

Multi-messenger astrophysics and Recent Results from IceCube



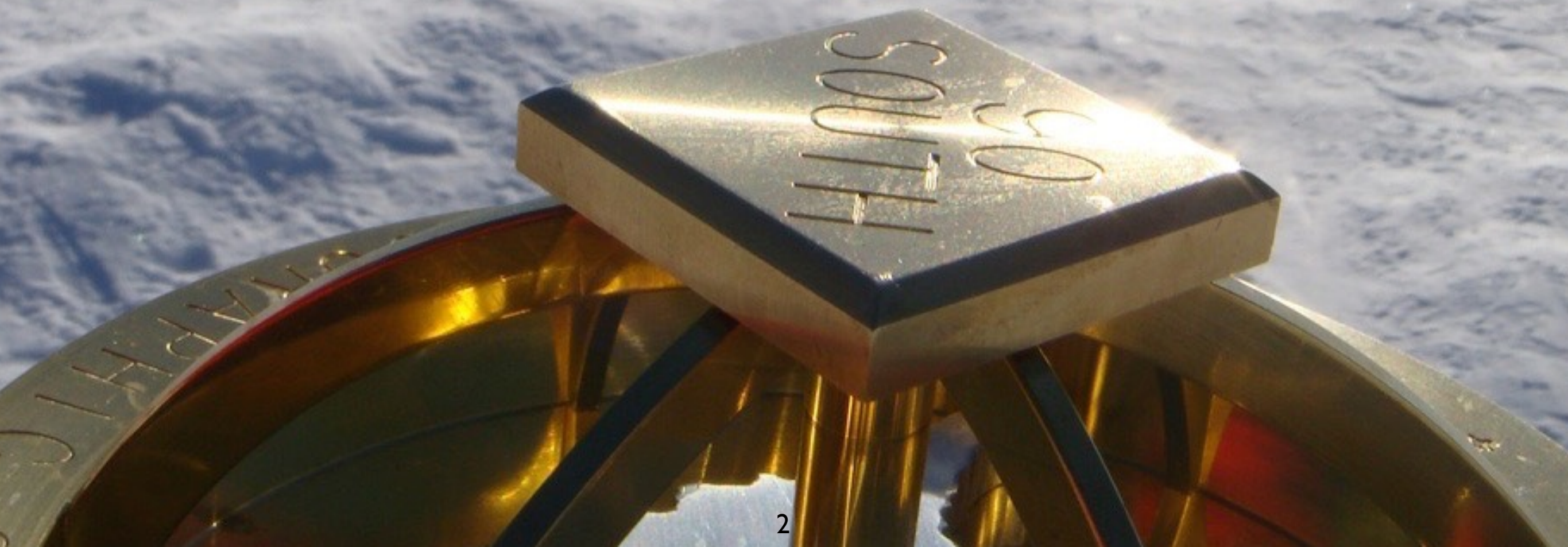
Carsten Rott

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KAS Fall Meeting Oct 16 - 18, 2019

- Motivation
- Neutrino Telescopes and IceCube
- Search for Astrophysical Neutrinos
- Multi-messenger Observations
- Outlook and Conclusions



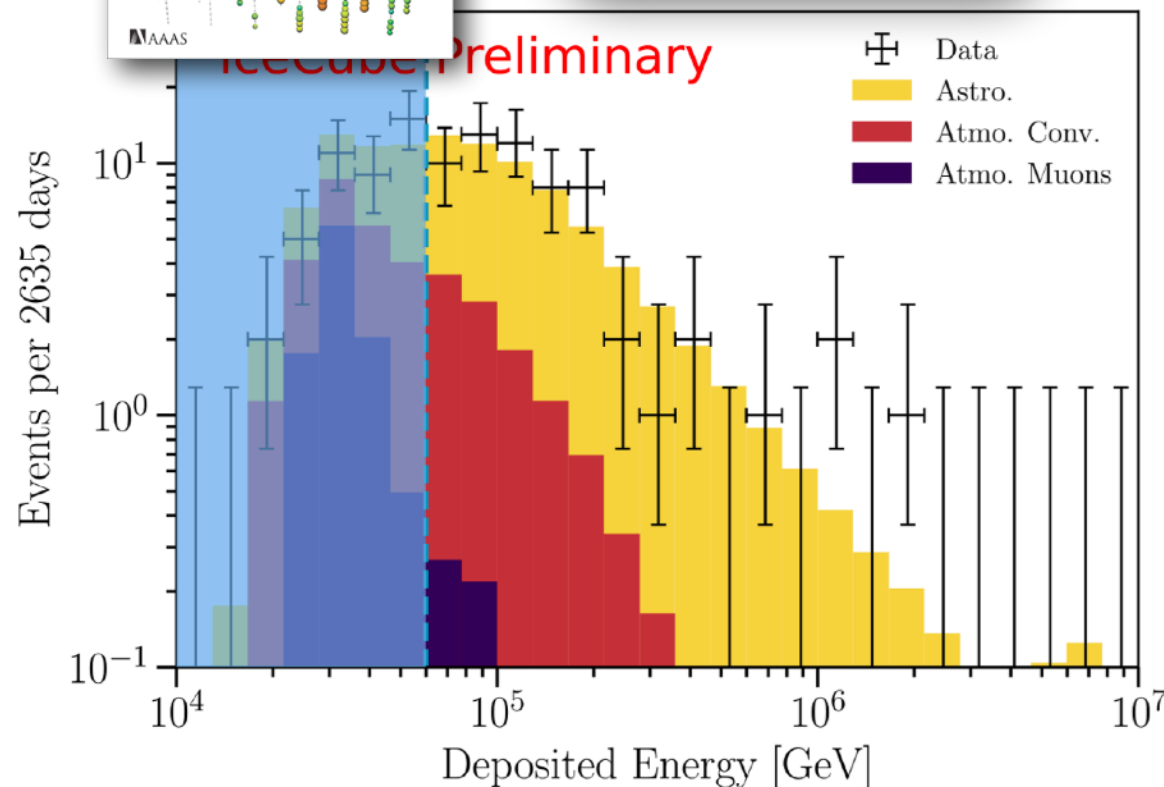
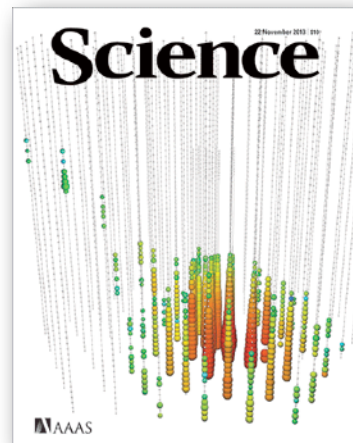
New Window to the Universe !



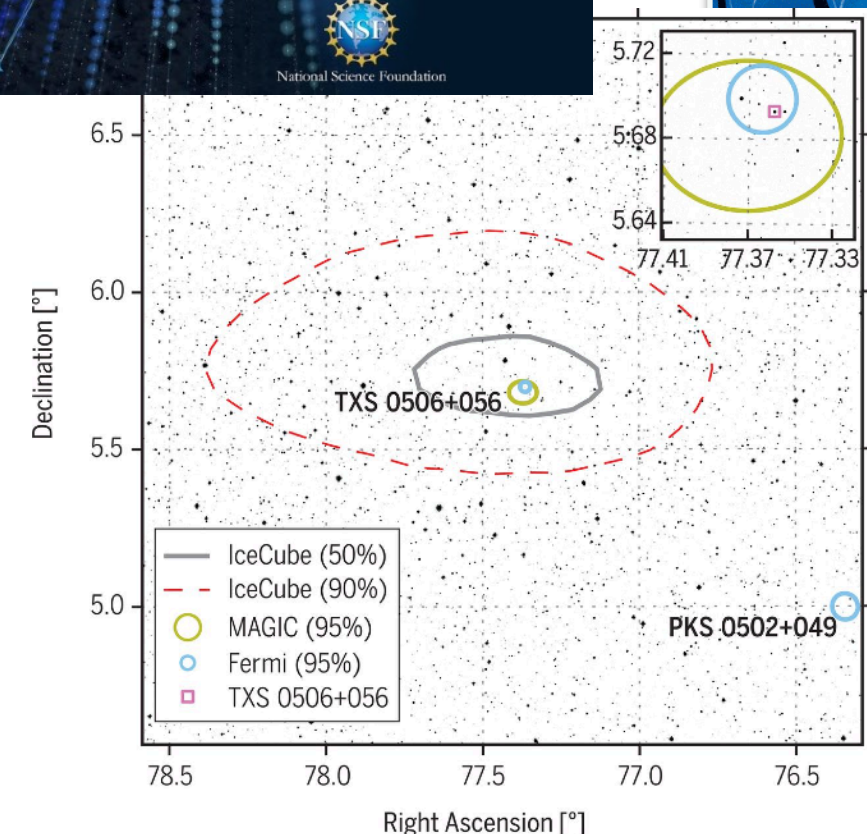
2002

Following the observation of supernova burst neutrinos in 1987, neutrino astronomy is becoming a reality quickly now ...

2013 Discovery of diffuse astrophysical neutrino flux

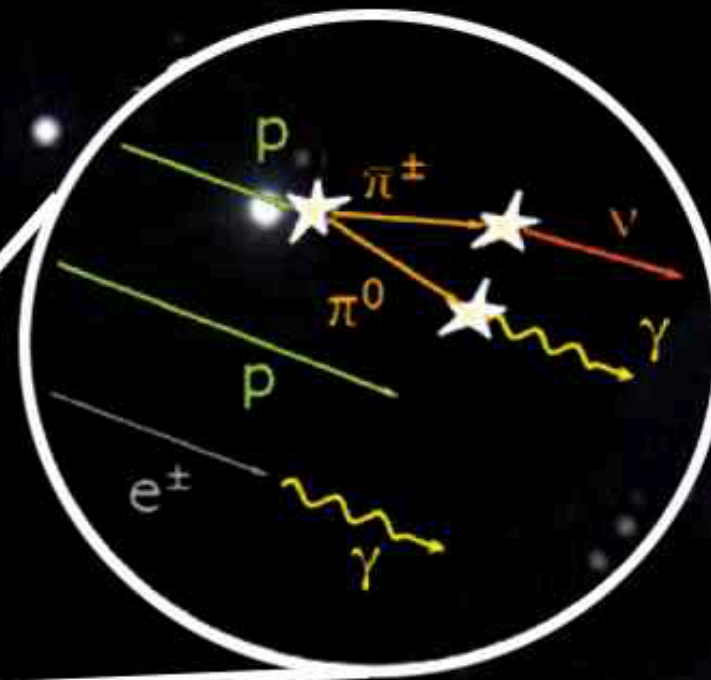


2018 Neutrino multi-messenger astroparticle physics



The Cosmic Ray Mystery

cosmic rays
+ neutrinos



γ

ν

P

Cosmic Ray Sources

- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB)
- Supernovae (SN)
- Galaxy Clusters
- Unknown



Victor Francis Hess

Discovery of
cosmic-rays



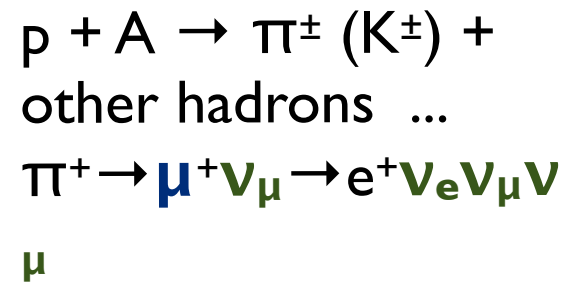
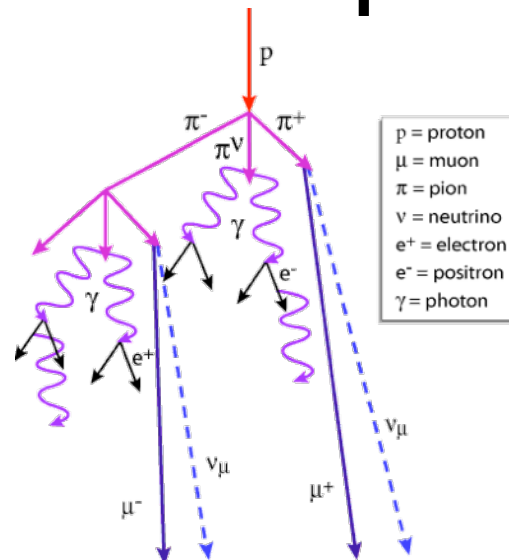
1936

Astrophysical Messengers

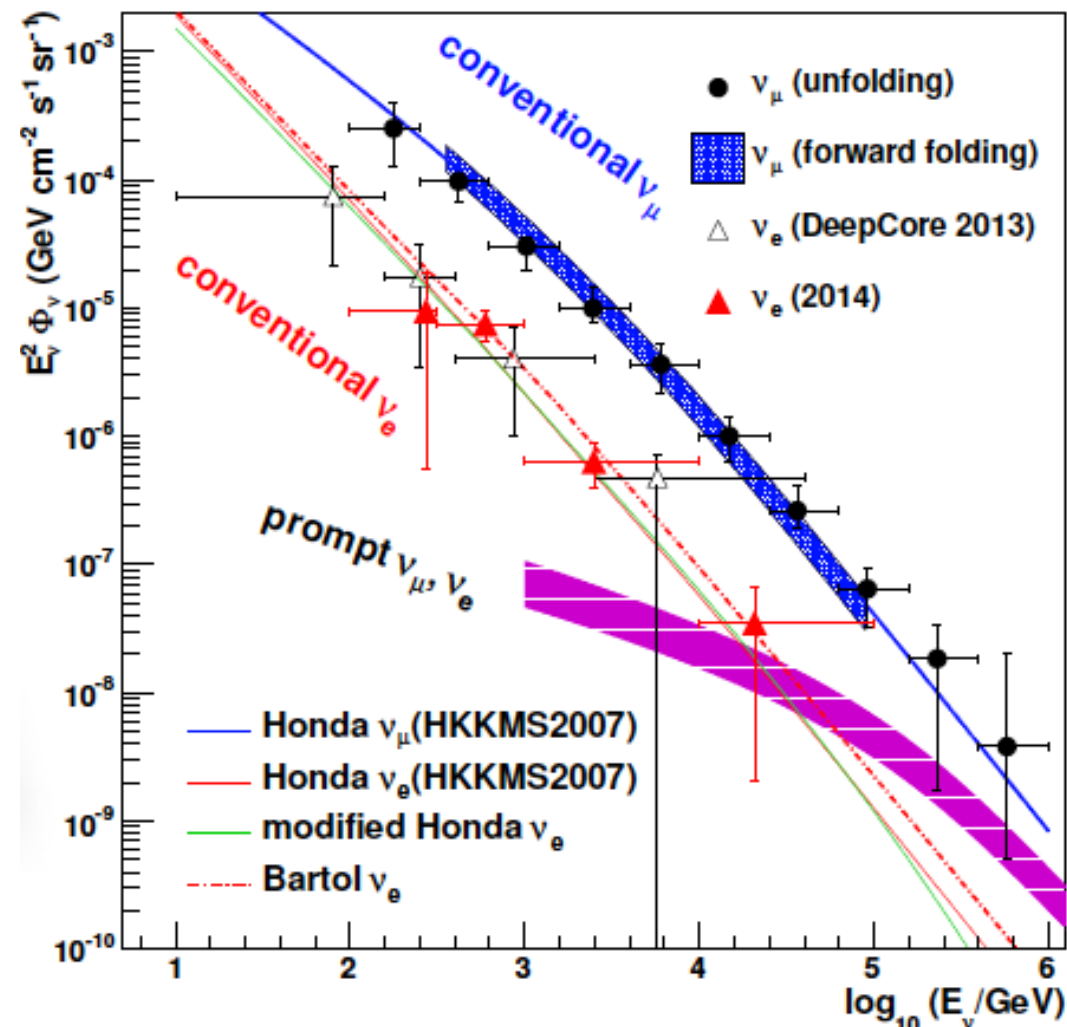
Sources of High Energy Neutrinos

Atmospheric Neutrinos

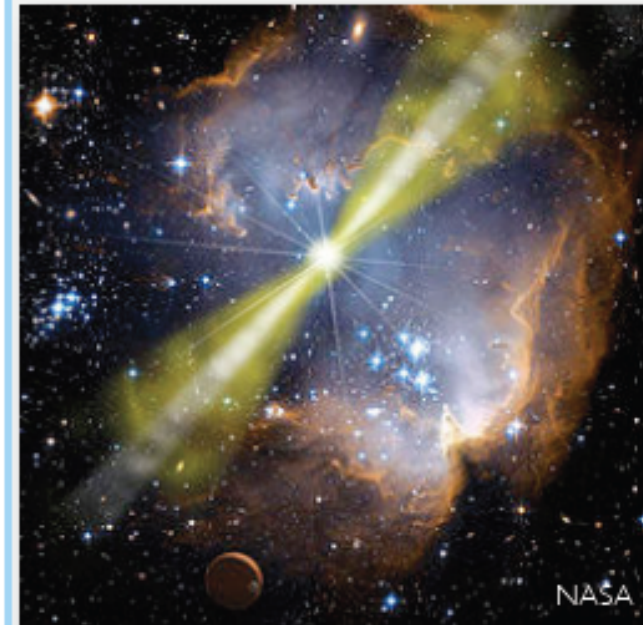
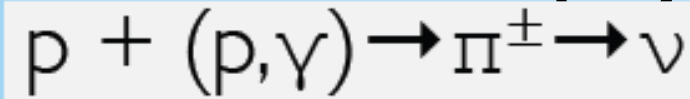
Cosmic rays interact in the upper atmosphere:



IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2

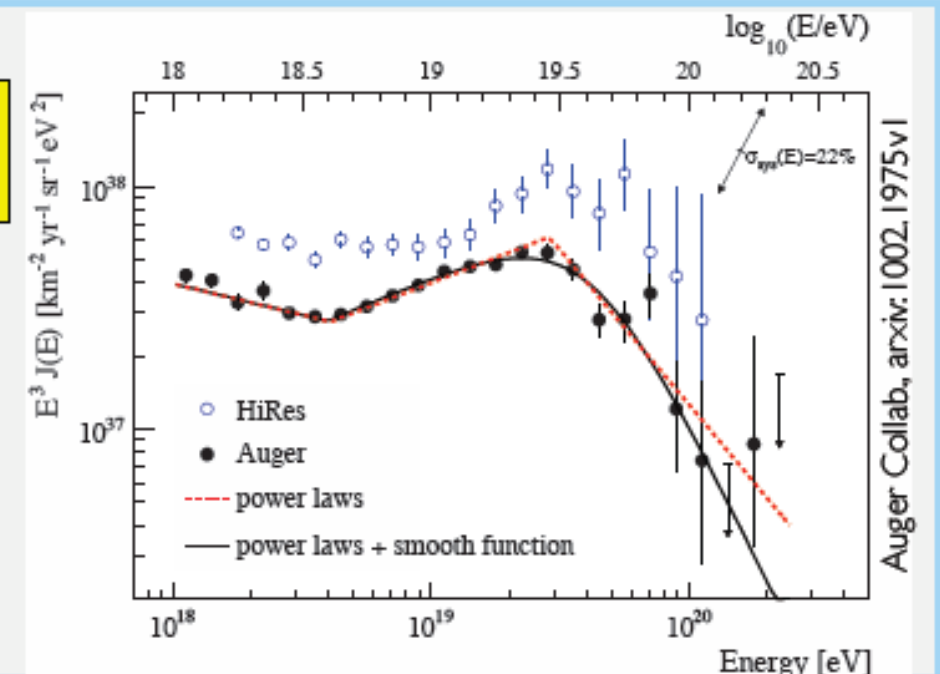
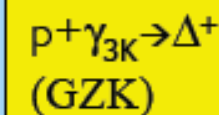


Astrophysical



Gamma-ray Bursts

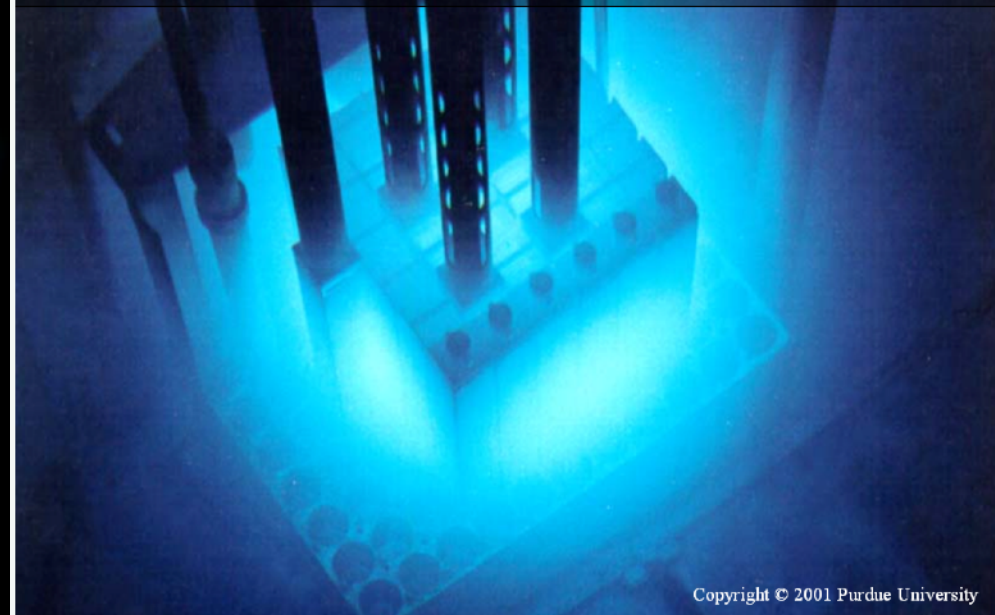
Active Galactic Nuclei



Principle of an optical Neutrino Telescope

Array of optical sensors capture the light

Charged particles (from a nuclear reactor in the picture) produce blue light in water



Copyright © 2001 Purdue University

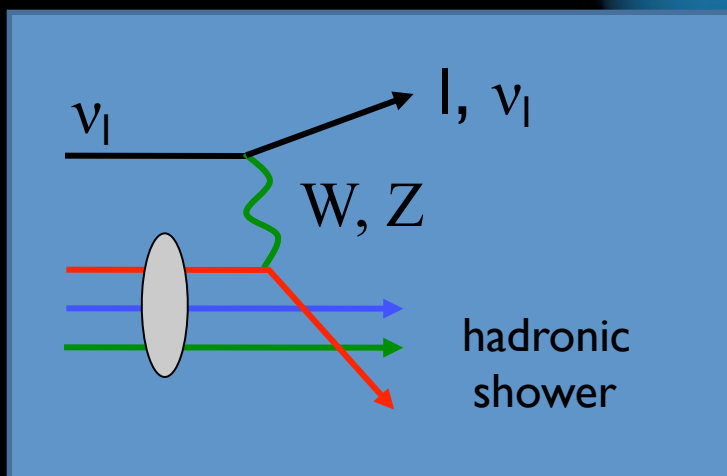
γ_c
Cherenkov
Radiation

41°

Muon

μ

interaction
Muon Neutrino

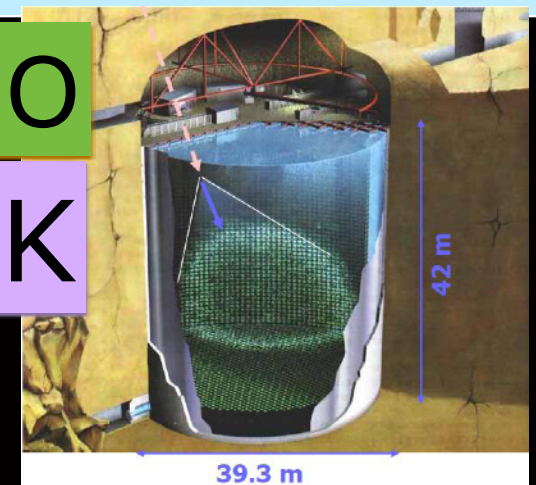


Neutrino Telescopes and IceCube

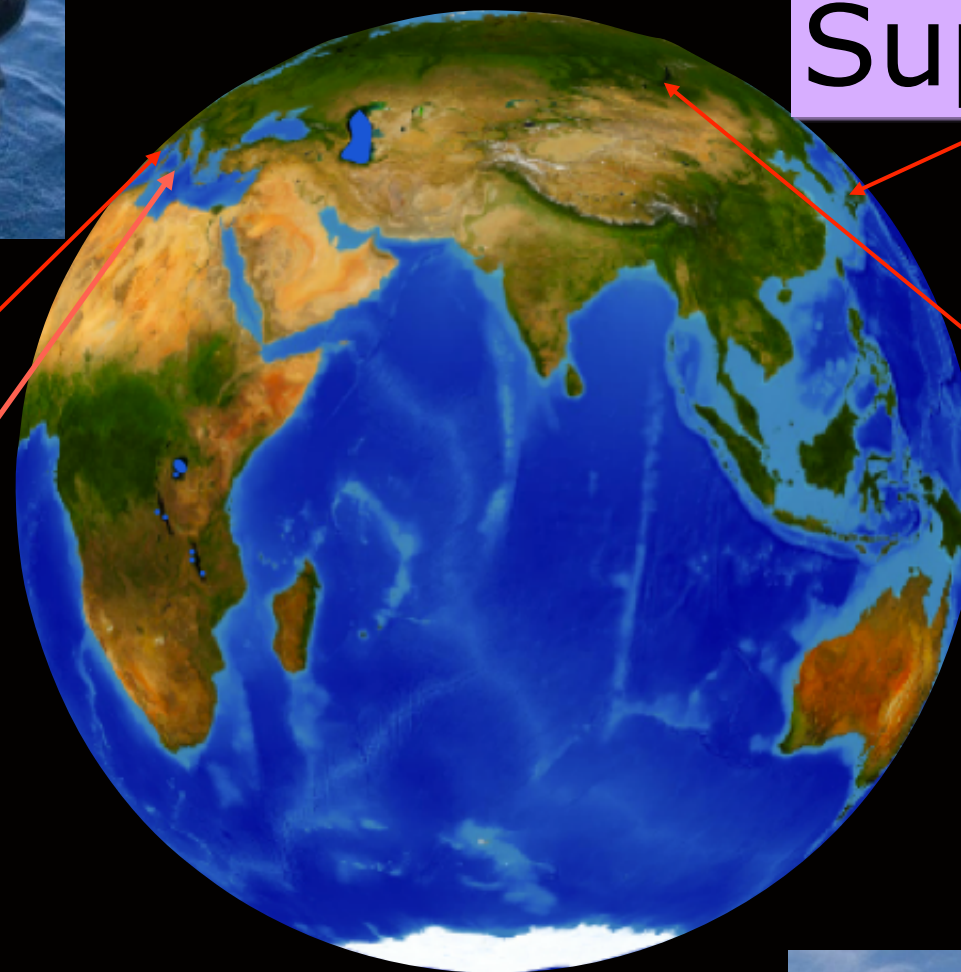
Large Water/Ice Cherenkov Neutrino Detectors

Hyper-K / KNO

Super-K



Lake Baikal
GVD



ANTARES

KM3NeT

Active

Prototype

Construction

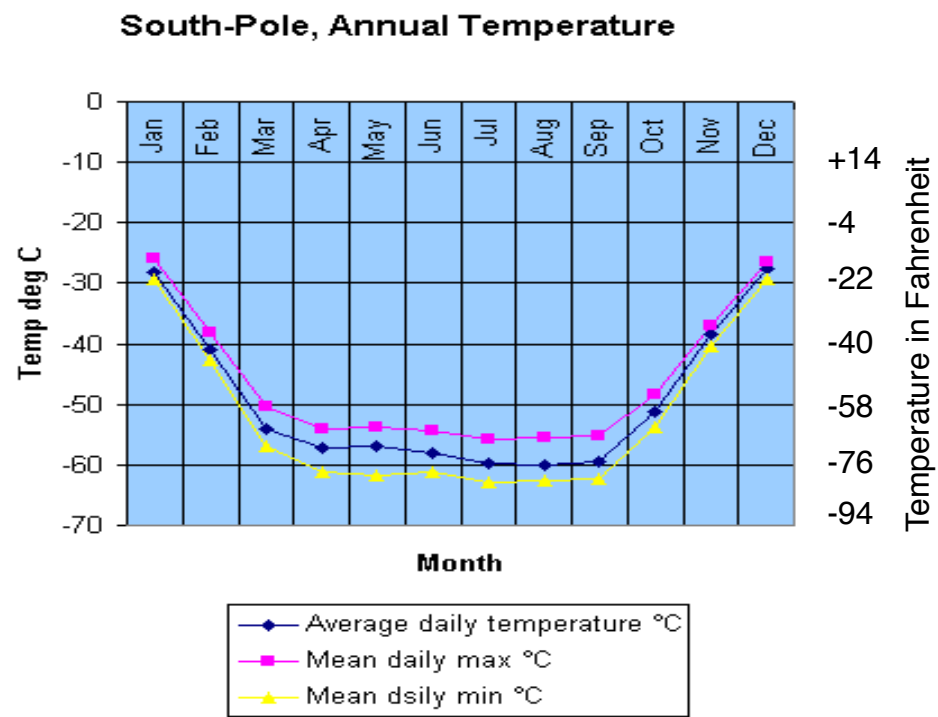
Planned

IceCube

Upgrade/Gen2



Laboratory at the South Pole



Geographic South Pole

Amundsen Scott
South Pole
Station

Road to work
Skiway

1 km

IceCube

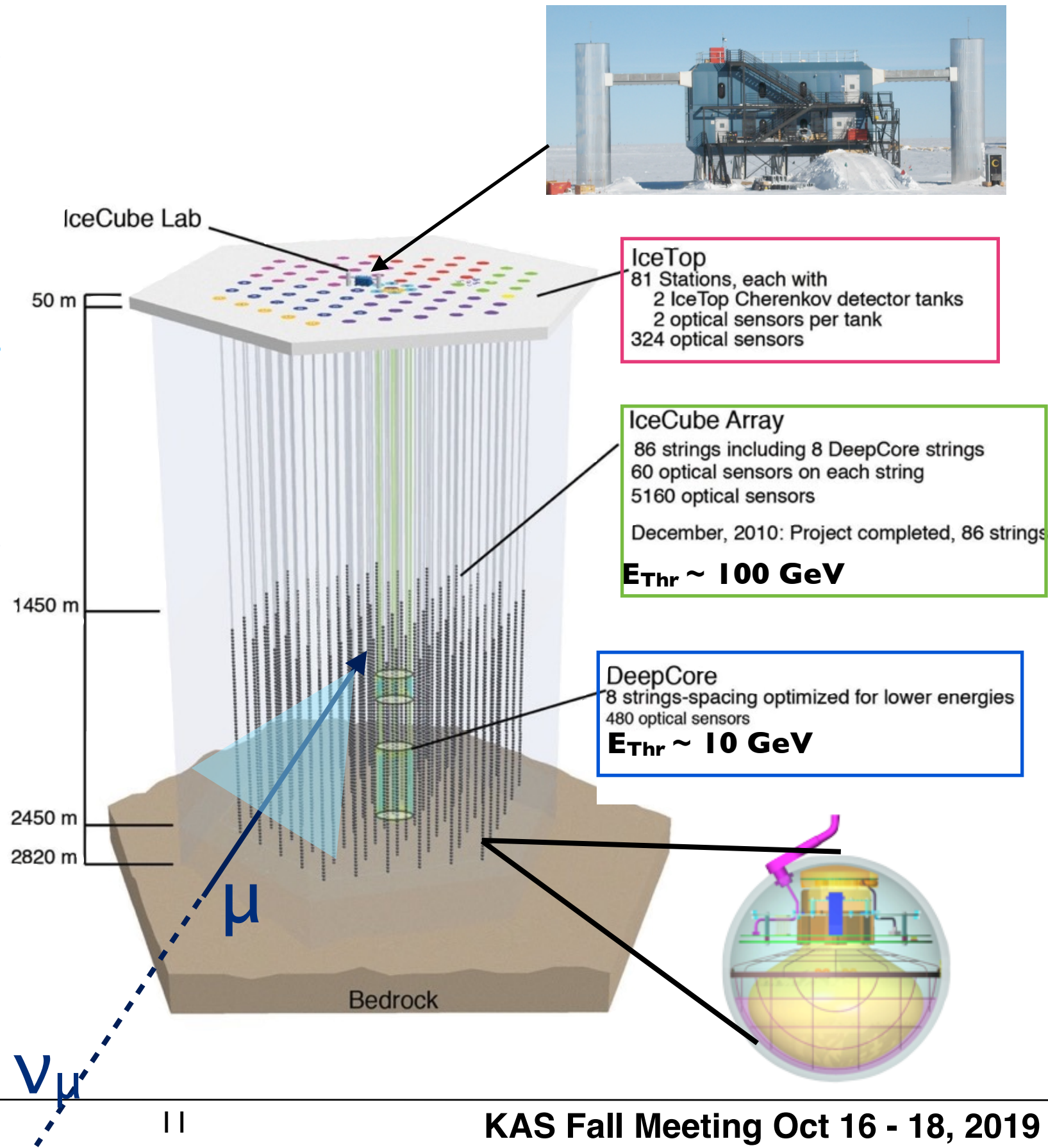
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010
- Extremely stable: >99% uptime and 98% of sensor modules in perfect condition !
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

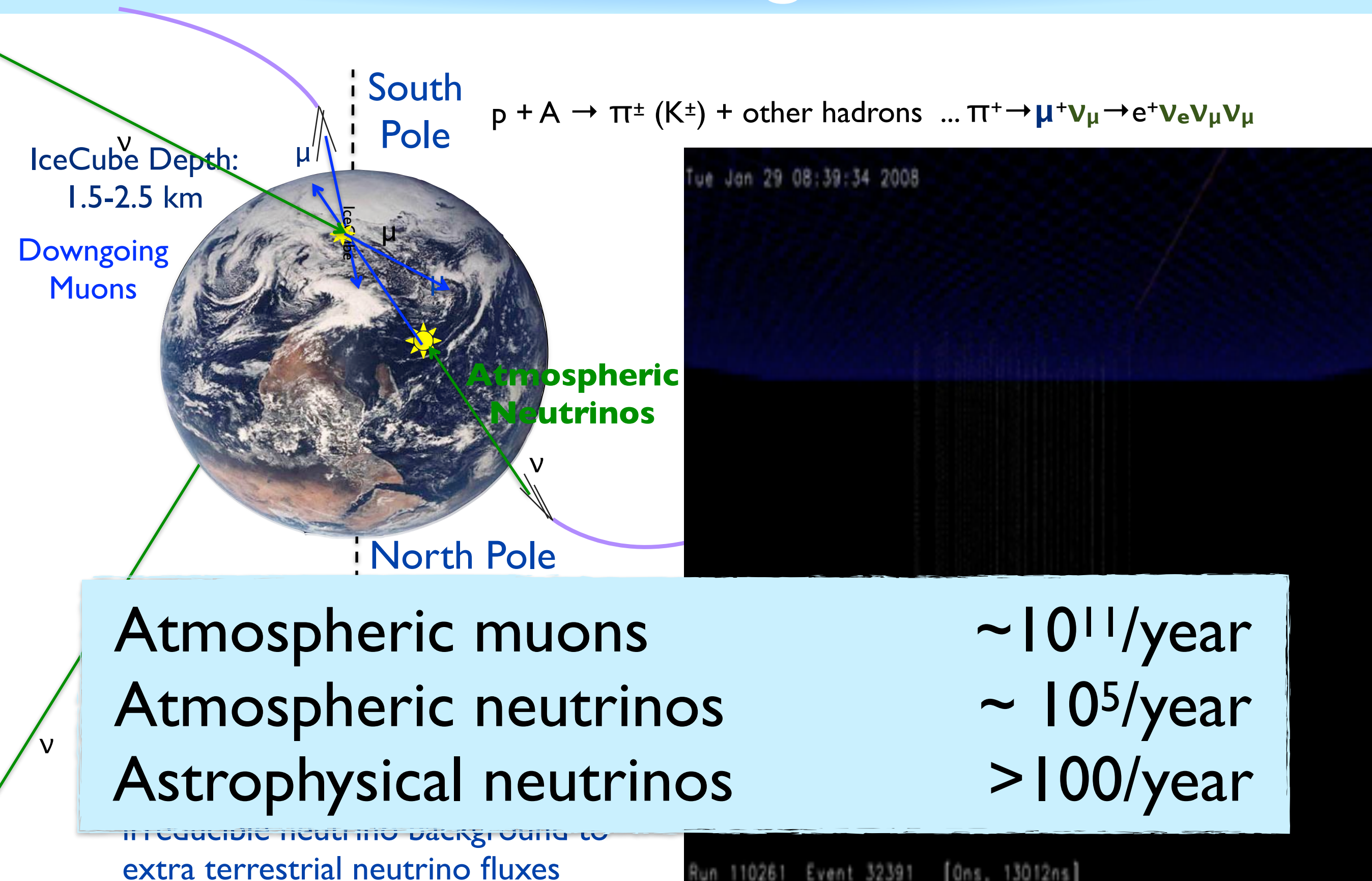
<이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.>

“한국 ‘세계적 리더’ 될 좋은 기회”

기초과학 투자 의지 활발, 한국에 새 연구 터전 등지.. 연구자·학생 영입해 연구

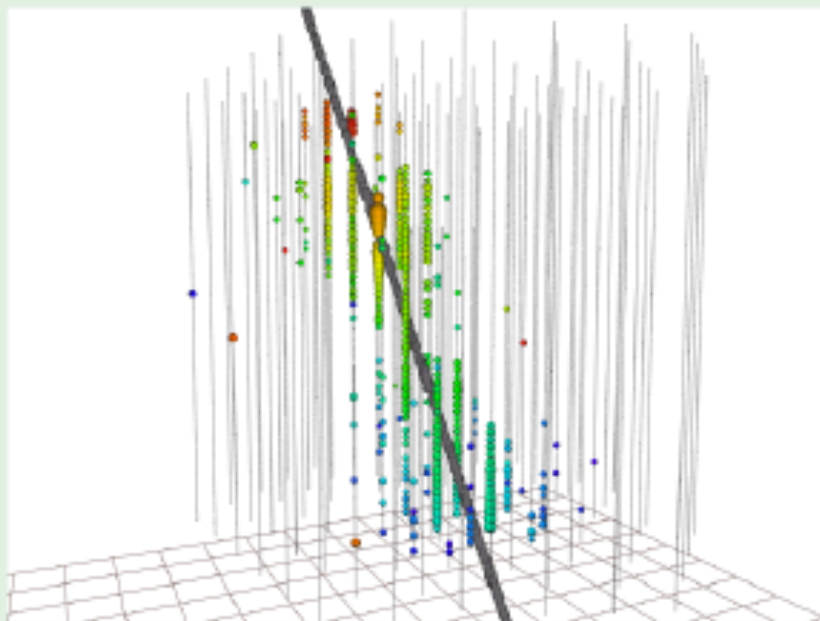


Signals in IceCube

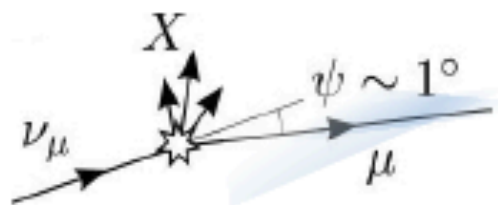


Event topologies in IceCube

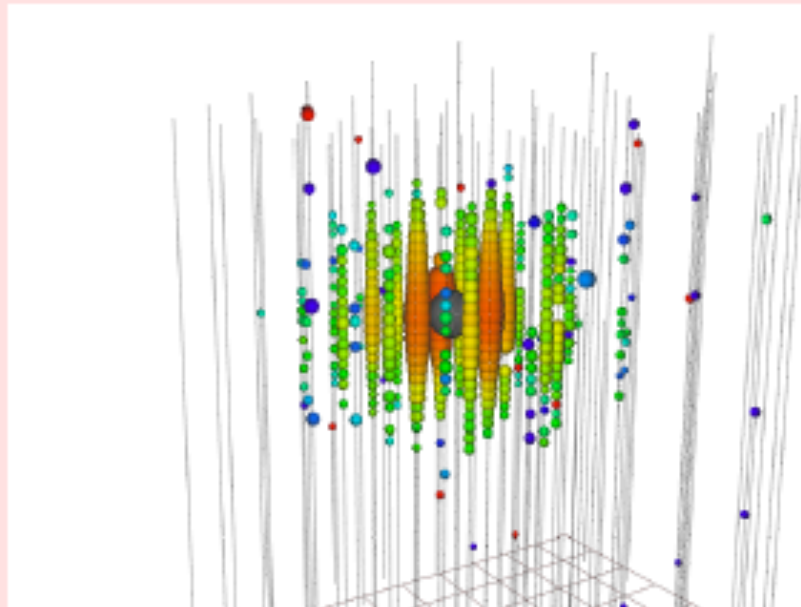
Track



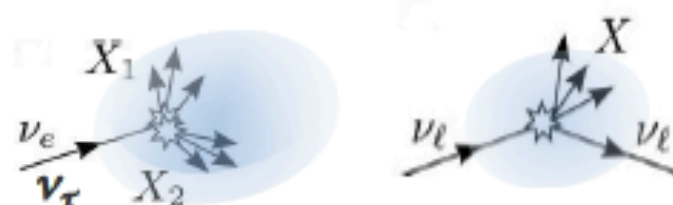
- Muon tracks (CC ν_μ)
- Resolution $< 1^\circ$
- Large energy uncertainties




Cascade



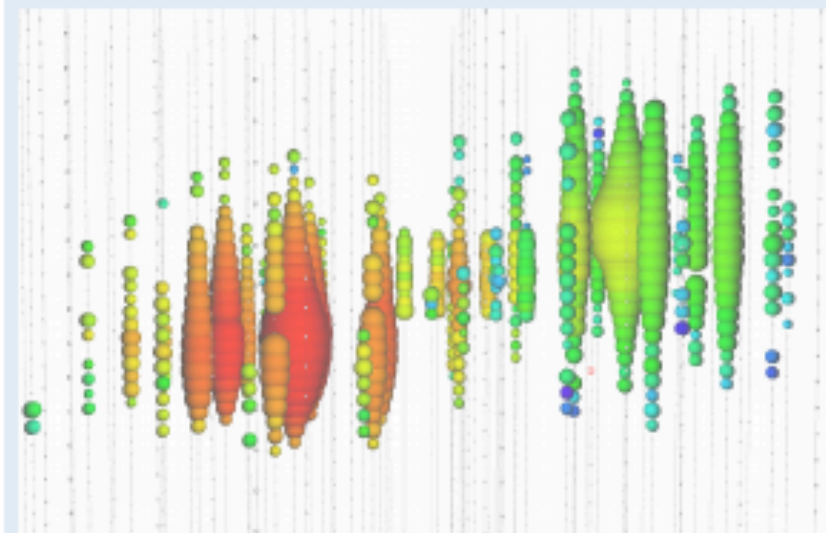
- NC or ν_e/ν_τ
- Resolution $\approx 15^\circ - 20^\circ$
- Energy resolution $\delta E/E \approx 15\%$



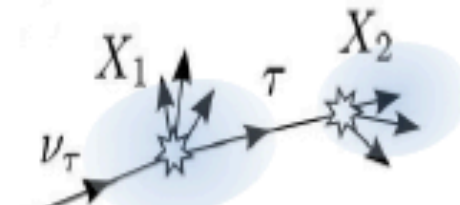
early  late

amount of light in detector $\propto \nu$ energy

Double-bang

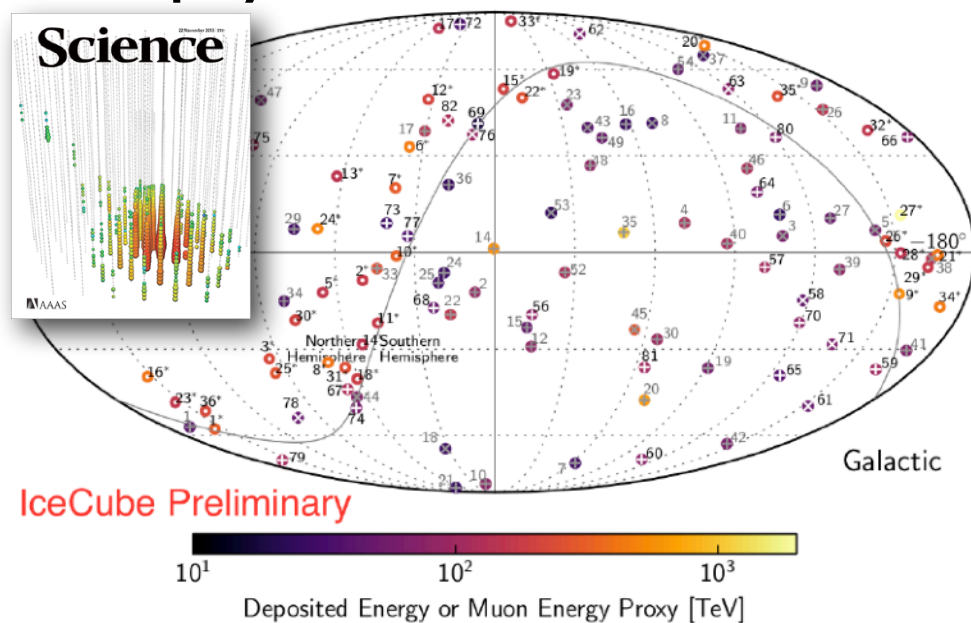


- High energy ν_τ (> 100 TeV)
- Not observed yet

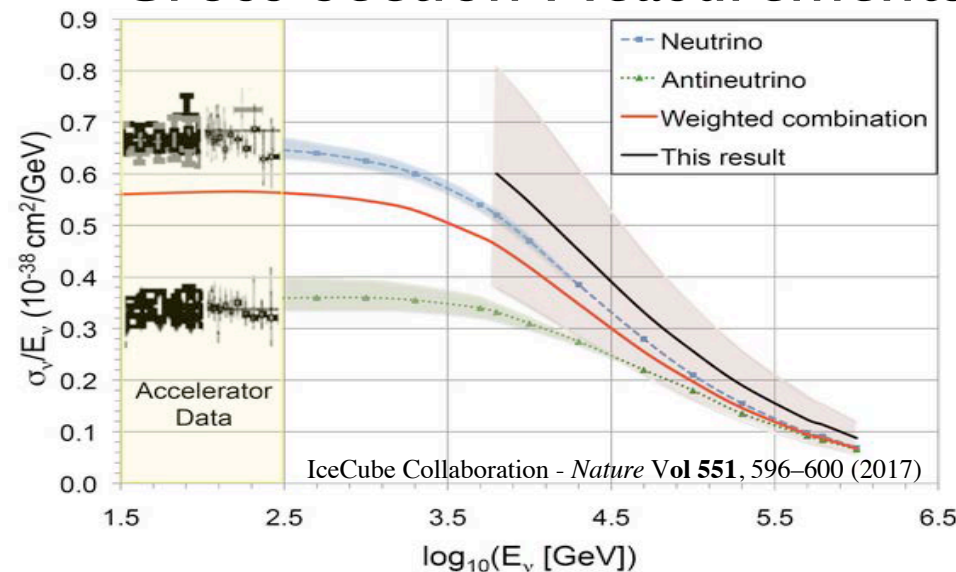


IceCube Science Program

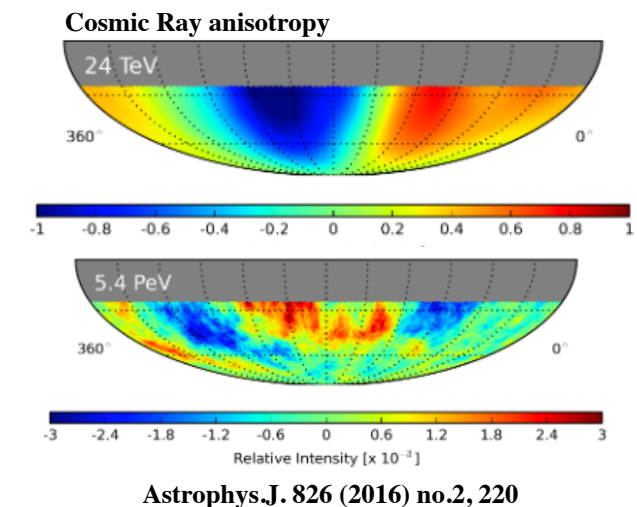
Astrophysical Neutrino Searches



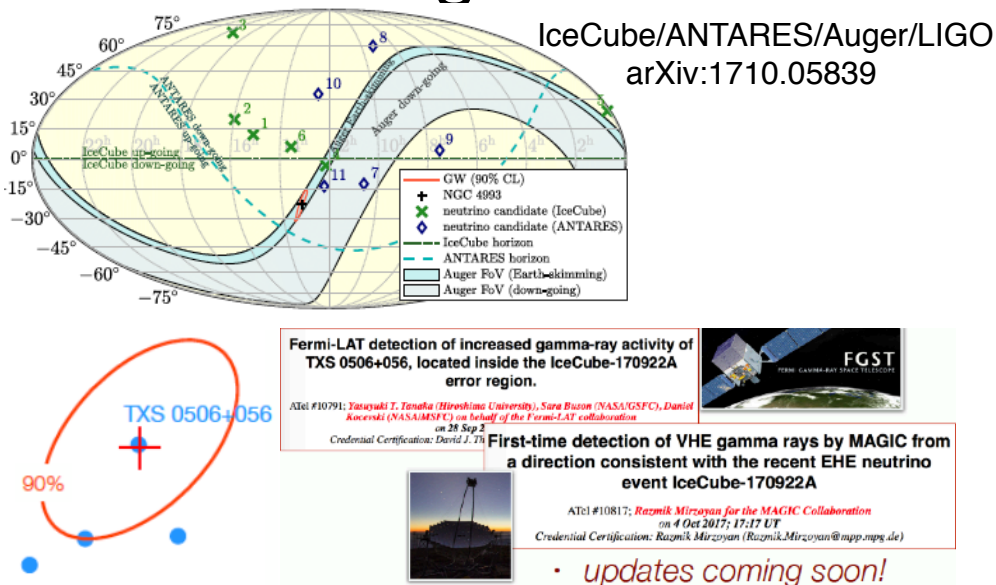
Neutrino Tomography / Neutrino Cross Section Measurements



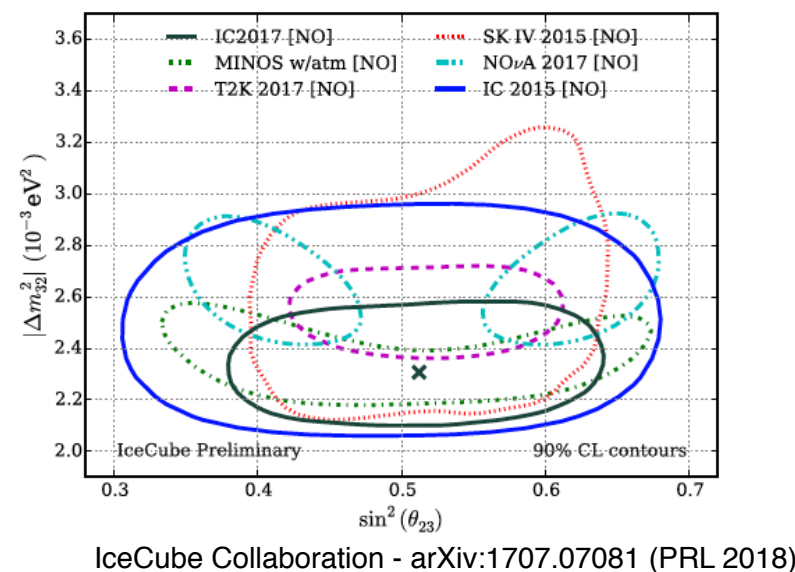
Cosmic Rays



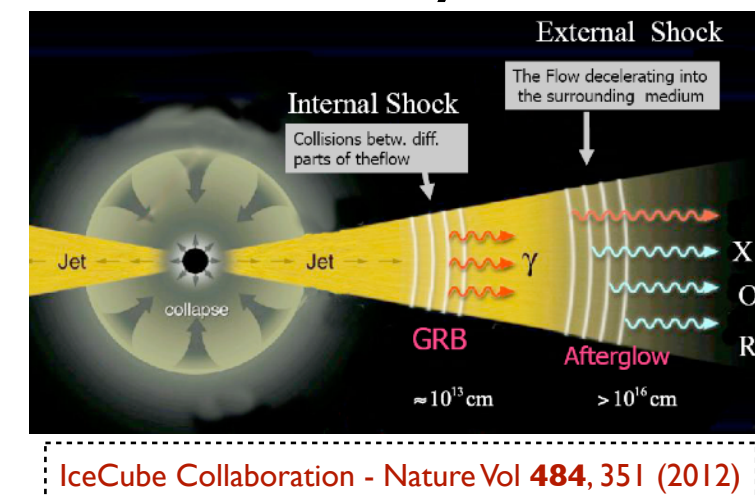
Multi-messenger Observations



Neutrino Oscillations



Gamma-ray bursts



Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

IceCube in Korea

SKKU Group



SKKU Group:
Carsten Rott
Dongyoung Jeong
Hrvoje Dujmovic
Jonghyun Kim
Woosik Kang
Christoph Toennis
Seongjin In
Seokmin Choi
Gyunho Yu
Minjin Jeong
Hyoungku Jeon

Sungkyunkwan University, IceCube Member since Summer 2013

- Beyond the Standard Model and **Dark Matter** Searches
 - Solar Dark Matter, Secluded Dark Matter, Galactic Dark Matter annihilation and decay, ...
- Solar Atmospheric Neutrinos
 - Search for signal from cosmic ray interactions in the **solar atmosphere**
- Ice Camera system development for IceCube Upgrade
 - Study refrozen ice in drill holes
 - Reduce largest remaining sources of systematic uncertainties for analyses
 - Improve pointing of neutrino events → **Multi-messenger science, optical follow-ups, realtime astronomy**

300 scientists
from 12 countries

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Université de Gand
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta-Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität
Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
Universität Münster
Universität Mainz
Universität Wuppertal

JAPAN
Osaka University
NEW ZEALAND
University of Canterbury
REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms Universitet
Uppsala Universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University

Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
University of Virginia and A&M
College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley

University of California, Irvine
University of Delaware
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin-Madison
University of Wisconsin-River Falls
Yale University

FUNDING AGENCIES

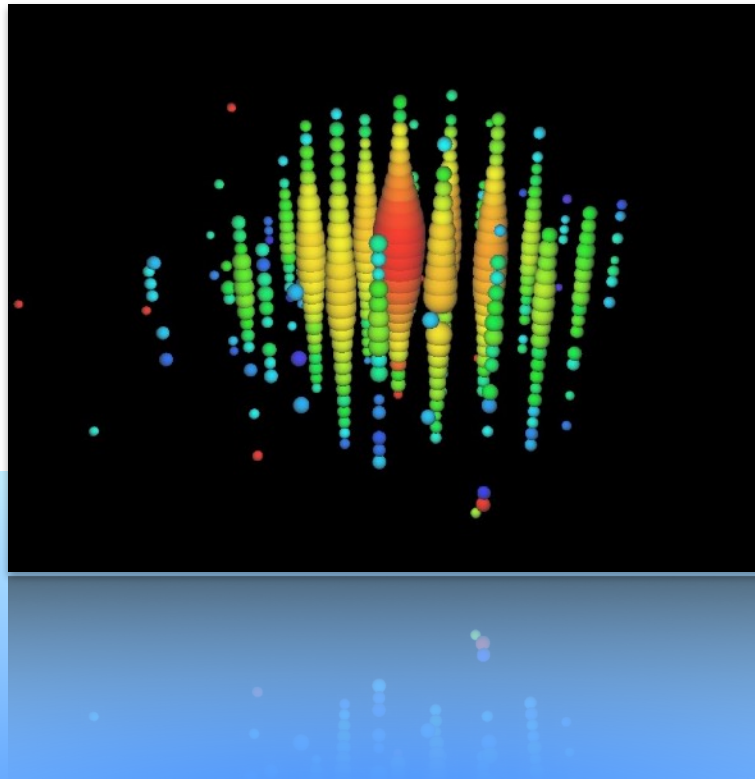
Fonds de la recherche en santé (FRS-FRSQ)
Fonds de la recherche en santé (FRS-FRSQ)
Fonds de la recherche en santé (FRS-FRSQ)

Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Japanese Ministry of Education, Culture, Sports, Science & Technology (MEXT)

Japan Society for the Promotion of Science (JSPS)
Korea Research Council of Science & Technology (KRCST)
Korea Science & Engineering Foundation (KSEF)

The Swedish Research Council (VR)
University of Wisconsin-Madison Research Foundation (UW-MRFRF)
U.S. National Science Foundation (NSF)





Astro-physical Neutrino Search

Finding astrophysical neutrinos



(1) Point source search

- Search for clustering of neutrinos from point in the sky

(2) Transient source search

- Search for spacial and temporal clustering of neutrinos

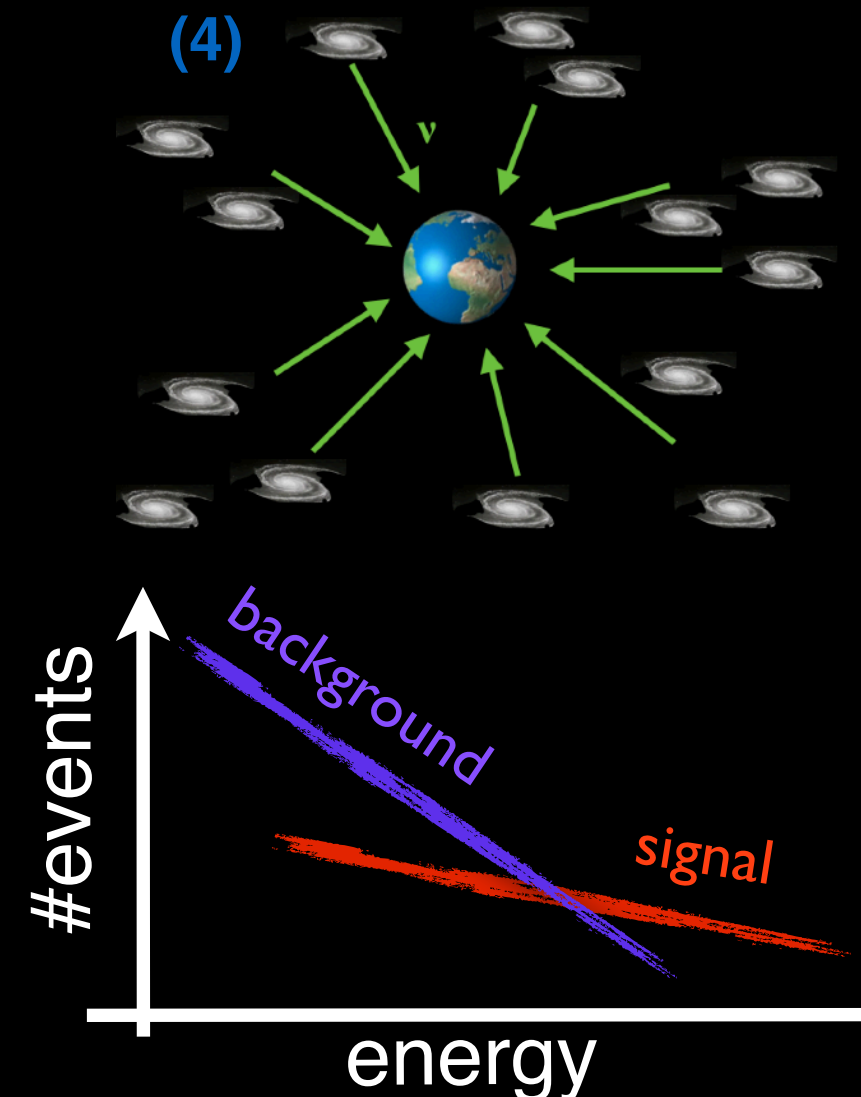
(3) Multi-messenger search

- Search for a coincidence between neutrino and other messenger particles spacial at particular time and location

(4) Diffuse search

- Search for spectral feature, inconsistent with atmospheric background predictions

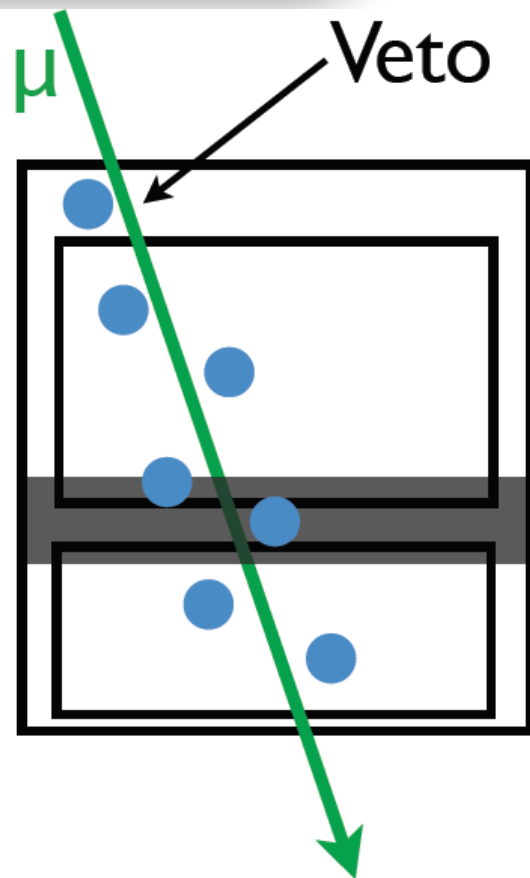
.... + various combinations and



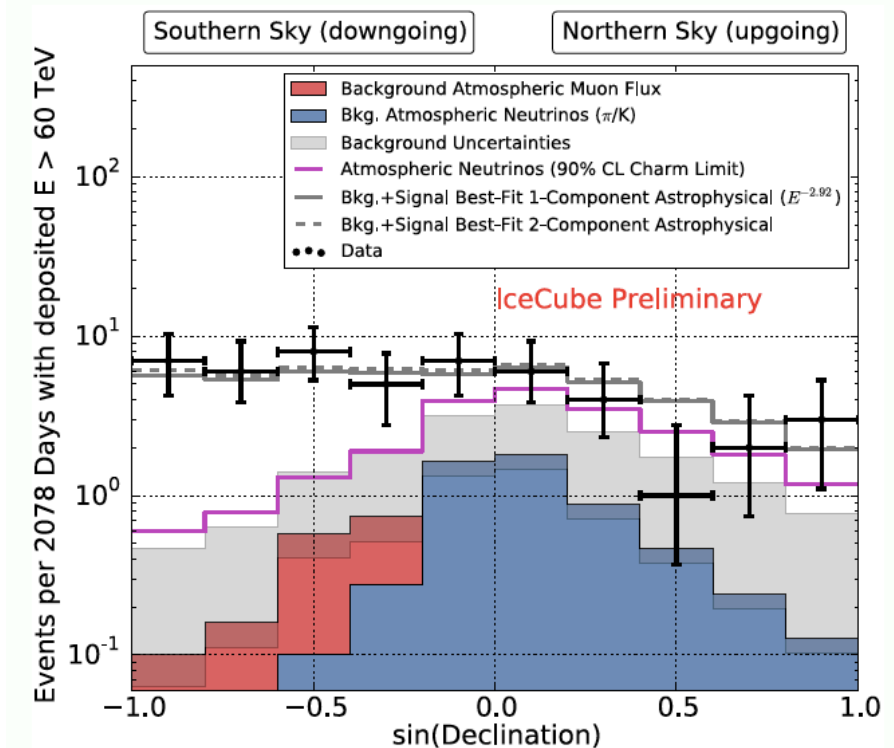
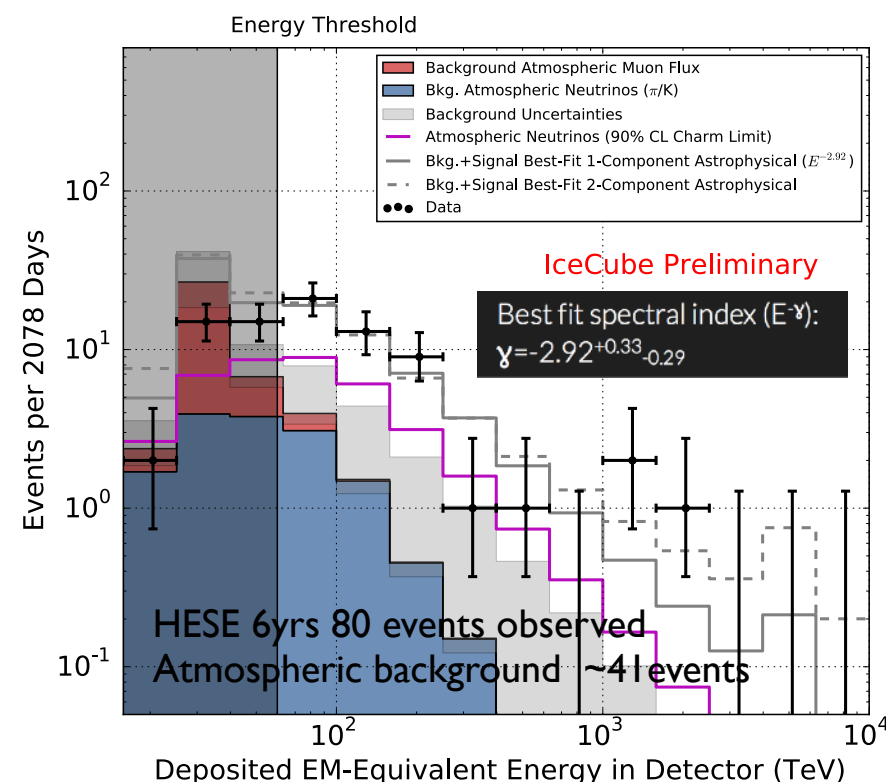
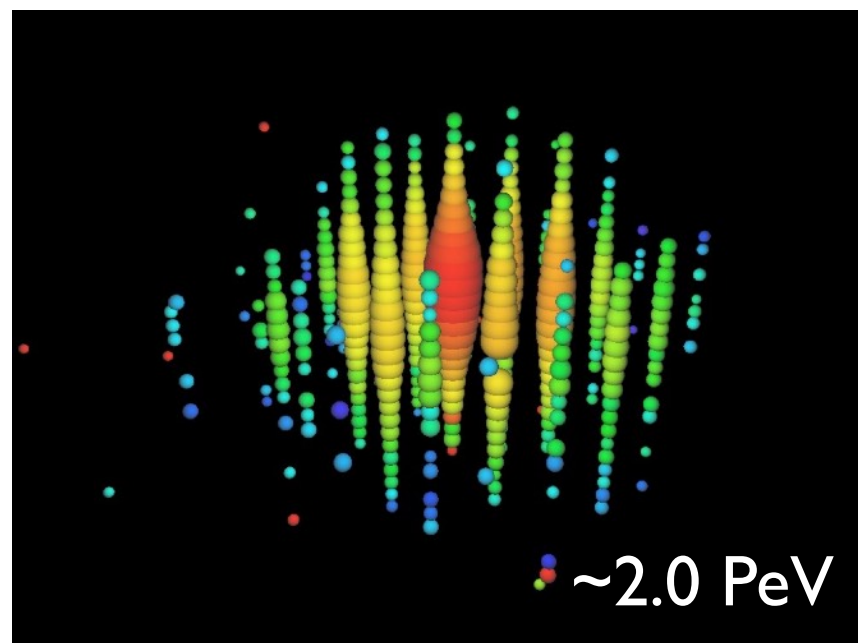
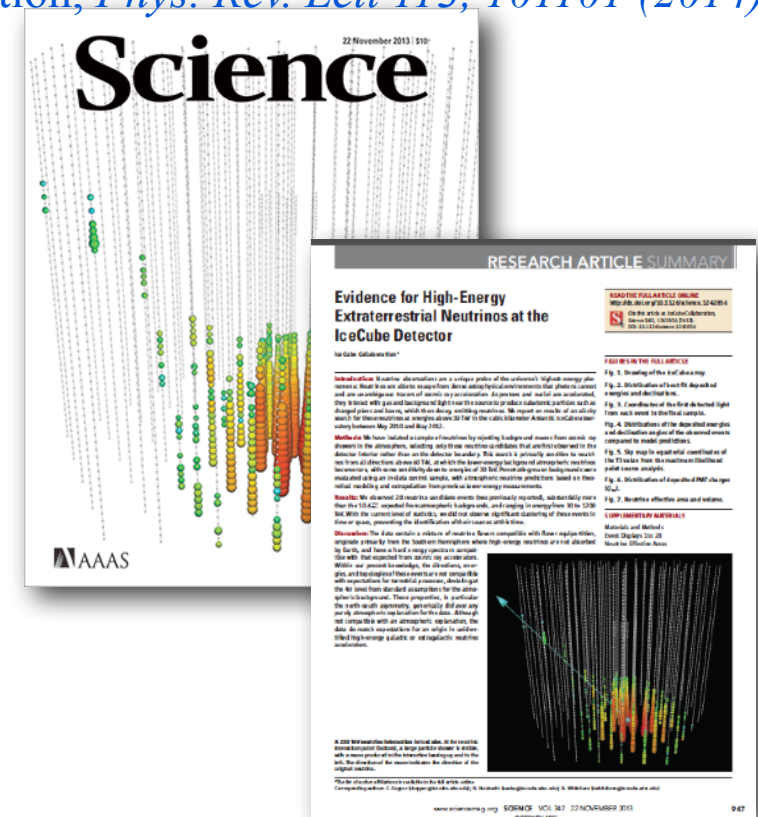


Observation of high-energy astrophysical neutrinos

IceCube Collaboration, *Science* 342, 1242856 (2013),
IceCube Collaboration, *Phys. Rev. Lett* 113, 101101 (2014)



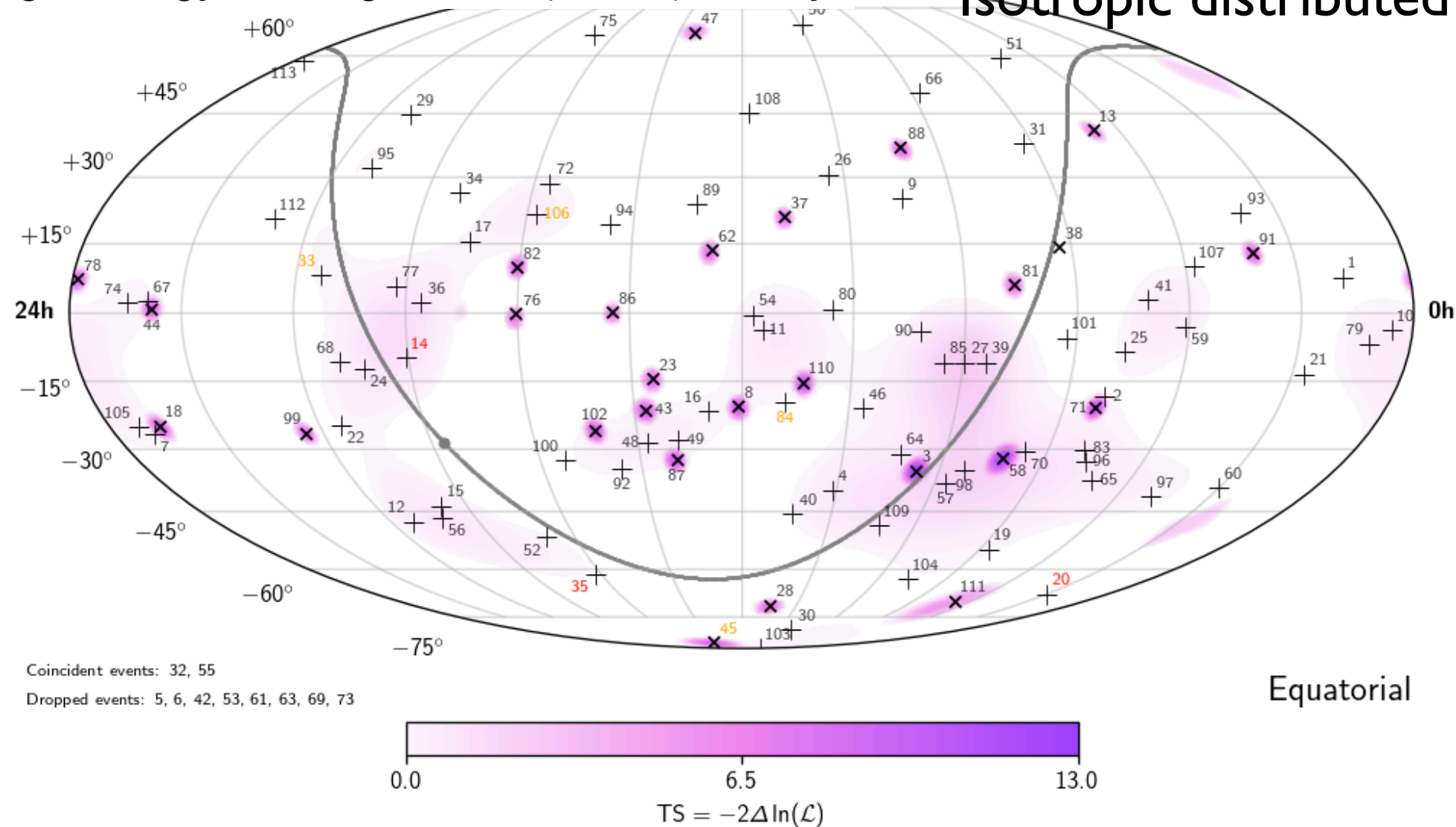
- Search for High-Energy Starting Events (HESE)
 - Efficient reject atmospheric backgrounds
 - Discovery of astrophysical neutrinos



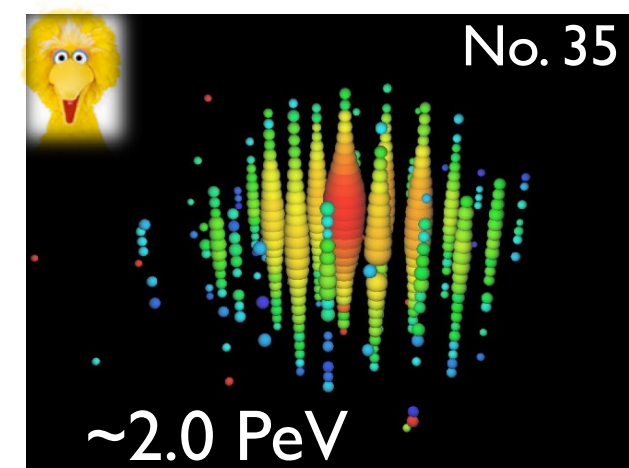
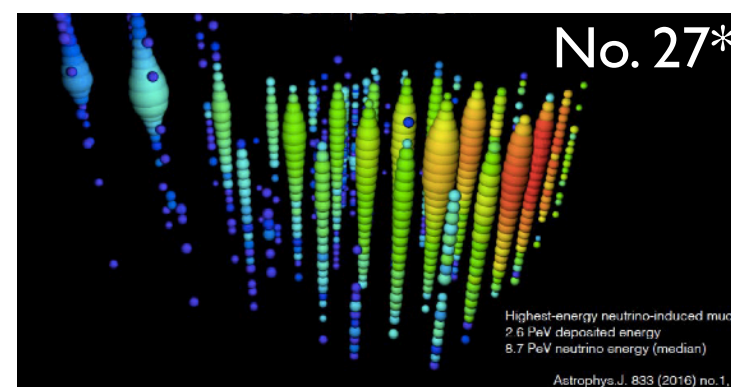
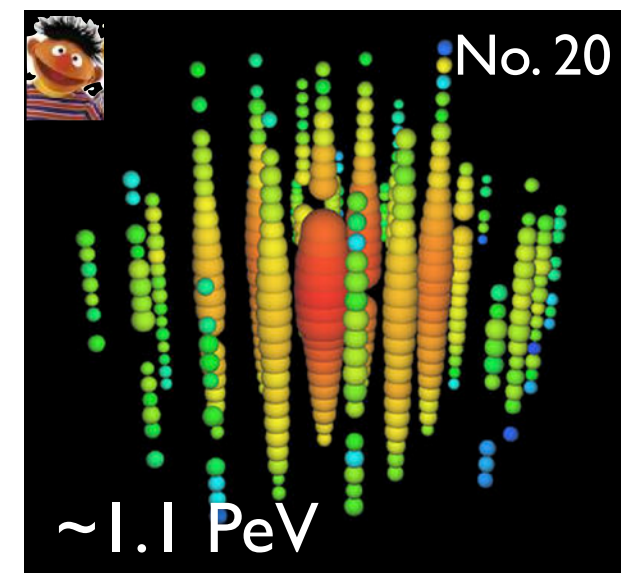
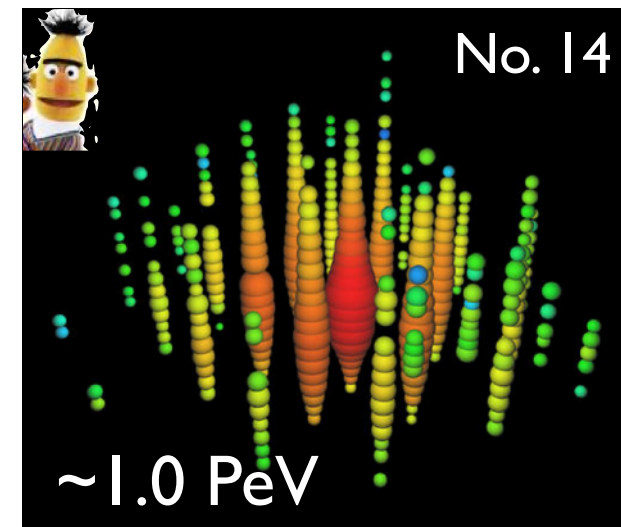
Arrival directions (highest energy events)

IceCube Collaboration, *Science* 342, 1242856 (2013)

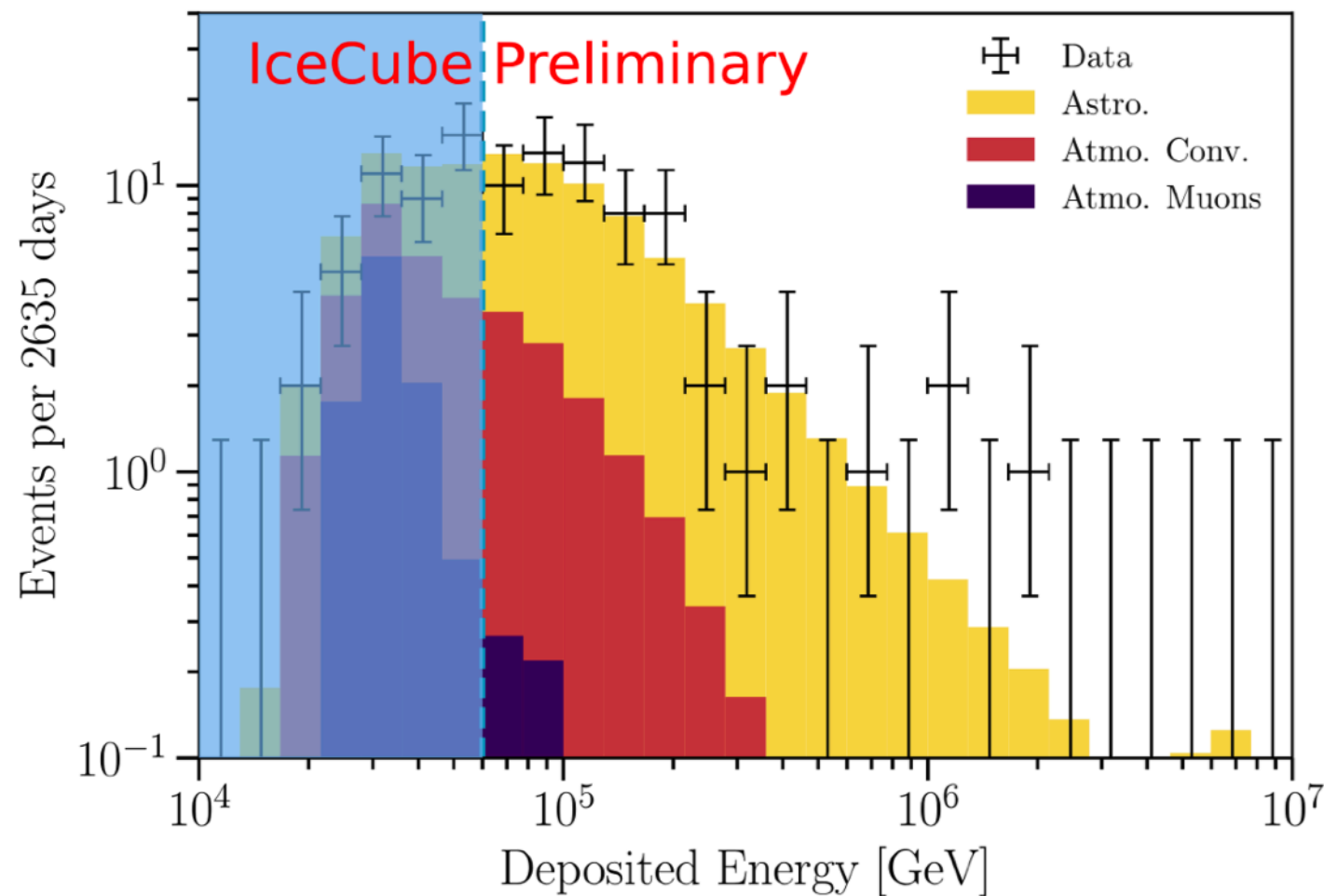
High-Energy Starting Events (HESE) – 7.5 yr



No evidence for point sources, nor a correlation with the galactic plane



Independent confirmation

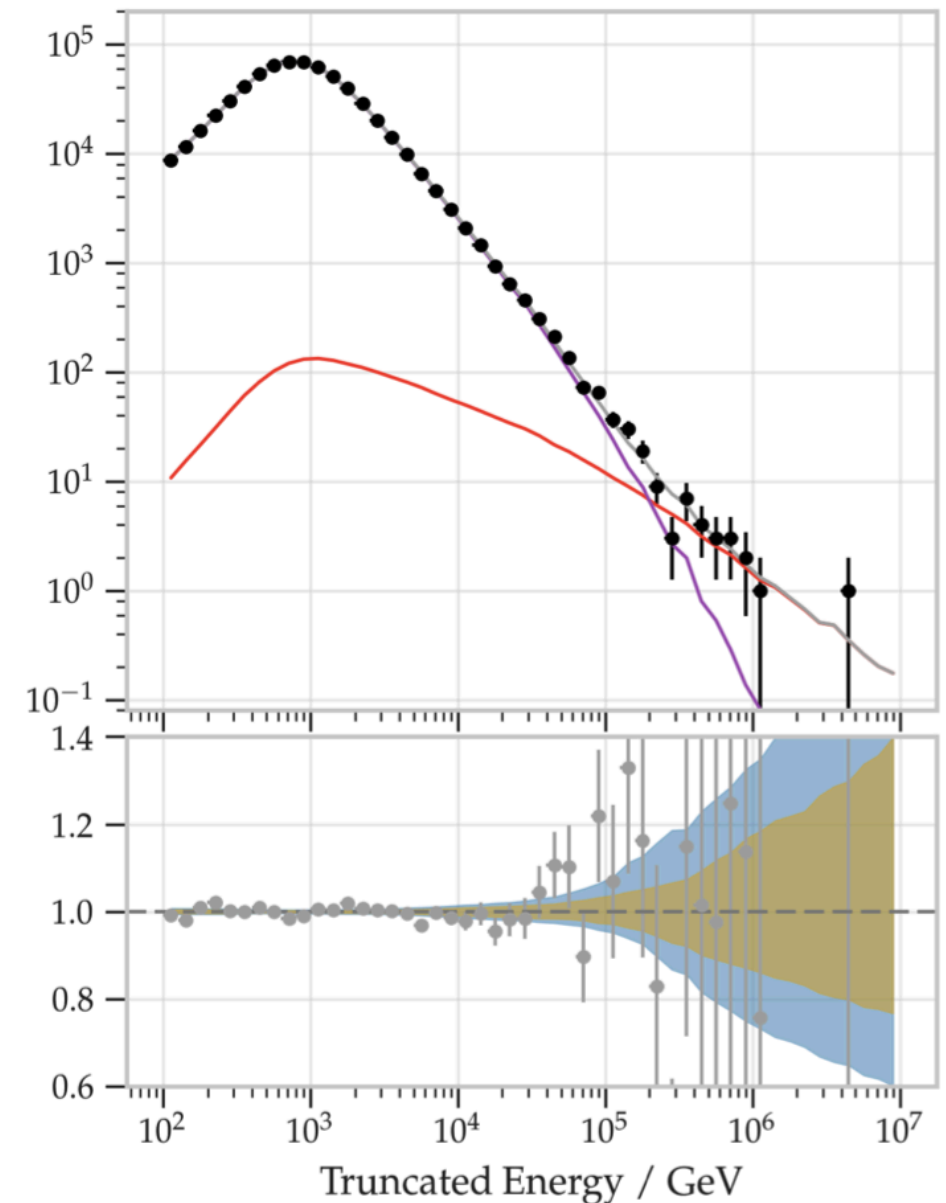


HESE 7.5 year

103 events

(60 events > 60 TeV)

Best-fit: $\gamma=2.87\pm0.3$



8-yr upgoing ν_μ “track”

36 events at >200 TeV (6.7σ)

- Best-fit: $\gamma=2.19\pm0.10$

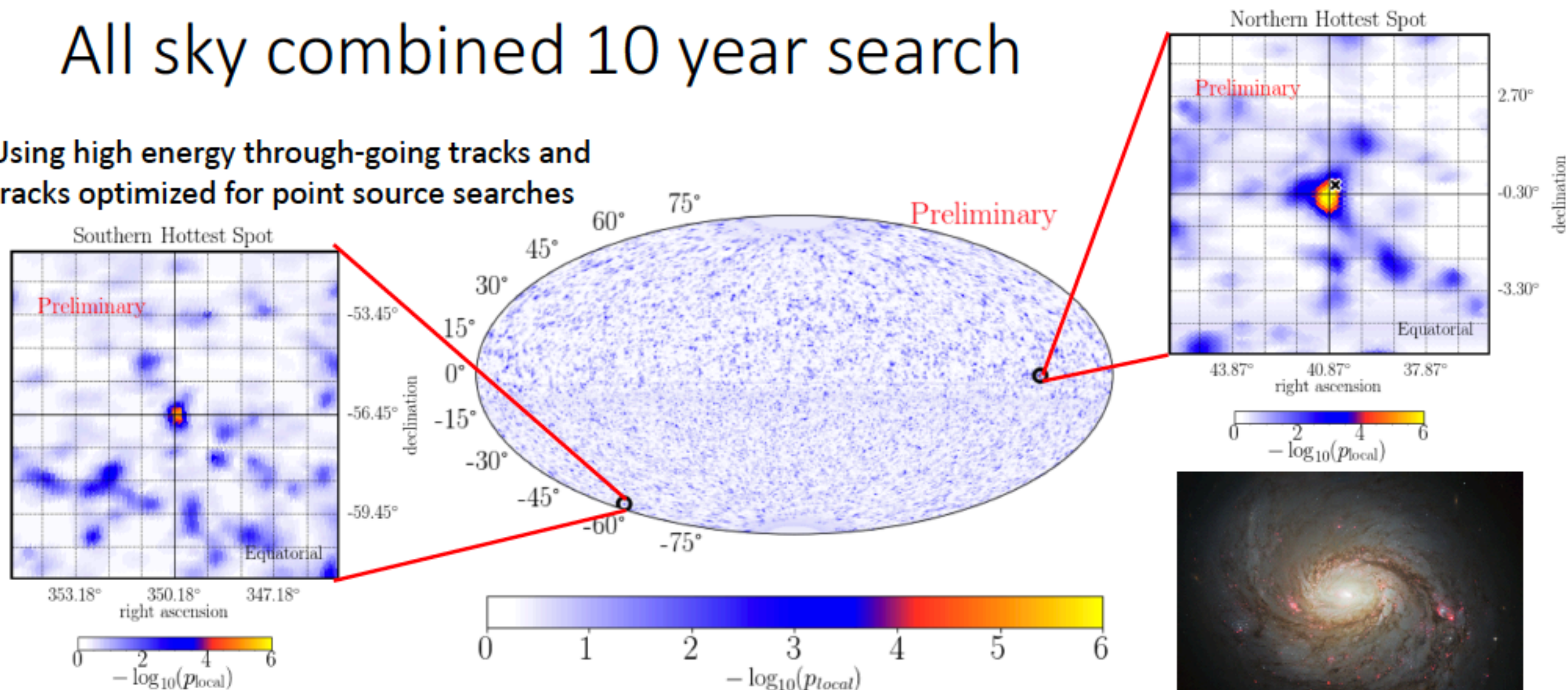
- ν_μ flux above 100 TeV:

$$E_V^2 \Phi_V = (1.01^{+0.26}_{-0.23}) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Point source search

All sky combined 10 year search

Using high energy through-going tracks and tracks optimized for point source searches



T. Carver NU5c

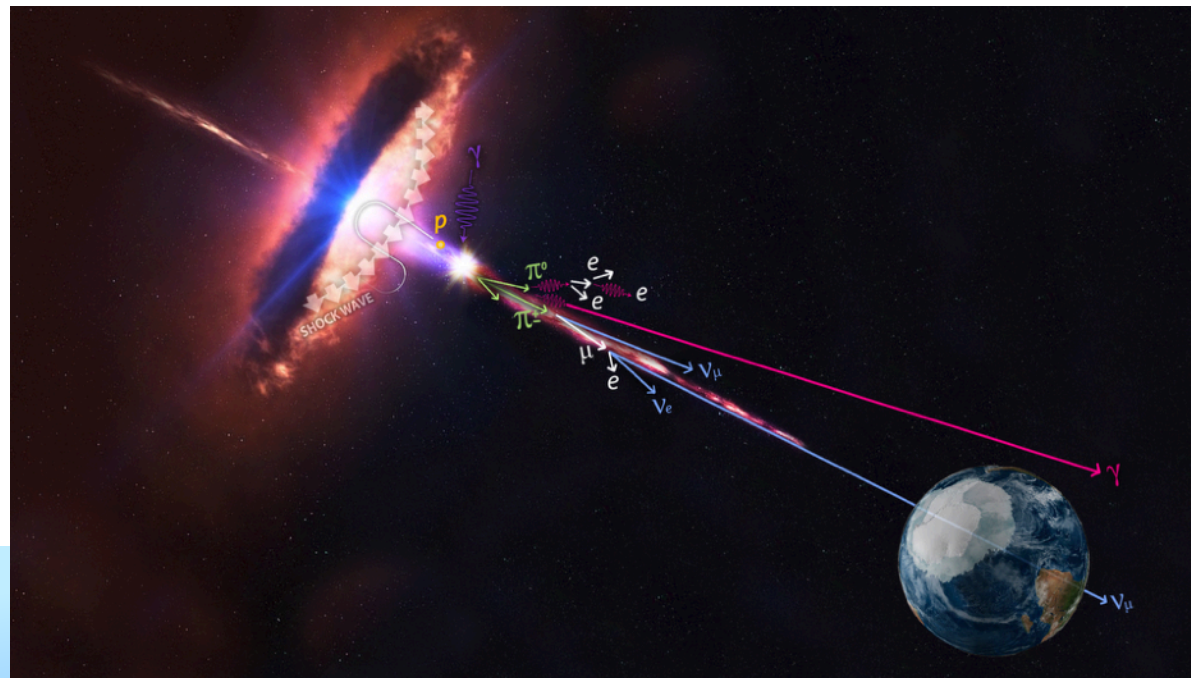
New source list of 110 Galactic and Extragalactic objects
Hottest spot in Northern Hemisphere coincides with
 2.9σ excess at the position of NGC 1068



NASA, ESA & A. van der Hoeven

7/29/19

14

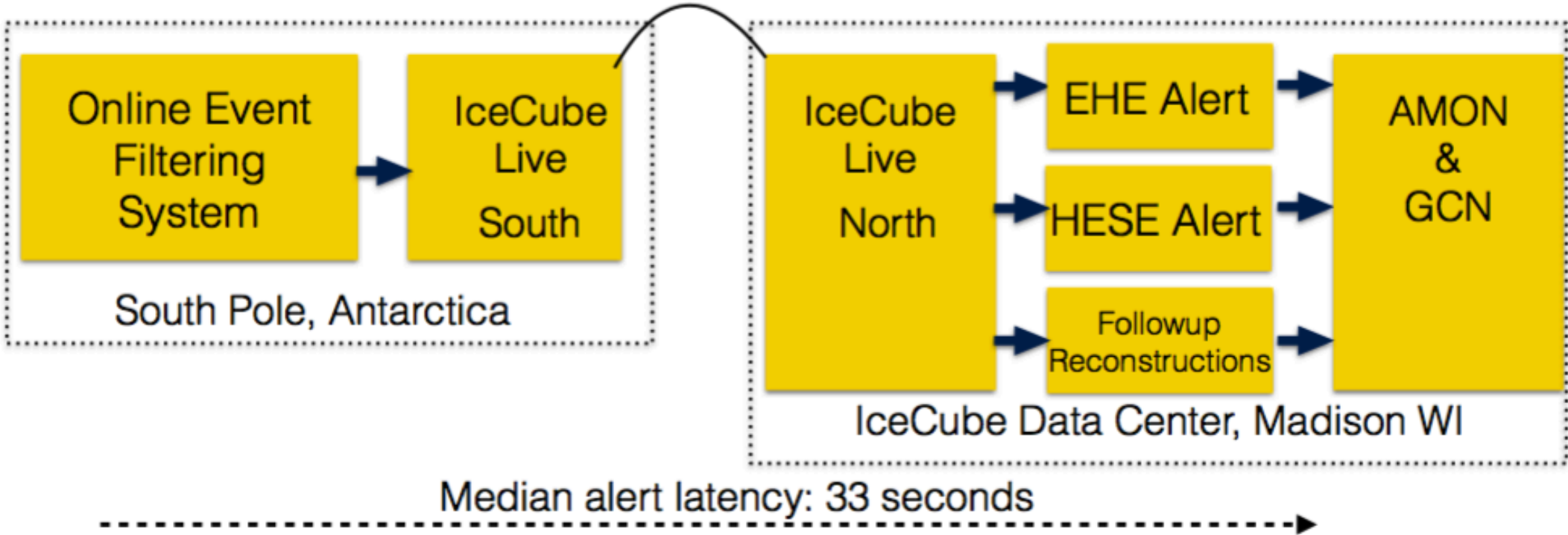


Multi-messenger Neutrino Astronomy and IceCube-170922A

IceCube-I70922A & TXS 0506+056

- Real-time alerts. Since 04/2016, $\approx 6\text{-}8/\text{yr}$
- Improved selection summer 2018
 - Good angular resolution ($0.5^\circ - 2^\circ$ 90% of events)
 - 50% astrophysical fraction

Updated alerts	Gold	Bronze
Signalness	> 50%	>30%
Expected signal/yr	6.6	2.8
Expected bkgd/yr	6.1	14.7



IceCube-170922A & TXS 0506+056

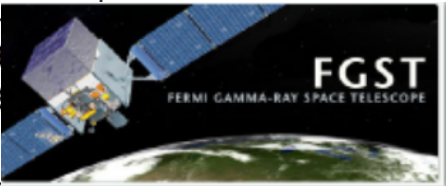
TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event

DATE: 17
FROM: E

Claudio Ko
report on

On 22 Sep,
probability
Extremely
normal on

Fermi-LAT detection of increased gamma-ray emission from TXS 0506+056, located inside the IceCube error region.




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

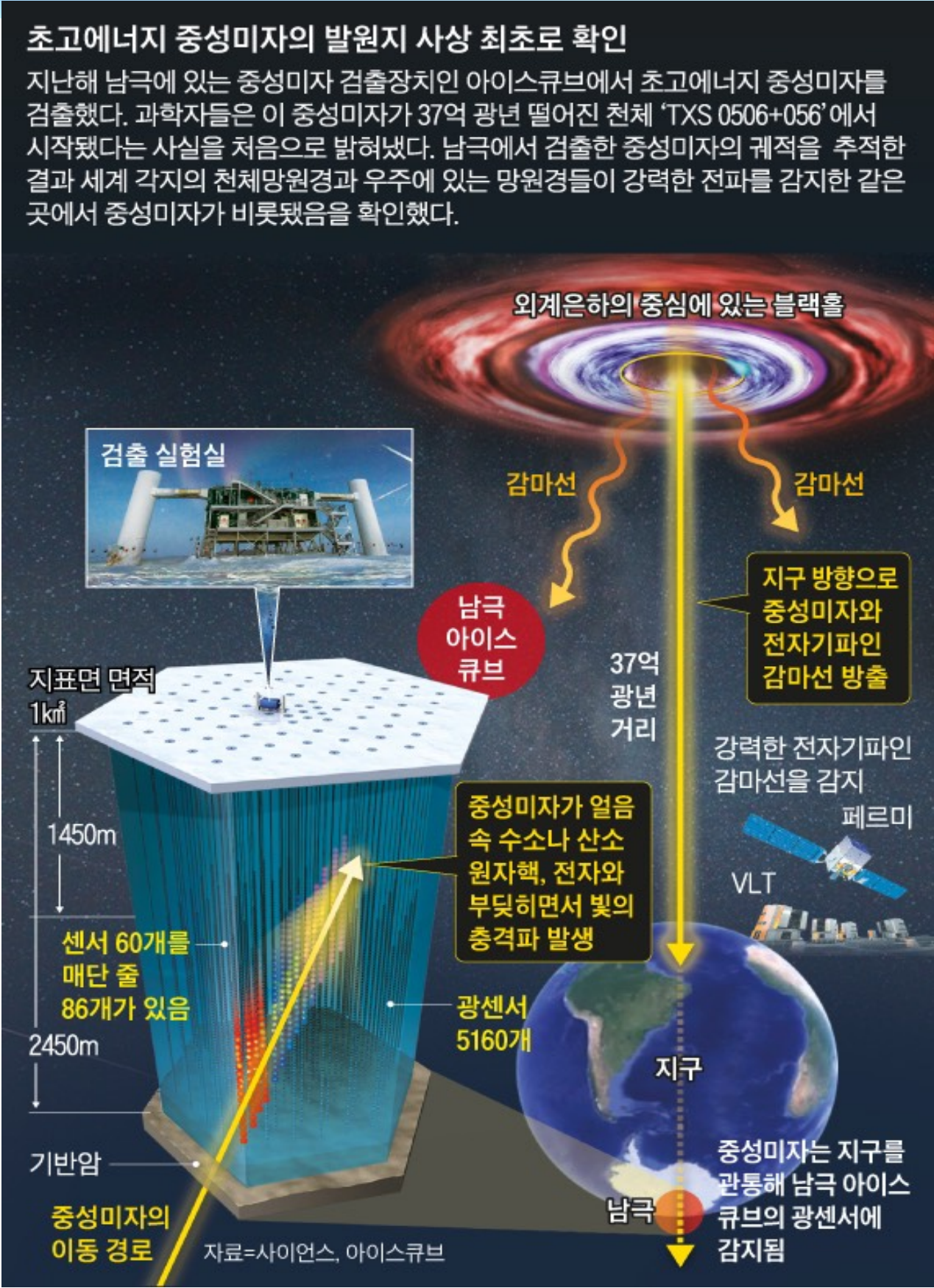
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

[Tweet](#) [Recommend 448](#)



After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916 Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 0 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 1 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h c

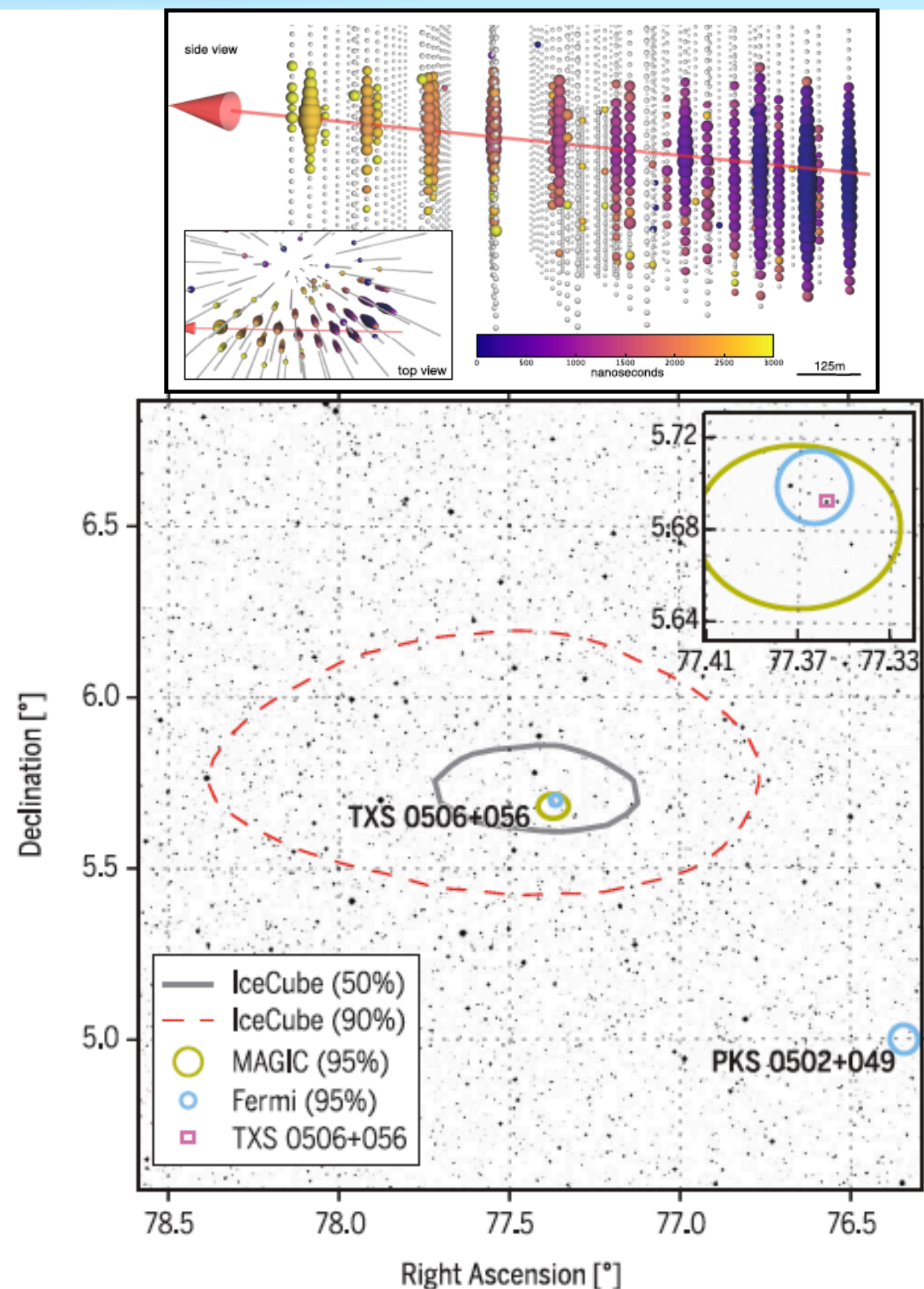
- September 22, 2017: a neutrino alert issued by IceCube
- Fermi-LAT and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
- Very active multi-messenger follow-up from radio to γ -rays



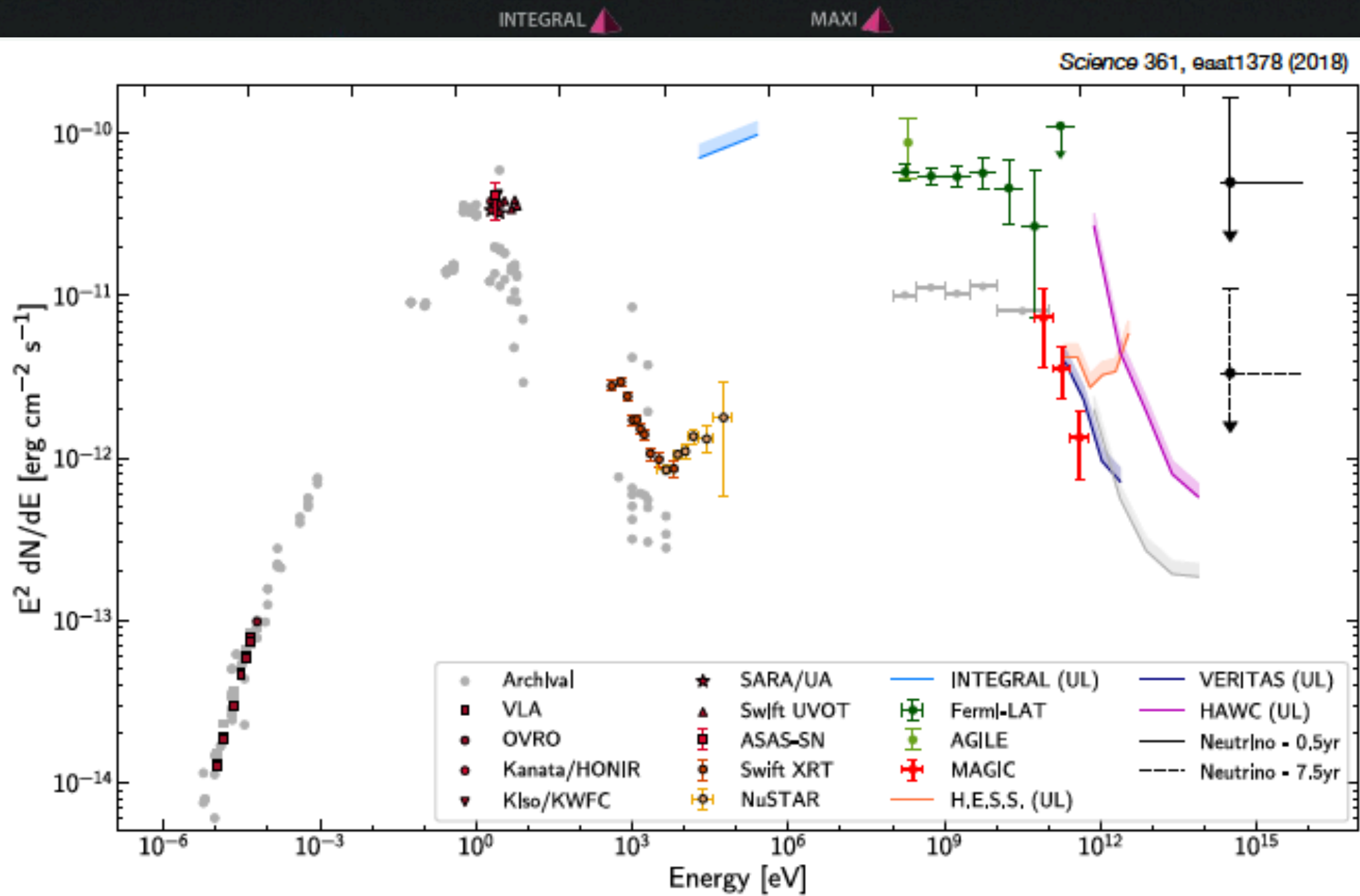
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- Chance probability of a Fermi-IceCube coincident observation: $\sim 3\sigma$ (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- **TXS 0506+056 redshift determined to be $z=0.3365$** (S. Paiano et al. *ApJL* 854.L32(2018))
- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or IES 1959+605



Follow-up Observations of IceCube Alert IC170922



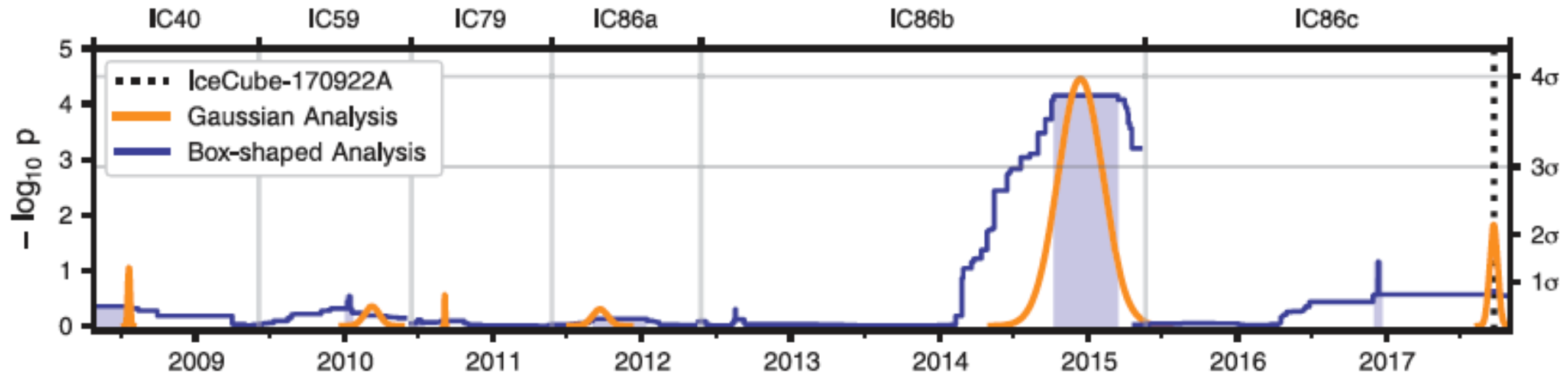
Observations

Earth
Space

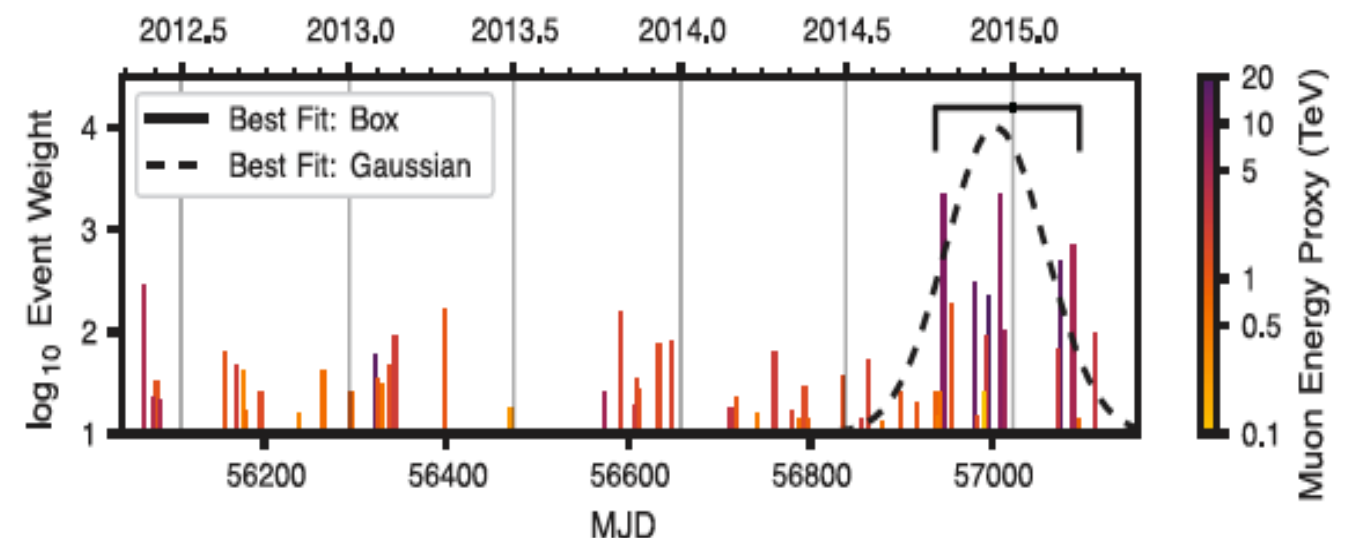
Detections

Observations with detection
Observations without detection

IceCube-I70922A



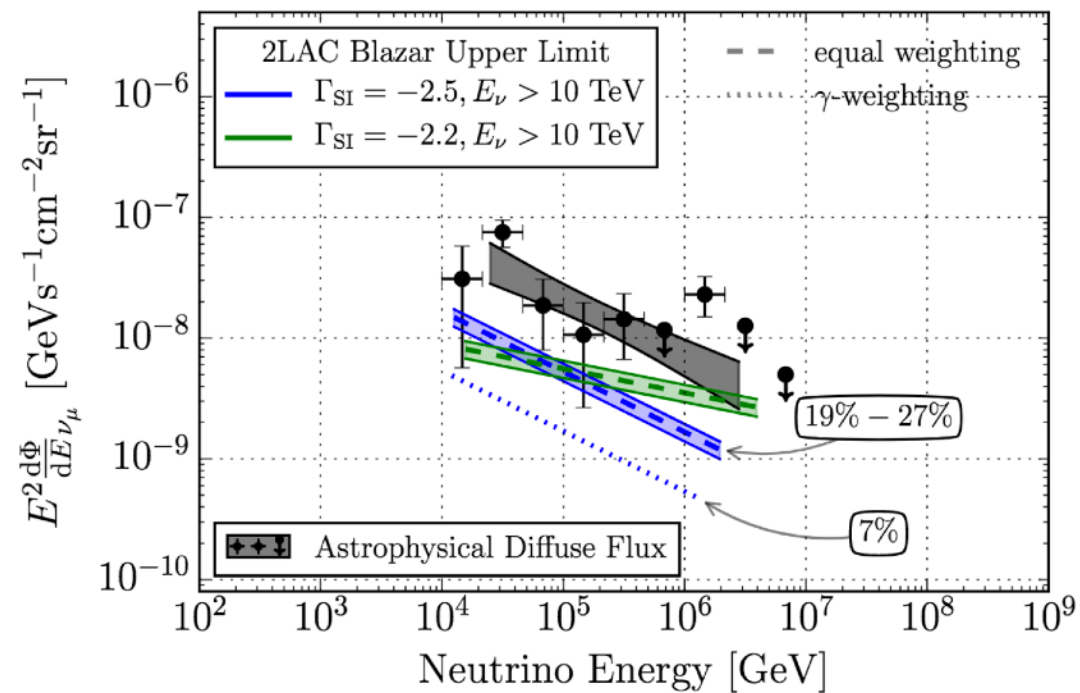
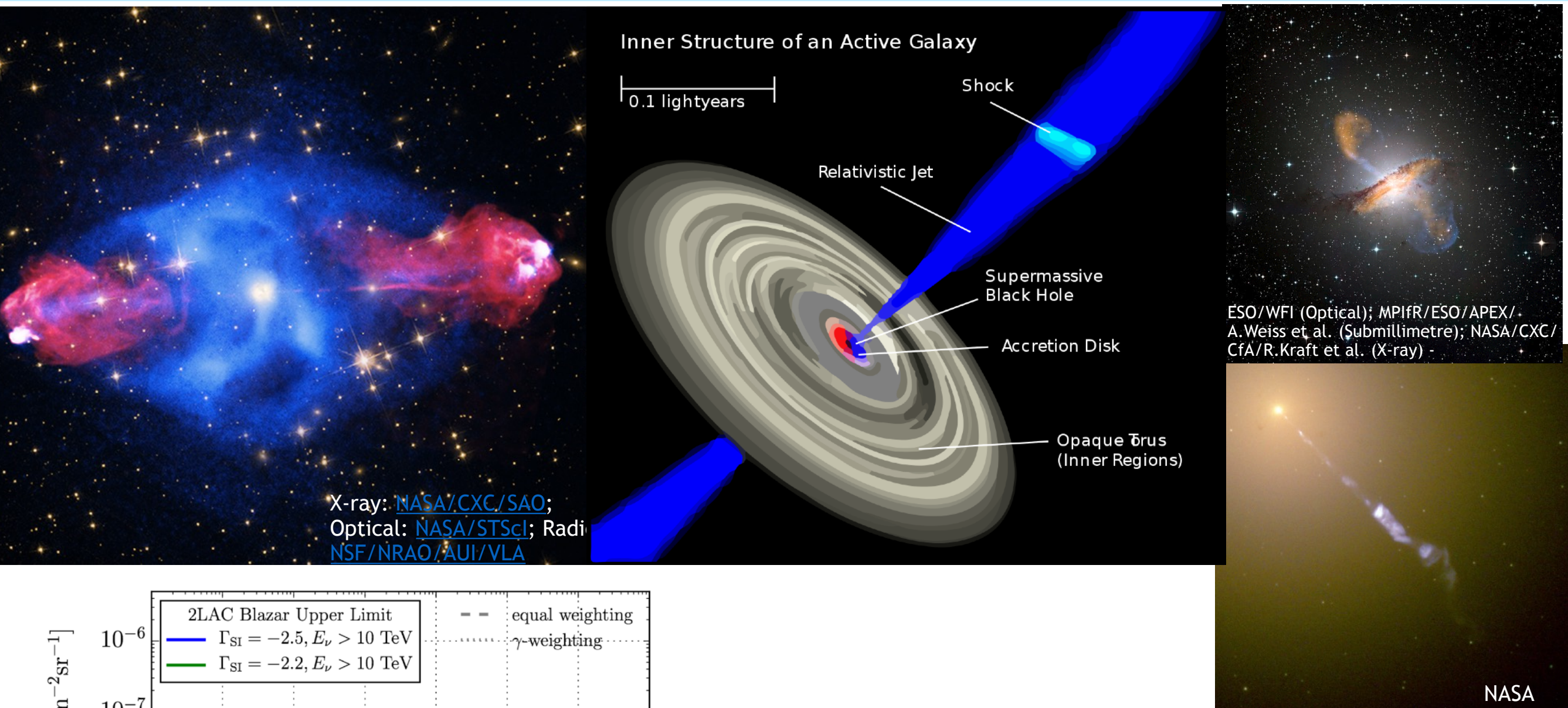
- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13 ± 5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-I70922A alert)



Time-independent weight of individual events during the IC86b period.

However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]

Active Galactic Nuclei: Cosmic Accelerators?



However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]

Recent follow-ups and source constraints

What else has been found? IC190730A

IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106

ATel #12967; **Ignacio Taboada (Georgia Institute of Technology), Robert Stein (DESY Zeuthen)**
on 30 Jul 2019; 23:58 UT
Credential Certification: Ignacio Taboada (itaboada@gatech.edu)

Subjects: Neutrinos, AGN

Referred to by ATel #: 12971, 12981, 12983, 12985, 12996

Optical follow-up of IceCube-190730A with ZTF

ATel #12974; **R. Stein (DESY), A. Franchini (DESY), M. M. Kasliwal (Caltech), I. Andreoni (Caltech), M. Coughlin (Caltech), L. P. Singer (NASA GSFC), F. Masci (IPAC), S. van Velzen (UMD)**
on 31 Jul 2019; 23:18 UT
Credential Certification: Anna Franchini (anna.franchini@desy.de)

Subjects: Optical, Neutrinos

Referred to by ATel #: 12983, 12985

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Optical fluxes of candidate neutrino blazar PKS 1502+106

ATel #12983; **William Keel, Marcos Santander (Univ. of Alabama)**
on 2 Aug 2019; 15:35 UT
Credential Certification: William Keel (wkeel@ua.edu)

Subjects: Optical, Neutrinos, Blazar

[Previous | Next | ADS]

IceCube-190730A: MASTER alert observations and analysis

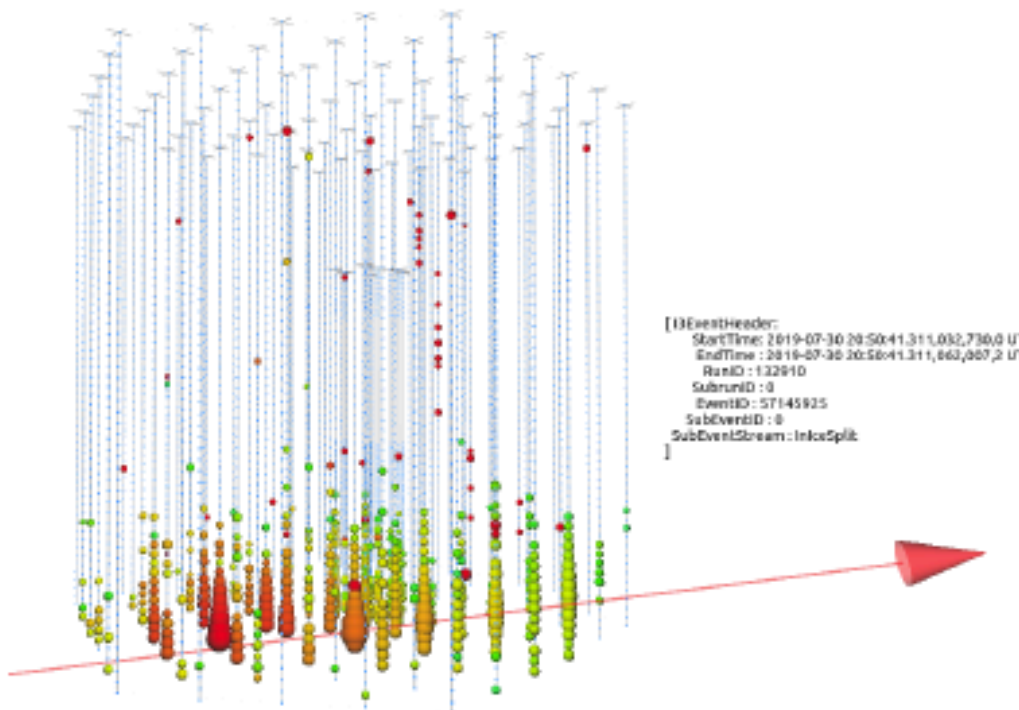
ATel #12971; **V. Lipasev, E. Gerasimov, V. Korneev, N. Tyurina, F. Bakulin, V. Vladimirov, P. Belavskiy, A. Kuznetsov, D. Vlasenko, I. Gerasimov, A. Popovych, D. Zinnakhor, V. Semik, A. Chasovnikov, V. Grishin, T. Pogrebenko (Lomonosov MSU), R. Rikalo, M. Serna (IAC), R. Podesta, C. Lopez, E. Podesta, C. Francile (OAE SINU), H. Levato (CATE SINT), D. Bachler (SAAO), O. Geras, N. M. Rudnev, O. Rykova (APL ISU), A. Thaler, D. Dornik (IKS of Potsdam Observatory), V. Farkas, A. Gerasimov, Yu. Serpichev (BSFU)**
on 31 Jul 2019; 16:25 UT
Credential Certification: Natalya Tyurina (n.tyurina@ast.su.ru)

Subjects: Optical, VHE, UHE, Neutrinos, AGN, Quasar

Referred to by ATel #: 12983, 12985

Followed up by ~17 instruments across ten decades of energy.

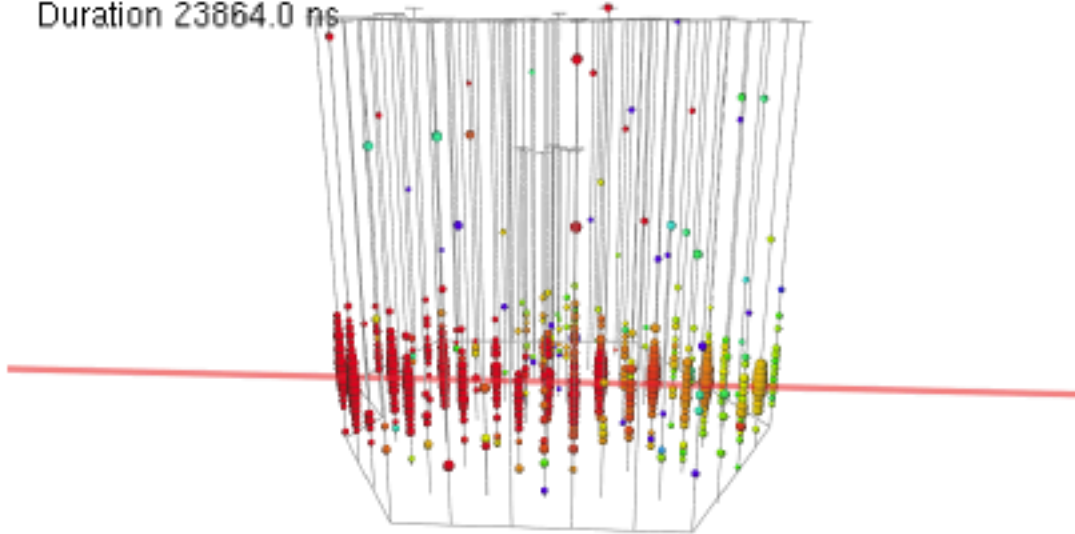
No short-term flaring activity in any wavelength, but long-term radio flare reported by OVRO.



What else has been found? IC190922B

Candidate supernova found, analysis ongoing.

Event 133092/52499868-0
Time 2019-09-22 23:03:55 UTC
Duration 23864.0 ns



TITLE: GCN CIRCULAR
NUMBER: 25806
SUBJECT: IceCube-190922B - IceCube observation of a high-energy neutrino candidate event
DATE: 19/09/23 01:58:33 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@umd.edu>

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A candidate supernova coincident with IceCube-190922B from ZTF

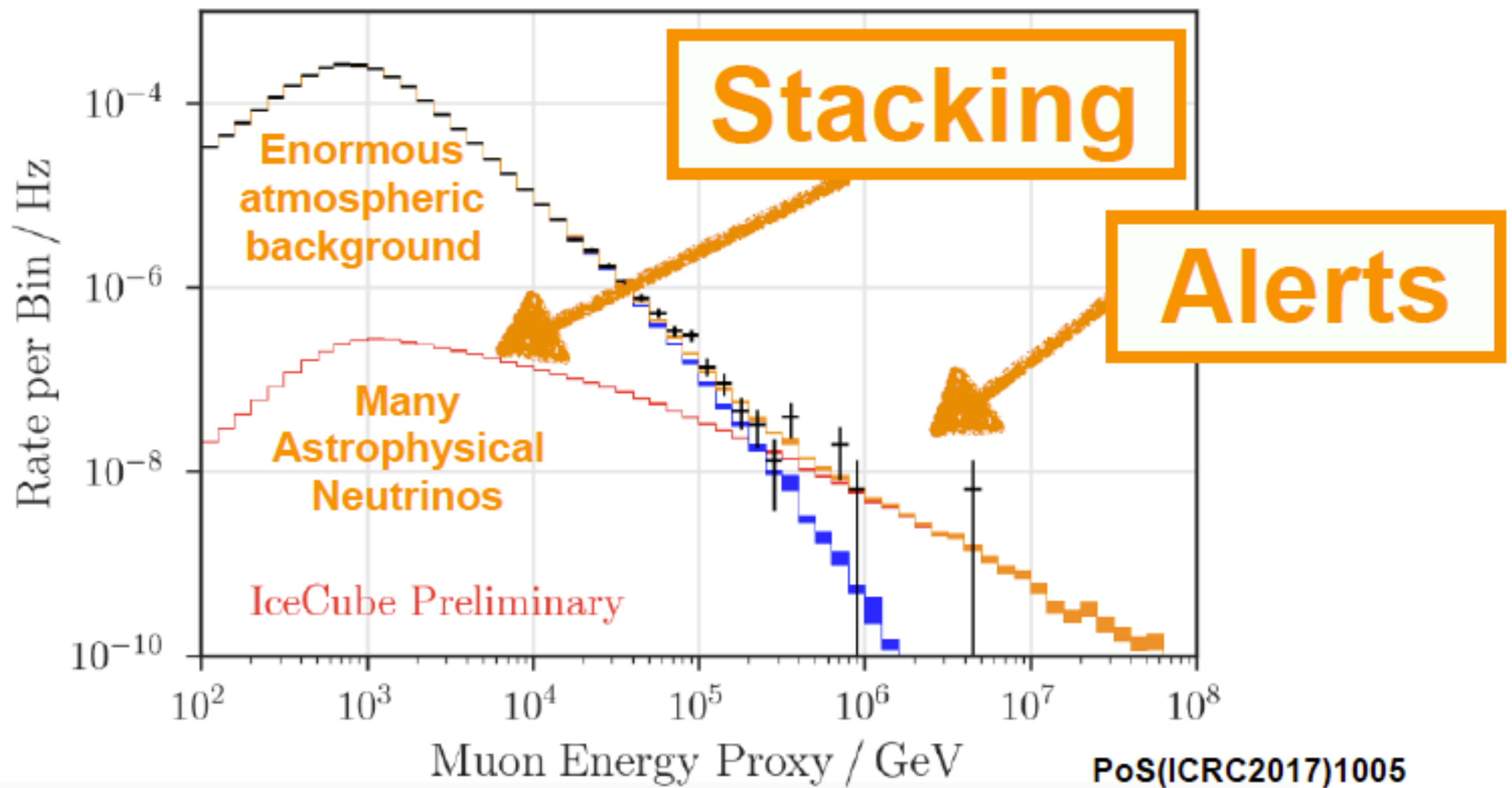
ATel #13125; *Robert Stein (DESY), Anna Franckowiak (DESY), Marek Kowalski (DESY), Mansi Kasliwal (Caltech)*

on 23 Sep 2019; 20:34 UT

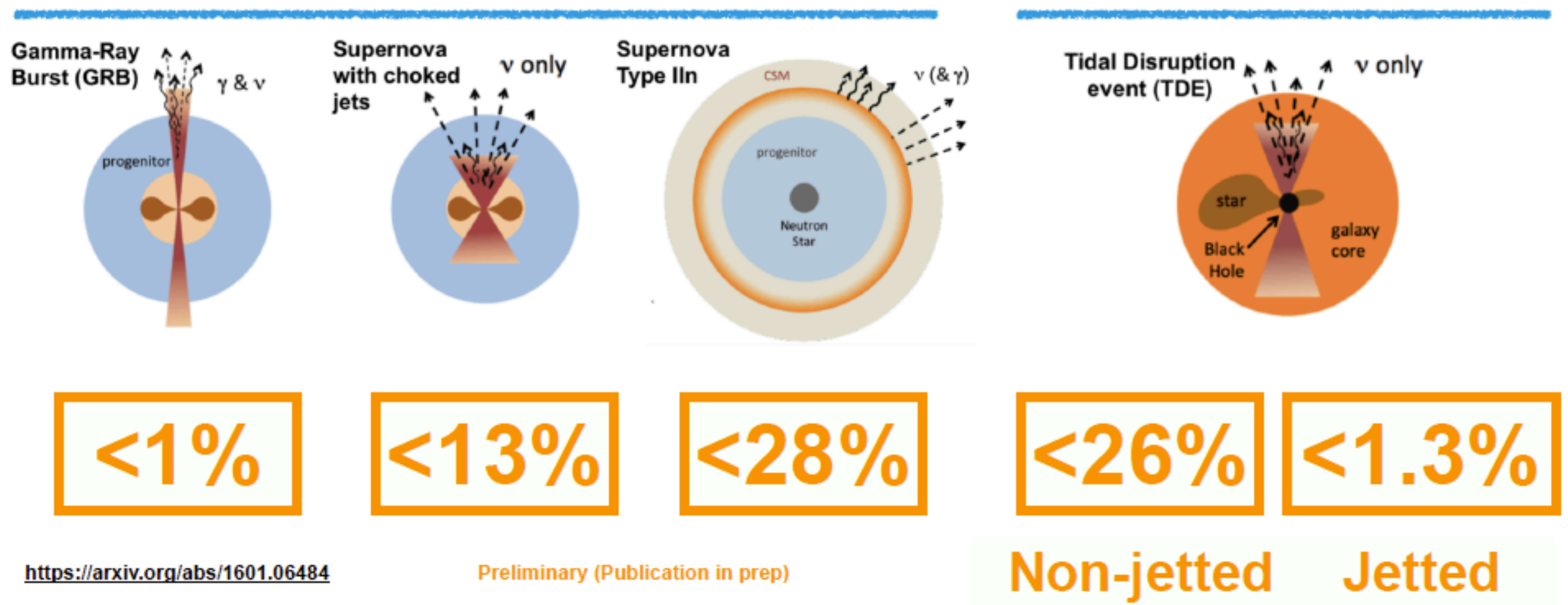
Credential Certification: Anna Franckowiak (anna.franckowiak@desy.de)

Subjects: Optical, Neutrinos, Request for Observations, Supernovae, Transient

+ + + Exp. data
 ■ Conv. atmospheric $\nu + \bar{\nu}$
 ■ Astrophysical $\nu + \bar{\nu}$
 ■ Combined $\nu + \bar{\nu}$



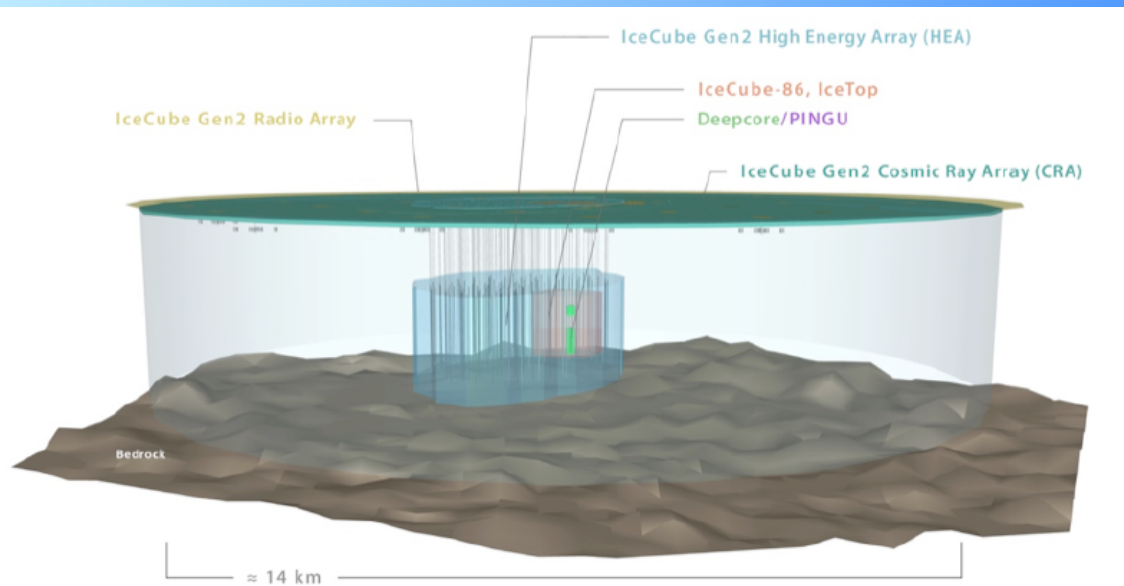
Present bound on sources



- Bounds on various source classes.
- Origin of astrophysical neutrino flux remains unknown

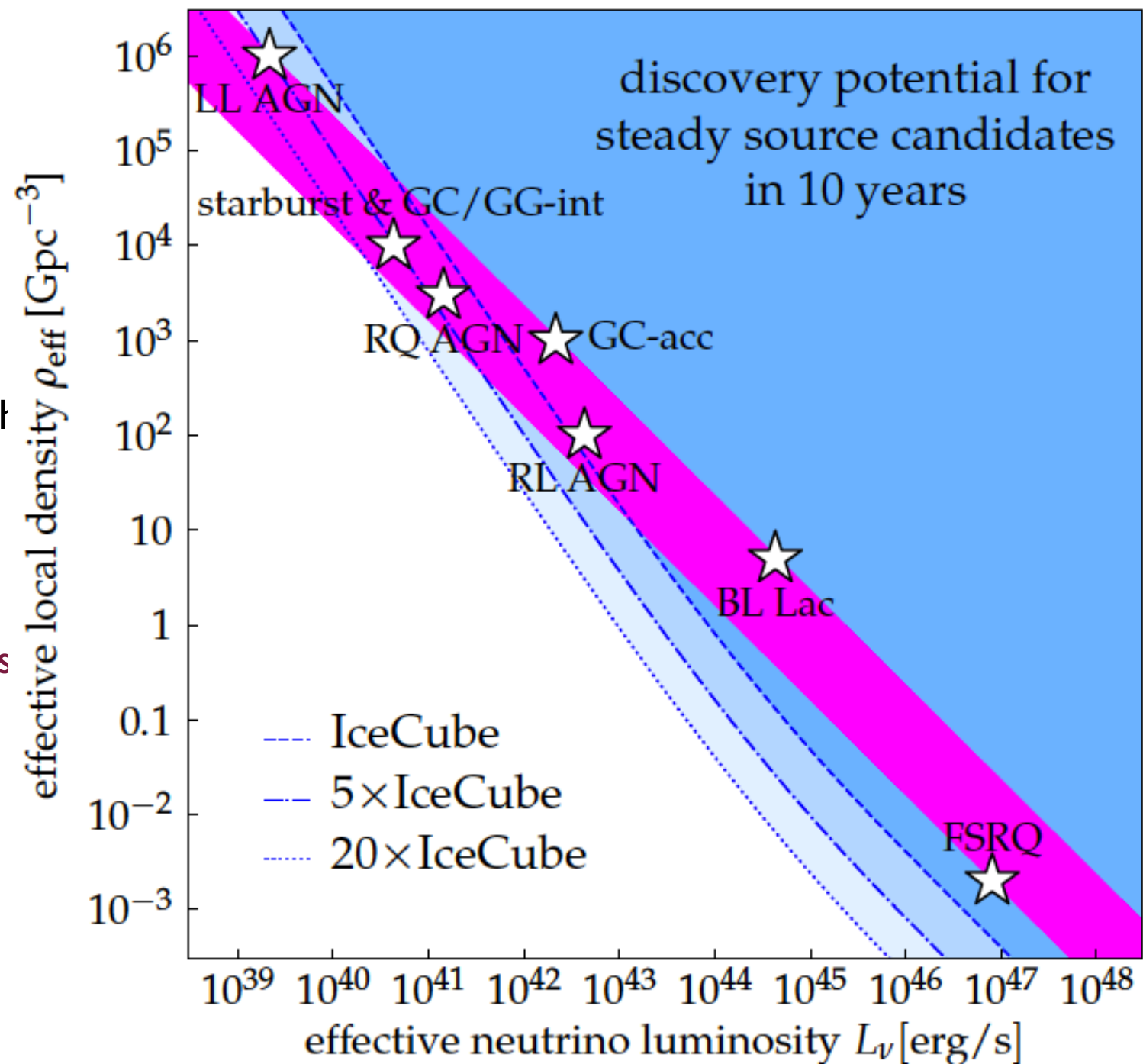
IceCube Upgrade

IceCube-Gen2

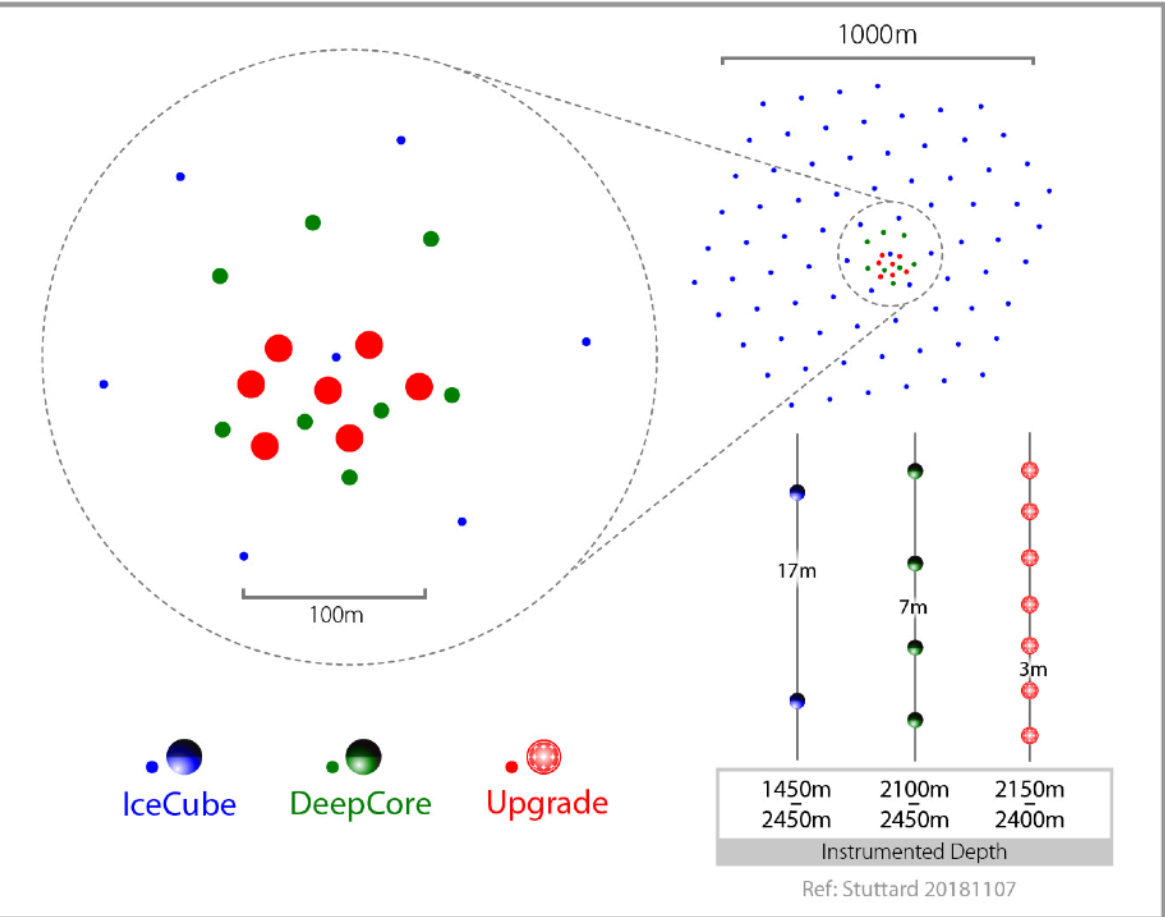


- IceCube has provided an amazing sample of events, but is still statistics limited
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
- Gen2 objectives
 - High precision flavor composition studies
 - Detailed measurement of features / cut-off in neutrino spectrum
 - Transients sources and multi-messenger astrophysics
 - Identify astrophysical neutrino sources
 - GZK neutrinos
 - New physics or something unexpected

Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos arXiv:1903.04334v1

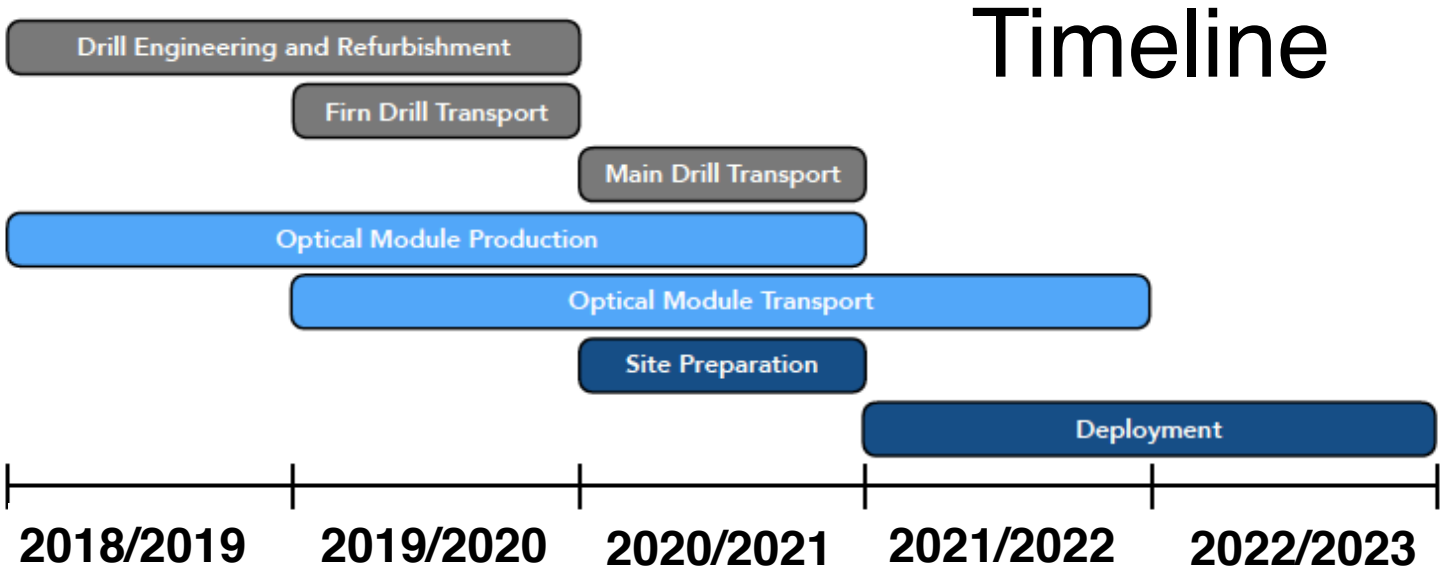


The IceCube Upgrade



Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125

- Science goals**
- Tau neutrino appearance - Test unitarity of the PMNS matrix
 - Recalibration campaign - Retroactively apply improved ice-model to archival data (since 2010)



IceCube DOM



35 cm

mDOM



36 cm

36 cm

- Directional information
- More sensitive area per module

D-Egg



30 cm

30 cm

11 cm

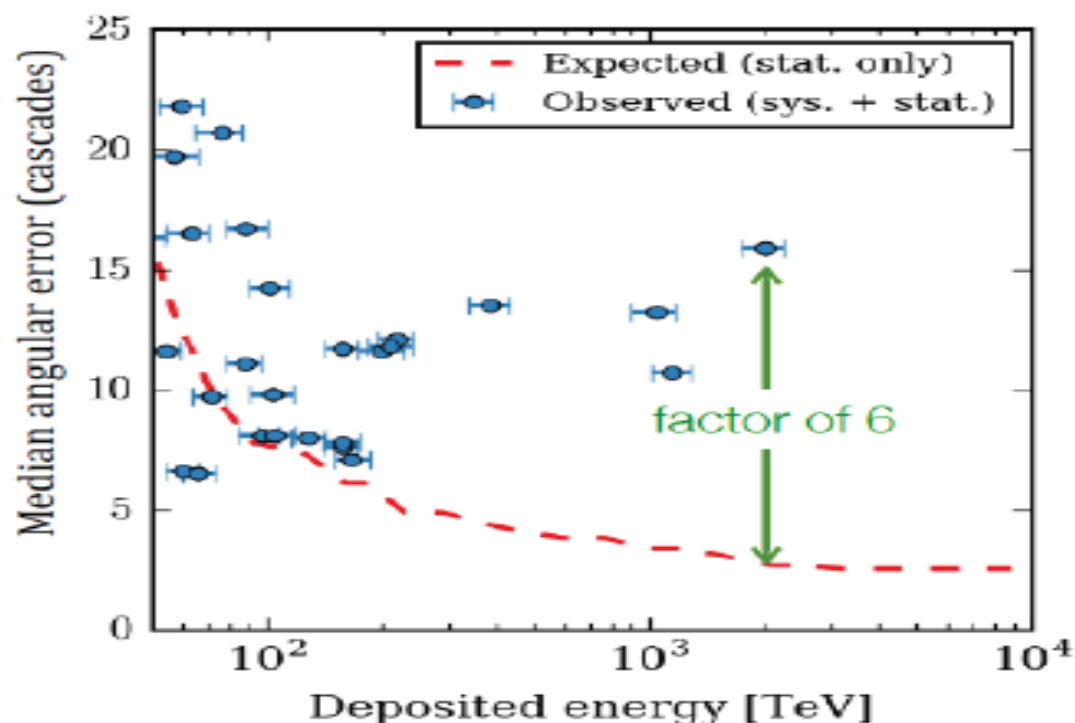
- Directional information
- More sensitive area per module
- Smaller geometry

Ice Camera System

- Ice properties dominant source of sys. uncertainties for most analyses
- Solution: SKKU ice camera system**
 - Monitor freeze in
 - Hole ice studies
 - Local ice environment
 - Position of the sensor in the hole
 - Geometry calibration
 - Survey capability



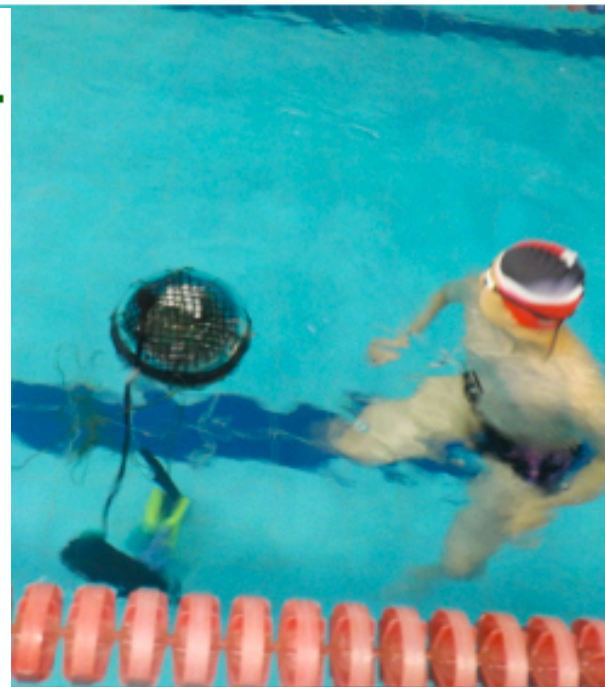
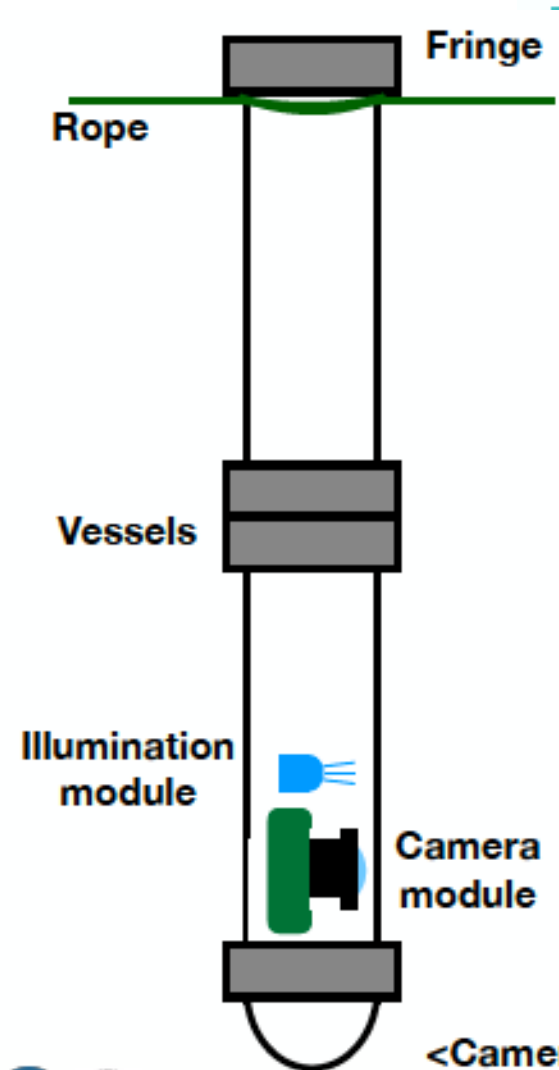
Example camera for illustration



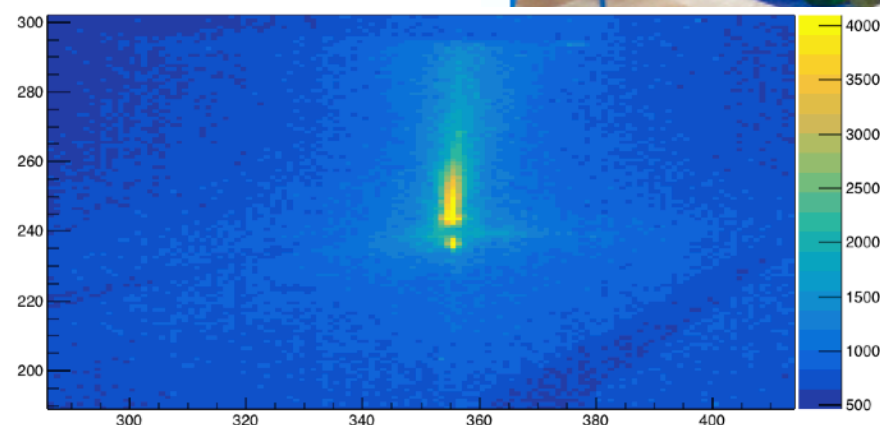
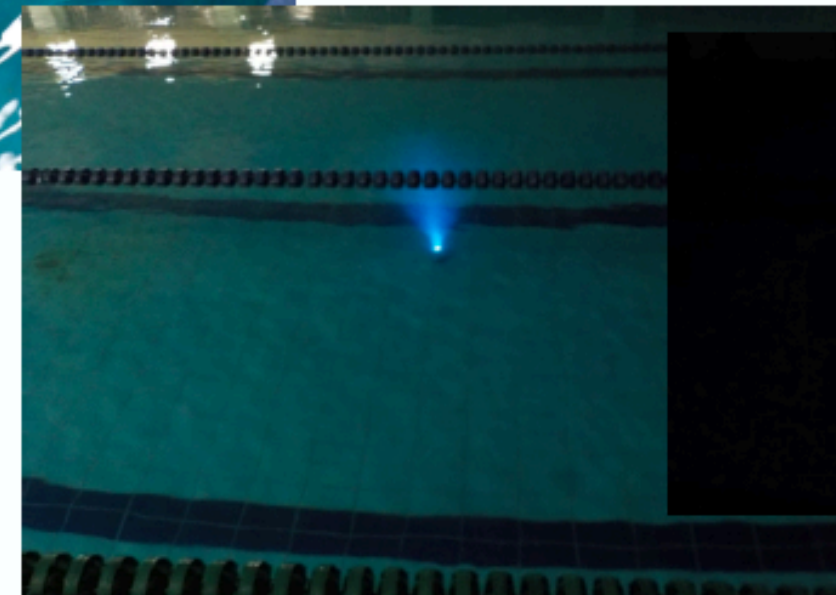
Camera system key to comprehensive understanding of the detector medium

- Camera system passed IceCube internal design and adopted as standard component for IceCube Upgrade
- Retroactively analyze more than 10 years of IceCube data with substantially improved angular and energy resolution

Camera testing ...



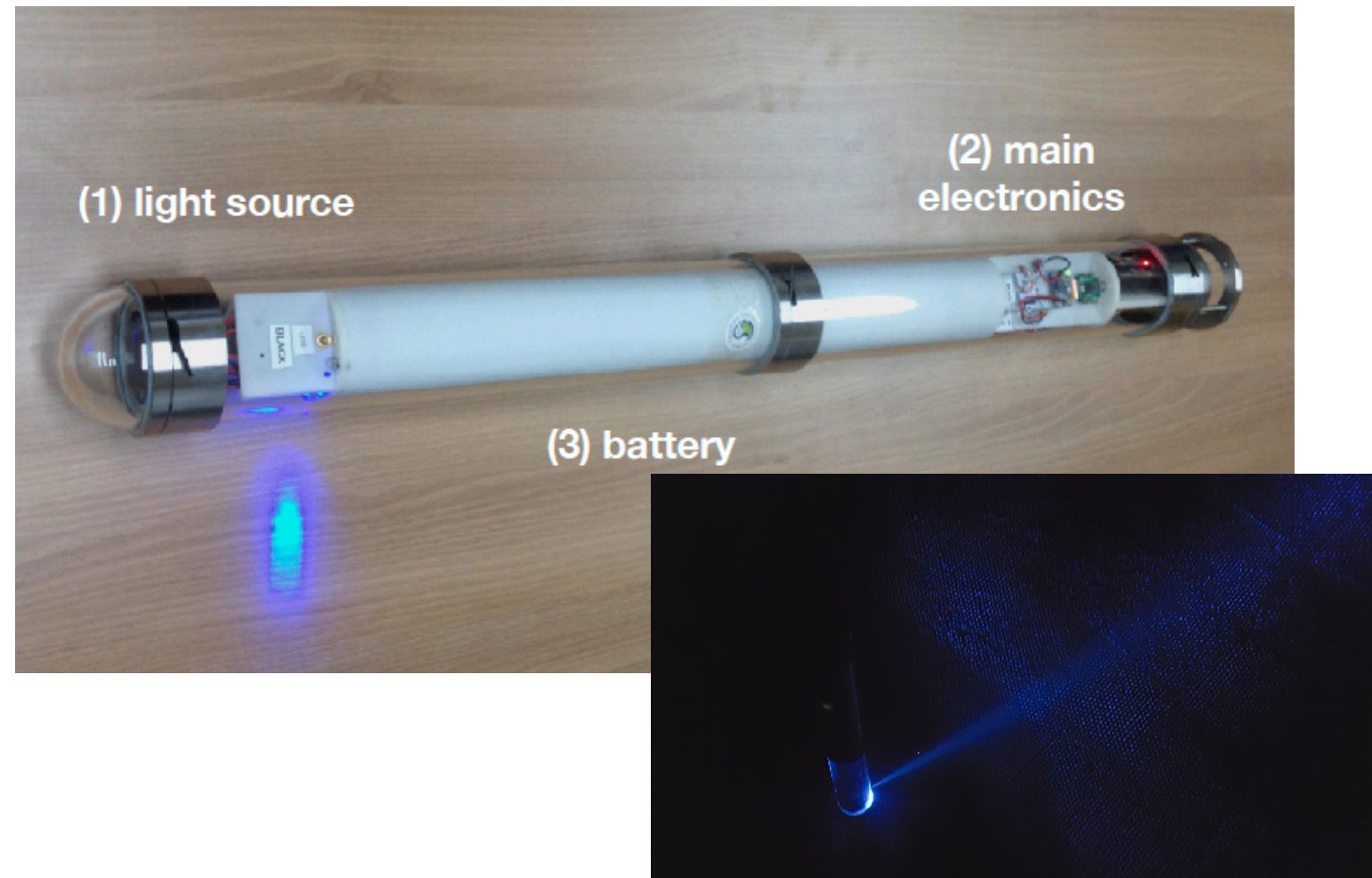
Gyeonggi Physical Education High school,
the public high school for athletes



Geometry measurements of order $\sim 10\text{cm}$ at 25m distances
Scattering cones clearly visible - scattering length measurements

SpiceCore Camera System

SKKU graduate student Hrvoje Dujmovic @ South Pole



- SPICE Core camera system was successfully deployed in January 2019 (one 7h deployment to the maximal depth of 1695m)
- Several hundred images taken - image analysis on-going
- Platform to test camera systems for integration into next-generation optical sensor modules

- High-energy astrophysical neutrinos have opened up a new window to the Universe
 - What's the origin of the high-energy neutrinos ?
- First compelling evidence of high-energy neutrinos with electromagnetic counterparts (TXS 0506+056)
- Neutrino astronomy is a central part of the multi messenger astroparticle physics field
- The IceCube Upgrade has just been approved and we can look forward to many exciting discoveries in the near future
- Entering the age of multi-messenger astroparticle physics - Combined observations with Electromagnetic / Gravitational Waves / Cosmic-rays / Neutrinos will / ... will revolutionize our understanding of the Universe
- High interest in expanding follow up programs !