Multi-messenger Astroparticle Physics with IceCube

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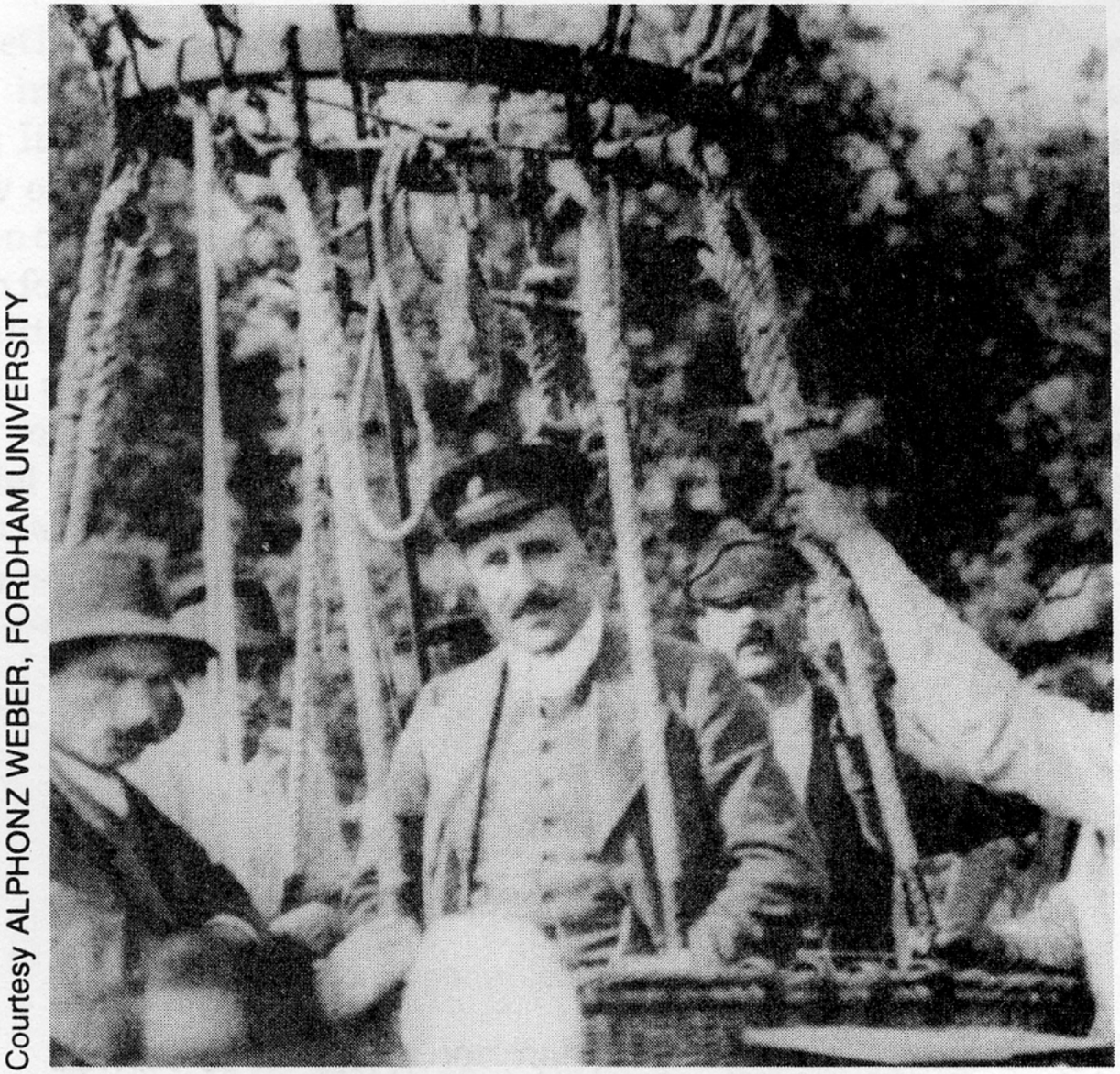
GW Astrophysics mini workshop @ Ewha

Outline

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

The Cosmic Ray Mystery

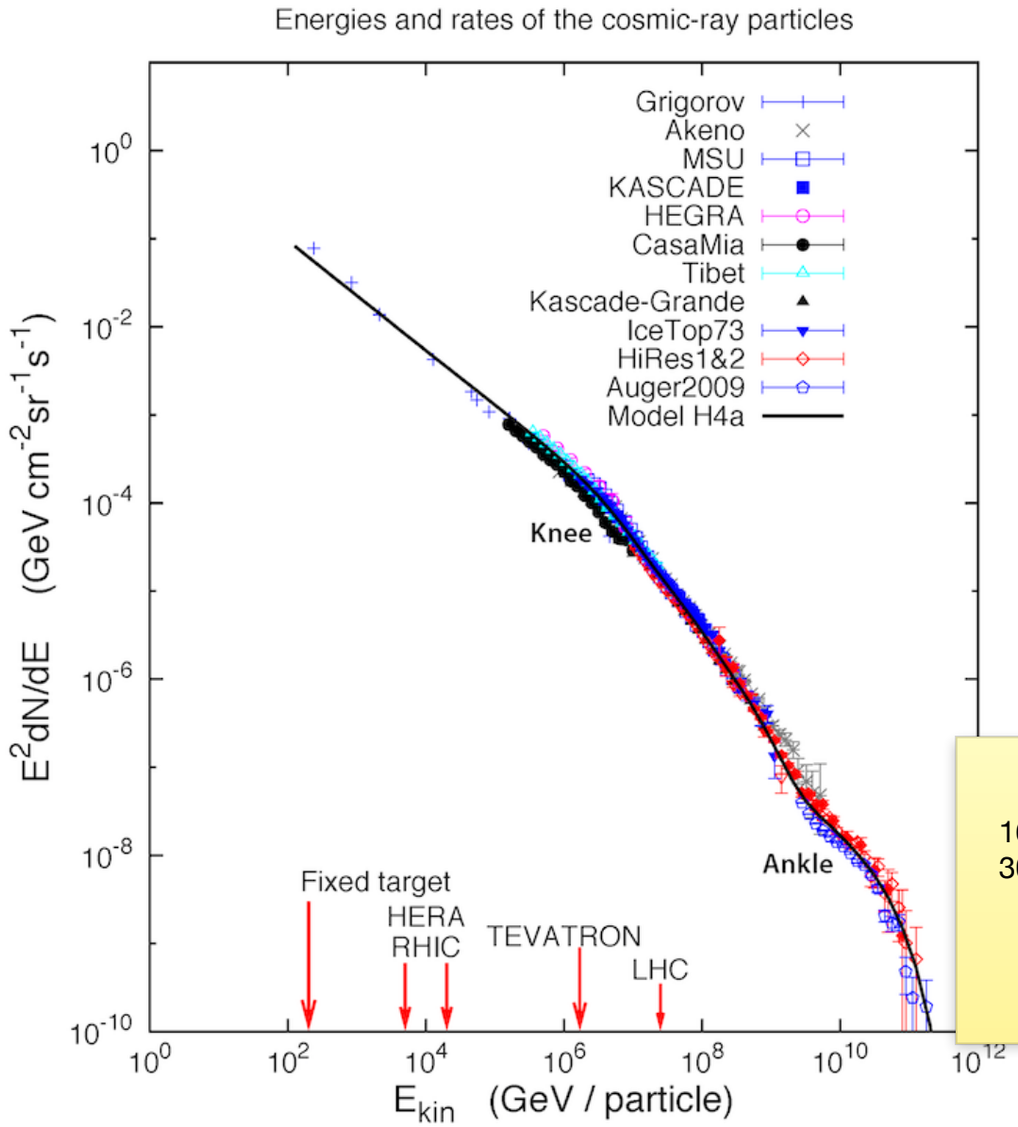
Victor Hess



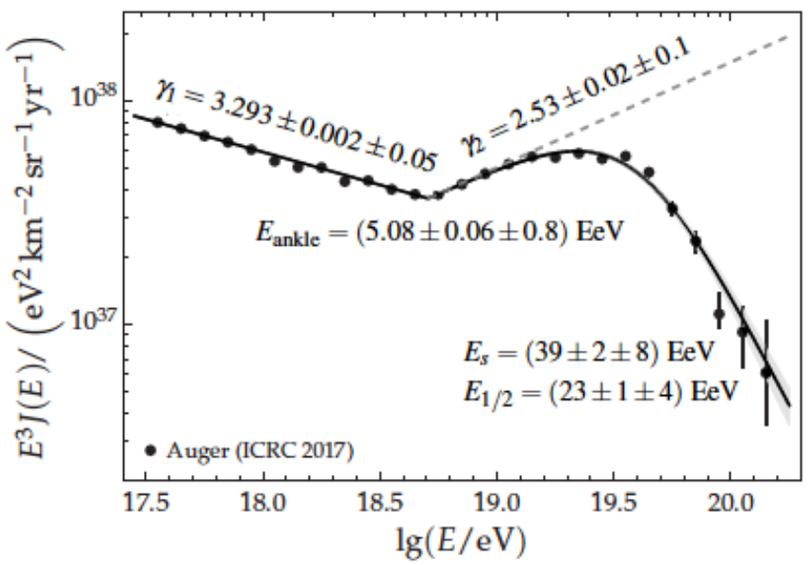
Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.

Cosmic rays



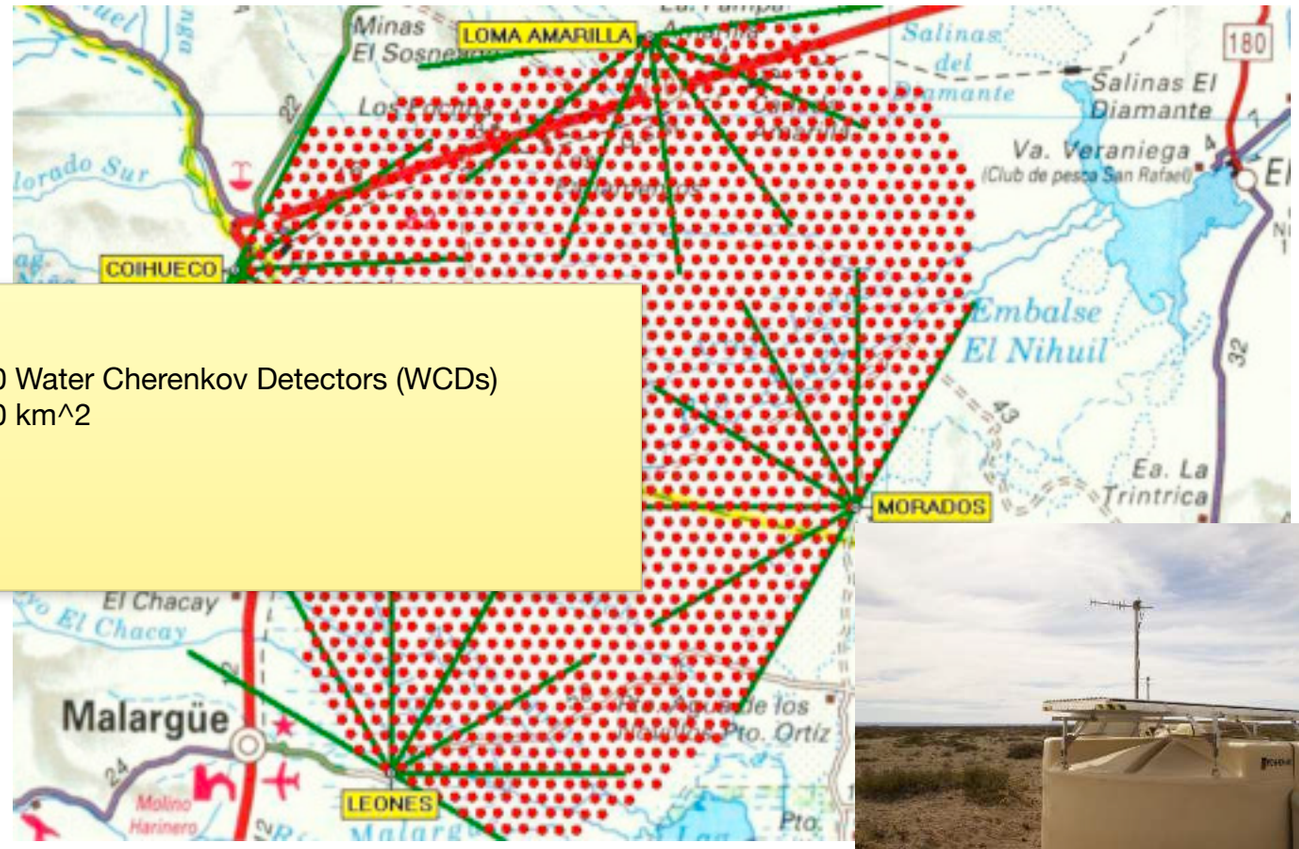
AUGER Collaboration ICRC2017



Cosmic rays have been observed with energies up to 10^{20}eV (100EeV) or 10^7 LHC beam energies

AUGER

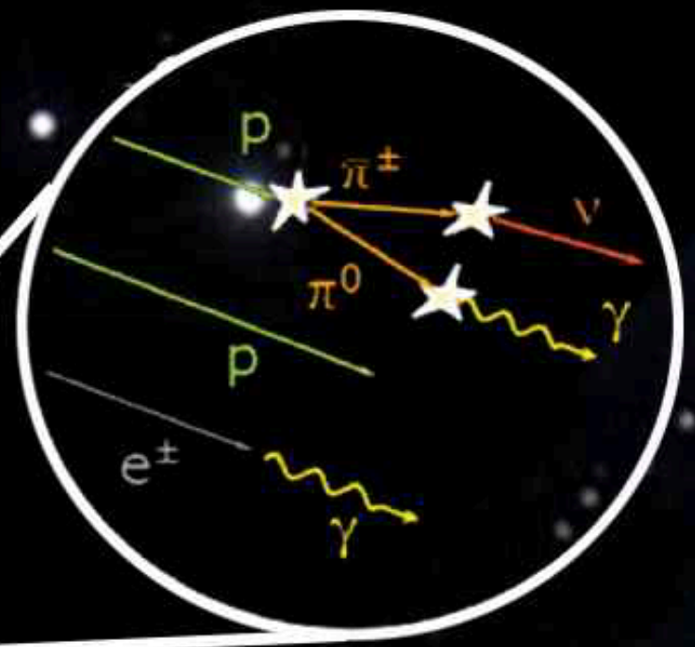
Malargüe, Mendoza



1600 Water Cherenkov Detectors (WCDs)
3000 km^2

- Cosmic ray spectrum extremely well measured (TA, Auger, …)
- Where are they coming from ?
- What cosmic sources accelerate these particles to energies well beyond that reached at LHC ?

cosmic rays
+ neutrinos



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

Victor Francis Hess

Discovery of cosmic-rays

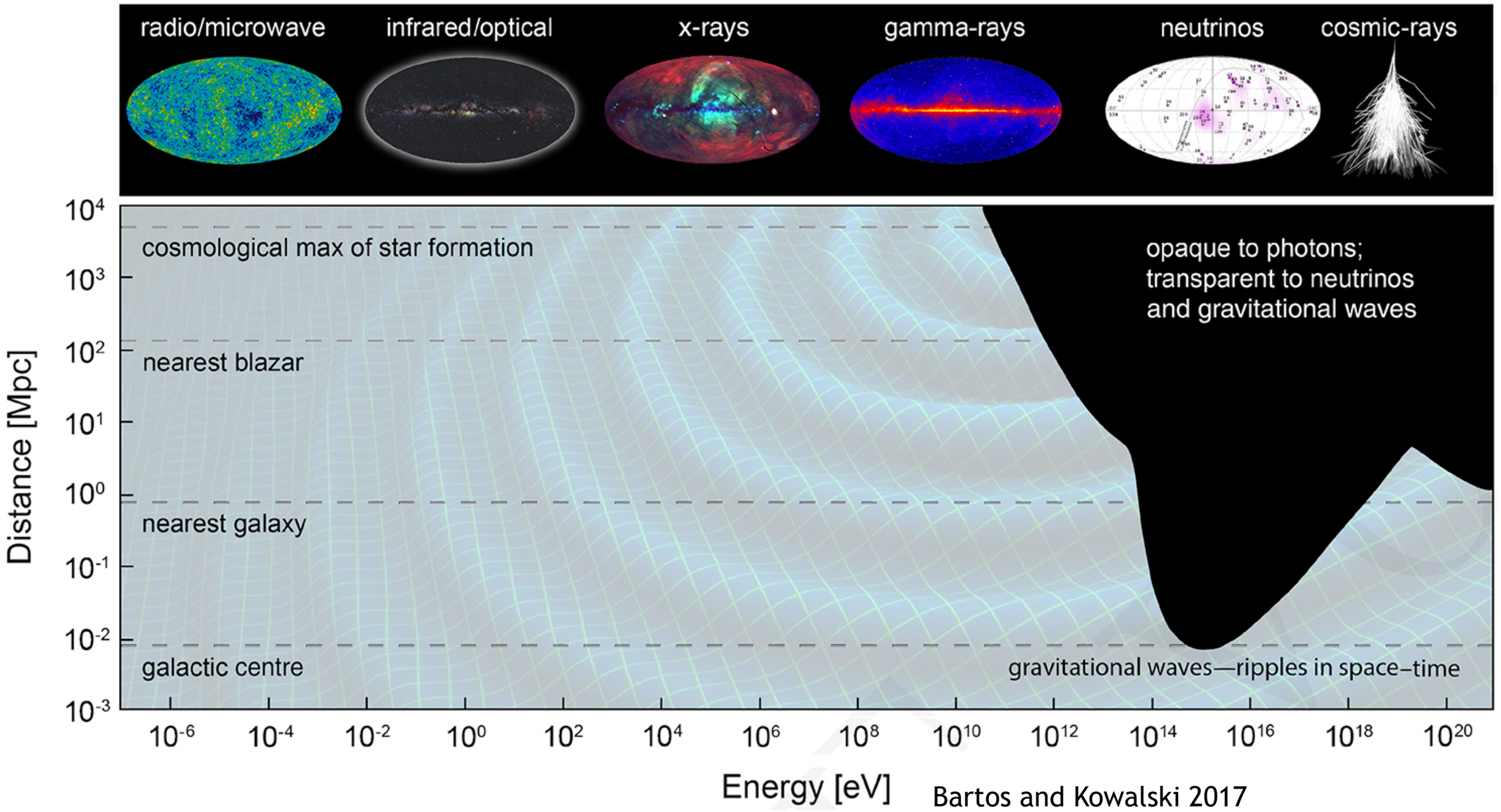
1936

γ

ν

P

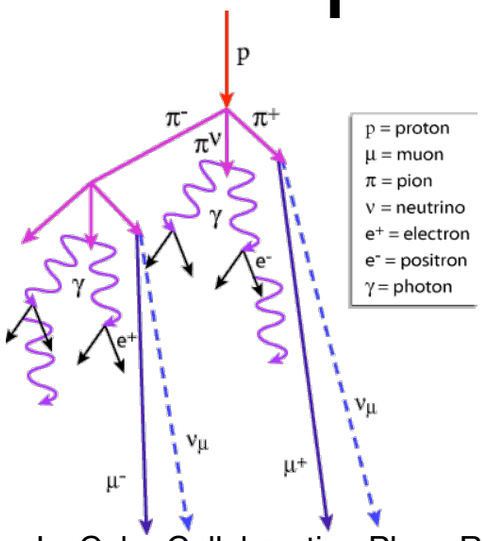
Astrophysical Messengers



Bartos and Kowalski 2017

Sources of High Energy Neutrinos

Atmospheric Neutrinos

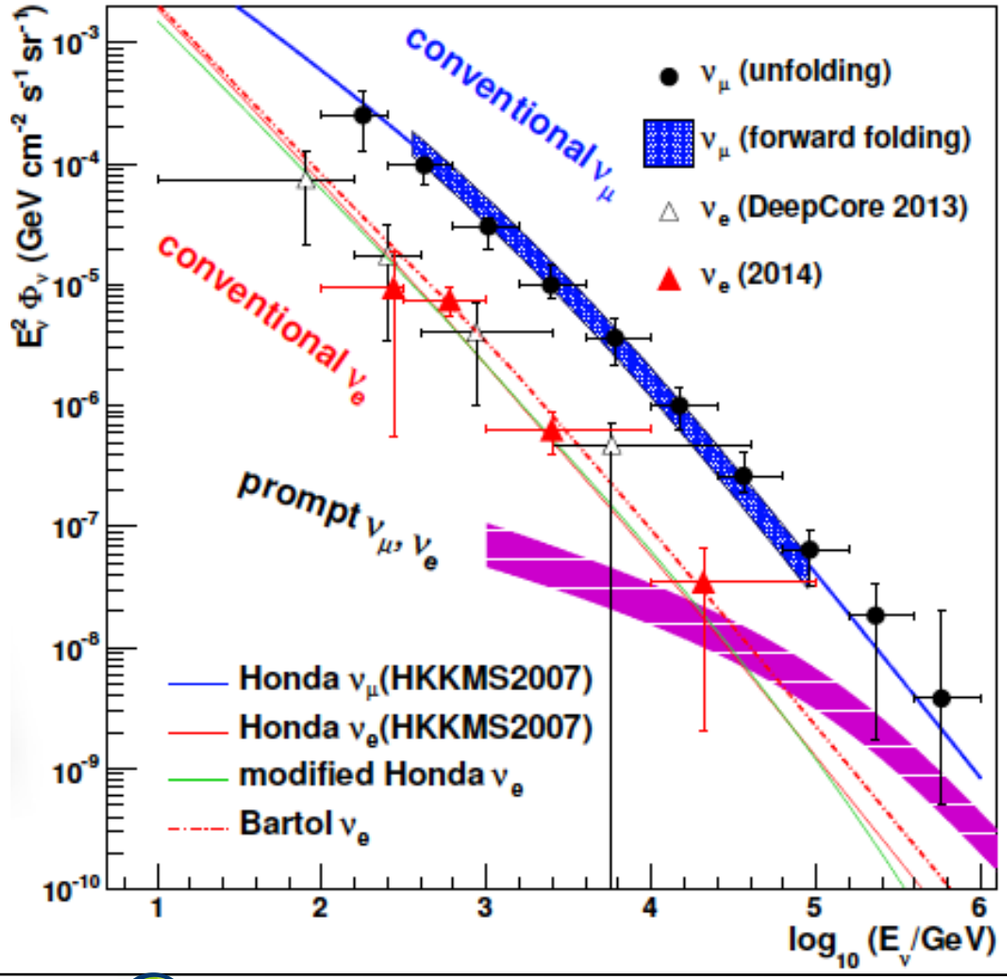


Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^{\pm} (K^{\pm}) +$ other hadrons ...

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

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

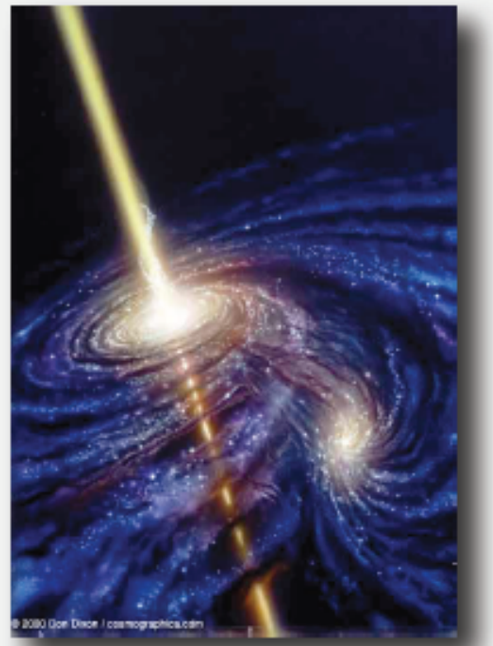


Astrophysical

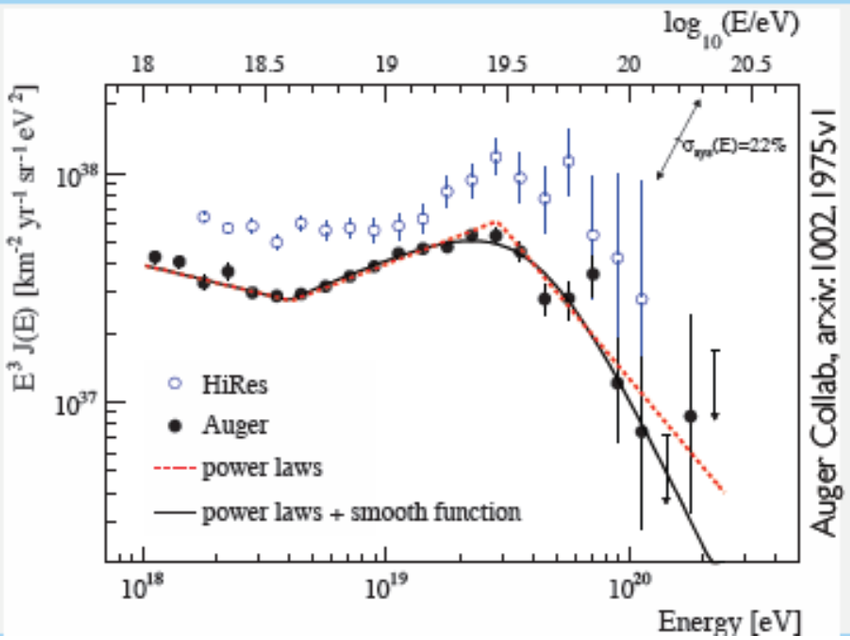
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Gamma-ray Bursts

Active Galactic Nuclei



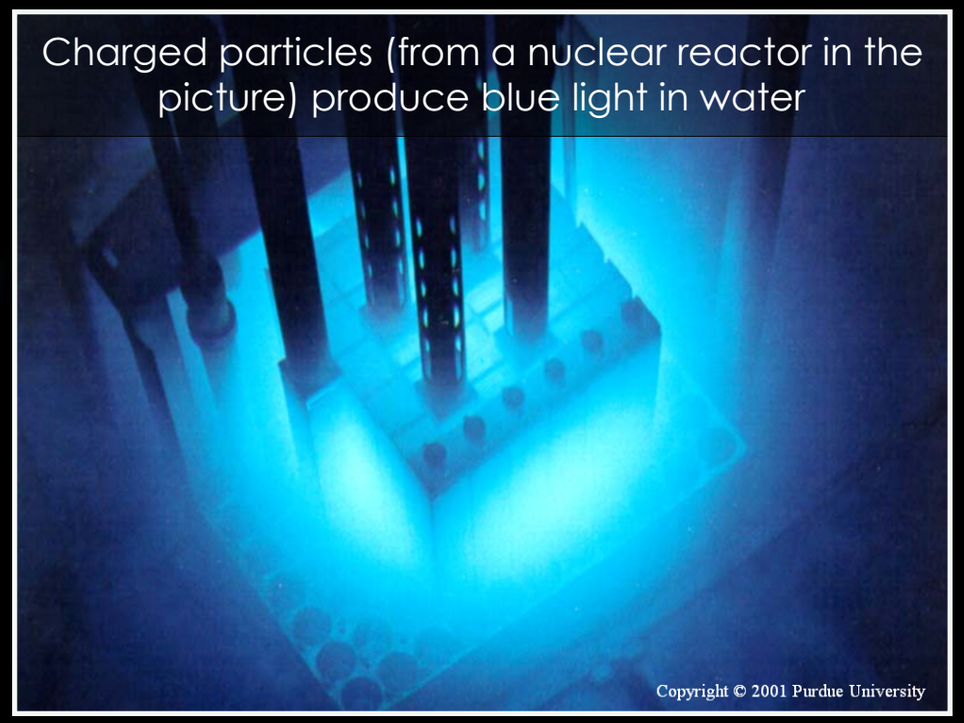
$p+\gamma_{3K} \rightarrow \Delta^+$ (GZK)



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



41°

$\gamma_č$

Cherenkov Radiation

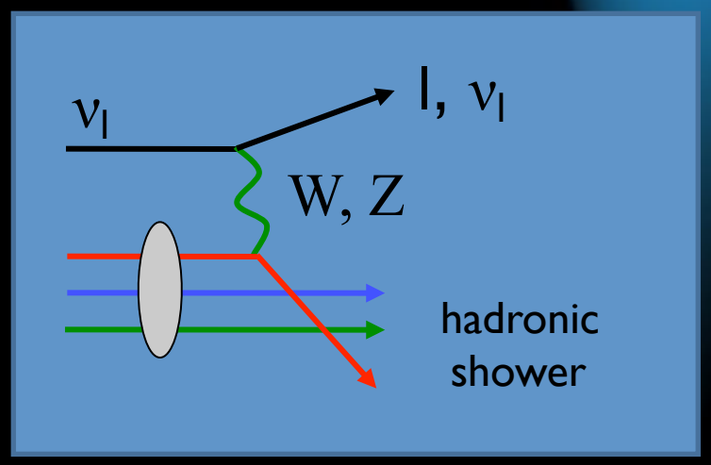
Muon

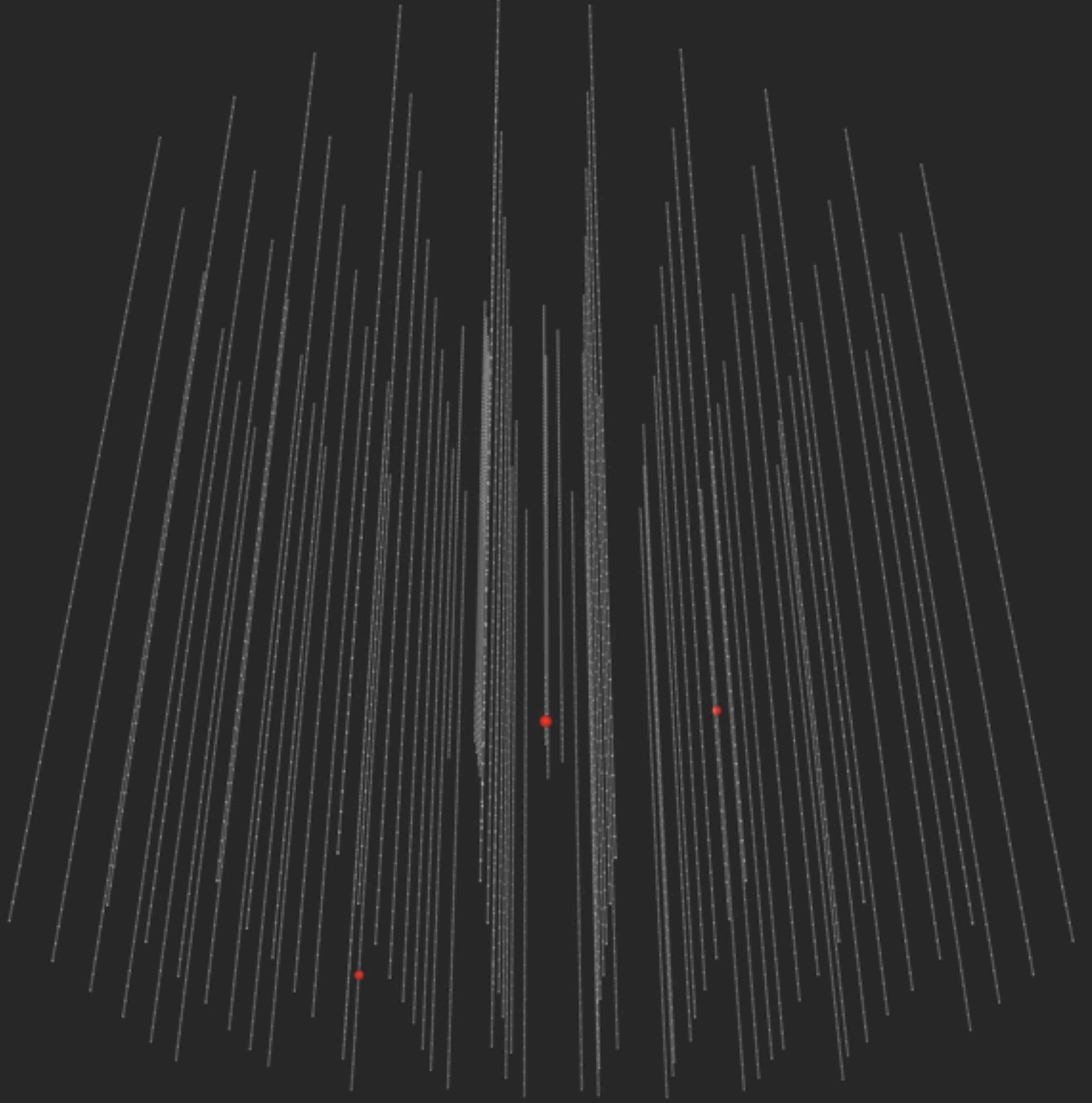
μ

Muon Neutrino

ν

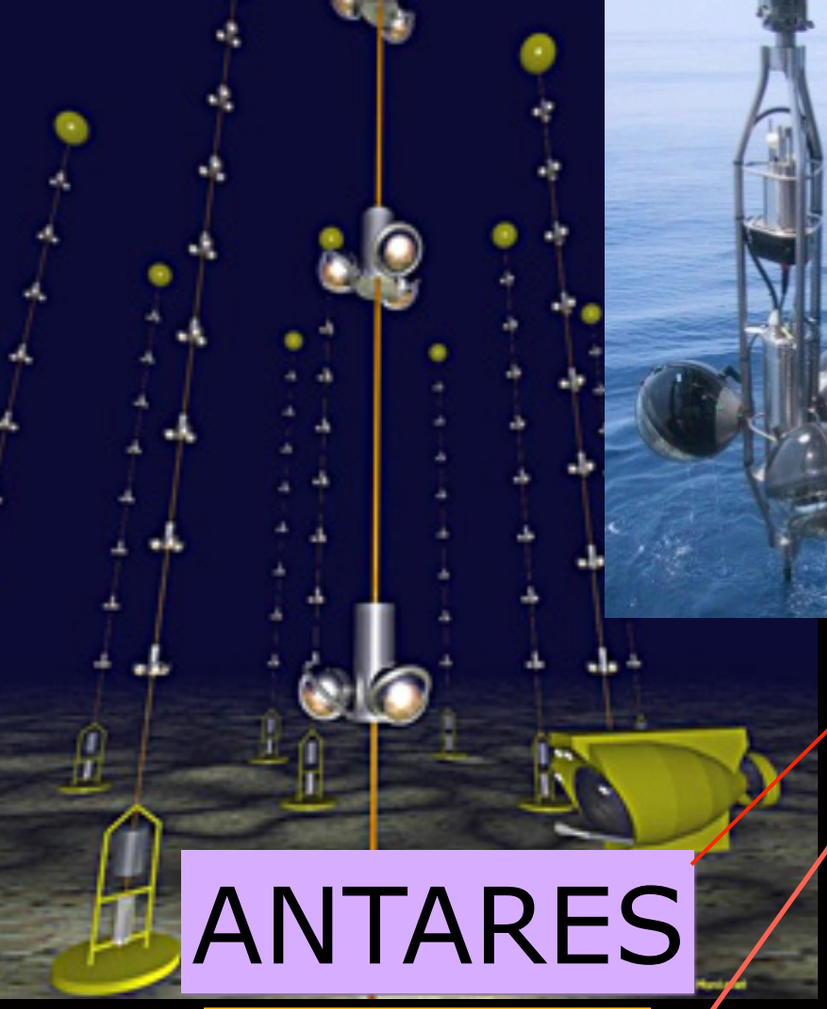
interaction



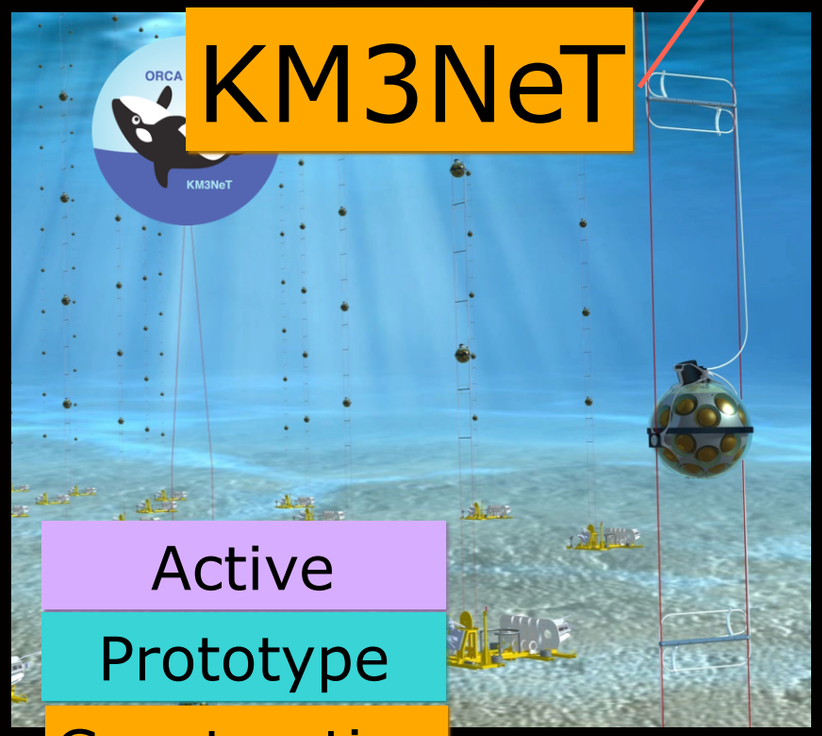


Neutrino Telescopes and IceCube

Large Water/Ice Cherenkov Neutrino Detectors



ANTARES



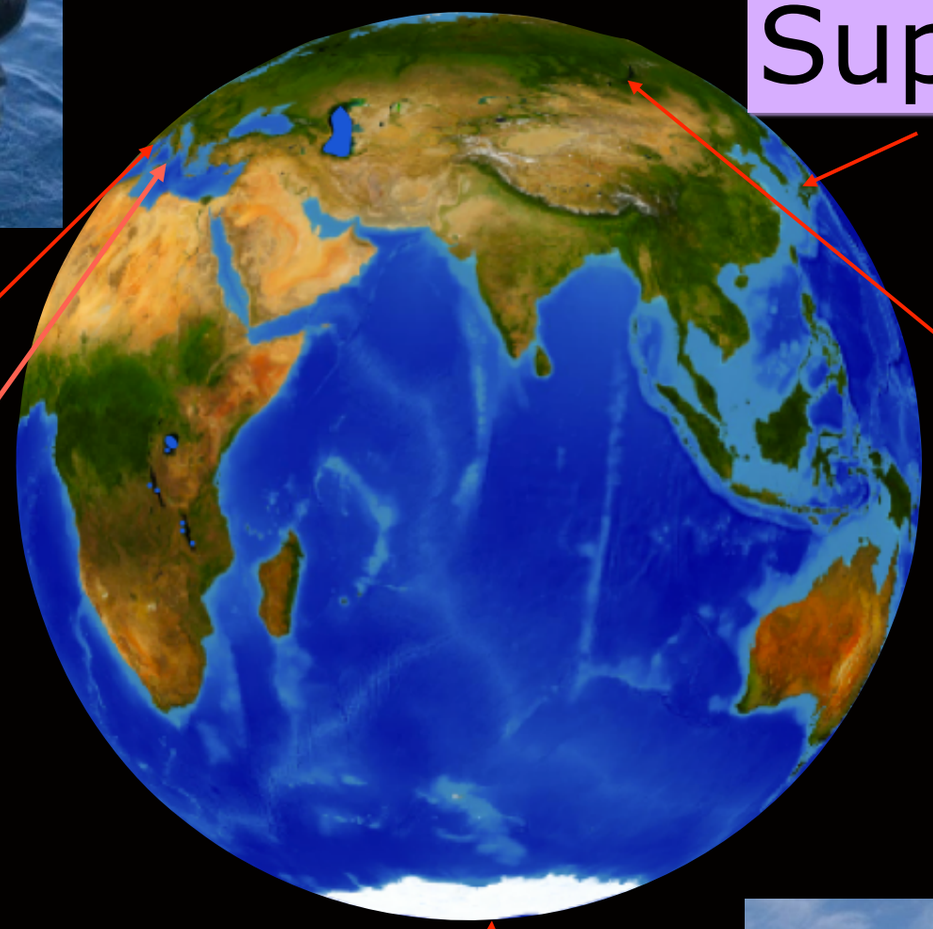
KM3NeT

Active

Prototype

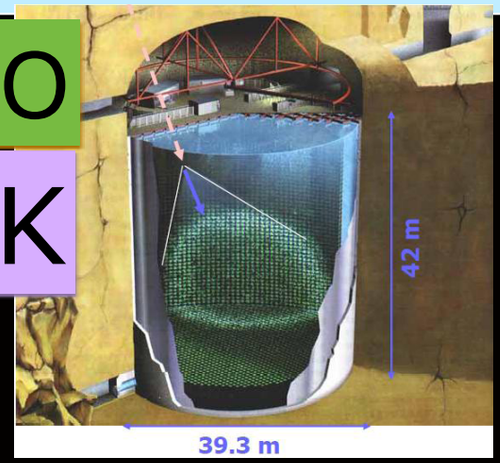
Construction

Planned



Hyper-K / KNO

Super-K



Lake Baikal

GVD

IceCube

Gen2/PINGU

Sungkyunkwan University
since 2013

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
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
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Michigan State University
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South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
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University of Kansas
University of Maryland
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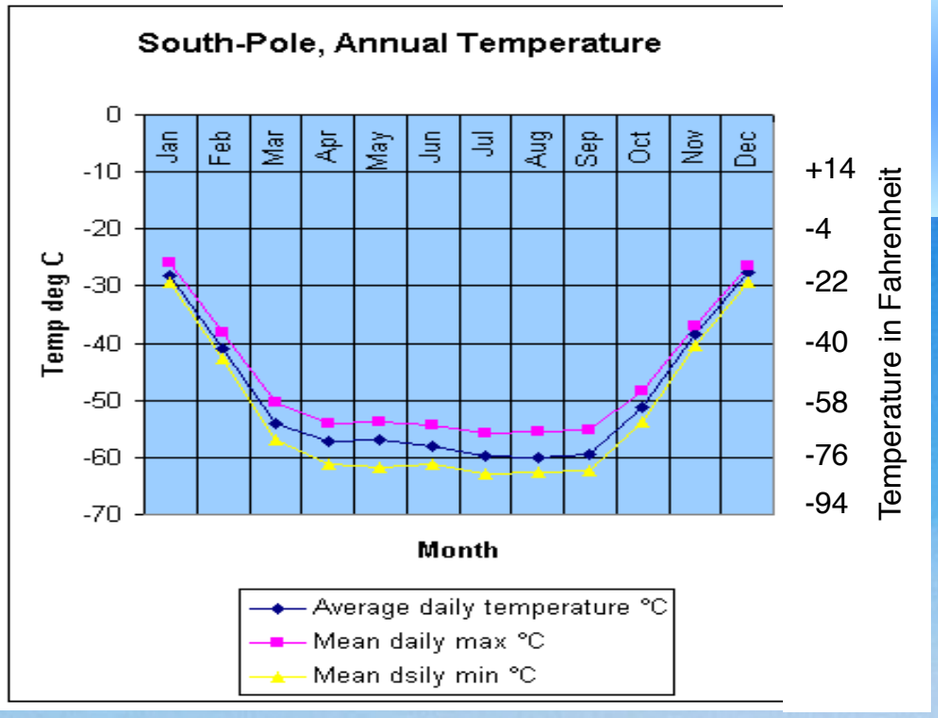
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube
South Pole Neutrino Observatory

Laboratory at the South Pole



Geographic South Pole

Amundsen Scott South Pole Station

Road to work

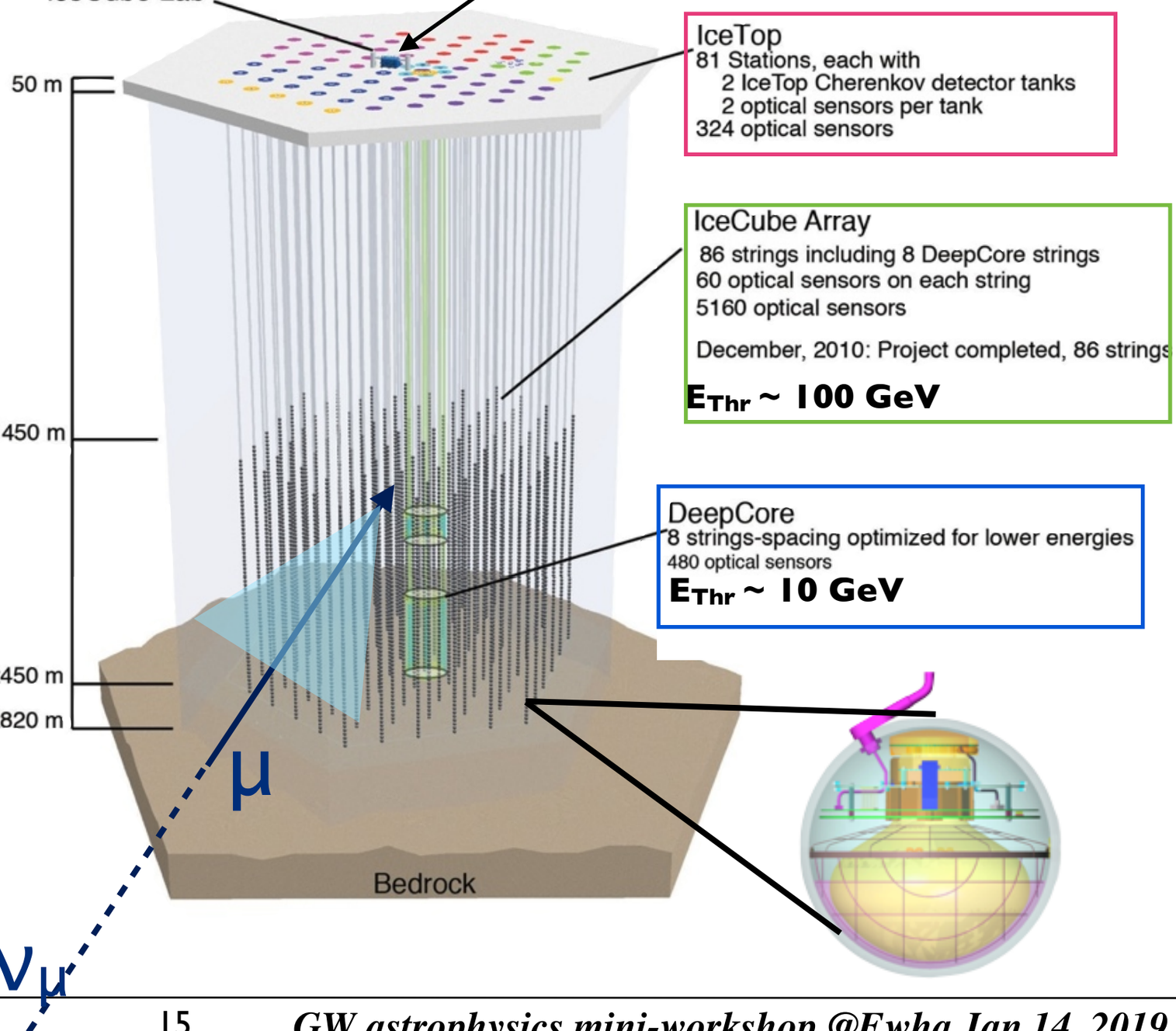
Skiway

1 km

IceCube

The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Detector completed in December 2010 after 7 years construction
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice



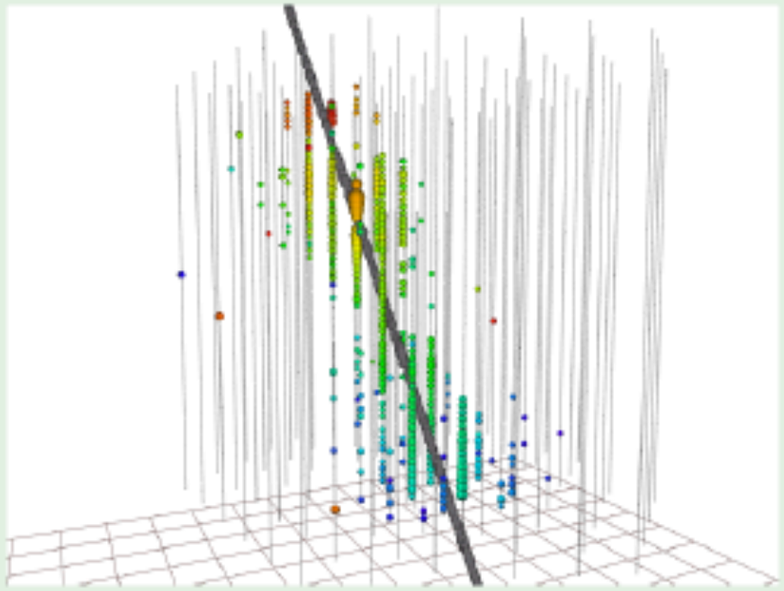
〈이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.〉

"한국 '세계적 리더' 될 좋은 기회"

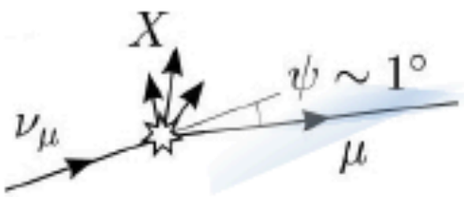
기초과학 투자 의지 활발, 한국에 새 연구 터전 등지.. 연구자-학생 영입해 연구

Event topologies in IceCube

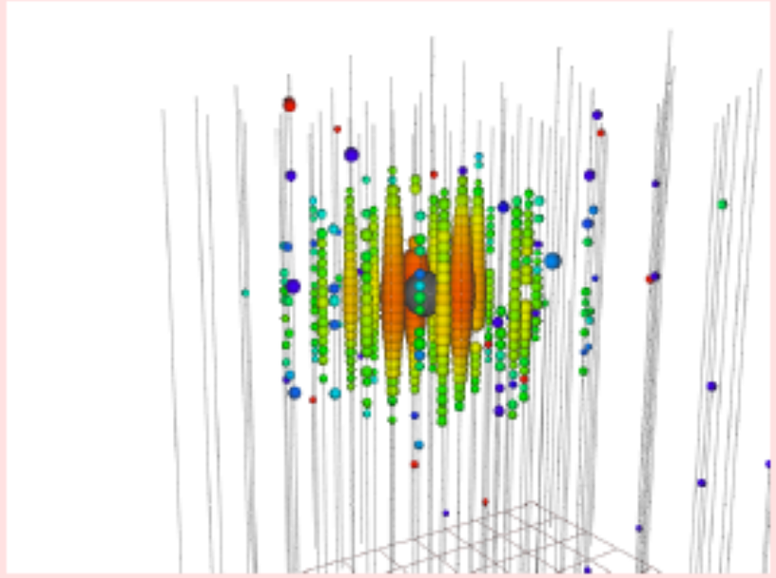
Track



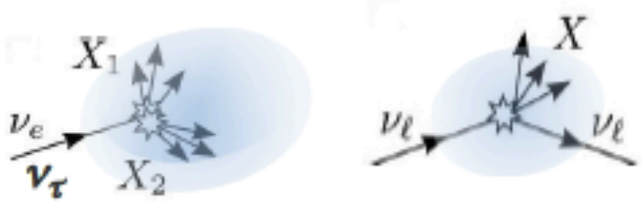
- Muon tracks (CC ν_μ)
- Resolution $< 1^\circ$
- Large energy uncertainties



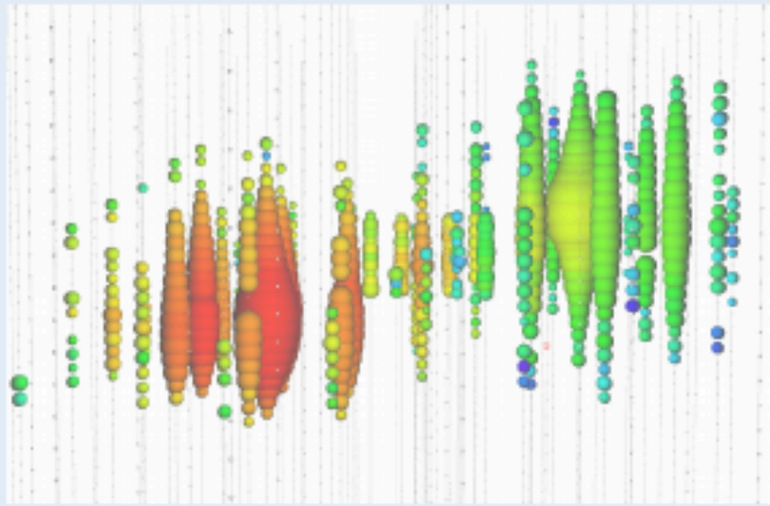
Cascade



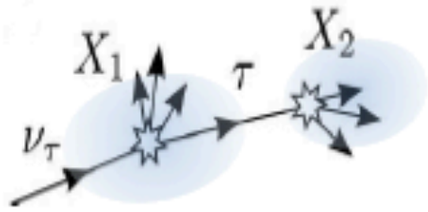
- NC or ν_e/ν_τ
- Resolution $\approx 15^\circ - 20^\circ$
- Energy resolution $\delta E/E \approx 15\%$



Double-bang

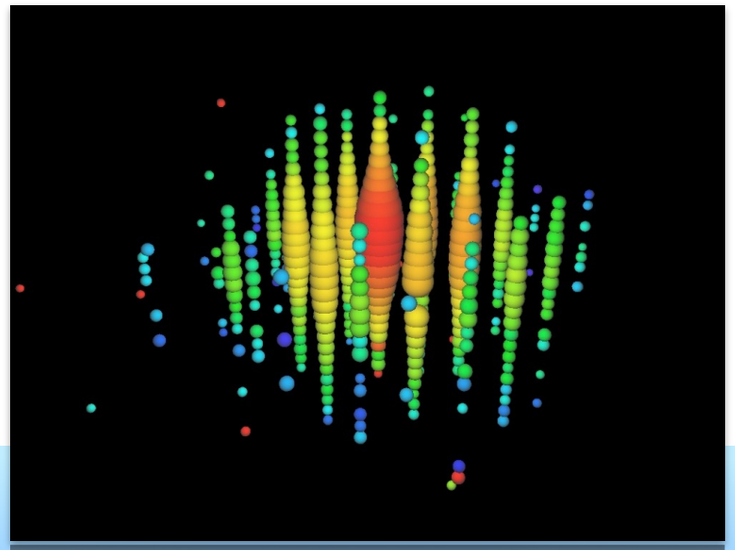


- High energy ν_τ (>100 TeV)
- Not observed yet



early — late

amount of light in detector $\propto$ ν energy

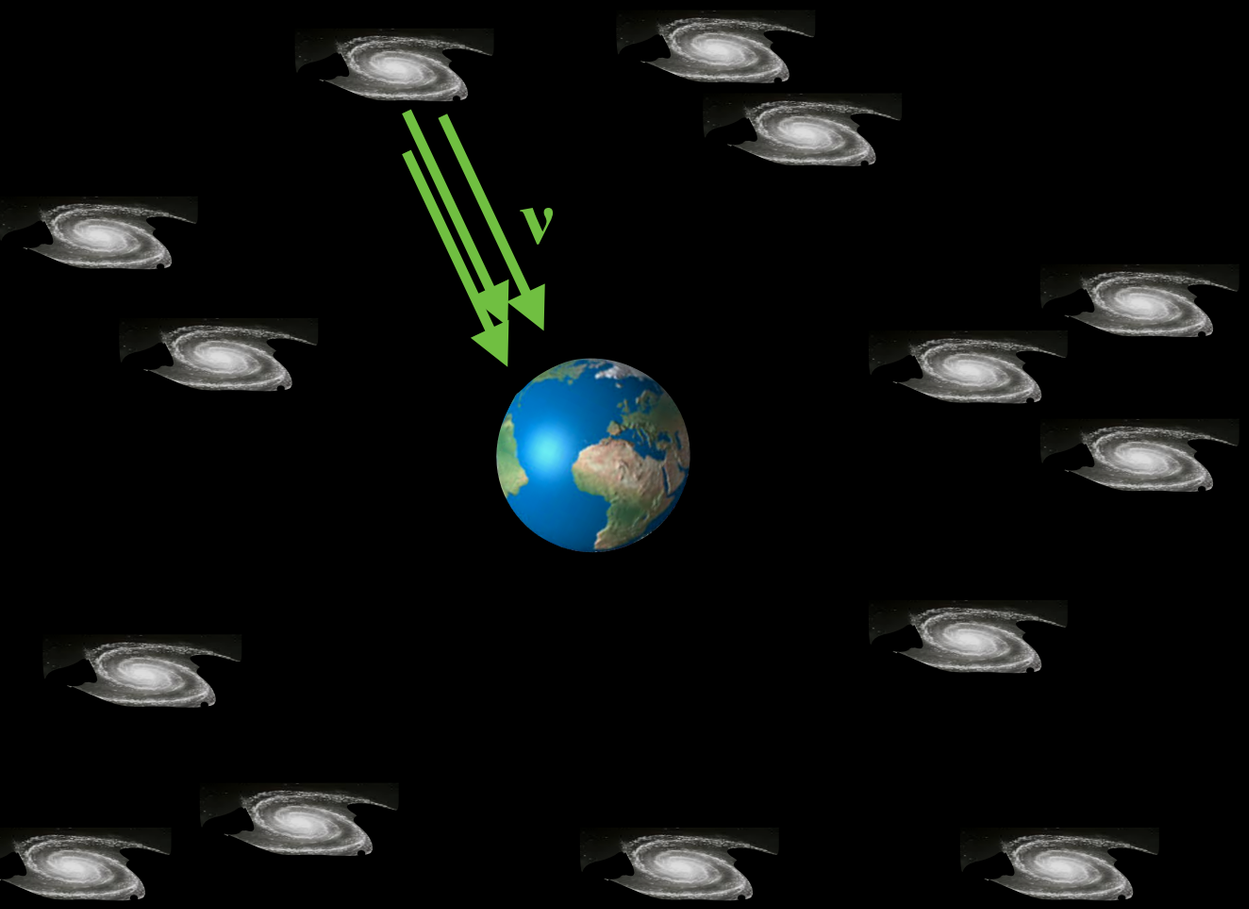


Astro-physical Neutrino Search

Finding astrophysical neutrinos

How to find astrophysical neutrinos ?

Finding astrophysical neutrinos



Point source search

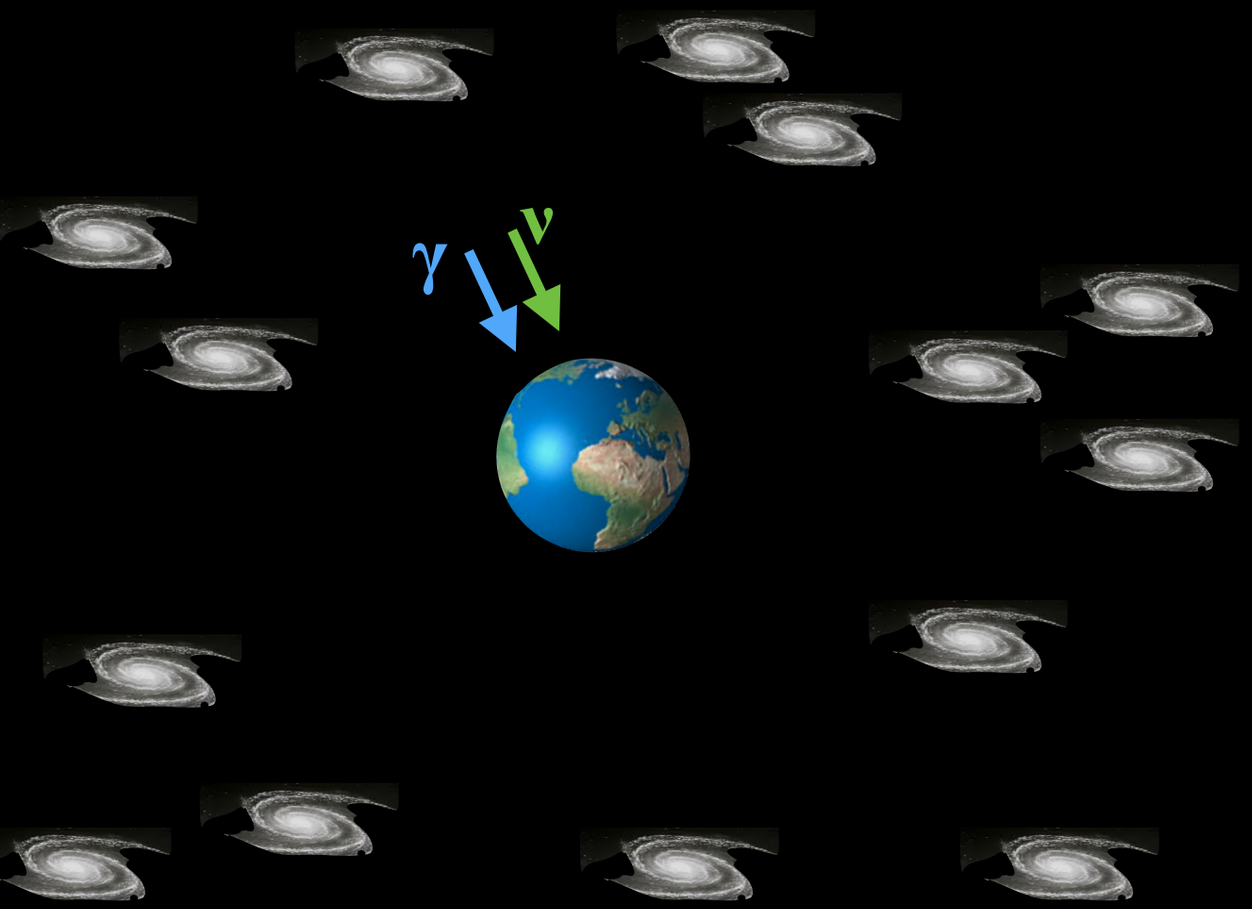
- search for clustering of neutrinos from point in the sky

Finding astrophysical neutrinos

Transient source search

- search for spacial and temporal clustering of neutrinos

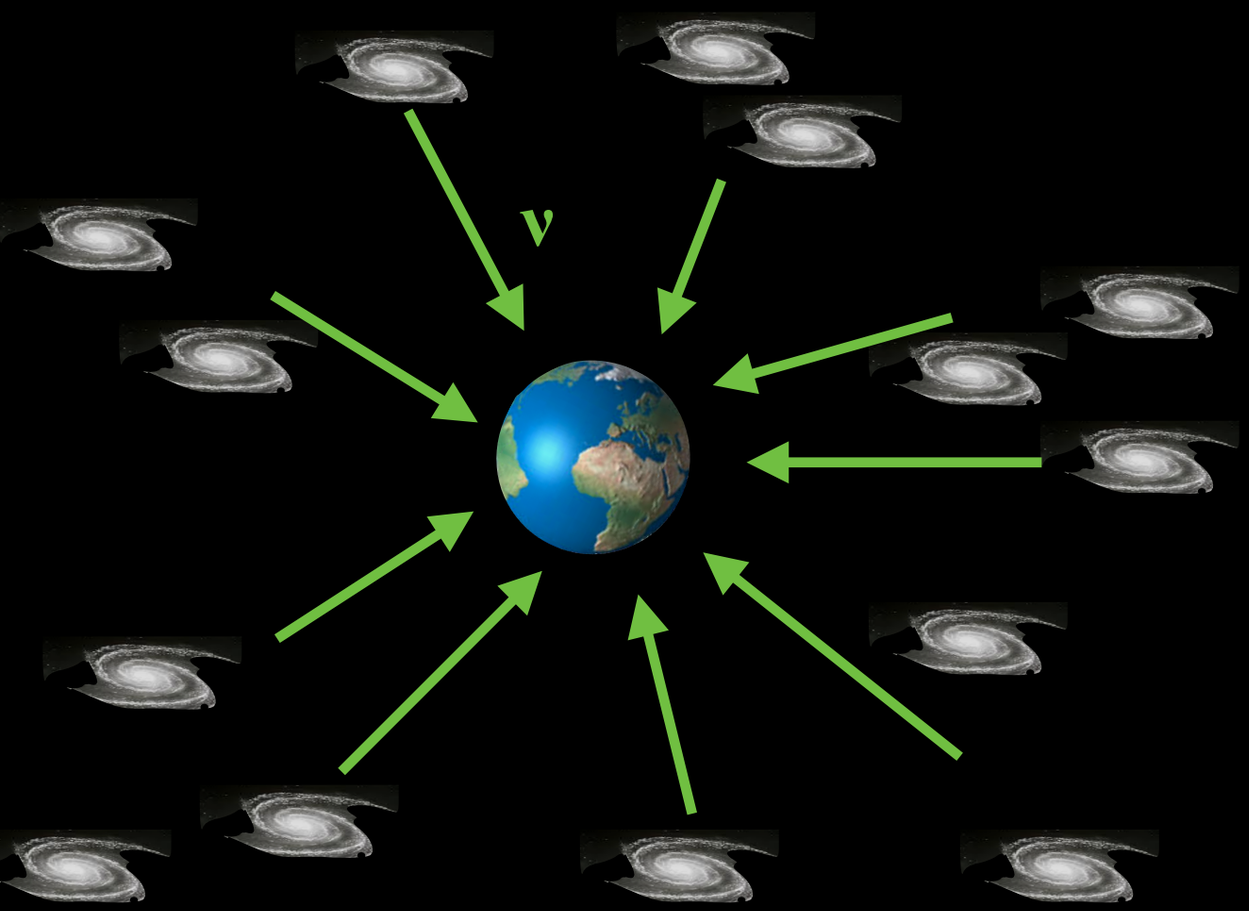
Finding astrophysical neutrinos



Multi-messenger search

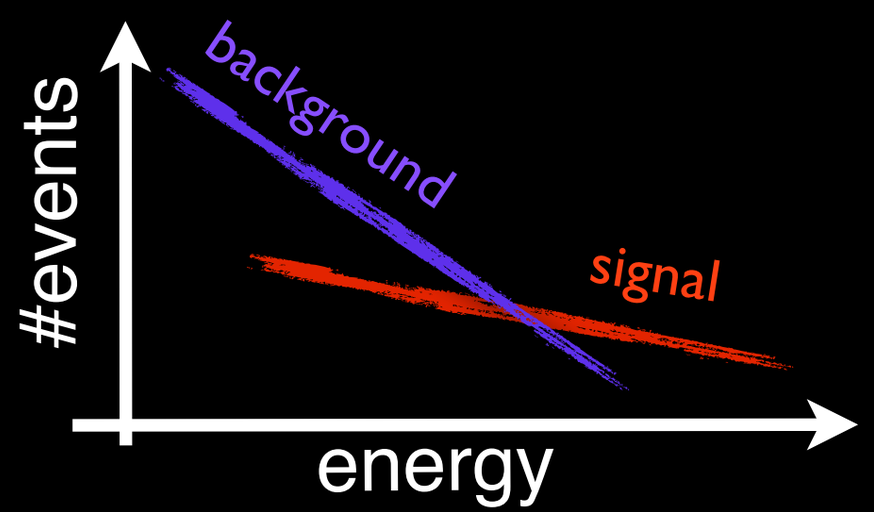
- search for a coincidence between neutrino and other messenger particles spacial at particular time and location

Finding astrophysical neutrinos

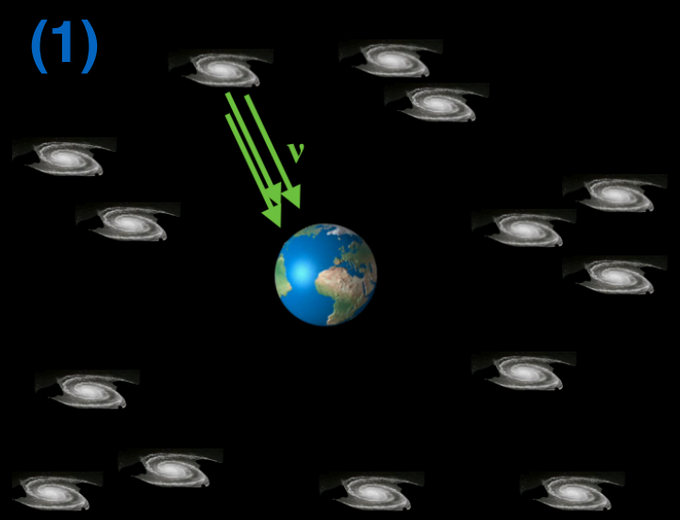


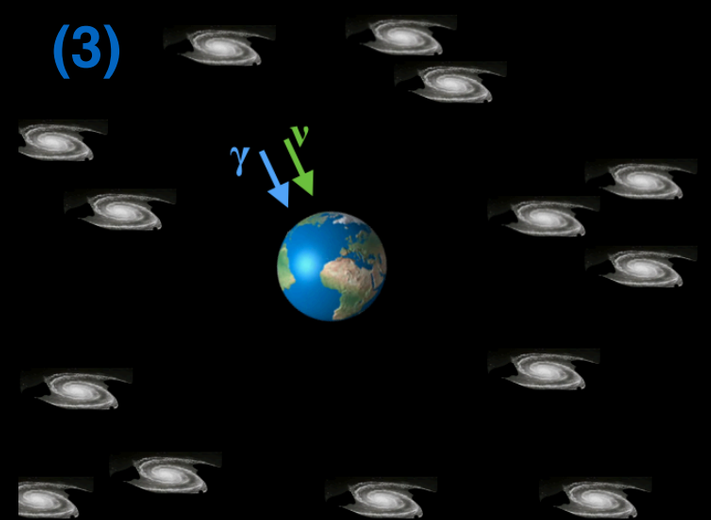
Diffuse search

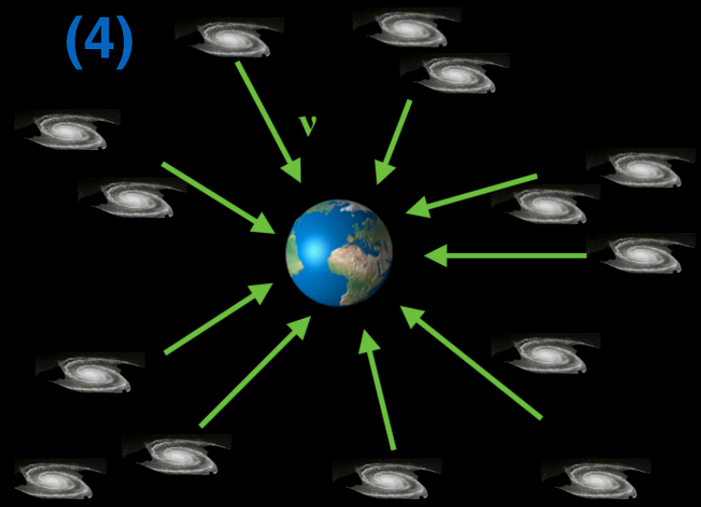
- search for spectral feature, inconsistent with atmospheric background predictions



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

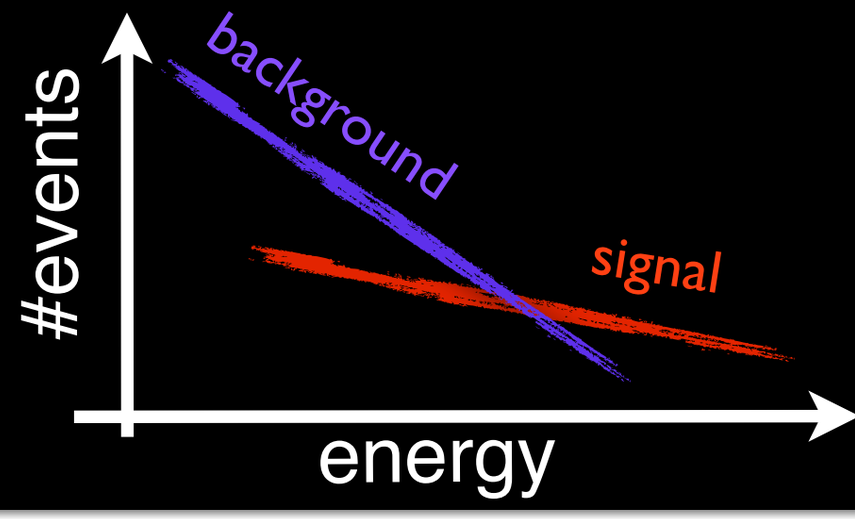
(3) Multi-messenger search

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

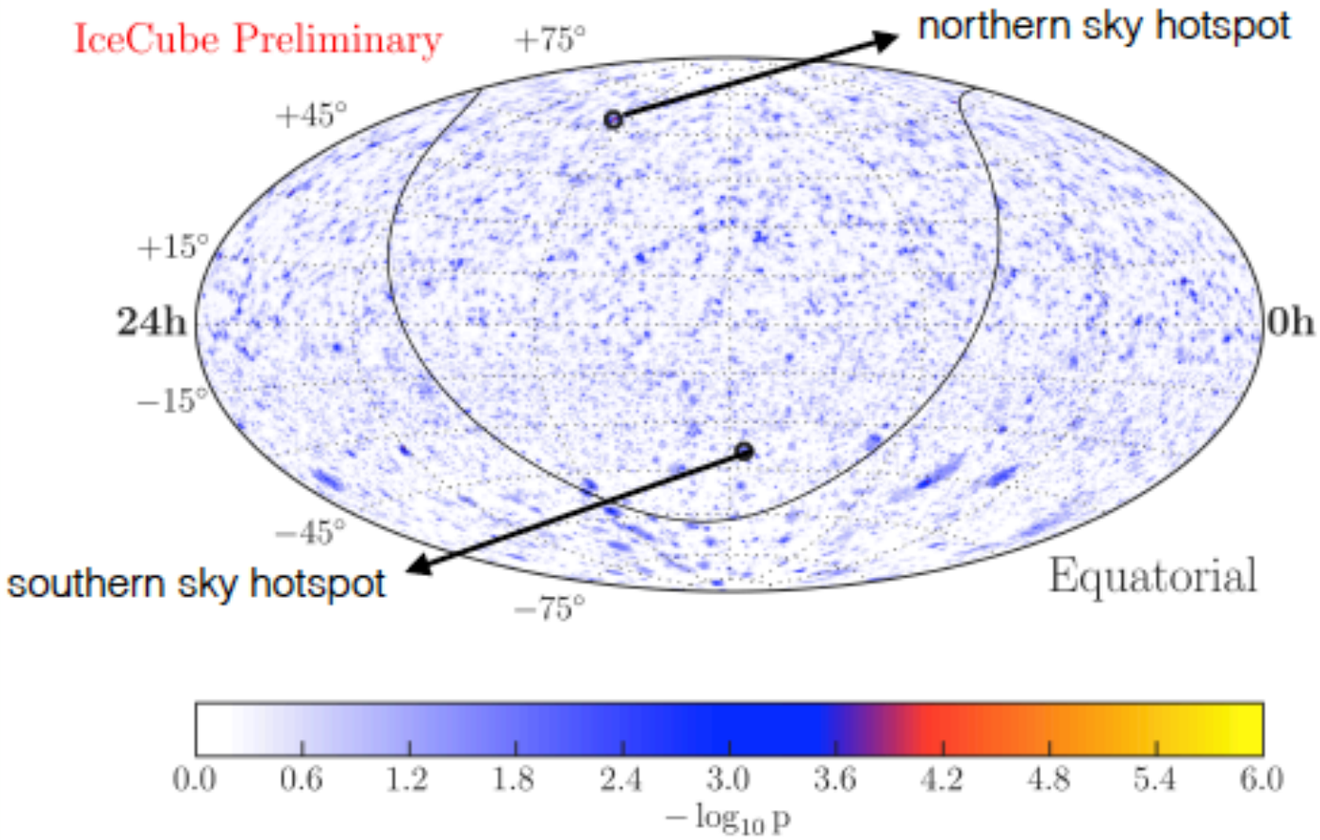
(4) Diffuse search

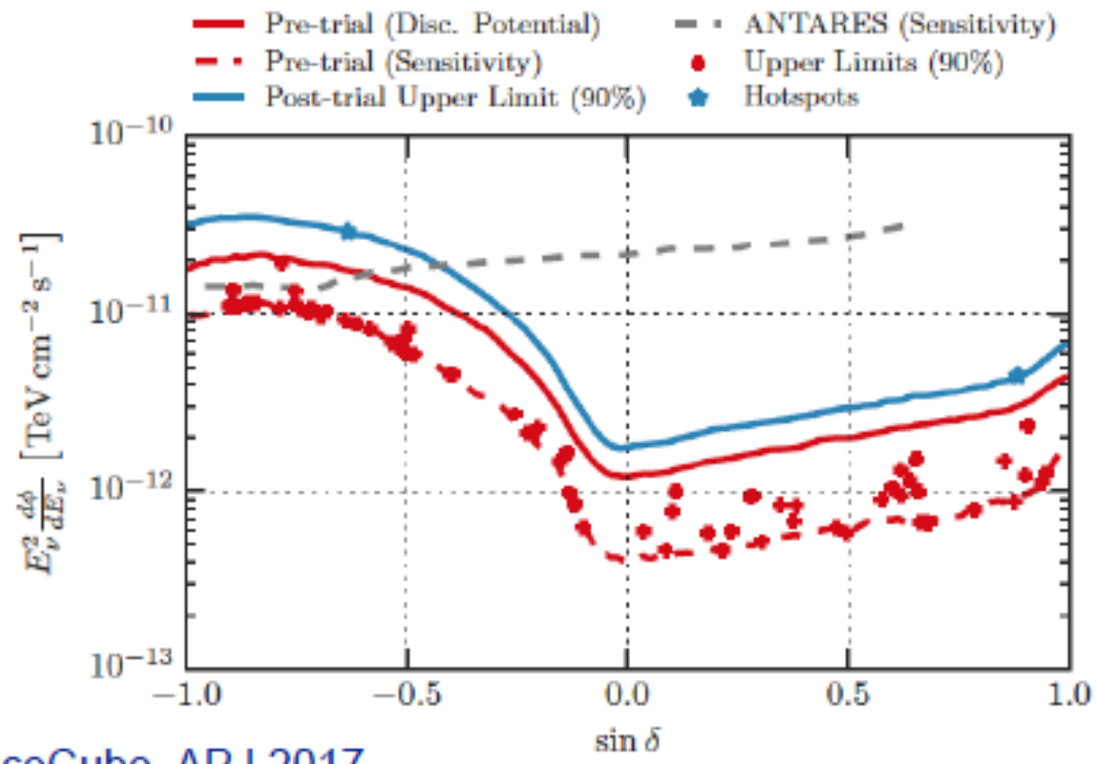
- search for spectral feature, inconsistent with atmospheric background predictions

…. + various combinations and



Point Source Search





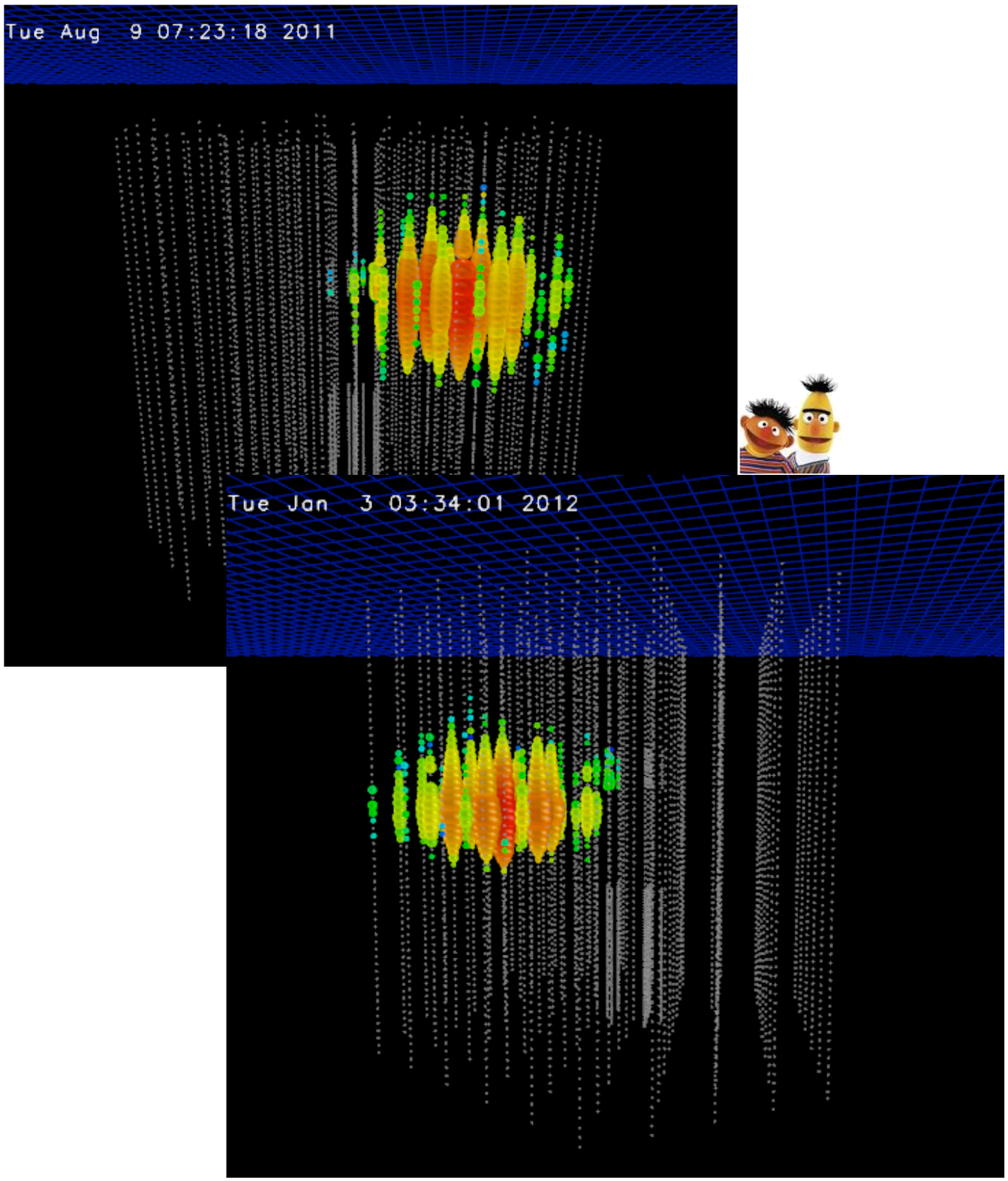
IceCube, APJ 2017

IceCube Searched for
- point sources
- extended sources
- catalog of sources
- diffuse Galactic emission

- No point/extended source found yet.
- No correlation with source catalogs found.

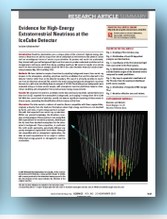
Search for highest energy neutrinos

IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356



In two years of data expect 0.08 events at high energies, but observed 2 events !!

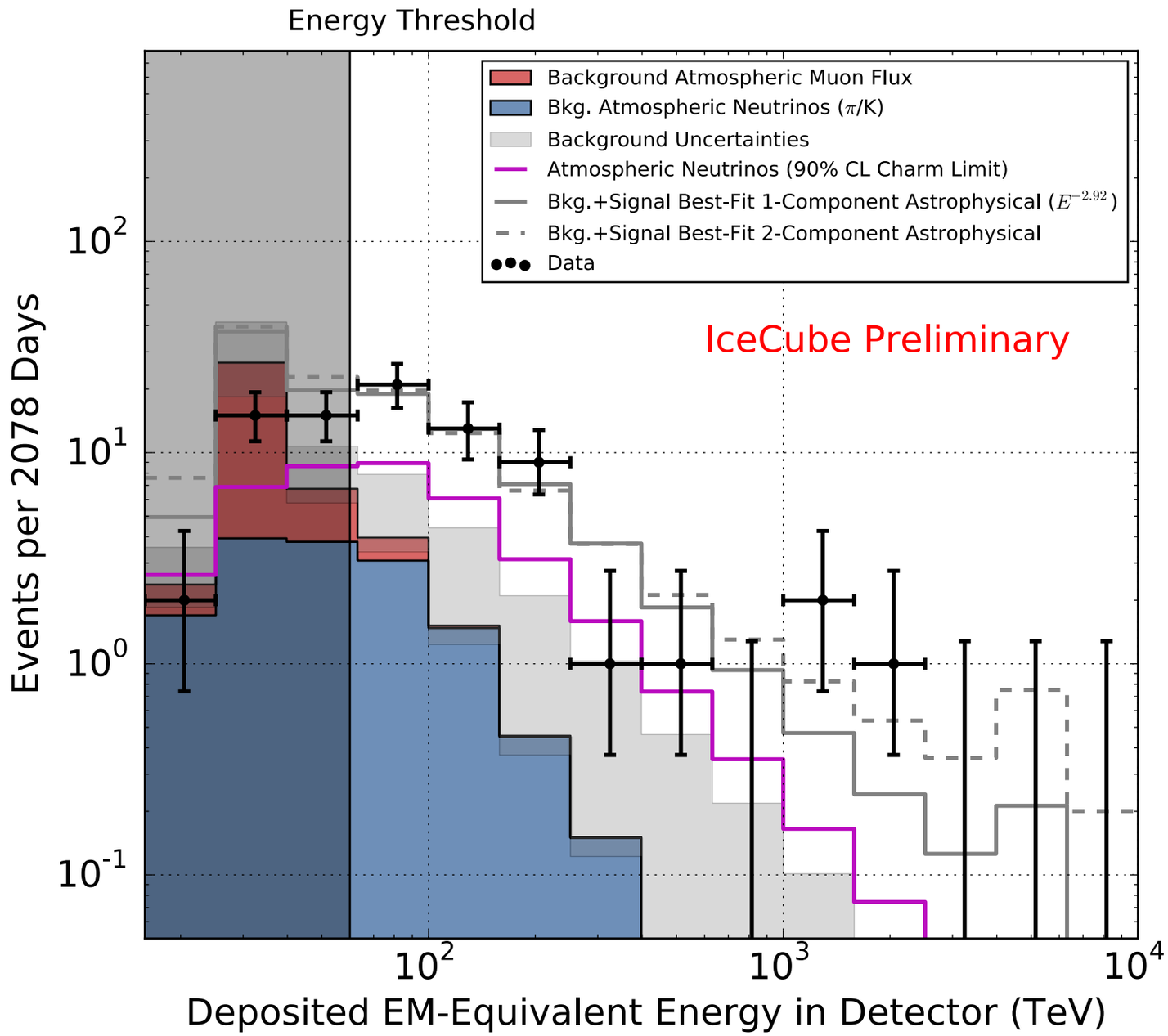
- Ernie ~1.15 PeV (~$1.9 \cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~$1.7 \cdot 10^{-4}$J)
- Topology of the events - cascades
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

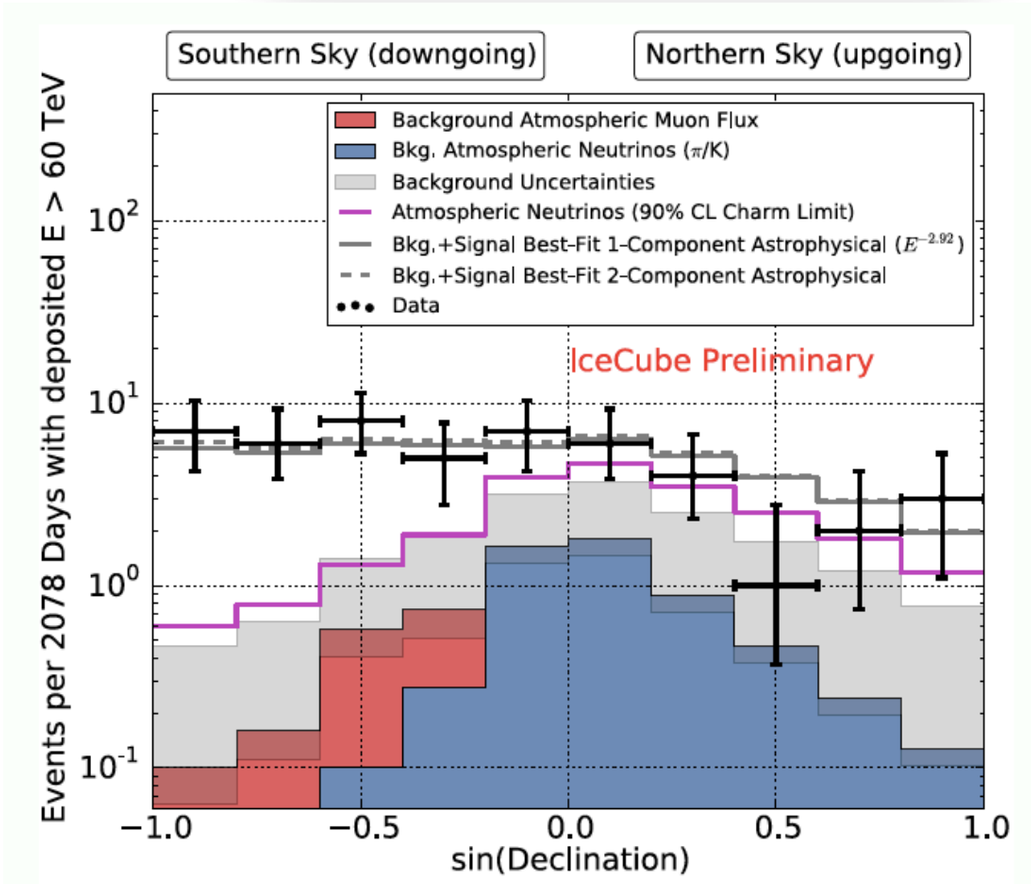



High-energy neutrino search 6years

HESE 6yrs 80 events (track-like & showers) observed

Expected from the Earth atmosphere ~41events



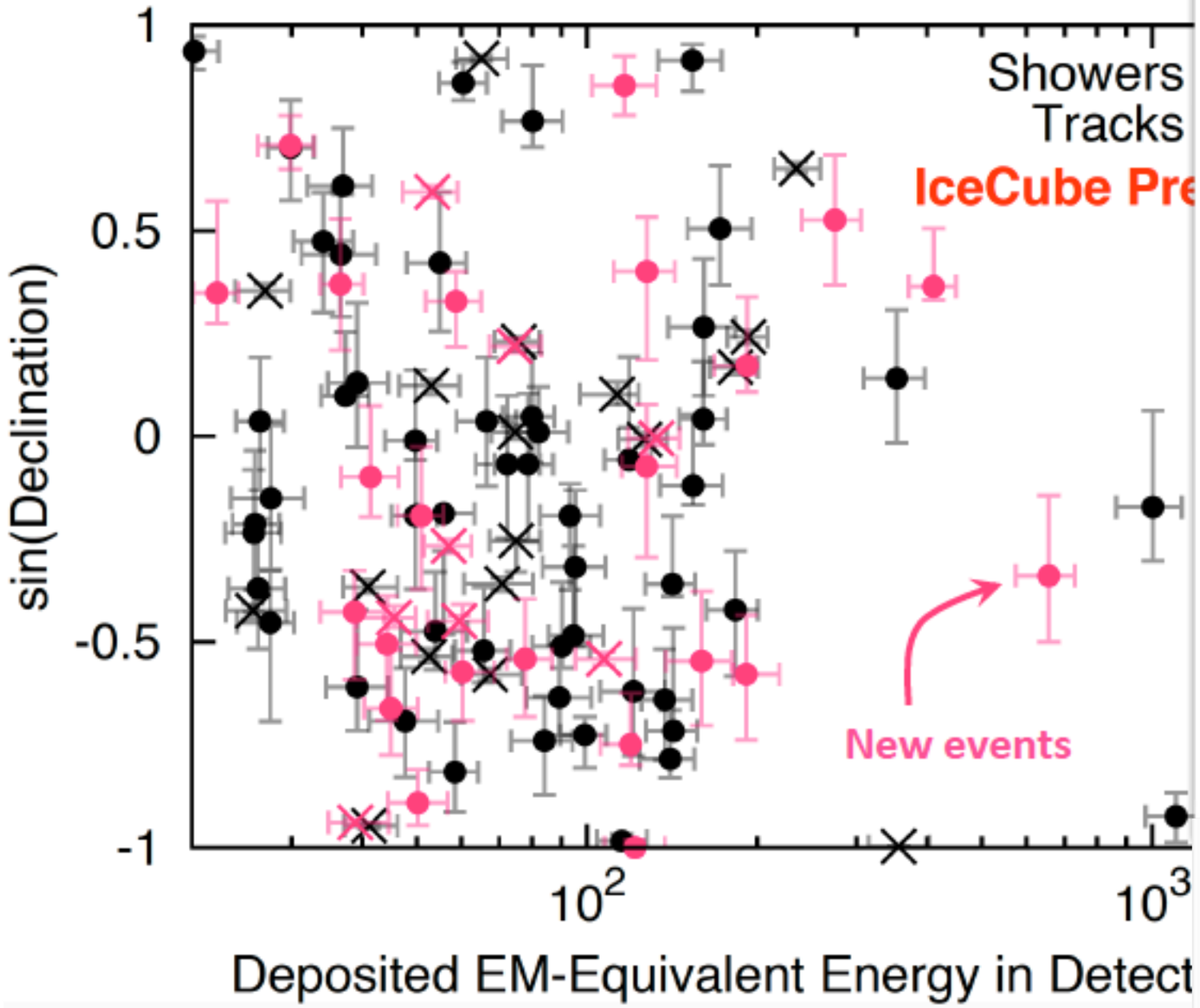


Best fit spectral index ($E^{-\gamma}$):

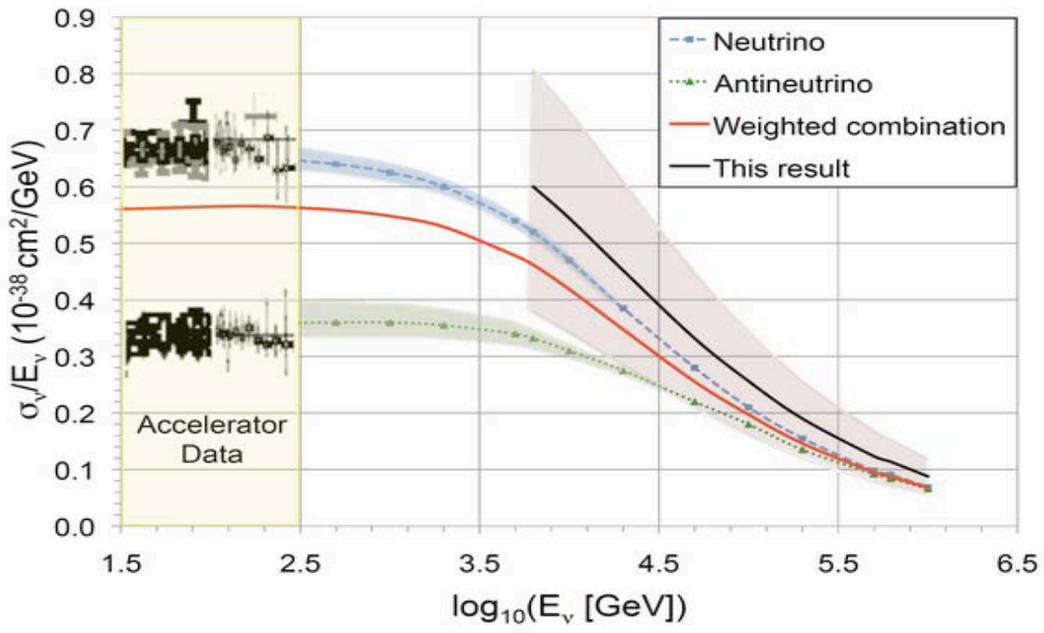
$\gamma = -2.92^{+0.33}_{-0.29}$

HE

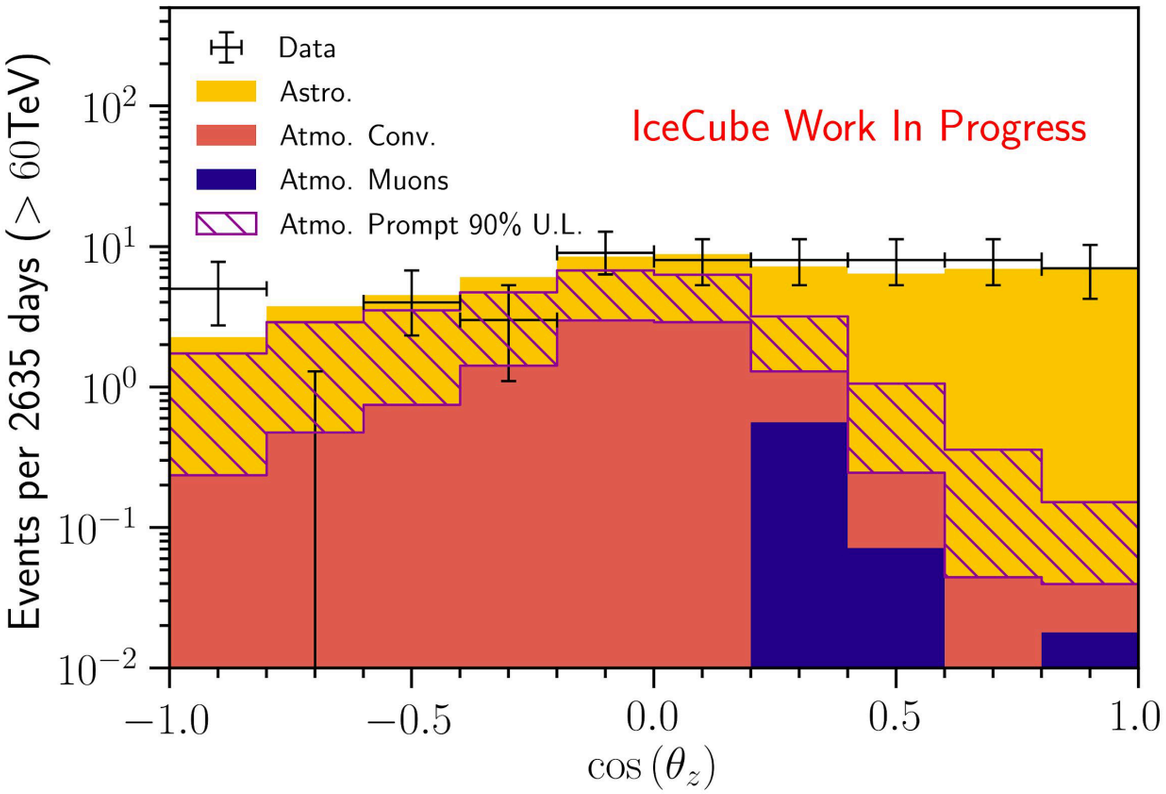
IceCube Collaboration, *Science* 342, 1242856 (2013)

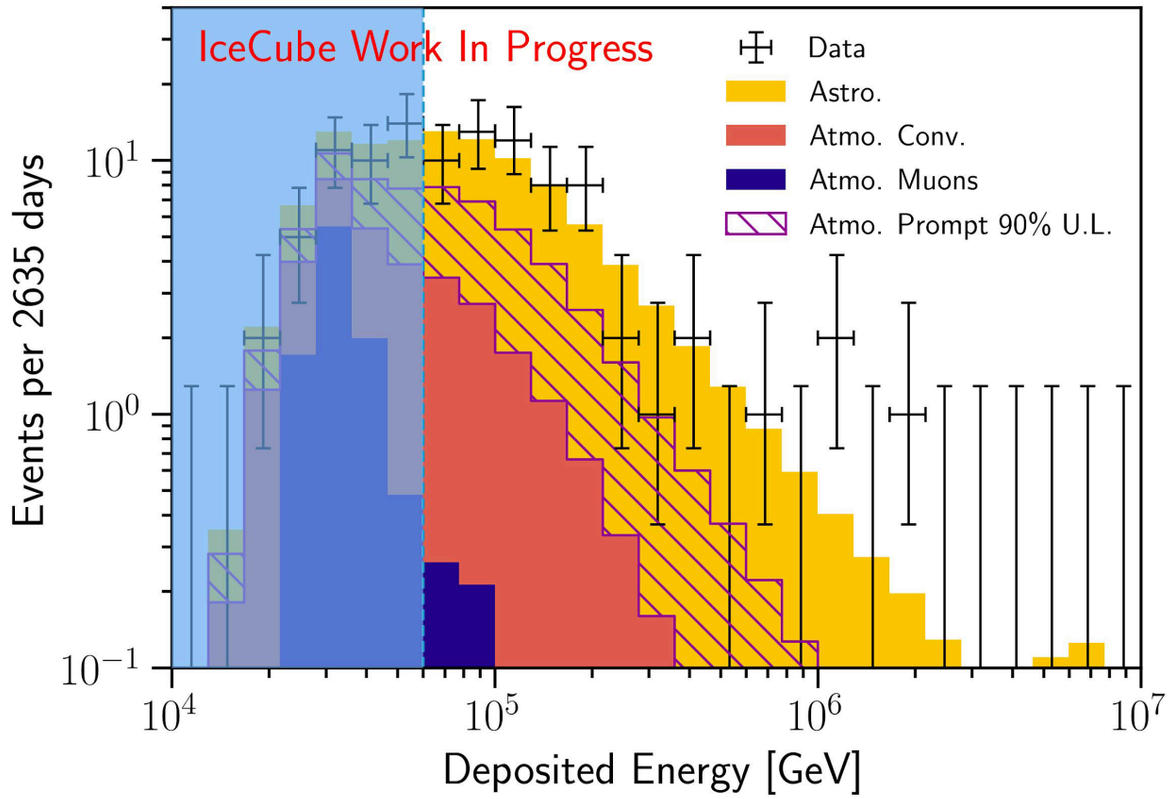


- Recently unblinded 1.5 additional years of data (new ca
- Topology ID added (Cascades, Tracks, Double Cascades
- Above 60TeV: 60 events - 17 new events in 2016/2017
- All energies: 102 events - 31 new events in 2016/2017 s



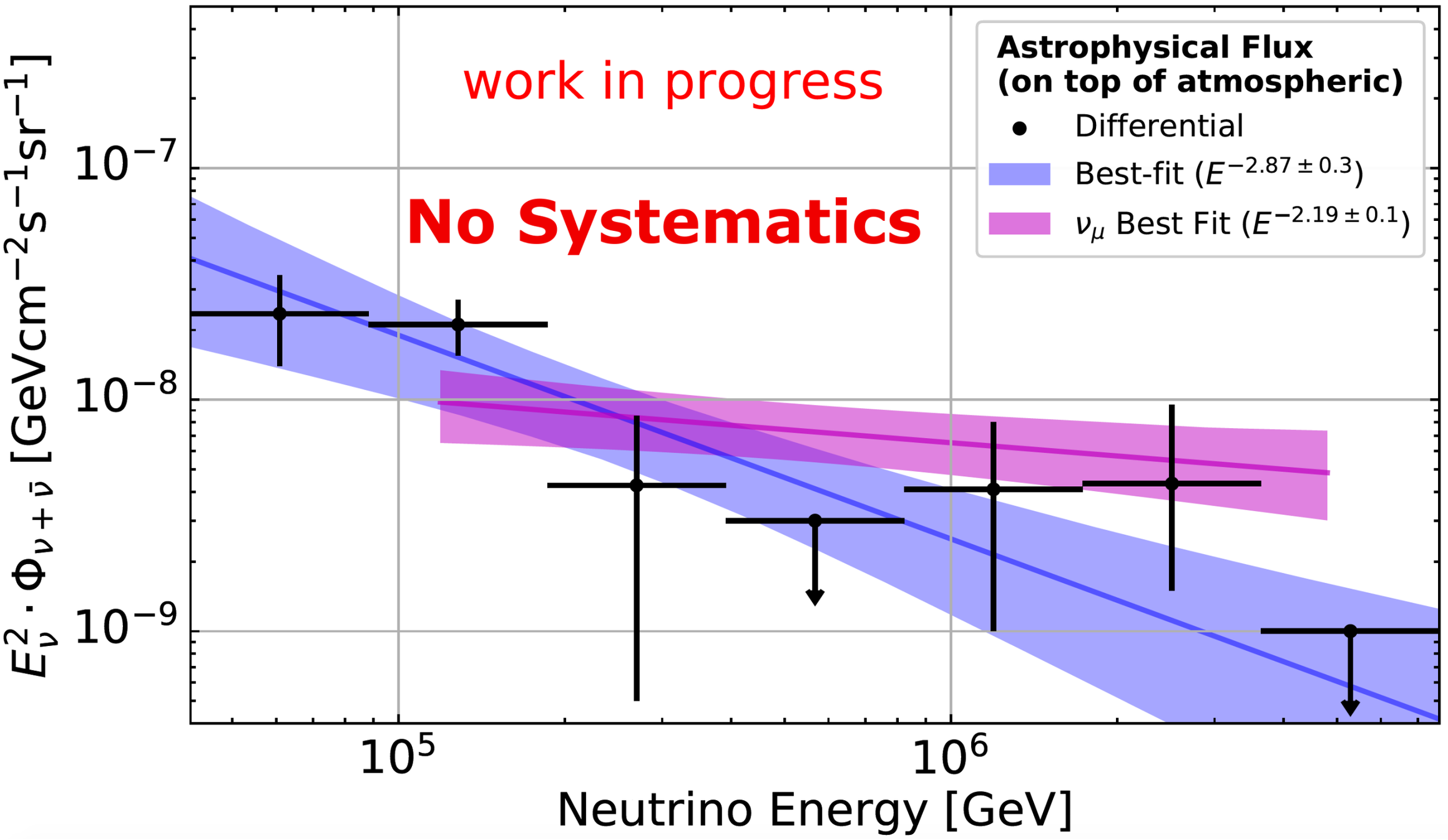
HESE 7.5yrs Zenith angle and Energy distribution





- Compatible with benchmark single power-law model.
- Best fit spectral index ($E^{-\gamma}$): $\gamma = 2.91^{+0.33}_{-0.22}$
- $E^2\phi = 2.19^{+1.10}_{-0.55} \times 10^{-8} \times (E / 100\text{TeV})^{-0.91}$ GeV cm^{-2} s^{-1} sr^{-1}

Neutrino energy spectrum

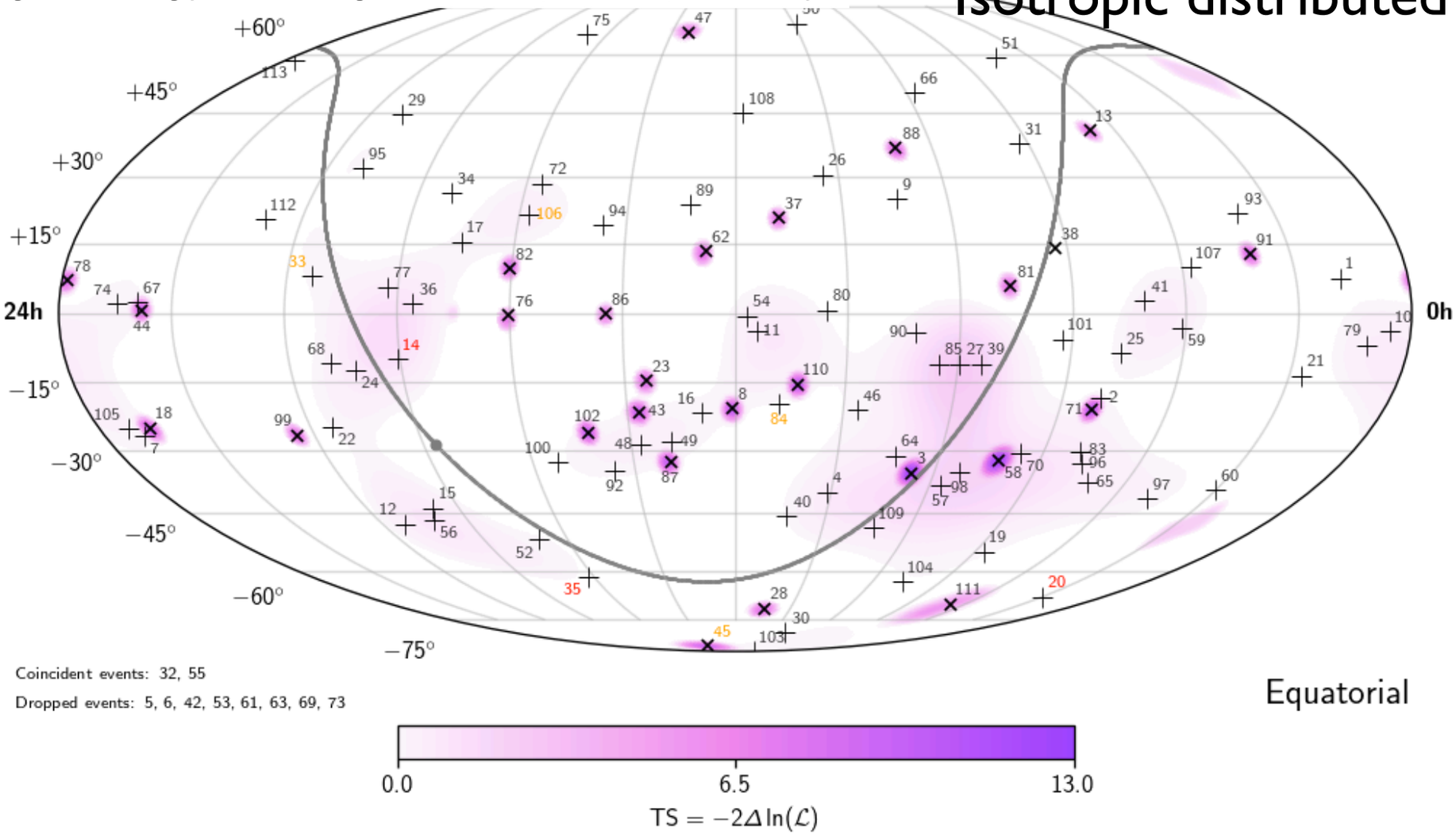


Arrival directions (highest energy events)

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

High-Energy Starting Events (HESE) – 7.5 yr

Isotropic distributed



Coincident events: 32, 55

Dropped events: 5, 6, 42, 53, 61, 63, 69, 73

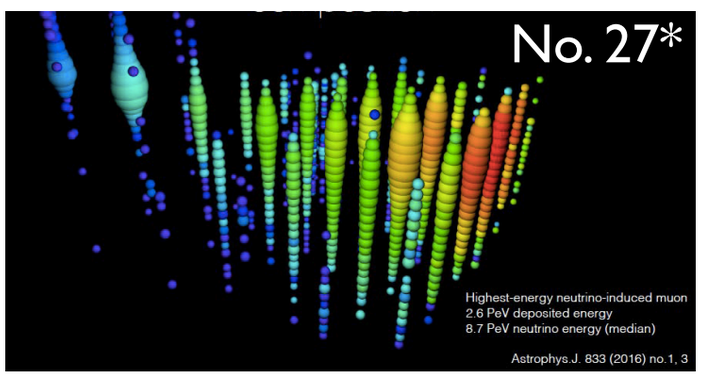
Equatorial

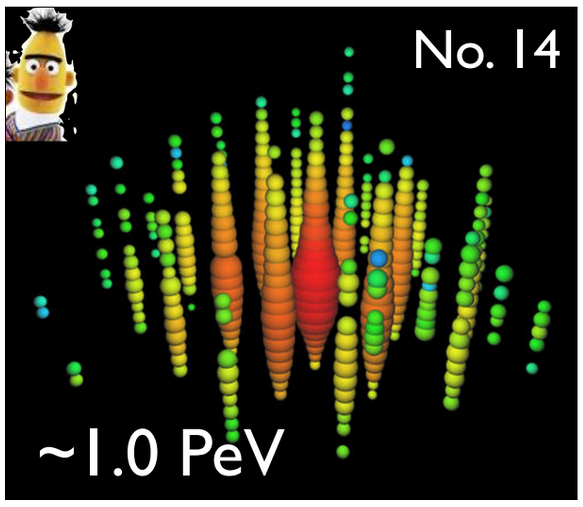
$E < 300$ TeV

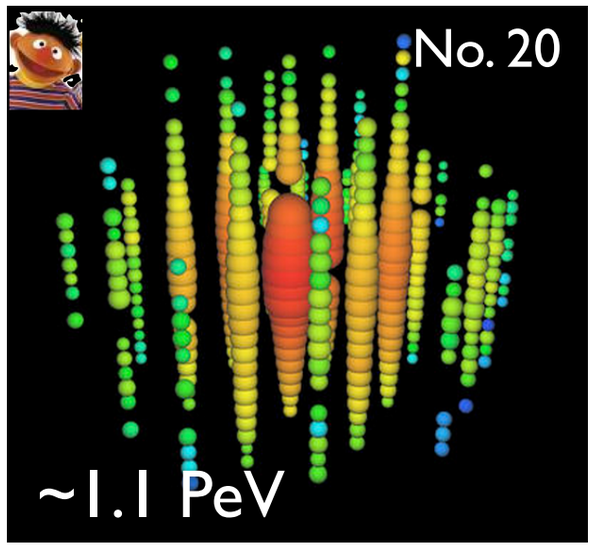
300 TeV $< E <$ 1 PeV

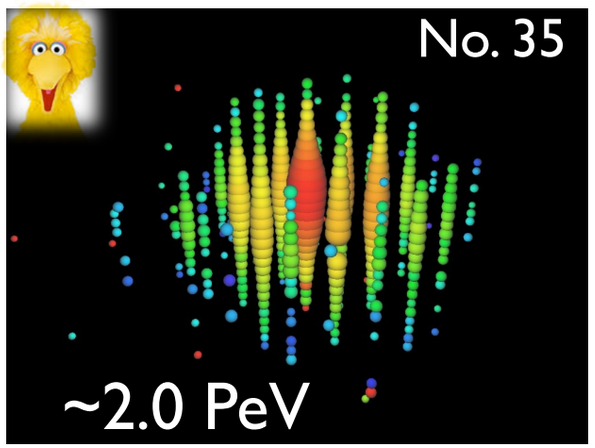
1 PeV $< E$

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



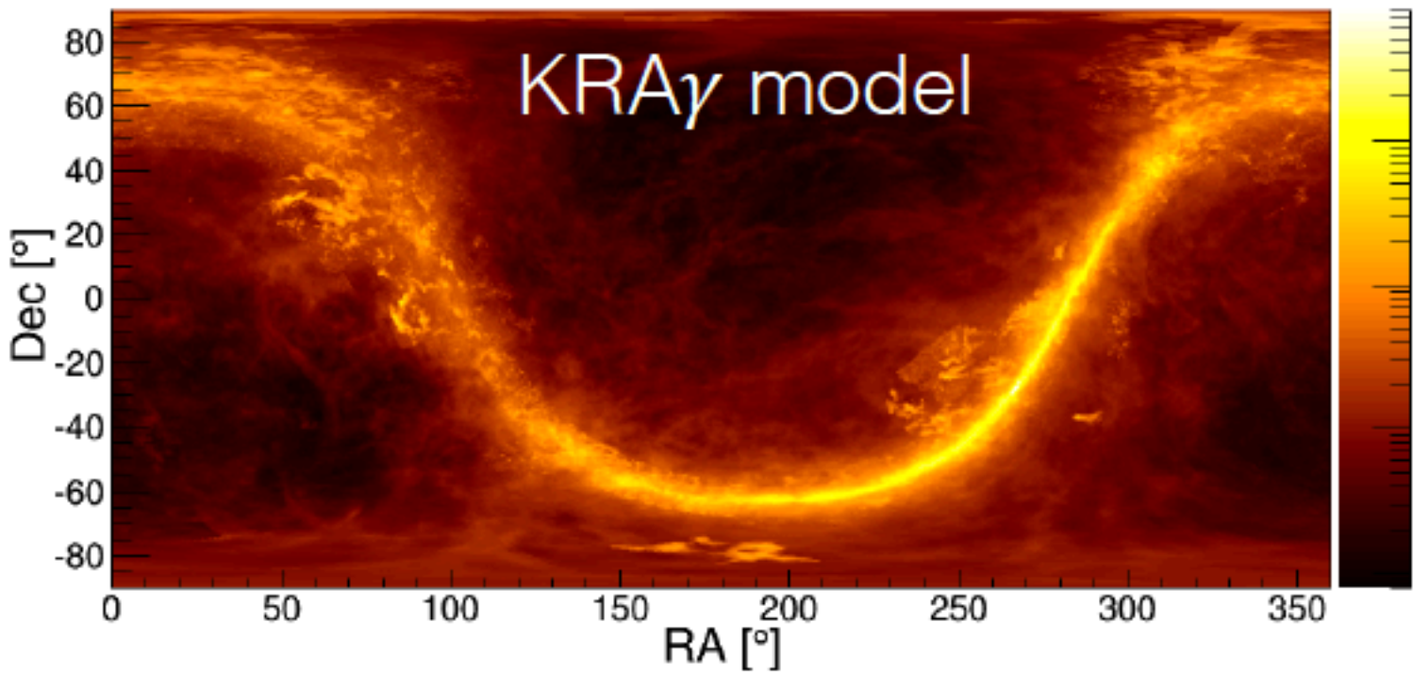


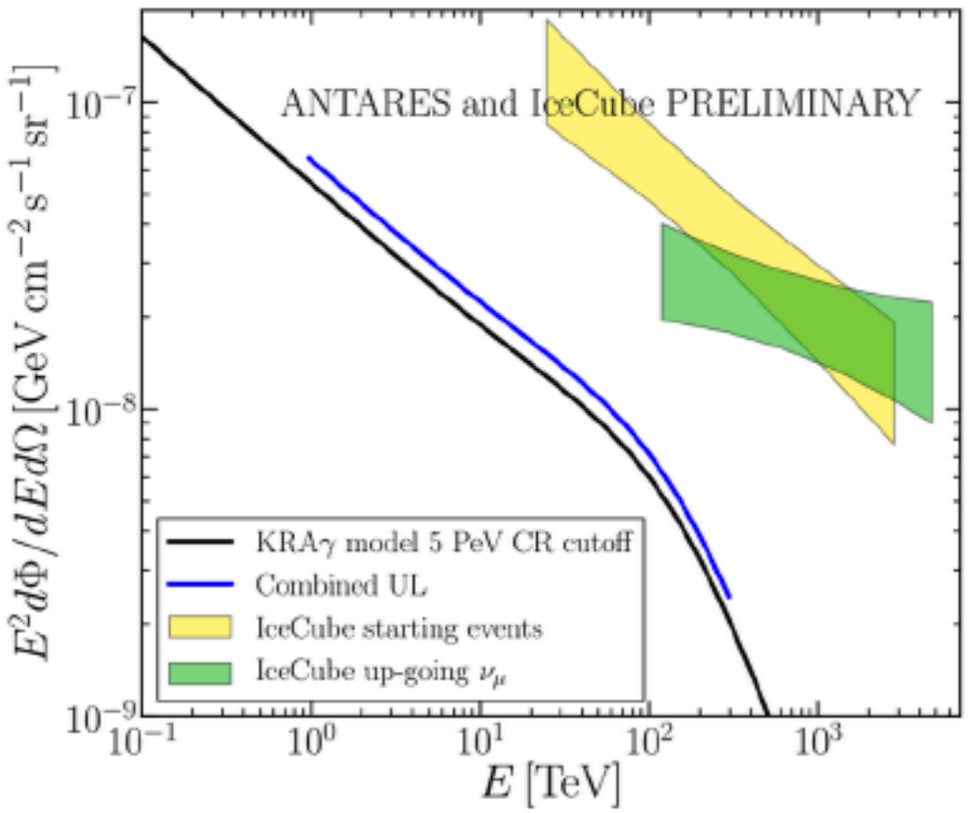


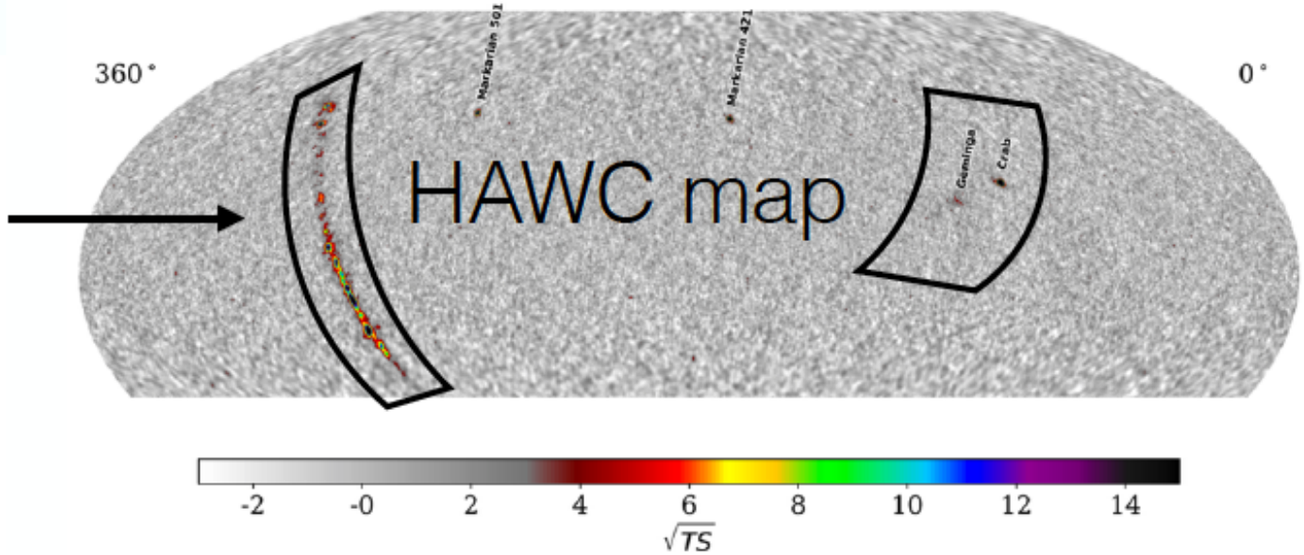


Galactic Neutrino Searches

- Combined ANTARES and IceCube search for diffuse ν emission from Galactic plane





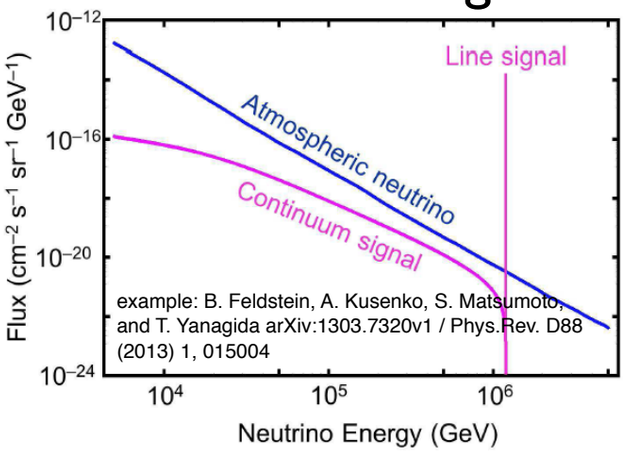


Diffuse astrophysical neutrino flux cannot be attributed to Galactic sources / Galactic plane

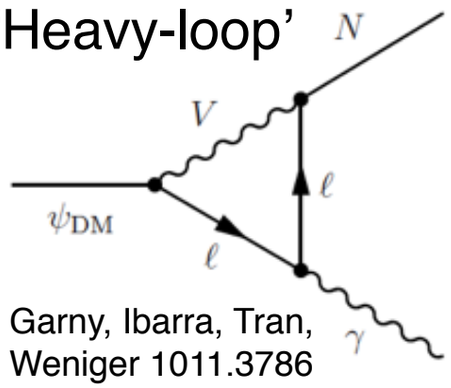
IceCube tested HAWC sources … no significant excess observed

Heavy Dark Matter Decay

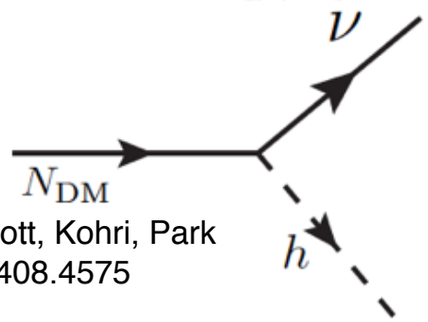
Decay process might produce mono-energetic neutrinos



'Heavy-loop'

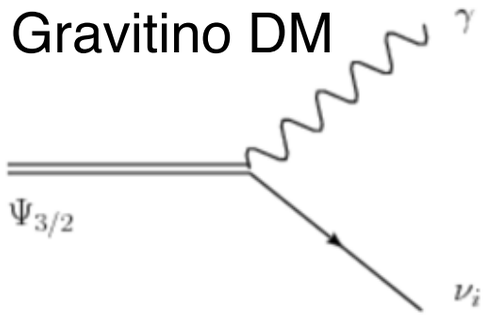


Garny, Ibarra, Tran, Weniger 1011.3786

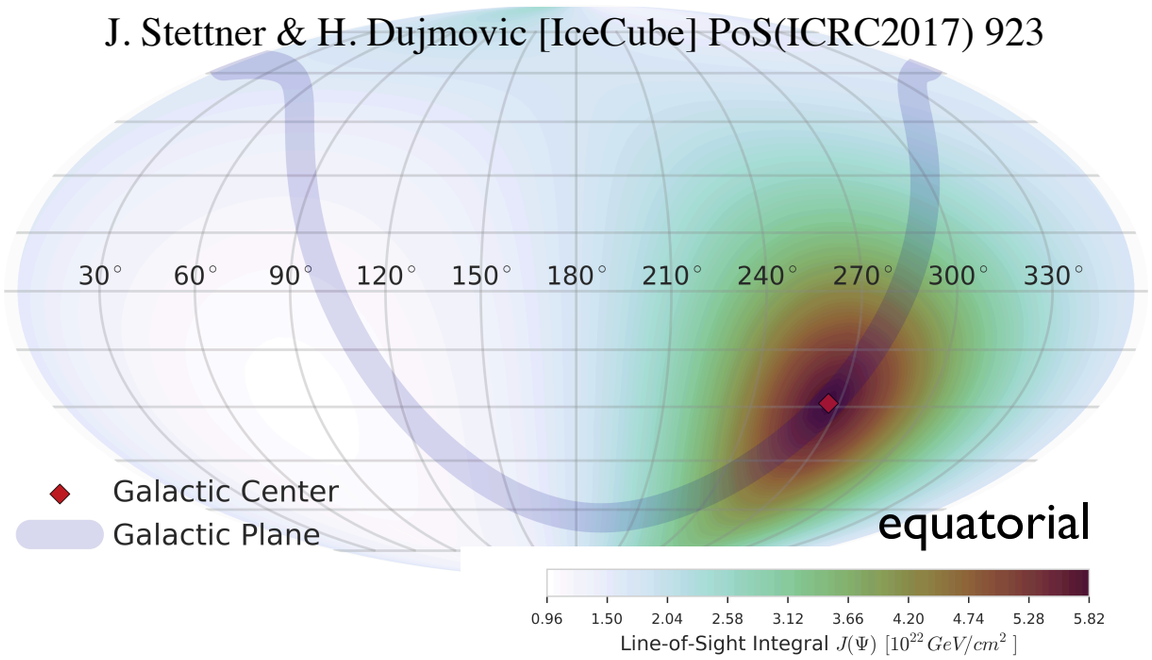


Rott, Kohri, Park 1408.4575

Gravitino DM



J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923



Two flux contributions: Galactic and Extra galactic

$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

- Characteristics of the signal components:
  - (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$

  - Dark Matter decay at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_{\mathrm{c}}}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} [(1+z)E_\nu]\, \mathrm{d}z$$

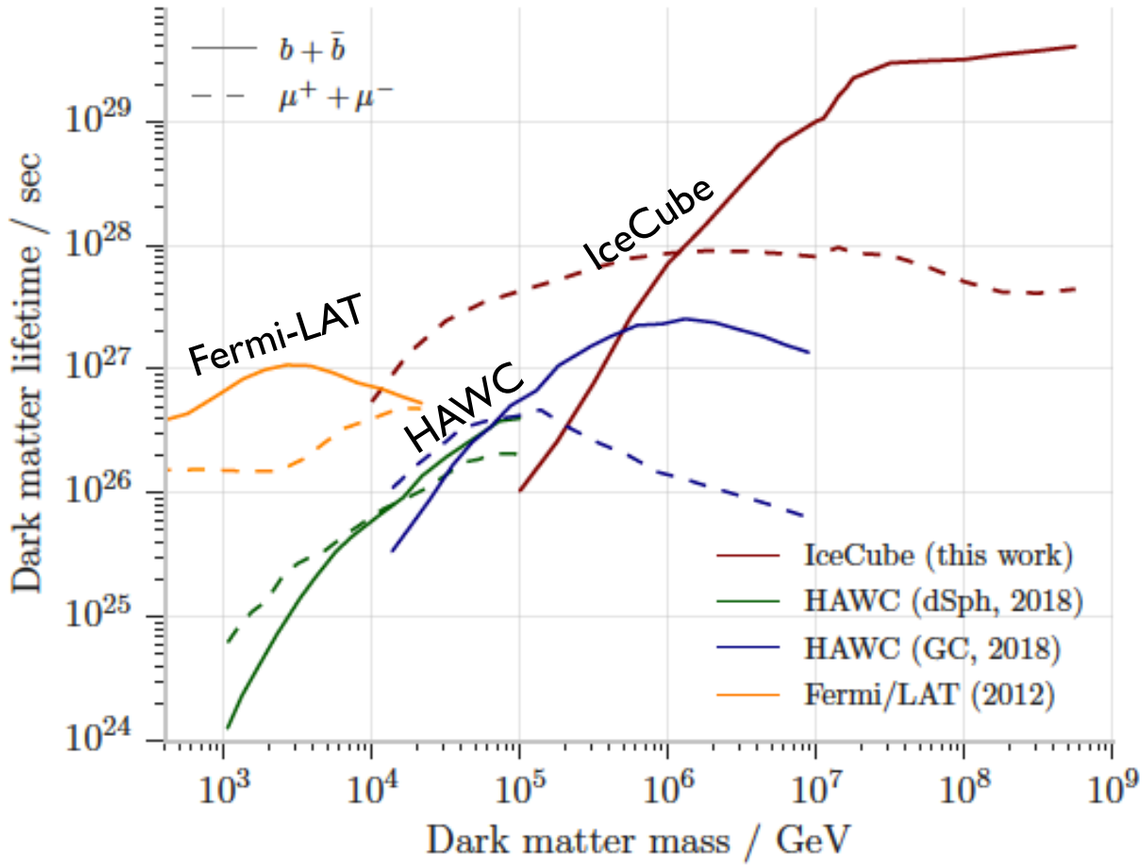
Dark Matter Decay with IceCube

J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923
IceCube Collaboration arXiv:1804.03848v1

- Two IceCube analyses have been performed on independent data samples
  - Track-like with six years of data
  - Cascade-like with two years of data

	Track-like	Cascade-like
Number of events	352,294	278
Livetime	2060 days	641 days
Sky coverage	North (zenith $> 85°$)	Full Sky
Atm. muon background	0.3%	10%
Median reconstr. error	$< 0.5°$ ($E_\nu > 100$ TeV)	$\sim 10°$
Energy uncertainty	$\sim 100\%$	$\sim 10\%$

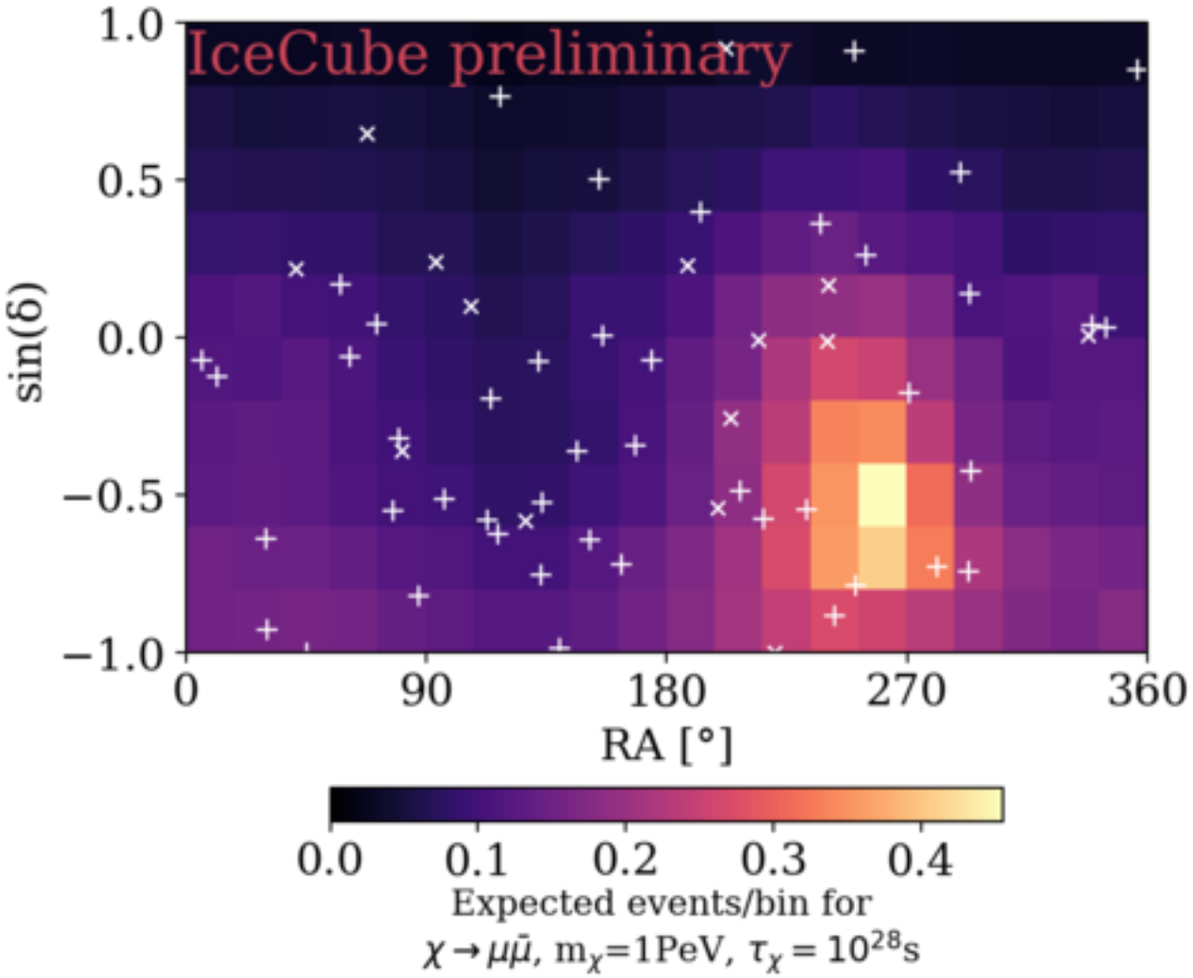
Test-Statistic: $$TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$$

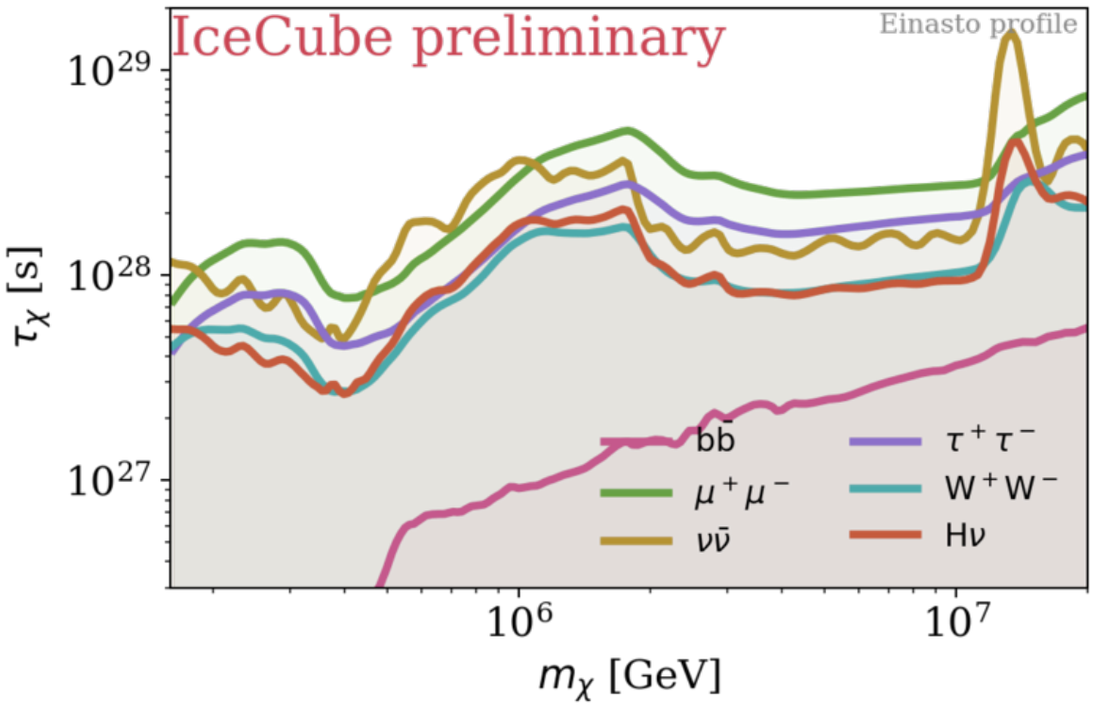


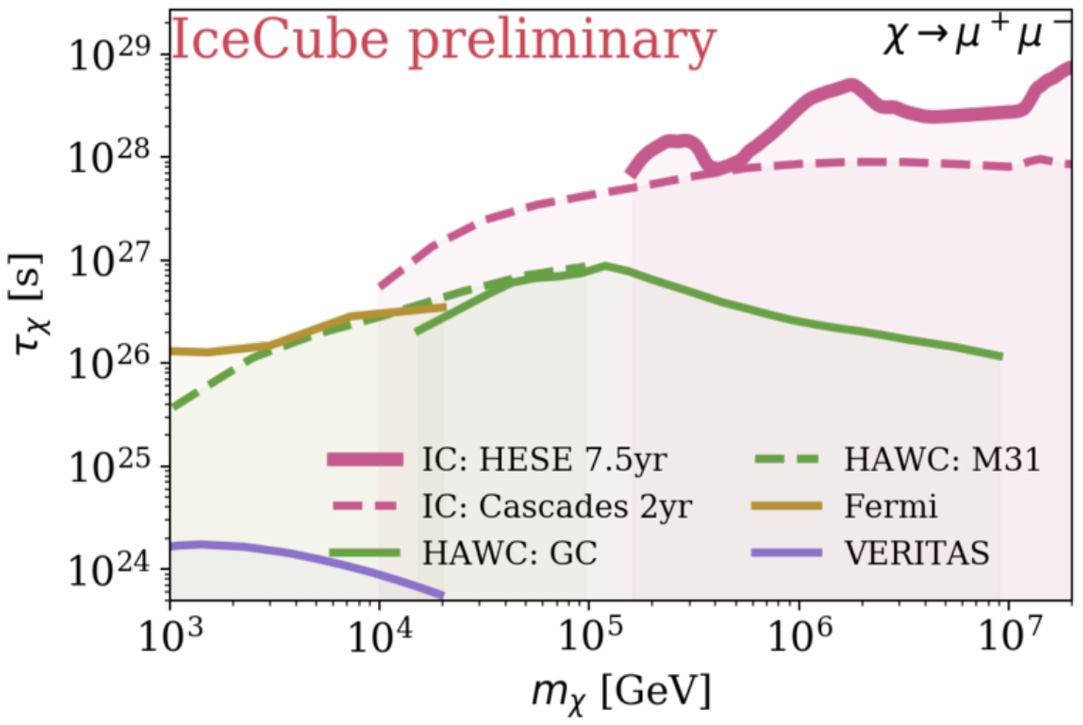
Bound on DM lifetime at ~10^{27}s obtained with IceCube data for m_{DM}>10TeV

- Dark matter alone cannot explain the observed astrophysical neutrino flux in IceCube
- Scenarios with a PeV neutrino line became less attractive with IceCube's observation of neutrino events well above this energy

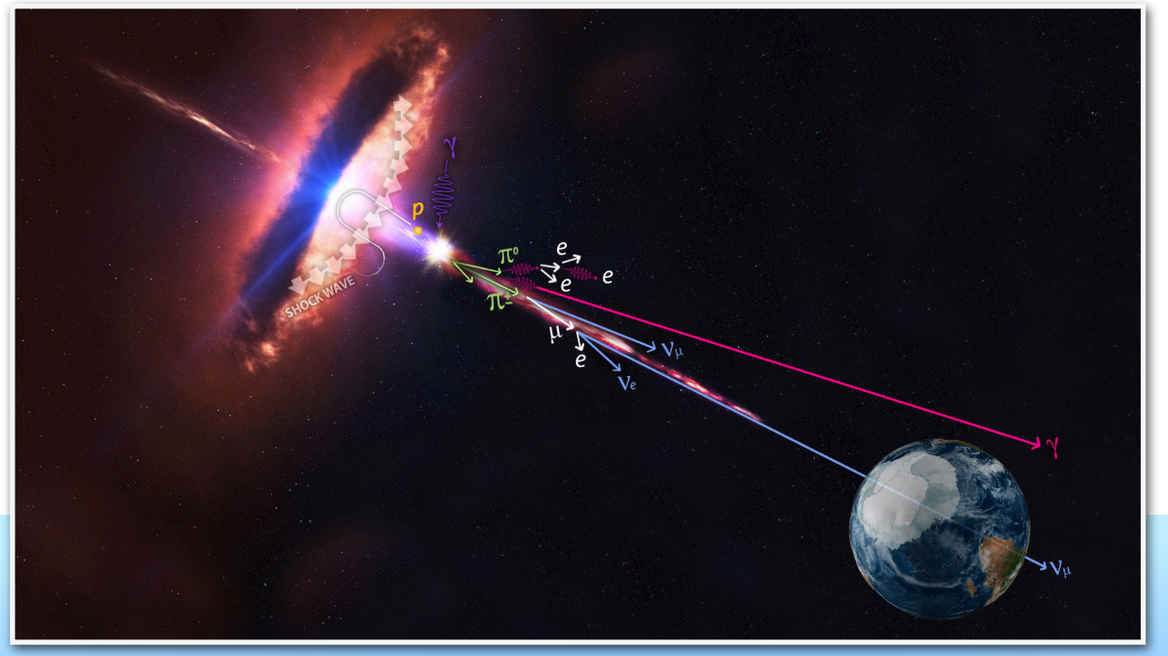
Search DM Decay with IceCube's 7years HESE Sample





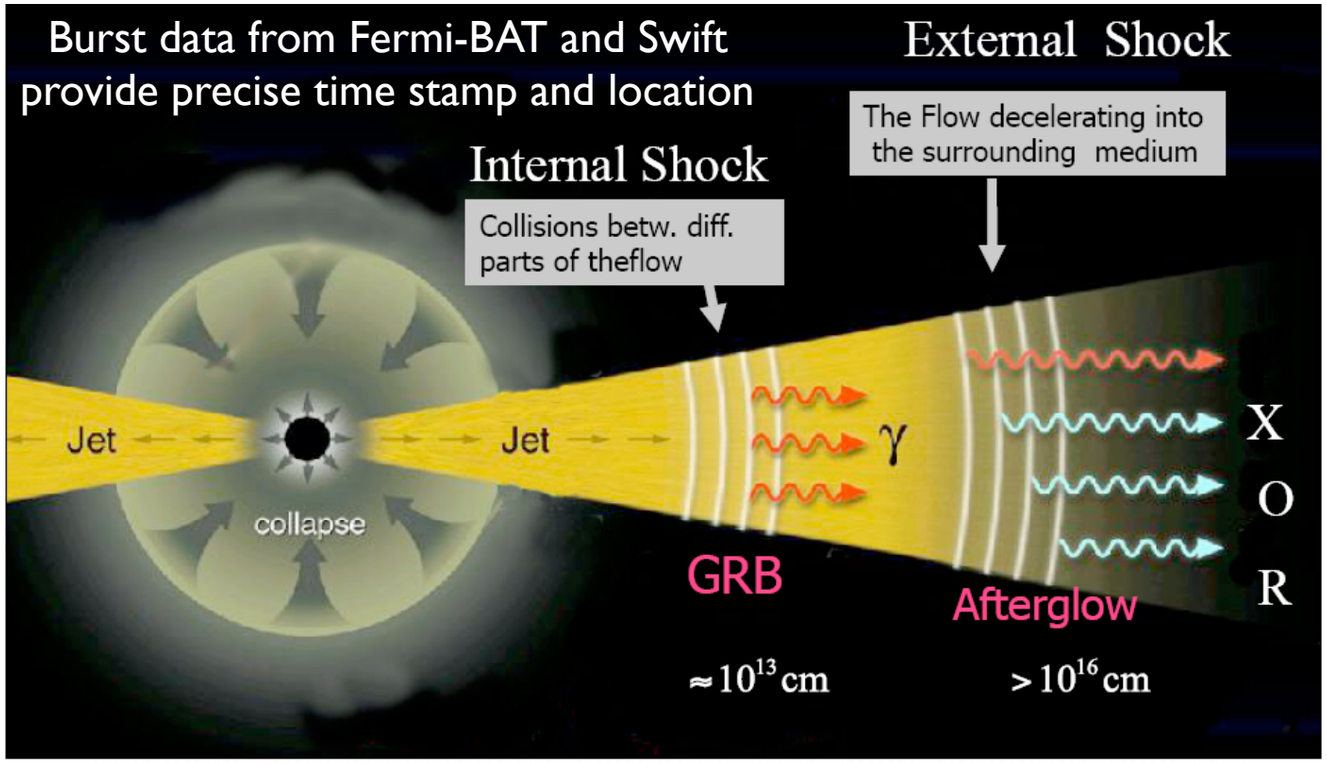


- 7 years of IceCube's HESE (High Energy Starting Events) Sample
  - Events with energies above >60TeV
- Binned likelihood analysis
- Most competitive limits above 100TeV for a large number of channel



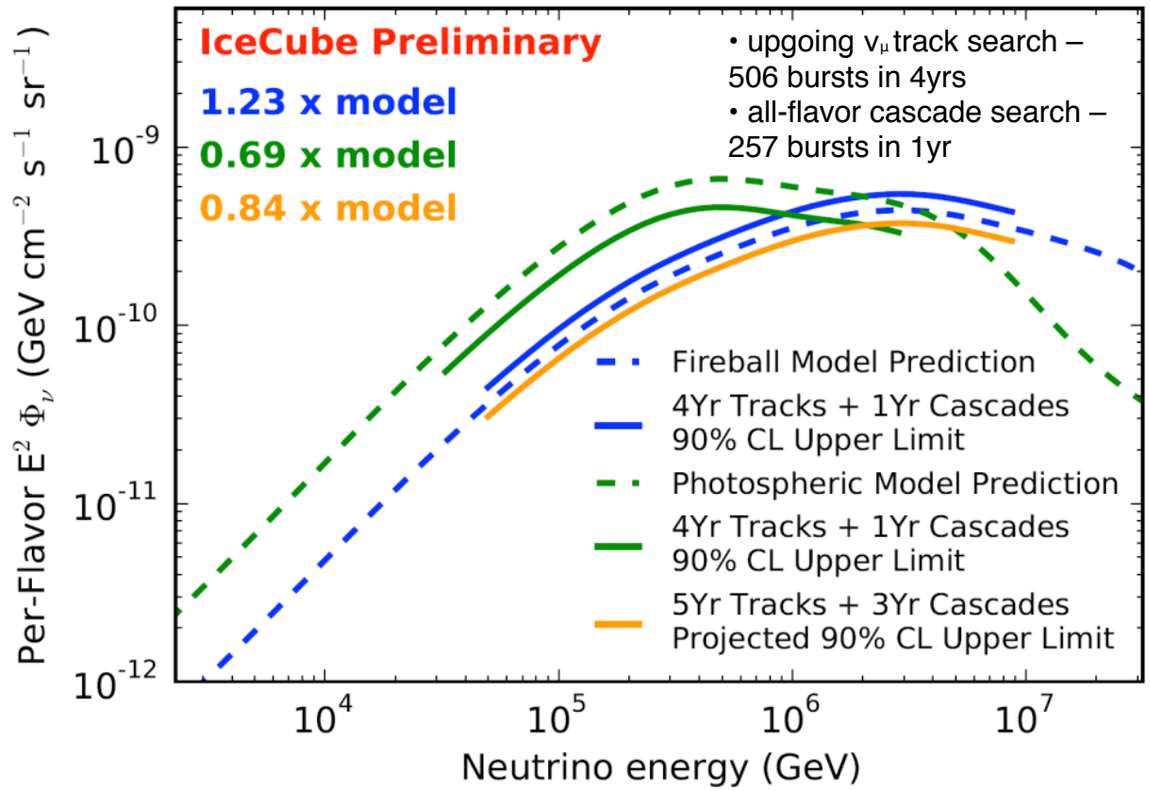
Multi-messenger Neutrino Astronomy and IceCube-170922A

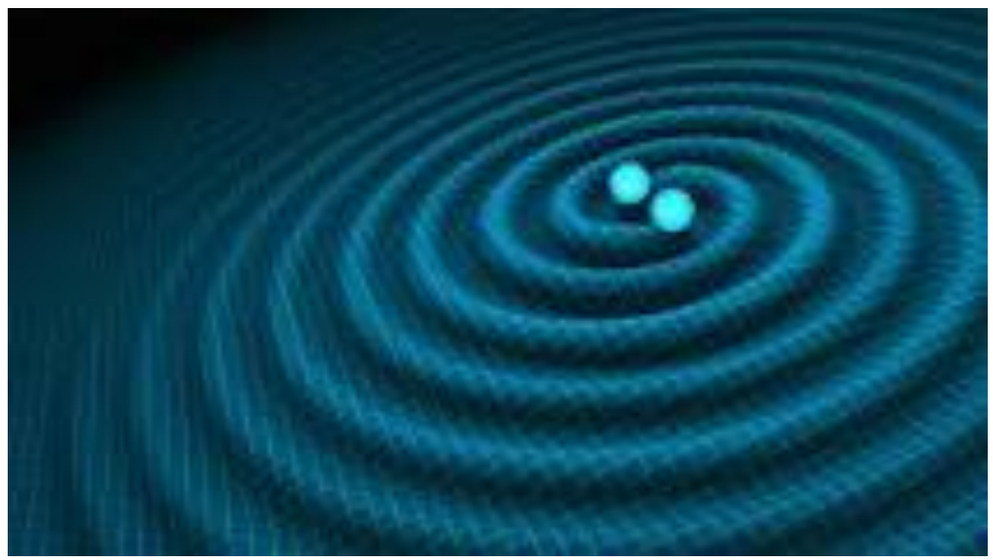
Transient Searches



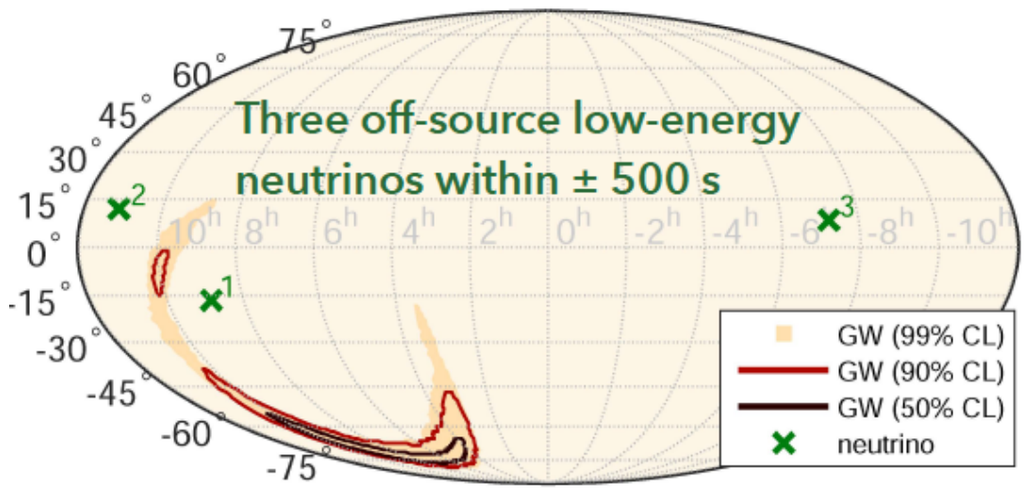
IceCube Collaboration - Nature Vol **484**, 351 (2012)

no coincidence found





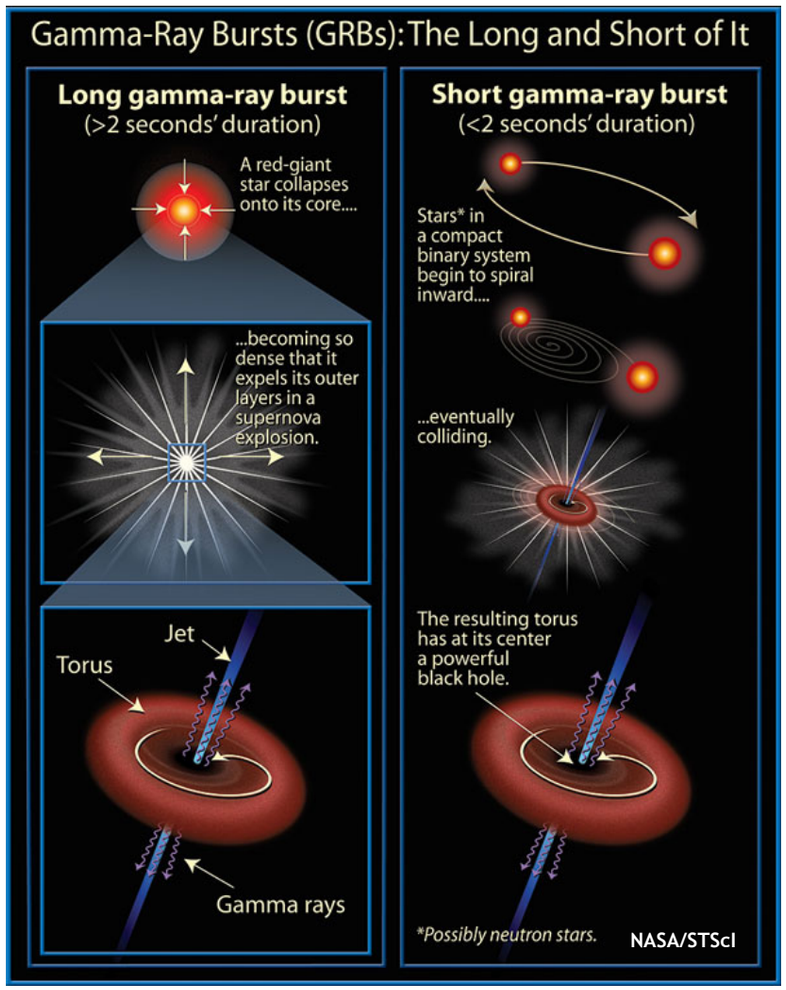
ANTARES Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, Virgo Collaboration [arXiv:1602.05411]

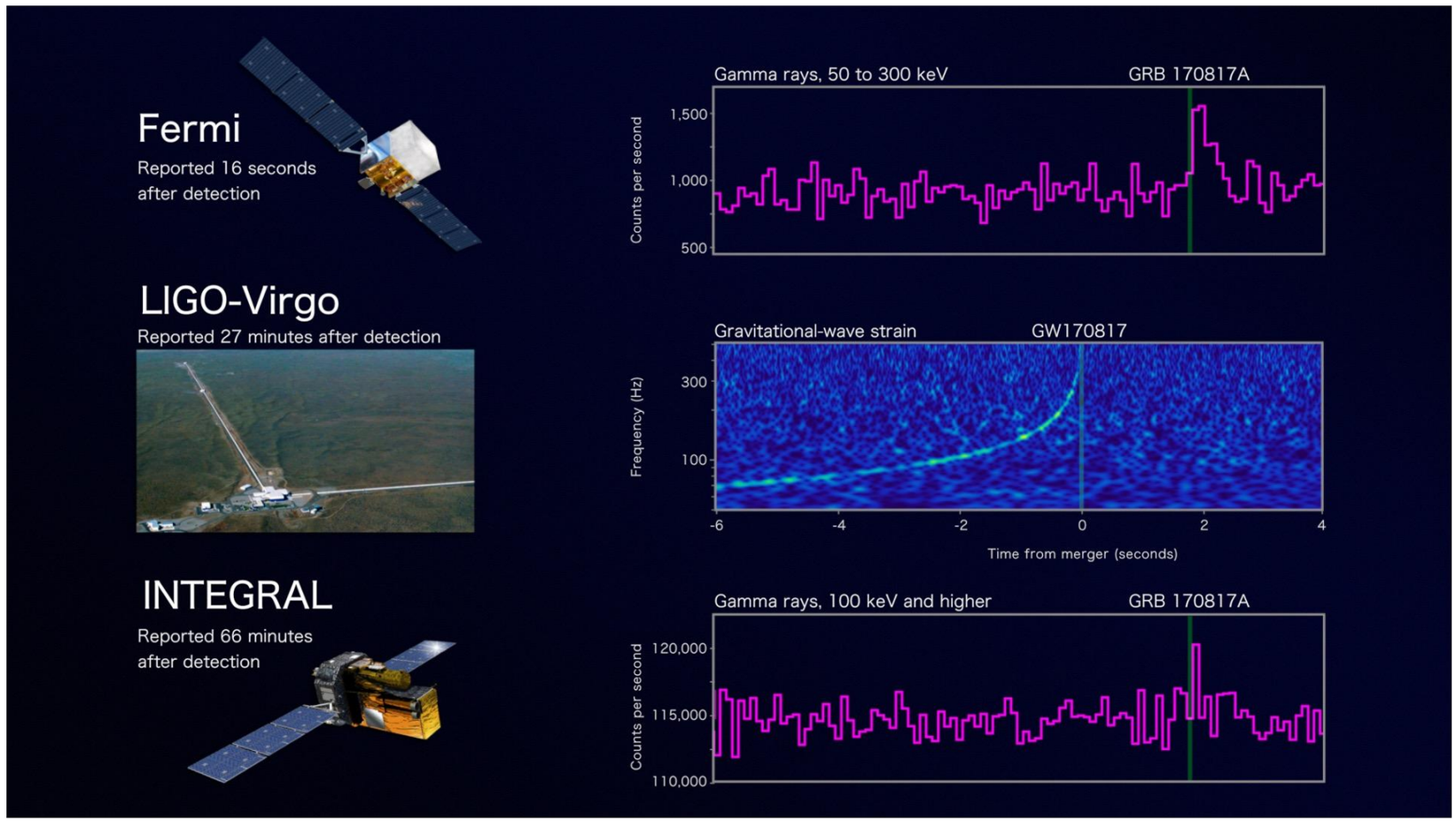


- Follow up on LIGO Gravitational Wave GW 150914
  - No neutrino association observed

We have a connection between gamma rays and gravitational waves…

GW170817/GRB170817A





LIGO/Virgo; Fermi; INTEGRAL; NASA/DOE; NSF; EGO; ESA.

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration, and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29

Abstract

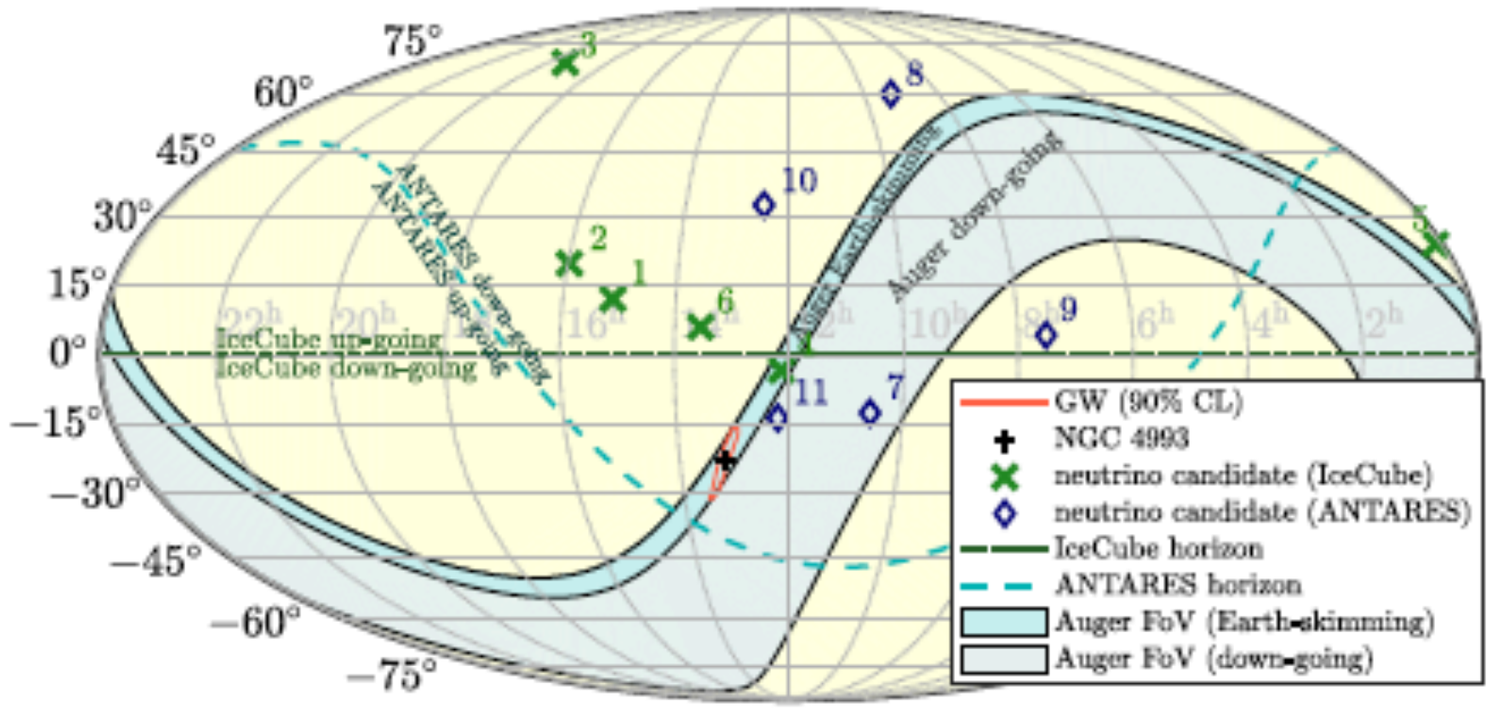
The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation mechanisms in relativistic outflows driven by the binary neutron star merger. The non-detection is consistent with model predictions of short GRBs observed at a large off-axis angle.

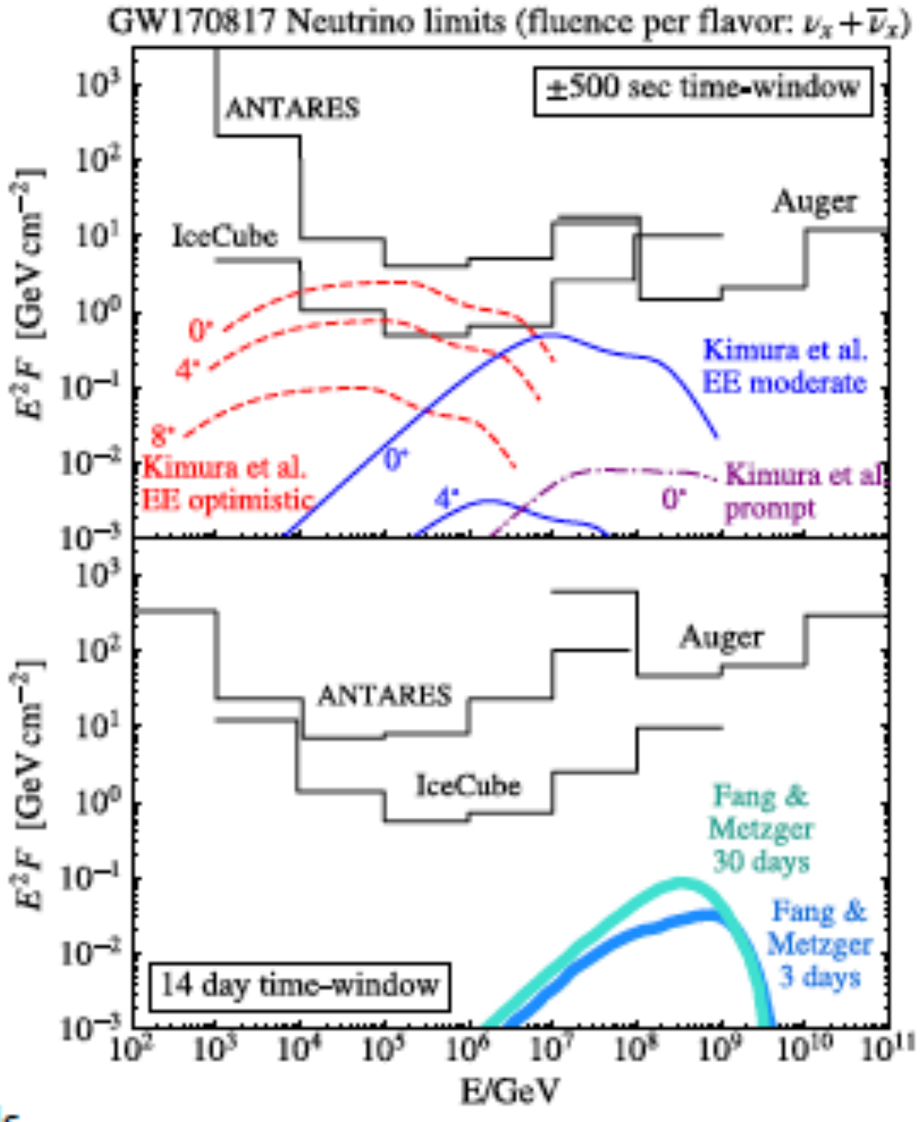
Gravitational Waves

GW170817

- binary neutron star inspiral
- followed by short GRB (observed by Fermi-GBM)

Imre Bartos Neutrino 2018

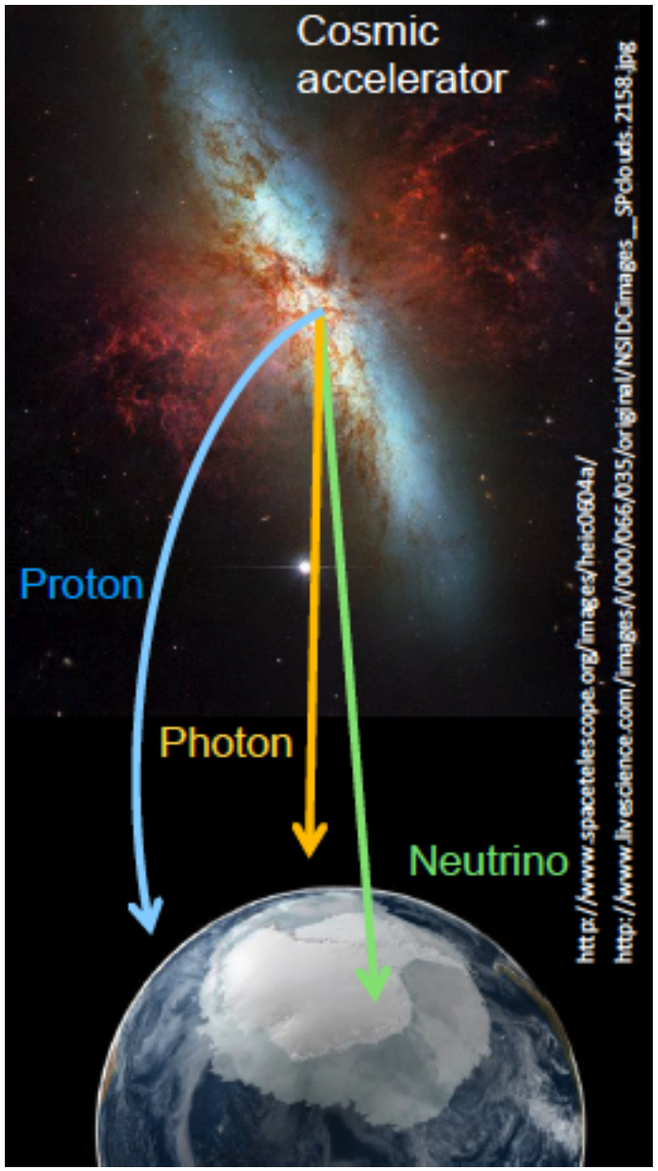


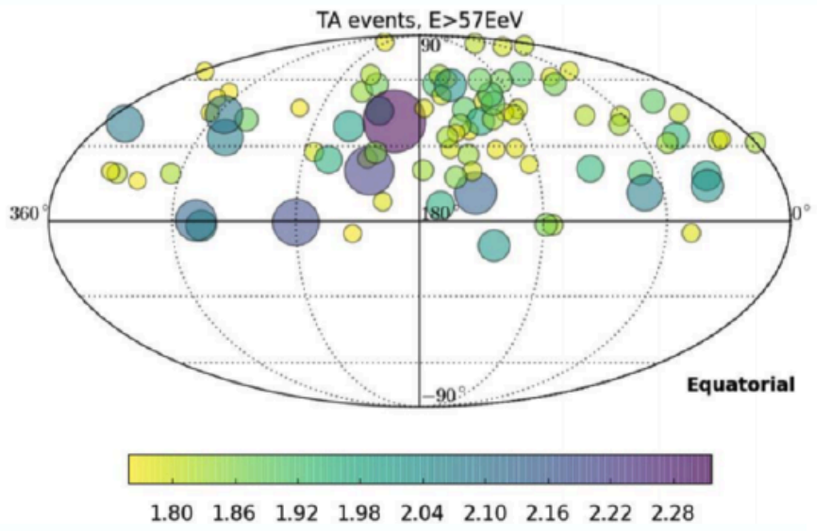


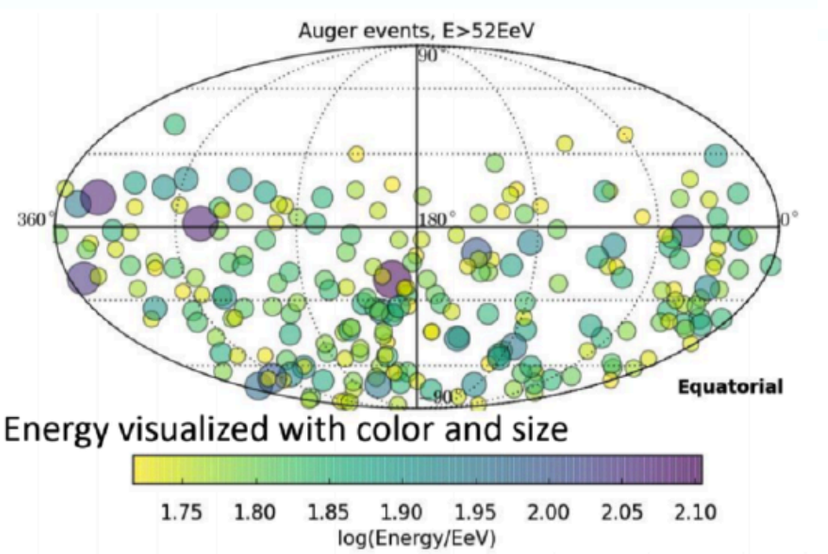
- Search within 1000 s and 2-week time windows (model motivated).
- Complementary sensitivity from the three detectors.
- No significant coincident detection.
- On-axis emission could have produced detectable emission in some models.

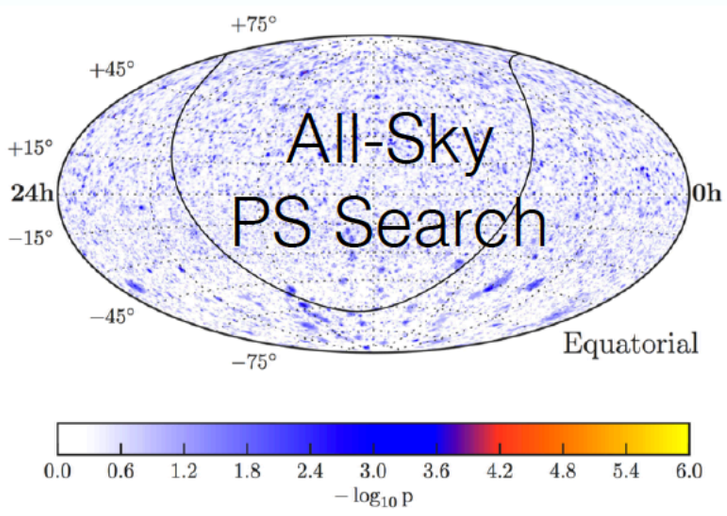
ANTARES, IceCube, Auger, LIGO, Virgo 2017

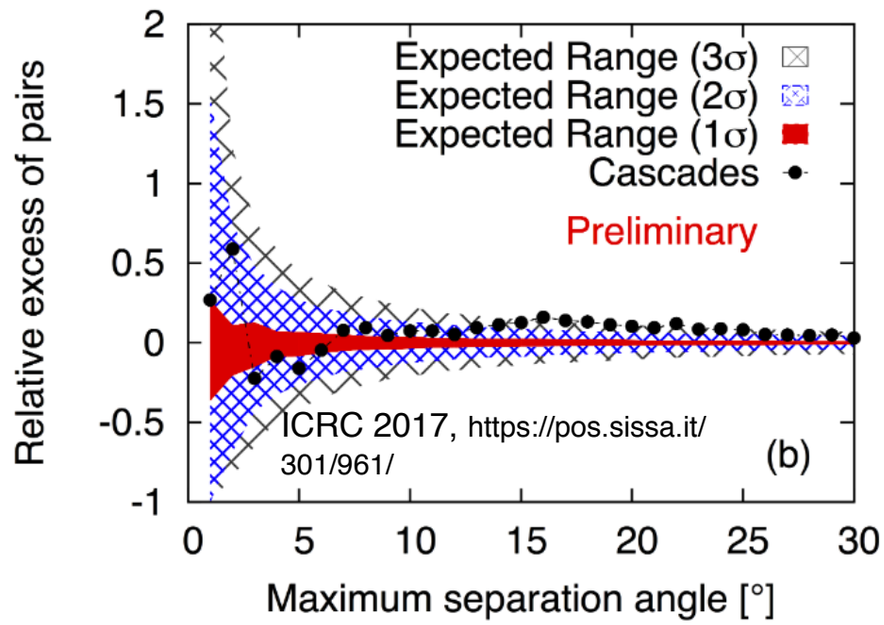
Cosmic-ray - Neutrino Correlations









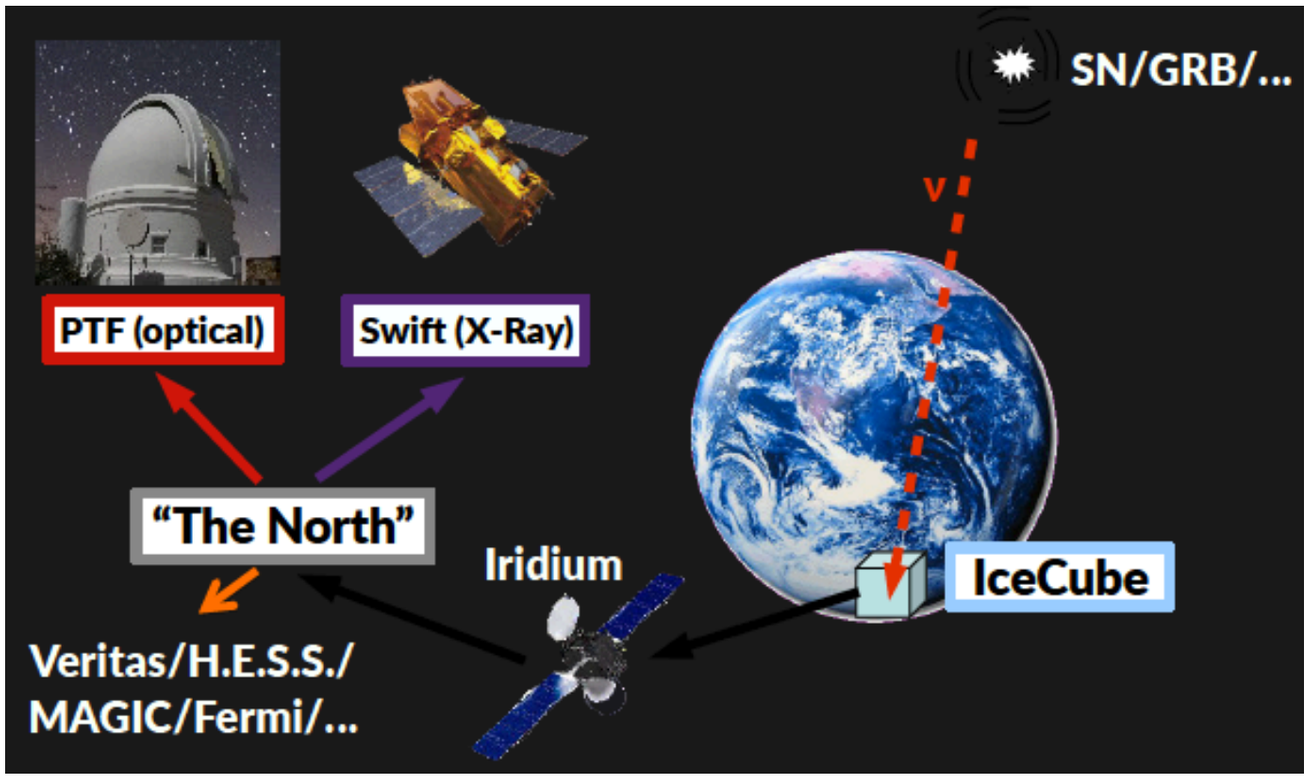


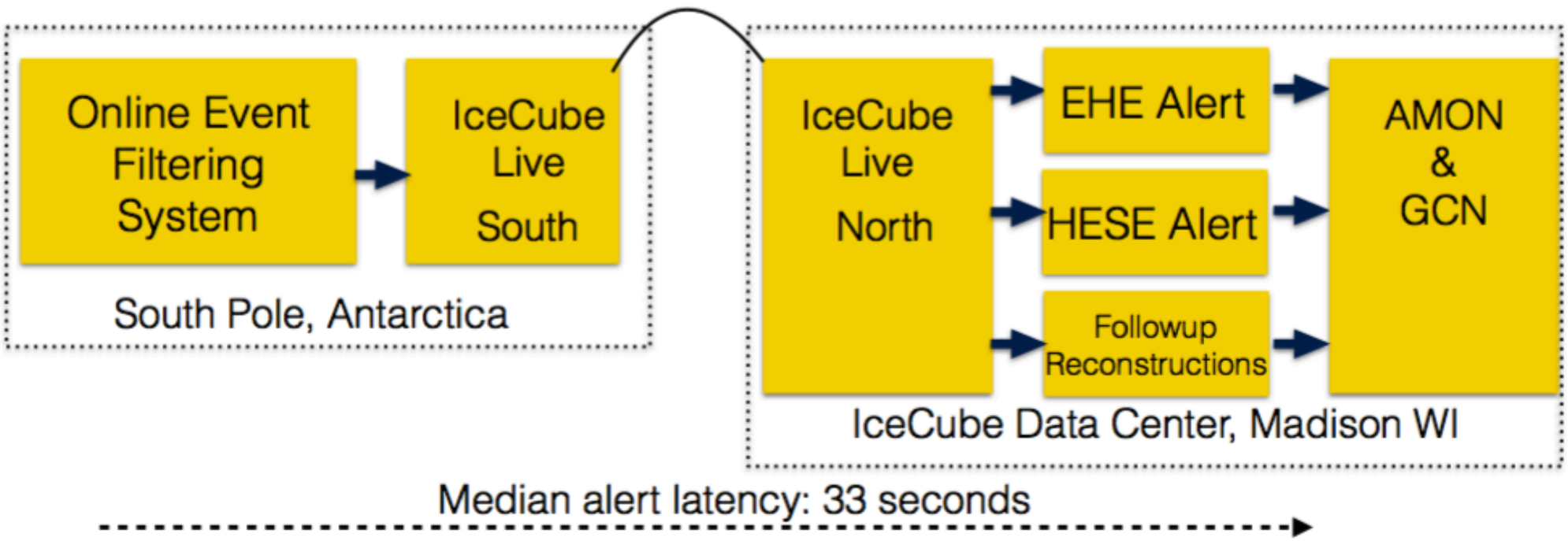
- No significant excess observed
- Interesting p-values seen in first analyses, but significance decreased (2015-2017)
- New more sensitive analyses coming up

Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056

- Real-time alerts. Since 04/2016, ≈6-8/yr
  - Improved selection summer 2018
    - Good angular resolution (0.5° - 2° 90% of events)
    - 50% astrophysical fraction





Astropart. Phys. 92 (2017) 30
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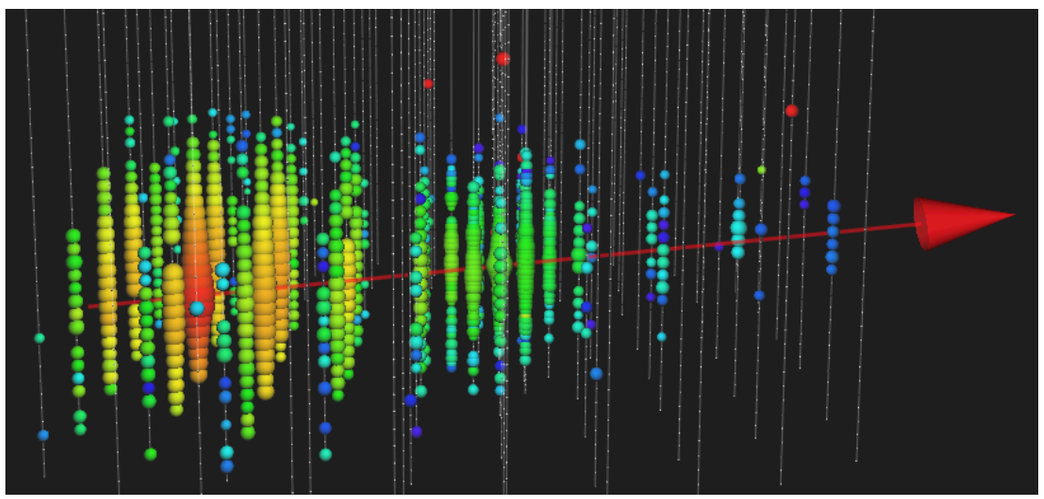
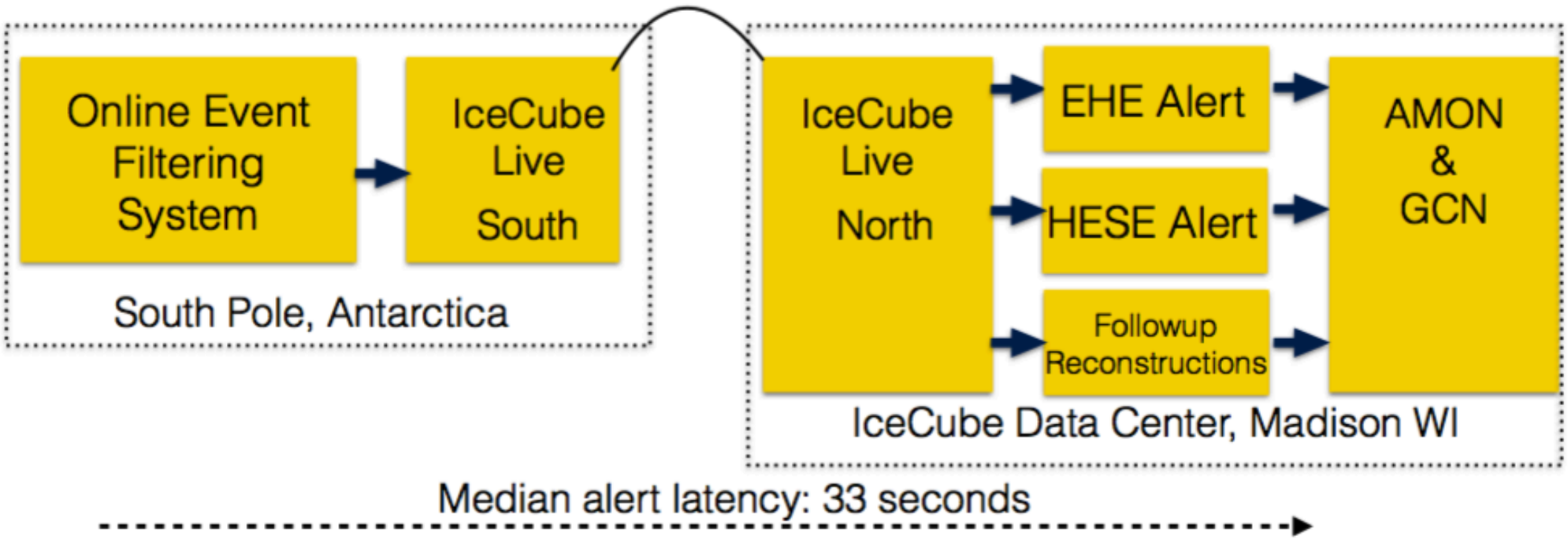


First public ν Alert: IceCube-160427



IC-170922A

Astropart. Phys. 92 (2017) 30

A&A 607 (2017) A115

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 I

On 22 Sep,
probability
Extremely
normal on

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

ATel #10791; Y
K

Crede

Subjects: Gamma

Referred to by A
10844, 10845, 10

Tweet Re

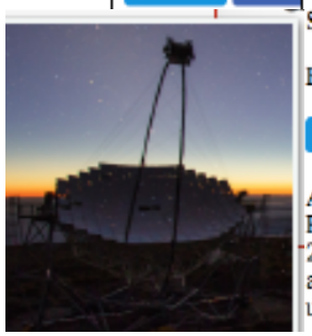
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

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

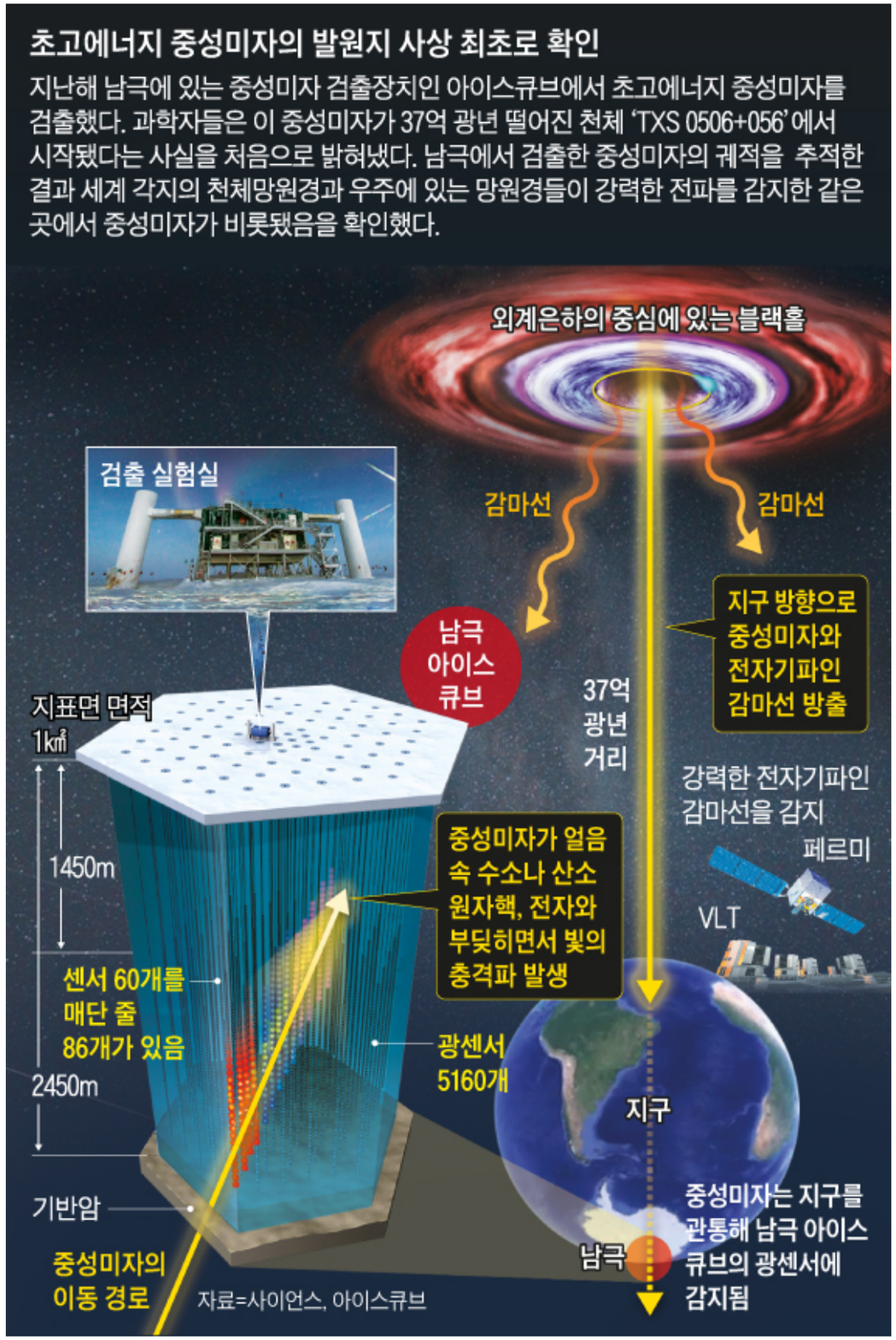
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

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 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 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 of

- 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



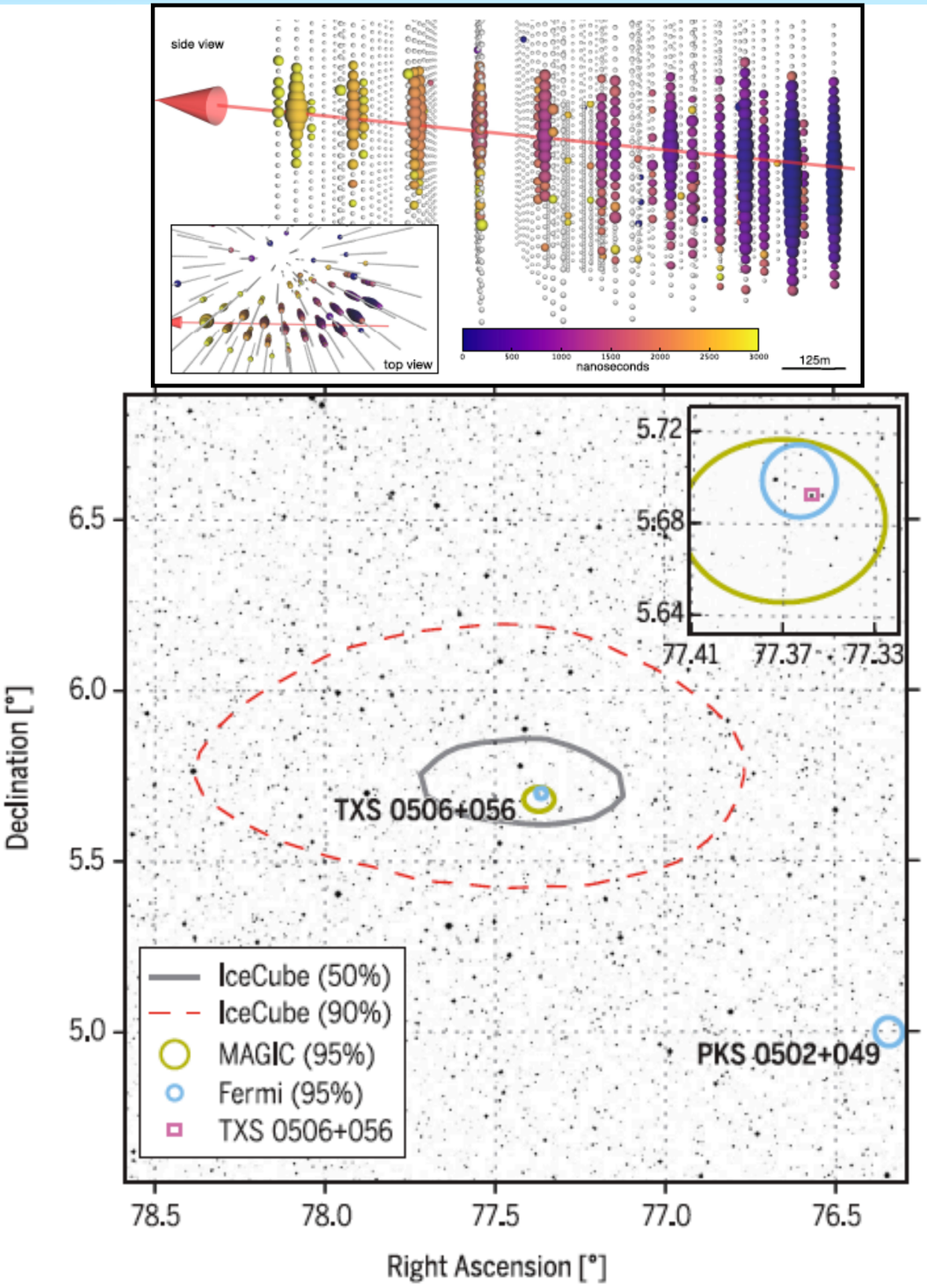
(Science 361, eaat1378 (2018)

IceCube-170922A

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

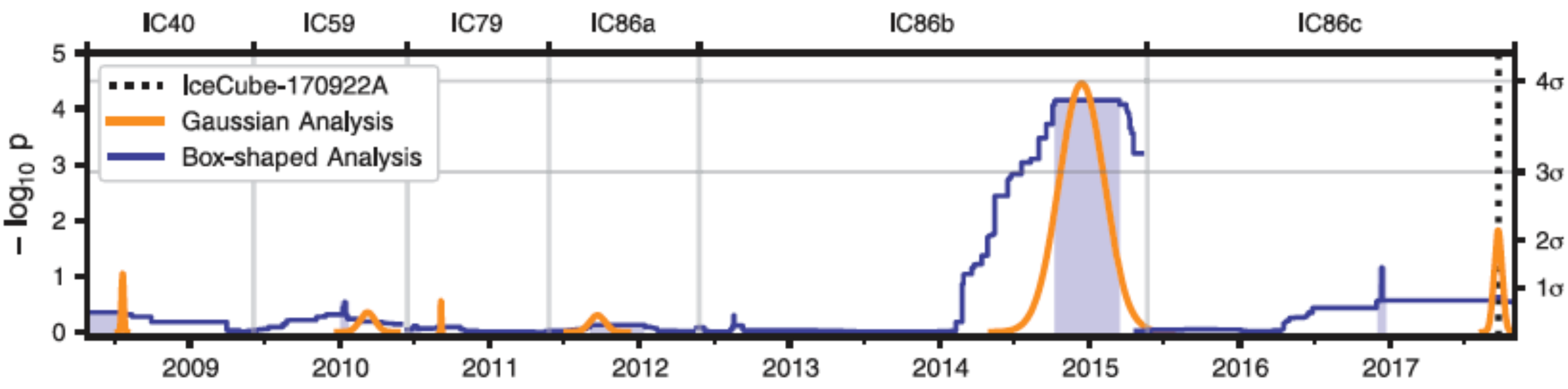
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- Chance probability of a Fermi-IceCube coincident observation: **~3σ** (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 1ES 1959+605

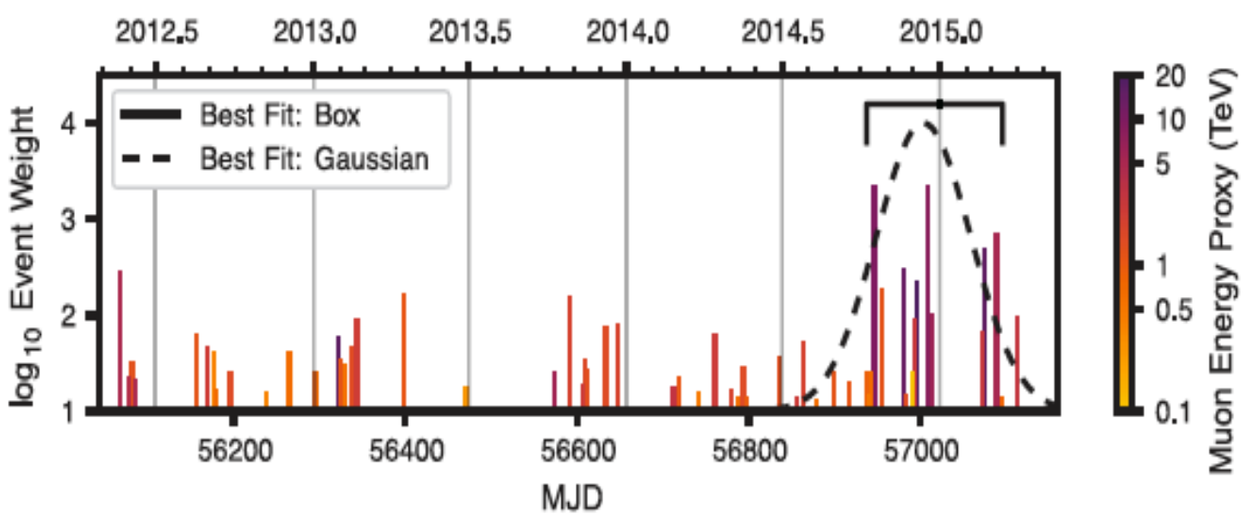


Science 361 (6398), 147-151.

IceCube-170922A

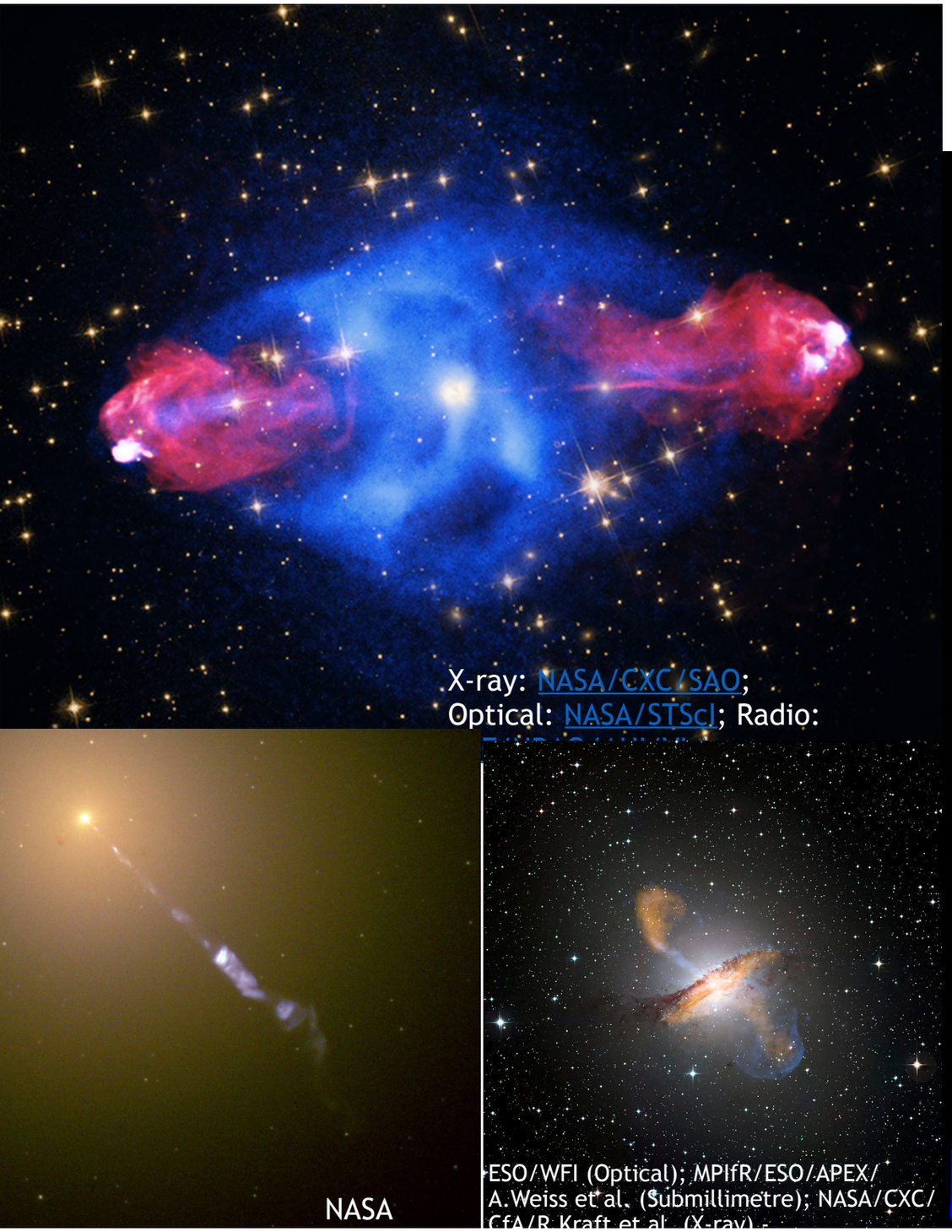


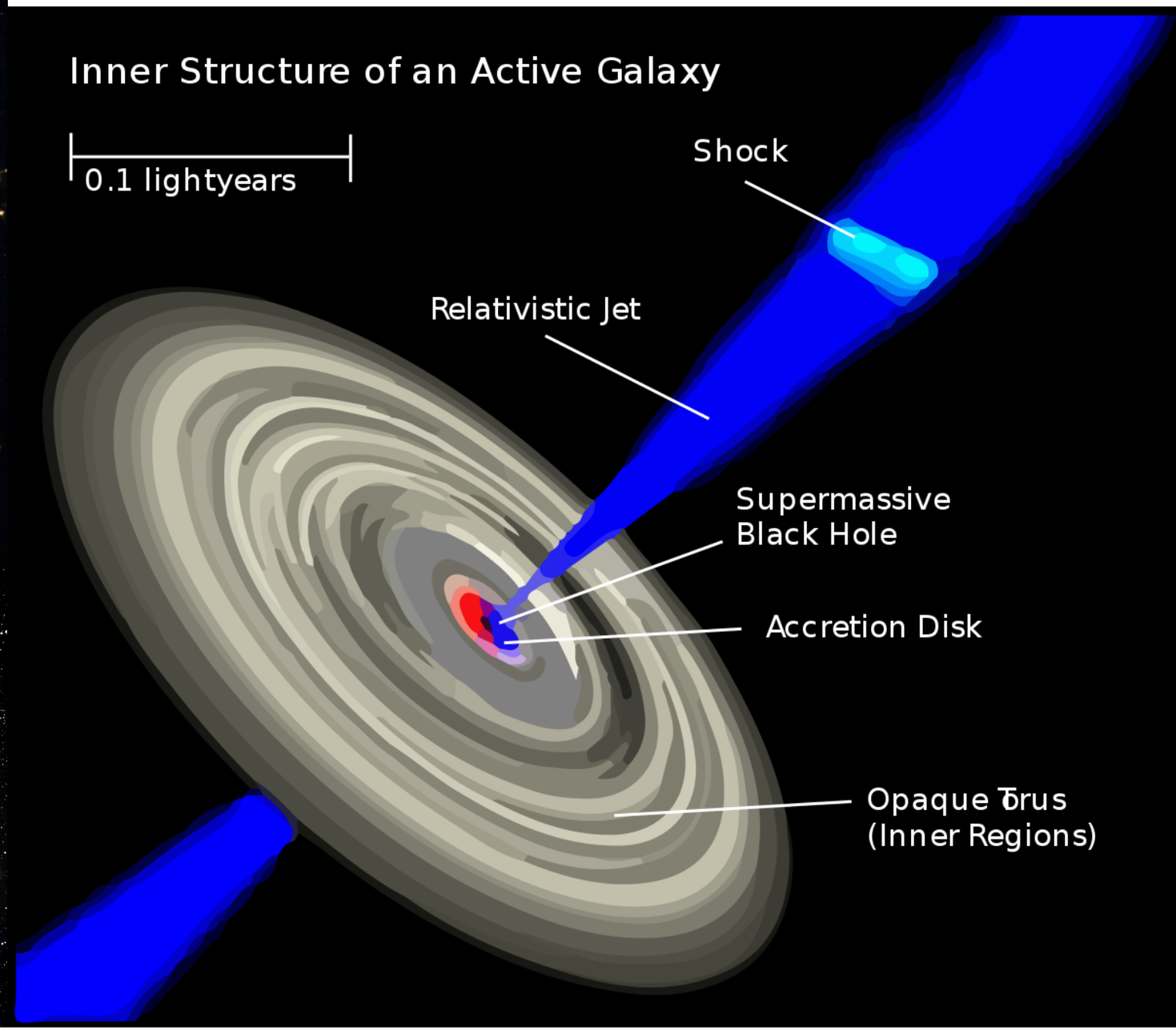
- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)



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

Active Galactic Nuclei: Cosmic Accelerators?





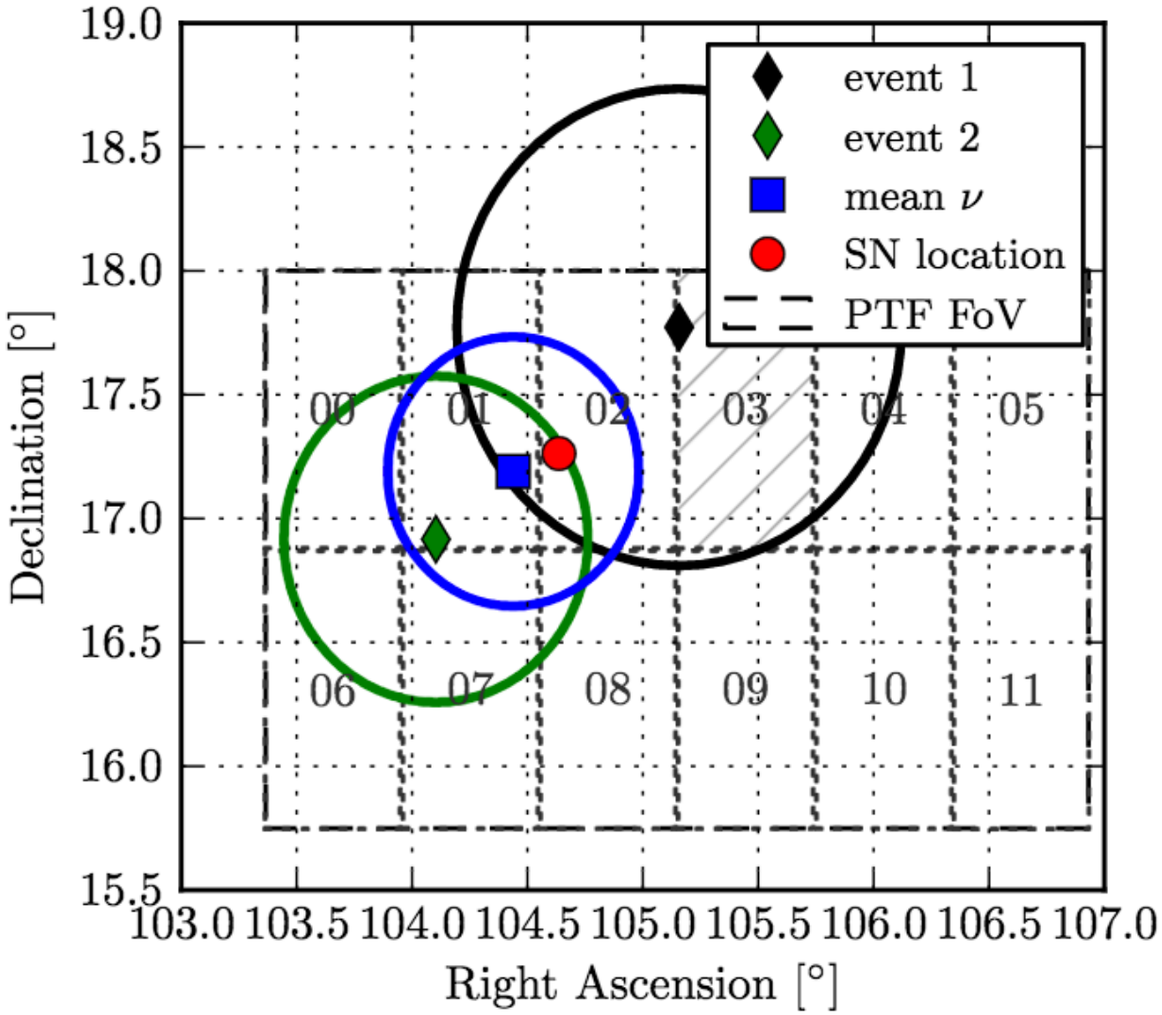
Distance scales …

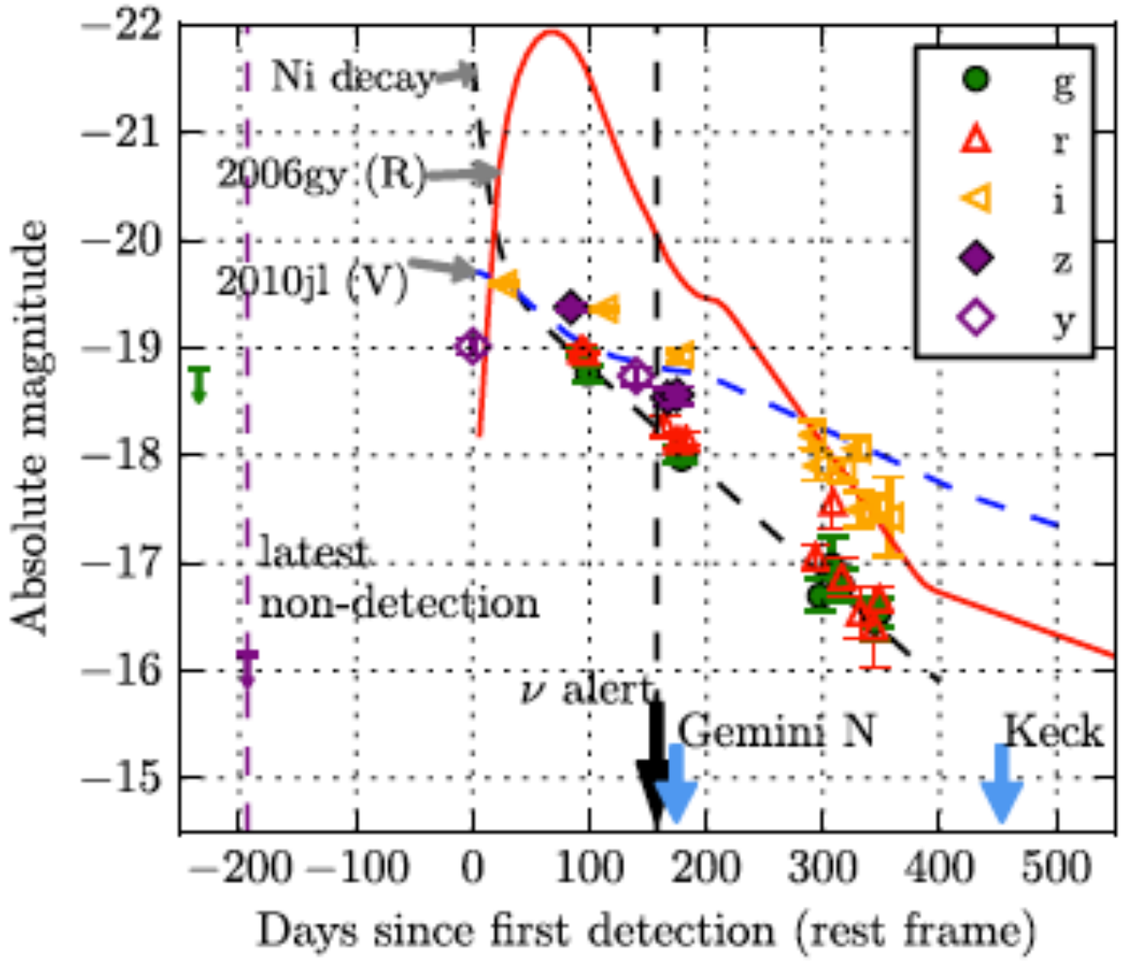
	Type	Distance (Source)	Events	MM
Diffuse	observation	~ Gpc	~10 / year (E>60TeV)	
IC170922A	observation	z~0.34 TXS 0506+056 (Blazar)	~1 (200TeV) +flare 13±5 (~TeV) + orphans	EM
Galactic plane	limit	~10kpc	100GeV - TeV (~hundreds)	gamma-ray - pion production
Optical follow up		z~0.02 (triplet) z~0.05 (doublet) z~1.1 (singlet)	background for triplet 1/15 year	optical follow up
Supernova Burst	sensitivity	~30 kpc		

Observation of Supernovae in Neutrino Follow-up

IceCube/PTF/Swift/Pan-STARRS Astrophys.J. 811 (2015) no.1, 52

Detection of a SN IIn in Optical Follow-up Observations of IceCube Neutrino Events





Optical Follow up resulted in the discovery of a Supernova Type IIn (z=0.0684)
PTF12csy 0.2° away from the neutrino alert direction.
Causal connection is unlikely, explosion at least 158 days before neutrino observation
A posteriori significance of the detection is 2.2σ

Neutrino Triplet

IceCube arXiv:1702.06131v1 (Astronomy & Astrophysics)

IceCube arXiv:1702.06131v1

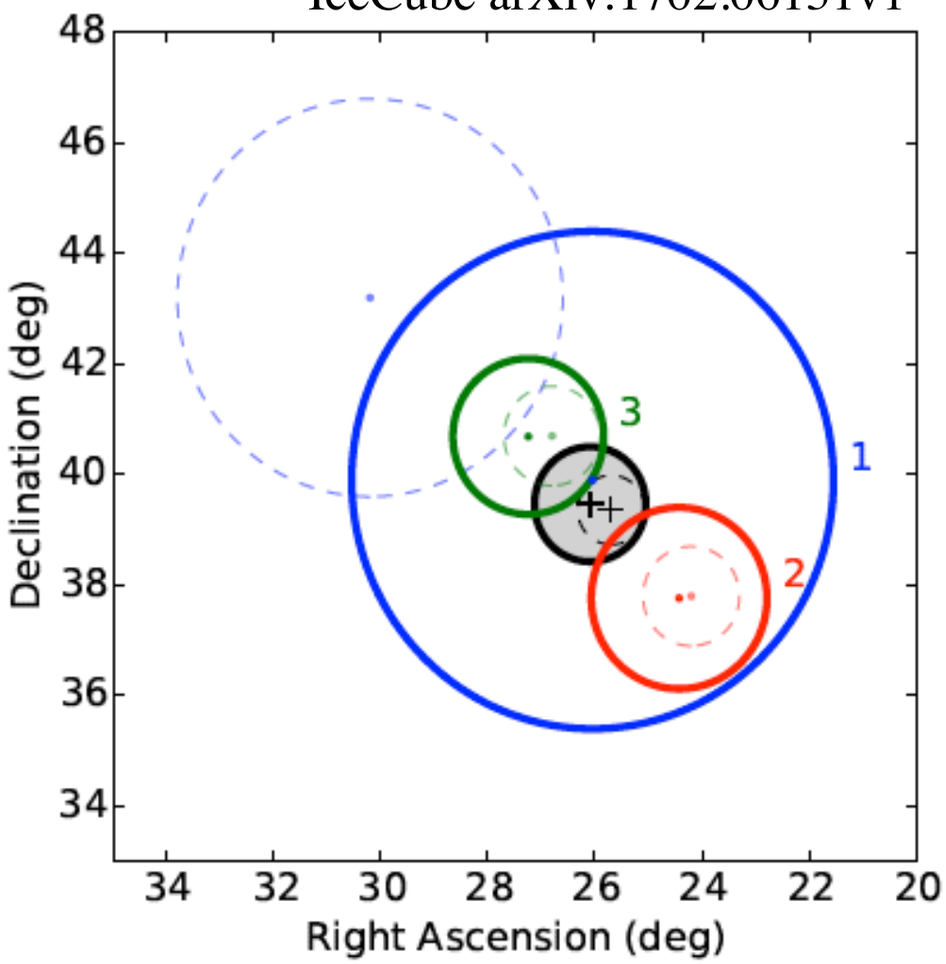


Fig. 1: Location of the three neutrino candidates in the triplet with their 50% error circles. The plus sign shows the combined direction and the shaded circle is the combined 50% error circle. The solid circles show the results of the MPE reconstruction which is as the default reconstruction in the following and the thin dashed circles correspond to the results of the Spline MPE reconstruction (compare Table 1).

IceCube arXiv:1702.06131v1

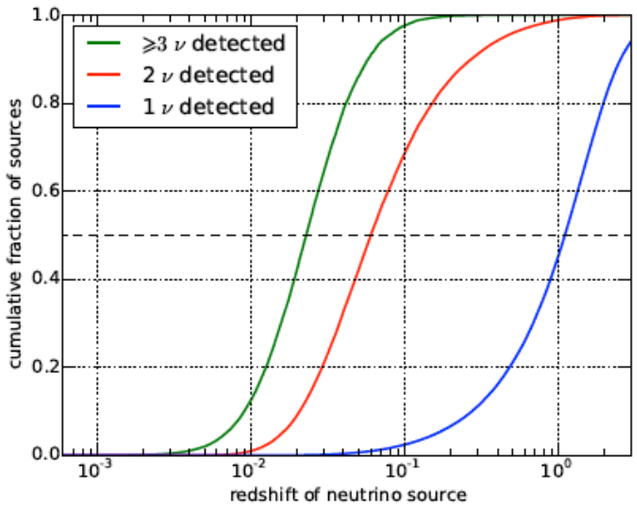
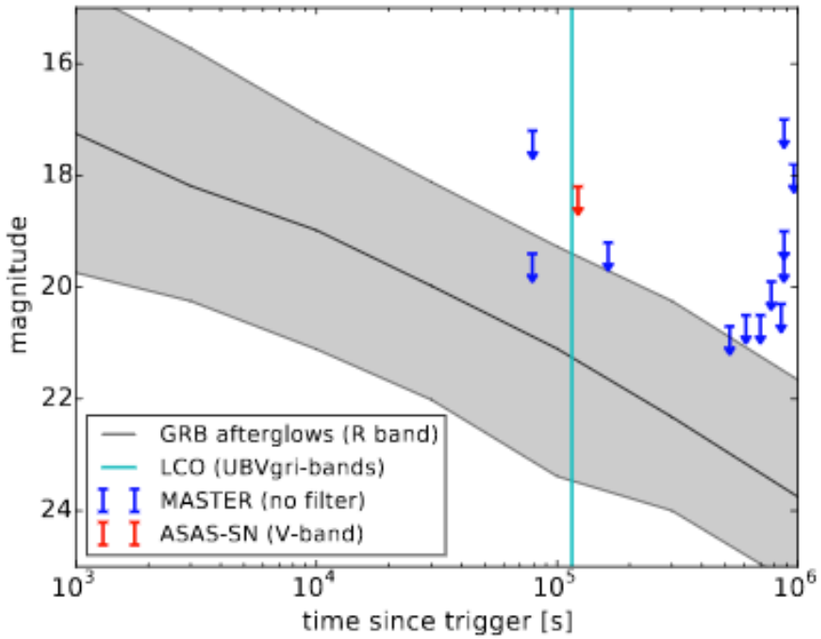


Fig. 8: Probability of detecting a neutrino source within a certain redshift. The figure was generated by simulating a population of transient neutrino sources with a density of $4\times10^{-6}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ distributed in redshift according to the star-formation rate and normalized to produce the detected astrophysical neutrino flux. Sources detected with only one single neutrino are on average far away (median redshift of 1.1), while sources detected with three or more neutrinos must be located nearby.



(b) Optical GRB light curves.

Time since trigger ~22h

Observation of a neutrino triplet event, optical follow up was triggered, no likely counterparts observed.
(Random neutrino triplet events occur every 13.6yrs)

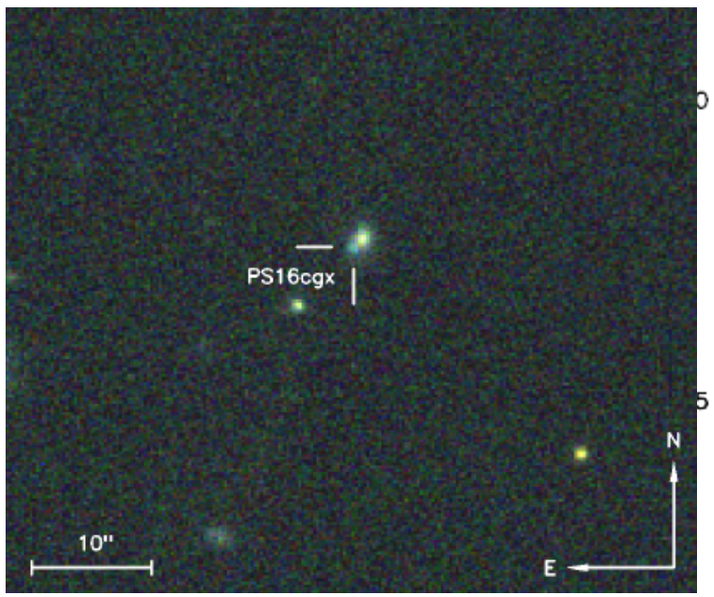
Search for transient optical counterparts to high-energy IceCube neutrinos with Pan-STARRS1

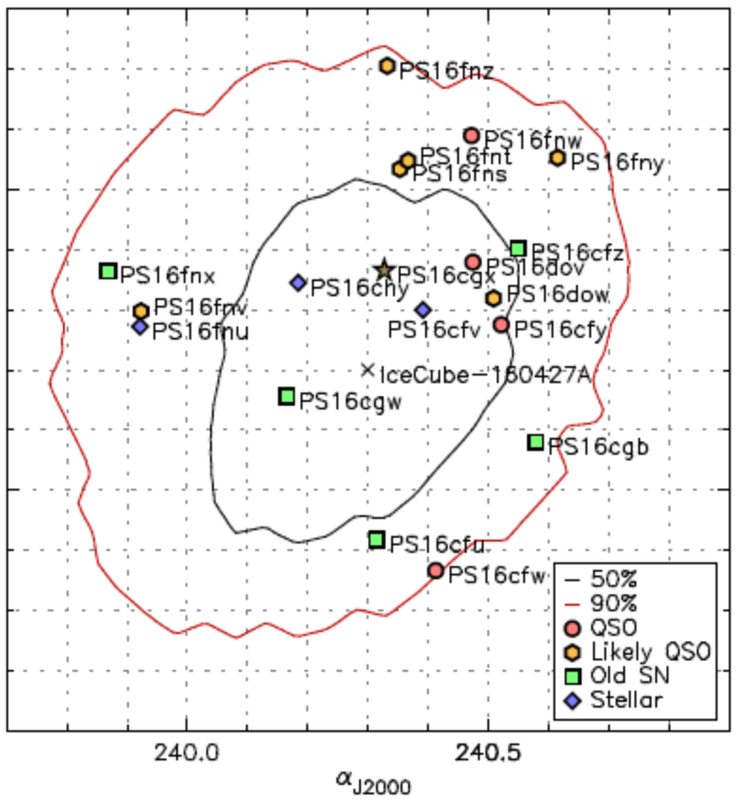
Neutrino event	Epoch (MJD)	Energy alert type	α_{J2000} (°)	δ_{J2000} (°)	90% error (°)	Pan-STARRS1 observations Start	End	$m_{\mathrm{depth},i_{P1}}$ (mag)	Number of transients
IceCube-160427A	57505.24481	HESE	240.3	9.7	0.45–0.54	57508.50	57550.46	22.5	19
IceCube-160731A	57600.07990	HESE+EHE	214.5	-0.3	0.75	57600.32	57626.28	22	11
IceCube-160806A	57606.51496	EHE	122.8	-0.8	0.5	Not visible	-	-	-
IceCube-160814A	57614.90688	HESE	200.3	-32.4	1.2–3.0	Not visible	-	-	-
IceCube-161103A	57695.38022	HESE	40.8	12.6	0.65–1.1	57695.47	57702.36	22	7
IceCube-161210A	57732.83797	EHE	46.6	15.0	0.4–1.1	Not observed	-	-	-
IceCube-170312A	57824.57615	HESE	305.2	-26.6	0.5	Not observed	-	-	-
IceCube-170321A	57833.31413	EHE	98.3	-15.0	1.2	57834.27	57859.27	22	2
IceCube-170506A	57879.52565	HESE	221.8	-26.0	2.0–3.0	Not observed	-	-	-
IceCube-170922A	58018.87118	EHE	77.4	5.7	0.3–0.95	Not observed	-	-	-
IceCube-171015A	58041.06562	HESE	162.9	-15.4	1.6–2.6	Not visible	-	-	-
IceCube-171028A	58054.35295	HESE	67.5	-69.8	>7–28	Not observed	-	-	-
IceCube-171106A	58063.77754	EHE	340.0	7.4	0.25–0.7	58065.34	58075.34	22.5	2

[a] https://icecube.wisc.edu/science/data/TXS0506_alerts

High-energy neutrino production in **Type Ic SNe** has been postulated to be possible, as a result of diffusive shock acceleration of protons in relativistic jets powered by a central engine

PS16cgx - spectroscopic follow up indicates it is Type Ia

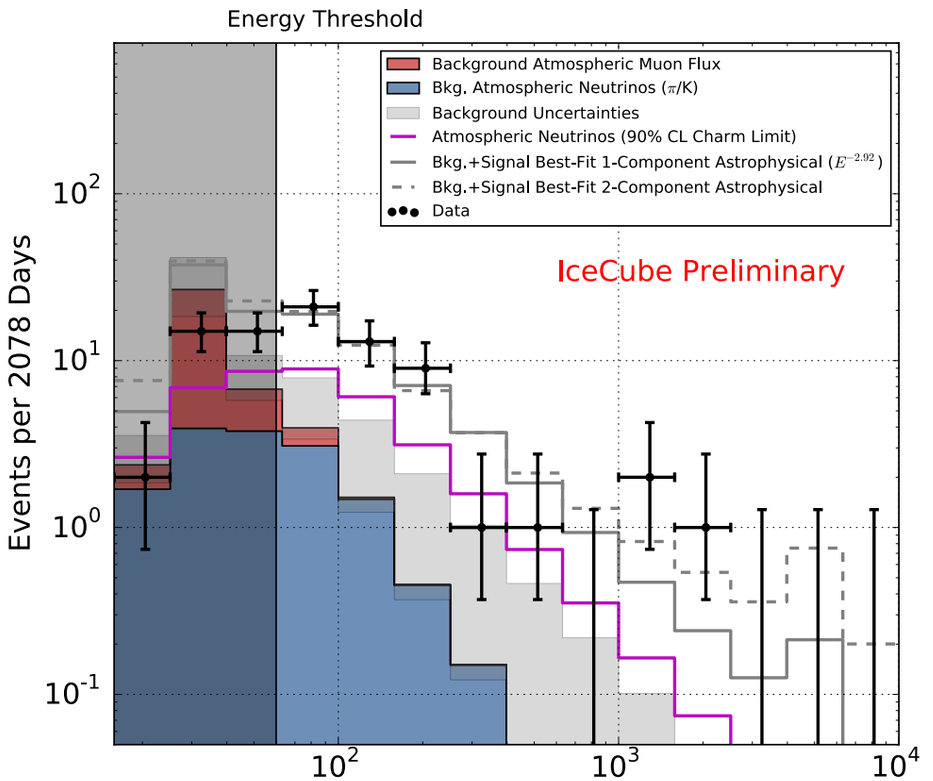




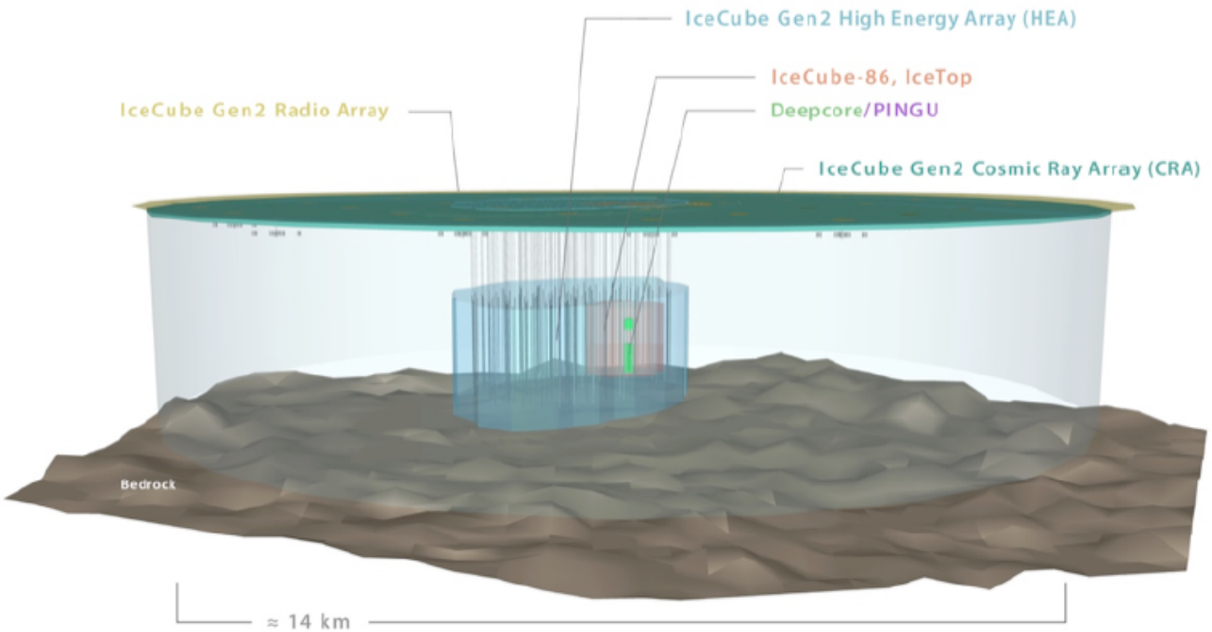
Future Plans

Next generation

- 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
  - So far non of the analyses has shown any evidence for point sources
- Where are the point sources?
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- New physics or something unexpected ?
- …



IceCube Gen2 Facility



Next generation

IceCube DOM

35 cm

mDOM

36 cm

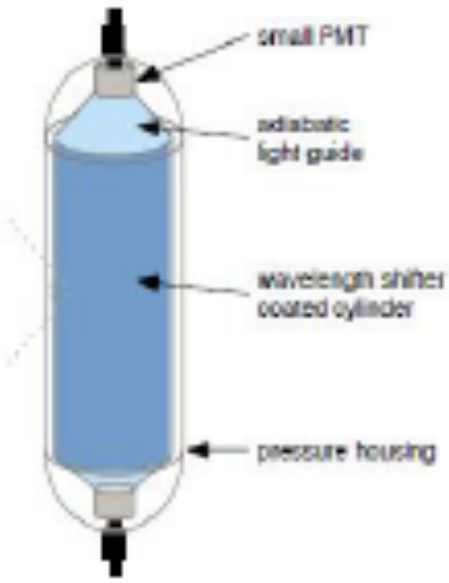
- Directional information
- More sensitive area per module

D-Egg

30 cm

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

WOM

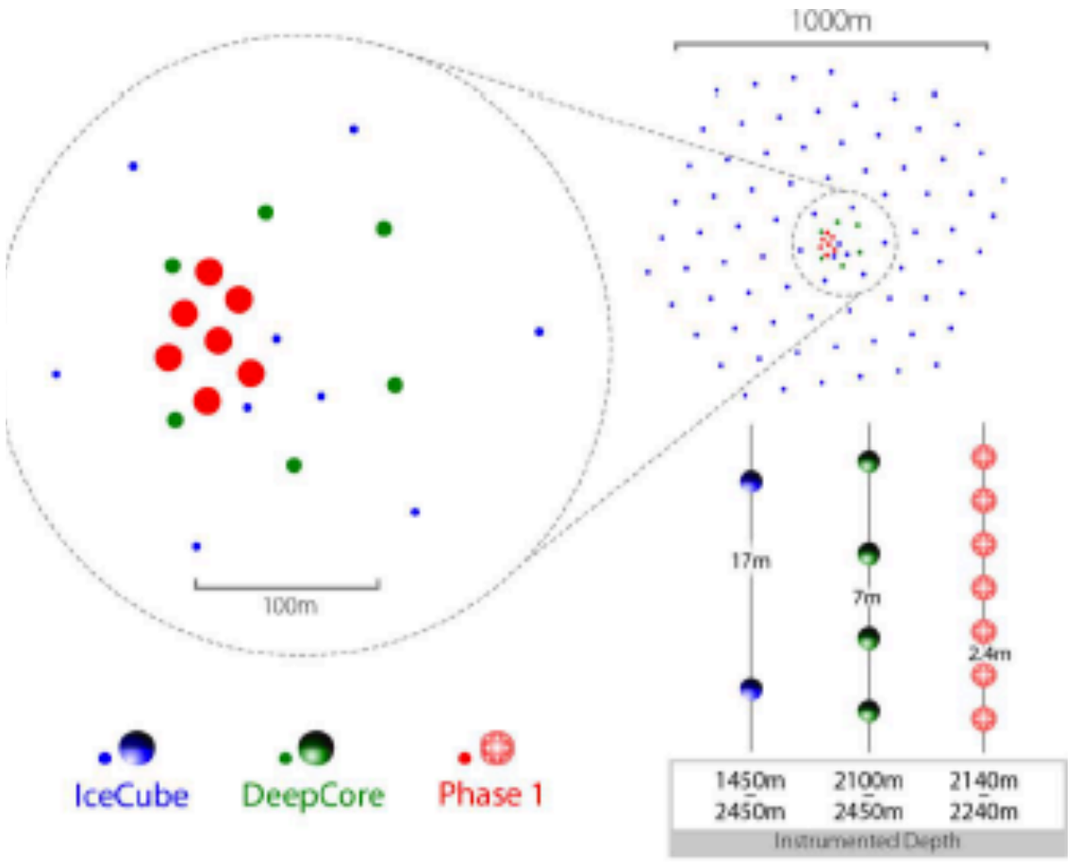


11 cm

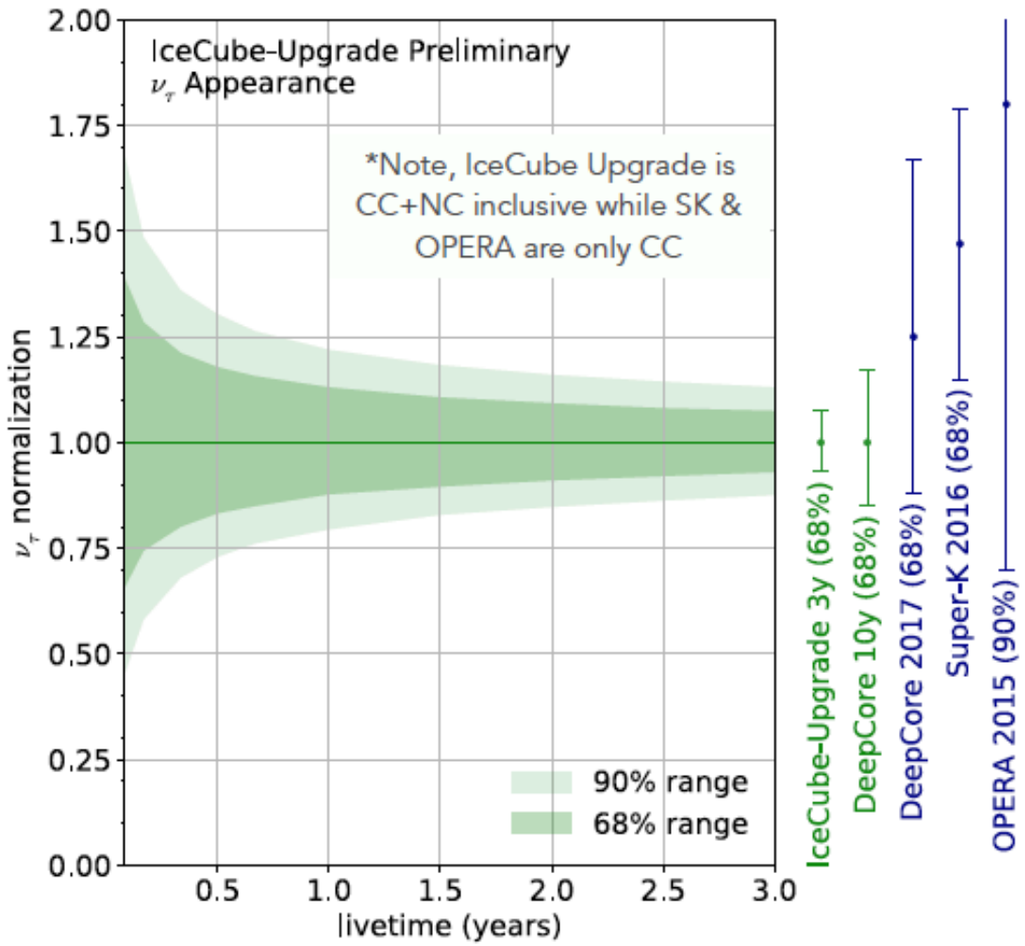
- more sensitive area per $
- Small diameter
- Lower noise rate

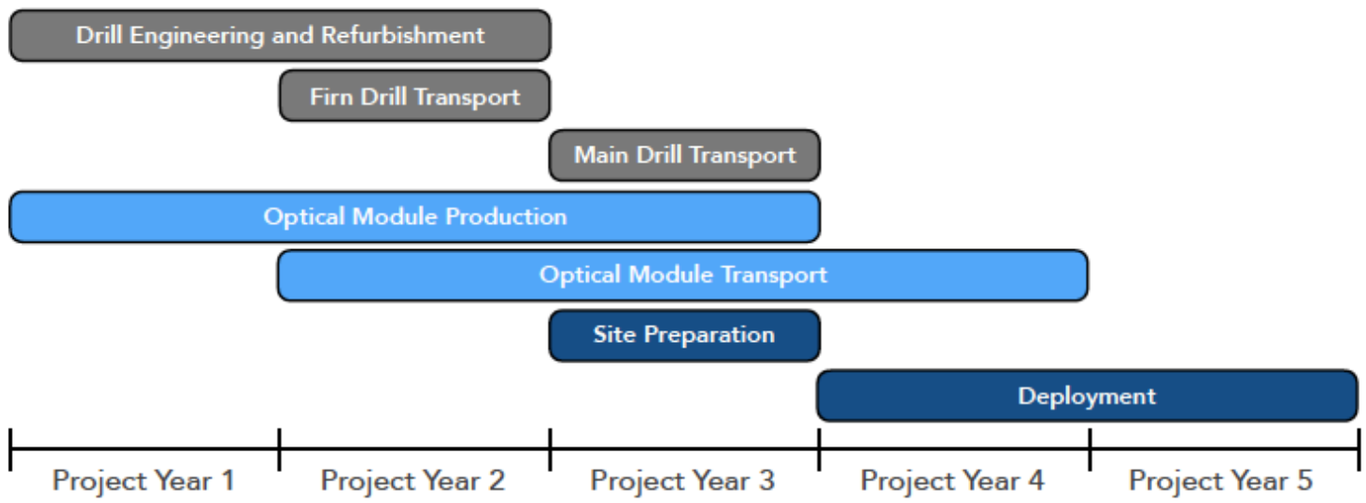
see also:
- PINGU LOI arXiv:1412.5106

The IceCube Upgrade



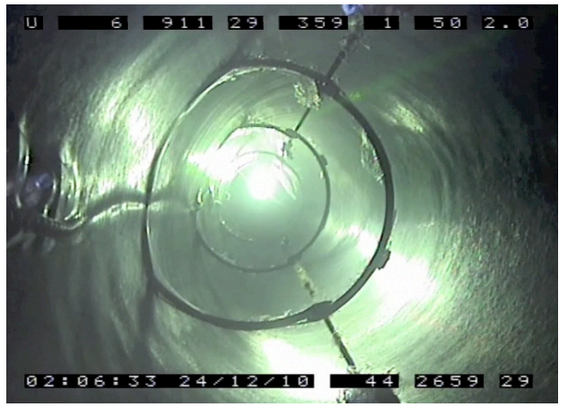
Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125



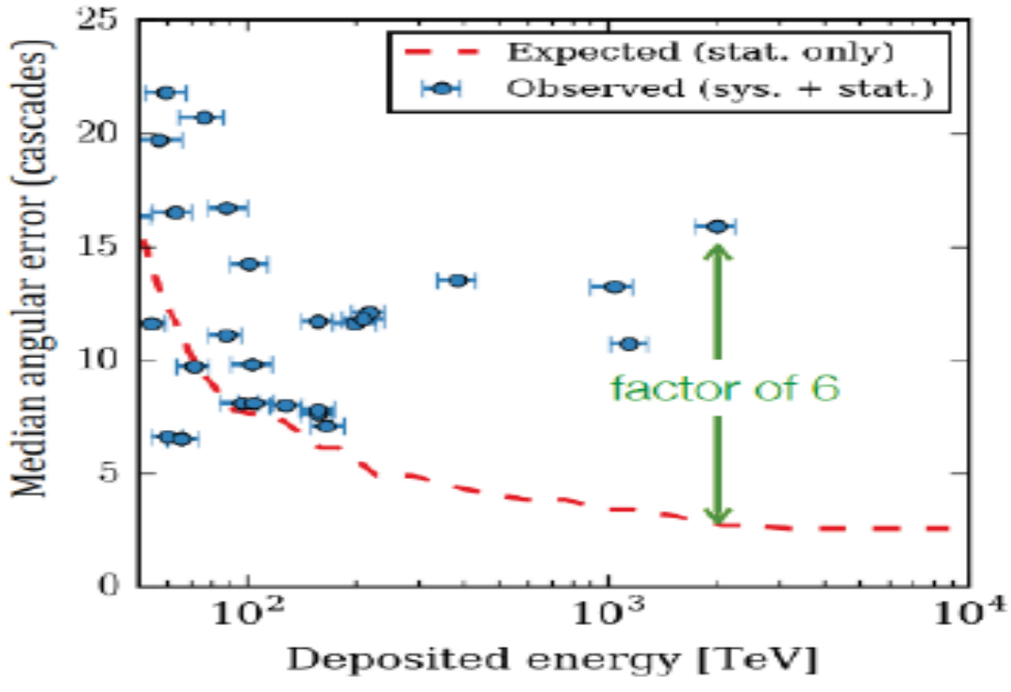


First step to restart South Pole activities
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies

Sungkyunkwan Ice Camera System



Special device Swedish Camera



- 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

Camera system key to comprehensive understanding of the detector medium

—> Retroactively analyze more than 10 years of IceCube data with substantially improved angular and energy resolution

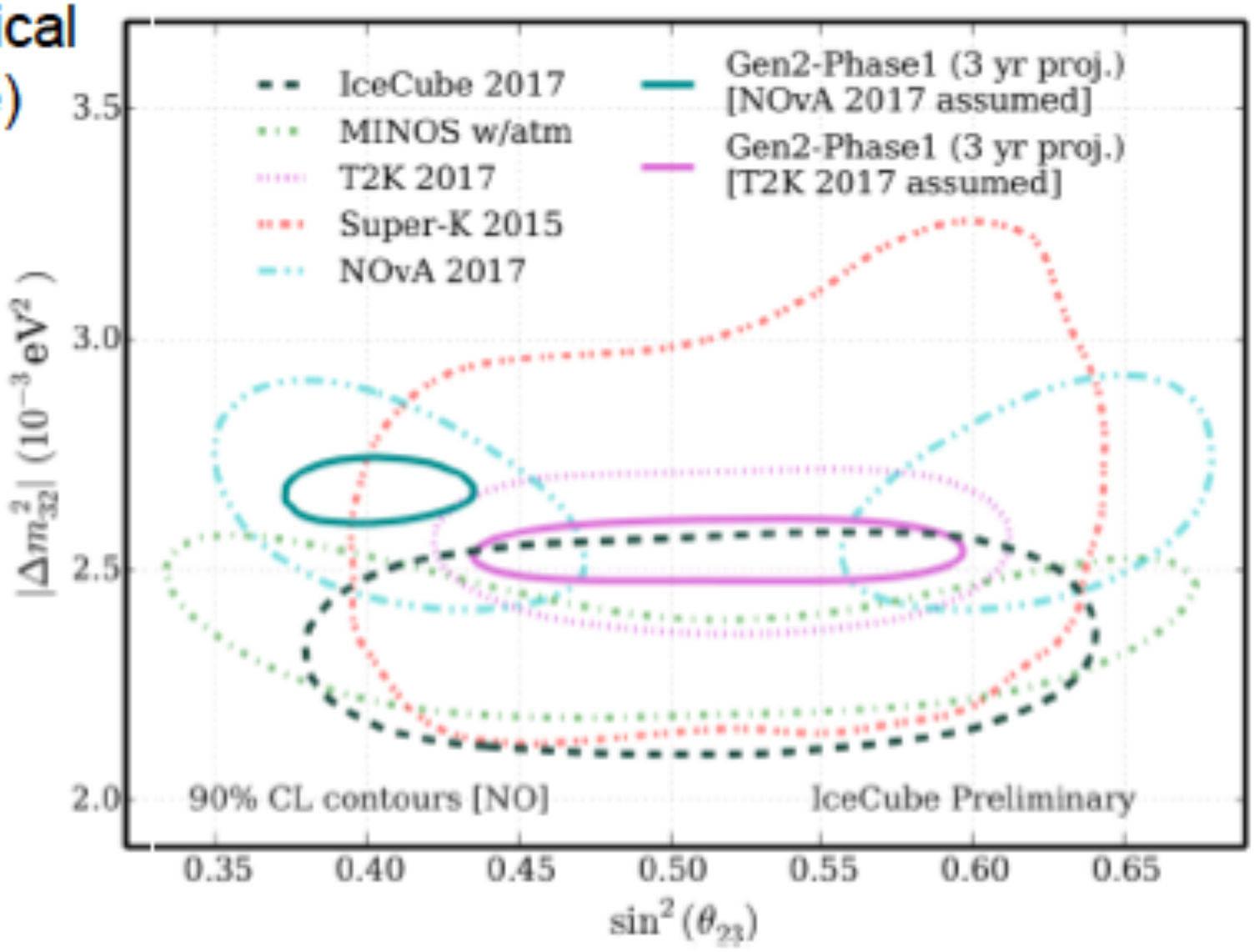
- High-energy astrophysical neutrinos have opened up a new window to the Universe
  - What's the origin of the high-energy neutrino
- Very strong bounds on dark matter scattering with nucleons
- Very diverse science program, IceCube turns out to be a treasure throve
- Neutrino astronomy is a central 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

Image:Stephan Richter, IceCube/NSF

Thanks

The IceCube Upgrade

- Target $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Detect ν_τ events on a statistical basis (up-going, shower-like)
- Case study for IceCube Upgrade:
  - ~2500 ν_τ events / year
  - Drastically improve measurement of atmospheric mixing parameters
  - Chance to determine octant of θ_{23}
- Also possible with ORCA

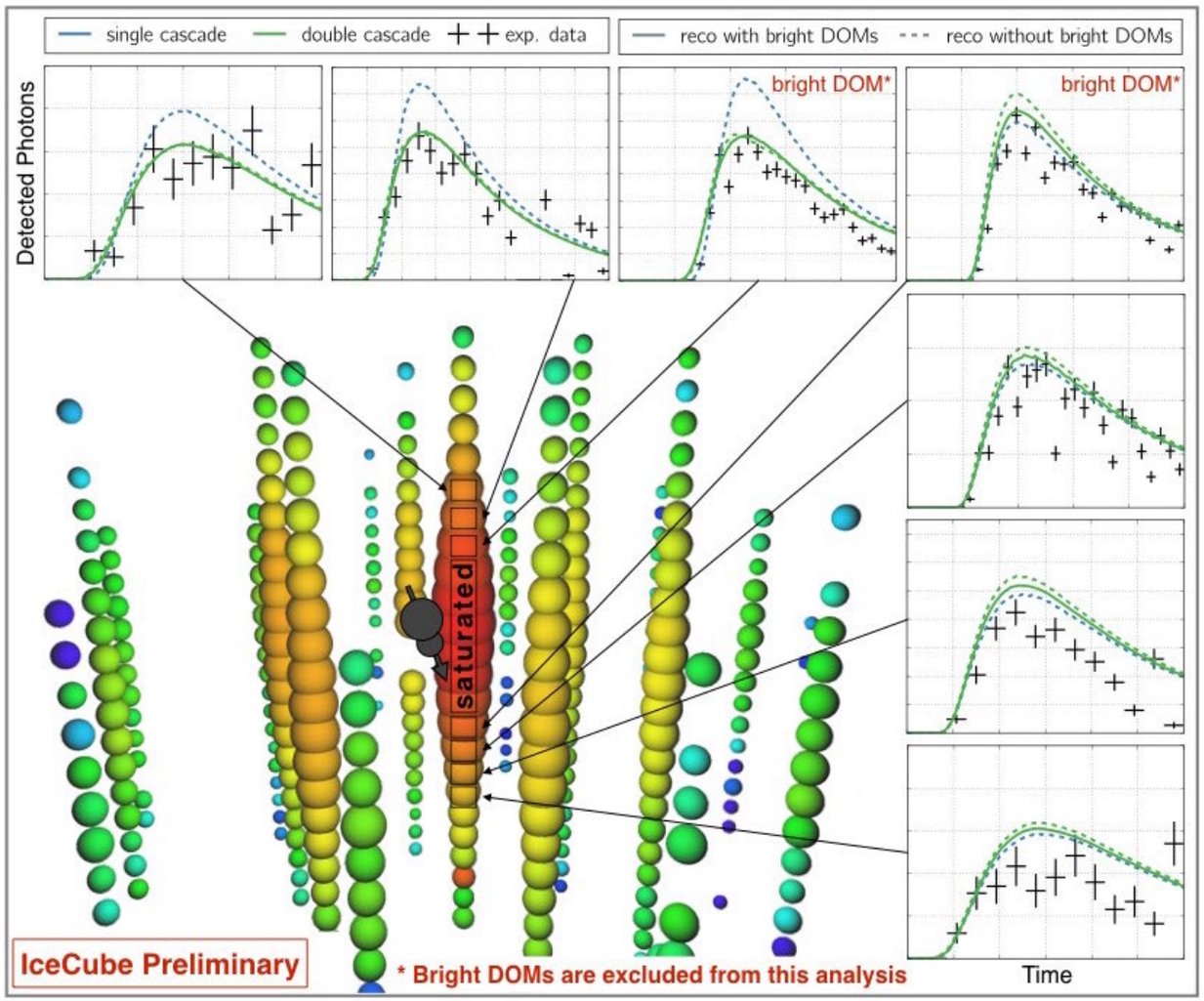


IceCube extremely competitive for neutrino oscillation parameter measurements using atmospheric neutrinos

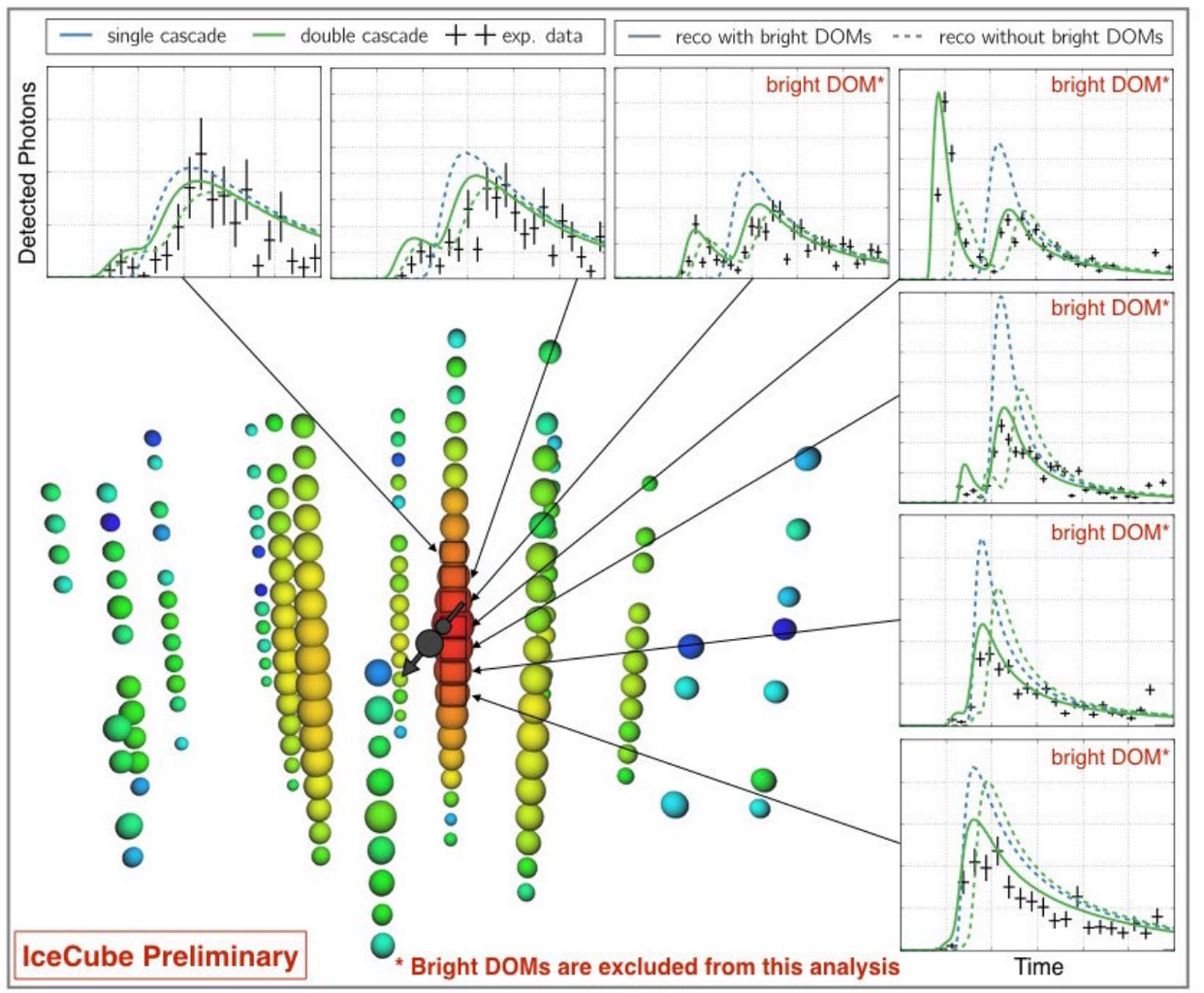
A Tau Neutrino Candidate …

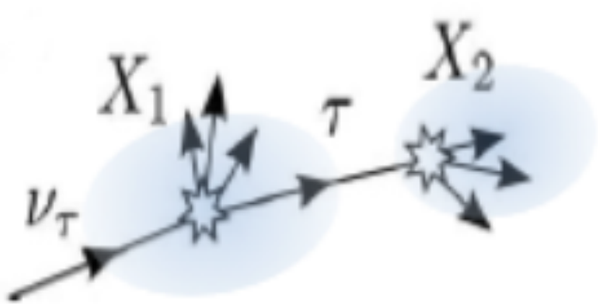
HESE 7.5yrs Tau Search

Double cascade Event #1



Double cascade Event #2

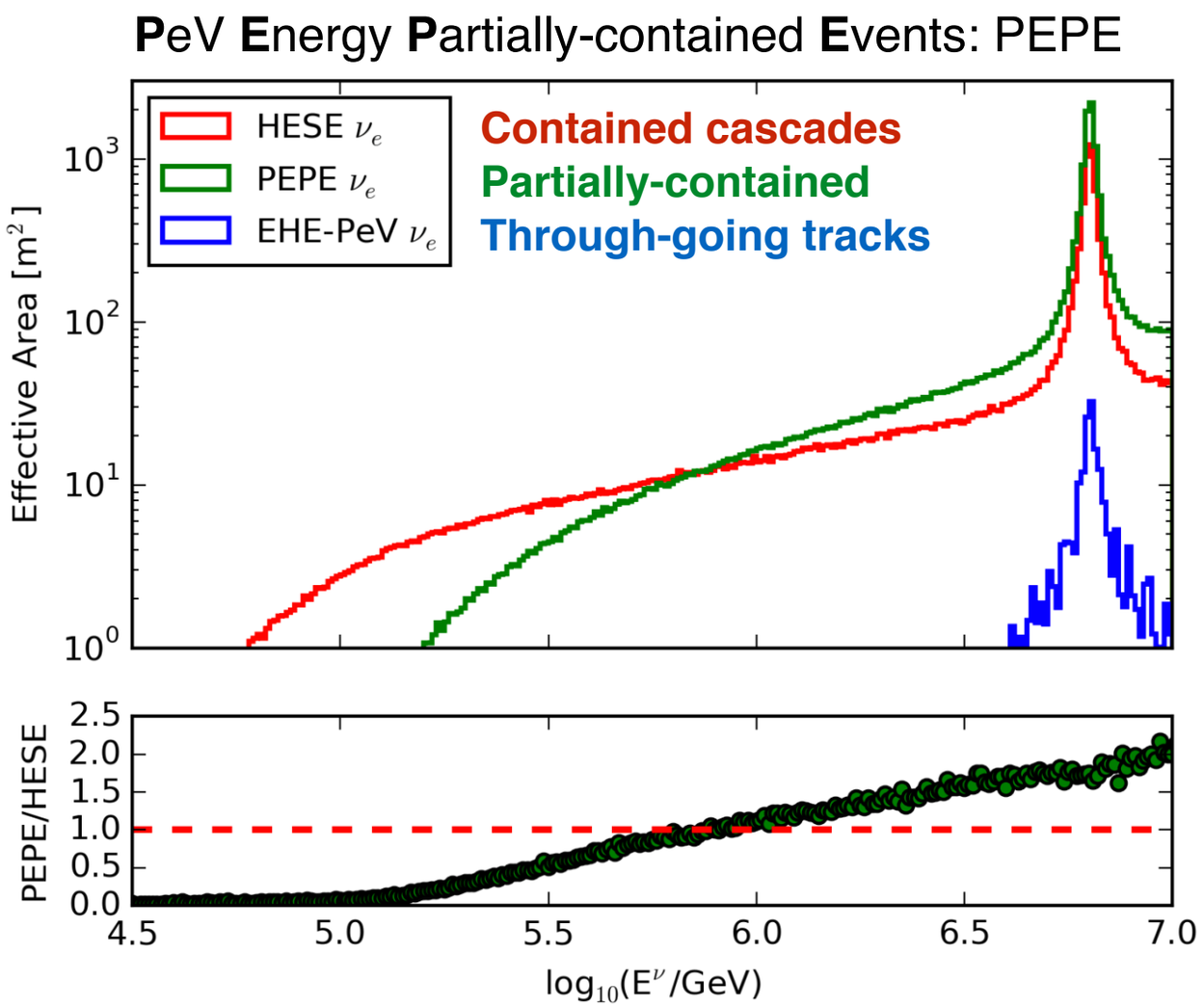


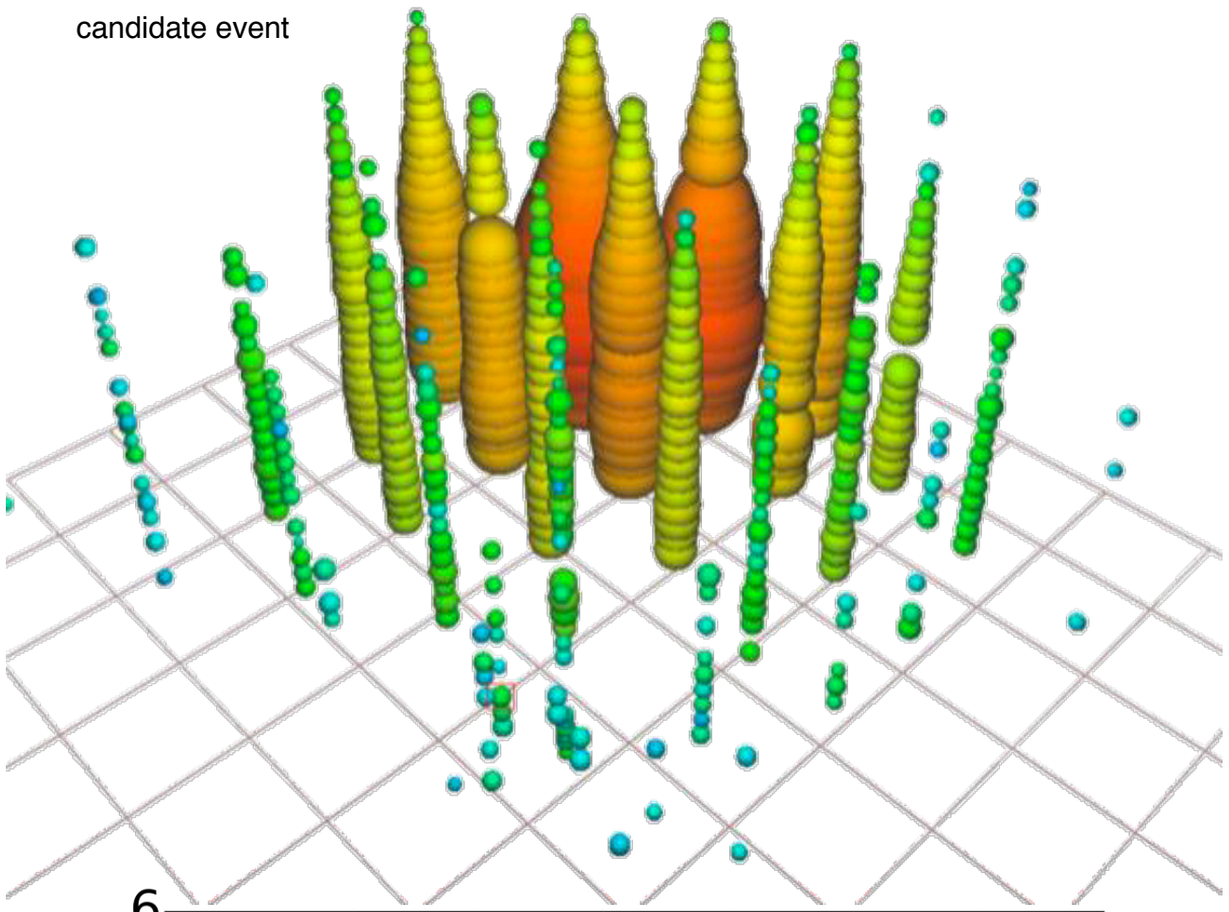


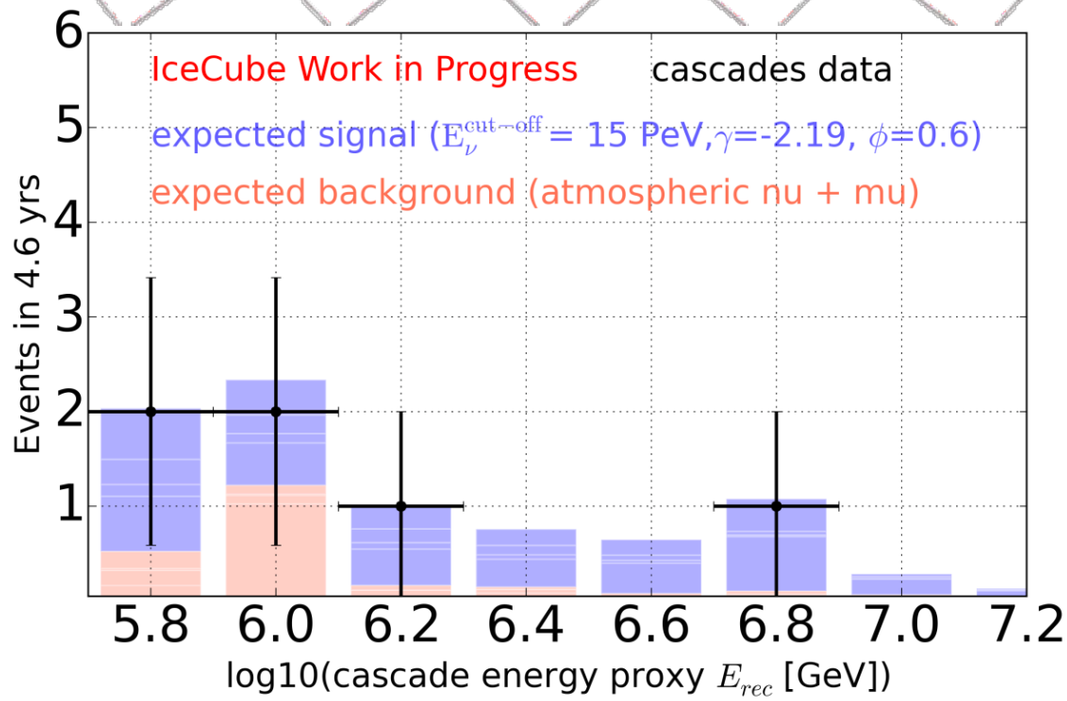
"Bright" (saturated) DOMs not used in reconstruction
Direction and two reconstructed cascades are shown in dark gray

First evidence for high-energy tau neutrinos !!

The global high-energy picture



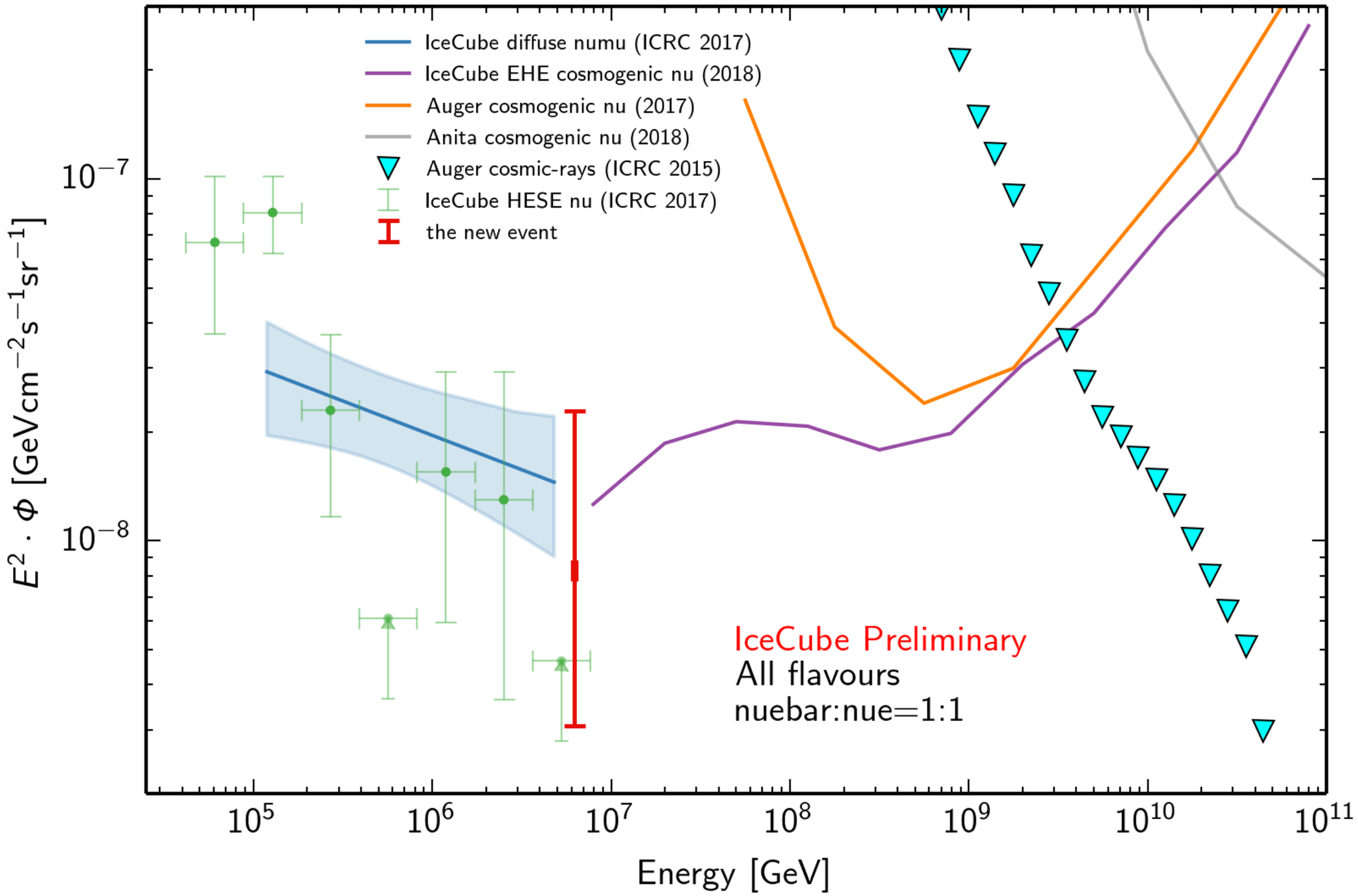




4.6 years (2012-2016) of data. **One event is at Glashow** bin

It is **brighter than all IceCube PeV events** even only partially-contained

The global high-energy picture



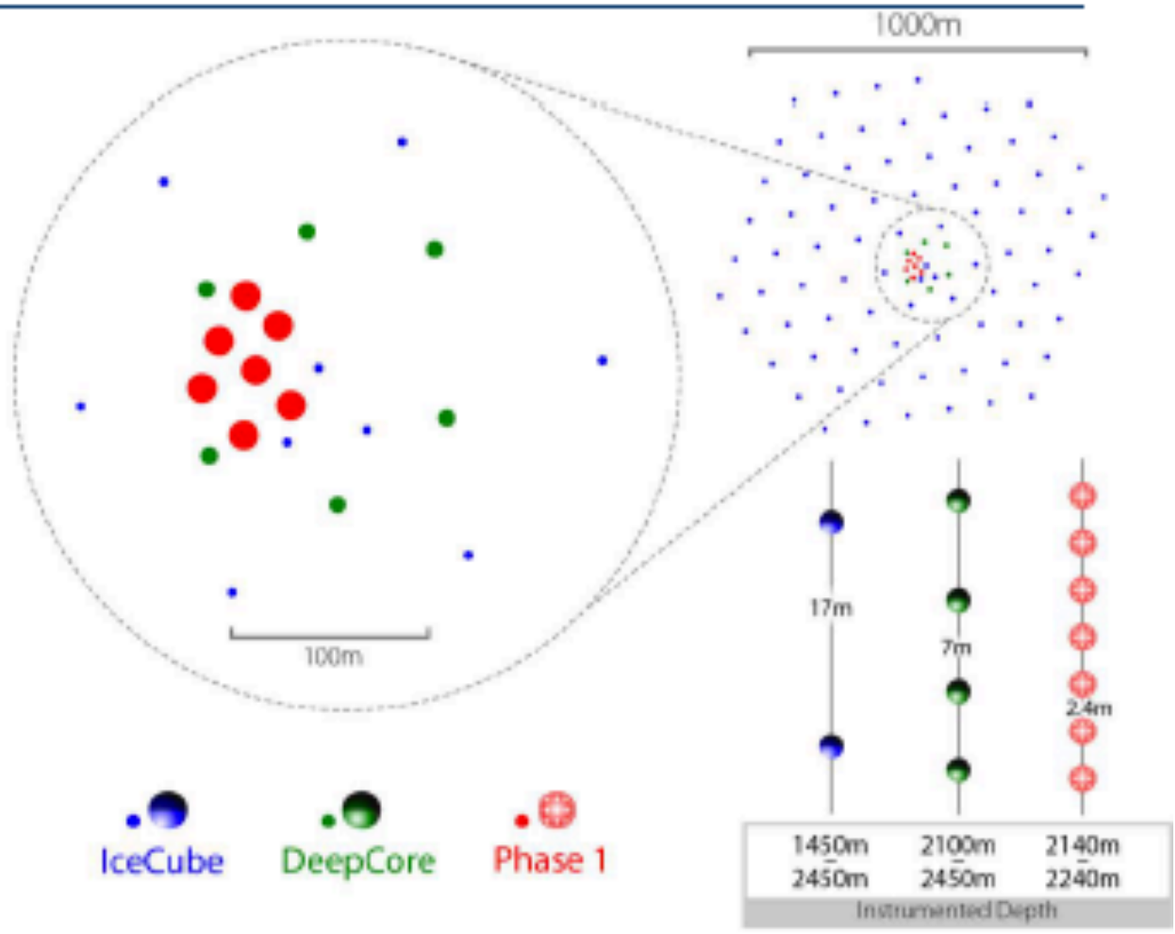
IceCube Upgrade

IceCube: next step = Upgrade

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

IceCube-Upgrade

- 7 additional strings in Deep Core domain, densely instrumented
- Objectives:
  - GeV neutrinos: τ appearance, Dark Matter, …
  - Improved understanding of ice properties → better precision, reduced systematic uncertainties
  - Opportunity to test new hardware developments
- Funding commitment expected very soon



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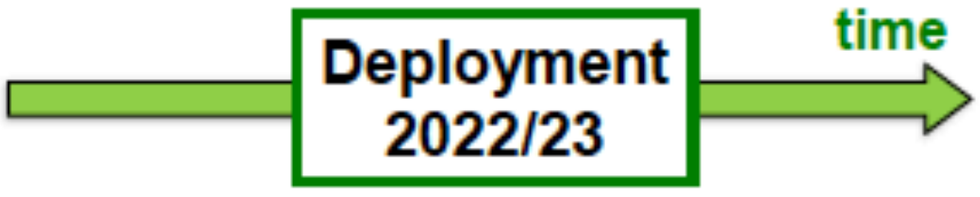
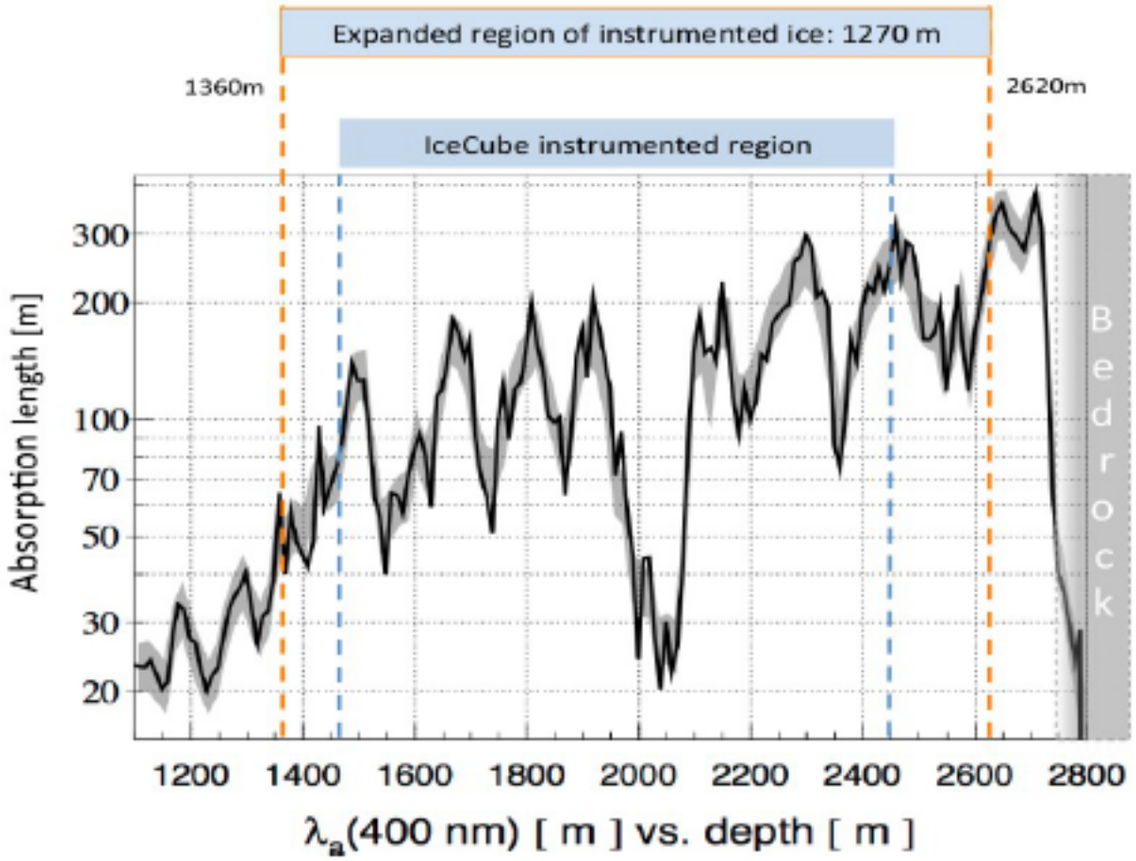
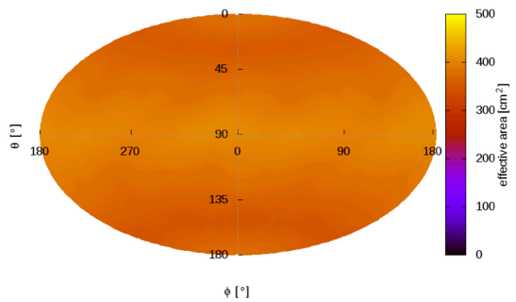


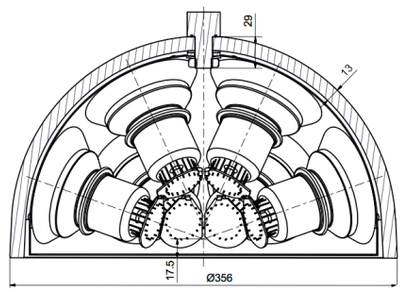
P[2/163] J. Evans

IceCube Gen2



Plan to use new sensor modules





IceCube Coll. Gen2 LOI arXiv:1412.5106