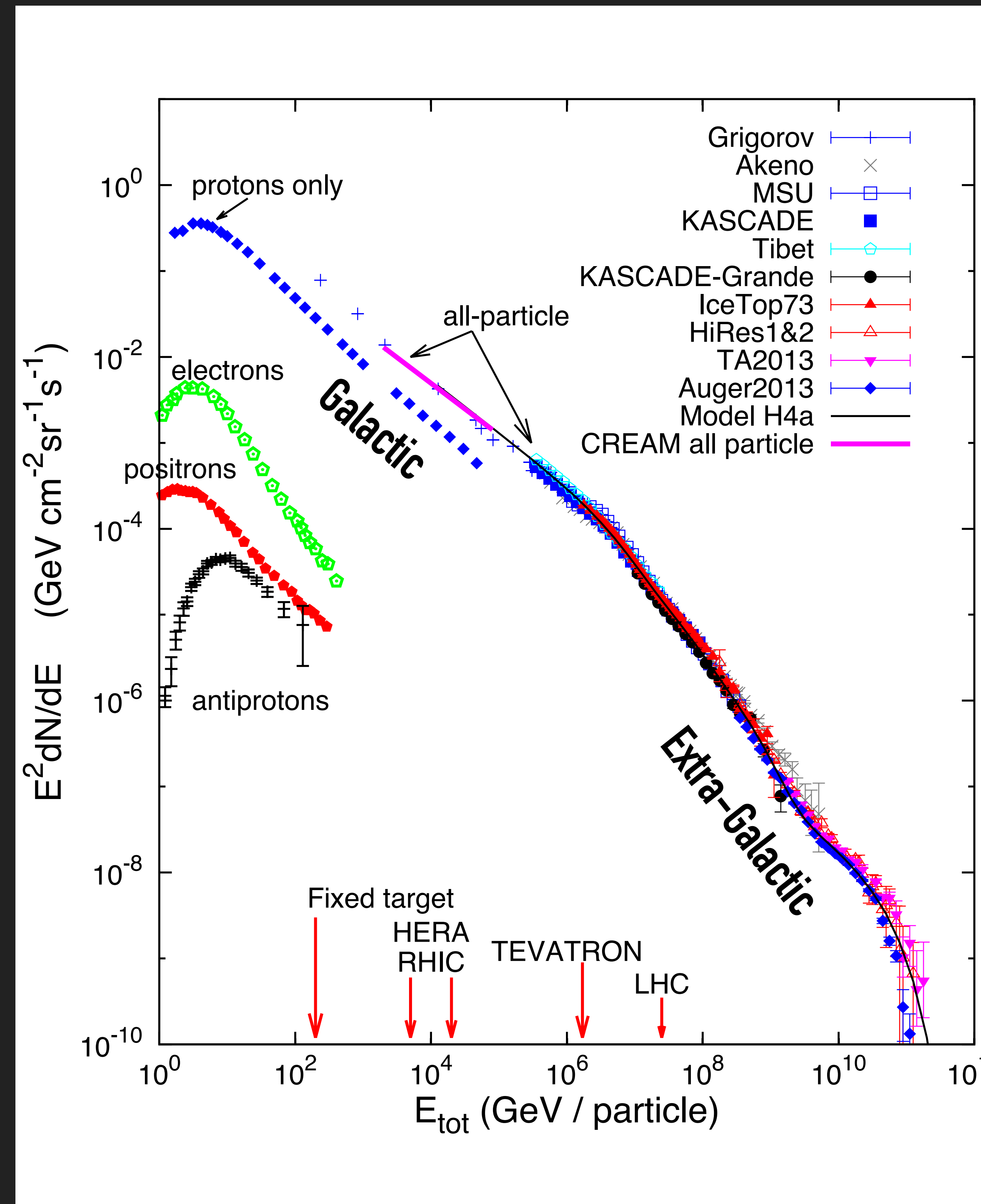
OUTLINE

- Introduction: Cosmic Rays and Neutrinos
- The IceCube Neutrino Telescope
- Results from IceCube: Astrophysical Neutrinos
- Conclusions

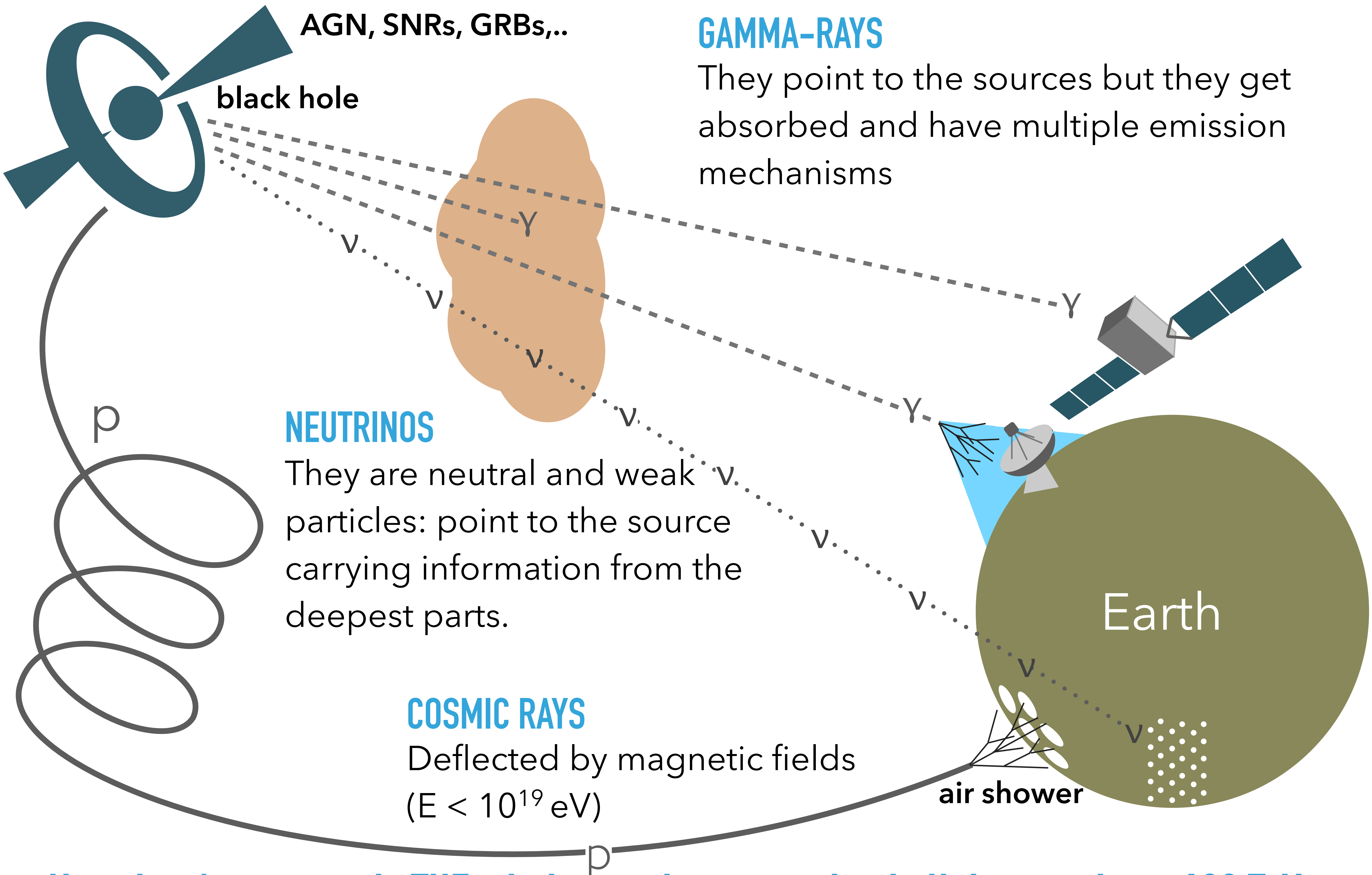
THE COSMIC-RAY MYSTERY

- Cosmic Rays discovered by Victor Hess (and others) in 1912
- Cosmic Rays spectrum spans 10 decades of energy. Origin still unknown.
    - Galactic CRs: Supernova remnants?
    - Extra-Galactic CRs: AGNs, GRBs, magnetars?





COSMIC MESSENGERS



GAMMA-RAYS

They point to the sources but they get absorbed and have multiple emission mechanisms

NEUTRINOS

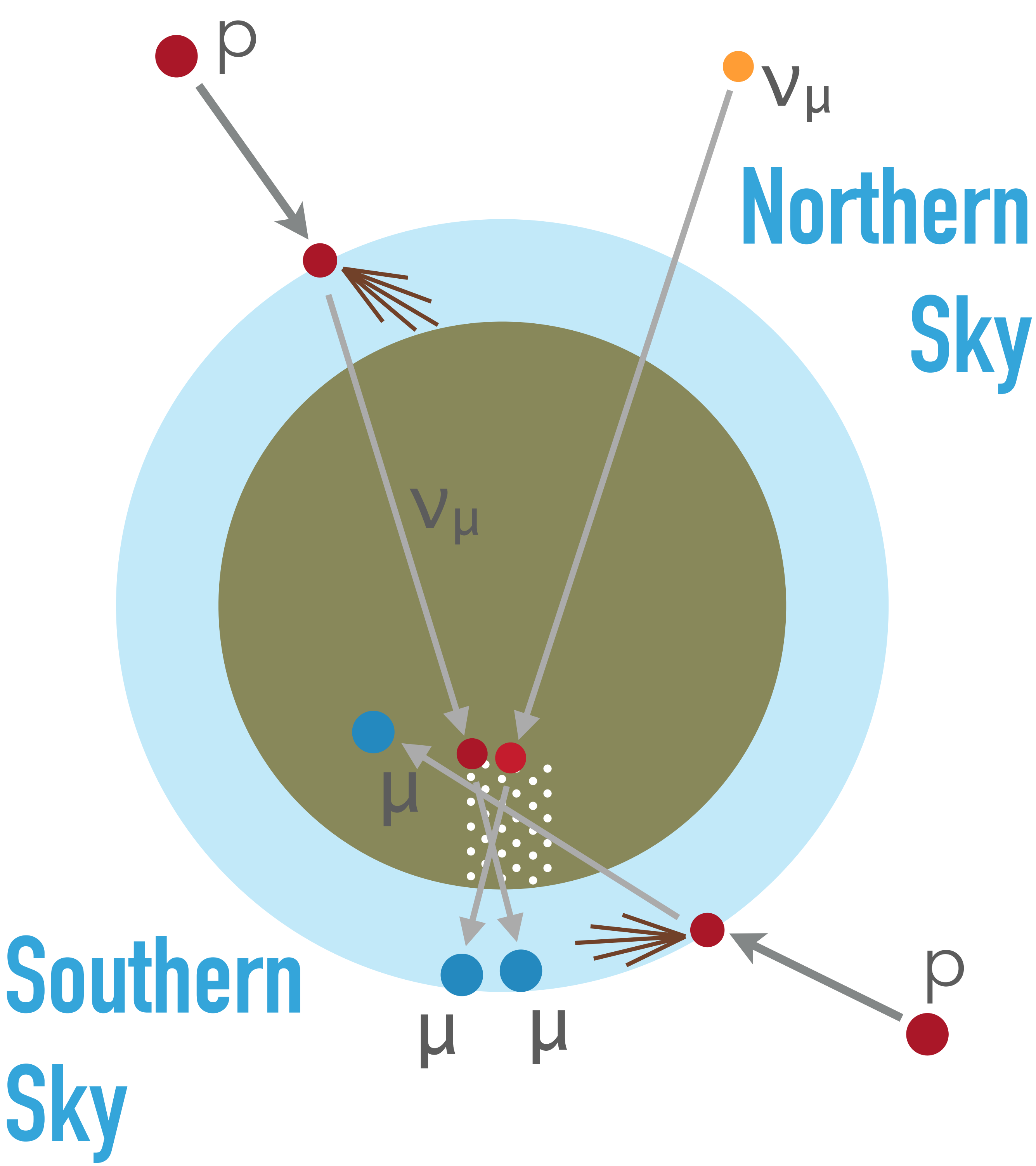
They are neutral and weak particles: point to the source carrying information from the deepest parts.

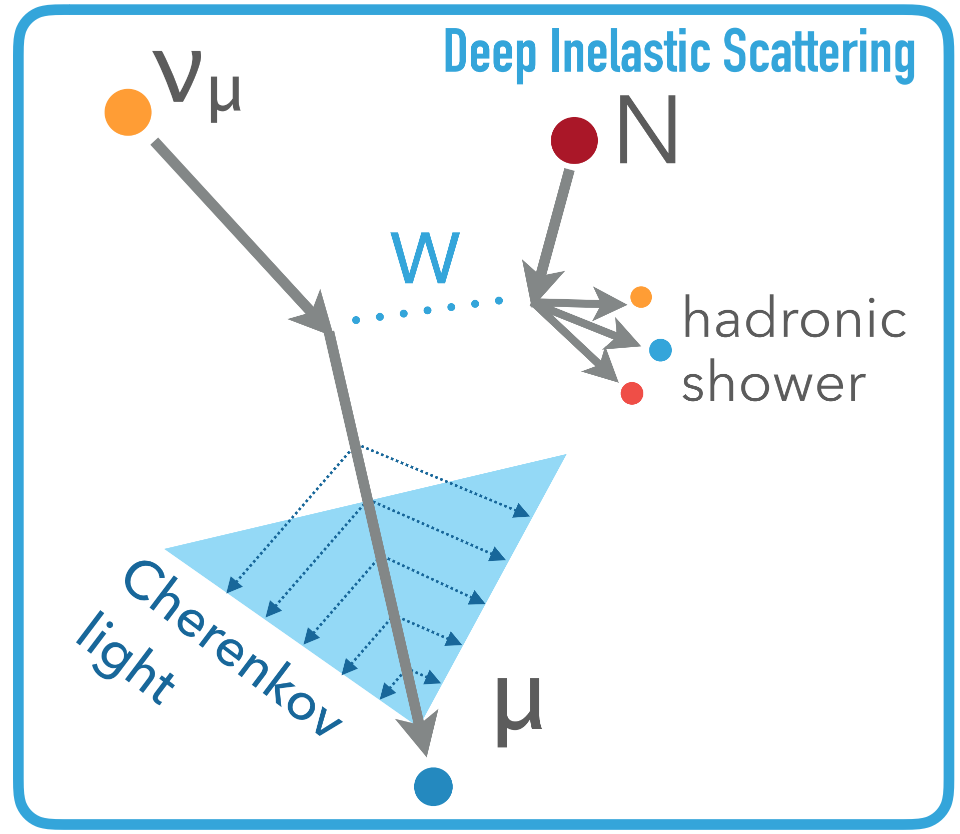
COSMIC RAYS

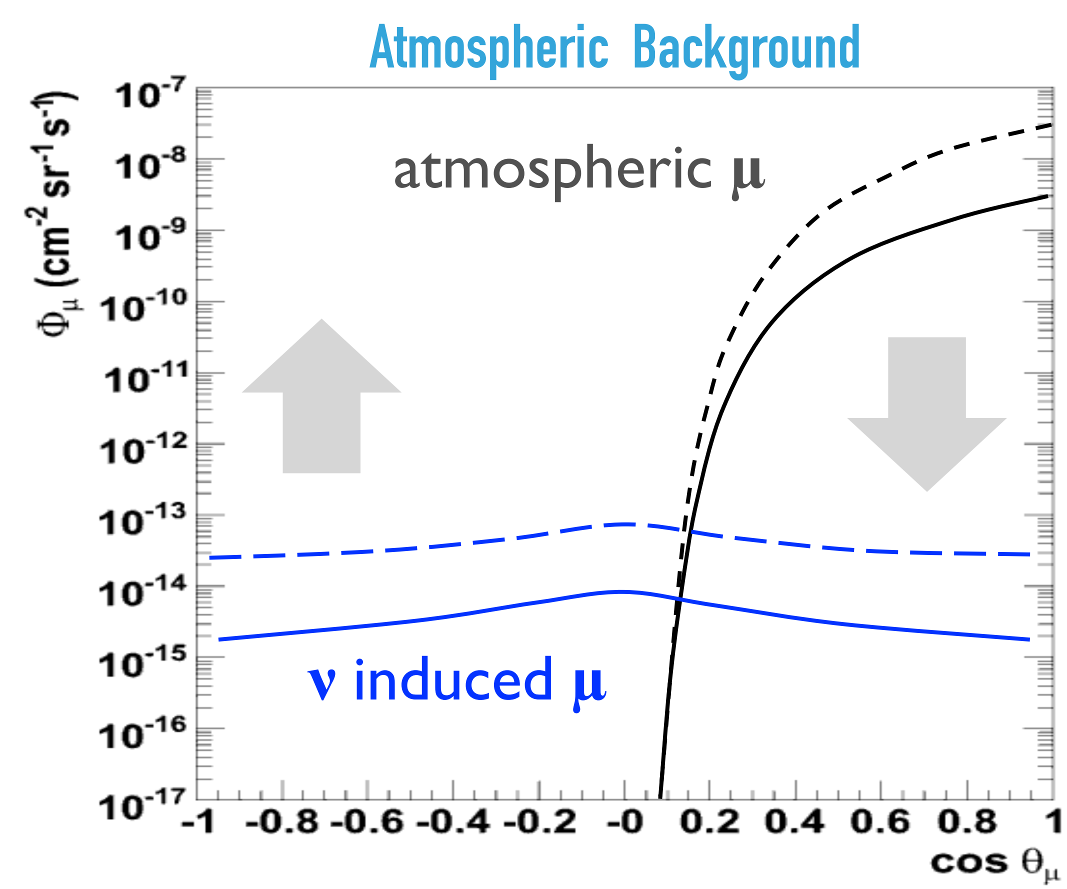
Deflected by magnetic fields ($E < 10^{19}$ eV)

Neutrino Astronomy is THE window to the extragalactic Universe above 100 TeV

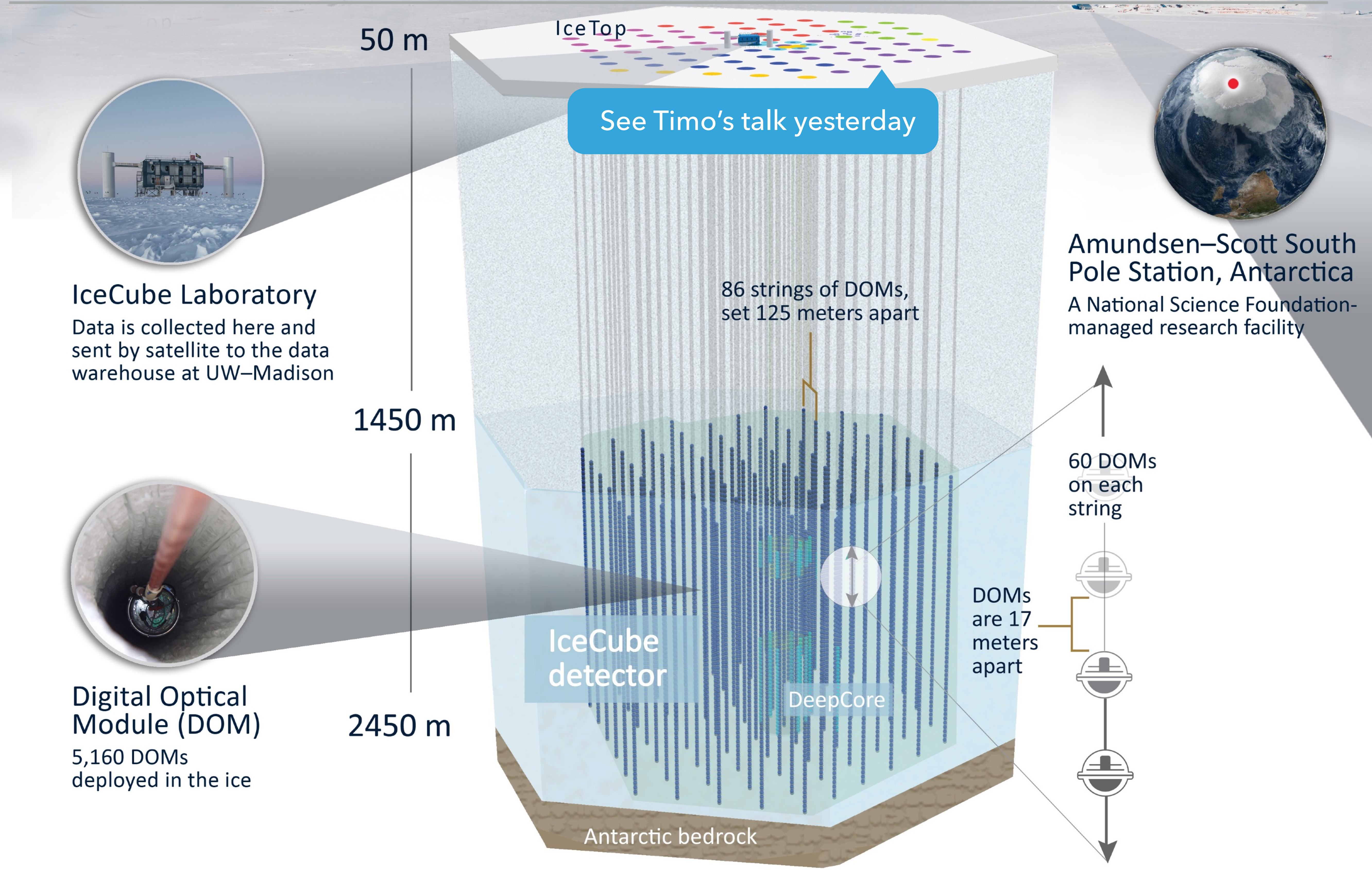
DETECTION PRINCIPLE







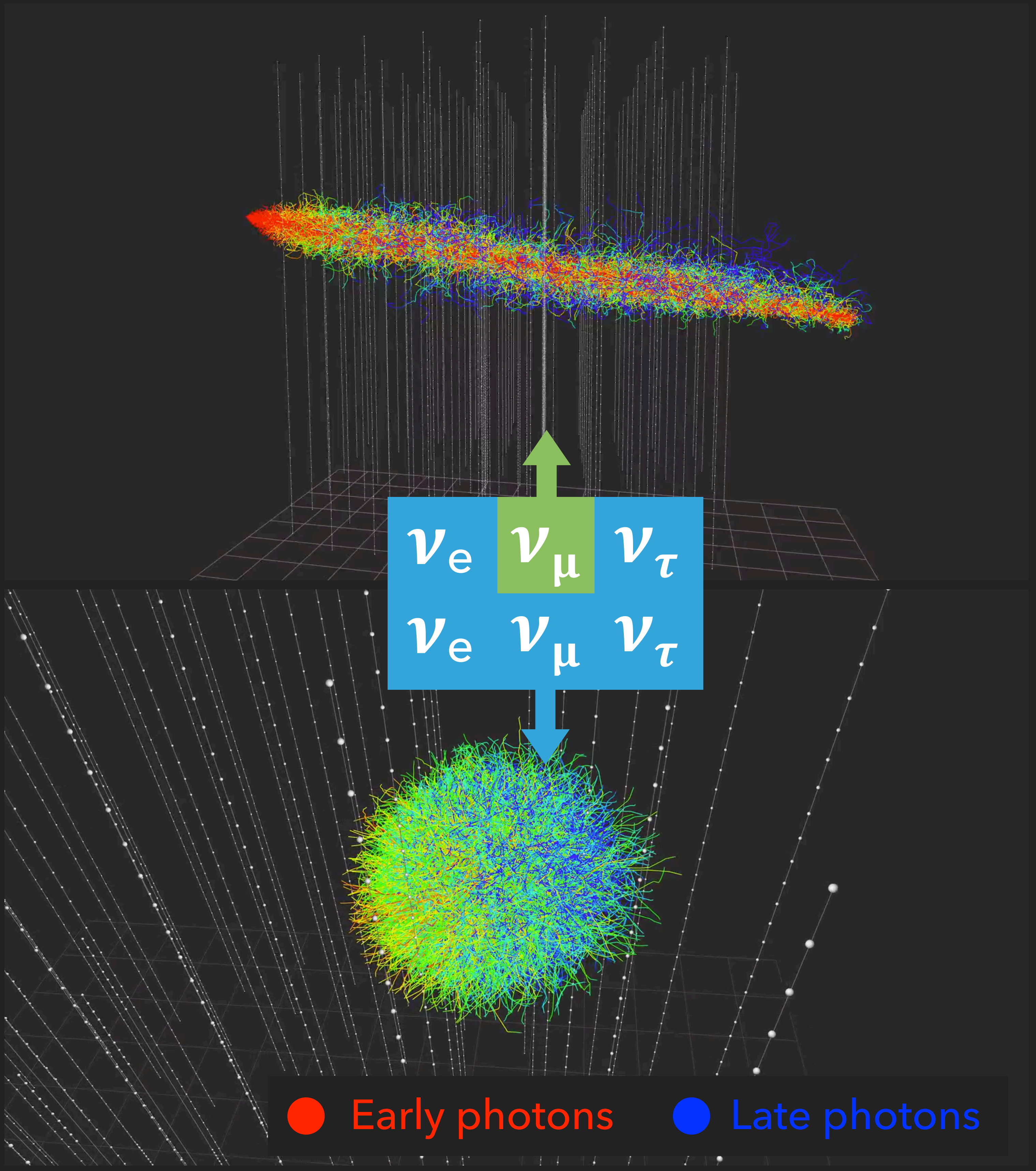
THE ICECUBE NEUTRINO OBSERVATORY



IN-ICE SIGNATURES

Track topology

- Good angular resolution 0.1° - 1° ➜ Neutrino Astronomy
- Vertex can outside the detector ➜ Increased effective volume



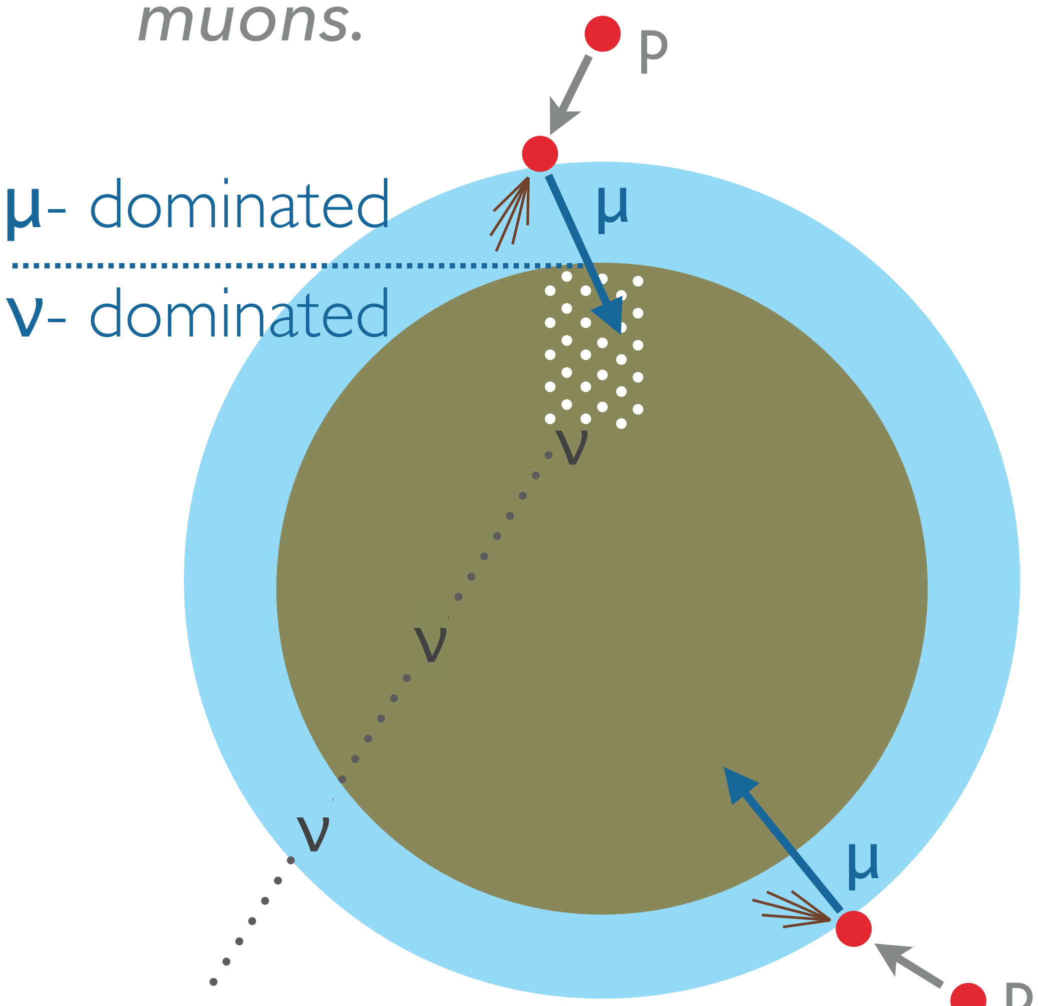
Cascade topology

- All flavors
- Fully active calorimeter ➜ Good energy resolution ±15% deposited energy
- Angular reconstruction possible ➜ ~10° > 100 TeV

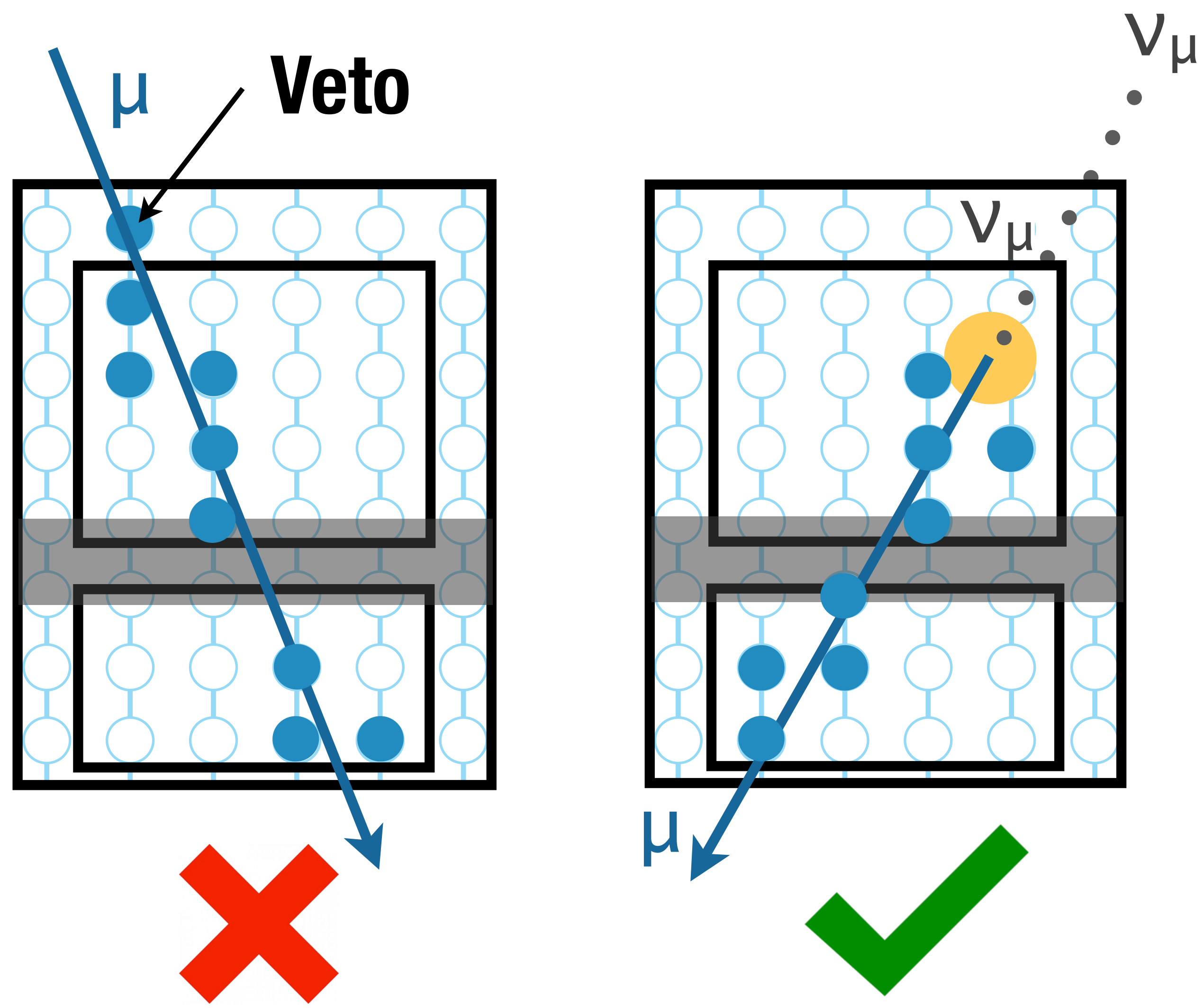
DIFFUSE SEARCHES

Sources may be numerous and faint, hard to resolve individually.

1 *Using up-going through-going muon events using Earth as a shield against atmospheric muons.*



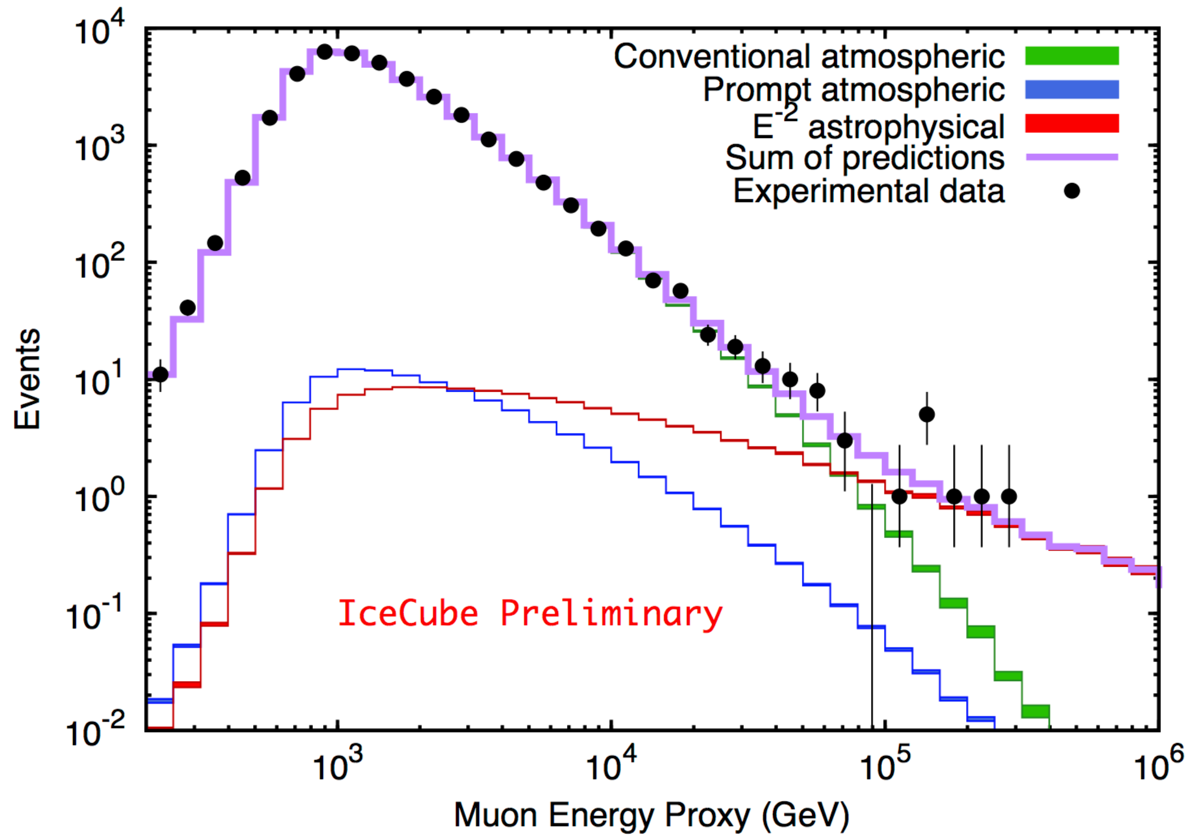
2 *Using the outer layers as an active veto to select starting events.*



1 DIFFUSE: THROUGH-GOING MUONS

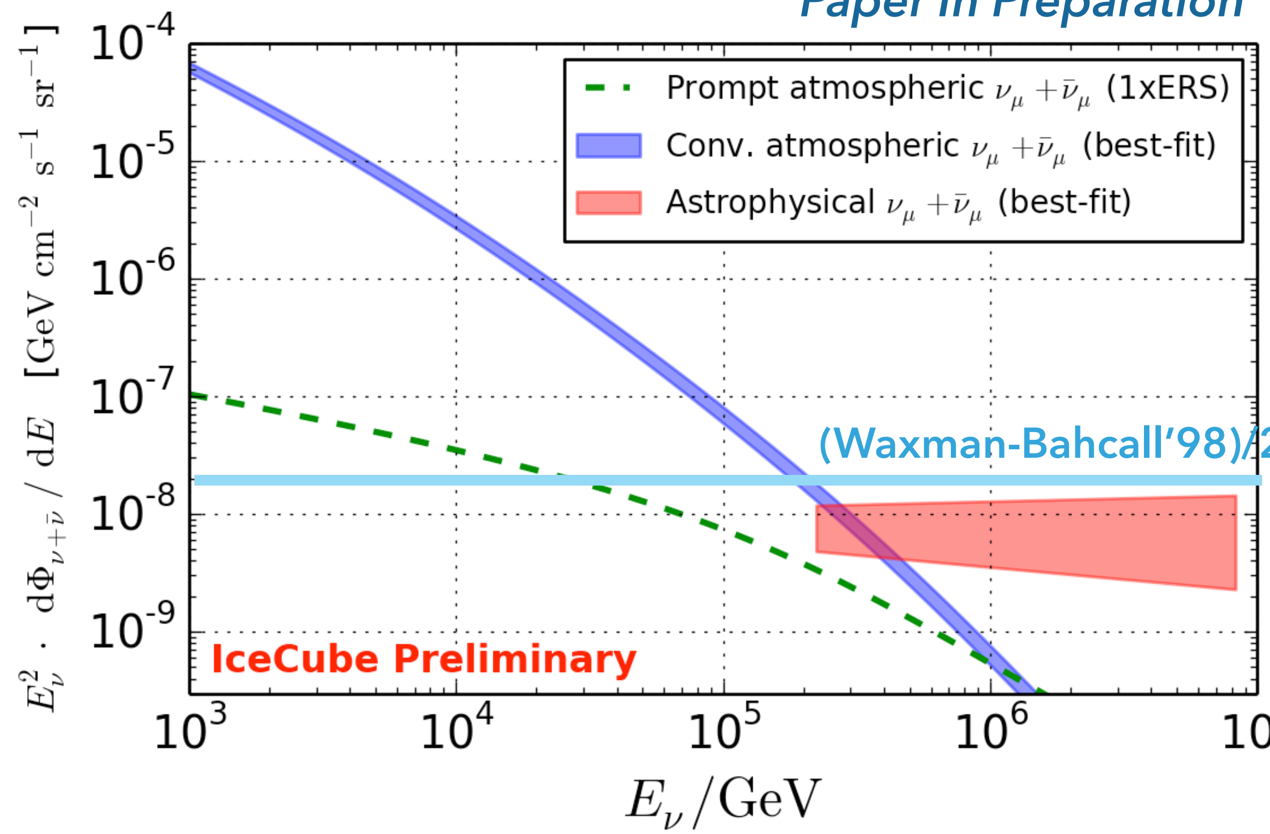
2 years

PRL 115, 081102 (2015)



6 years

TeVPA 2015, Tokyo. Paper In Preparation



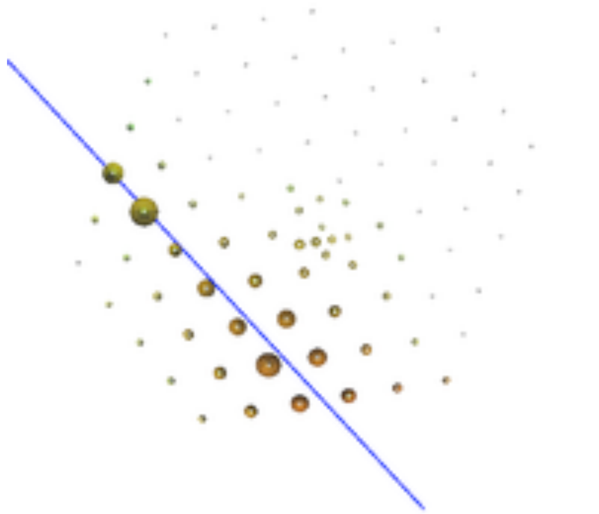
- First evidence (3.7σ) of an extra ν_μ-based astrophysical component already seen with **2 years** of data.
- Latest results (5.9σ) with **6 years.**

Measured flux:

hard spectrum

$$\Phi(E_\nu) = 0.82^{+0.30}_{-0.26} \times 10^{-18} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}(\mathrm{E}_\nu/100\ \mathrm{TeV})^{(-2.08\pm0.13)}$$

DIFFUSE: THE MULTI-PEV EVENT

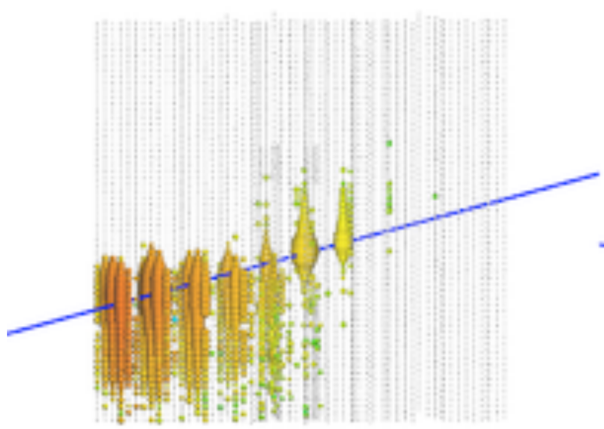


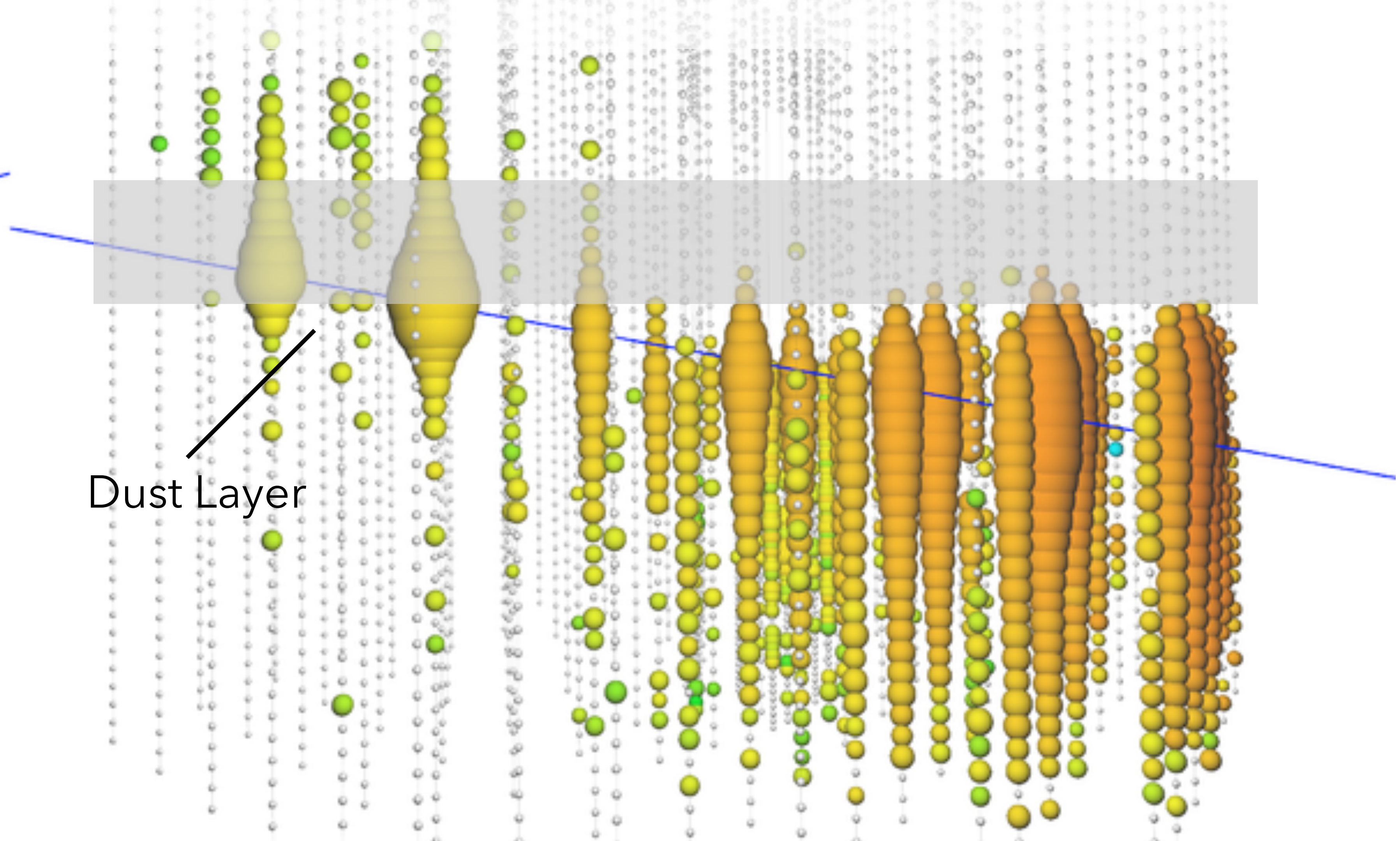
A multi-PeV event was observed in the through-going muon sample:

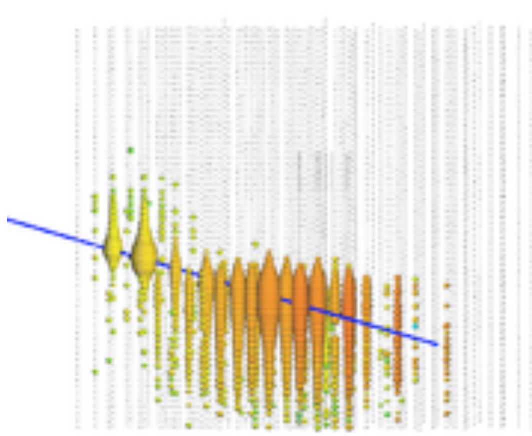
deposited energy: 2.6±0.3 PeV (lower limit on neutrino energy)

date: June 11, 2014

direction: 11.48° dec / 110.34° RA







DIFFUSE: STARTING TRACK EVENTS

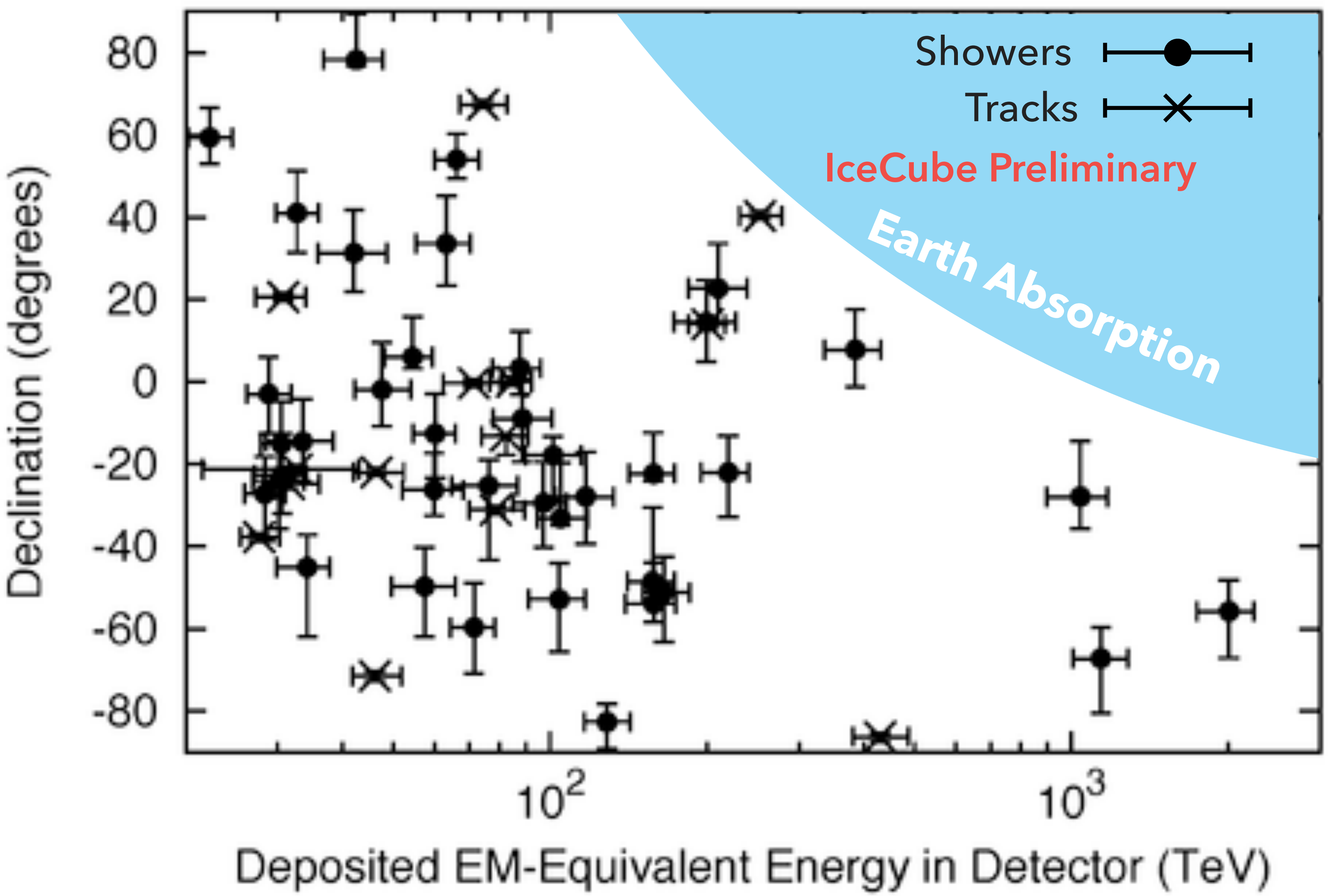
- Results from 4 years of data.
- Analysis is sensitive to track and cascade topologies.
- Lower energy thershold

expected background

atm. neutrino $9^{+8.0}_{-2.2}$

atm. muons 12.5 ± 5.1

events observed $53_{(+1)}$



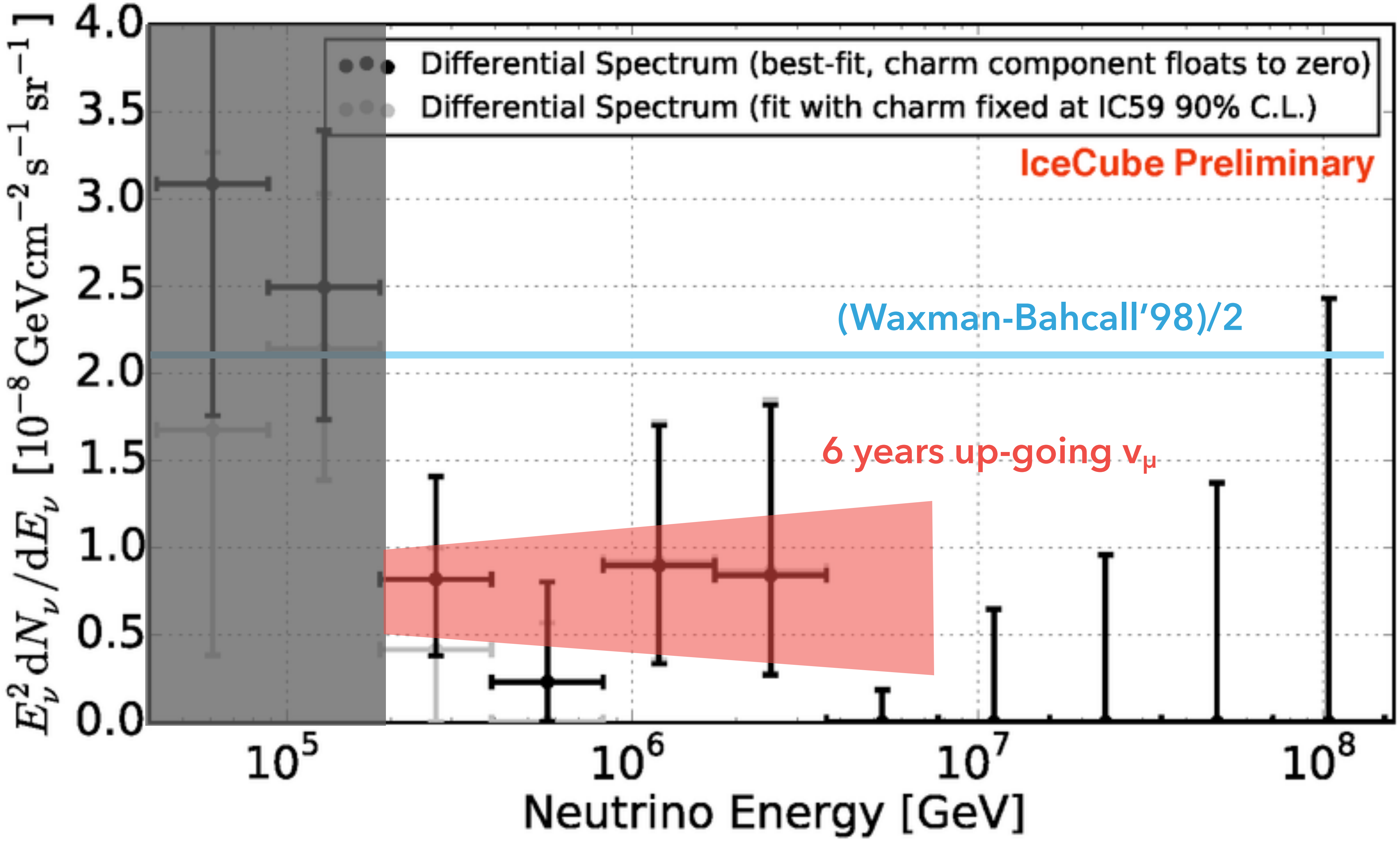
6.5σ

for 53(+1) events

arXiv:1510.05223
PoS(ICRC2015)1081

DIFFUSE: STARTING TRACK EVENTS

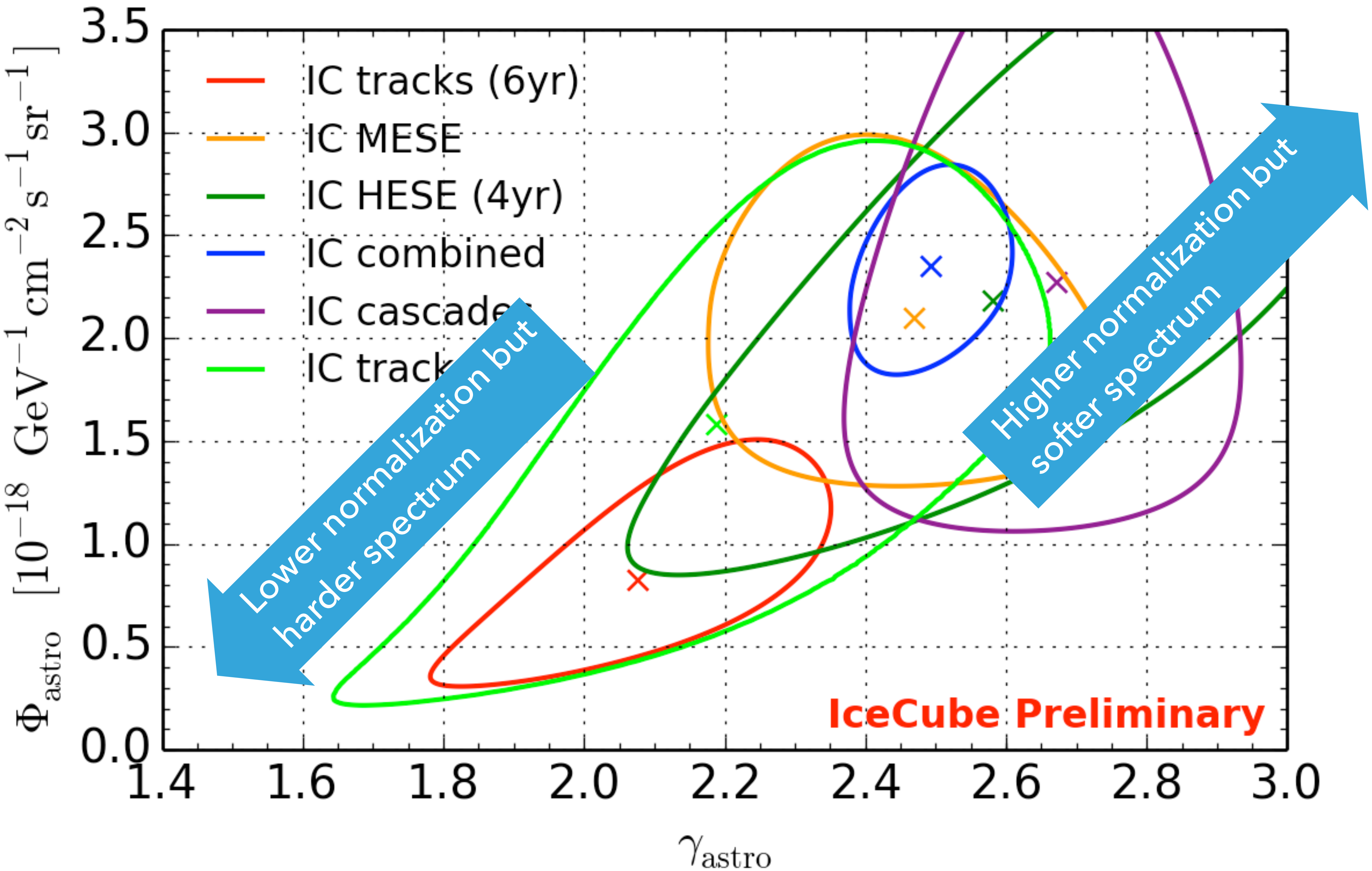
Assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino



- The measured flux seems to tend towards a soft spectrum driven by lower energy bins (threshold ~ 60 TeV)

arXiv:1510.05223
PoS(ICRC2015)1081

DIFFUSE: COMPATIBILITY OF RESULTS



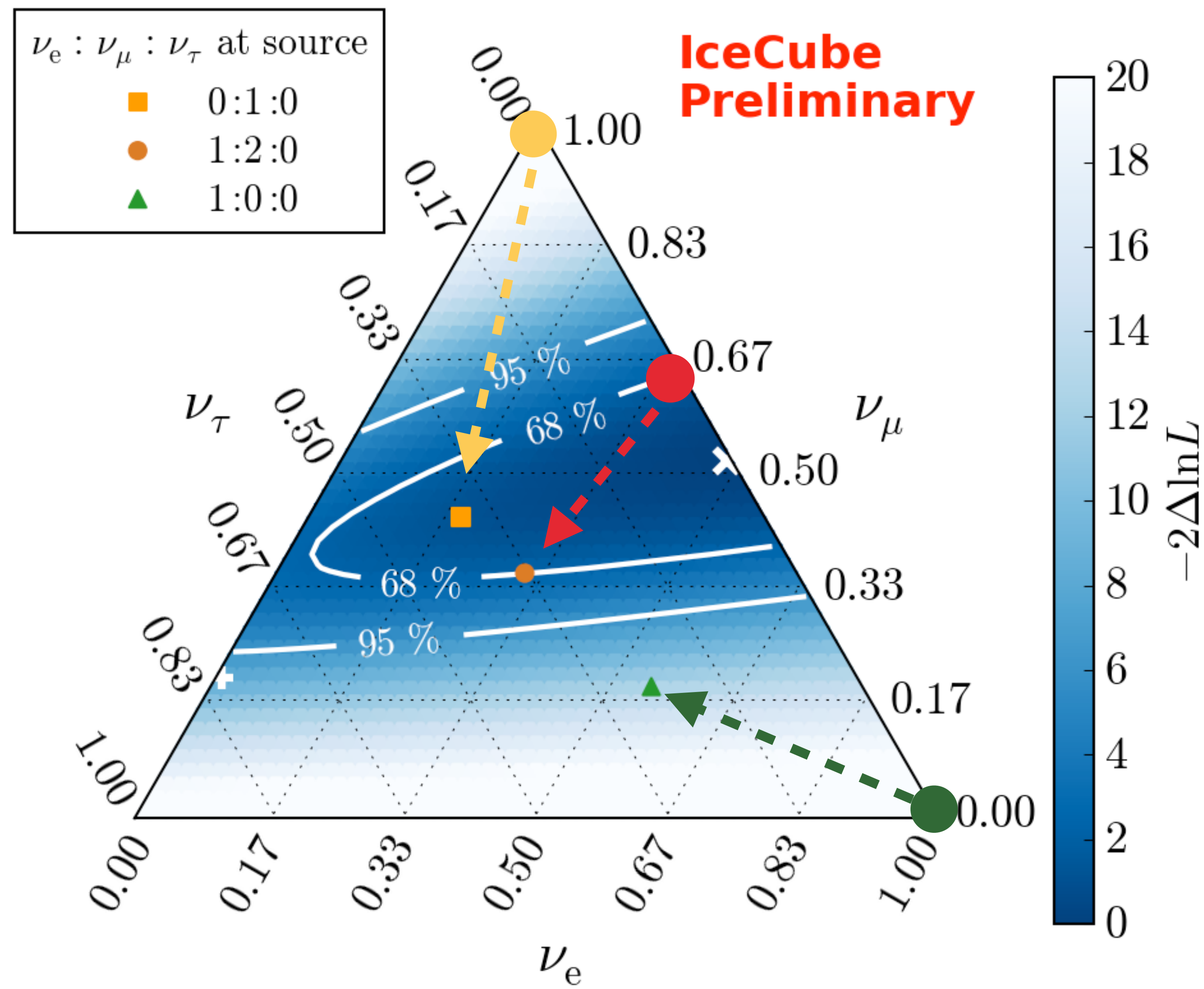
- Departing from the single unbroken power-law hypothesis $E^{-\gamma}$?

DIFFUSE: COMPATIBILITY OF RESULTS

Sources ········· Earth ···▸

	ν_e	ν_μ	ν_τ		ν_e	ν_μ	ν_τ
Pion Decay	1	2	0		1	1	1
Muon damped	0	1	0		0.2	0.39	0.39
Neutron decay	1	0	0		0.56	0.22	0.22

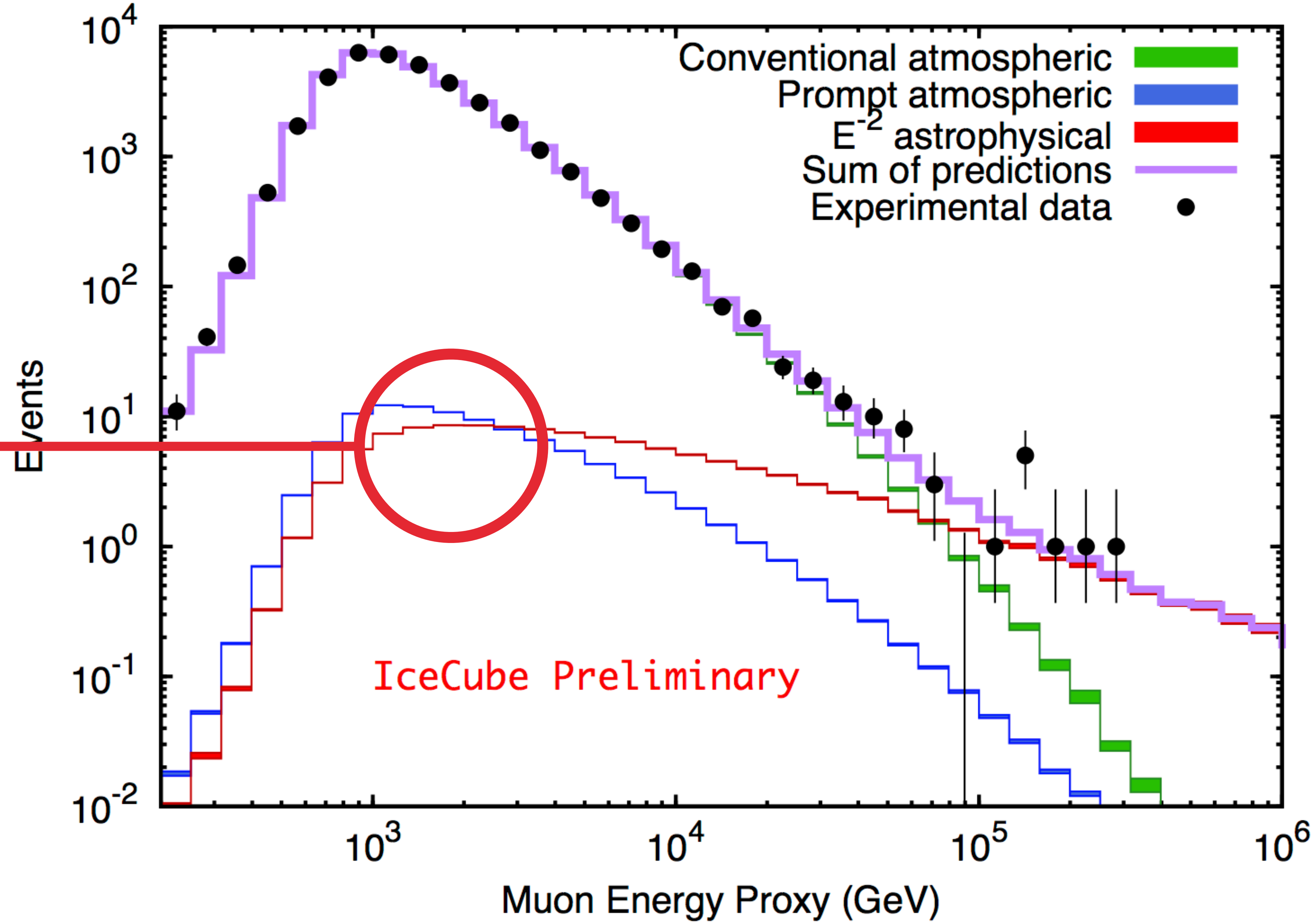
- Only a small region of flavor ratios allowed at Earth after cosmological distances.
- Both muon damped and pion decay models allowed. **Neutron decay** excluded **at 3.7σ**



ApJ 809, 98 (2015)/ PoS(ICRC2015)1066

FROM DIFFUSE TO POINT-SOURCE SEARCHES

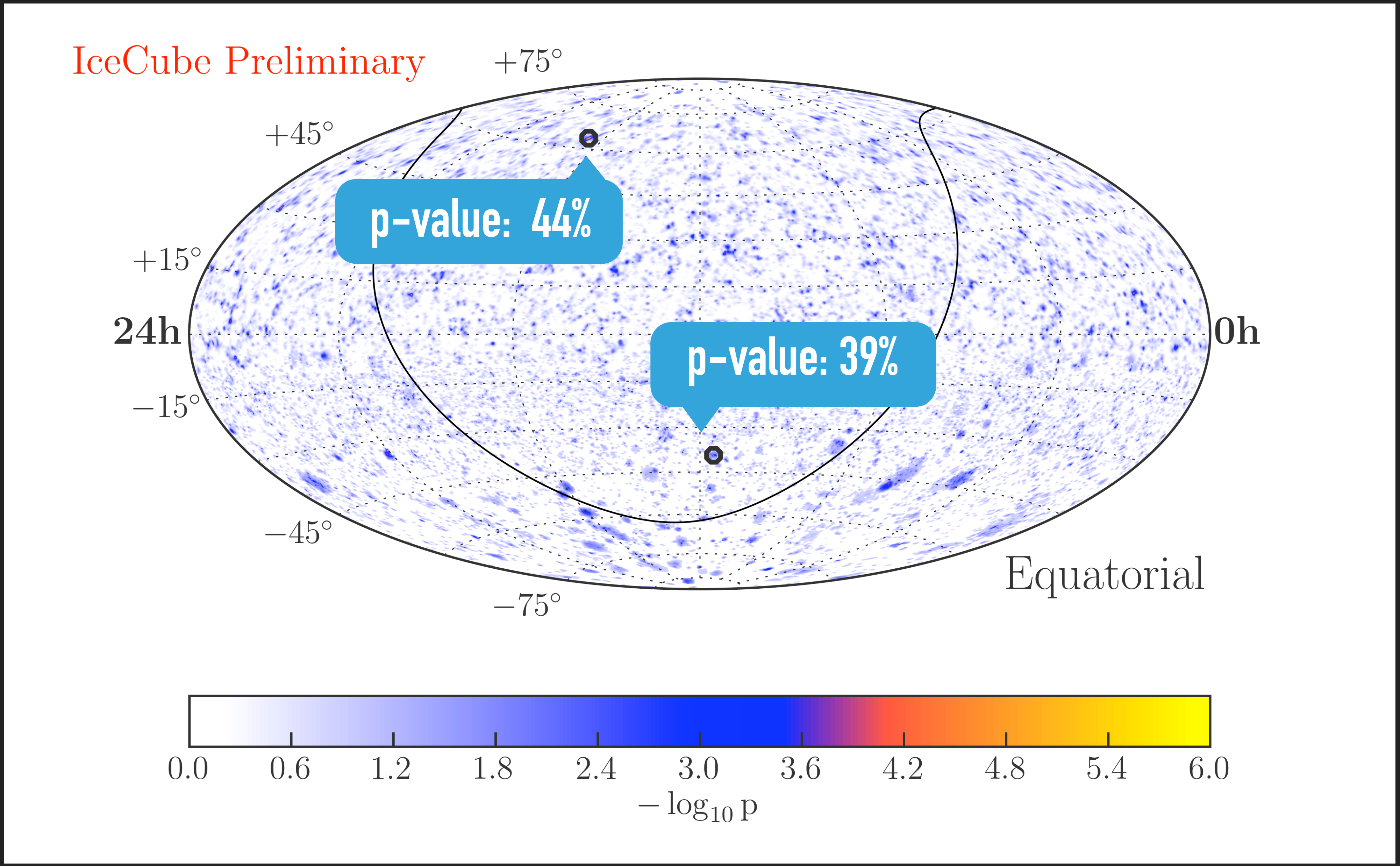
~100s astrophysical tracks hidden in an overwhelming background of atmospheric neutrinos



- Through-going muons have **excellent pointing**. Atmospheric neutrino background is small when looking for clusterings in the sky!

POINT-SOURCES: THROUGH-GOING MUONS

- Using **6 years** through-going sample, best sample for point-source searches.
- No significant excess found.

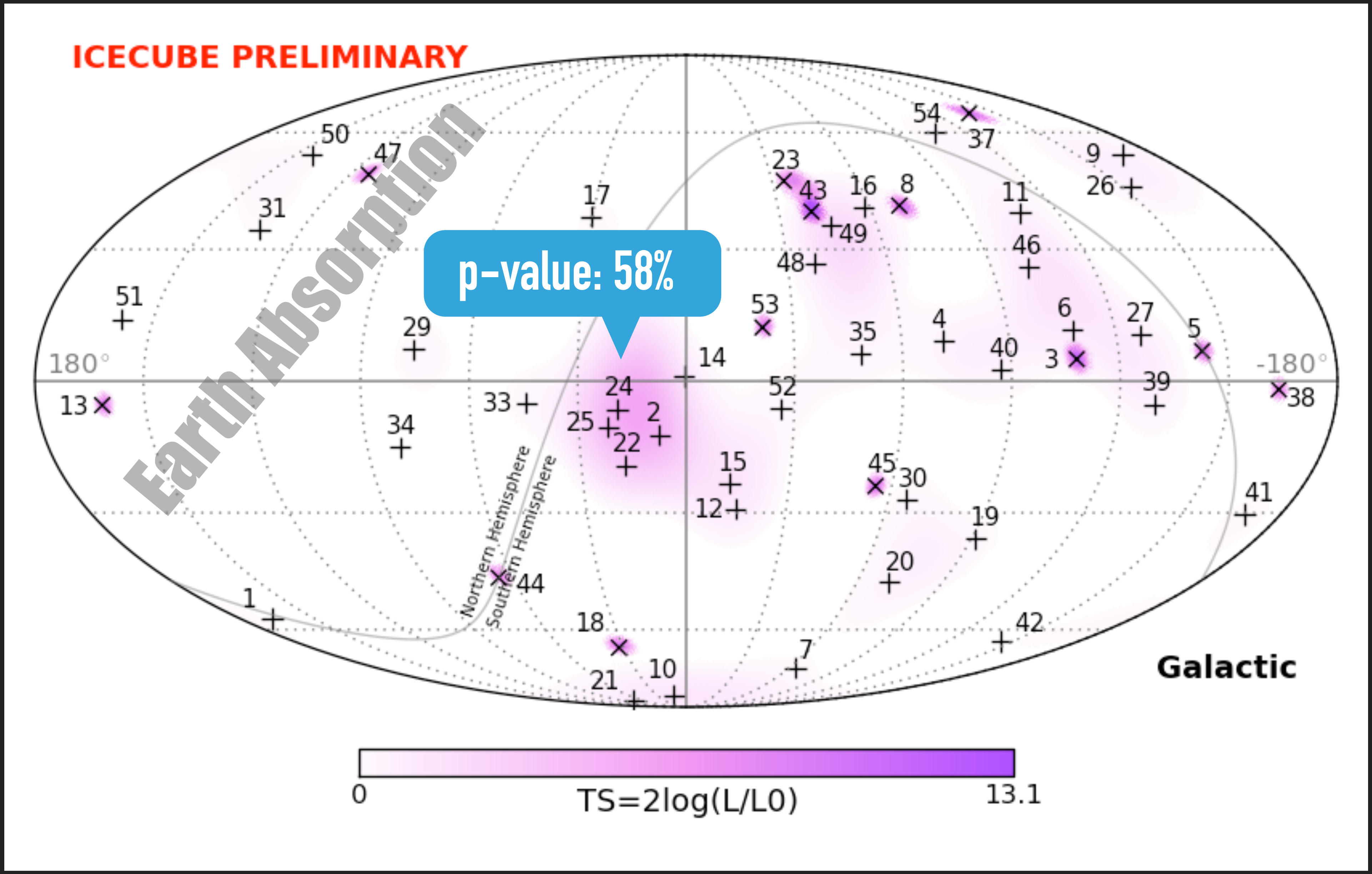


arXiv:1510.05222
PoS(ICRC2015)1047

New: Analysis using combined data from ANTARES

See Agustin's talk next

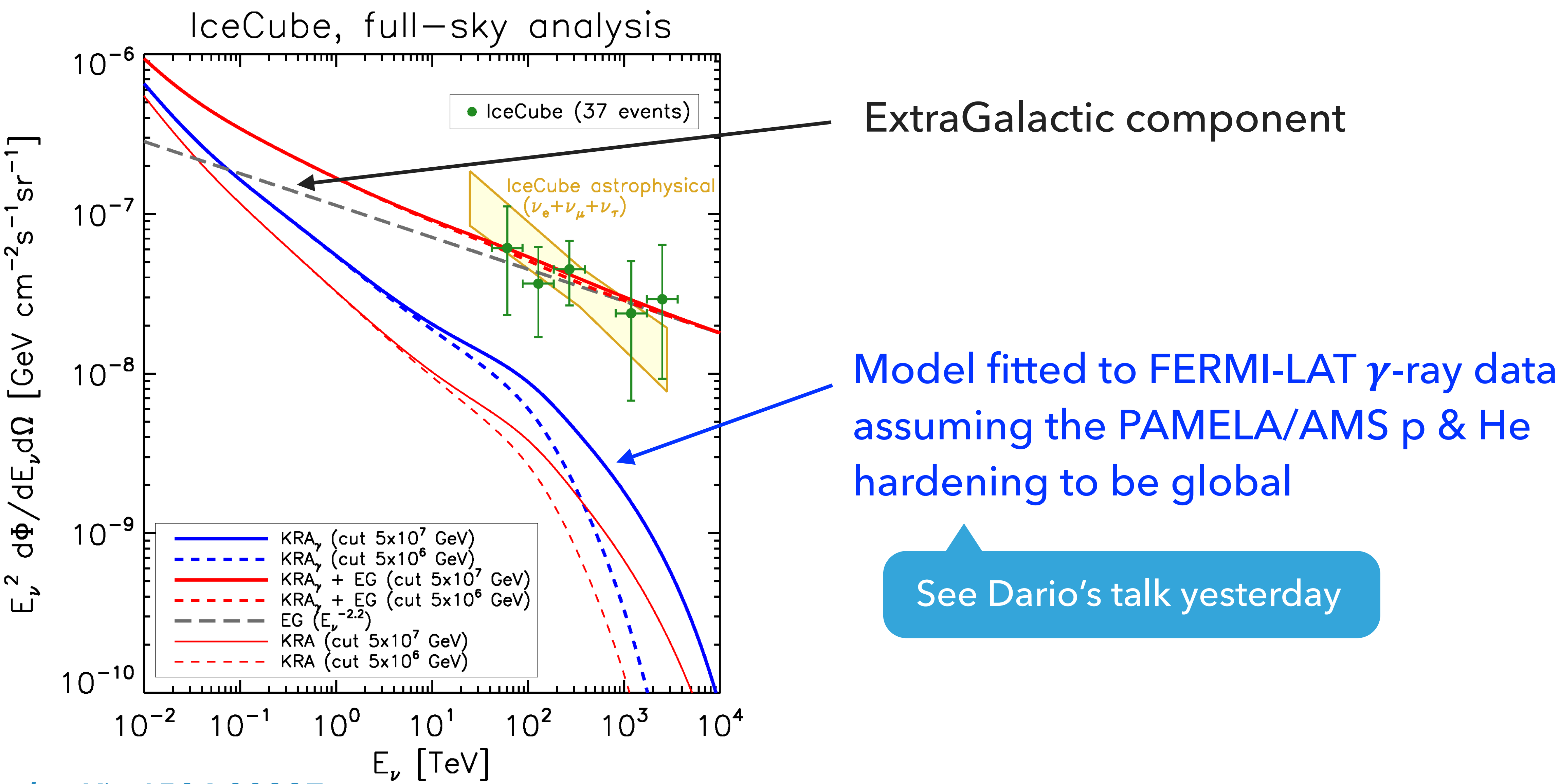
POINT-SOURCES: HIGH ENERGY STARTING EVENTS



- Uses a modified version of the standard through-going analysis.
- Several other searches performed (galactic plane, transients, etc.) No significant evidence of clustering was found.

WHERE ARE THE SOURCES? GALACTIC

- Arrival distribution of events limit a galactic component **< 50%** *[Ahlers et al. arXiv:1505.03156].*



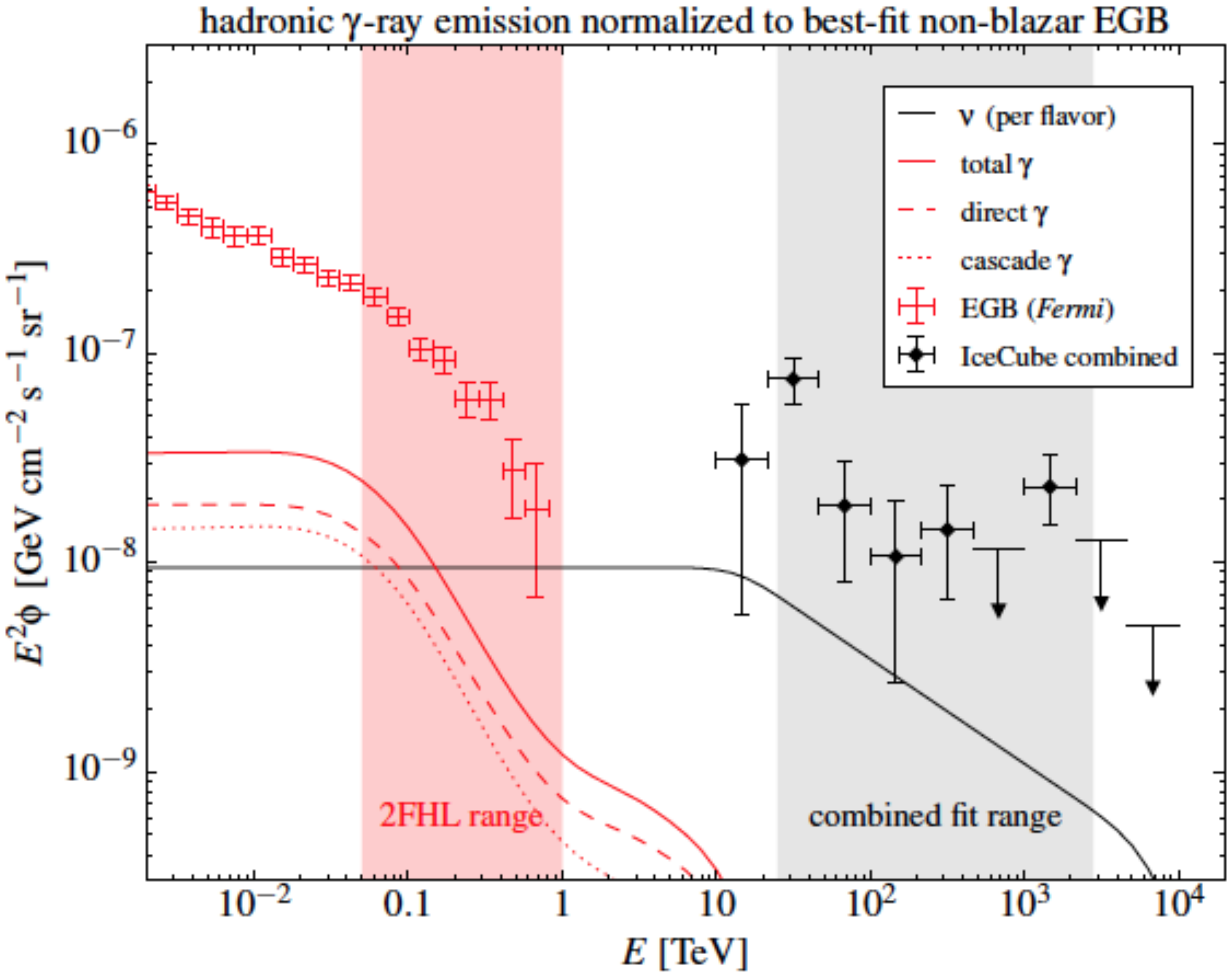
See Dario's talk yesterday

Gaggero et al. arXiv:1504.00227

- Further constrains on gamma-ray diffuse emission reduces up to a **25% of the neutrino flux** *[Gaggero et al. arXiv:1505.00227]*
- An **extra-galactic component** needs to be invoked.

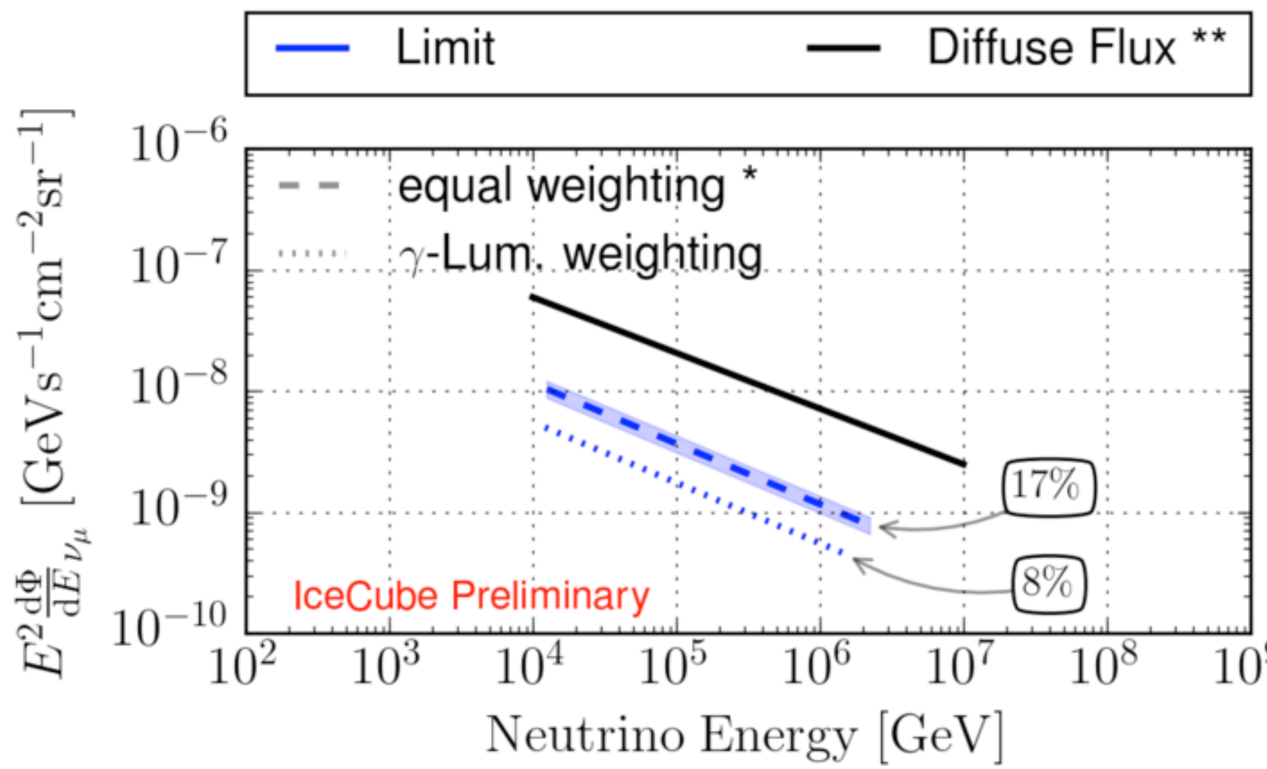
WHERE ARE THE SOURCES? EXTRA-GALACTIC

STAR FORMING GALAXIES



Bechtol et al. arXiv:1511.00688

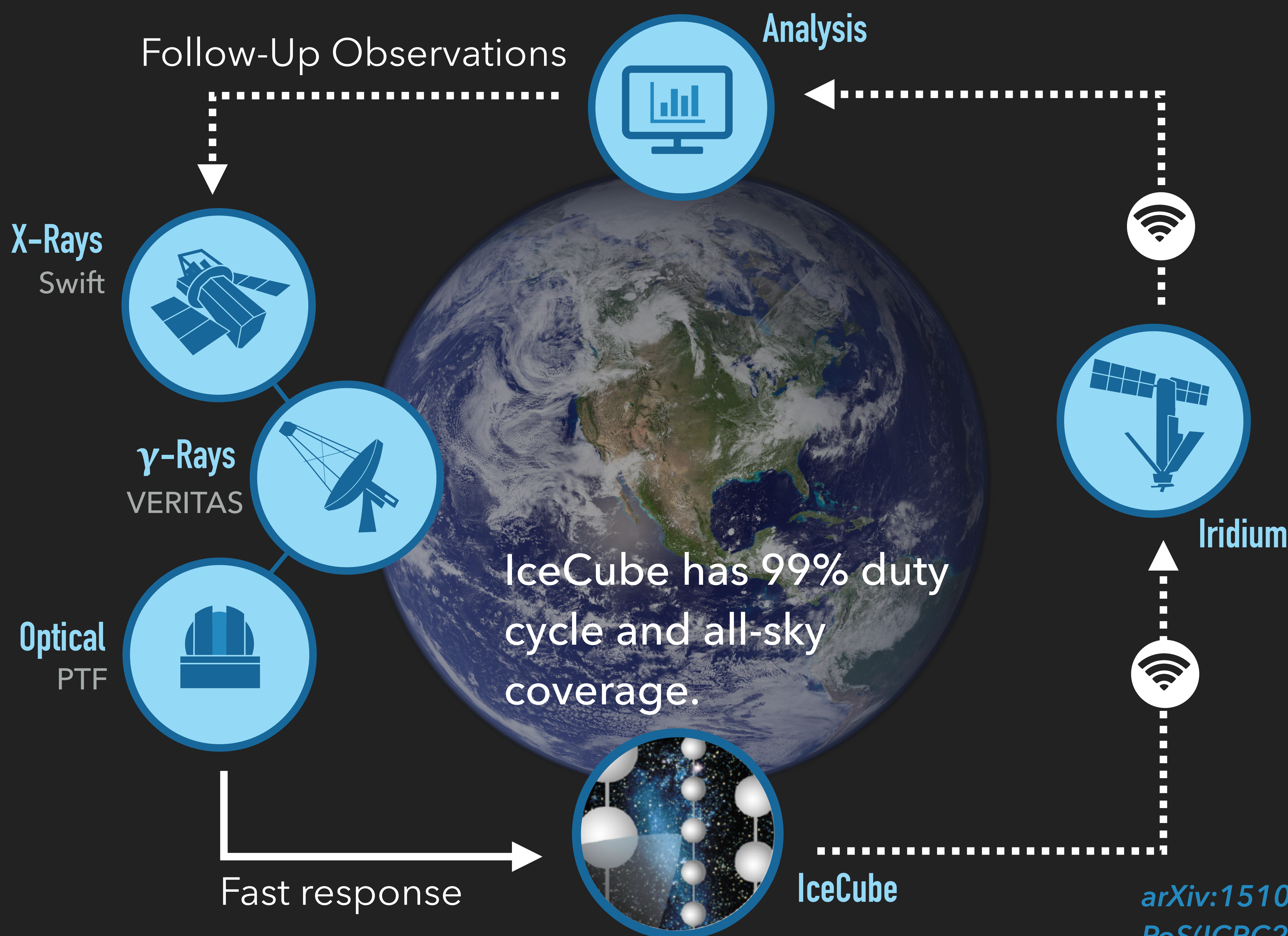
BLAZARS



RICAP 2014 Proceedings
Paper in preparation

- Too many neutrinos to be from Star Forming Galaxies (diffuse γ-ray limited by the non-blazar component of the EGB).
- Blazar population study indicates at most **25%** of neutrinos from 2LAC Blazars.
- Gamma-Ray Bursts? Prompt emission also excluded based on IceCube results.
- So, what's left? Hidden sources?

MULTIMESSENGER: REALTIME FRAMEWORK

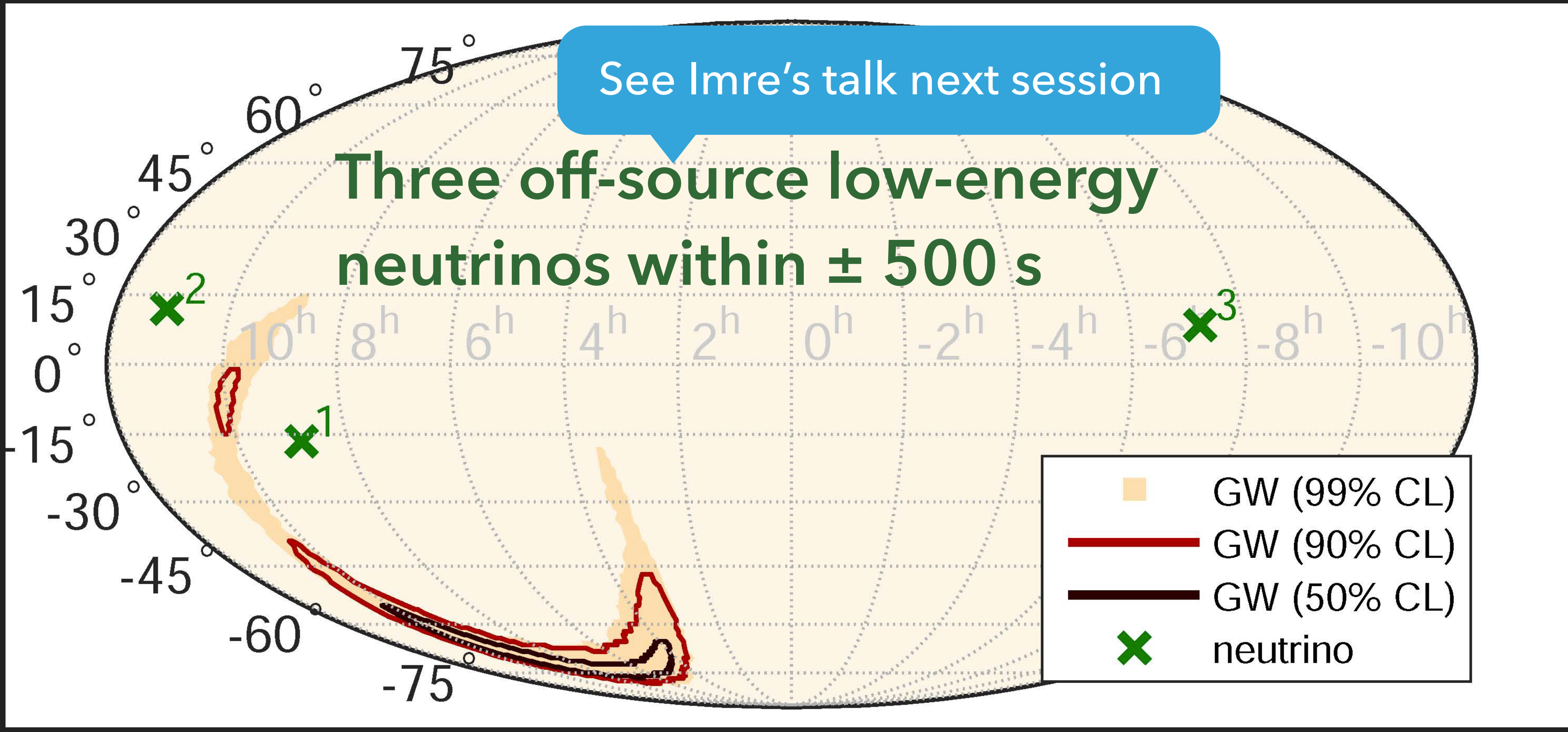


arXiv:1510.05222
PoS(ICRC2015)1069

MULTIMESSENGER: GRAVITATIONAL WAVES

- LIGO discovered **gravitational waves!**
- IceCube/ ANTARES did a follow-up of LIGO GW150914

ANTARES Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, Virgo Collaboration [arXiv:1602.05411]



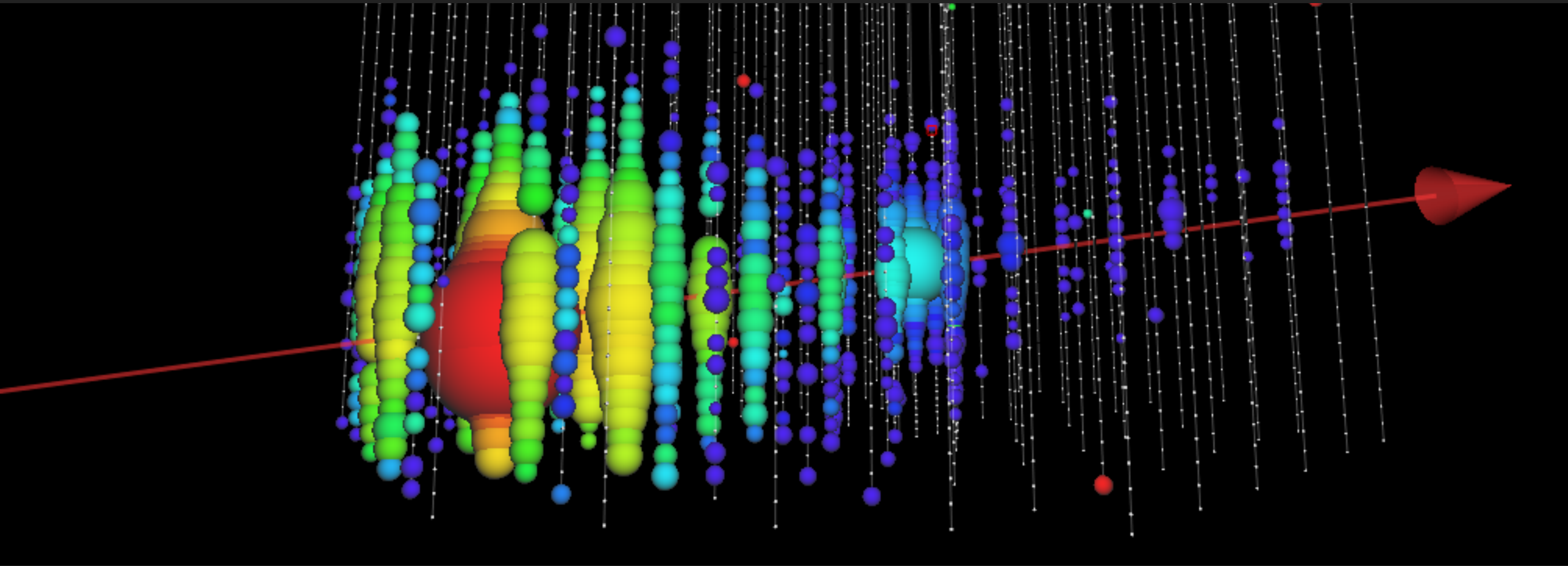
- No neutrino association found (expected from BH mergers)
- A **fast-response analysis** is being put in place to respond quickly to this kind of astronomical events.

MULTIMESSENGER: ICECUBE HESE EVENTS


```
//////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                  240.7644d {+16h 03m 03s} (current),
                  239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                   +9.2972d {+09d 17' 50"} (current),
                   +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;   118 DOY;   16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
SUN_DIST:         145.82 [deg]   Sun_angle= 10.3 [hr] (West of
Sun)
MOON_POSTN:       282.67d {+18h 50m 41s}  -18.11d {-18d 06' 31"}
MOON_DIST:         49.62 [deg]
GAL_COORDS:        20.70, 41.68 [deg] galactic lon,lat of the
event
ECL_COORDS:       236.19, 29.39 [deg] ecliptic lon,lat of the
event
COMMENTS:         AMON_ICECUBE_HESE.
```

- An alert system based on HESE track-like events.
- Expected ~ 4 alert notices per year (1 astrophysical, 3 background)
- One event found few weeks after the system was put in place! (ST ~ 0.9)

MULTIMESSENGER: REACTIONS TO ICECUBE-160427A



- GCN 19364 – Fermi Gamma-Ray Burst Monitor - No detection
- GCN 19360 – Fermi LAT – 5 unrelated blazars
- GCN 19361 – HAWC – no detection
- GCN 19362 – MASTER – no detection
- GCN 19377 – VERITAS – no detection
- GCN 19392 – iPalomar Transient Factory – 3 transients, all AGN
- GCN 19427 – FACT Cherenkov TeV Telescope – no detection
- GCN 19426 - Interplanetary Network – no detection
- GCN 19381 - Pan-STARRS - 7 SN candidates, one consistent with type Ic supernova.

ICECUBE-GEN2 A VISION FOR THE FUTURE

PINGU

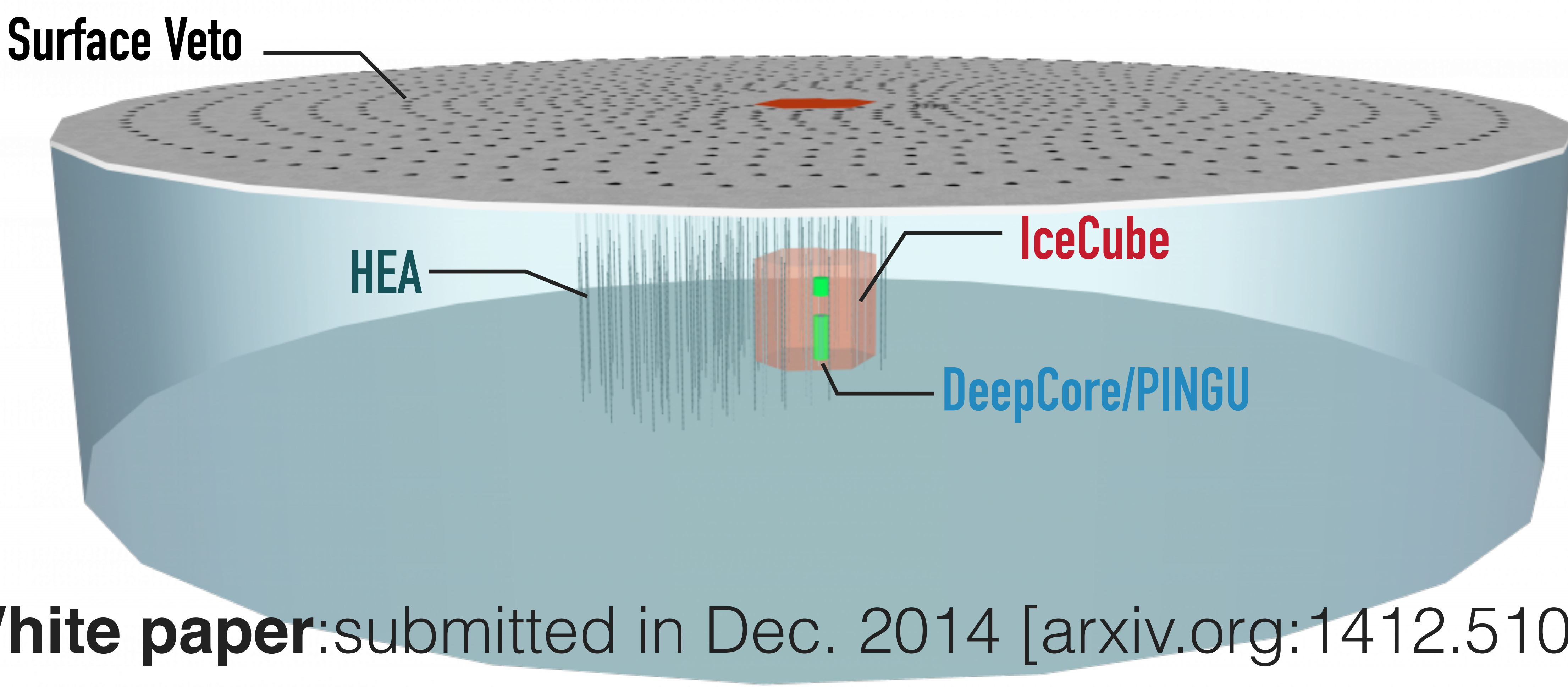
- Further in-fill
- Lower the energy threshold few GeV
- Neutrino Mass Hierarchy
- Dark Matter + Solar Flares

High Energy Array (HEA)

- Extension of IceCube array
- Look for high-energy events
- GZK and astrophysical neutrinos

\+ **Radio Array:** 100-300 km^2 for extremely high energies ($\geq 10^{18}$ eV)

Surface Veto: Air showerdetector with 75 km^2 / 100 TeV threshold



White paper:submitted in Dec. 2014 [arxiv.org:1412.5106]

CONCLUSIONS

- The future exploration of the high energy universe belongs to Neutrino Astronomy.
- IceCube has started to characterize the observed astrophysical neutrino flux.
- Future discoveries will be only possible with multimessenger campaigns. IceCube is actively interconnected in the realtime network sending and receiving alerts.
- Different components (IceTop-2, HEA, Radio Array,…) will make IceCube-Gen2 a global neutrino observatory.
- Many other analysis results not presented here: Dark Matter, Oscillations, Sterile Neutrinos, Cosmic Ray Anisotropy,…