Astroparticle Physics with the IceCube Neutrino Telescope

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Natural science and your future - HOKMA Lecture at Ehwa

Overview

- Motivation
- Neutrino Detection
- Introduction to Neutrino Telescopes
  - The IceCube Neutrino Telescope and it's science program
  - The Search for Astrophysical Neutrinos
  - Multi-messenger astroparticle physics & IC170922A
- Conclusions

The Cosmic Ray Mystery

Victor Hess

Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

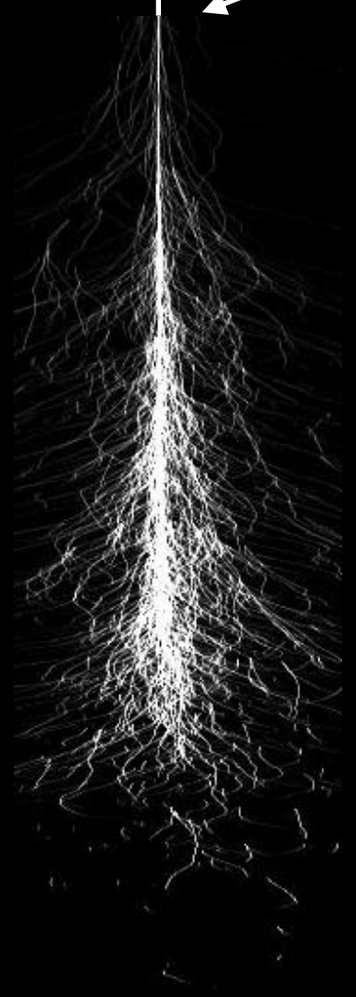
Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.

primary particle

stratospheric balloon

~40km

collision point of
primary particle



~20km altitude

~5km altitude
Victor Hess

Victor Hess 1912

Surface of the Earth

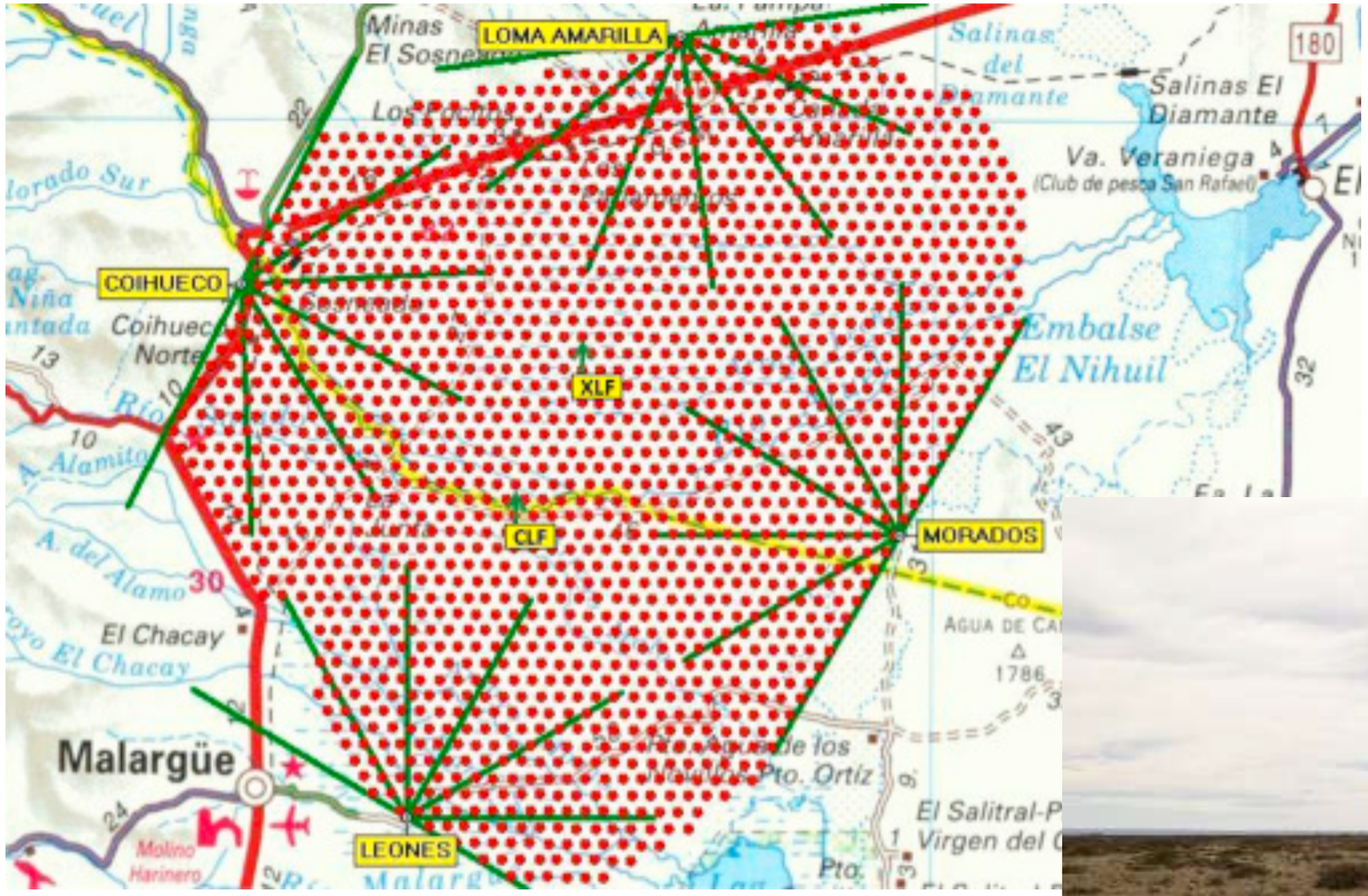
1600 Water Cherenkov Detectors (WCDs)
3000 km^2

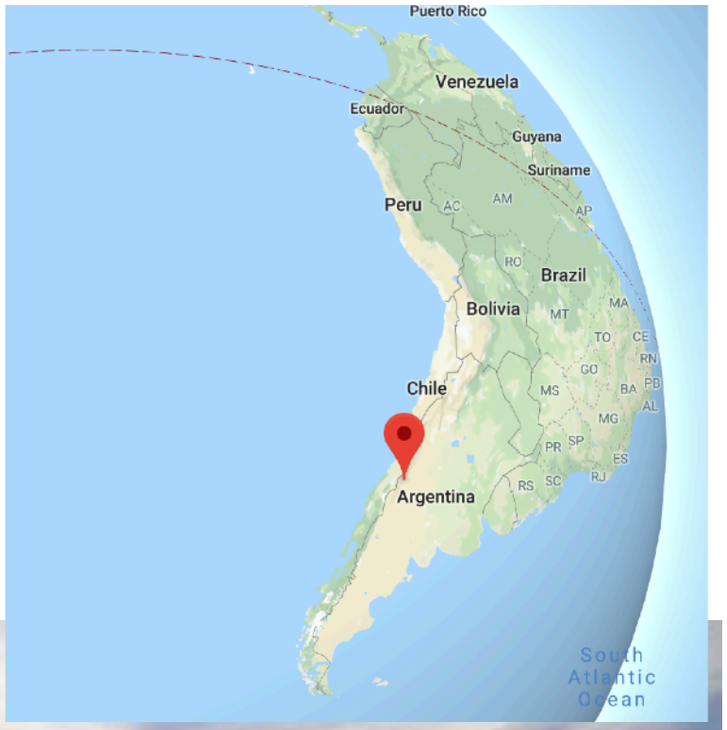
Cosmic rays

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

AUGER

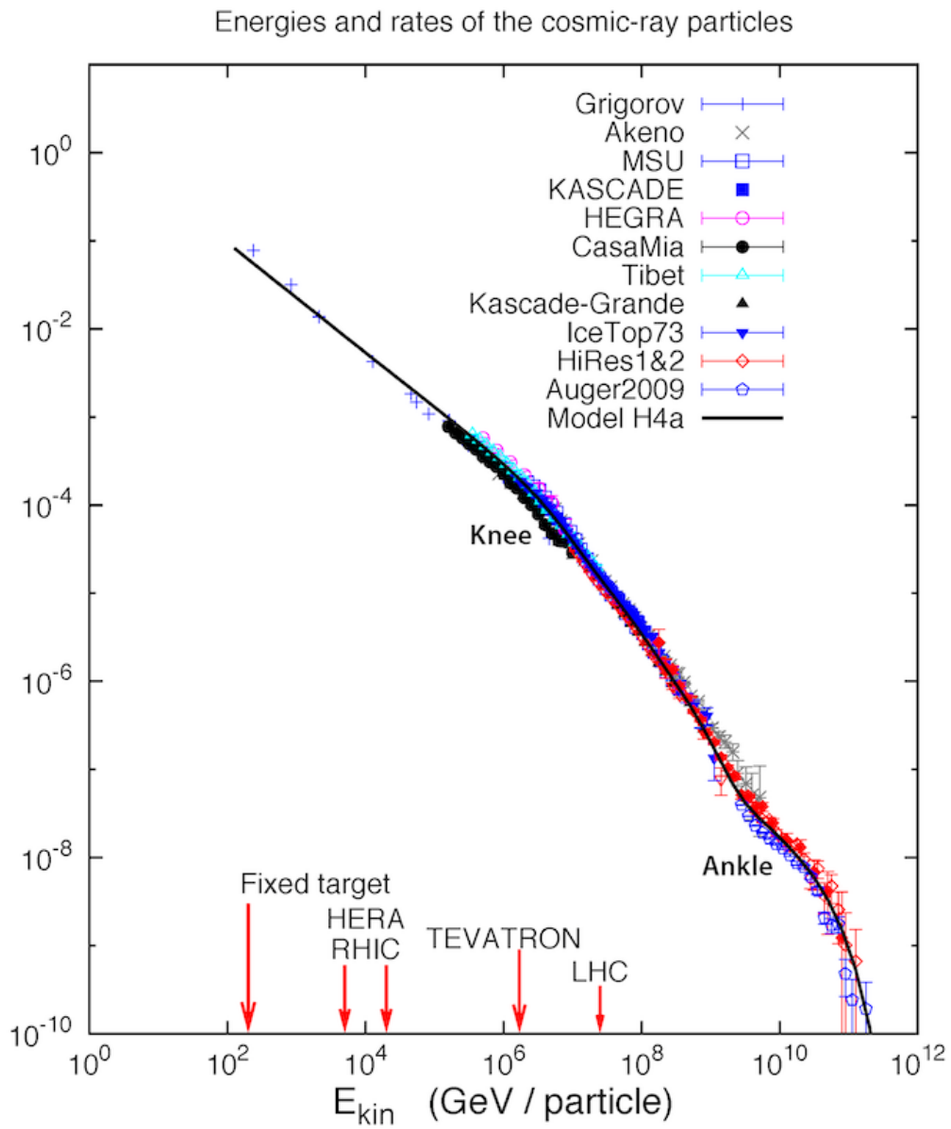
Malargüe, Mendoza





- 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



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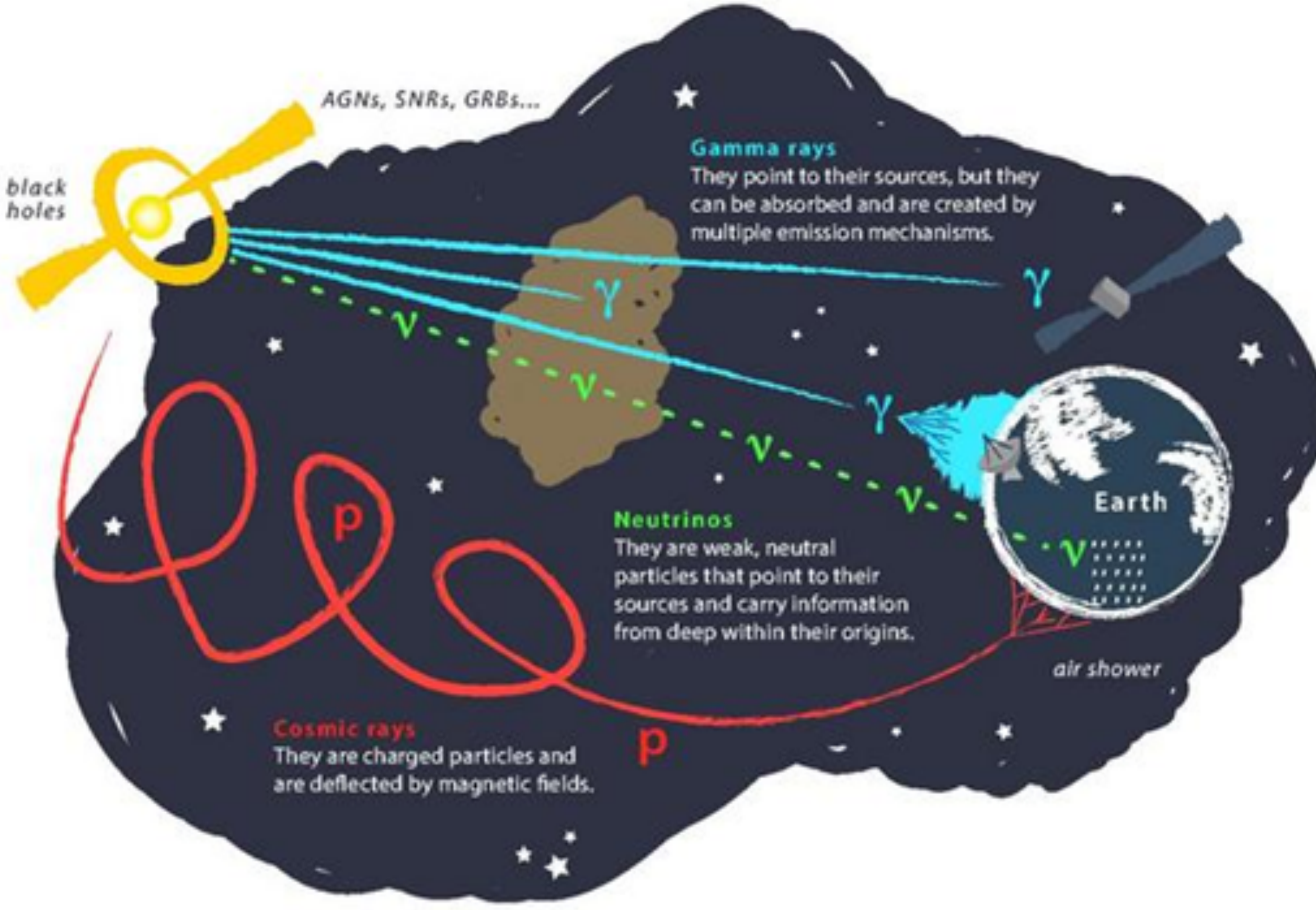
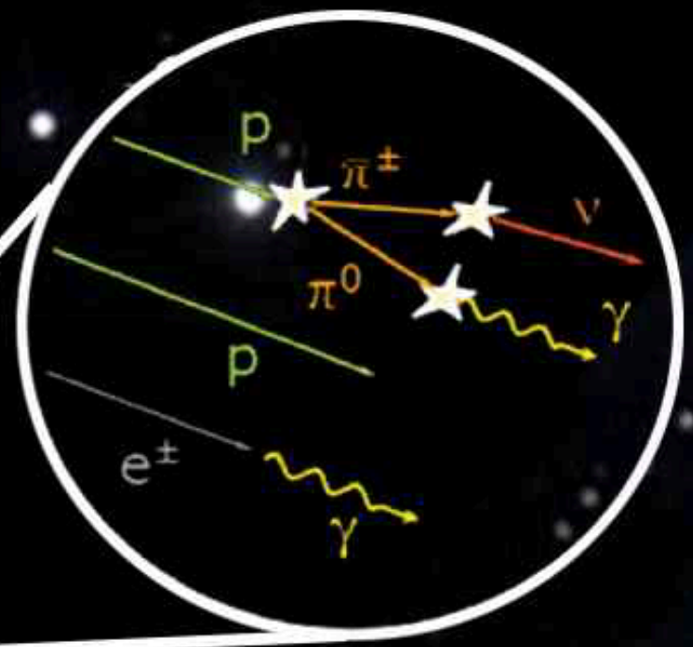

AGNs, SNRs, GRBs...
black holes
Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.
γ
γ
γ
ν
ν
ν
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.
Earth
air shower
p
p
Cosmic rays
They are charged particles and are deflected by magnetic fields.

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

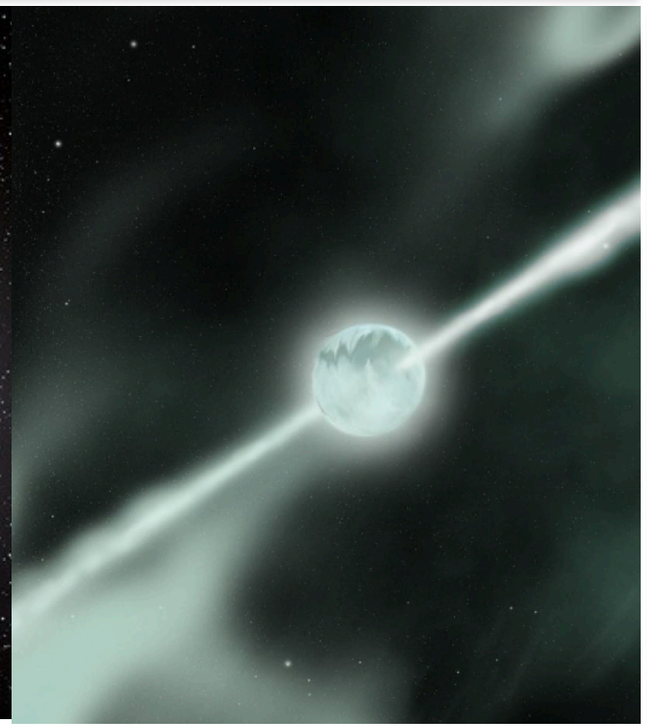
γ

ν

P

Astrophysical Messengers

Potential sources of high-energy neutrinos

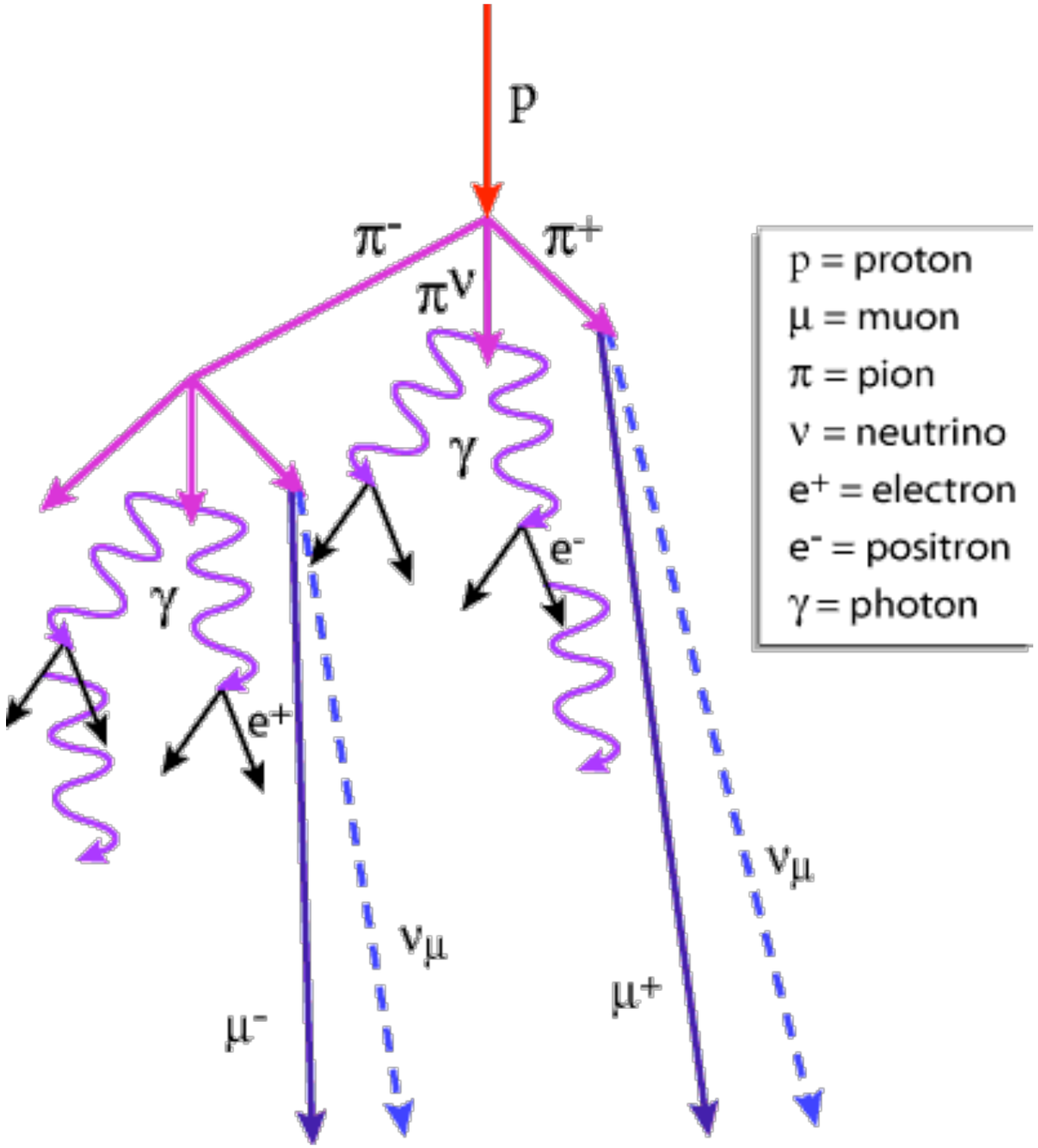
Galactic sources	Extragalactic sources		Exotic
			
Supernova remnants	Active Galactic Nuclei	Gamma-ray bursts	Something unexpected

Atmospheric Neutrinos

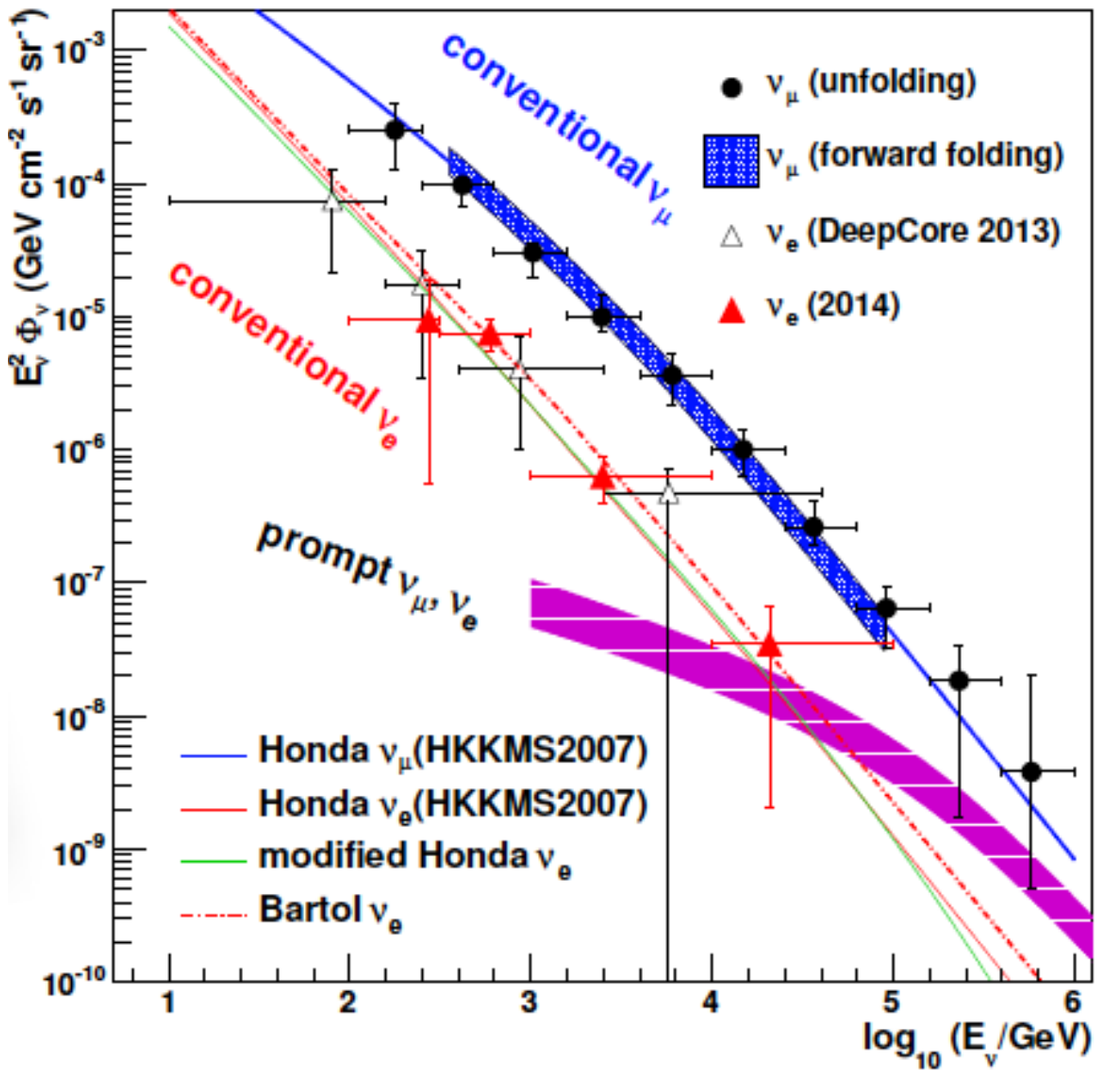
Cosmic rays interact in the upper atmosphere:

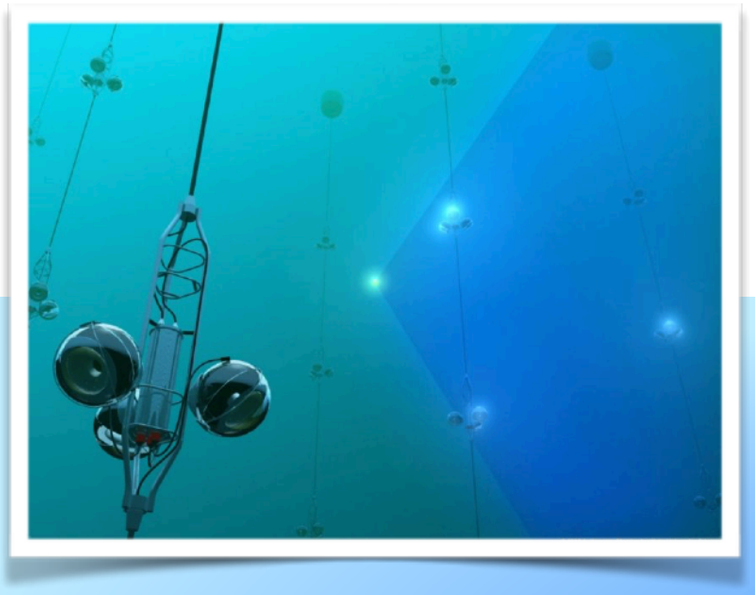
$p + A \rightarrow \pi^{\pm} (K^{\pm}) +$ other hadrons ...

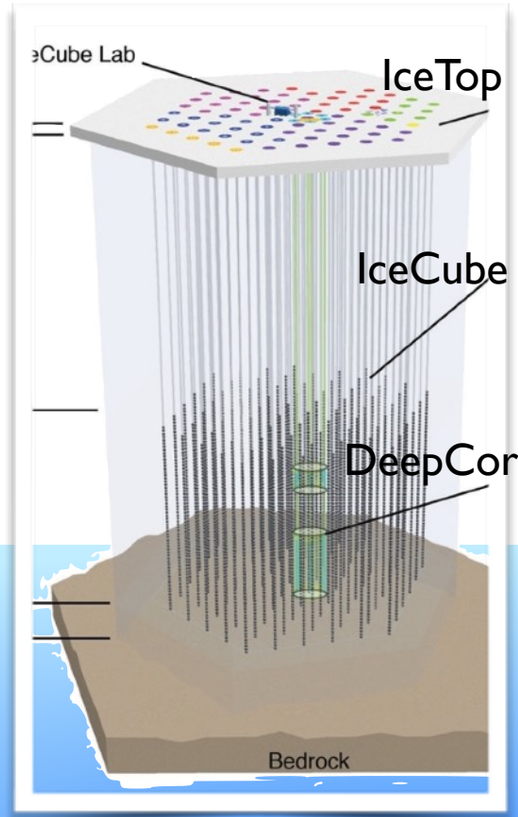
$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$



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



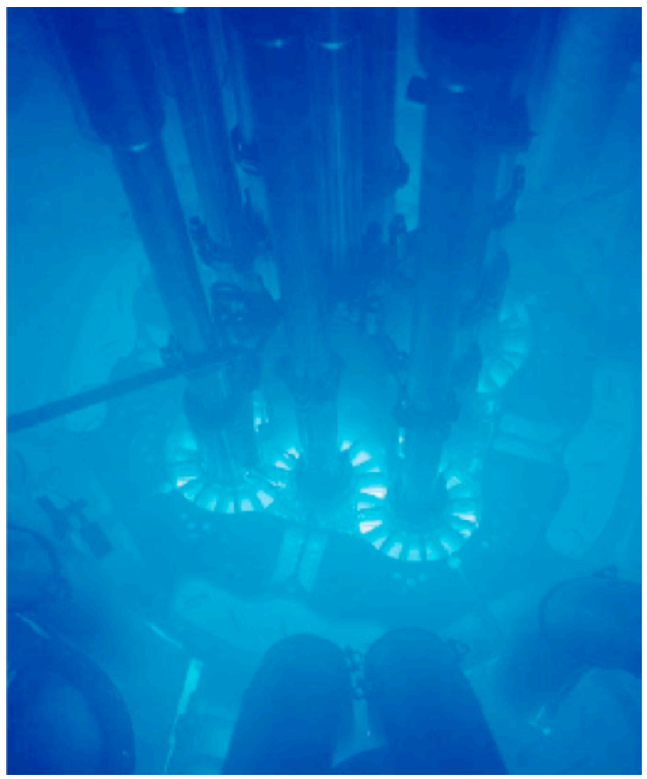


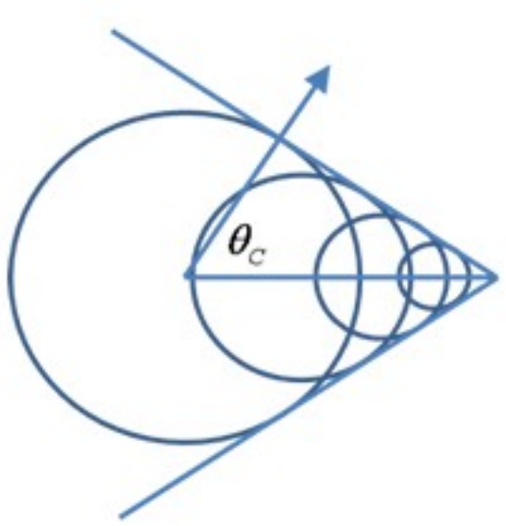


Neutrino Telescope Landscape

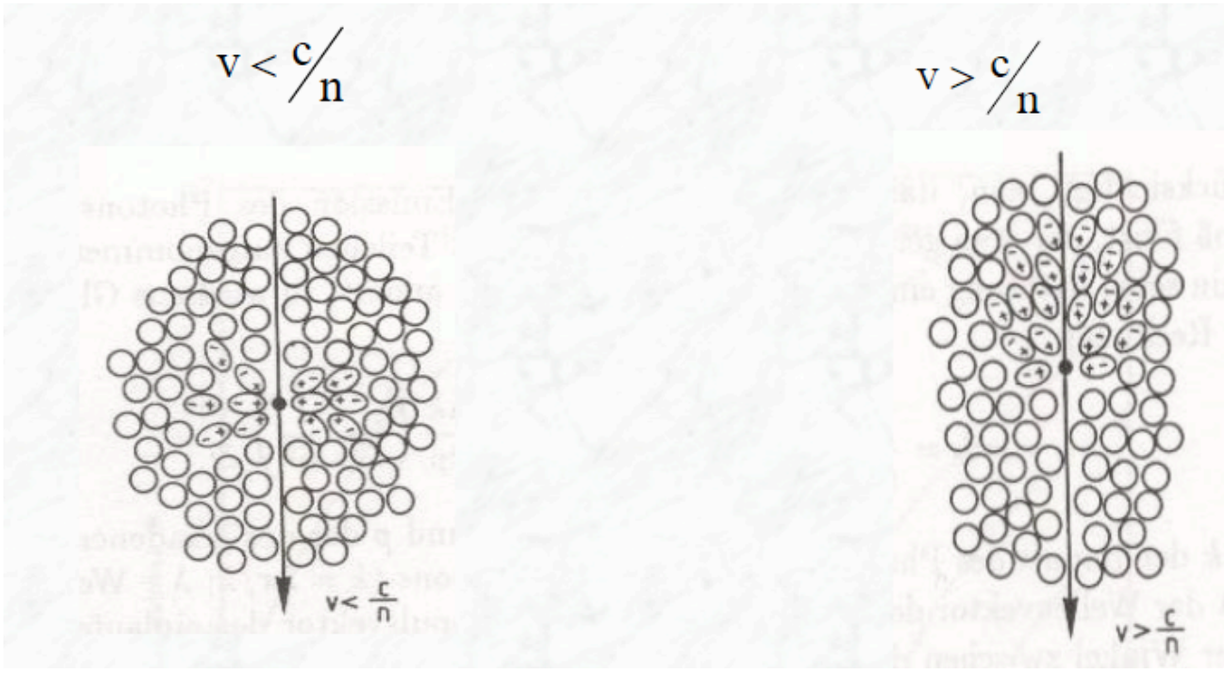
Cherenkov light in water/ice

- Neutrinos interact in water
  - Produces charged particle (muon for example)
  - Energetic muon is relativistic travels with the speed of light, speed of light in water v=c/n
    - Index of refraction of water n = 1.33
  - Cherenkov light is emitted
    - Characteristic emission angle
      - in water ~43°
      - in ice ~41°





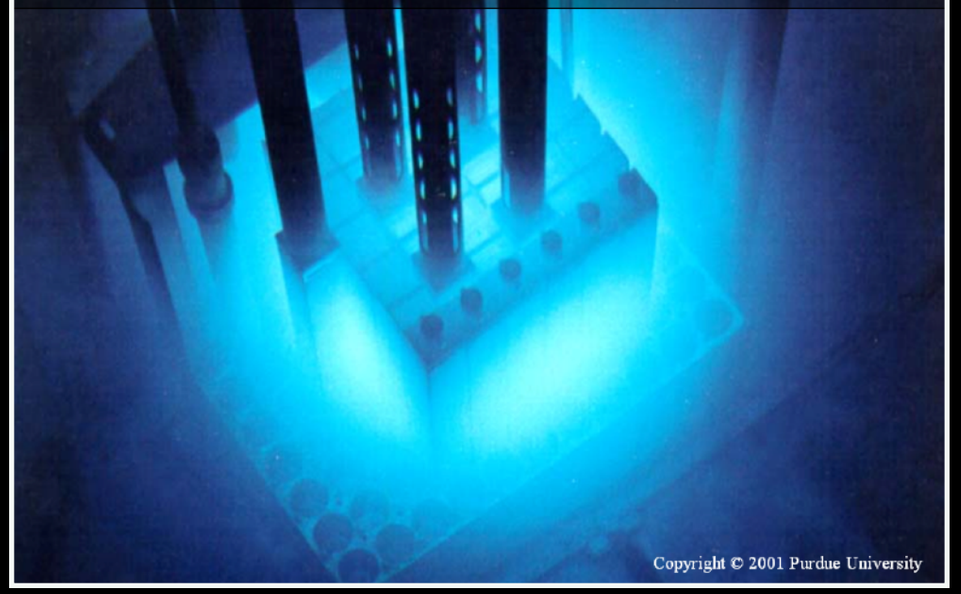
$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$



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

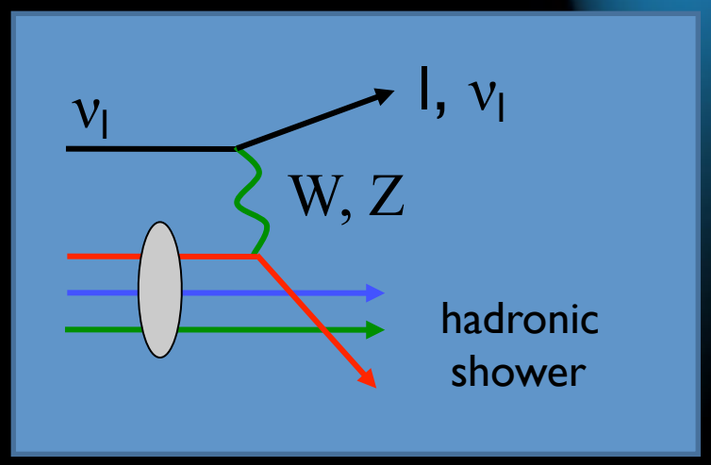
Muon

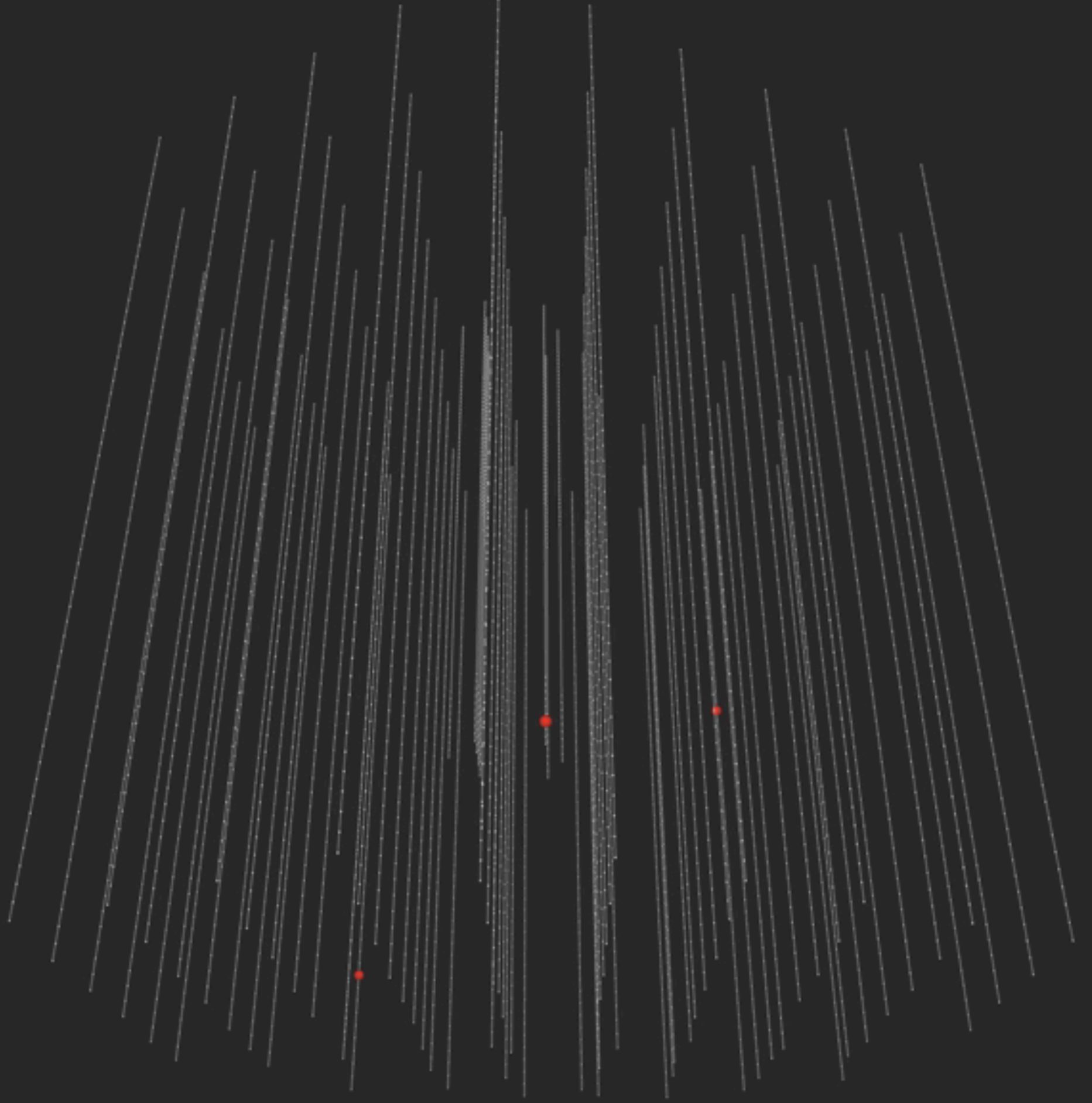
μ

Muon Neutrino

ν

interaction





Neutrino Telescopes

Neutrino Telescopes

ANTARES

Lake Baikal

GVD

KM3NeT
ORCA

IceCube

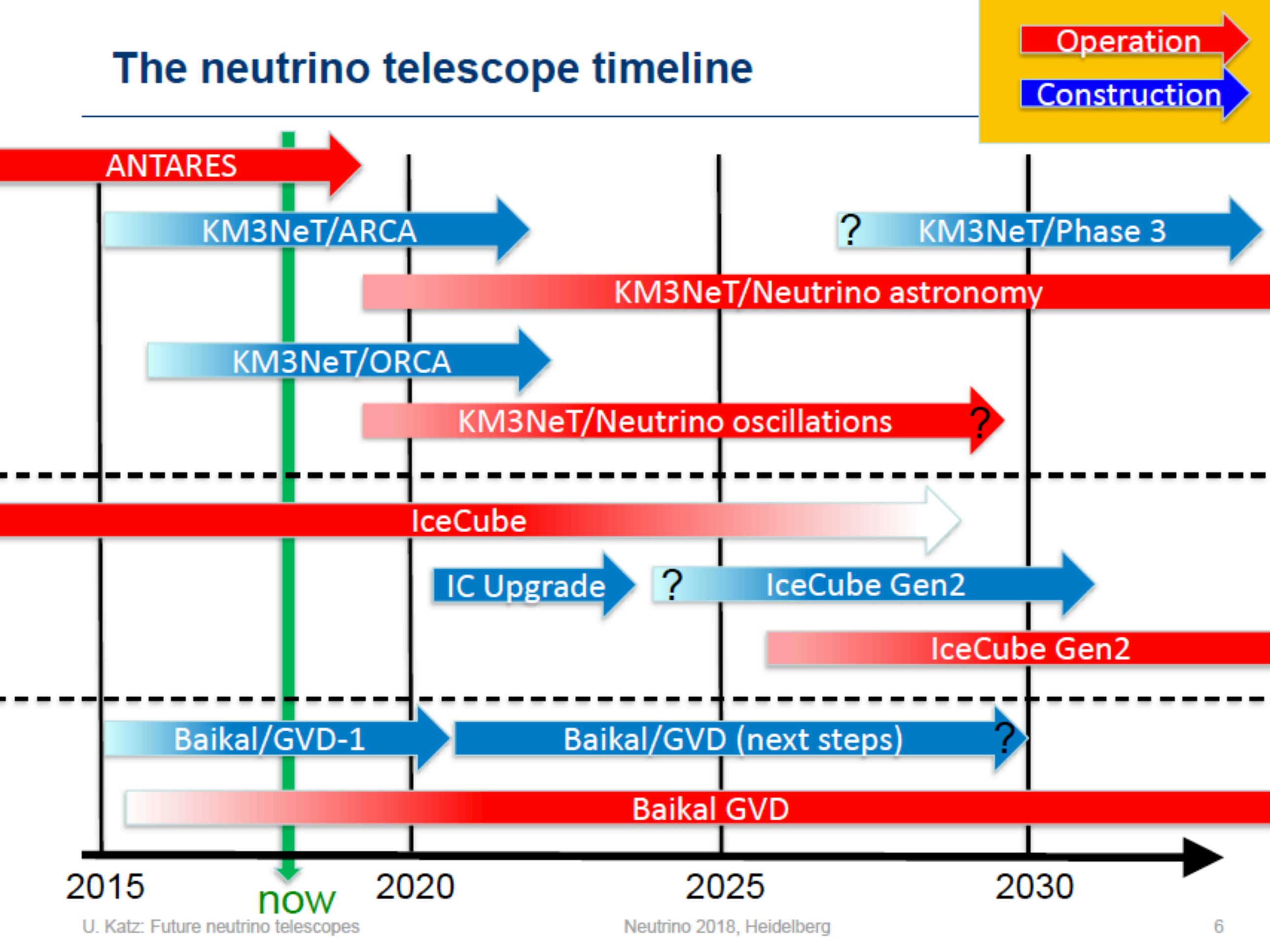
Upgrade/Gen2/PINGU

Active

Construction

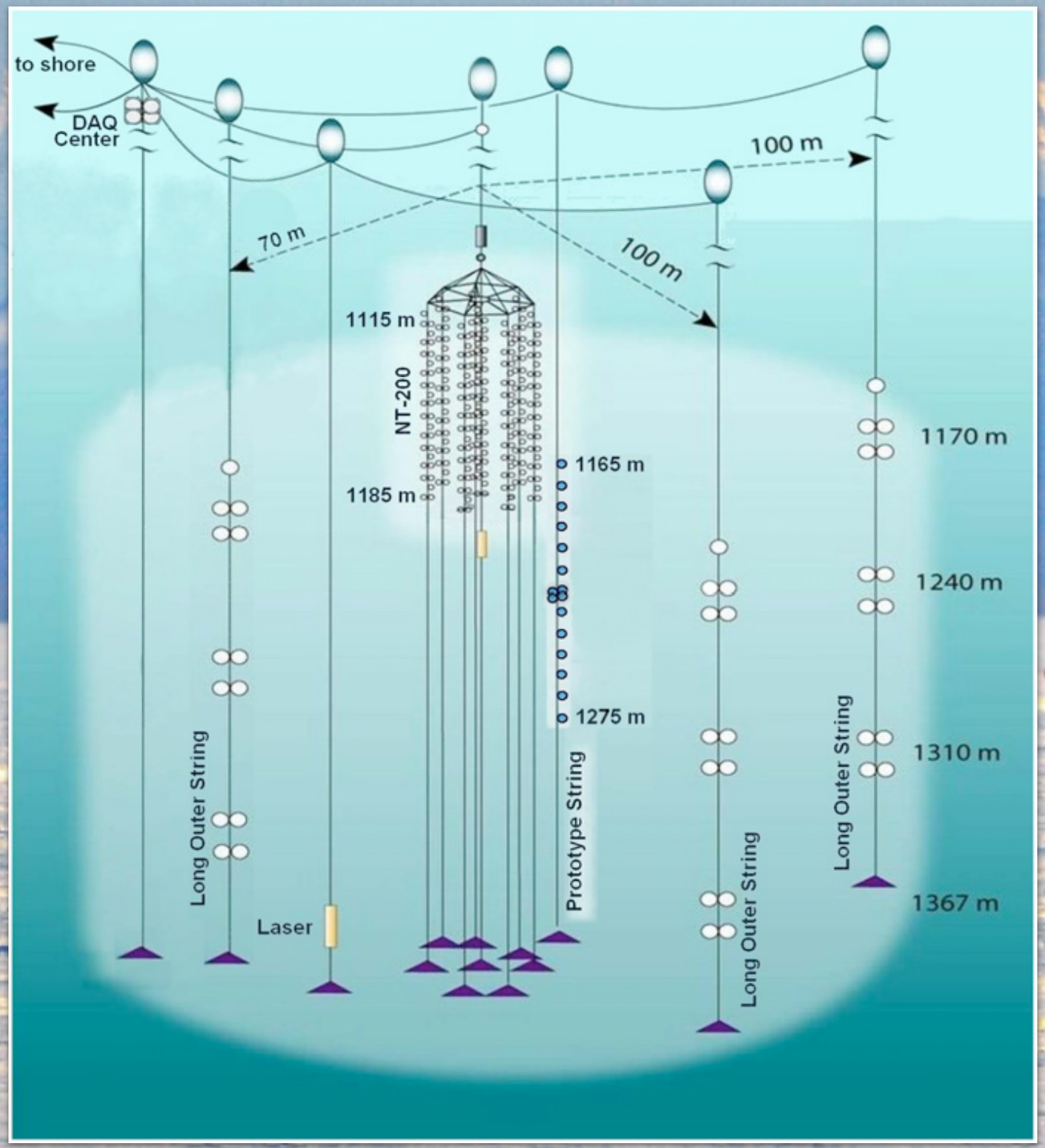
Planned

The neutrino telescope timeline

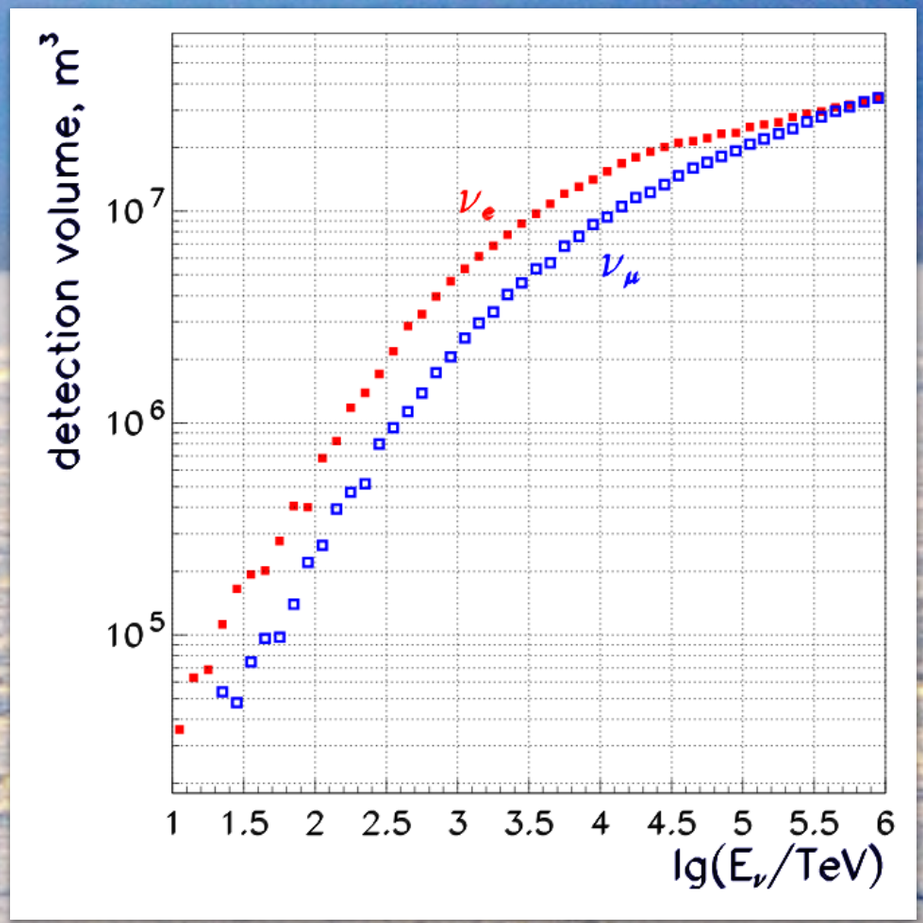


Lake Baikal

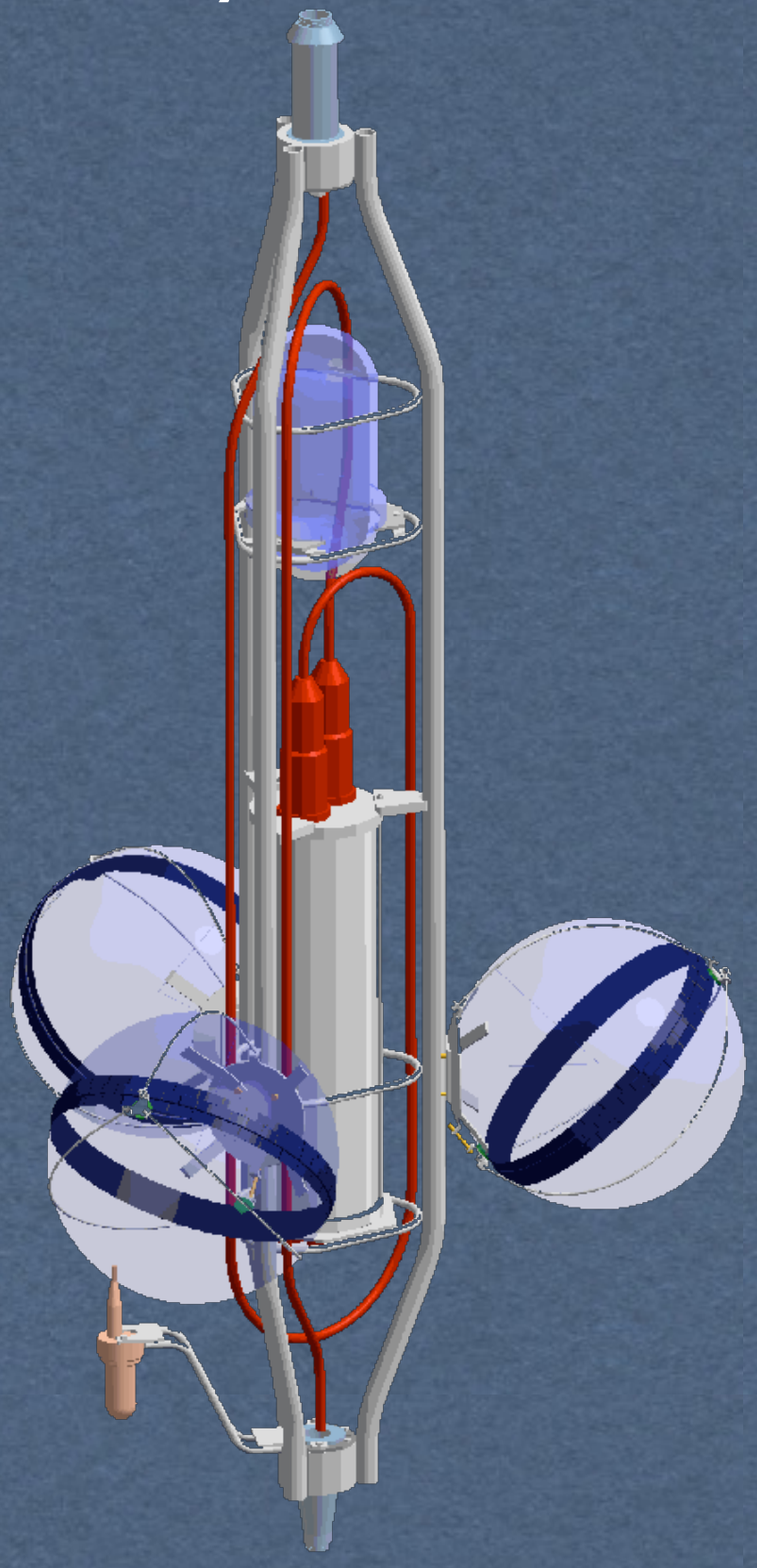
arXiv:astro-ph/0609743



228 PMTs
~0.1MT Volume



Storey with 3OMs



- 12 lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs
- ~10MT

Resolution:
Position < 10 cm
Timing ~ 0.5 ns

70m

Junction Box

nautile

NIM A 656 (2011) 11-38

©Montanet

The IceCube Neutrino Telescope

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
Technische Universität München
Universität Münster
Universität Mainz
Universität Wuppertal

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms Universitet
Uppsala Universitet

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UNITED STATES
Clark Atlanta University
Drexel 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
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
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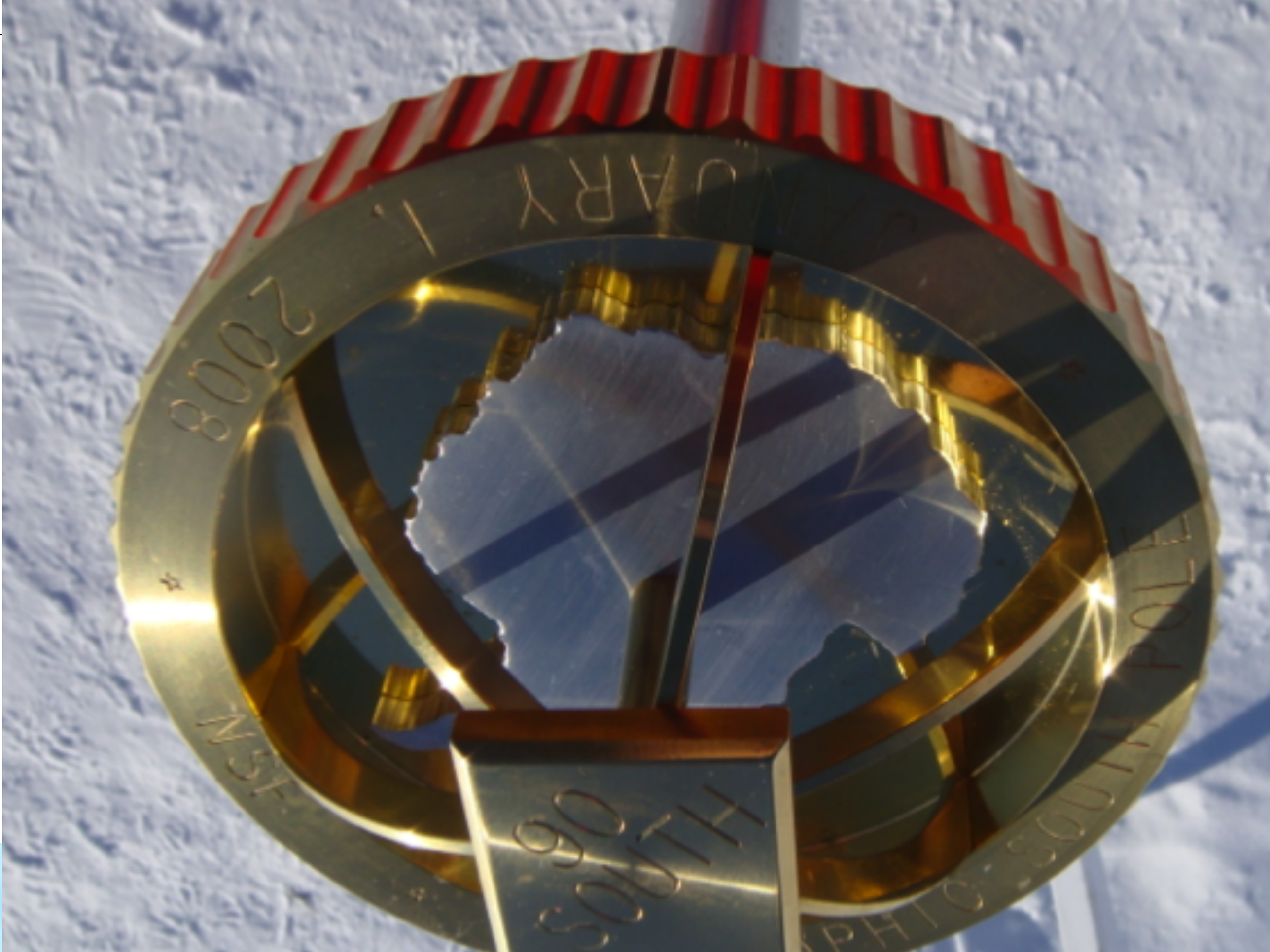
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche 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


JANUARY 1, 2008
SOUTH POLE

How to get there ?

Arrival

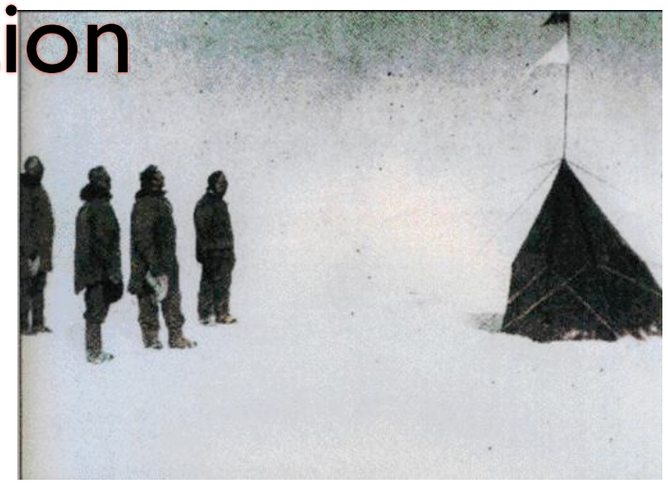
Research/Expedition Team

Travel

Conduct Experiments

TAKING AN OBSERVATION AT THE POLE.

Station



Lasting Memories

Brain Korea(BK) Project, Ice Cube Antartica Joint Reserch

News more ›

- Leading 'humanism Renaissance' by 617 years of ...
- The World cup star, Seol Kihyeon is retired, beco...
- Lee Wangeun, Chairman of Shinsung Solar Energ...

Notice more ›

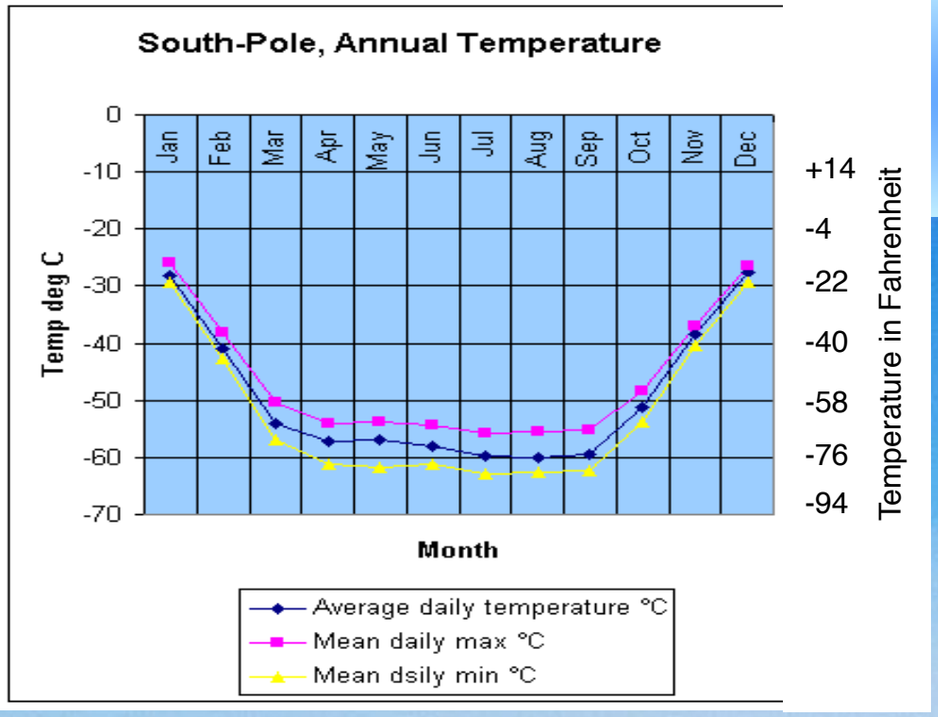
- Course lists of Dept. of Energy Science 2015 Sprin..
- Announcement to New International Students
- [Dormitory] 2015 Spring Myeongnyunhaksa Admi..

SKKU Reputation

SKKU News

Academics

Laboratory at the South Pole



Geographic South Pole

Amundsen Scott South Pole Station

Road to work

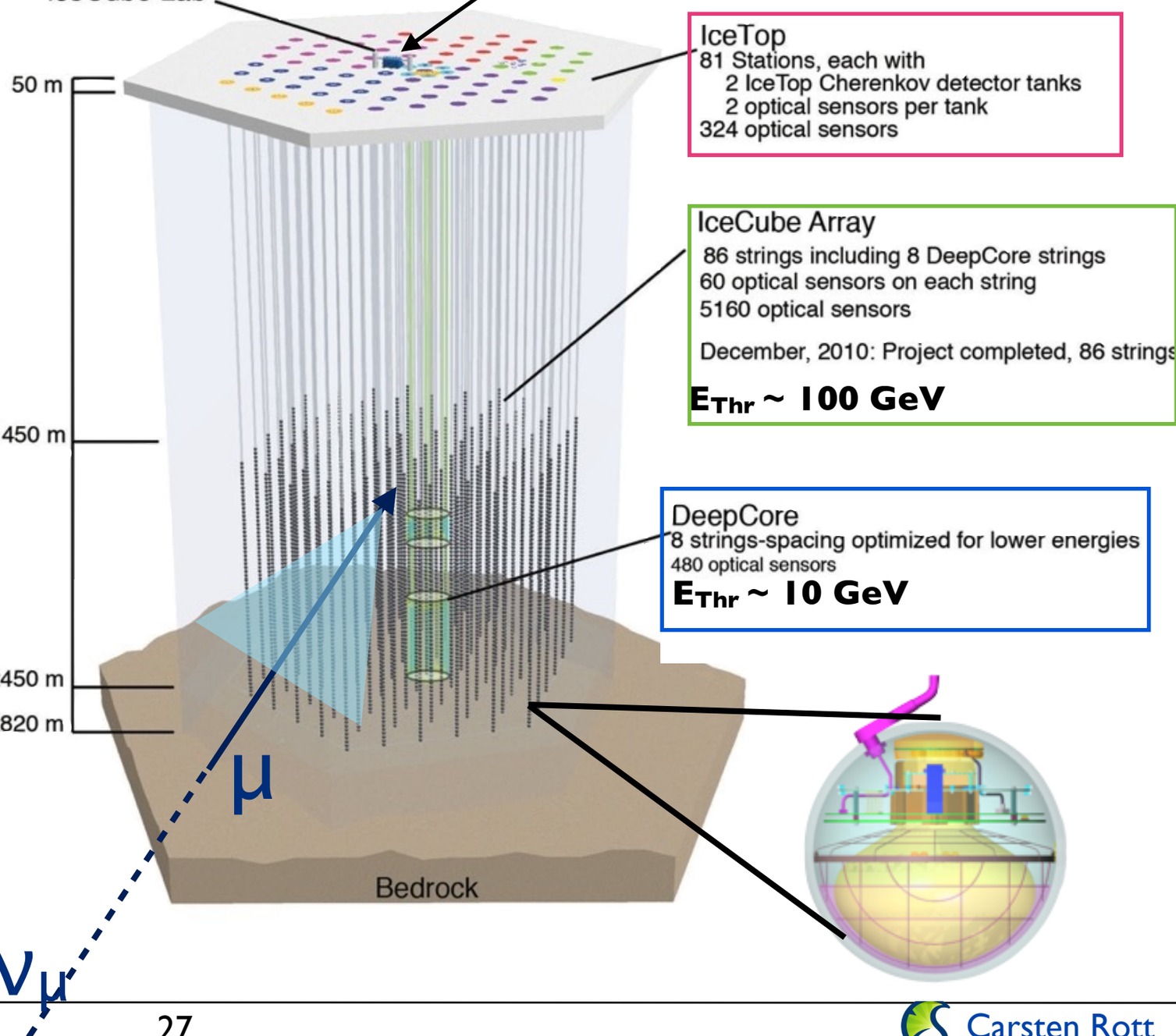
Skiway

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

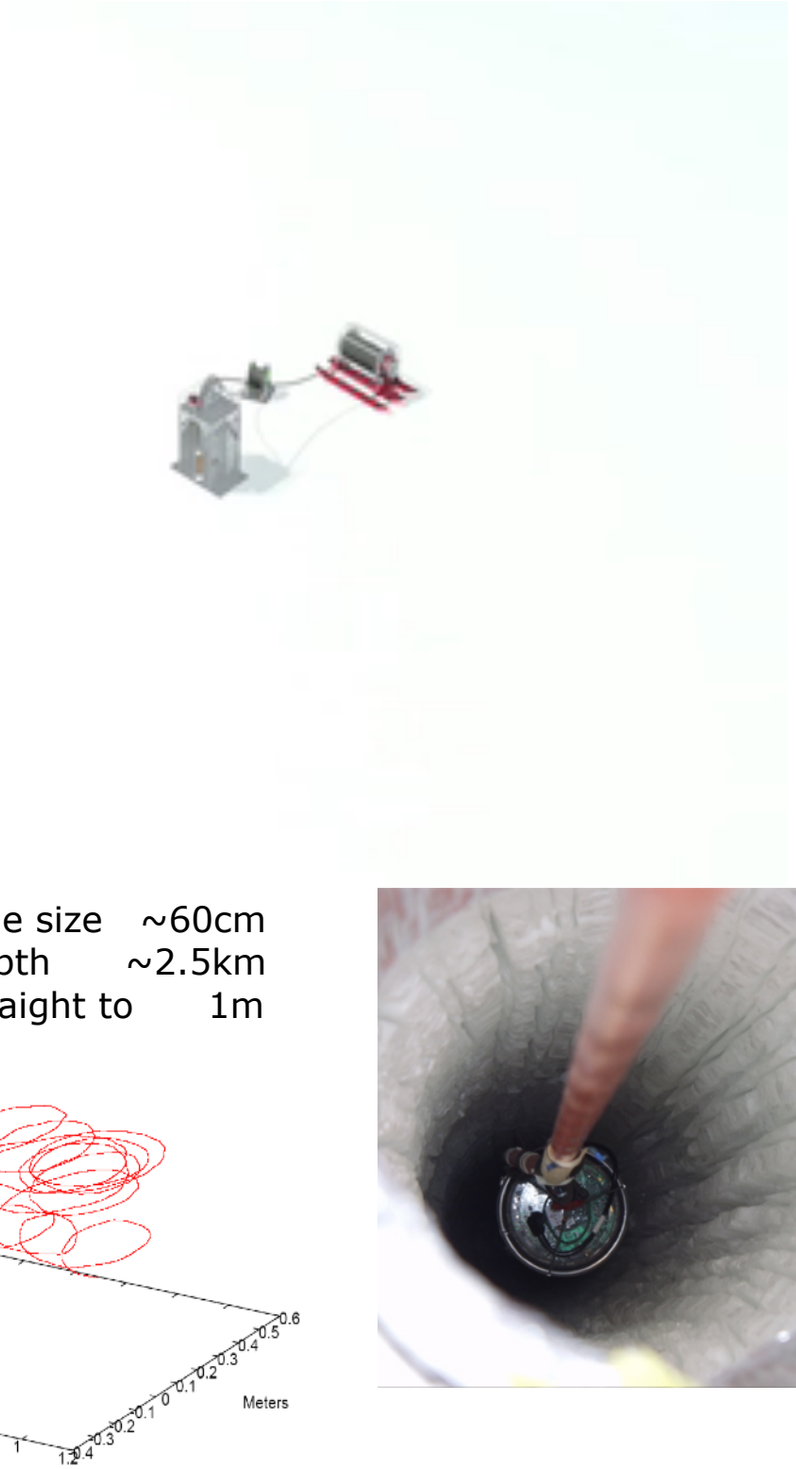


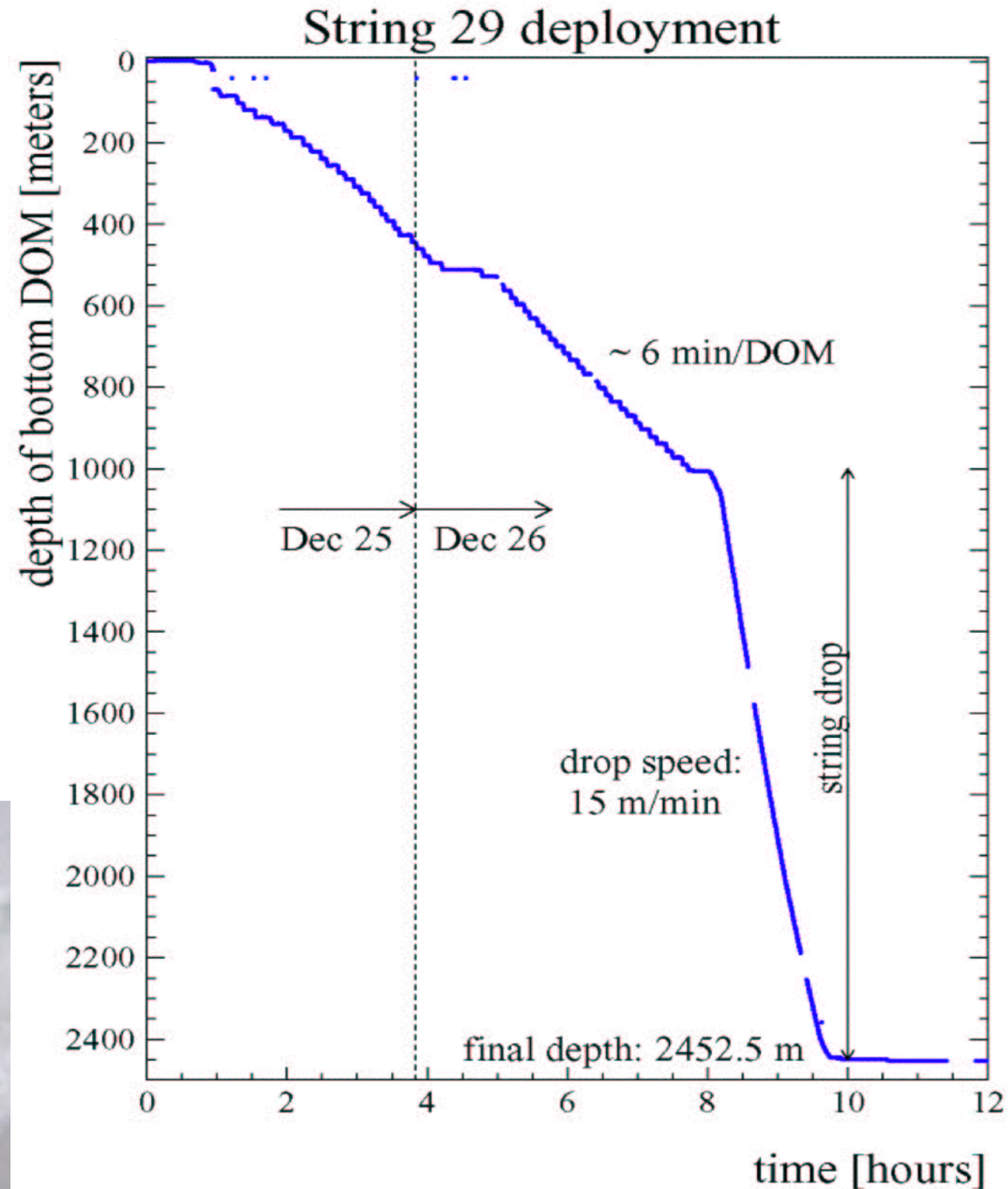
〈이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.〉

"한국 '세계적 리더' 될 좋은 기회"

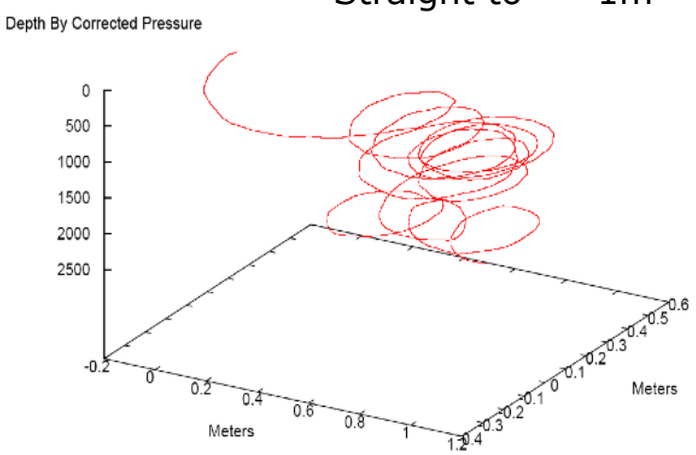
기초과학 투자 의지 활발, 한국에 새 연구 터전 등지.. 연구자-학생 영입해 연구

Drilling & Deployment

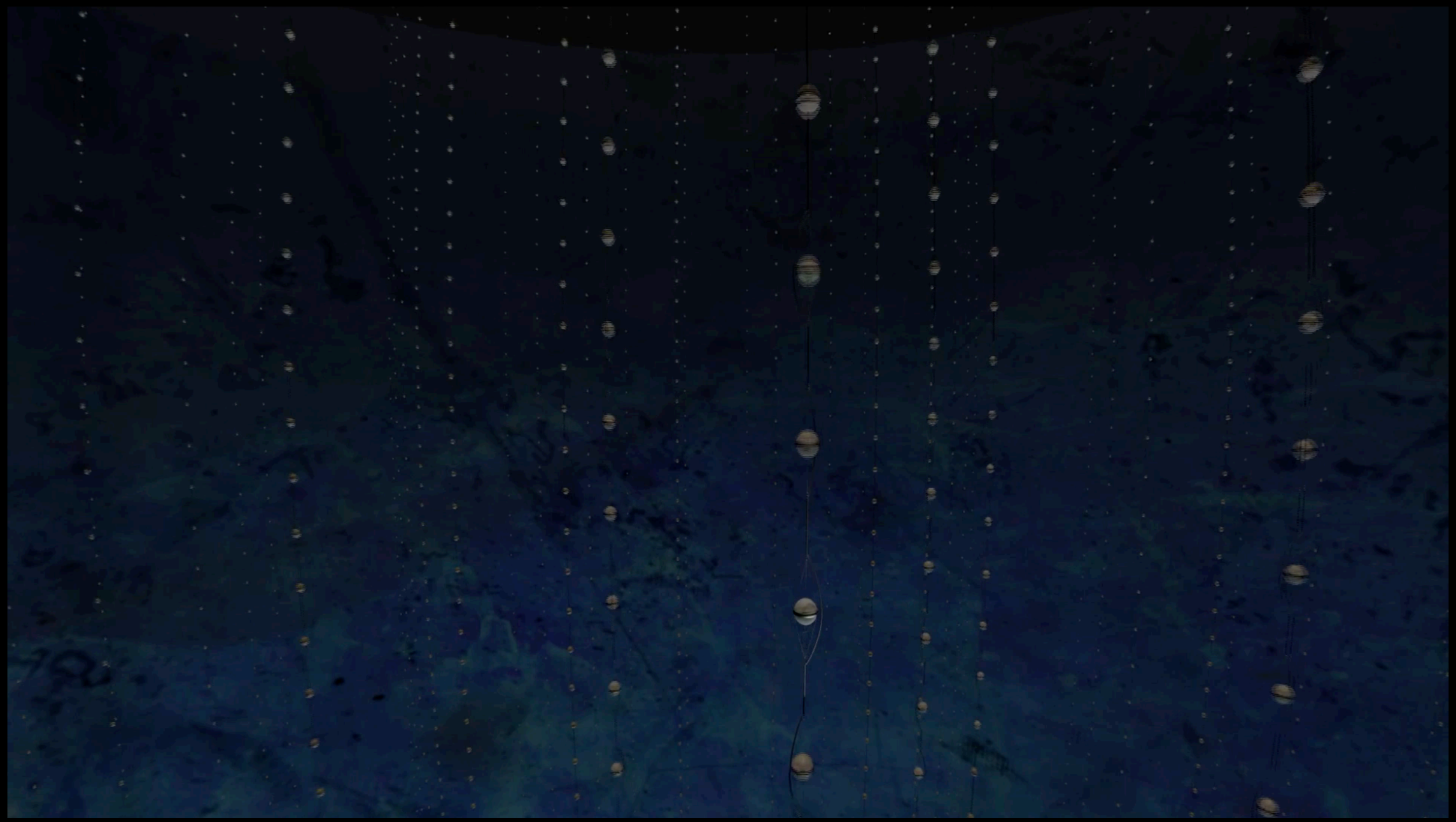




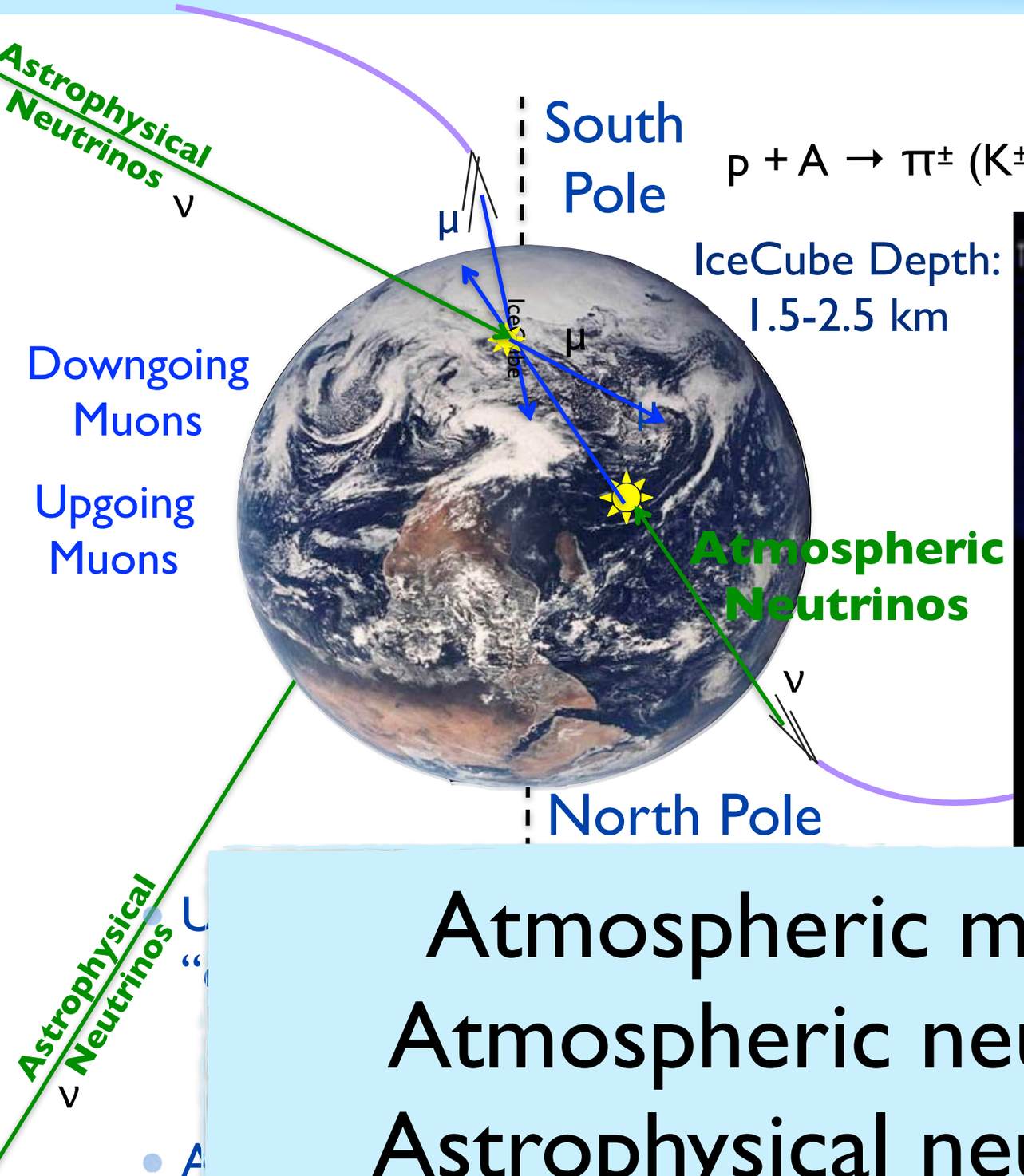
- Hole size ~60cm
- Depth ~2.5km
- Straight to 1m



Drilling to 2500 m < 40h
String deployment ~ 12h

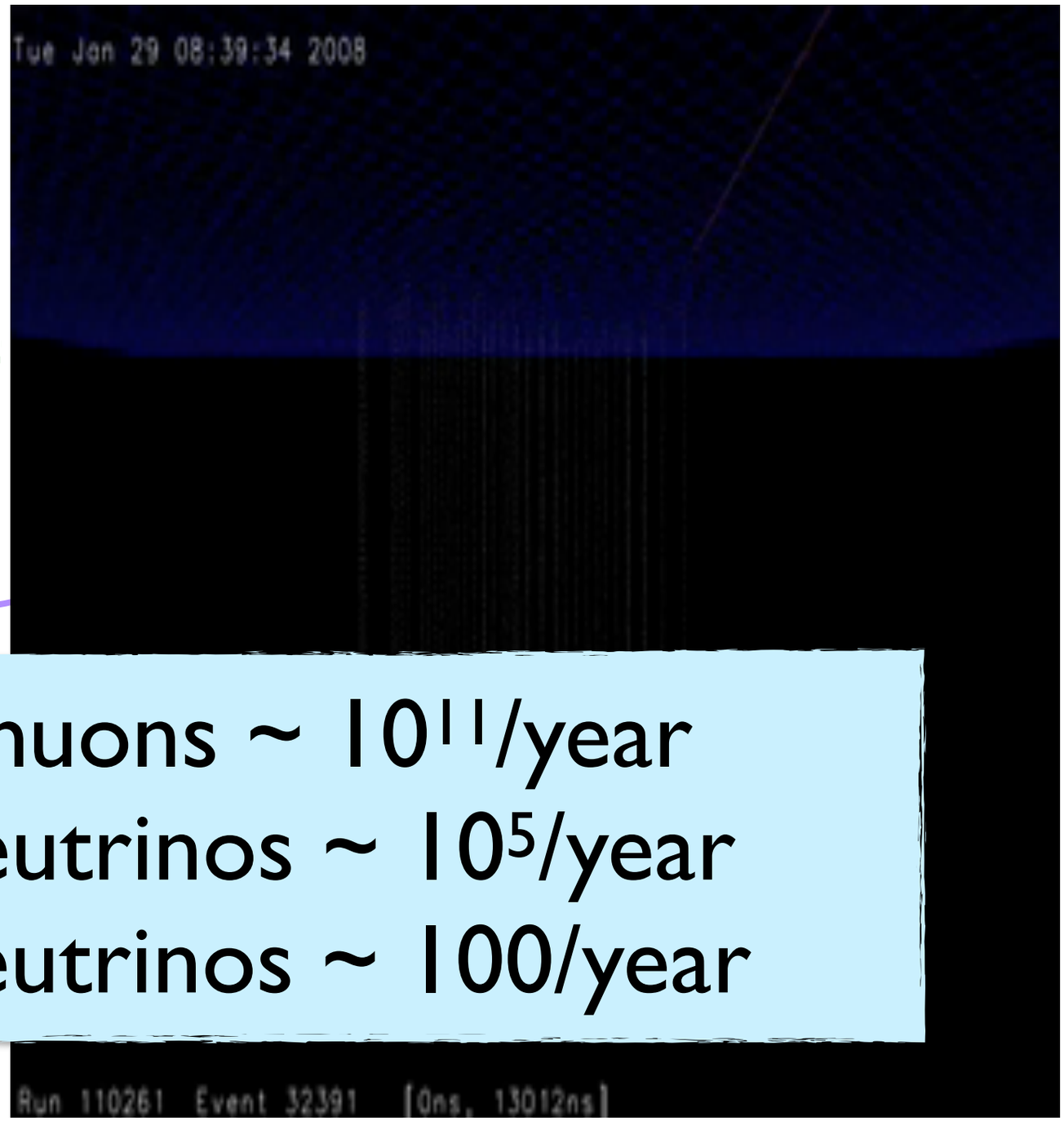


Signals in IceCube



$p + A \rightarrow \pi^{\pm}\,(K^{\pm}) + \text{other hadrons} \quad \ldots \pi^{+} \rightarrow \mu^{+}\nu_{\mu} \rightarrow e^{+}\nu_{e}\nu_{\mu}\nu_{\mu}$

IceCube Depth: 1.5-2.5 km

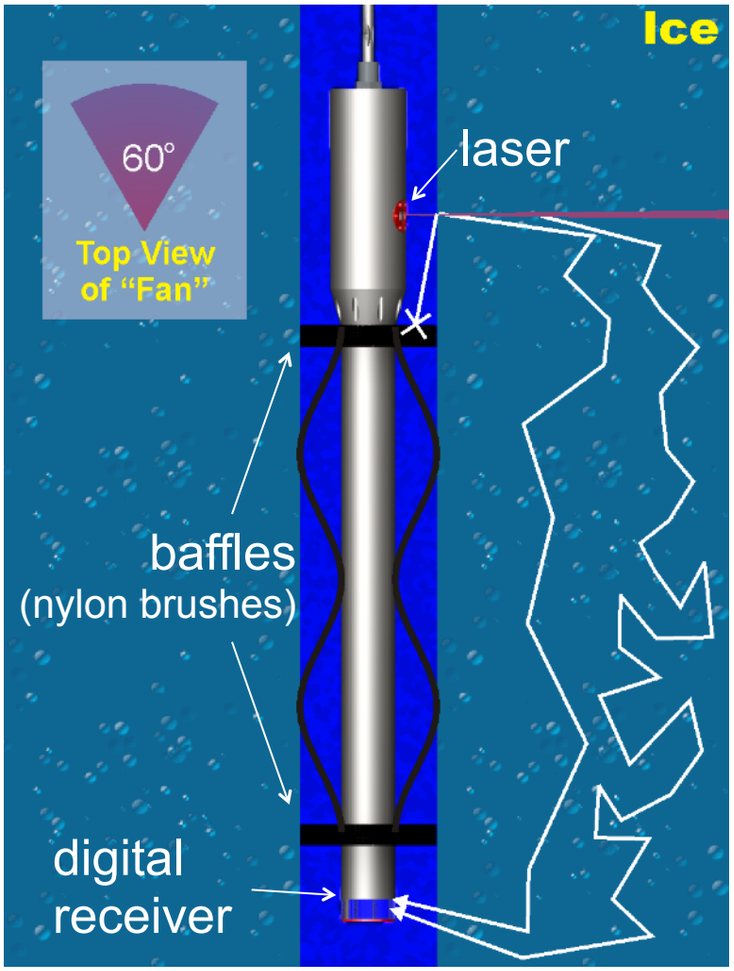


- U
- A

irreducible neutrino background to extra terrestrial neutrino fluxes

Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ 100/year

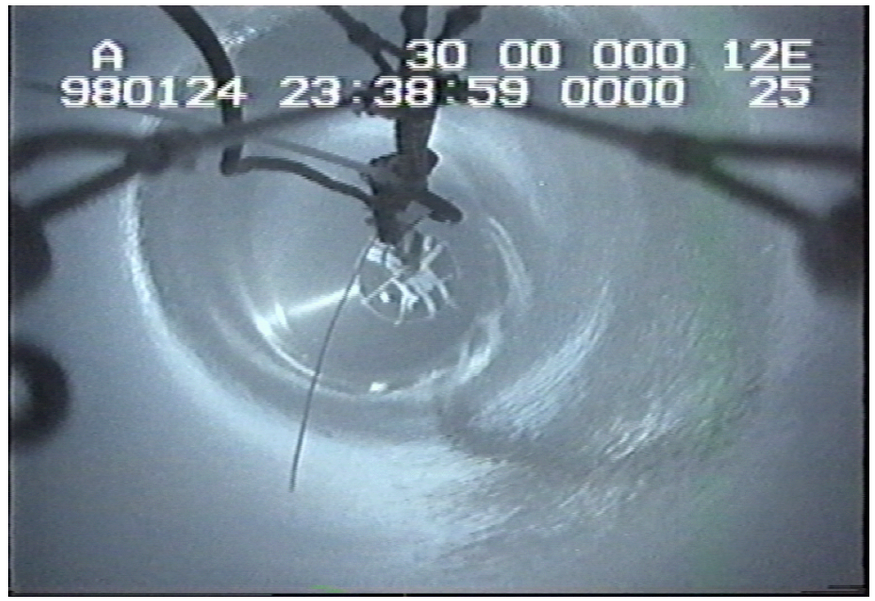
The Ice

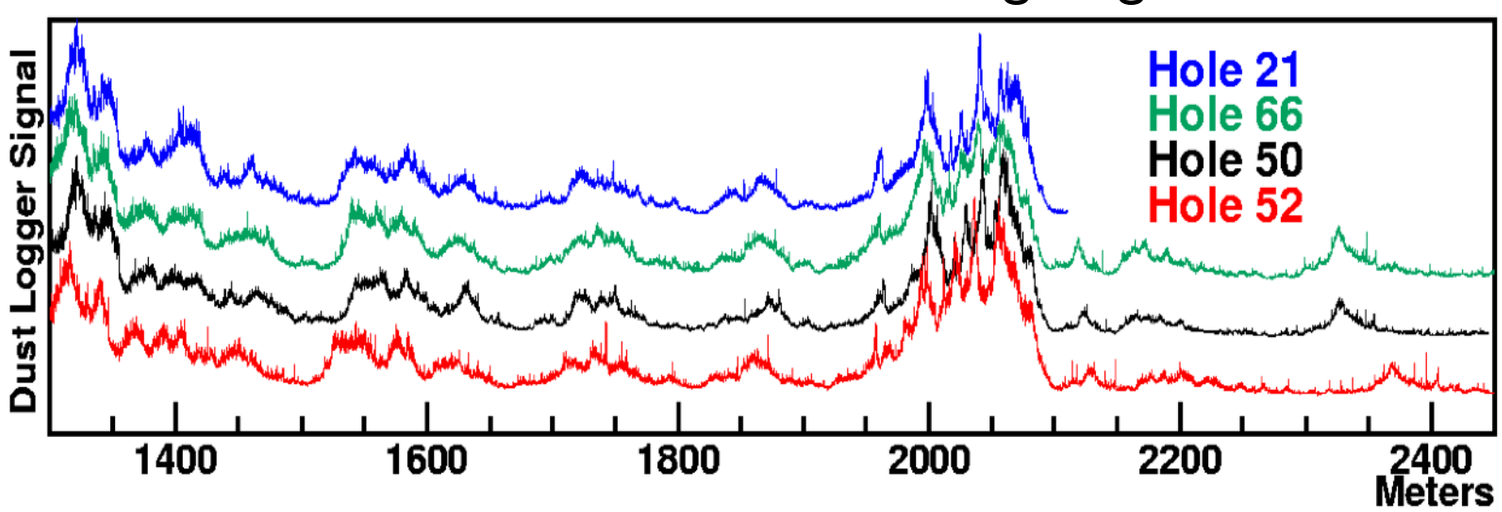


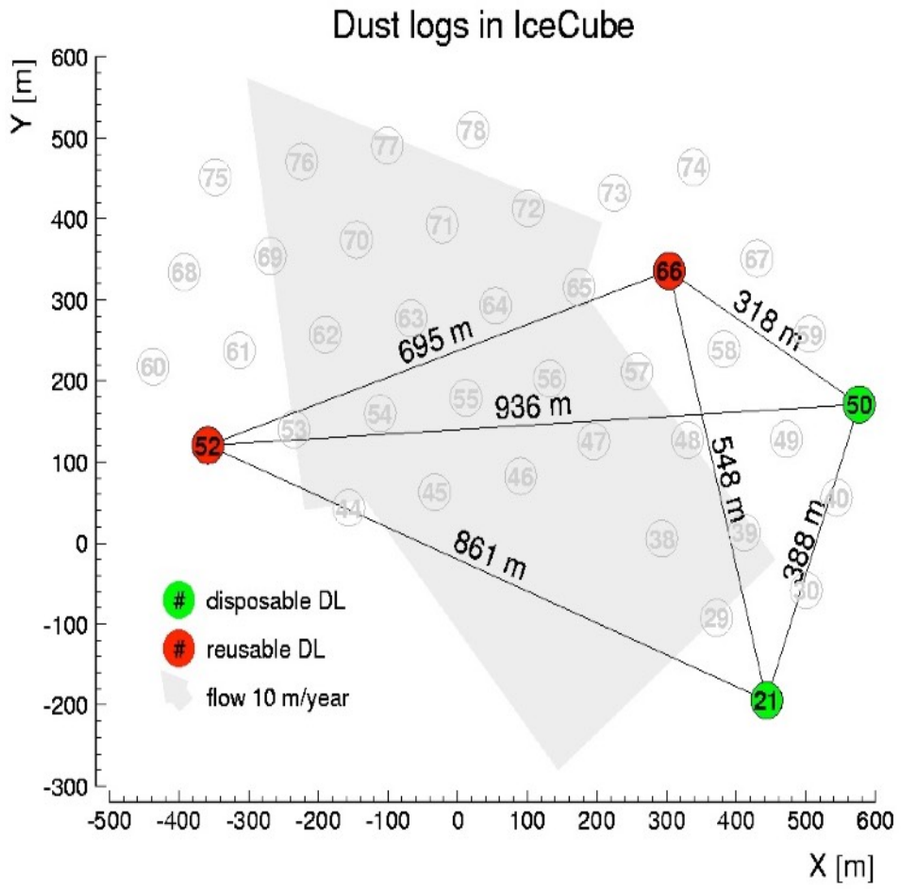
Major calibration efforts resulted in a very precise understanding of the ice surrounding the IceCube detector

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - One pair of Camera DOMs

absorption length ~ 210m
scattering length ~20-40m



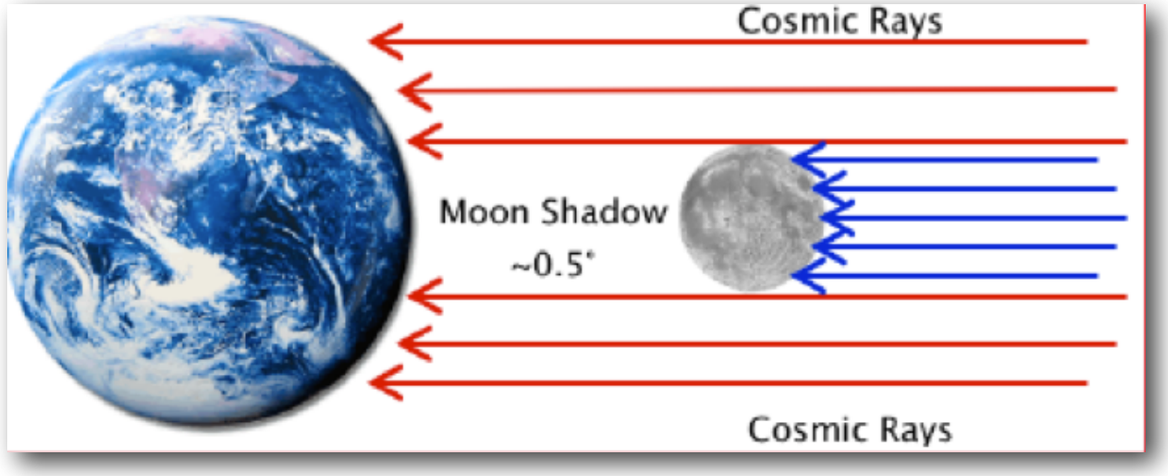




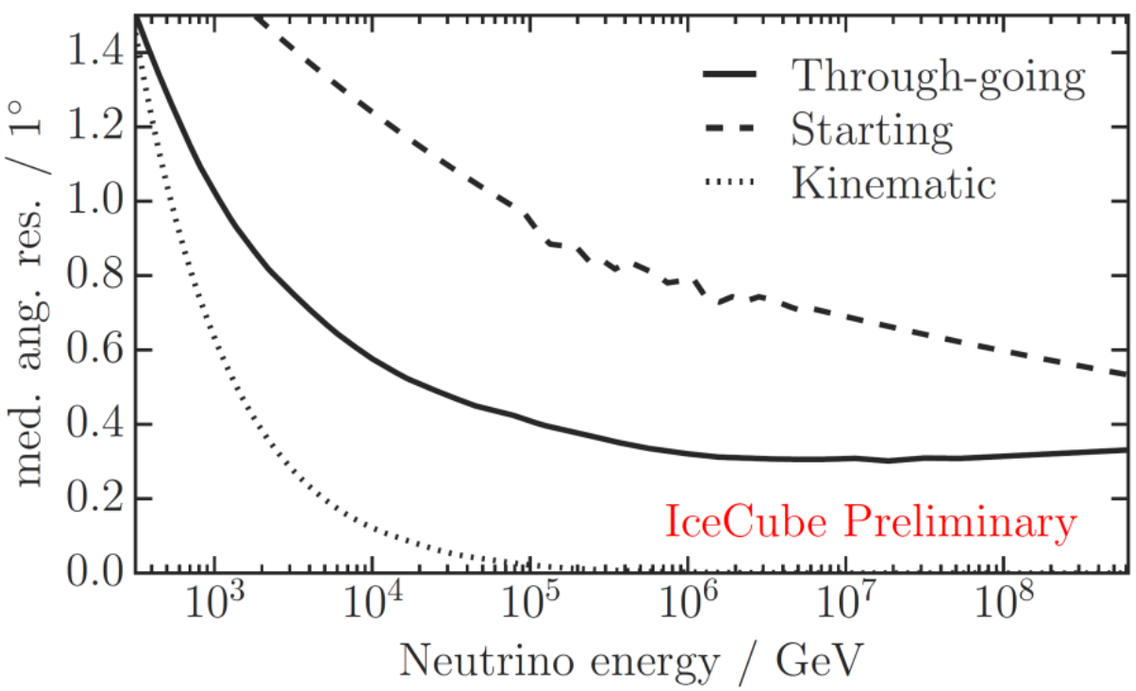
Calibration and Performance

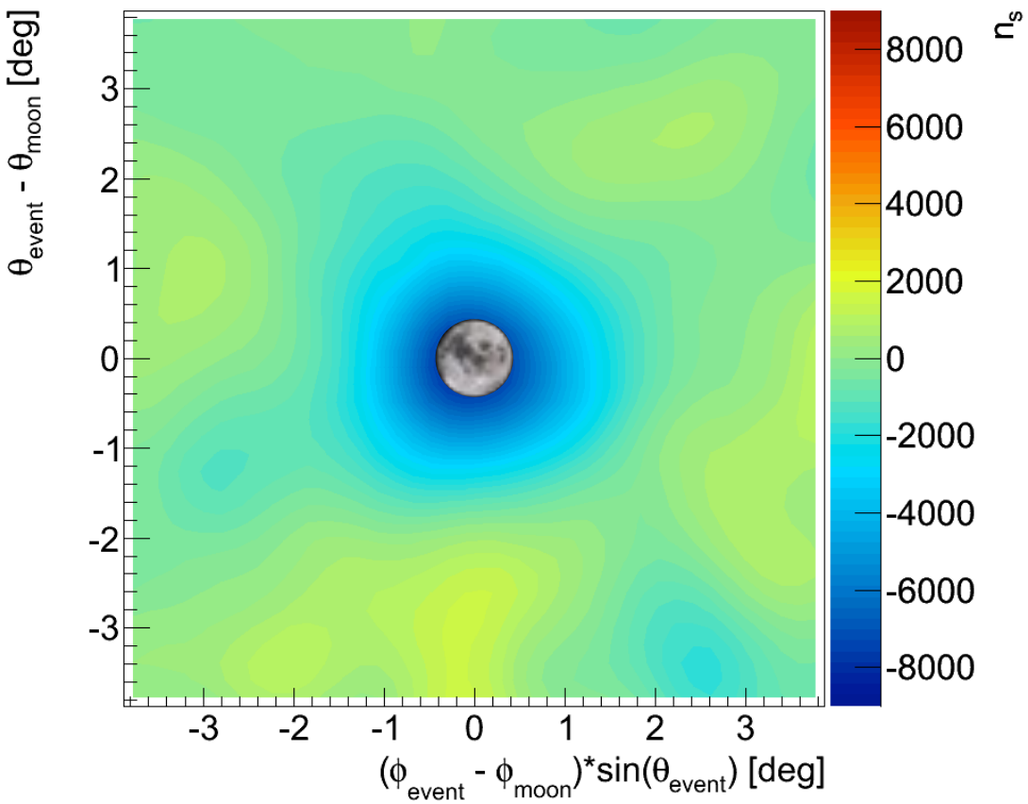
Physical Review D89 (2014) 102004

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - Moon Shadow
  - Atmospheric Neutrinos
  - Minimum-ionizing Muons



- Moon blocks cosmic rays - Observed muon deficit 14σ significance
- systematic pointing error <0.1°





Event Topologies in IceCube

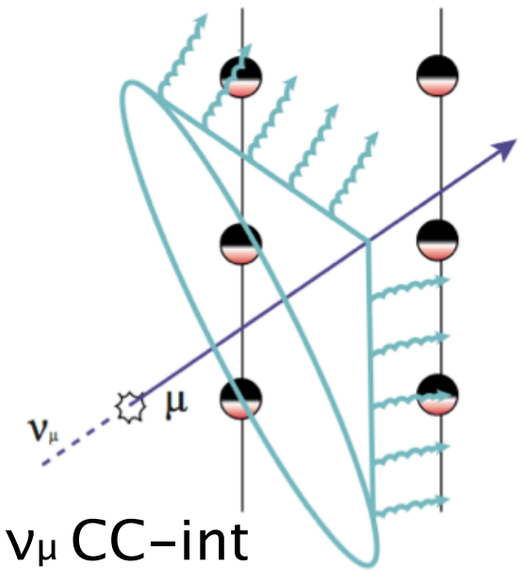
Track topology

(e.g. induced by muon neutrino)

CC: ν_μ

Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



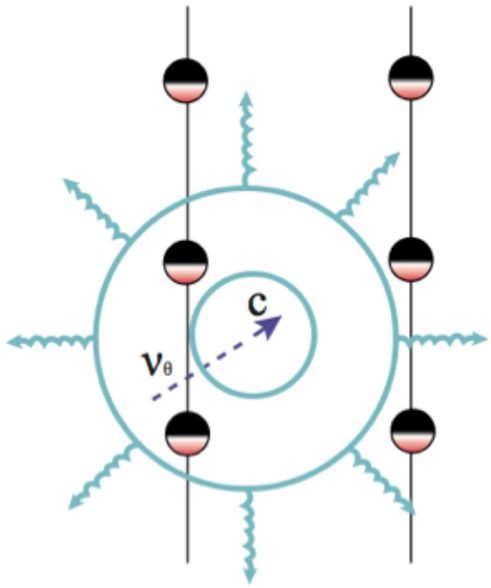
ν_μ CC–int

Cascade topology

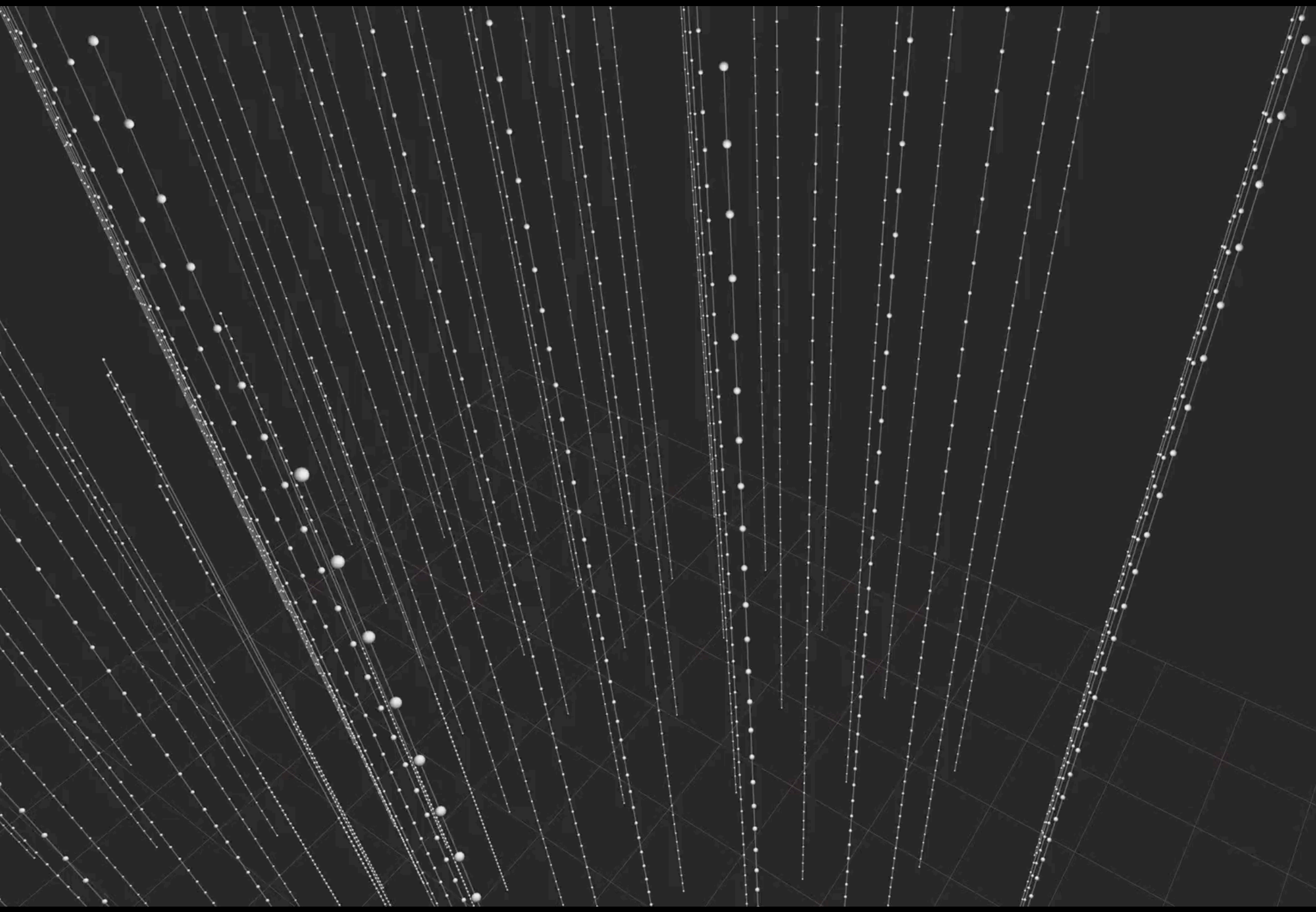
(e.g. induced by electron neutrino)

CC: ν_e ν_τ
NC: ν_e ν_μ ν_τ

Good energy resolution, 15%
Some pointing,
10° - 15°



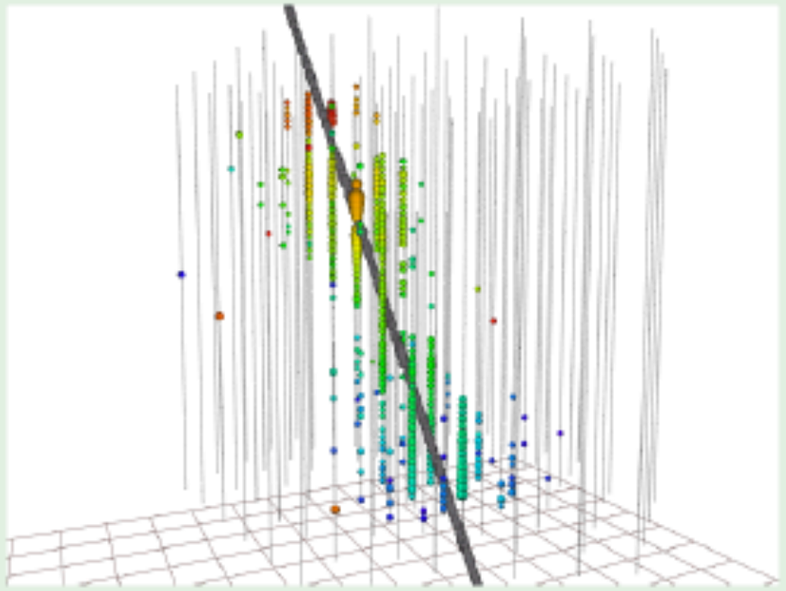
ν_e ν_τ CC–int & ν_i NC–int



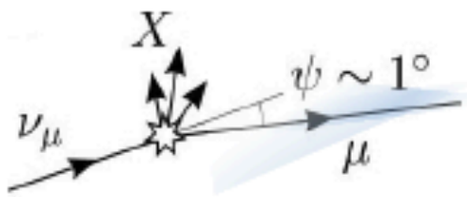
Color indicates on-time or delayed

Event topologies in IceCube

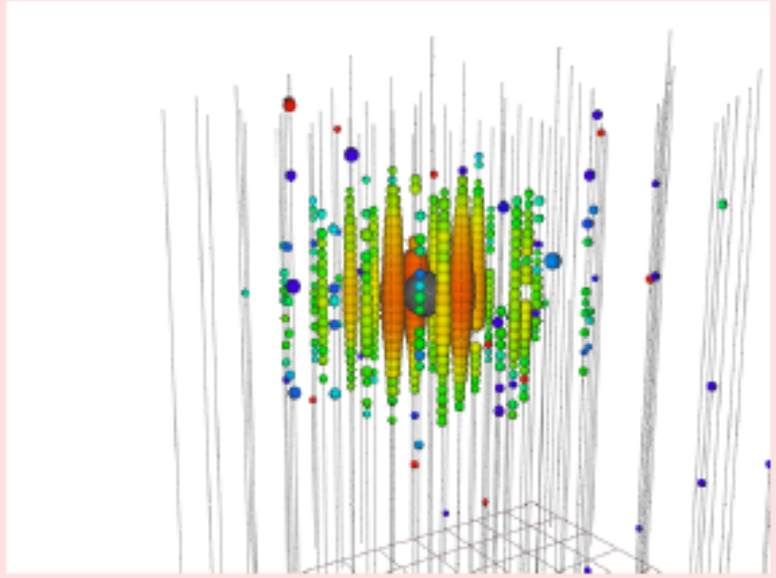
Track



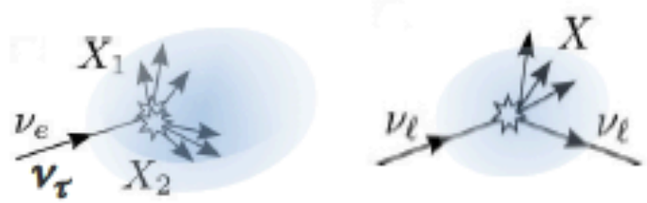
- Muon tracks (CC ν_μ)
- Resolution $< 1^\circ$
- Large energy uncertainties



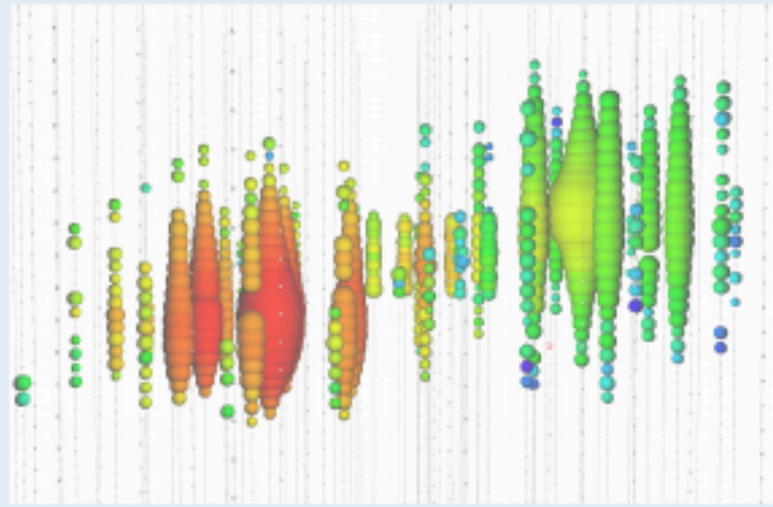
Cascade



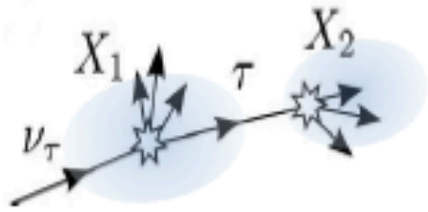
- NC or ν_e/ν_τ
- Resolution $\approx 15^\circ - 20^\circ$
- Energy resolution $\delta E/E \approx 15\%$



Double-bang



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



early  late

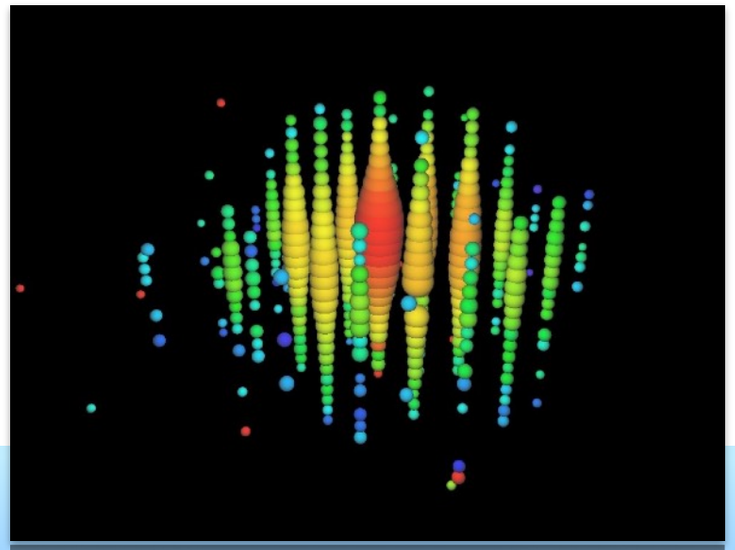
amount of light in detector $\propto$ ν energy

Selected Results and Science Program

Scientific Scope

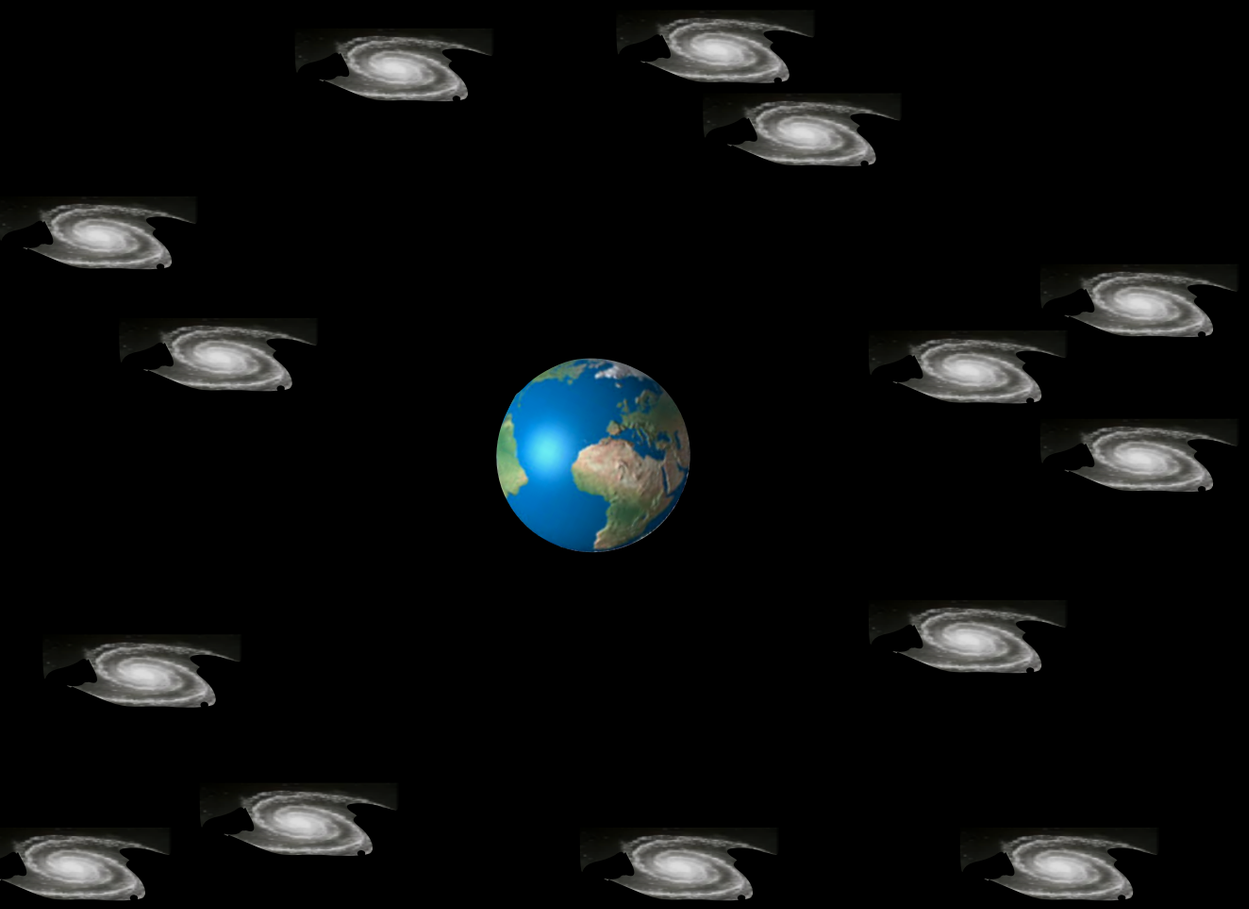
- ASTROPHYSICS
  - point sources of ν's (SNR, AGN …), extended sources
  - transients (GRBs, AGN flares …)
  - diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- COSMIC RAY PHYSICS
  - energy spectrum around "knee", composition, anisotropy
- DARK MATTER
  - indirect searches (Earth, Sun, Galactic center/halo)
- EXOTICS
  - magnetic monopoles
- PARTICLE PHYSICS
  - ν oscillations, sterile ν's
  - charm in CR interactions
  - violation of Lorentz invariance
- SUPERNOVAE (galactic/LMC)
- GLACIOLOGY & EARTH SCIENCE

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



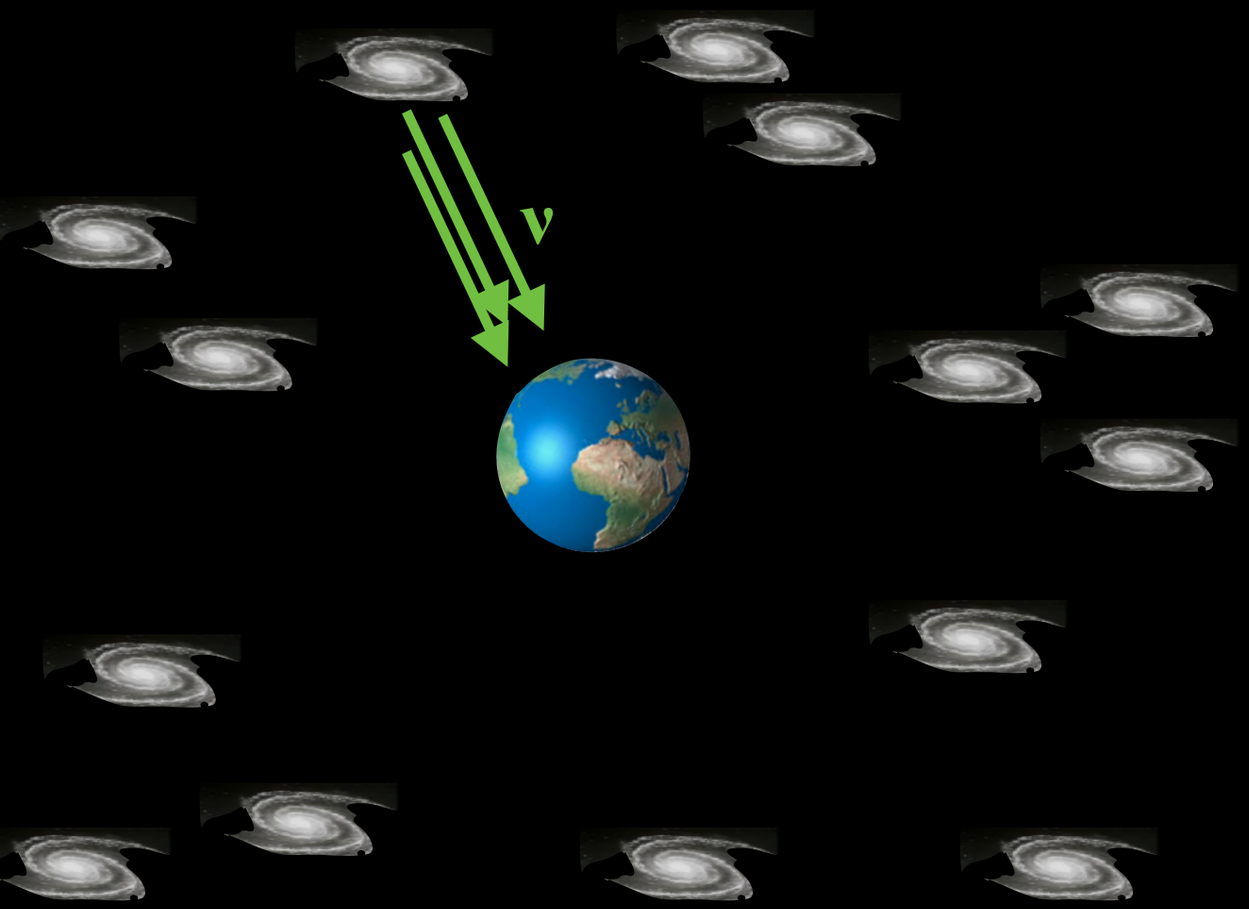
Astro-physical Neutrino Search

Finding astrophysical neutrinos



How to find astrophysical neutrinos ?

Finding astrophysical neutrinos



Point source search

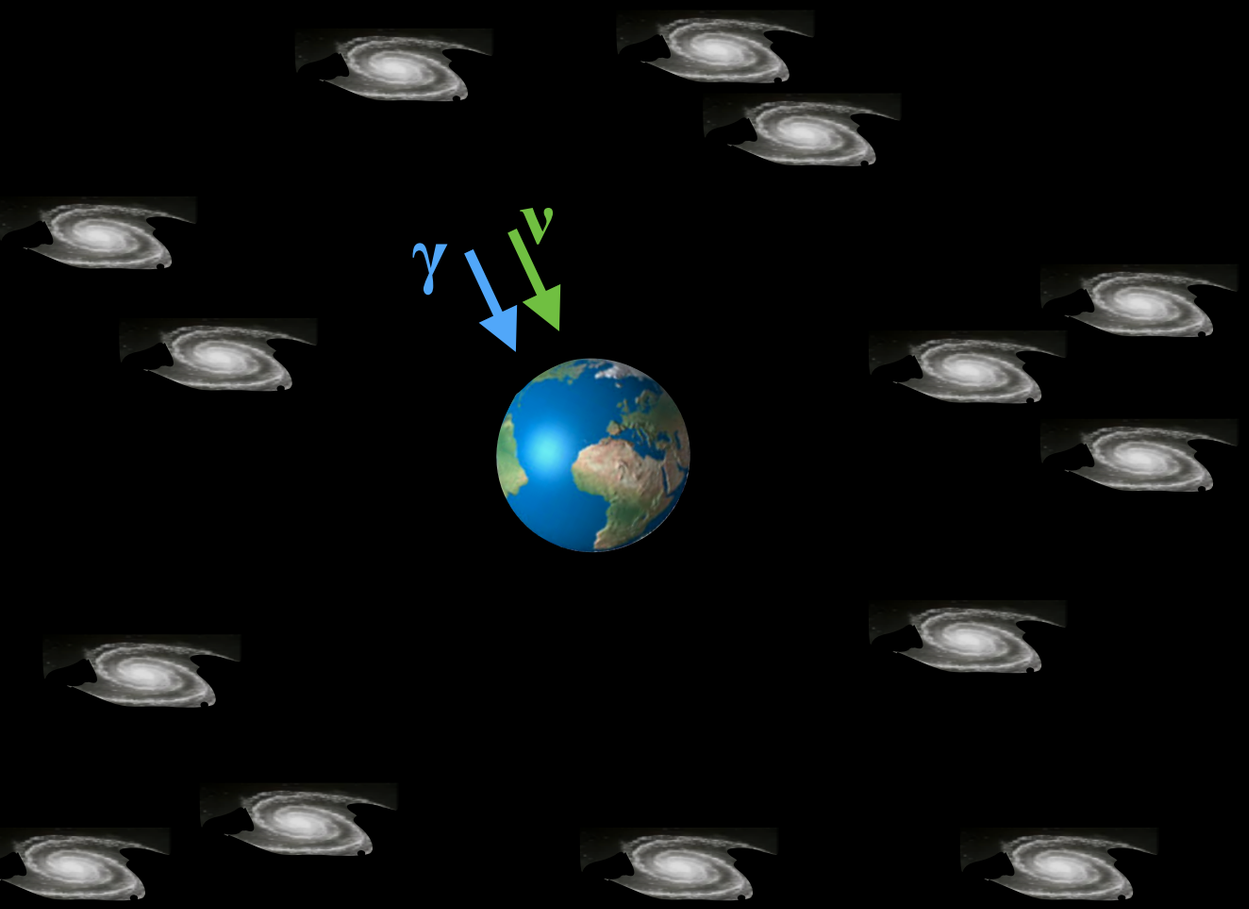
- search for clustering of neutrinos from point in the sky

Finding astrophysical neutrinos

Transient source search

- search for spacial and temporal clustering of neutrinos

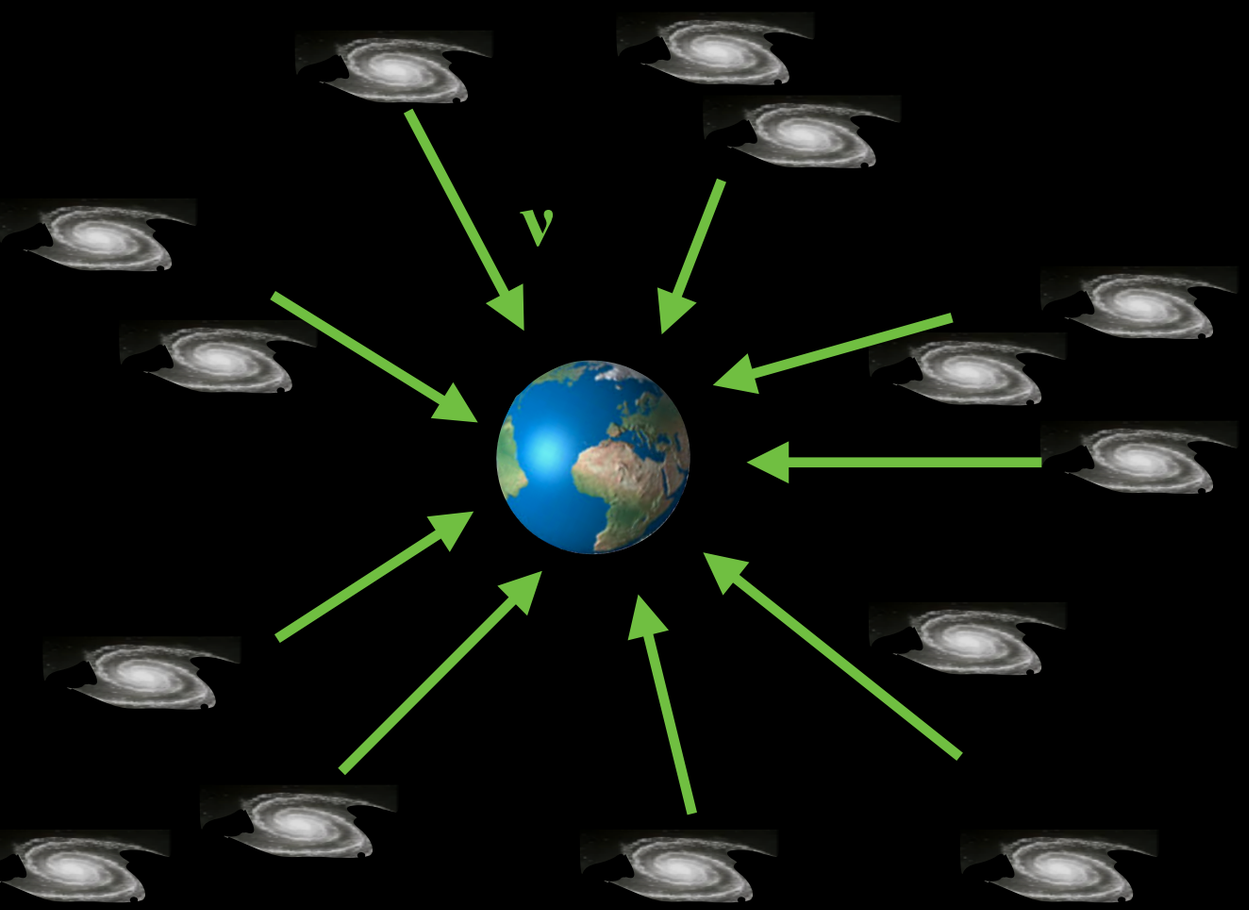
Finding astrophysical neutrinos



Multi-messenger search

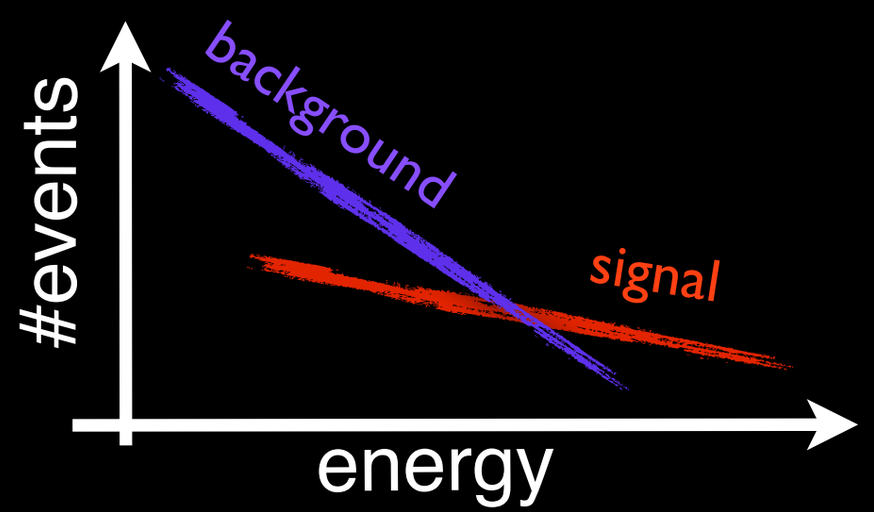
- search for a coincidence between neutrino and other messenger particles spacial at particular time and location

Finding astrophysical neutrinos

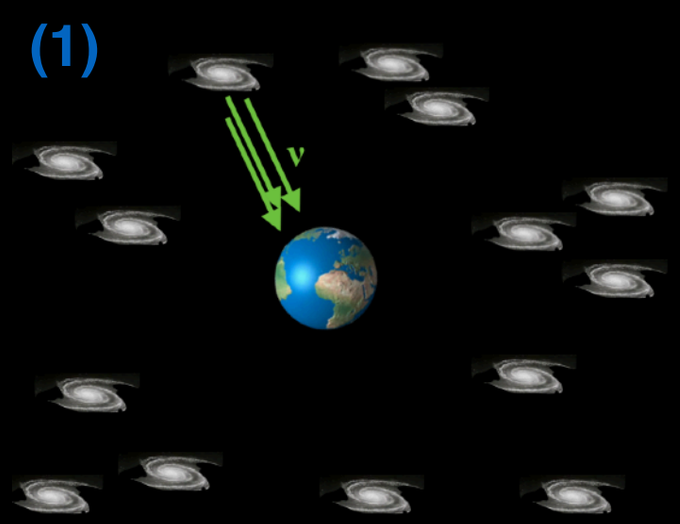


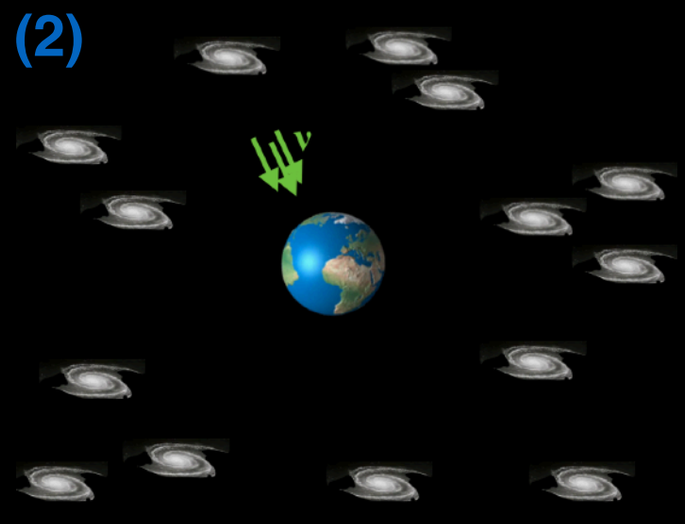
Diffuse search

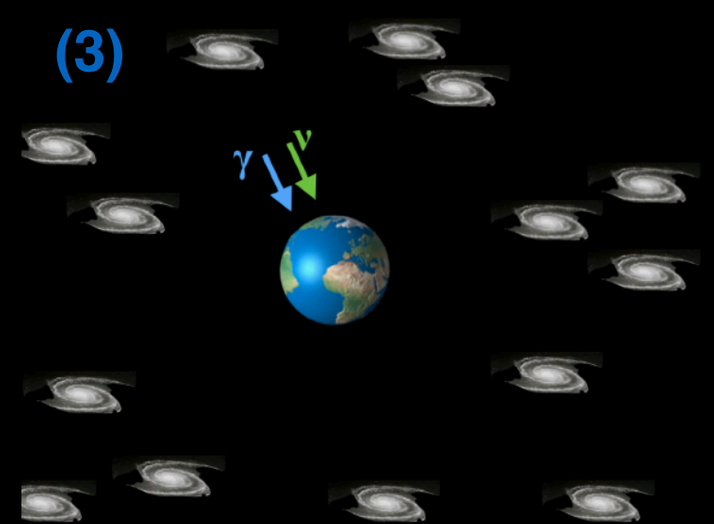
- search for spectral feature, inconsistent with atmospheric background predictions

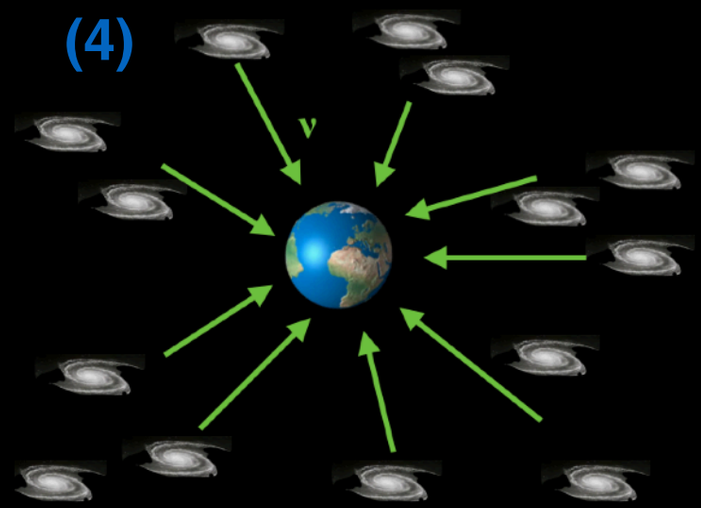


Finding astrophysical neutrinos









(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

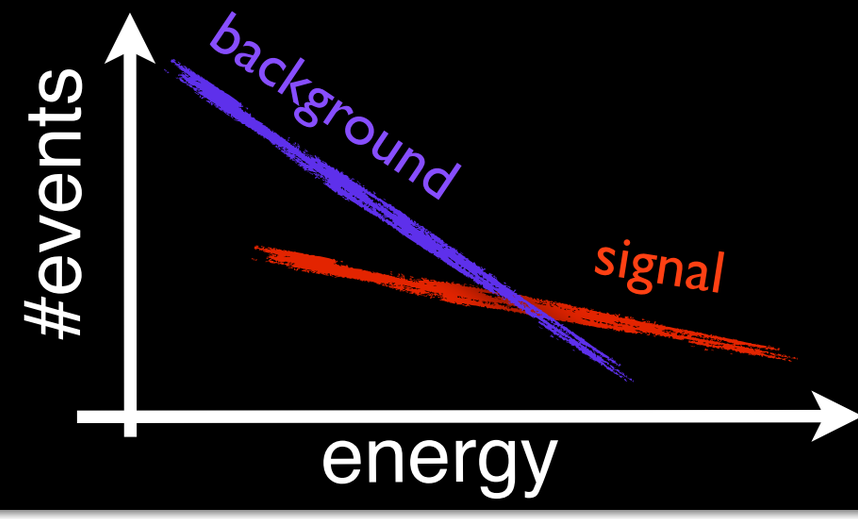
(3) Multi-messenger search

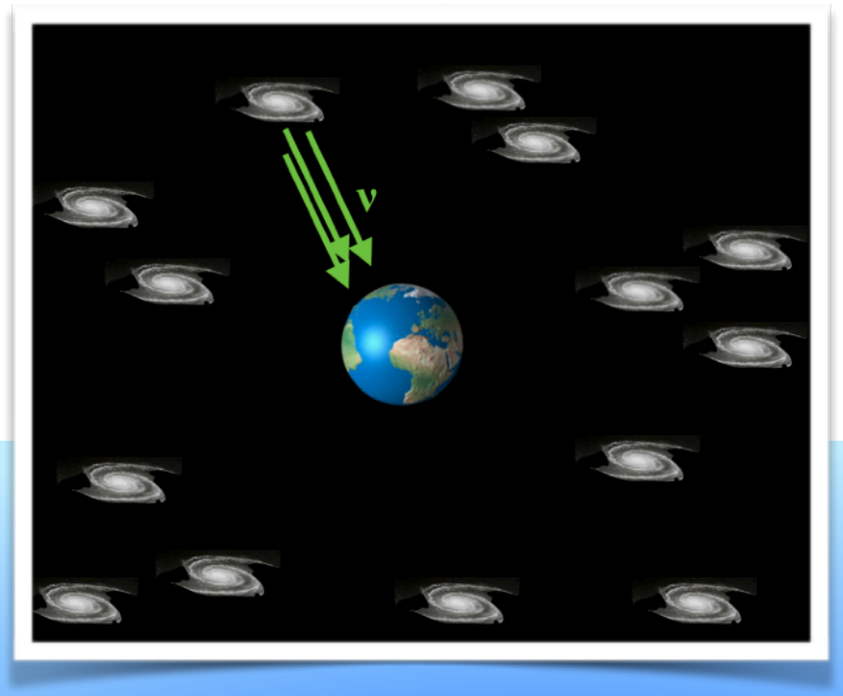
- search for a coincidence between neutrino and other messenger particles spacial at particular time and location

(4) Diffuse search

- search for spectral feature, inconsistent with atmospheric background predictions

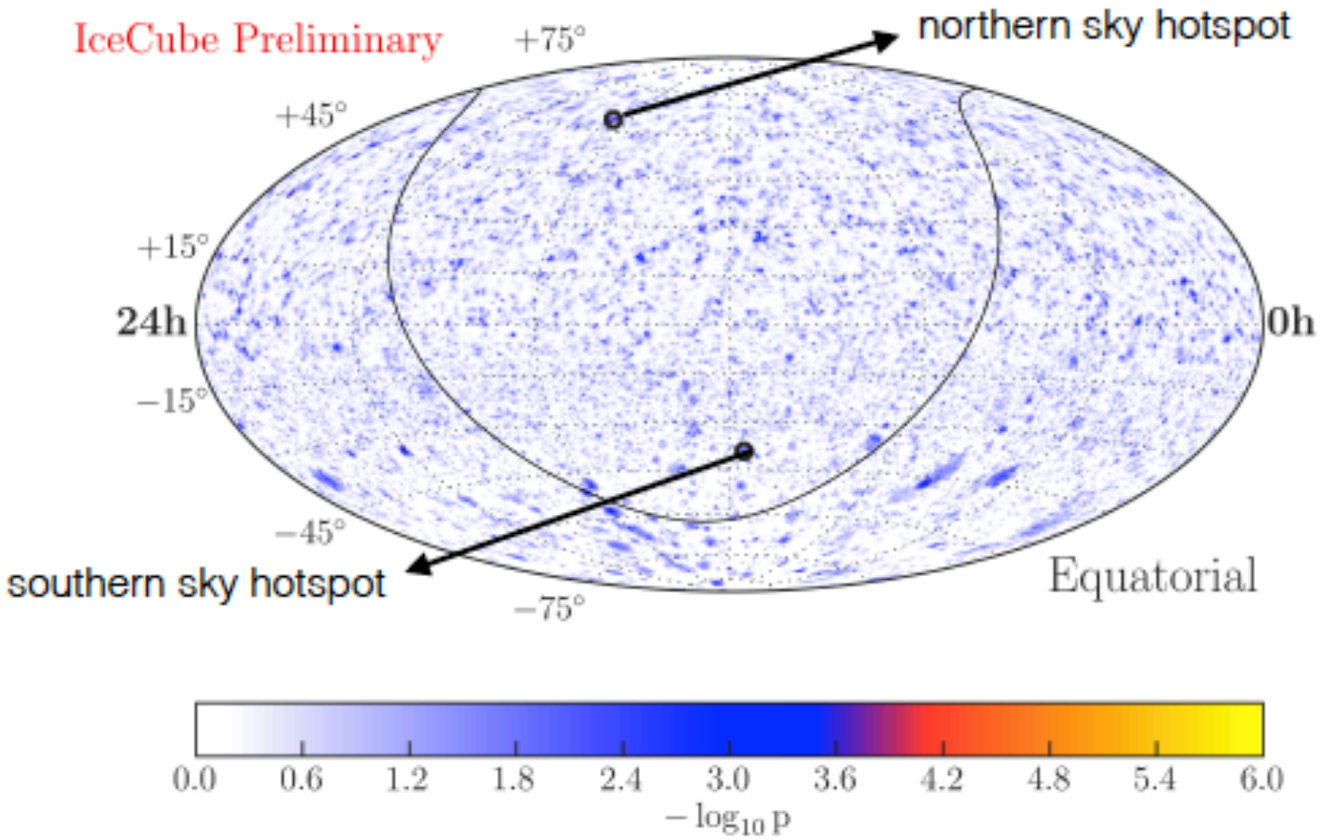
…. + various combinations and

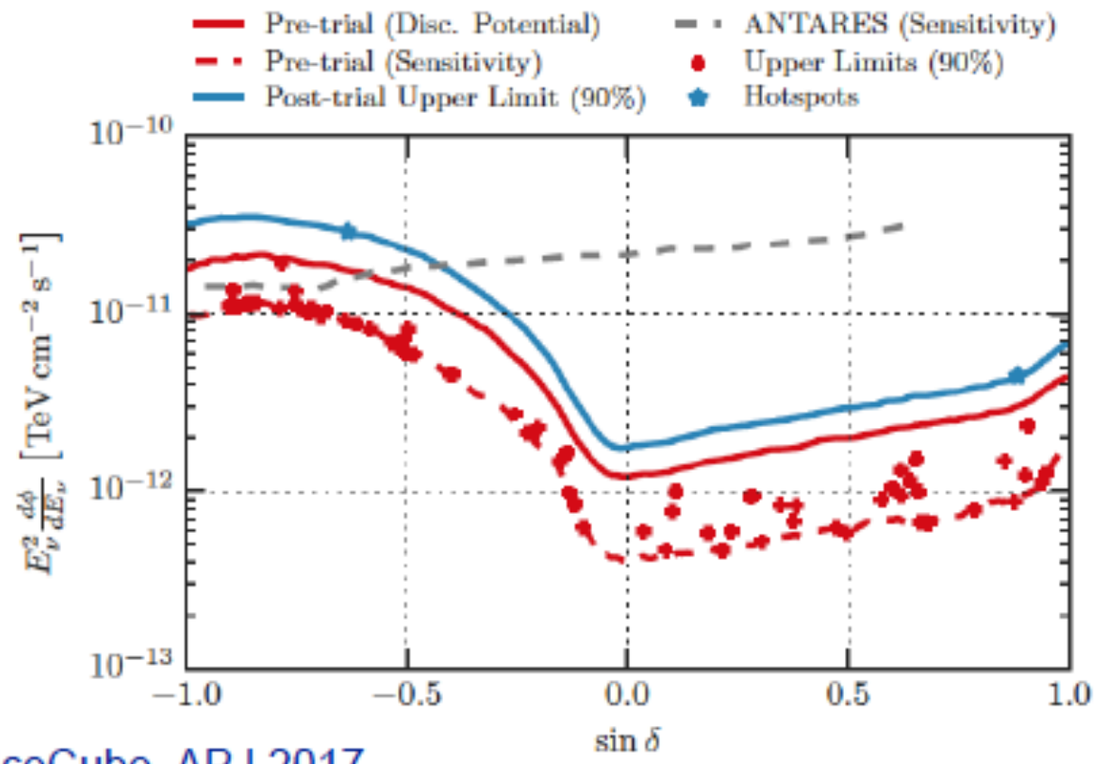




Point source search

Point Source Search

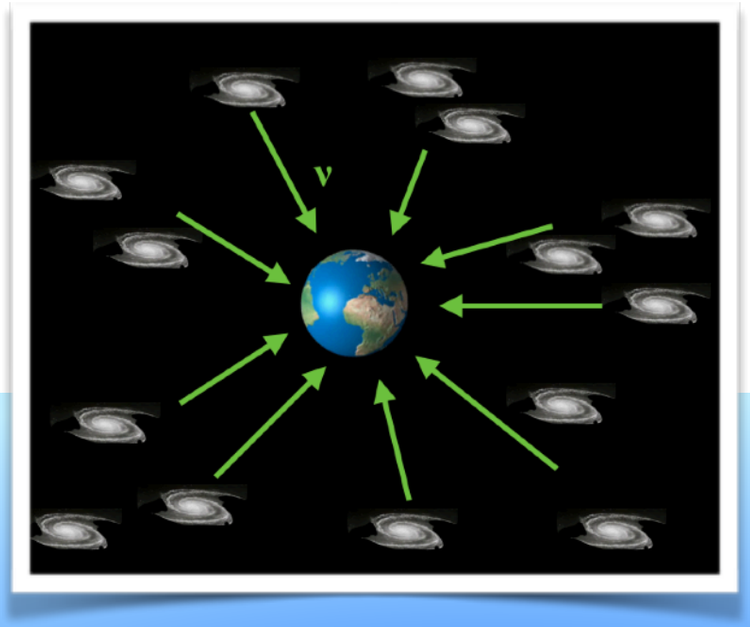




IceCube, APJ 2017

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

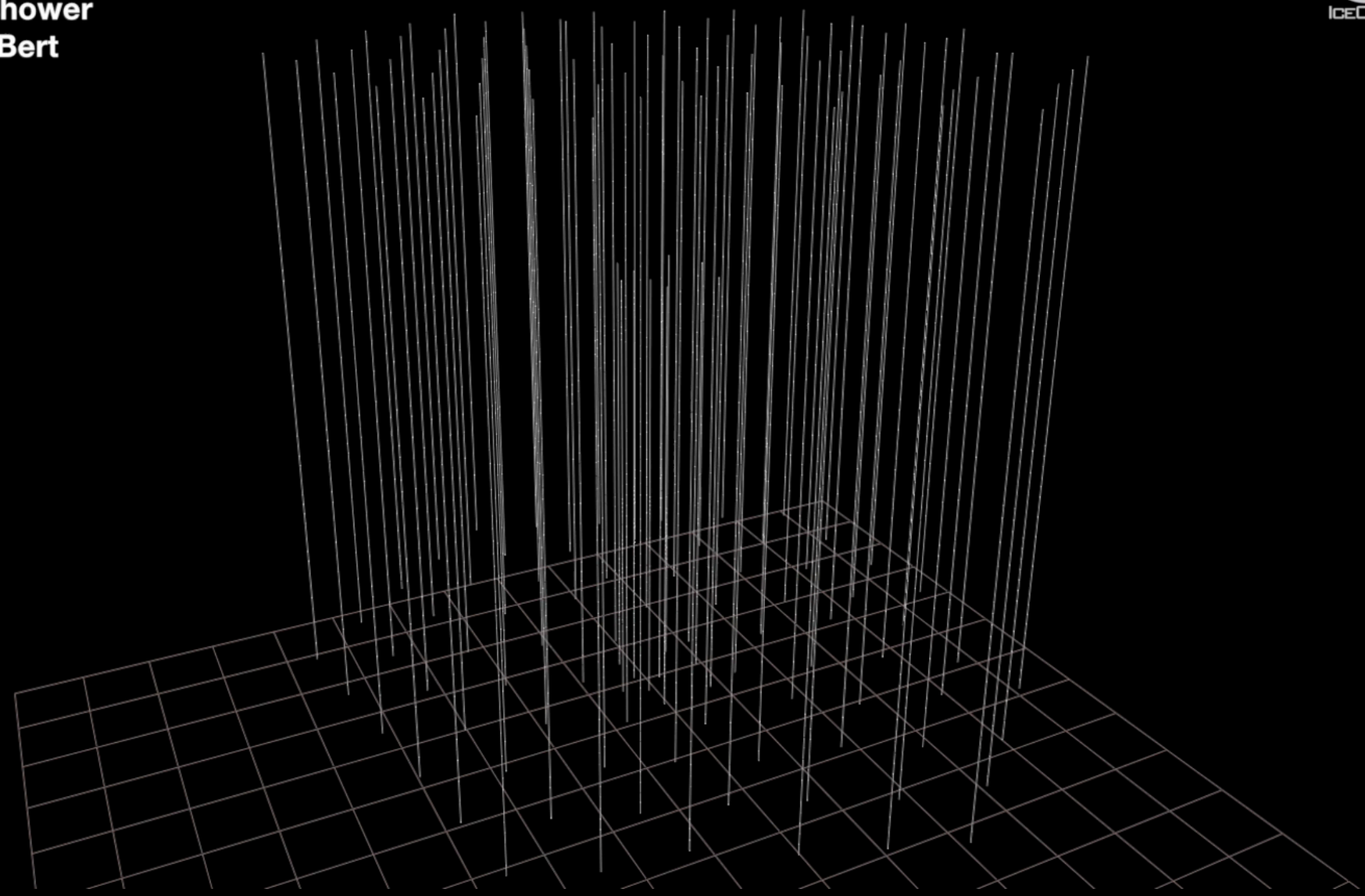
- No point/extended source found yet.
- No correlation with source catalogs found.



Diffuse Neutrino Flux Search

A cosmic neutrino interacts INSIDE the detector: it is too energetic to be produced in the atmosphere

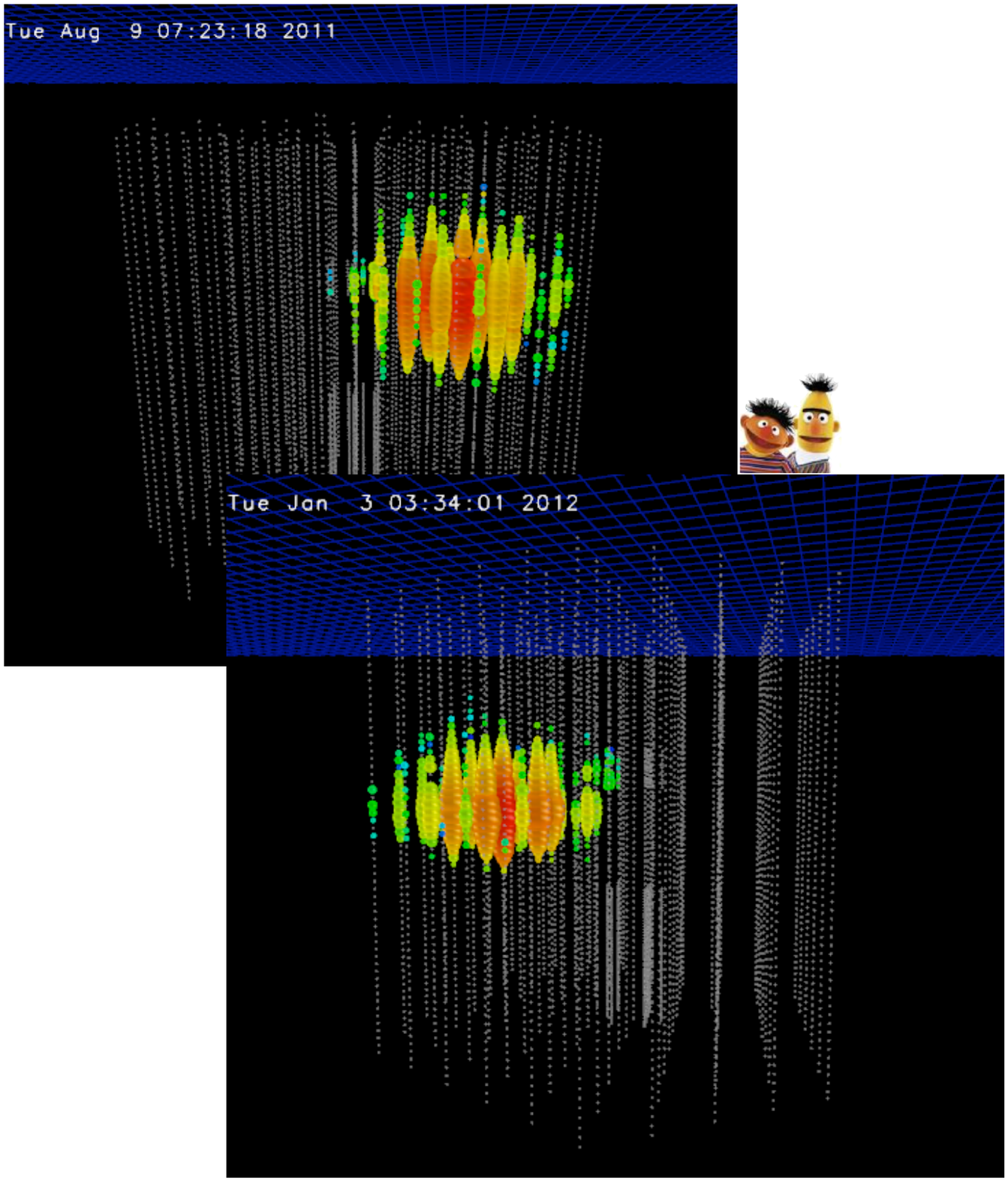
date: **August 9, 2011**
energy: **1.04 PeV**
topology: **shower**
nickname: **Bert**



> 300 optical sensors; > 100,000 photons; 2 nanosec time resolution

Search for highest energy neutrinos

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

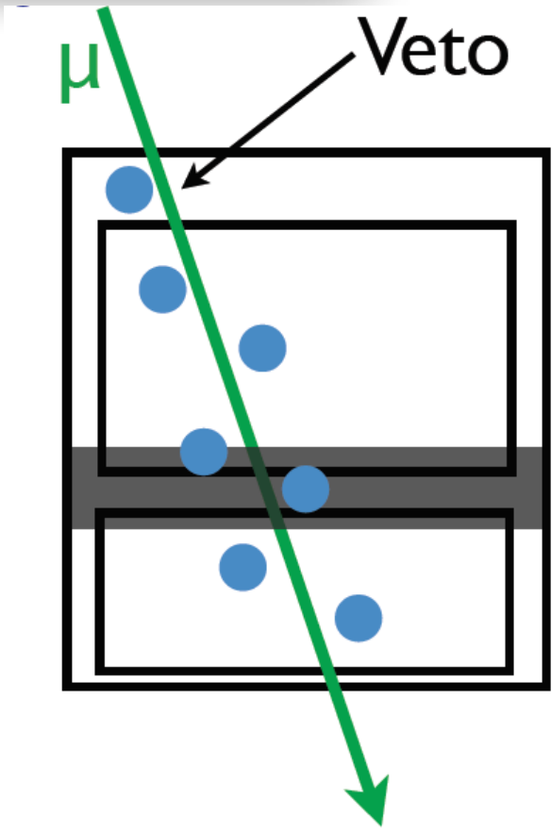


In two years of data expect 0.08 events at high energies, but observed 2 events !!

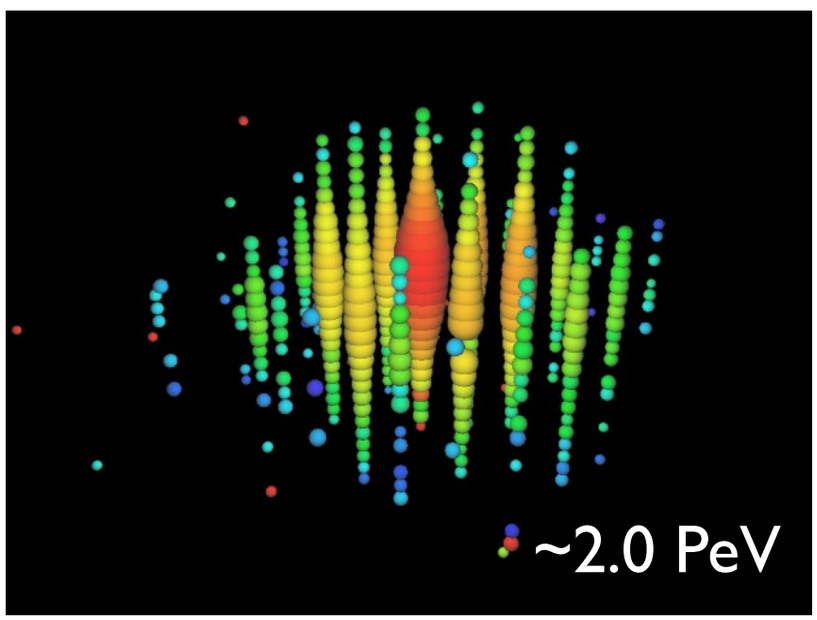
- Ernie ~1.15 PeV (~$1.9 \cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~$1.7 \cdot 10^{-4}$J)
- Topology of the events - cascades
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

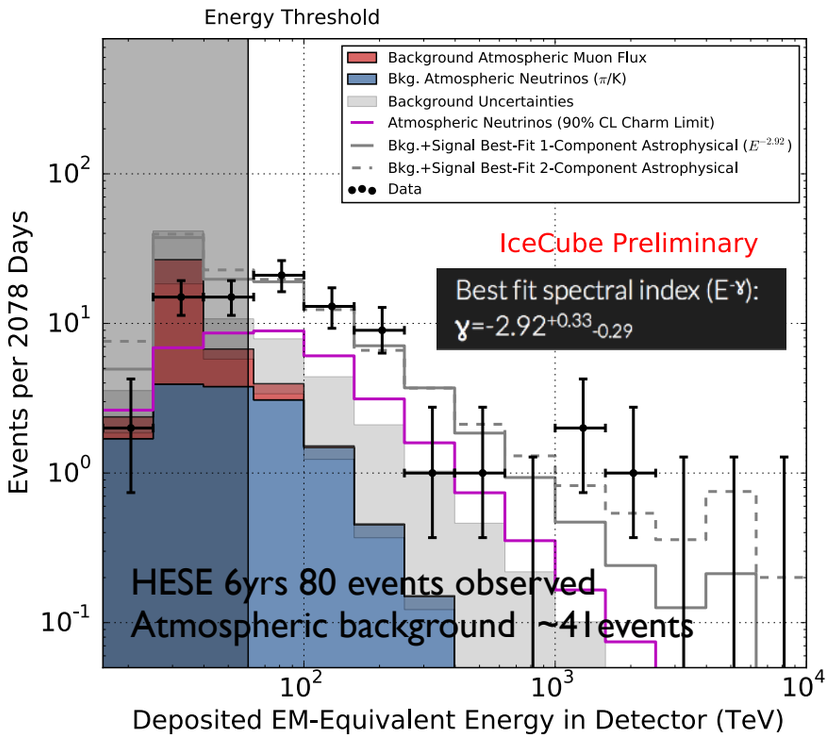
Observation of high-energy astrophysical neutrinos

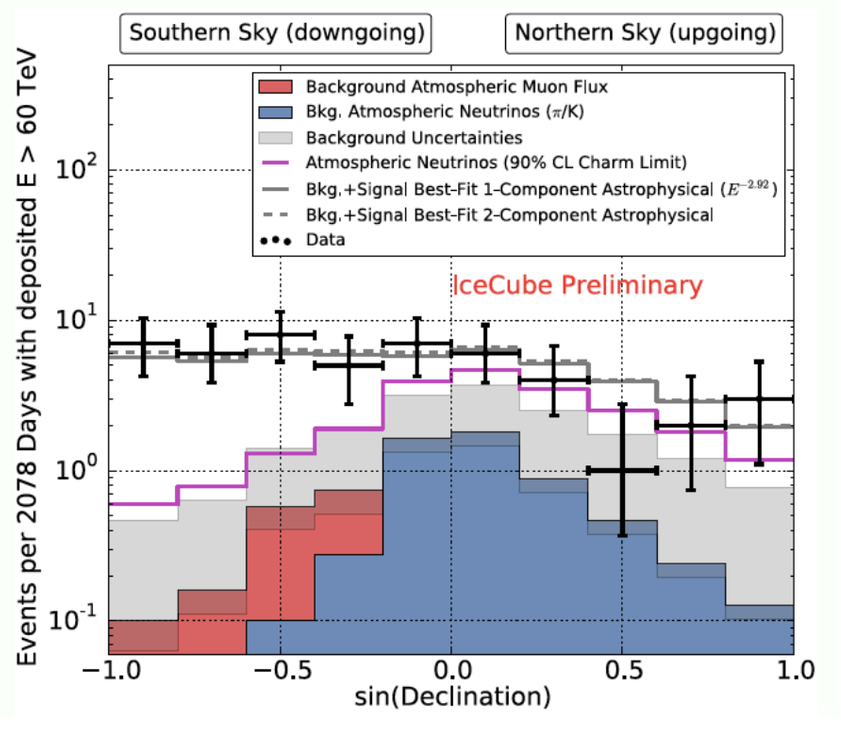
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*



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



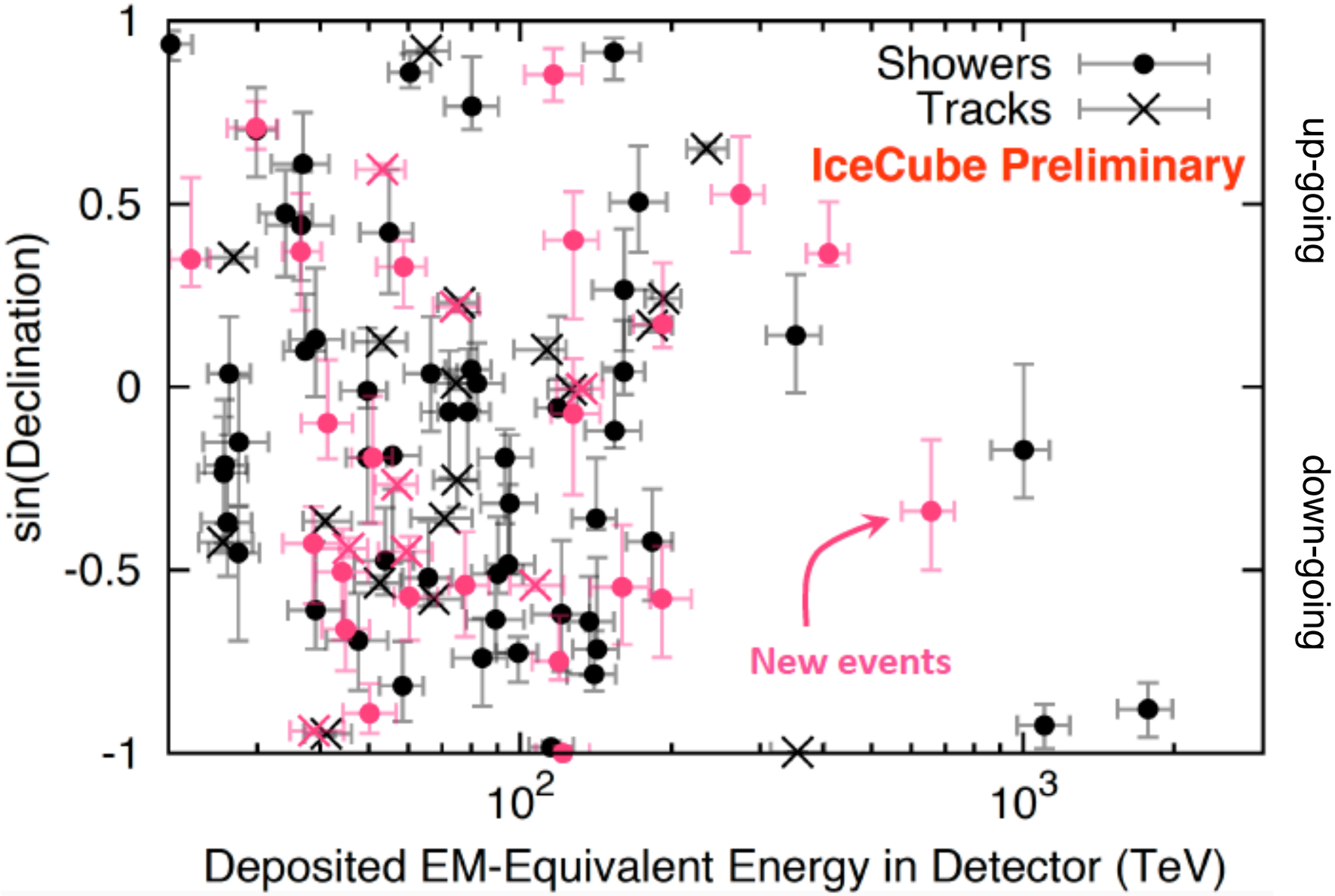


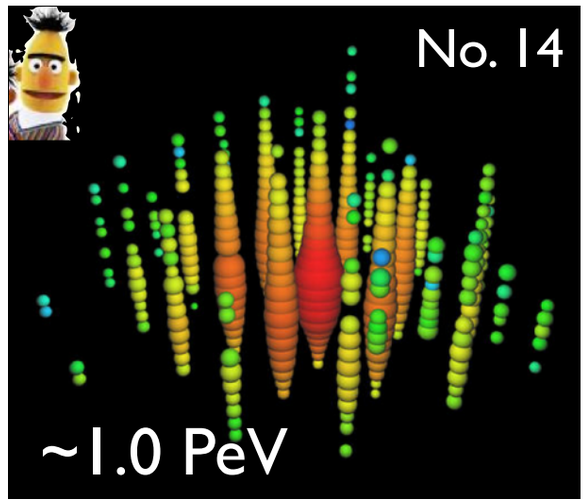


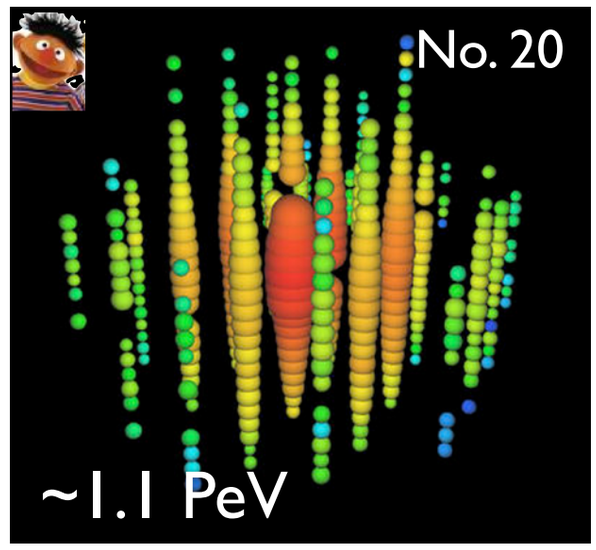
High-Energy Starting Events (HESE) – 7.5 yr

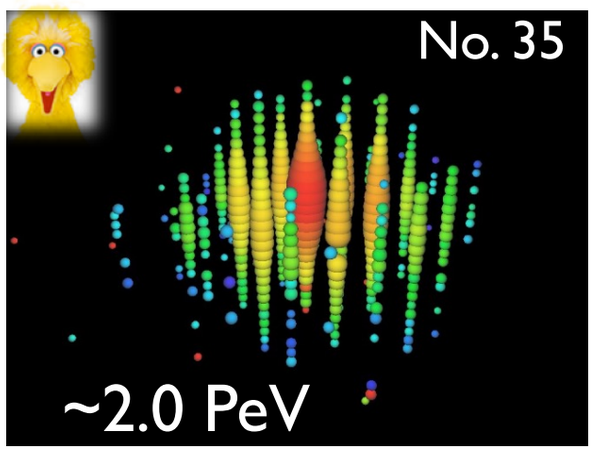
HESE7.5yrs results

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







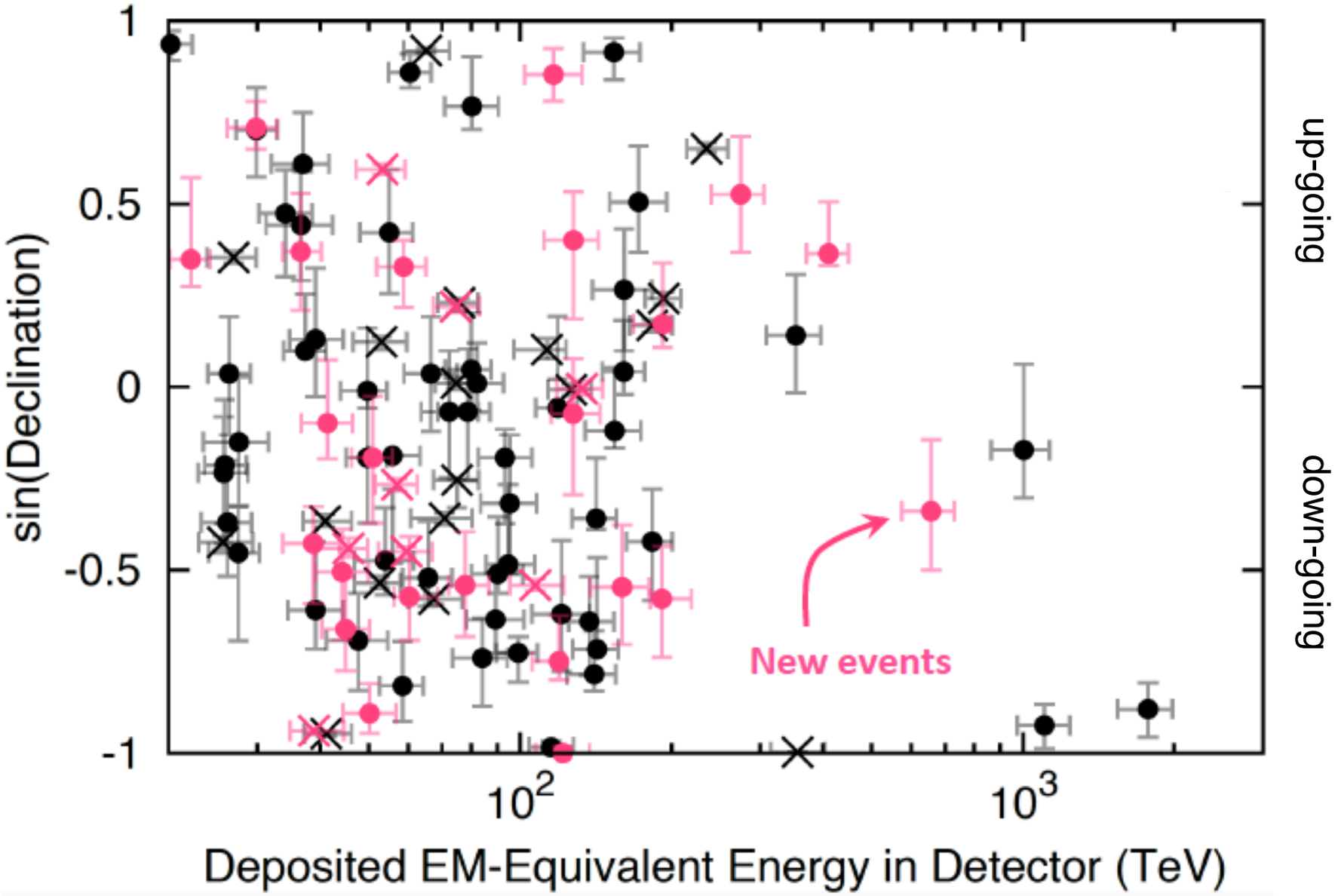


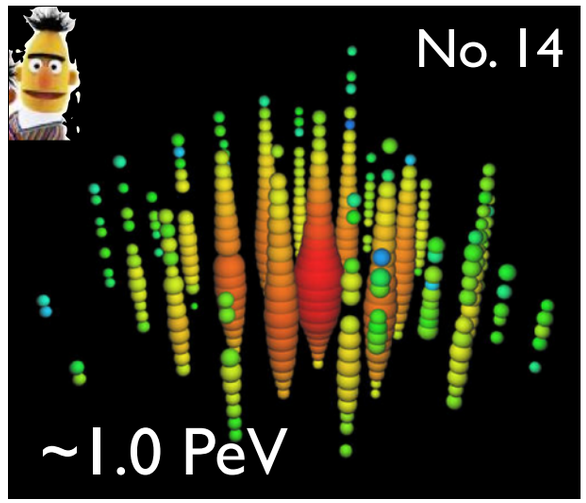
- Recently unblinded 1.5 additional years of data (new calibration)
- Topology ID added (Cascades, Tracks, Double Cascades)
- Above 60TeV: 60 events - 17 new events in 2016/2017 season
- All energies: 102 events - 31 new events in 2016/2017 season

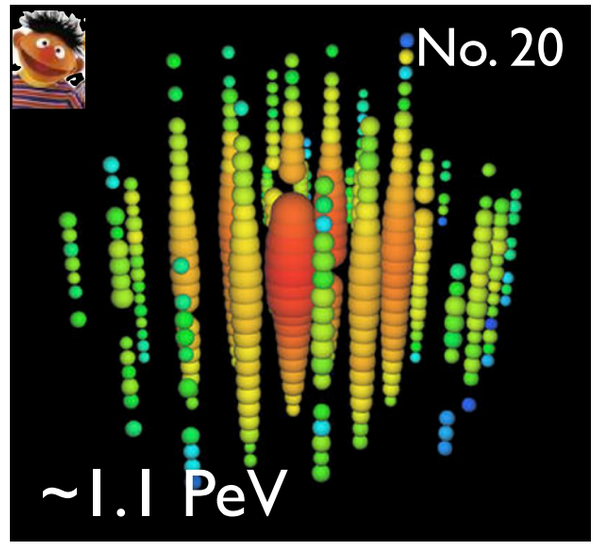
High-Energy Starting Events (HESE) – 7.5 yr

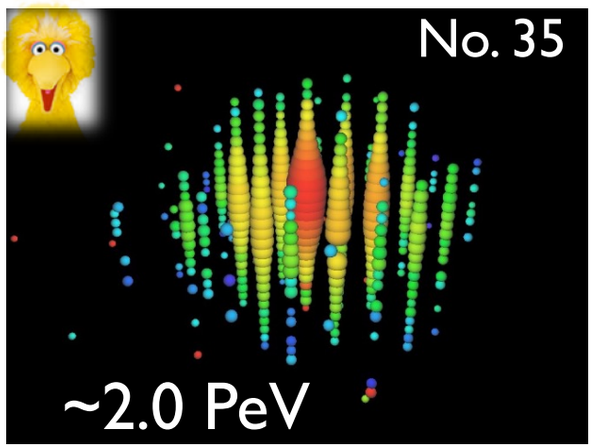
HESE7.5yrs results

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









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HE

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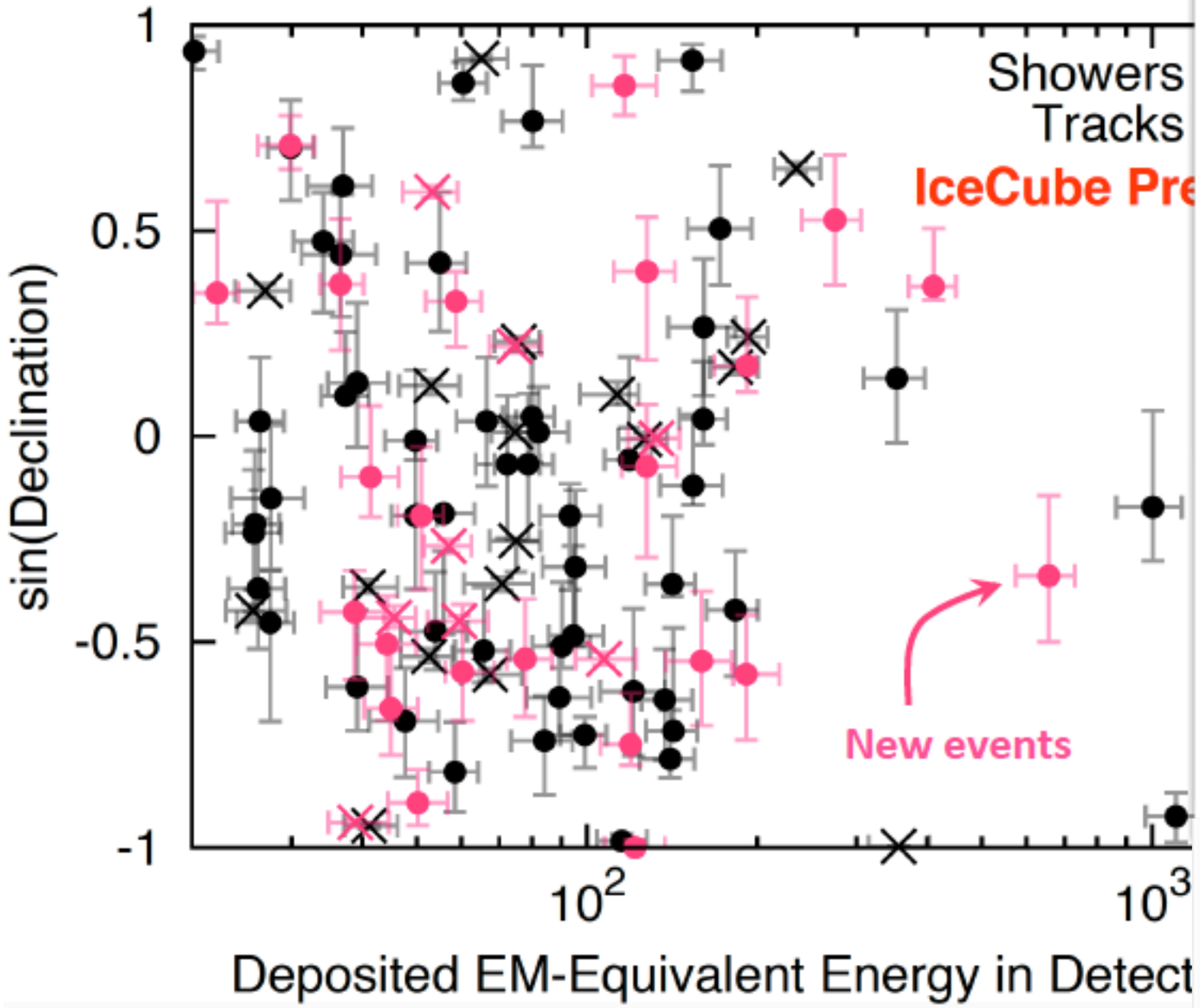

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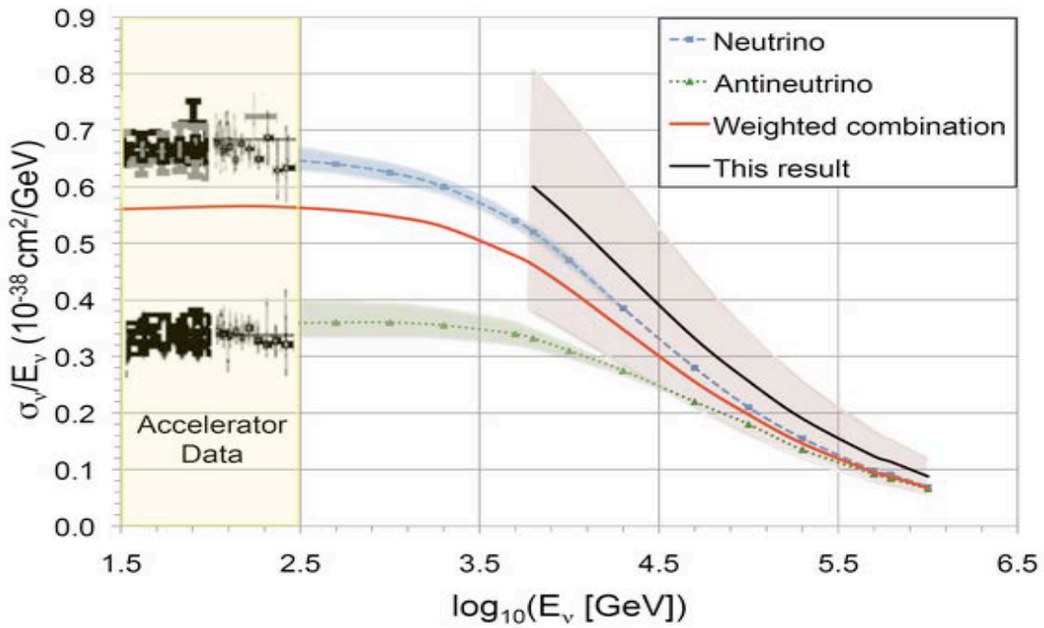
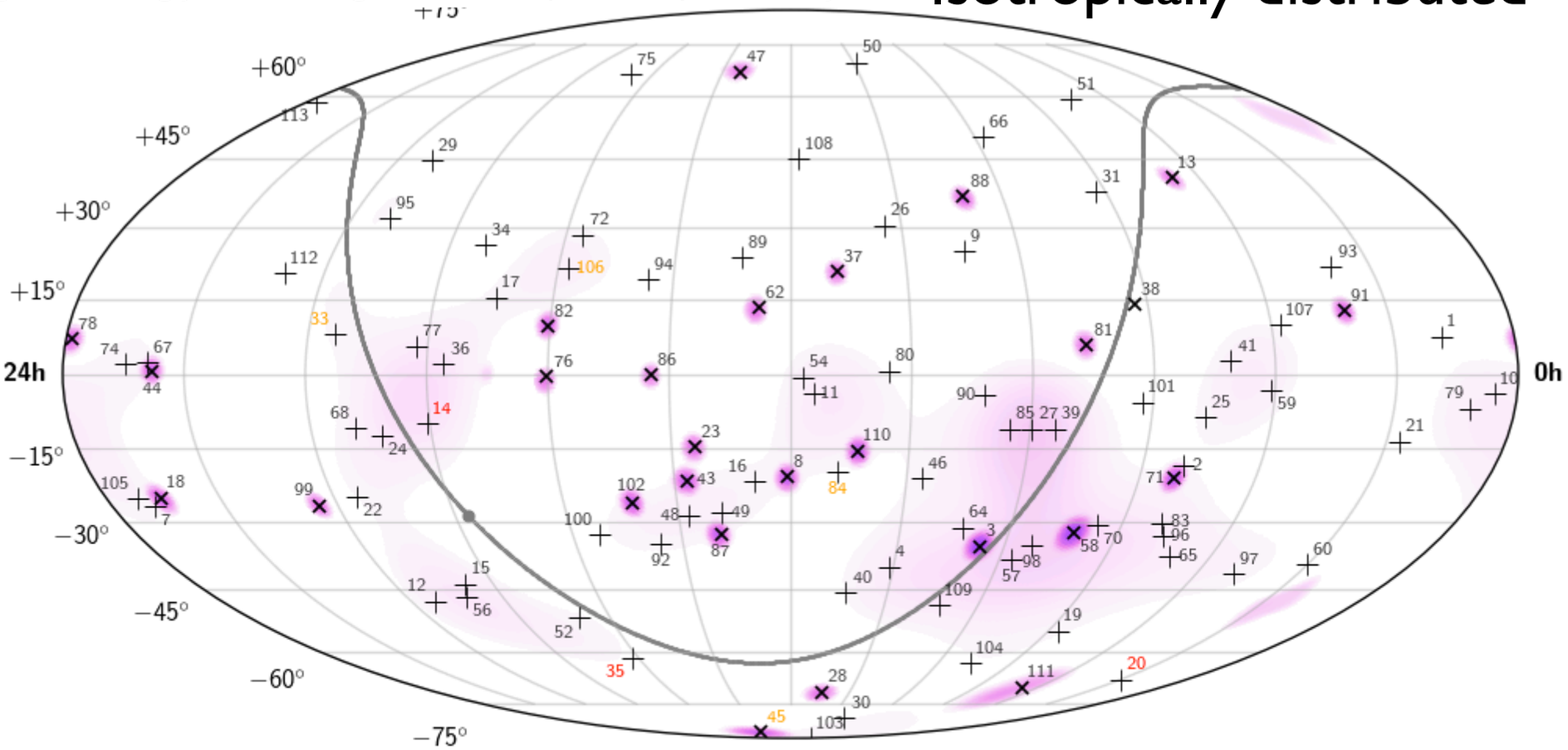


Arrival directions (highest energy events)

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

High-Energy Starting Events (HESE) – 7.5 yr

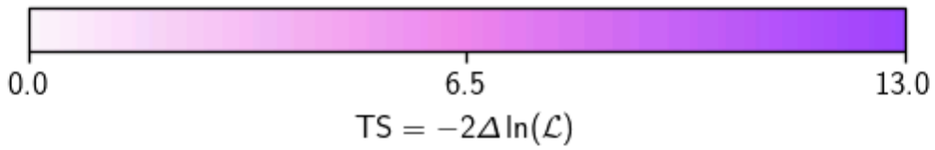
Isotropically distributed



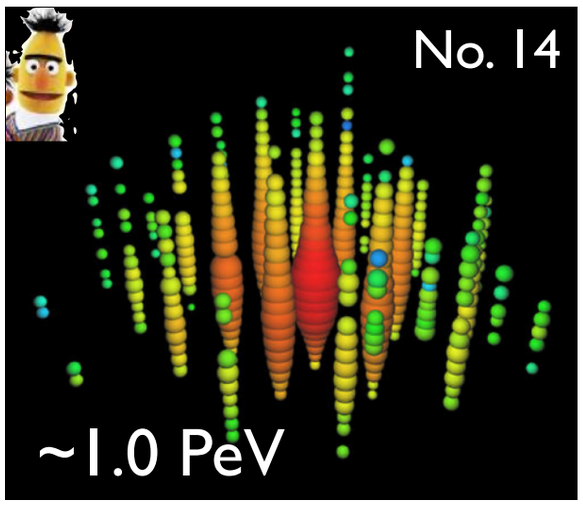
Coincident events: 32, 55

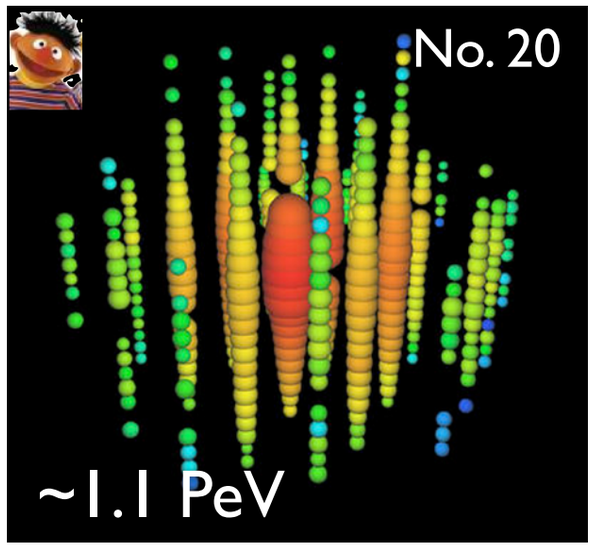
Dropped events: 5, 6, 42, 53, 61, 63, 69, 73

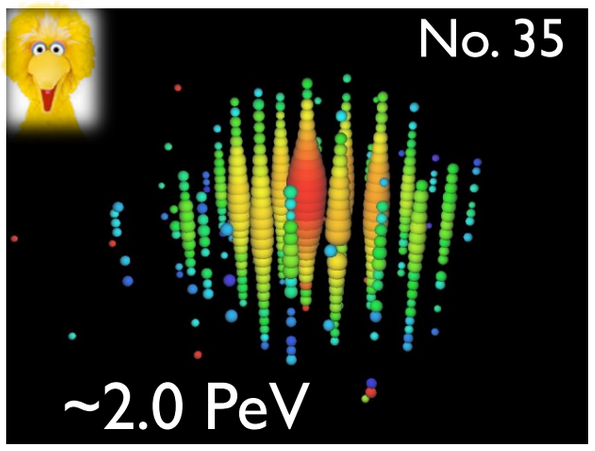
Equatorial



$E < 300\,\text{TeV}$ $300\,\text{TeV} < E < 1\,\text{PeV}$ $1\,\text{PeV} < E$

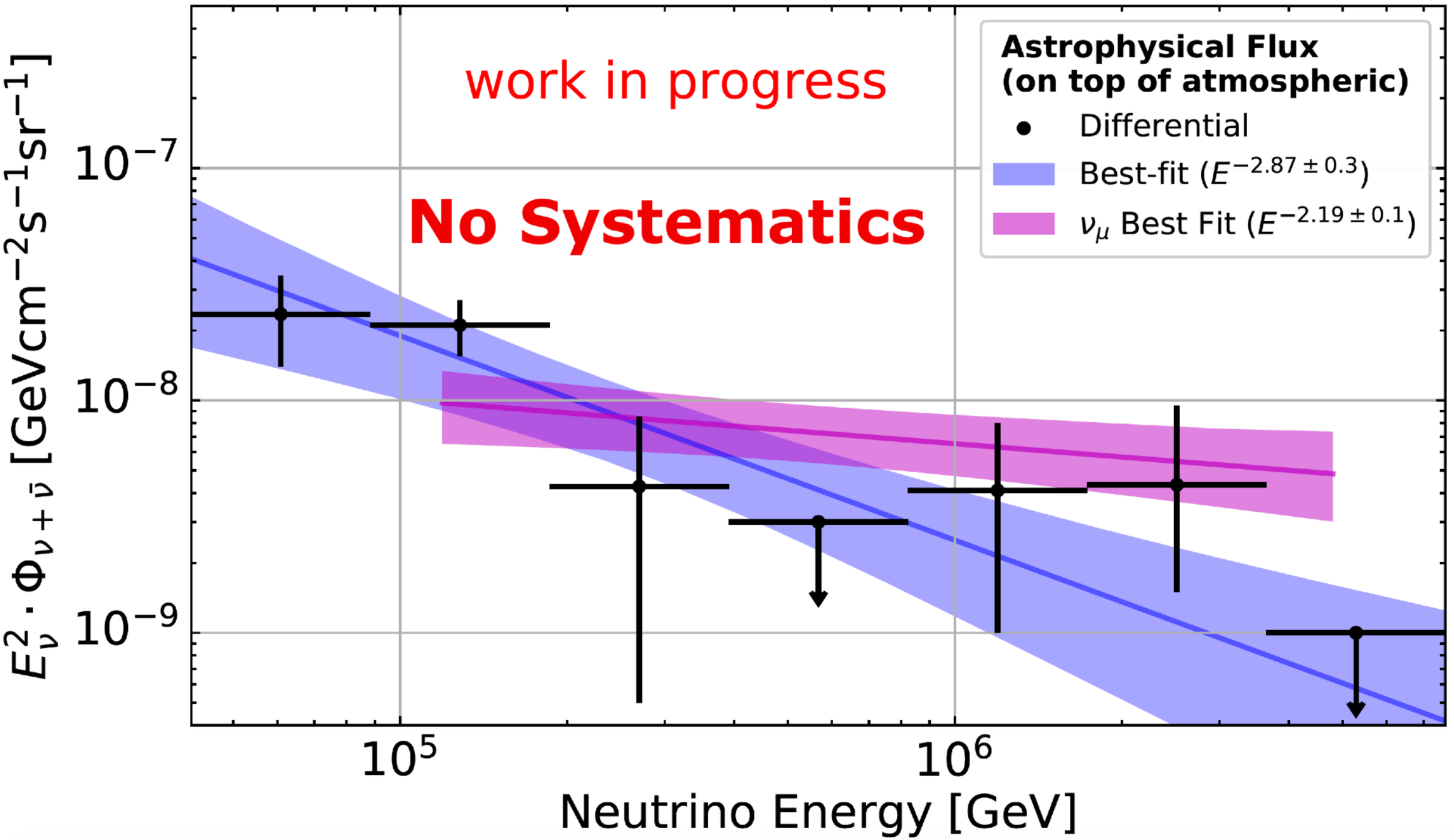


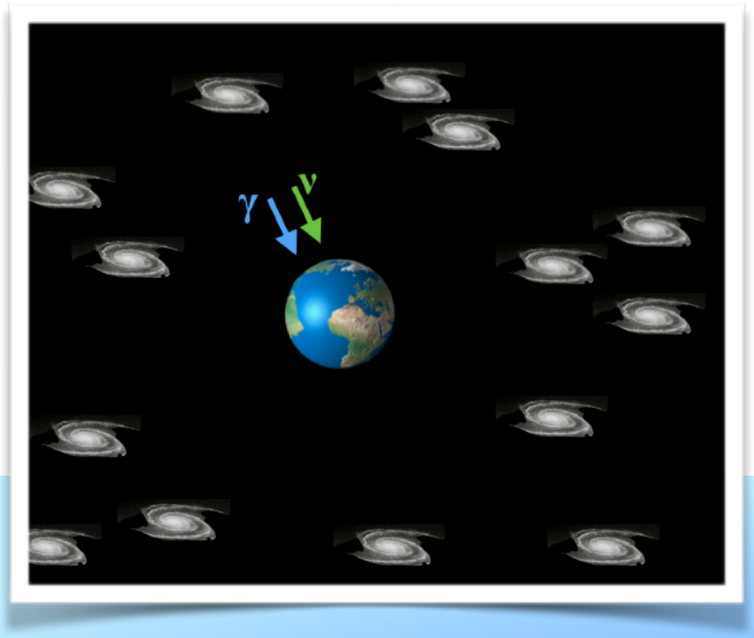




No evidence for point sources, nor a correlation with the galactic plane

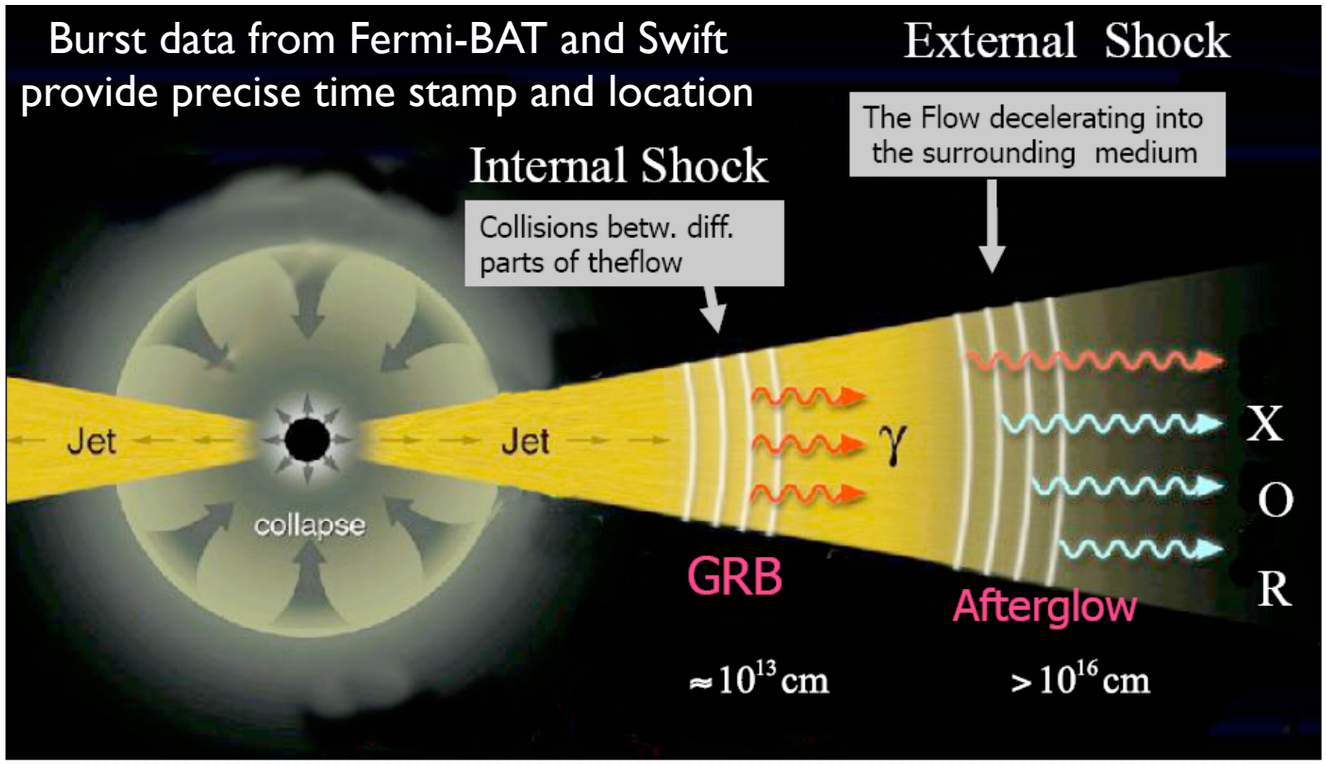
Neutrino energy spectrum



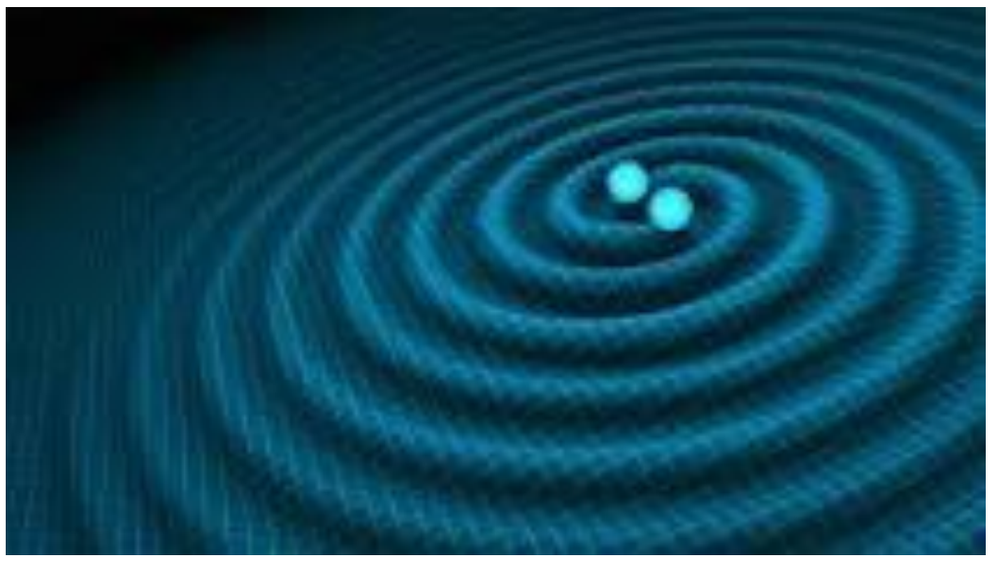


Multi-messenger Neutrino Astronomy and IceCube-170922A

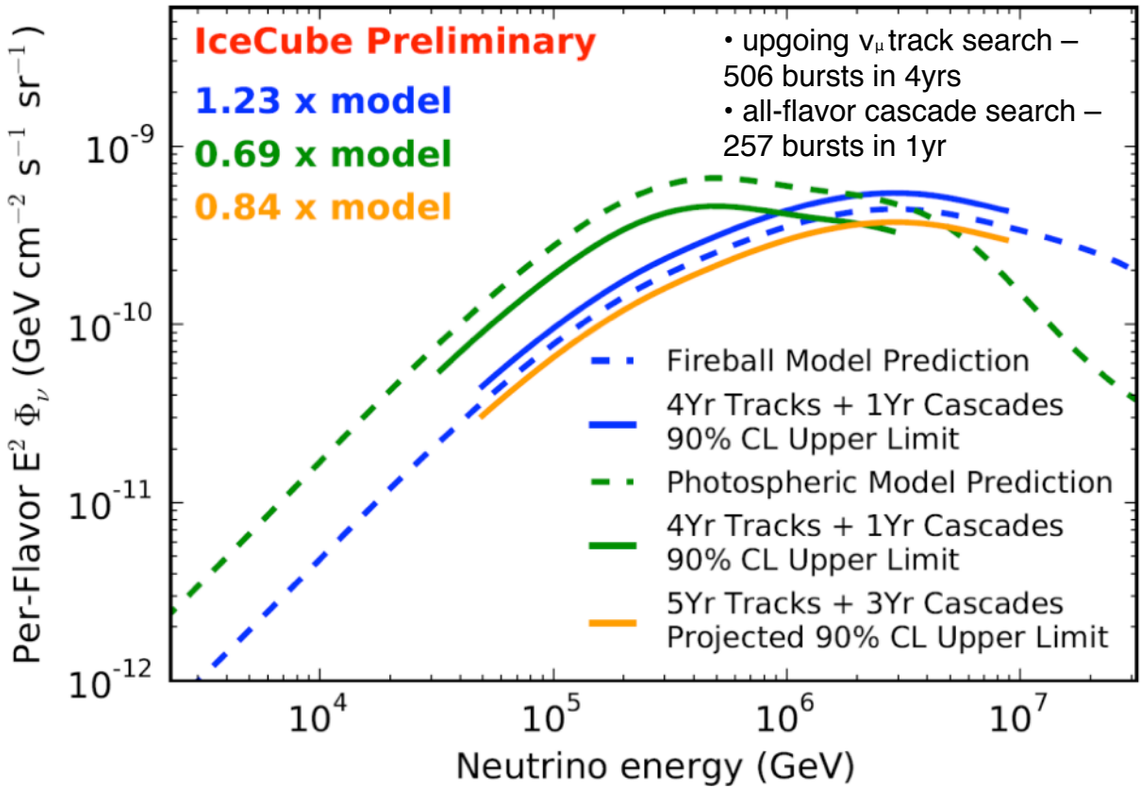
Transient Searches



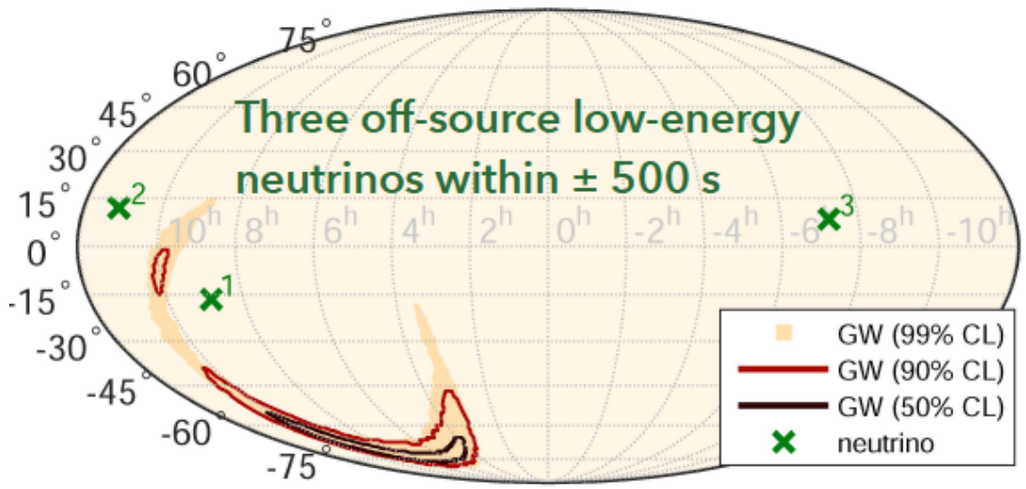
IceCube Collaboration - Nature Vol **484**, 351 (2012)



no coincidence found



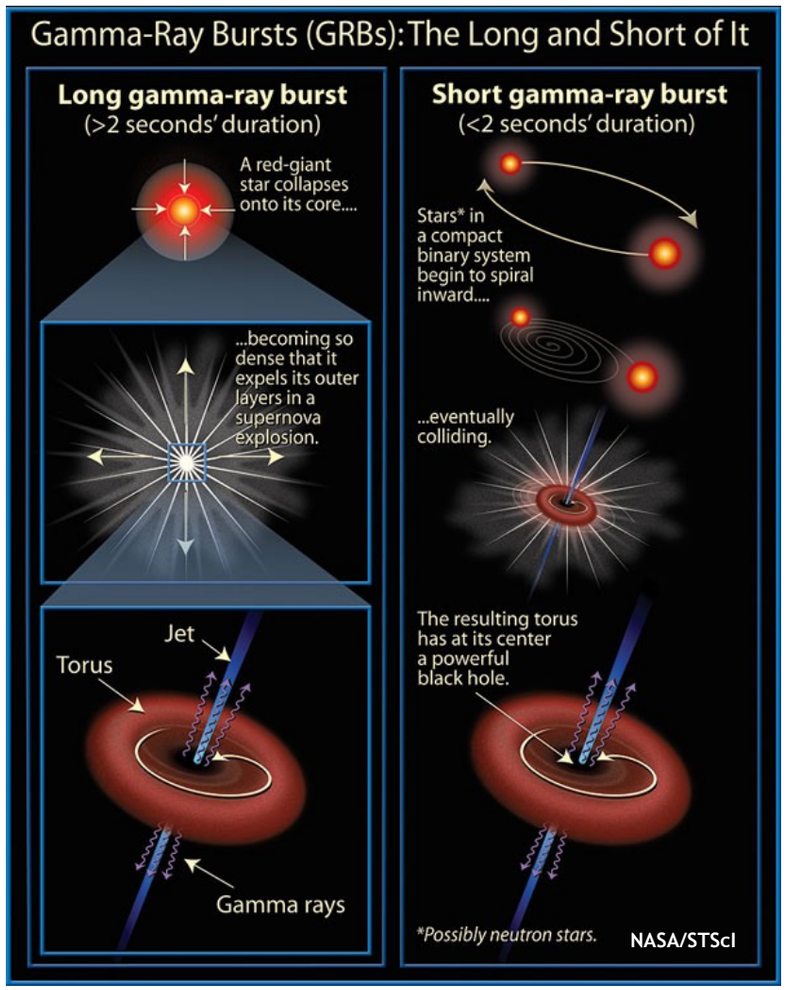
ANTARES Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, Virgo Collaboration [arXiv:1602.05411]

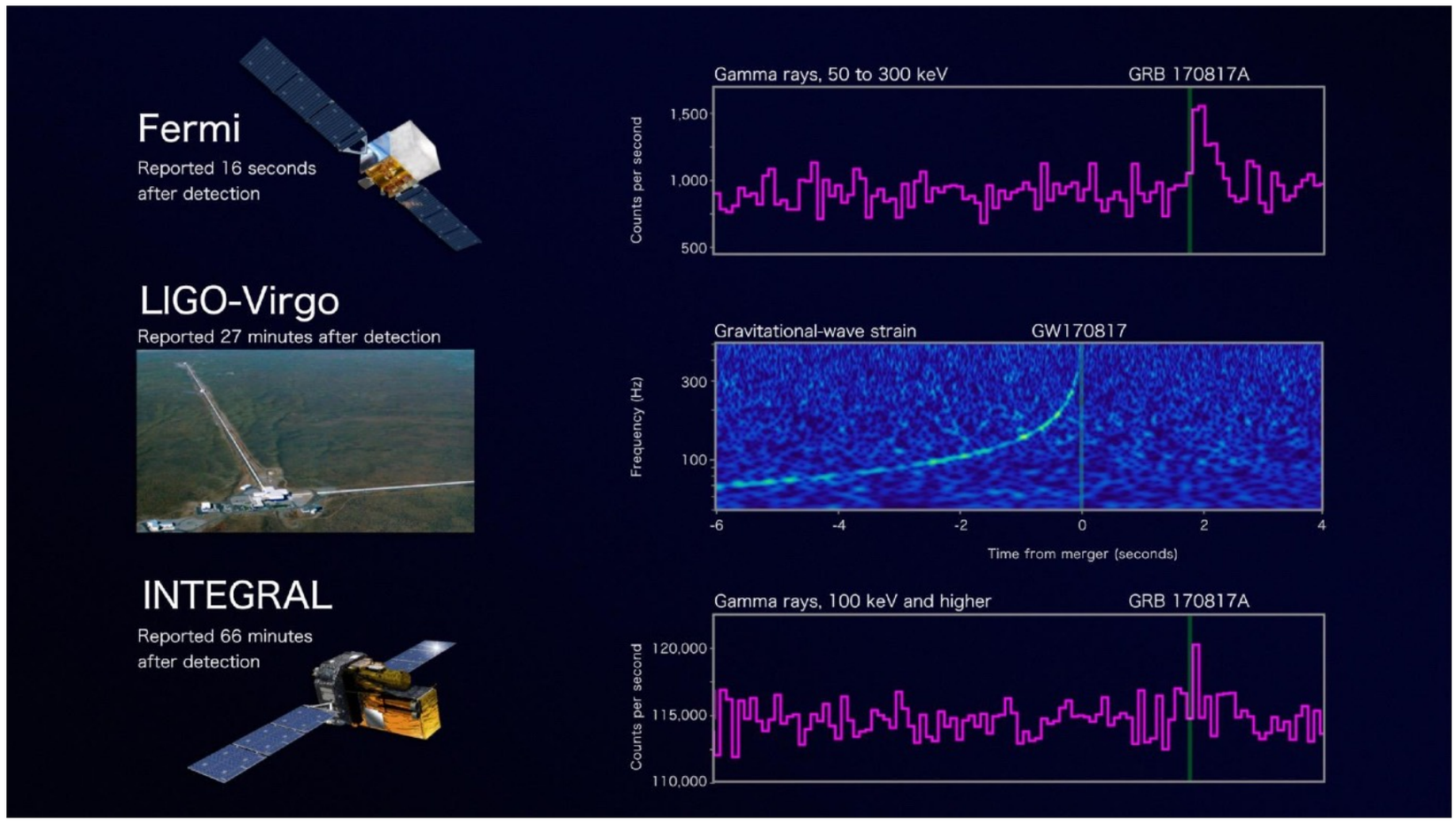


- Follow up on LIGO Gravitational Wave GW 150914
  - No neutrino association observed

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

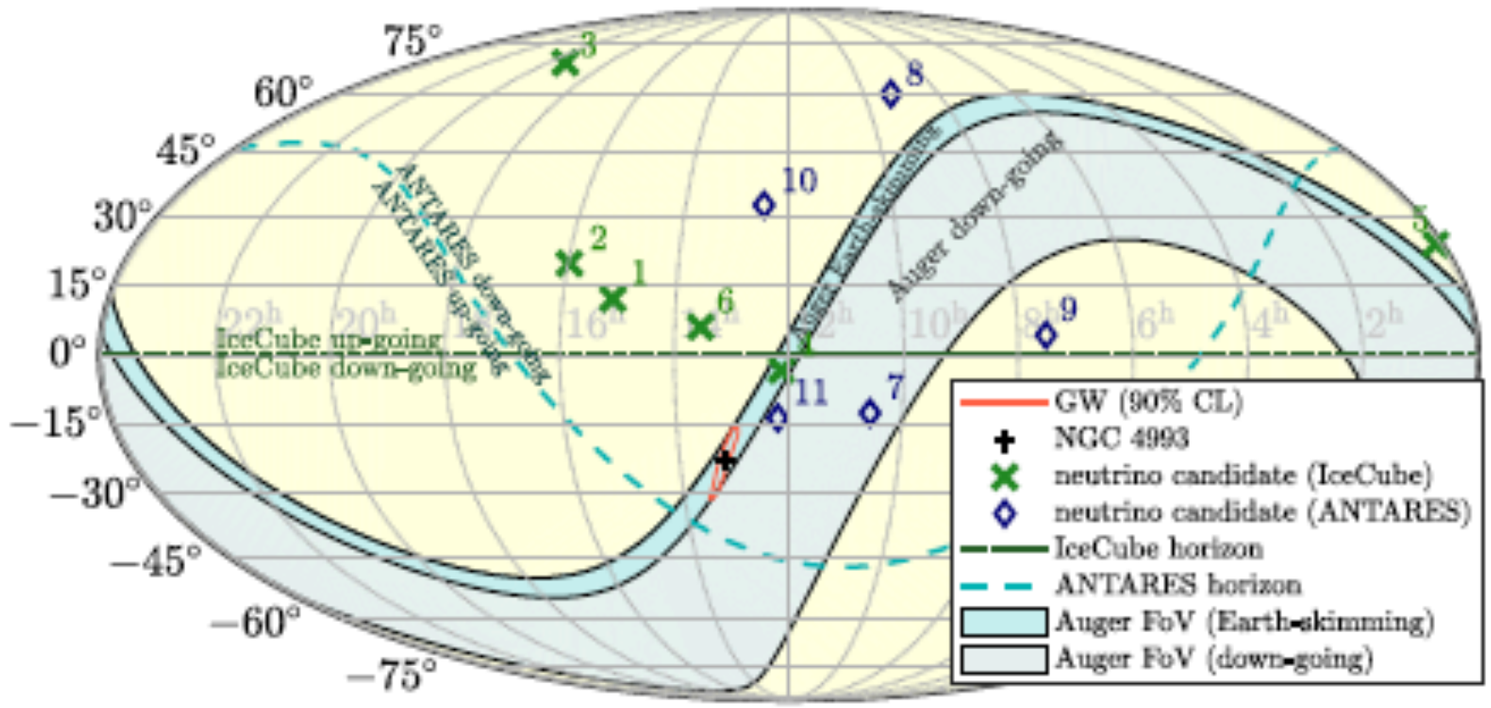
The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield 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.

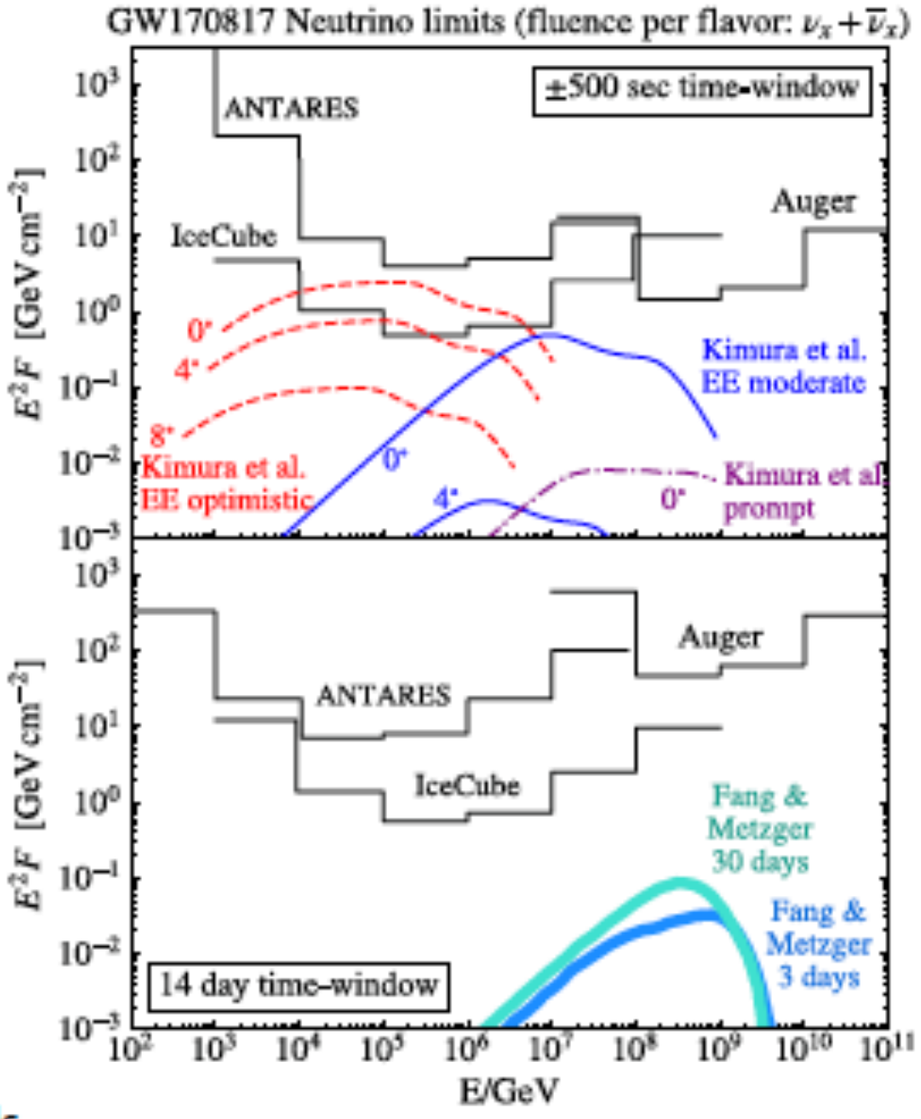
Gravitational Waves

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.

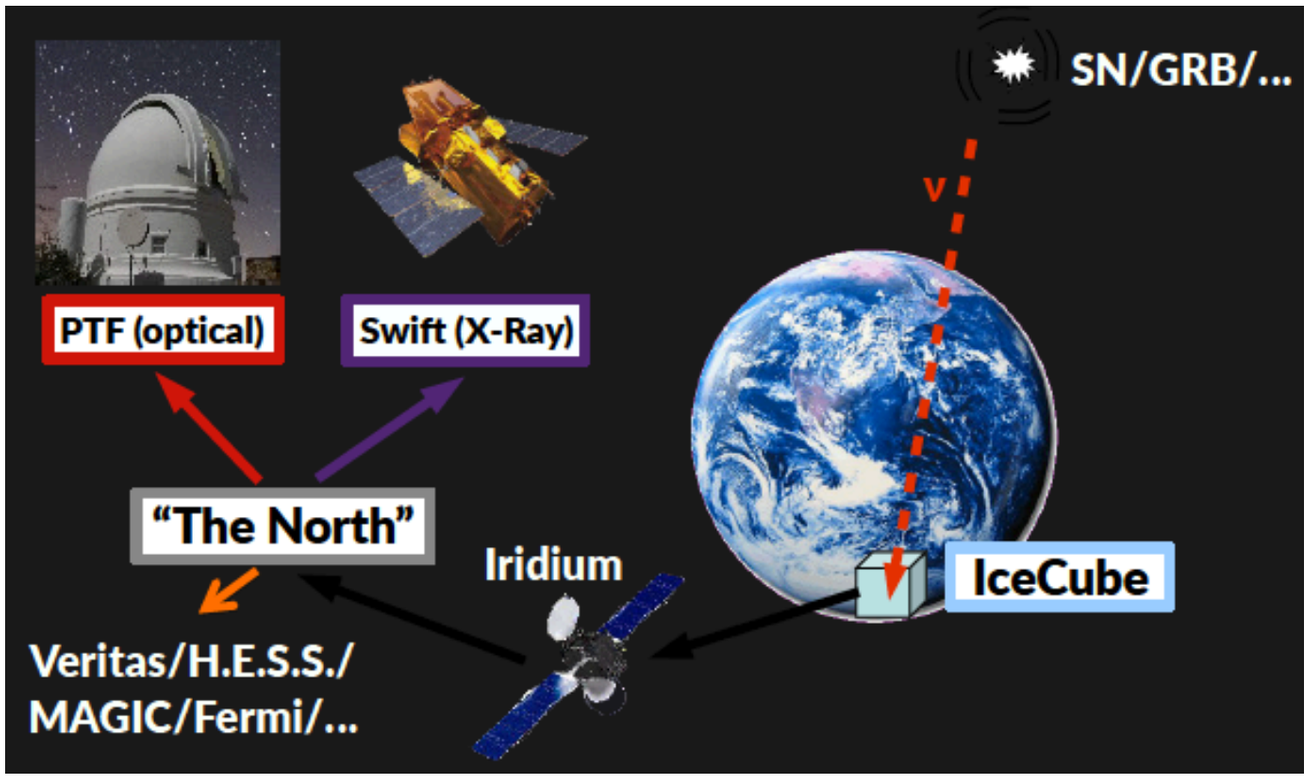
ANTARES, IceCube, Auger, LIGO, Virgo 2017

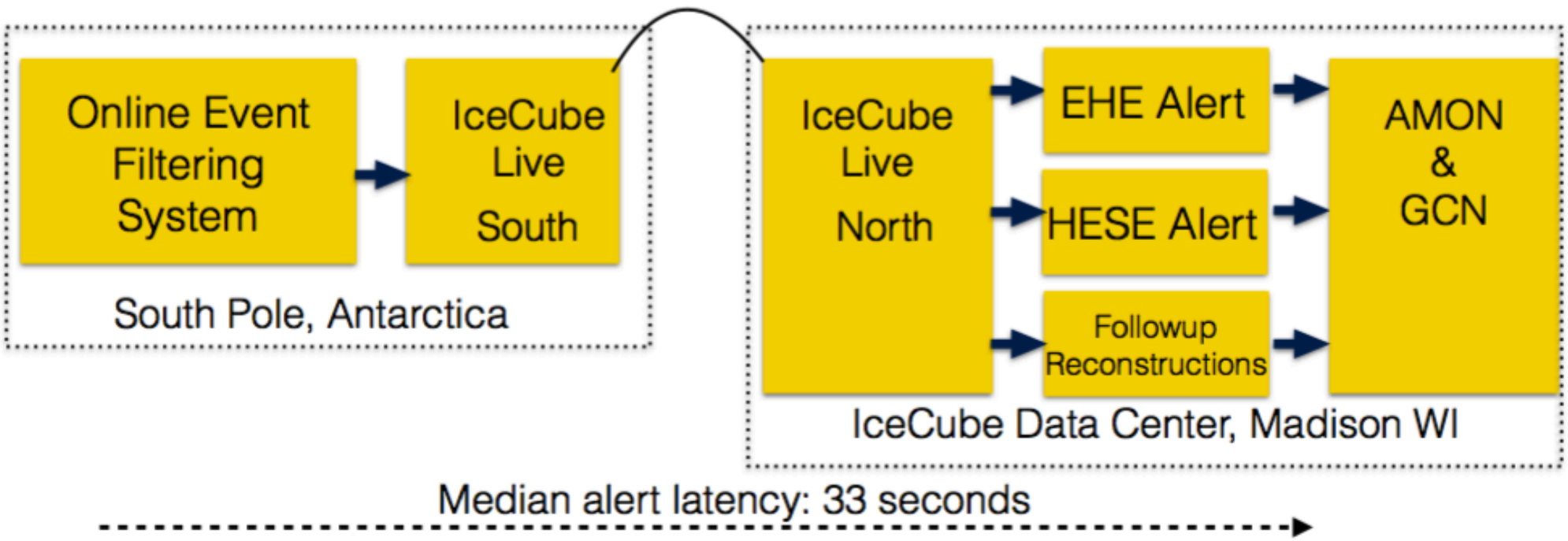
Astropart. Phys. 92 (2017) 30

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





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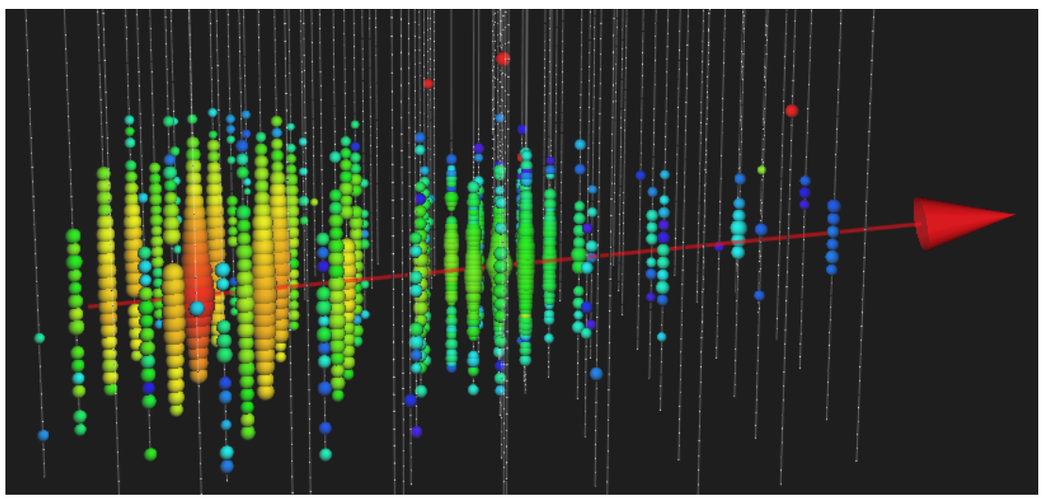
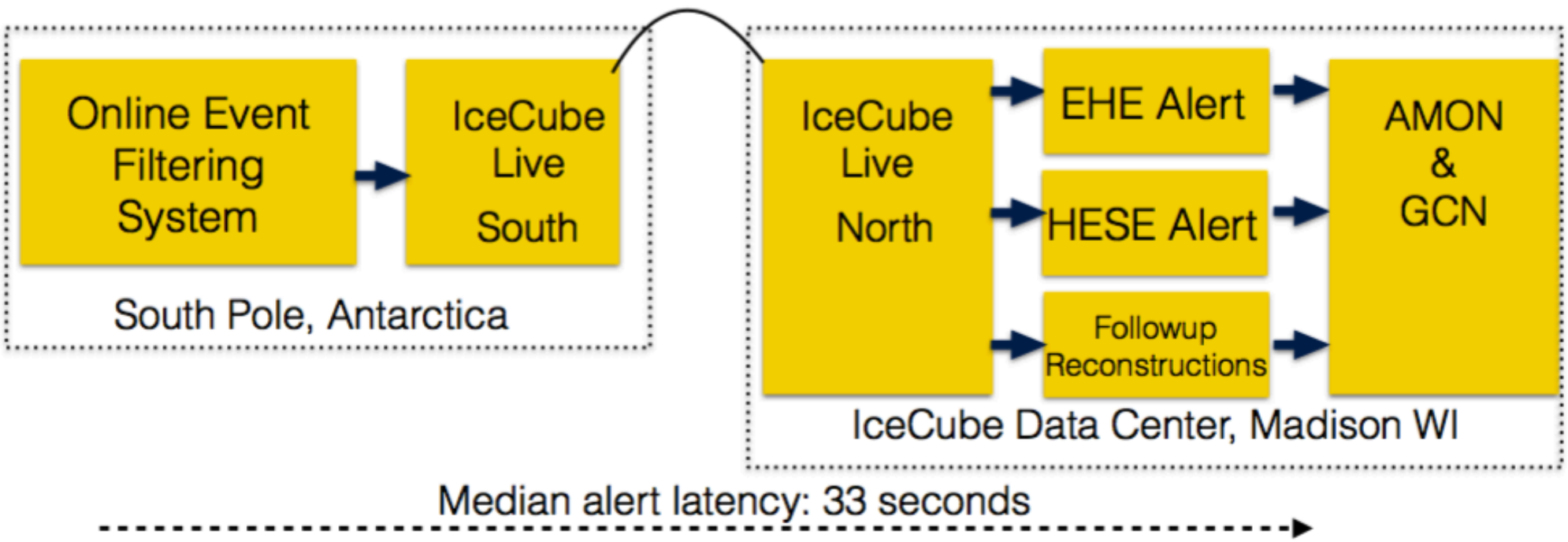


First public ν Alert: IceCube-160427



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

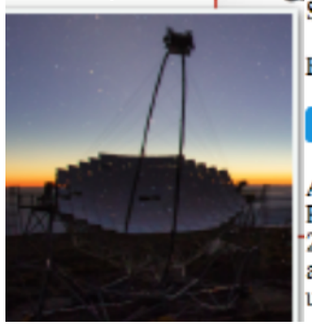
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

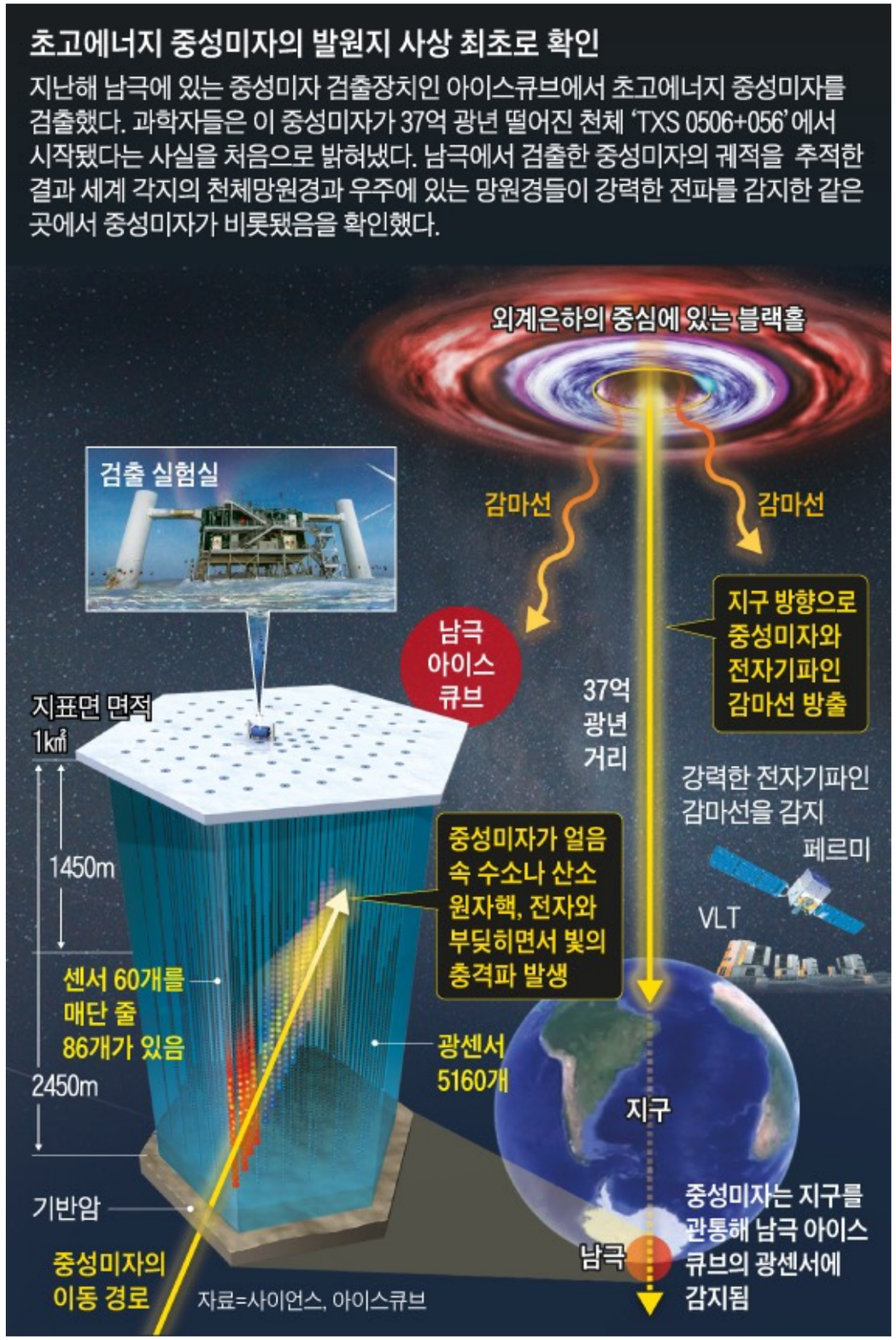
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

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



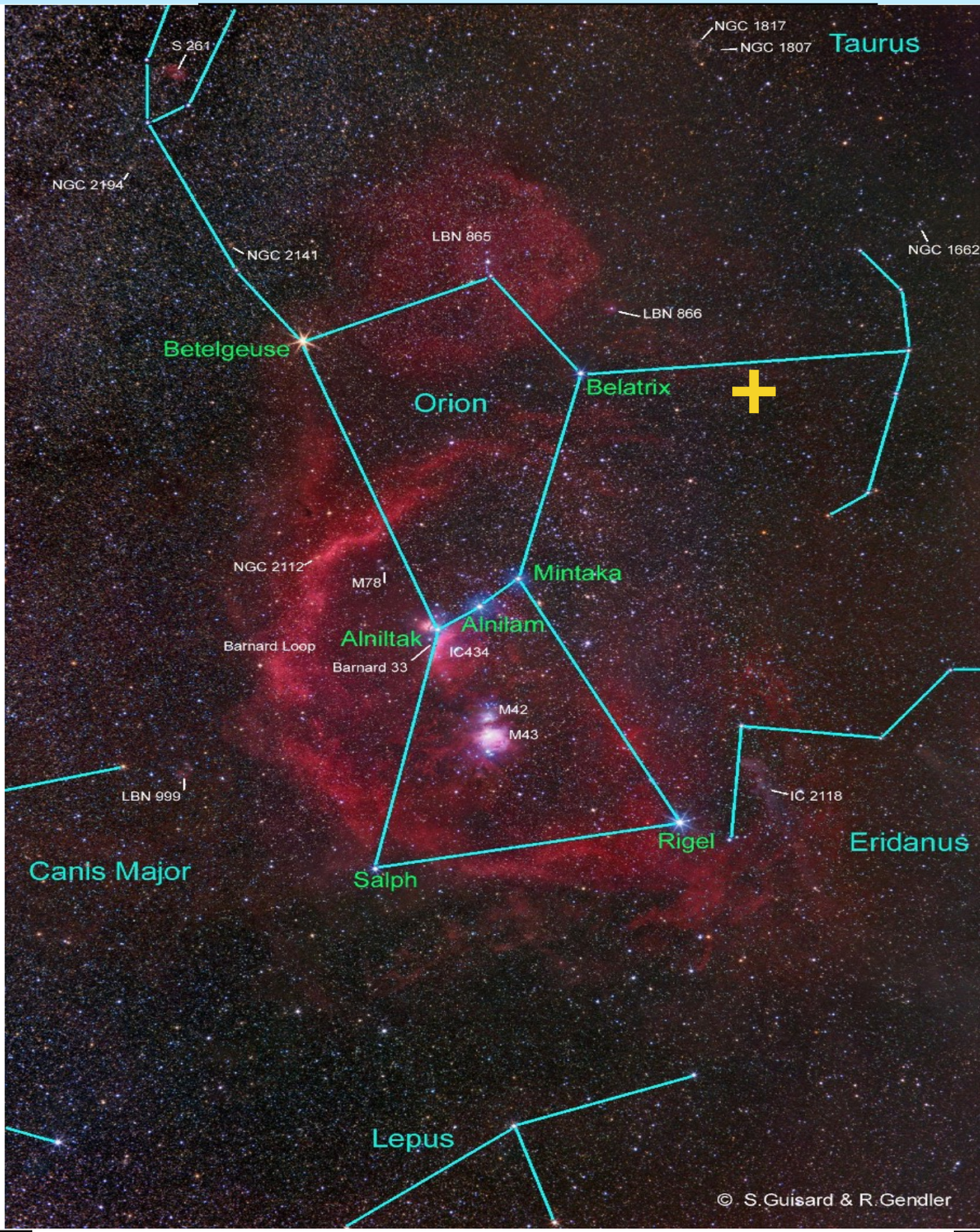
(Science 361, eaat1378 (2018)

IceCube-170922A

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

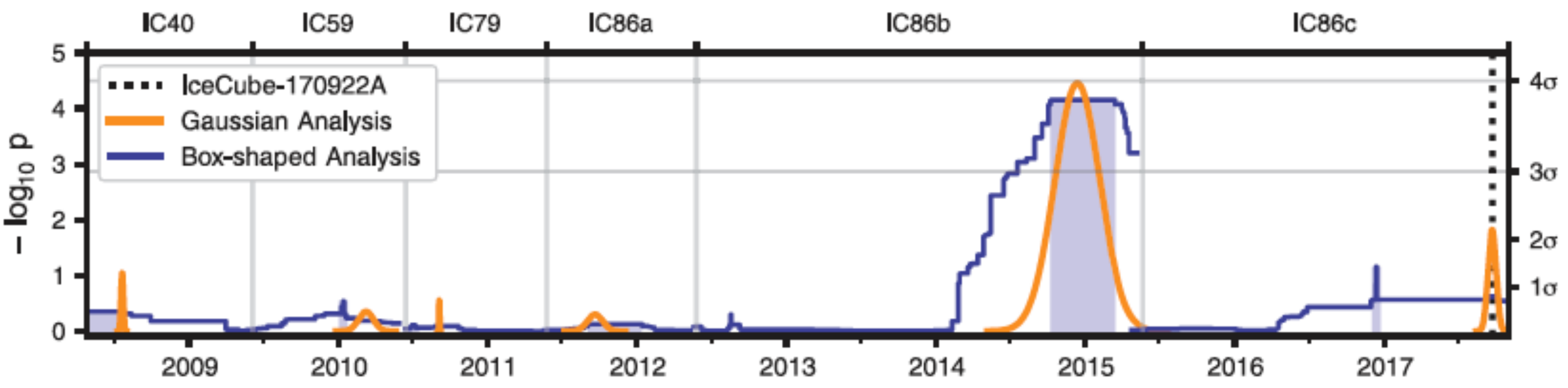
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- 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

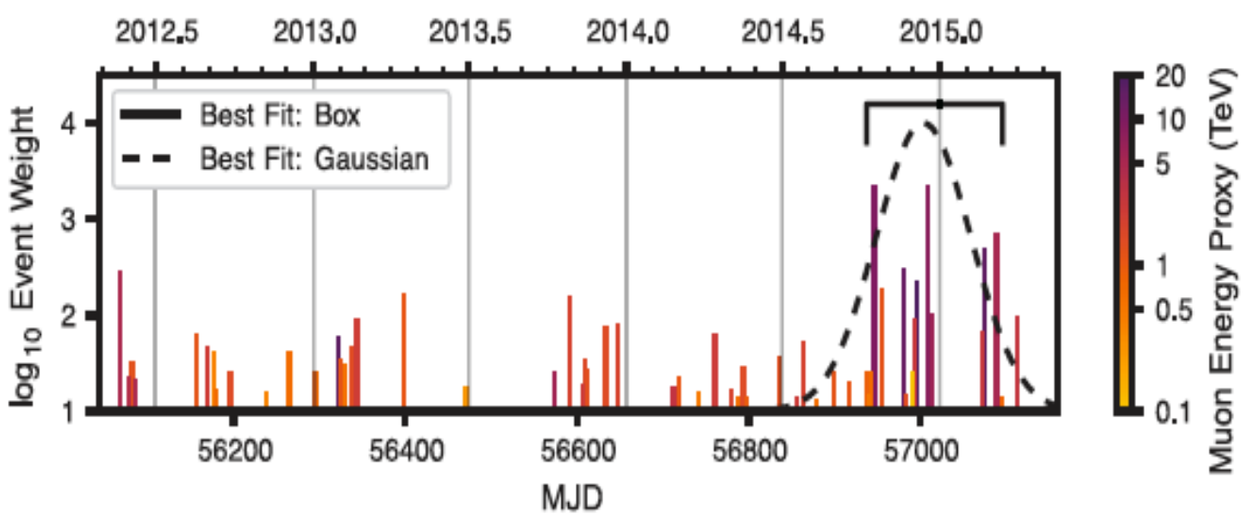


Science 361 (6398), 147-151.

IceCube-170922A



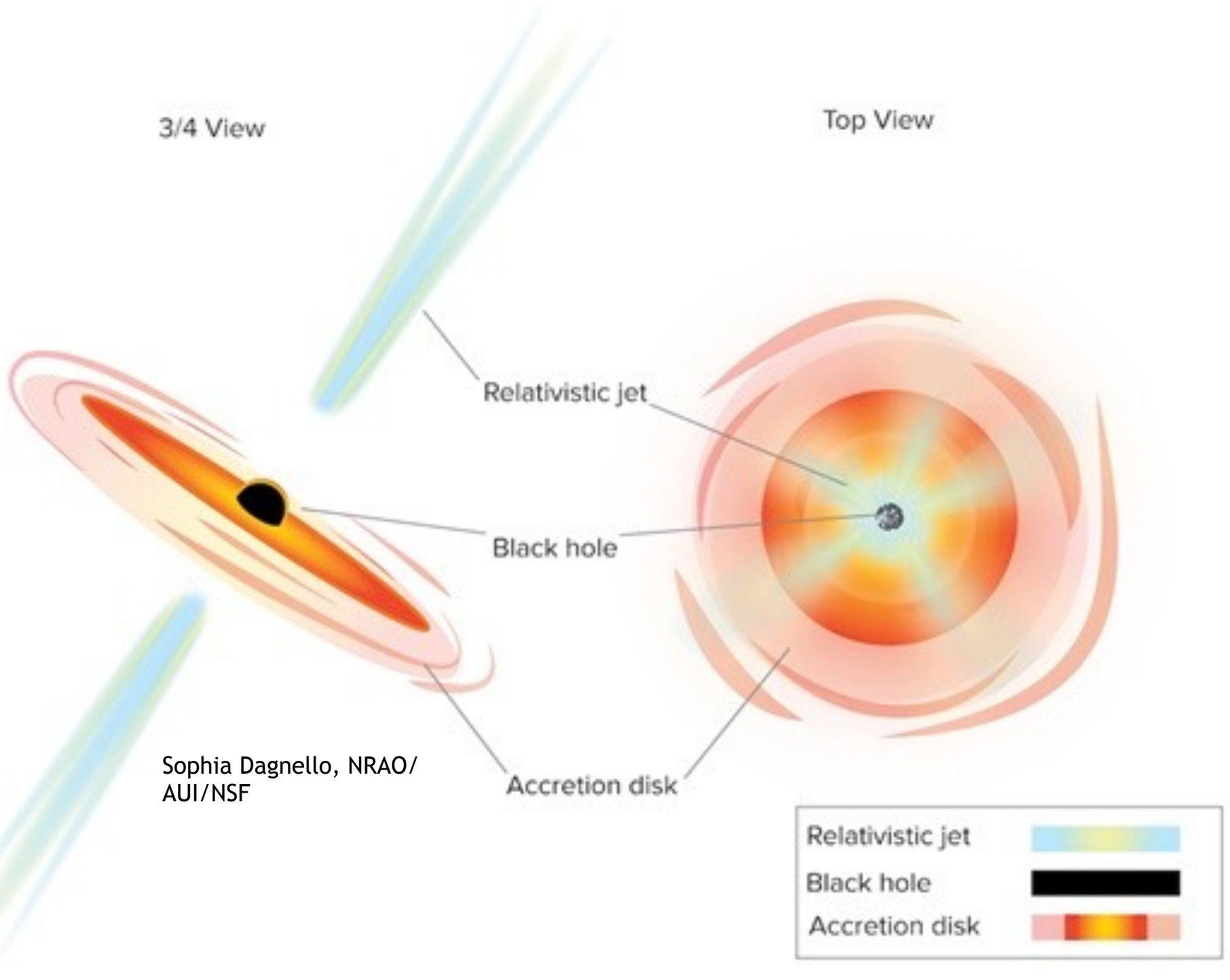
- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)



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

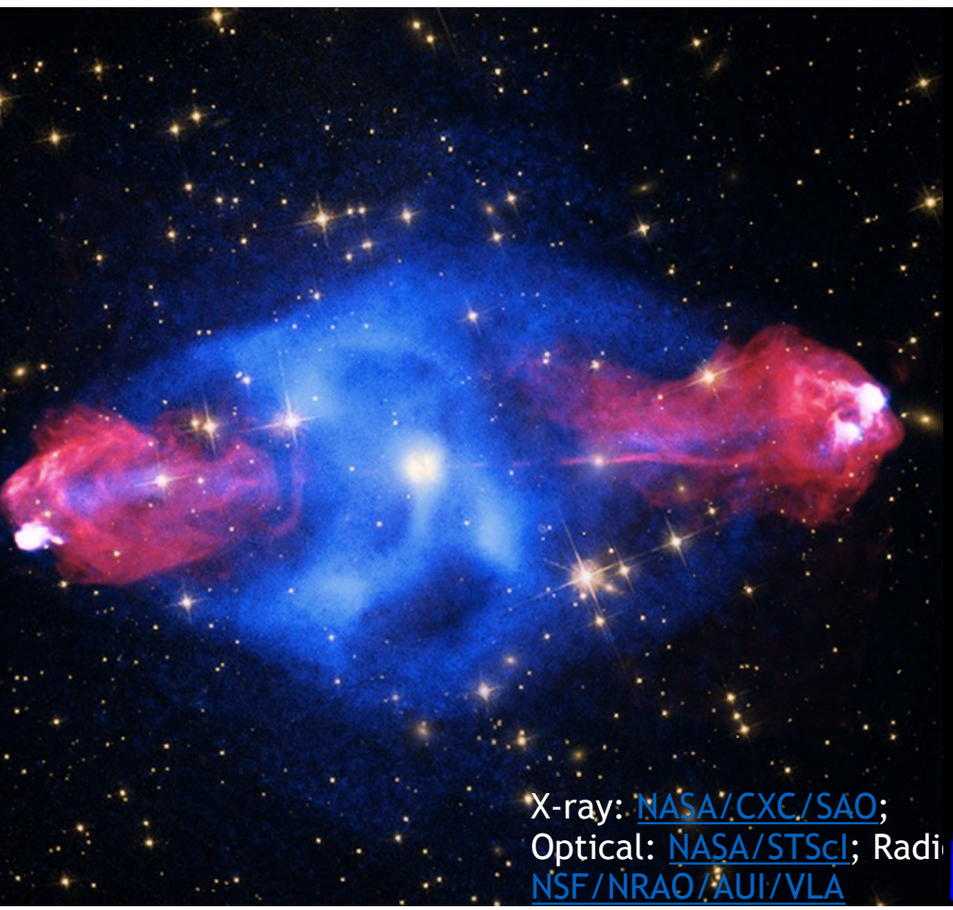
One type of AGN: the blazar

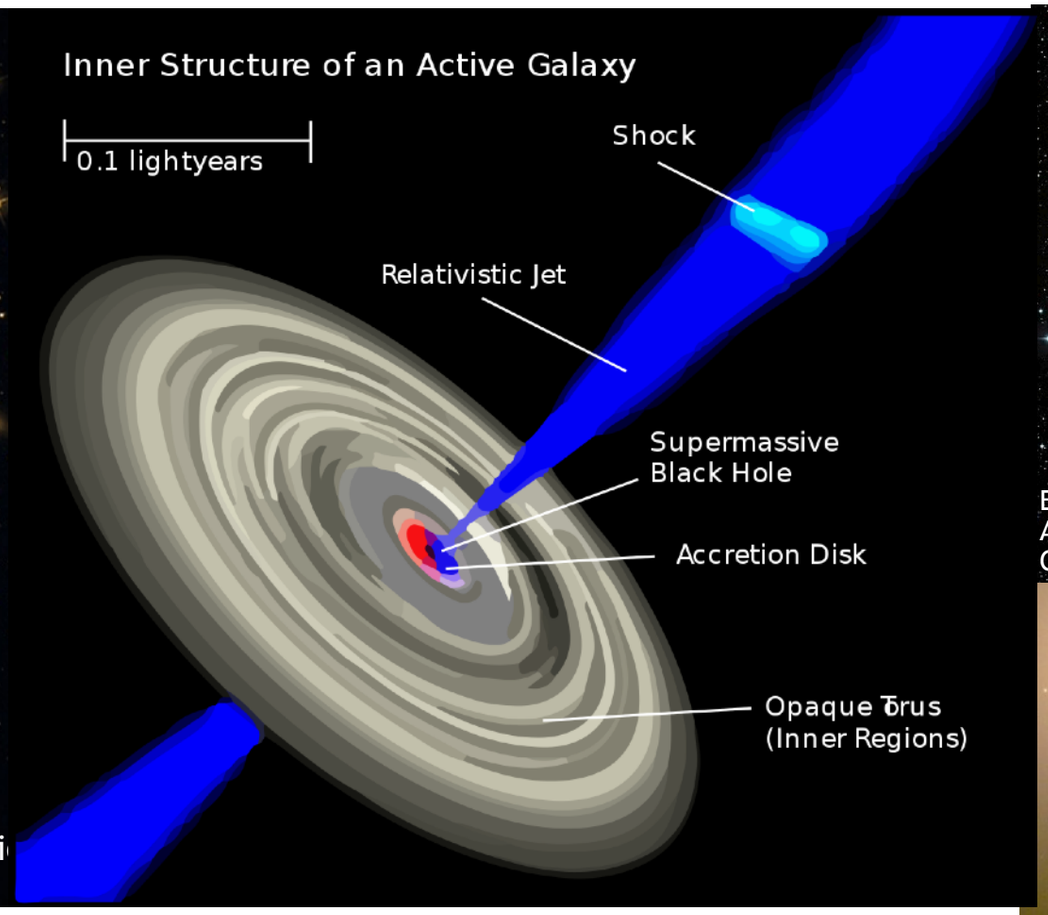
A blazar is an AGN with a jet pointed at the Earth.

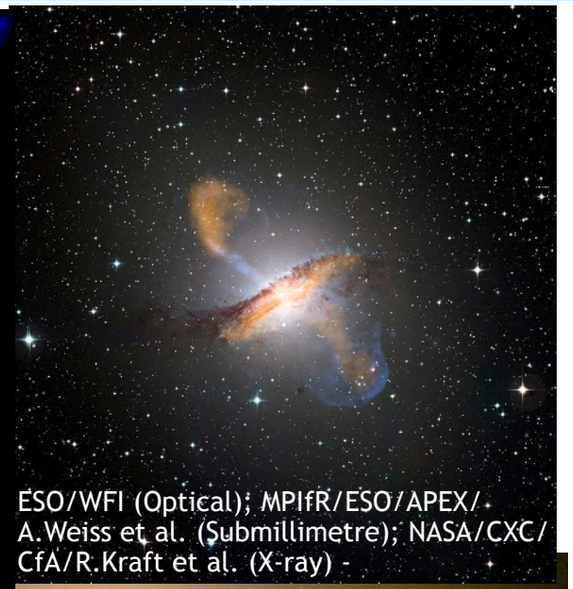


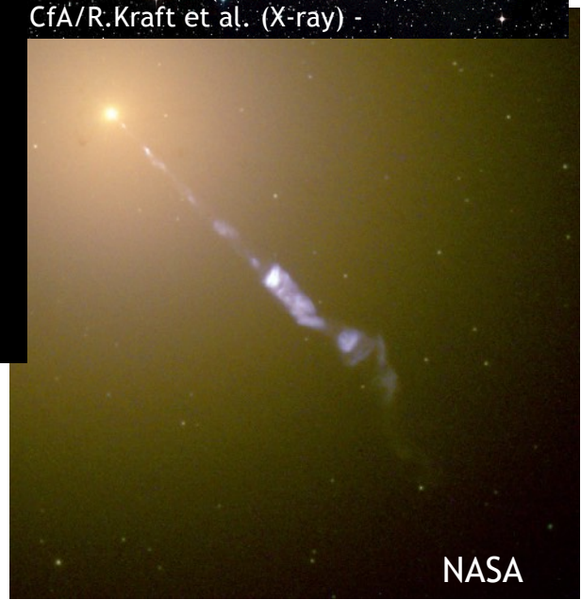
Sophia Dagnello, NRAO/ AUI/NSF

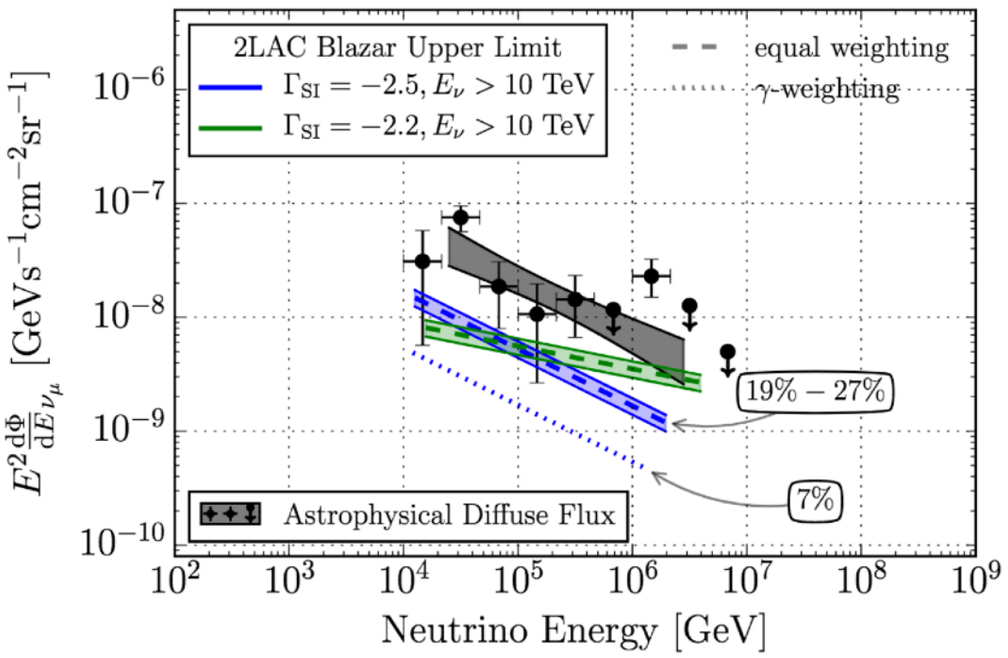
Active Galactic Nuclei: Cosmic Accelerators?







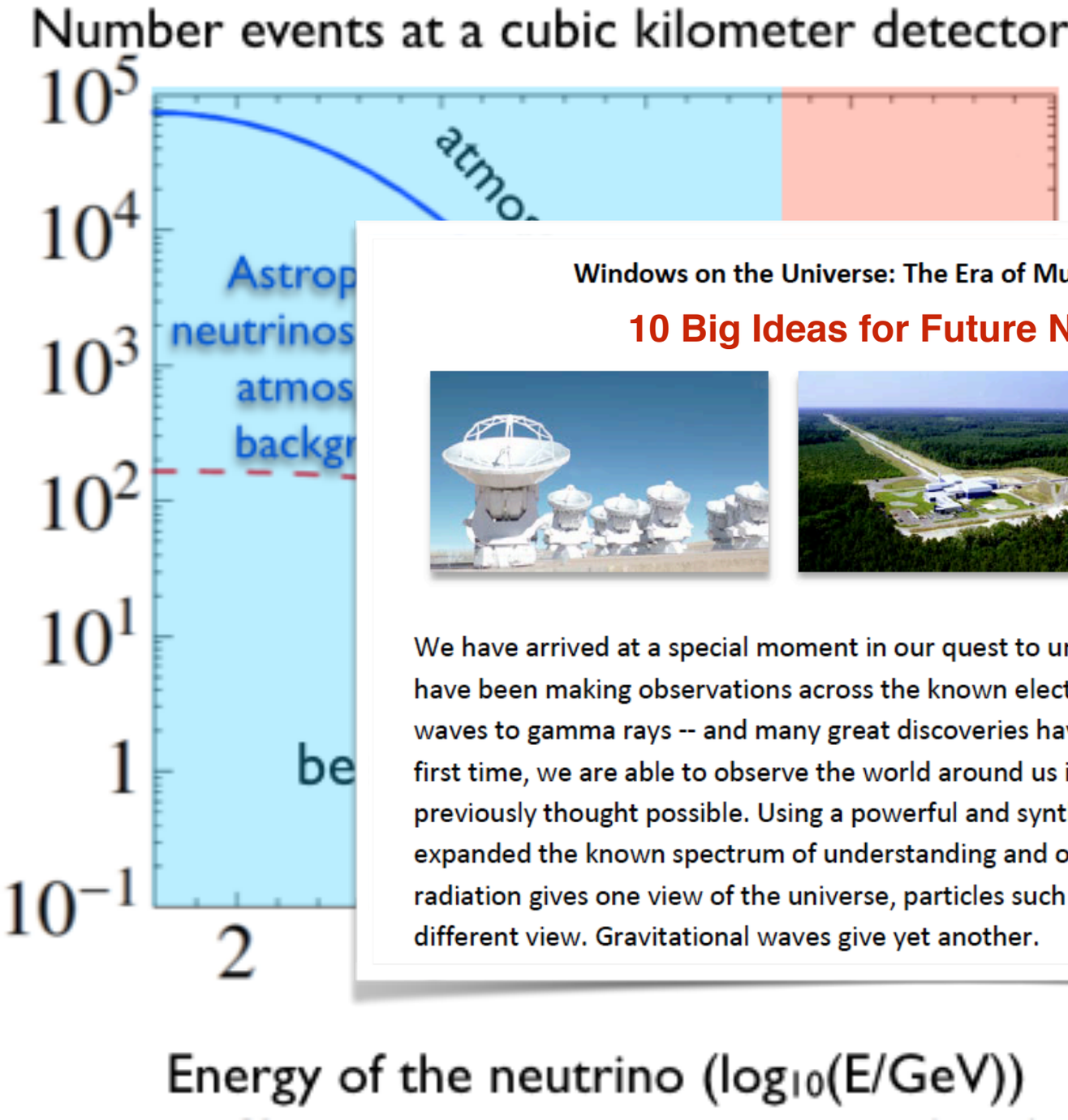




However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]

What's next ...

Multi-messenger



Windows on the Universe: The Era of Multi-messenger Astrophysics

10 Big Ideas for Future NSF Investments

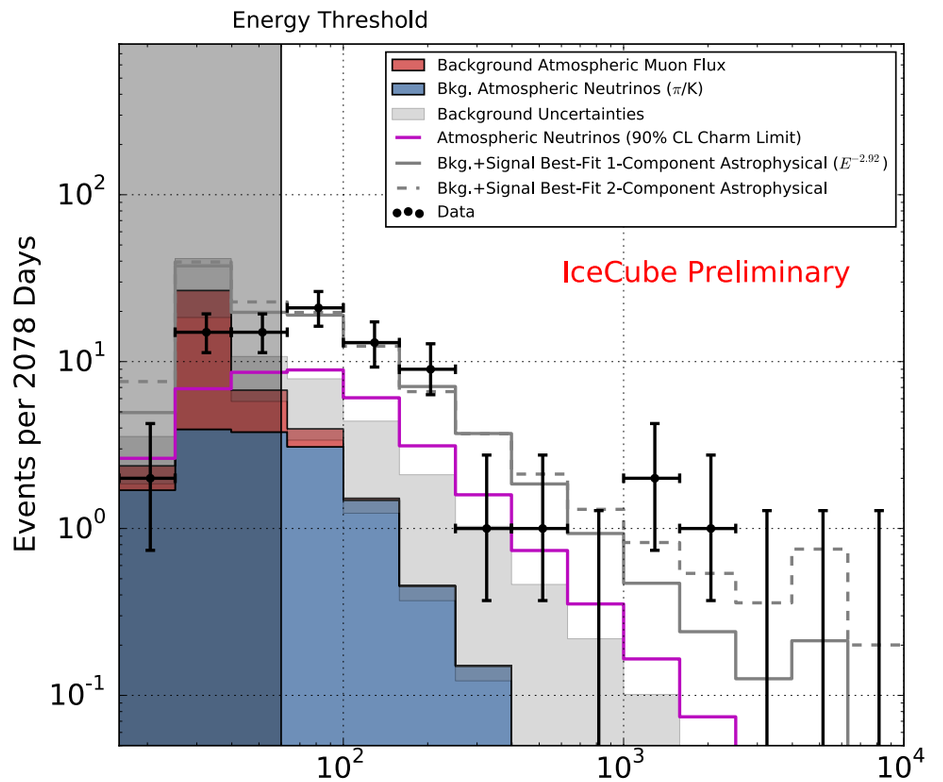
We have arrived at a special moment in our quest to understand the universe. For years, we have been making observations across the known electromagnetic spectrum -- from radio waves to gamma rays -- and many great discoveries have been made as a result. Now, for the first time, we are able to observe the world around us in fundamentally different ways than we previously thought possible. Using a powerful and synthetic collection of approaches, we have expanded the known spectrum of understanding and observing reality. Just as electromagnetic radiation gives one view of the universe, particles such as neutrinos and cosmic rays provide a different view. Gravitational waves give yet another.

hysical
hidden in
neutrino

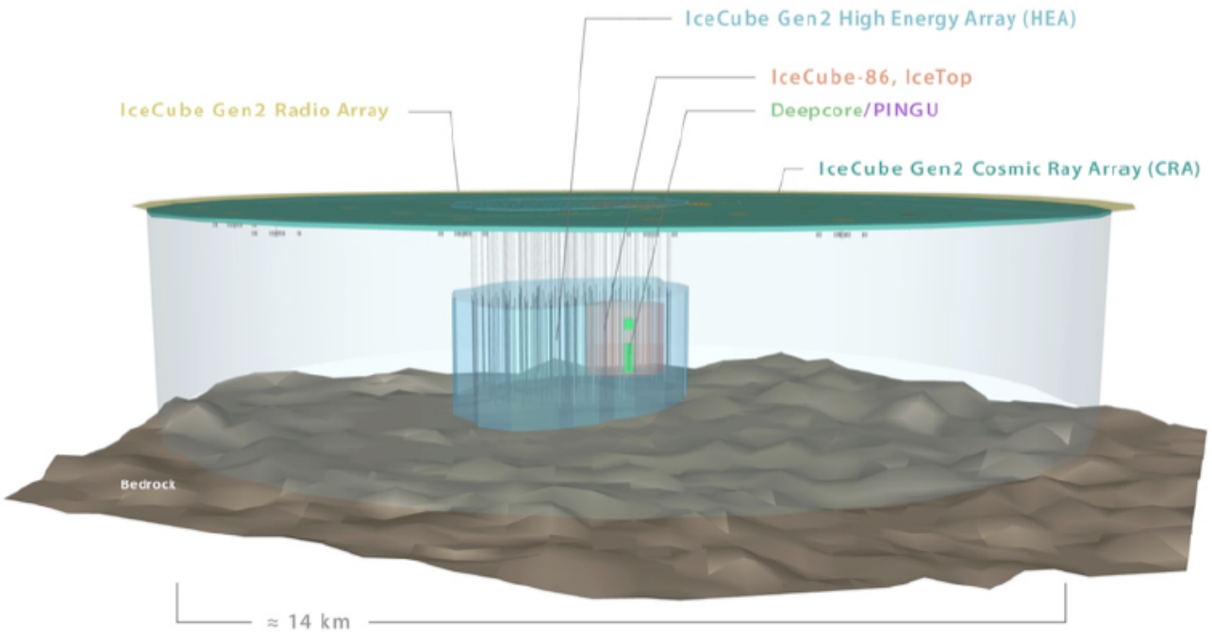
Multi-messenger methods could identify them

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

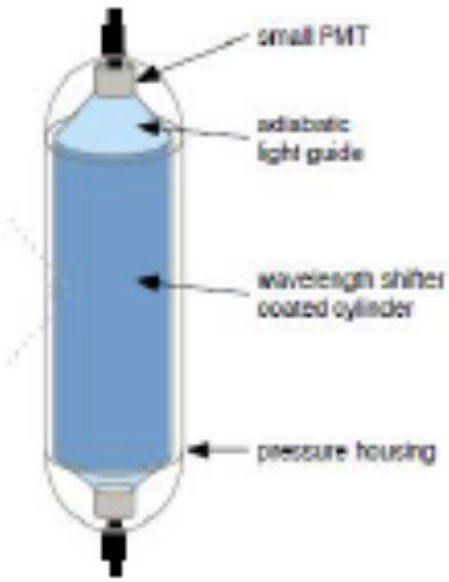
- Directional information
- More sensitive area per module

D-Egg

30 cm

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

WOM

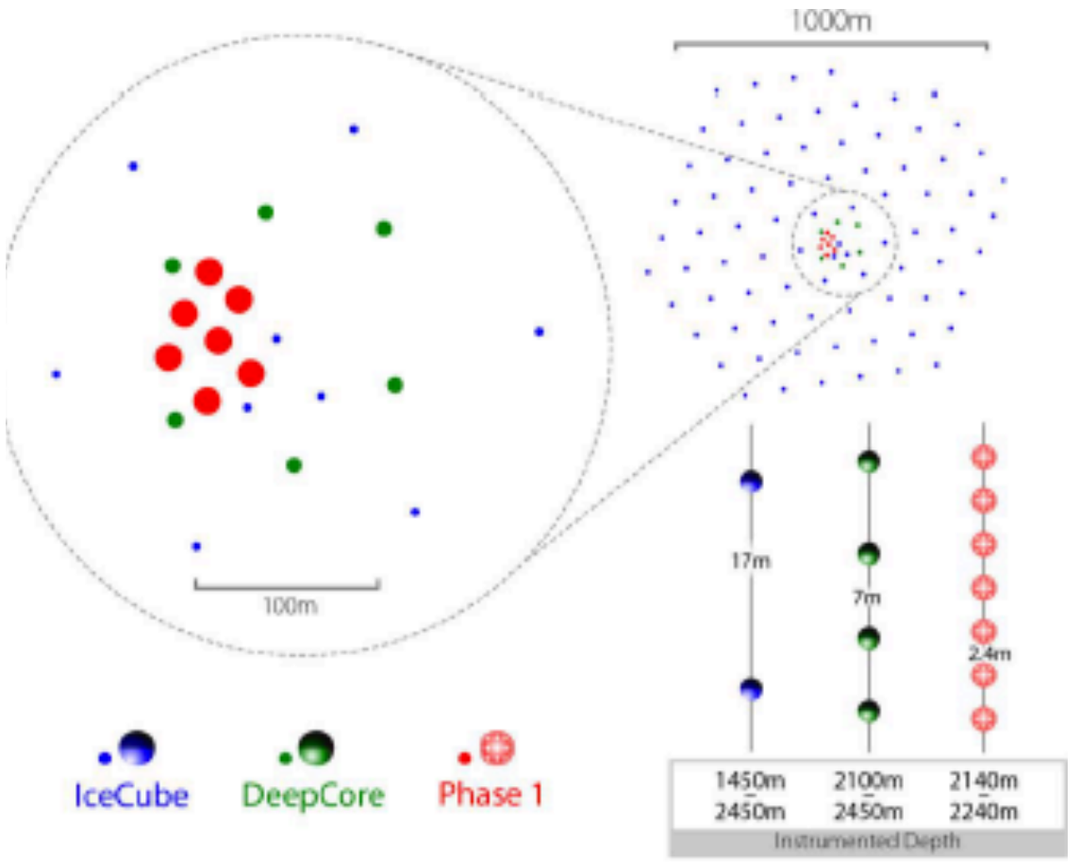


11 cm

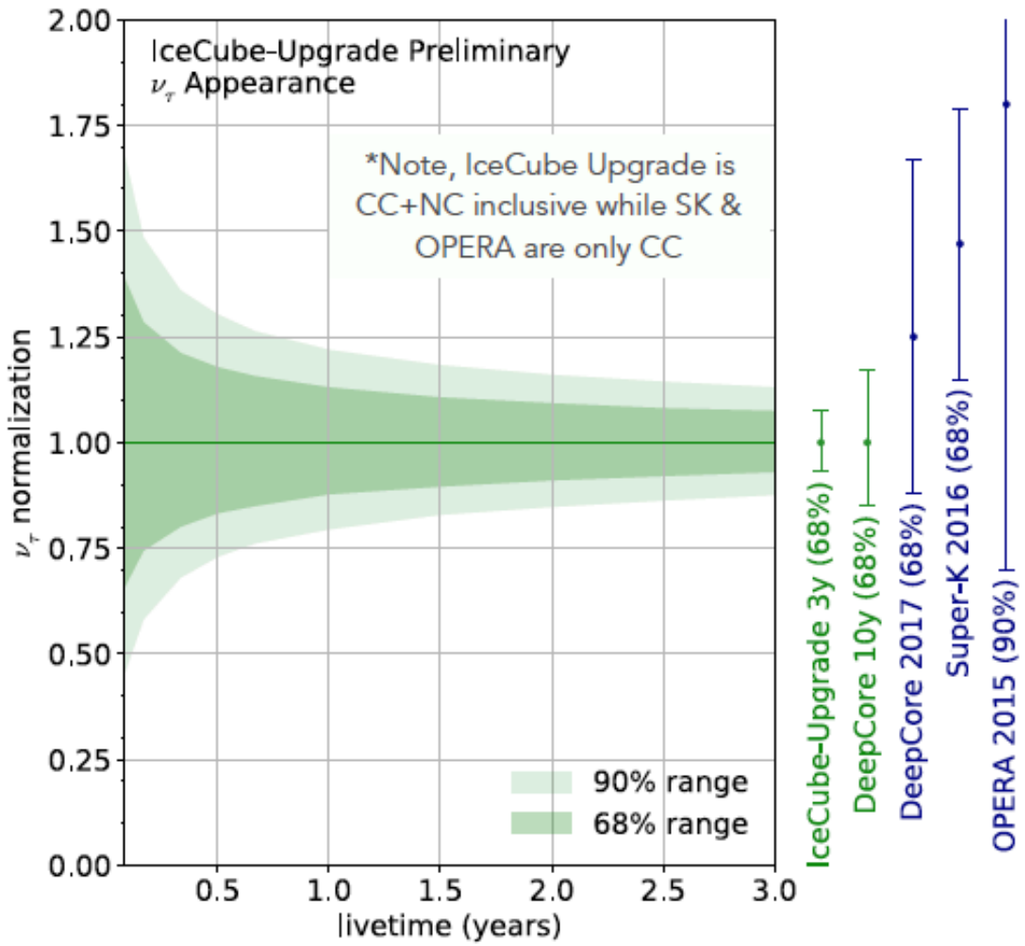
- more sensitive area per $
- Small diameter
- Lower noise rate

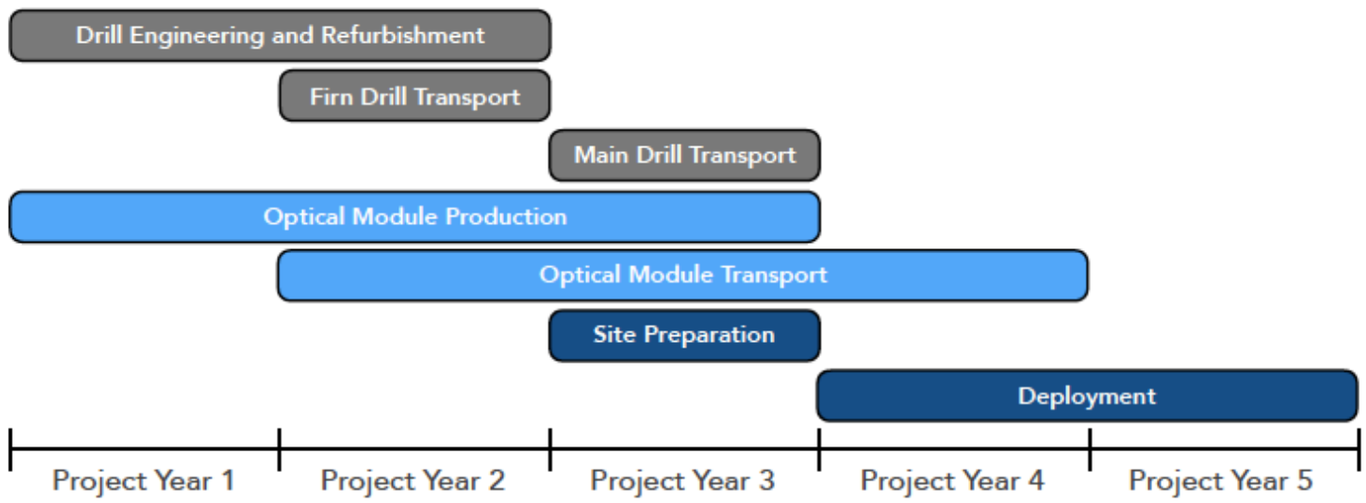
see also:
- PINGU LOI arXiv:1412.5106

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

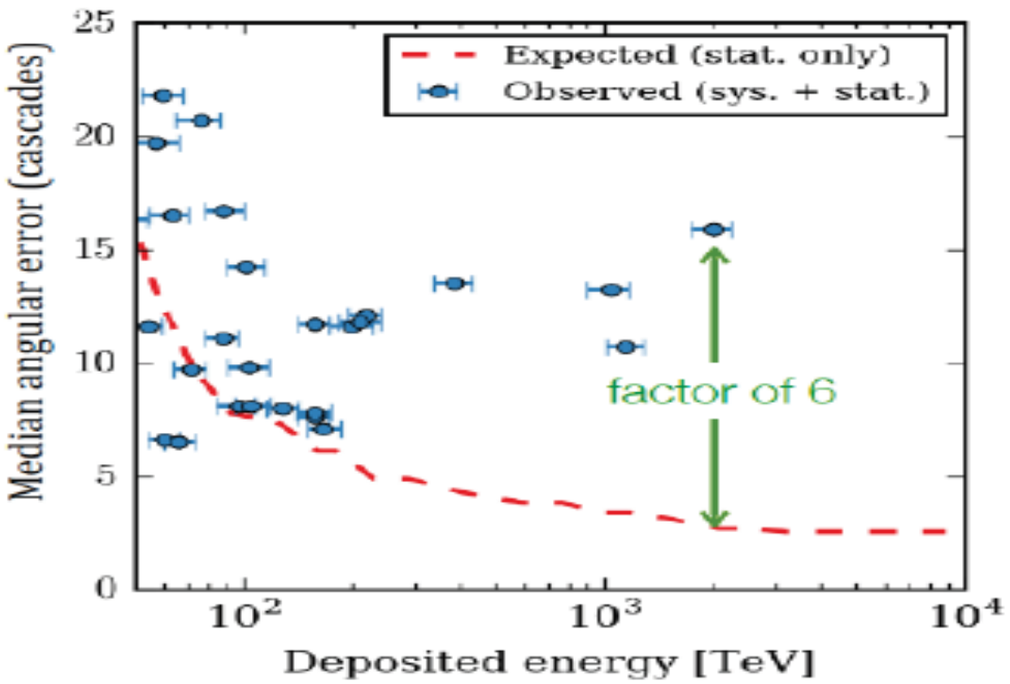




First step to restart South Pole activities
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies

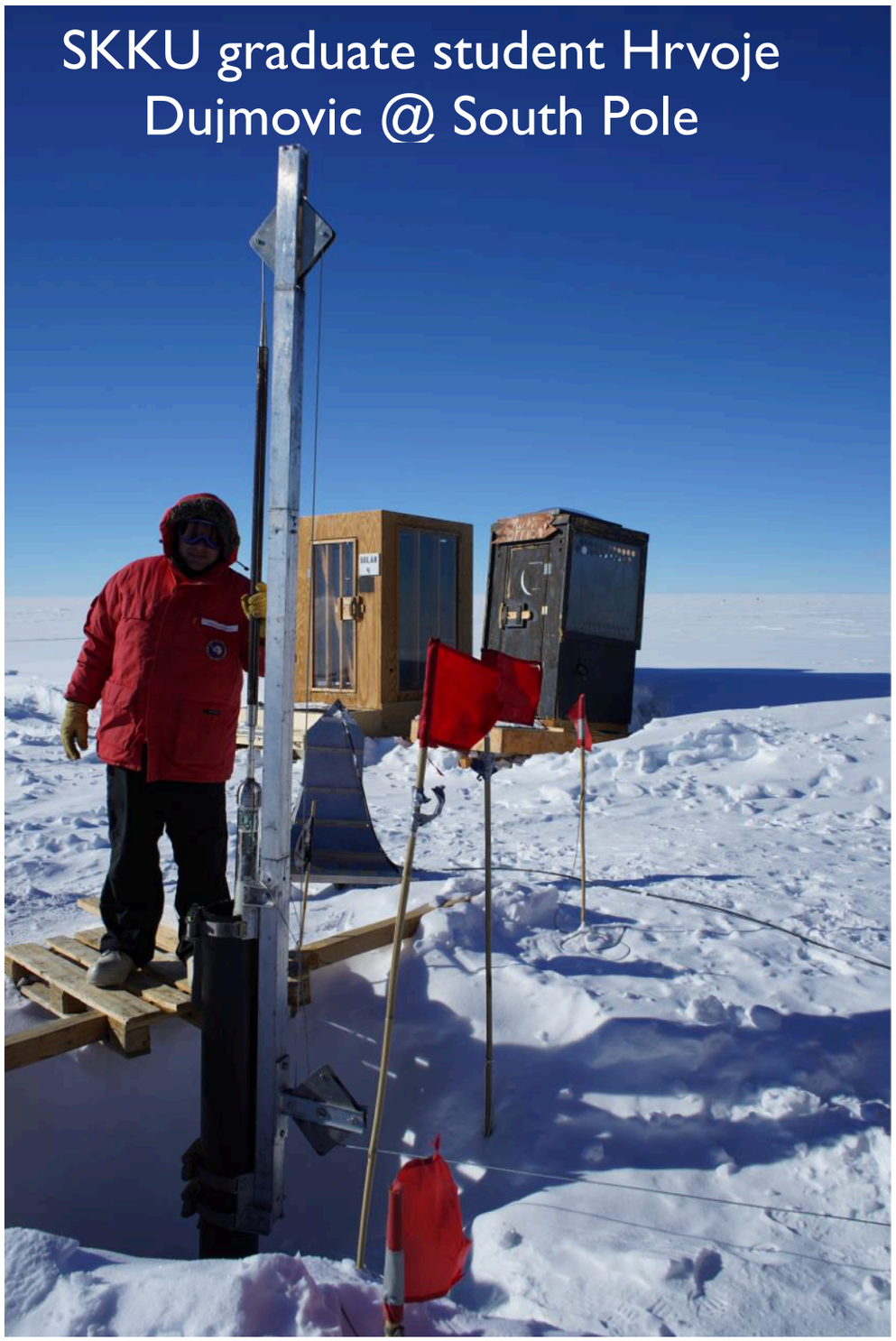
Ice Camera System

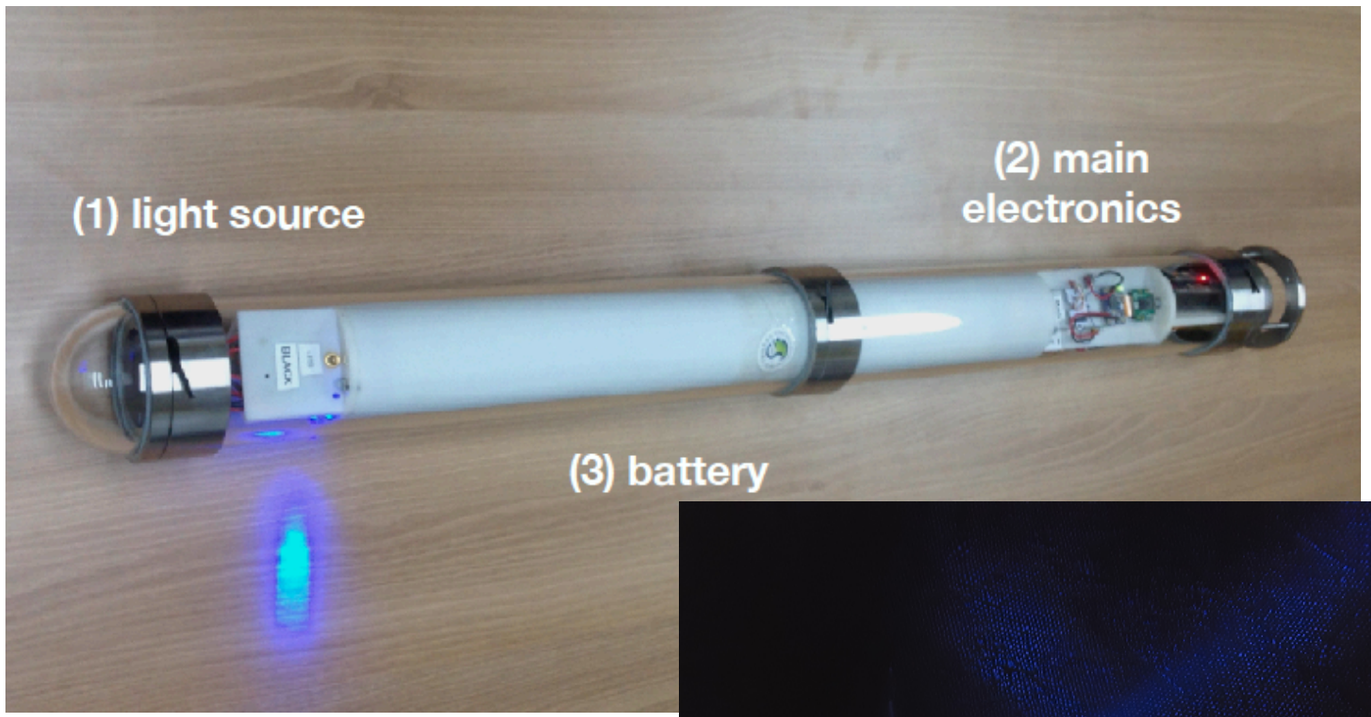
- Ice properties dominant source of sys. uncertainties for most analyses
- Solution: SKKU ice camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability

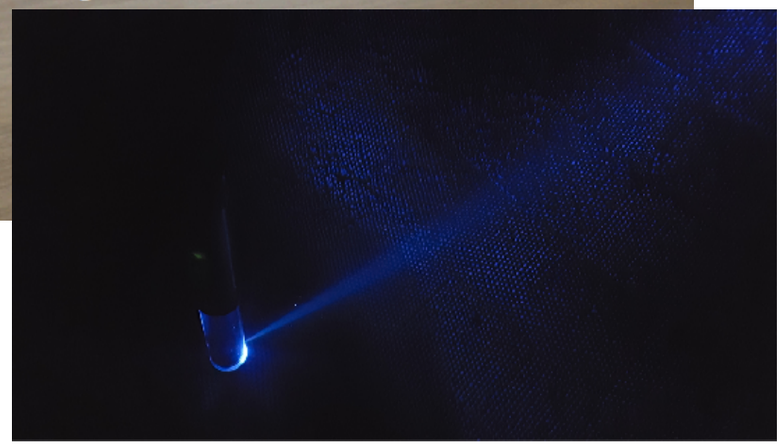


Camera system key to comprehensive understanding of the detector medium
—> Retroactively analyze more than 10 years of IceCube data with substantially improved angular and energy resolution

SpiceCore Camera System







- 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

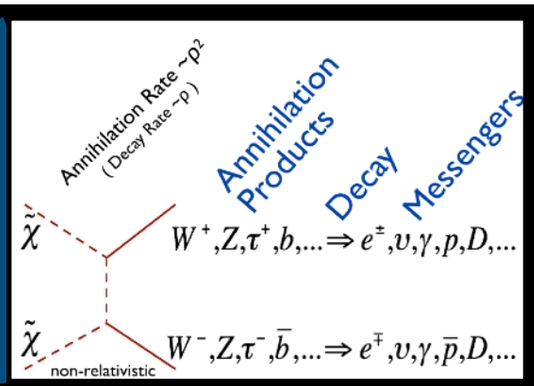
- High-energy astrophysical neutrinos have opened up a new window to the Universe
  - What's the origin of the high-energy neutrino
- Very strong bounds on dark matter scattering with nucleons
- Very diverse science program, IceCube turns out to be a treasure throve
- Neutrino astronomy is a central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

Search for Dark Matter

Solar Dark Matter



ρ_χ χ χ velocity distribution

Sun

ν interactions

ν oscillations

ν_μ

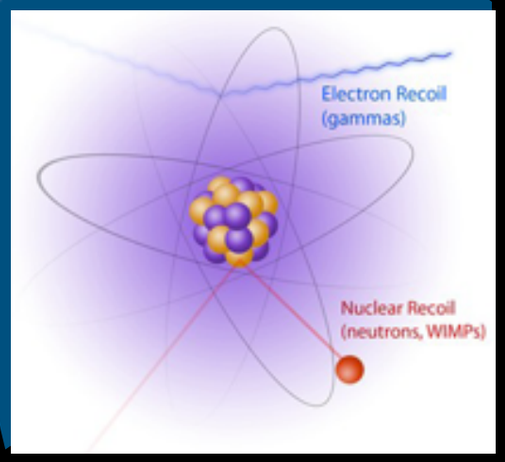
Earth

$\sigma_{\rm ann}$

$\sigma_{\rm scatt}$

$\Gamma_{\rm capture}$

$\Gamma_{\rm ann}$



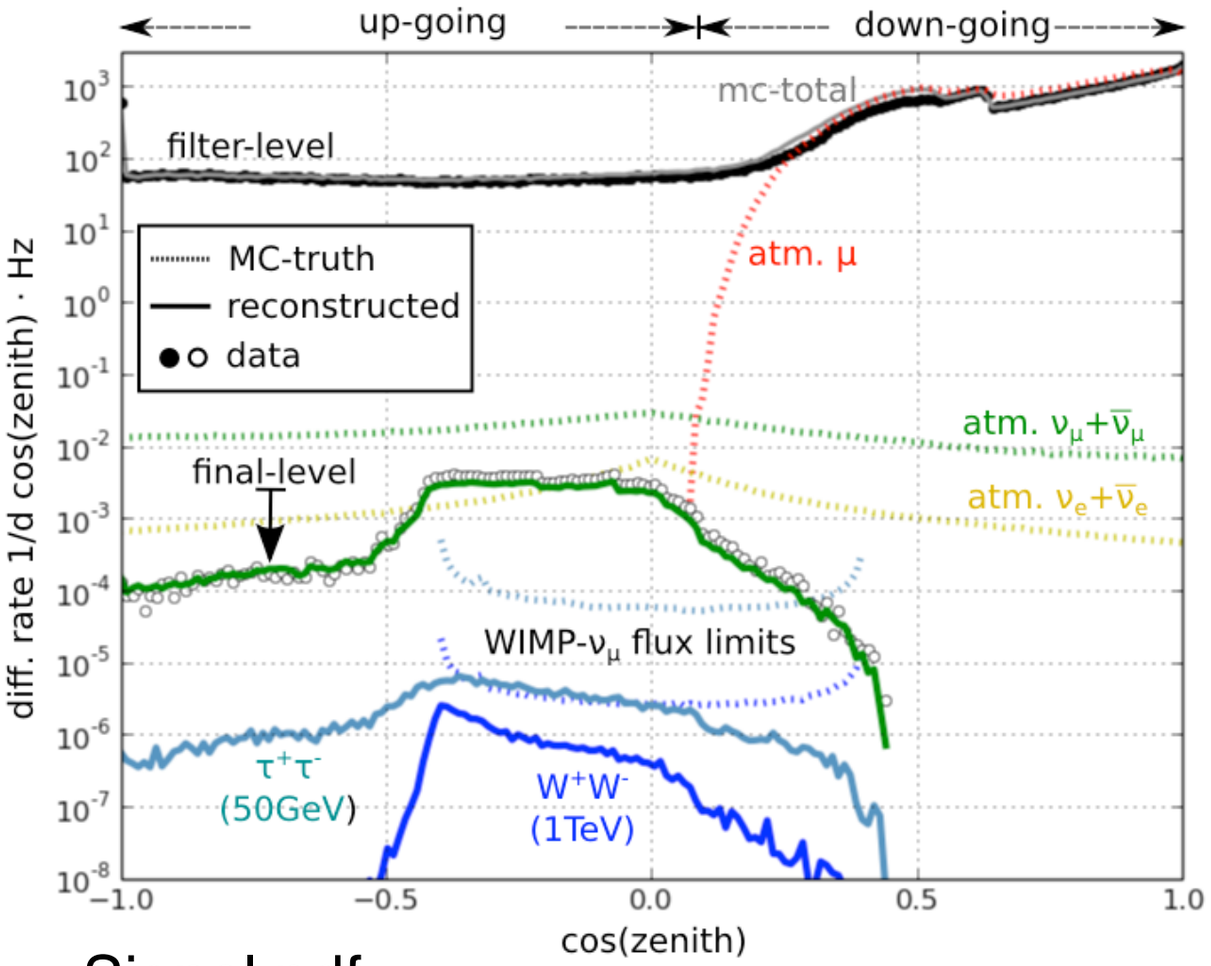
μ

Detector

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Search for Dark Matter in the Sun



Signal pdf:

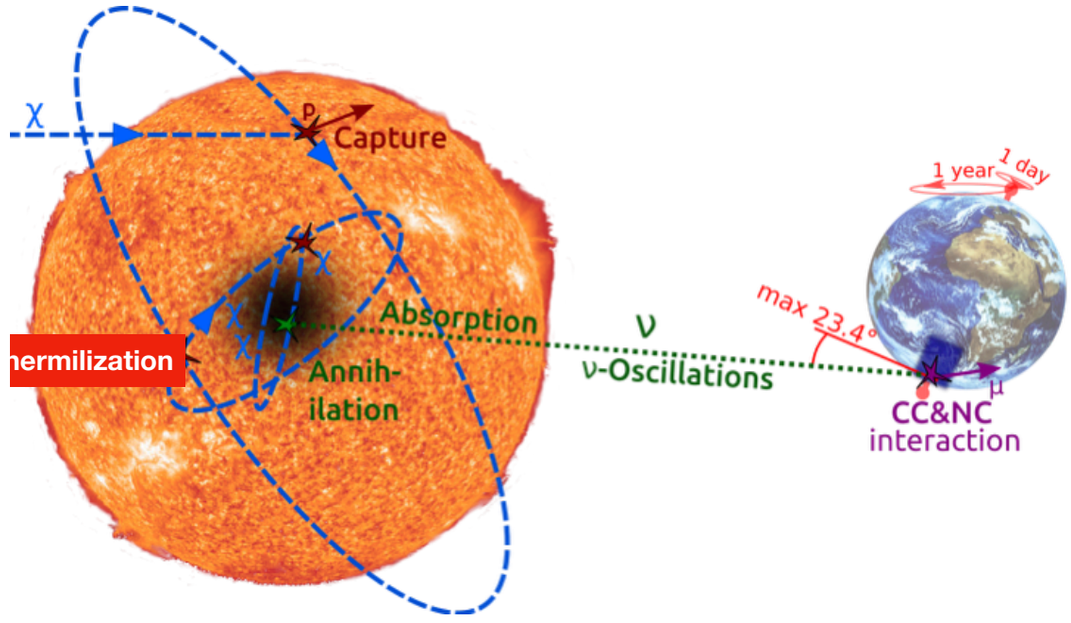
Spectral part

$$S_i(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, E_i, m_\chi, c_{\rm ann}) = \mathscr{K}(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, \kappa_i) \times \mathscr{E}_{m_\chi, c_{\rm ann}}(E_i)$$

Monovariate Fisher Bingham distribution from directional statistics

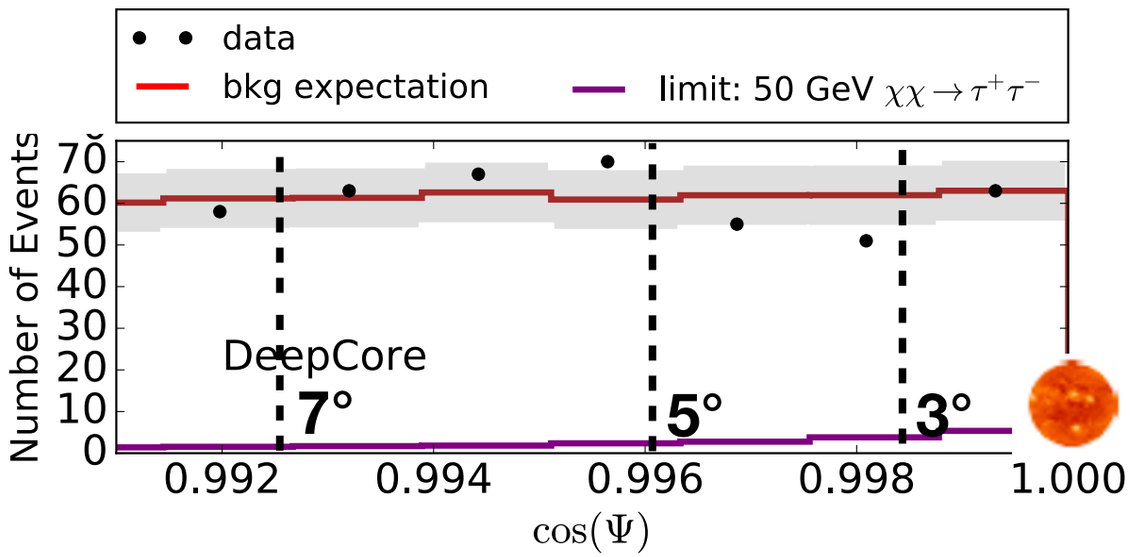
Background pdf: $\mathscr{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\rm atm})$

Likelihood: $\mathscr{L}(n_{\rm s}) = \prod_N \left(\frac{n_{\rm s}}{N} S_i + (1 - \frac{n_{\rm s}}{N})\mathscr{B}_i\right)$



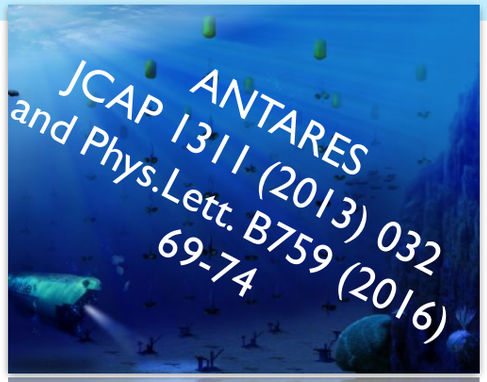
Observed events

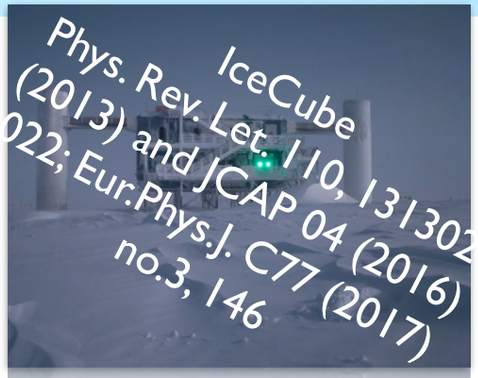
IceCube Eur.Phys.J. C77 (2017) no.3, 146

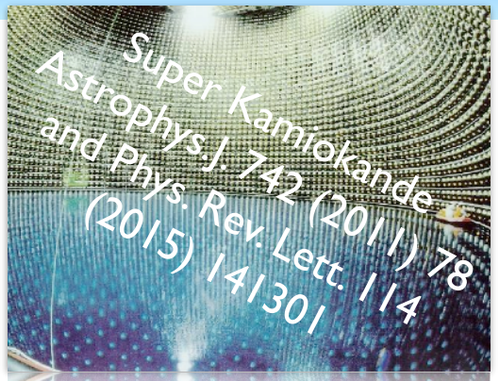


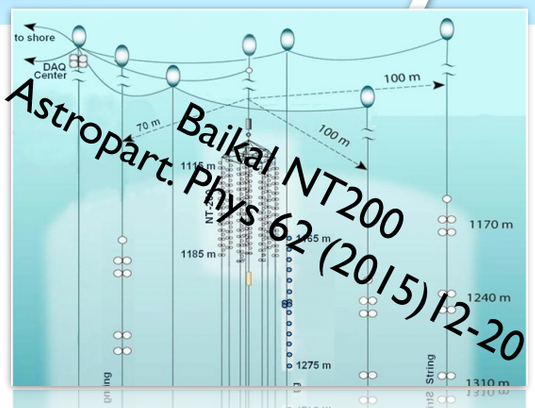
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Observed events consistent with background only expectations

Solar Dark Matter Summary

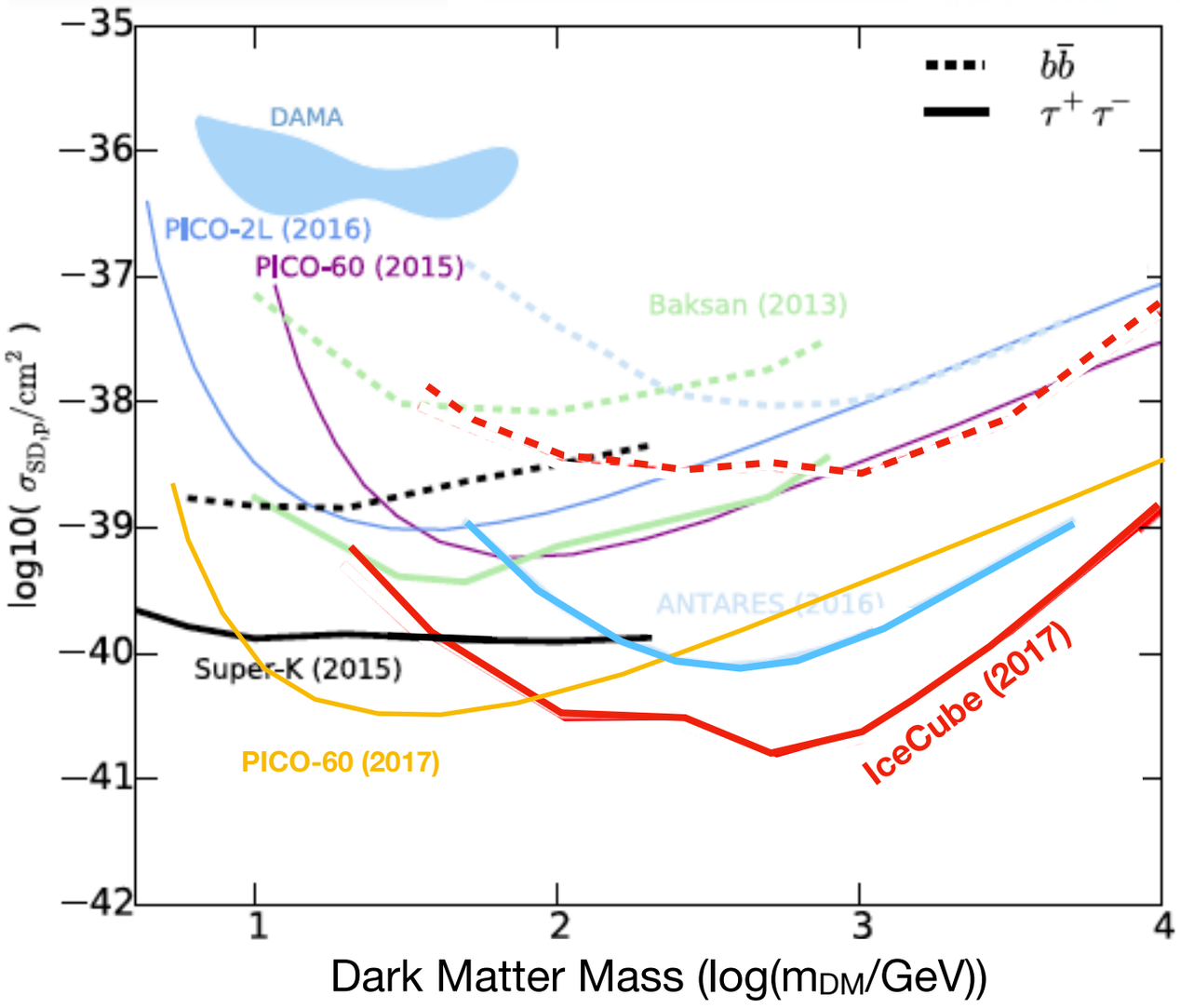




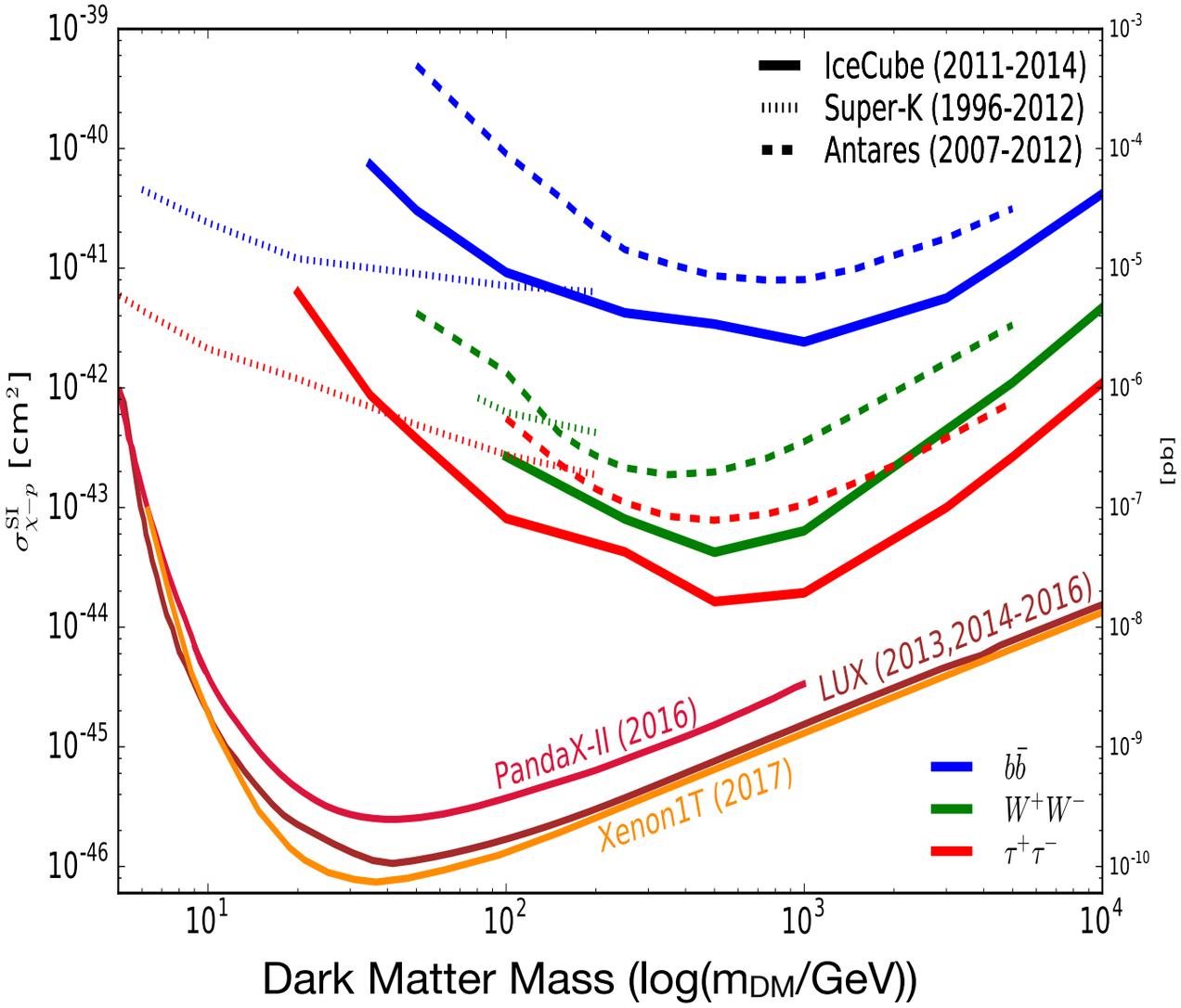




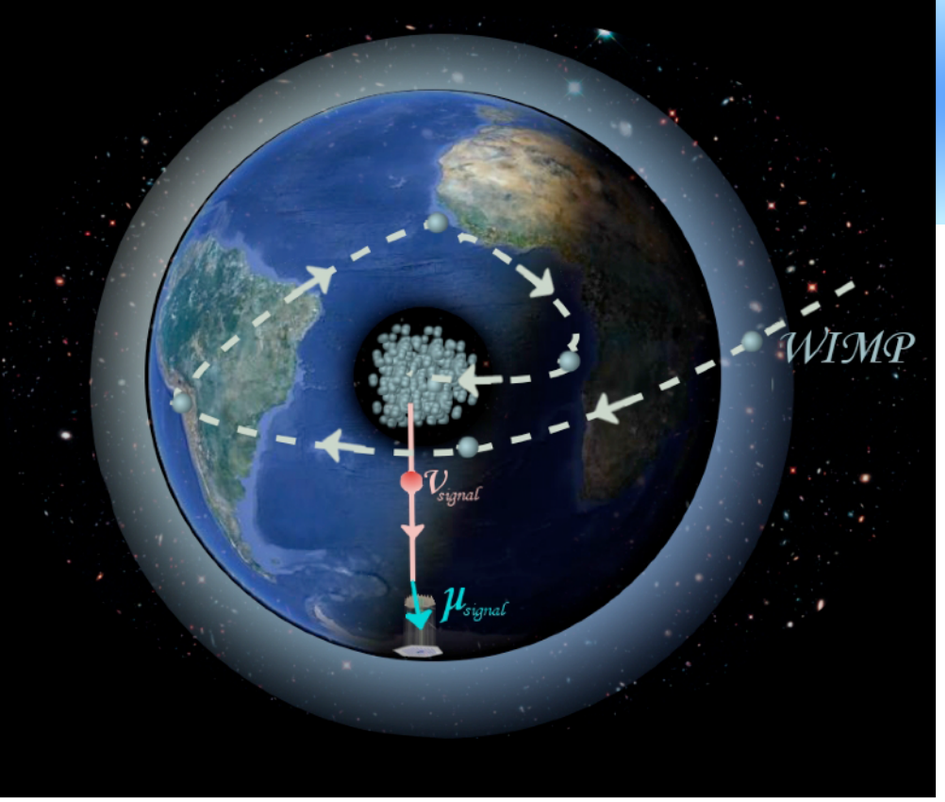
Spin-dependent scattering



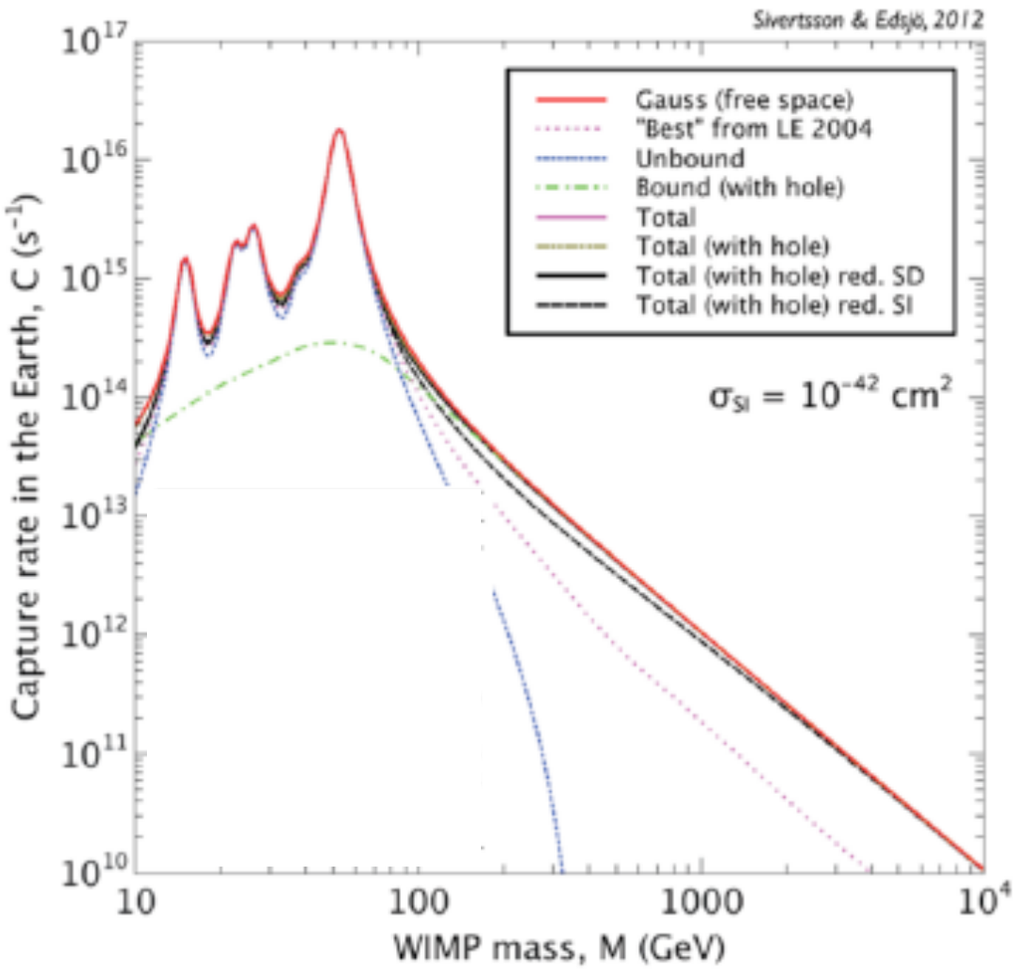
Spin-independent scattering

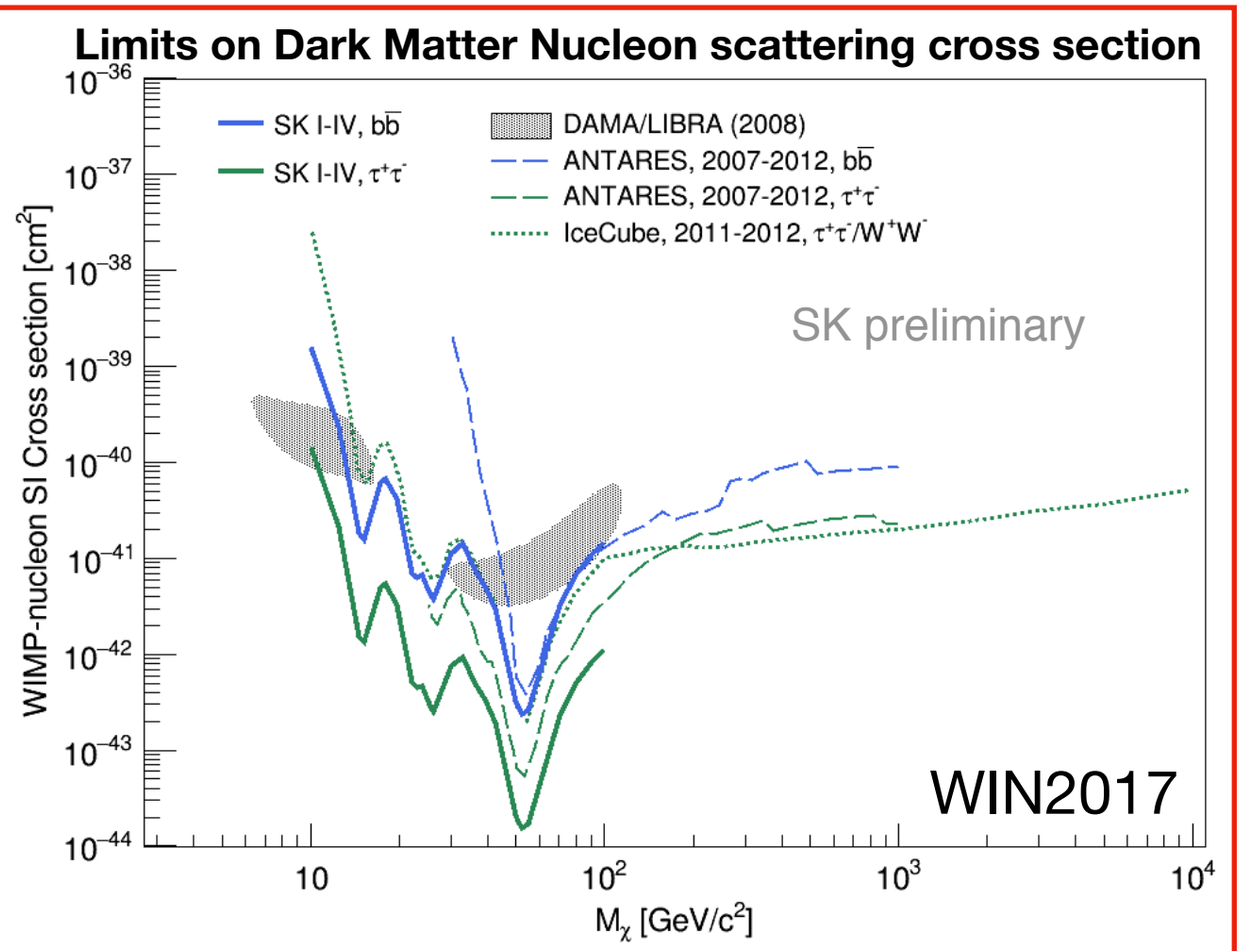


Earth WIMPs

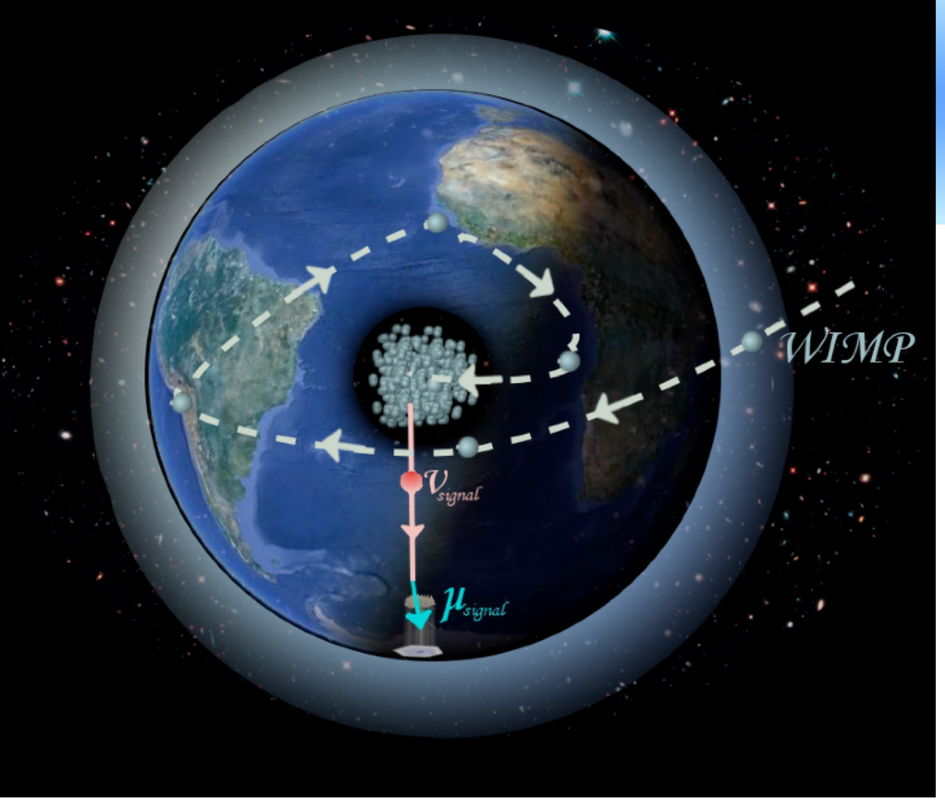


- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- No off-source region





Earth WIMPs



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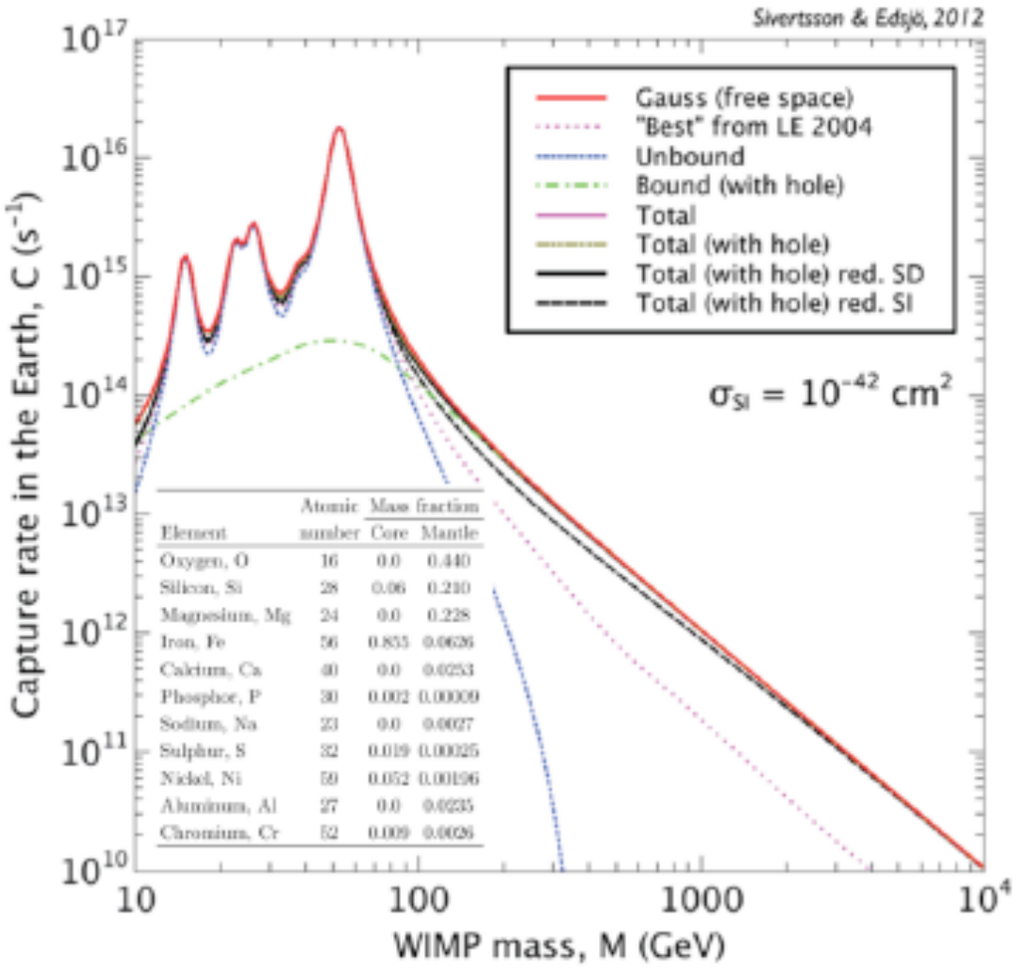
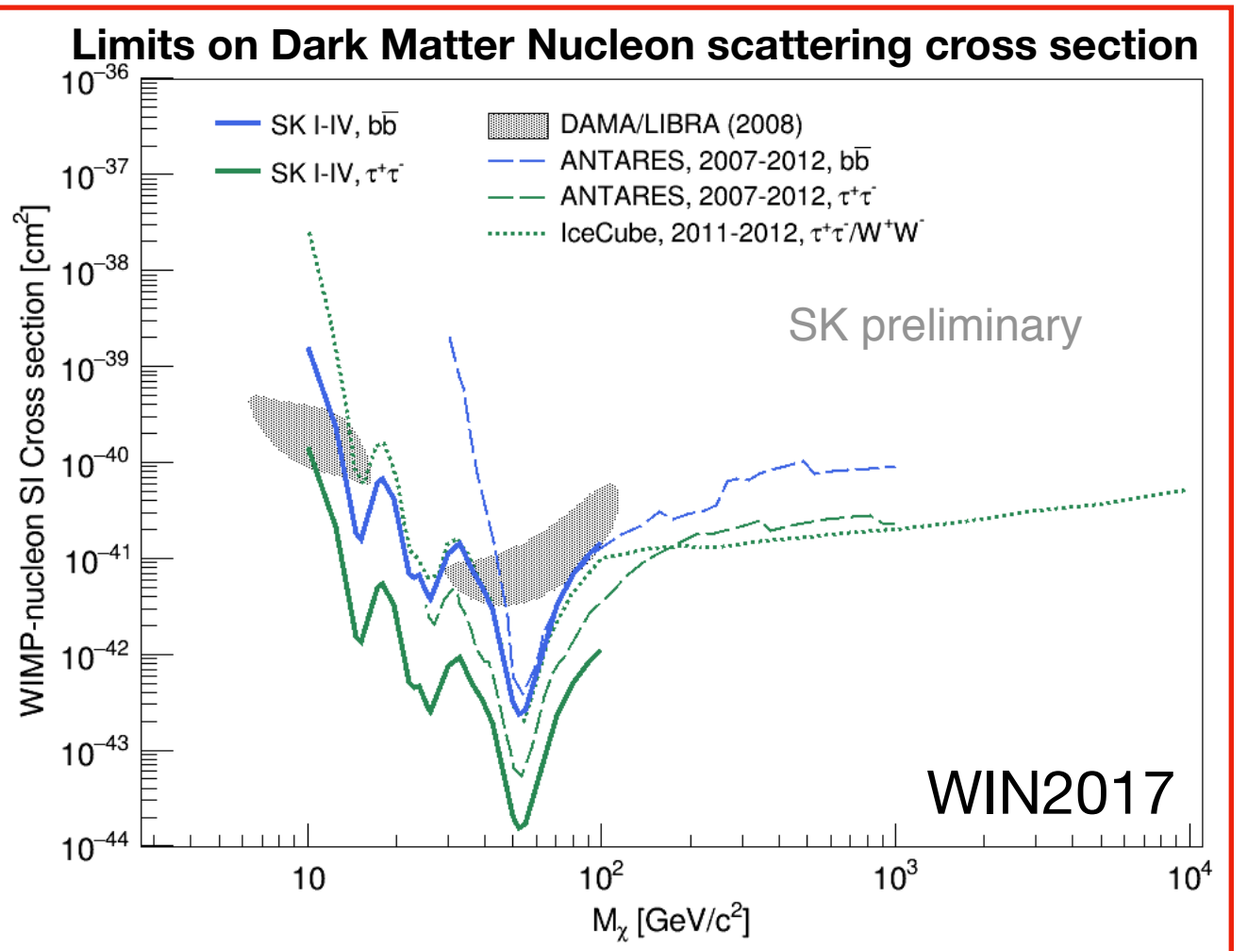
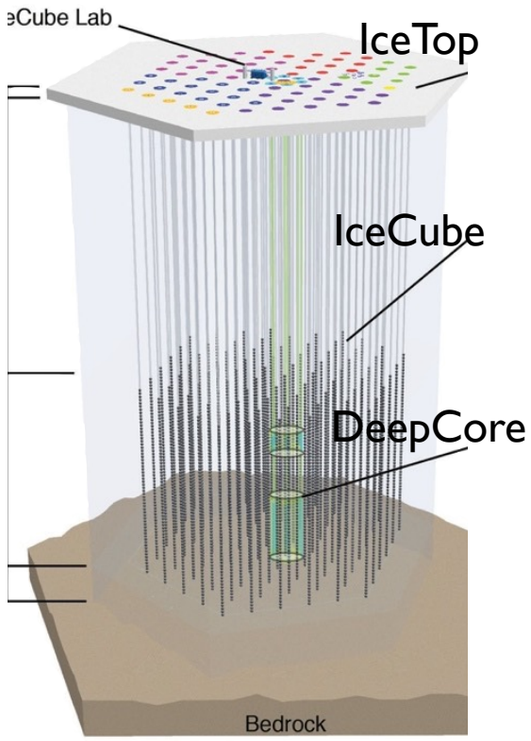


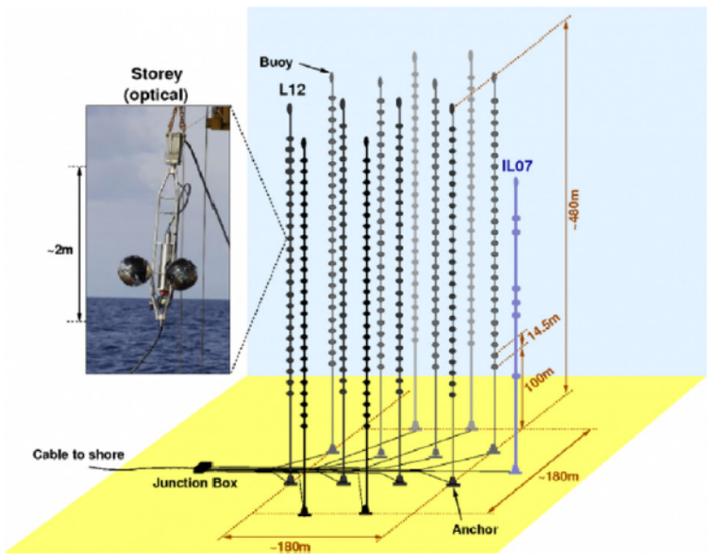


Thanks !

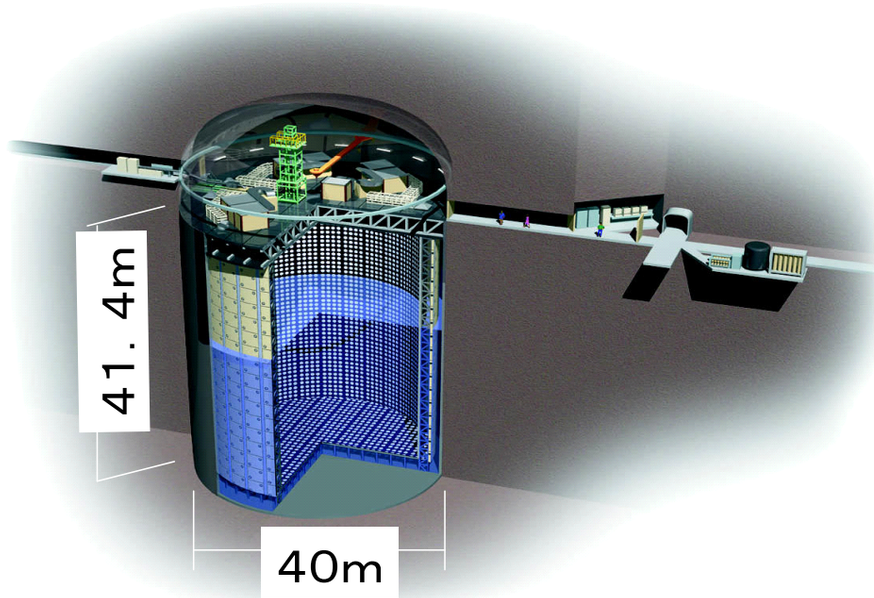
Atmospheric Neutrino Telescopes / Detectors



- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km^3
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension



- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008 ; Phyiscs data taking since 2007



- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

Detect Cherenkov light from neutrino interaction products

Main backgrounds: Atmospheric neutrino, atmospheric muons (down-going)