ISAPP Summer School Lecture
Part 2

Carsten Rott (SKKU)

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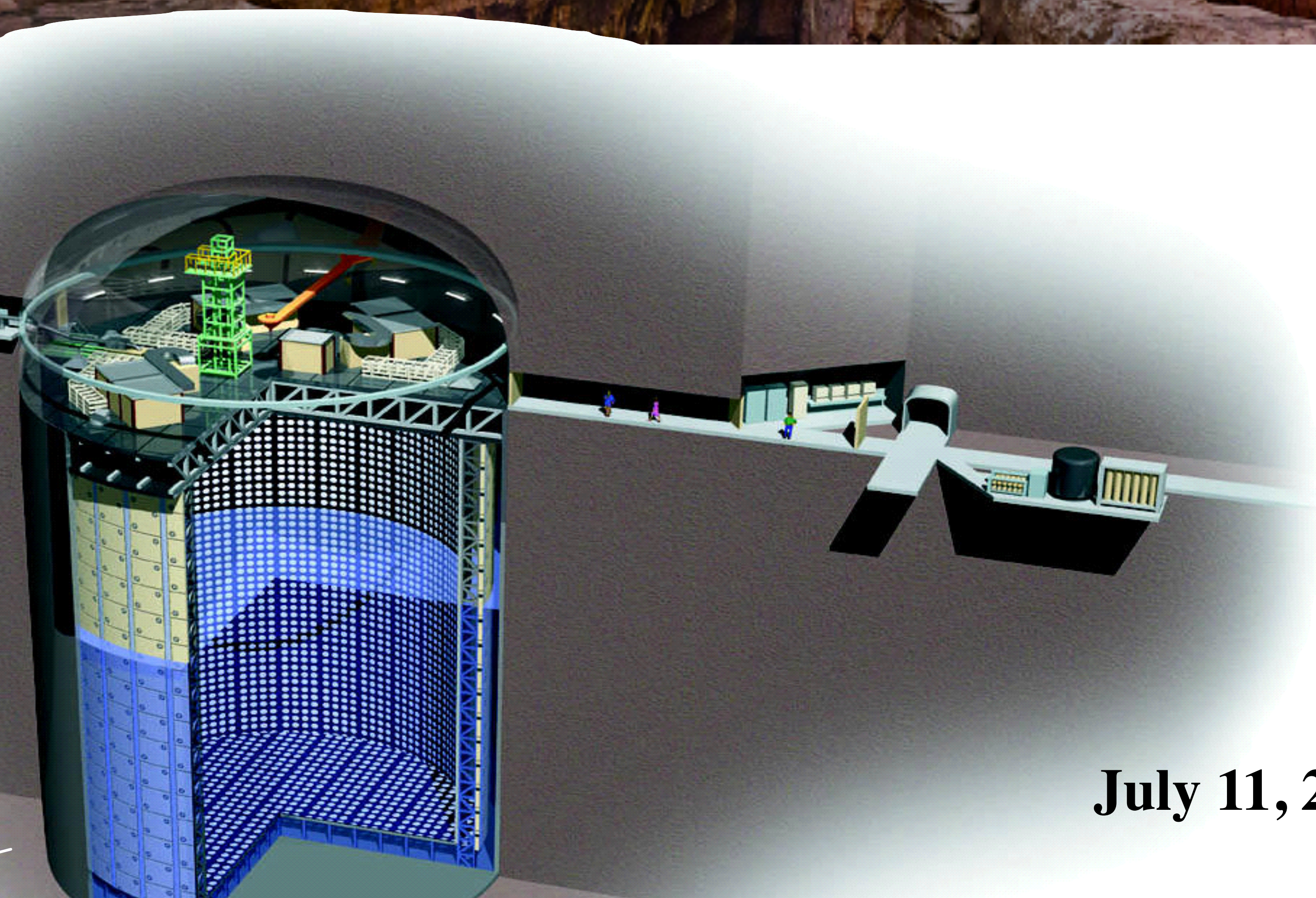
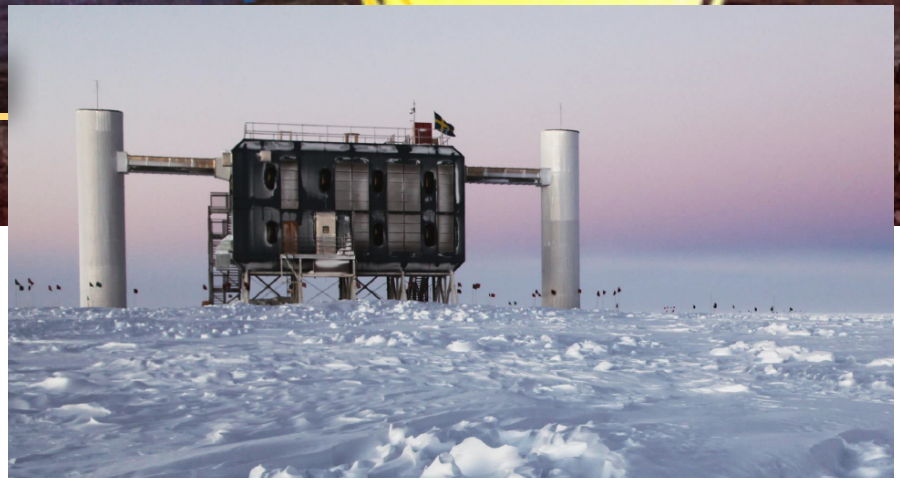
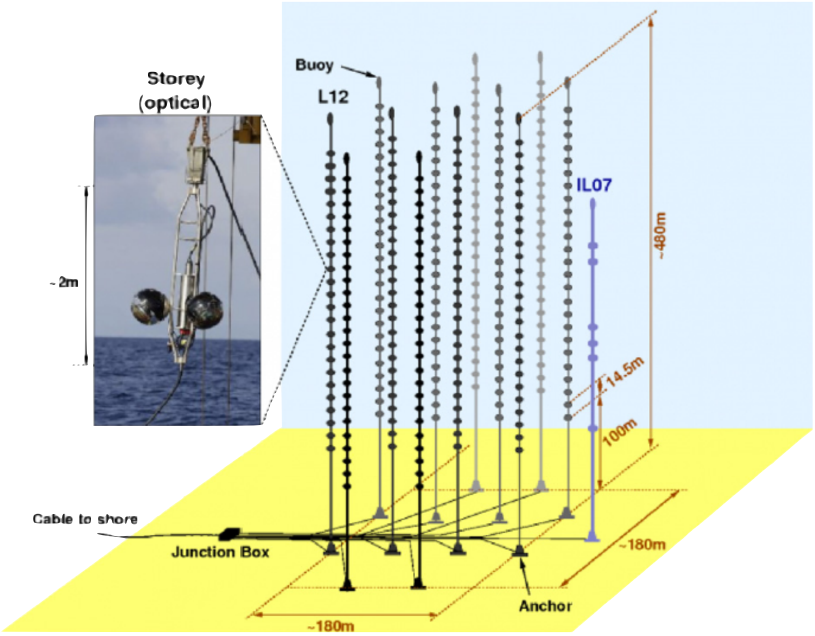






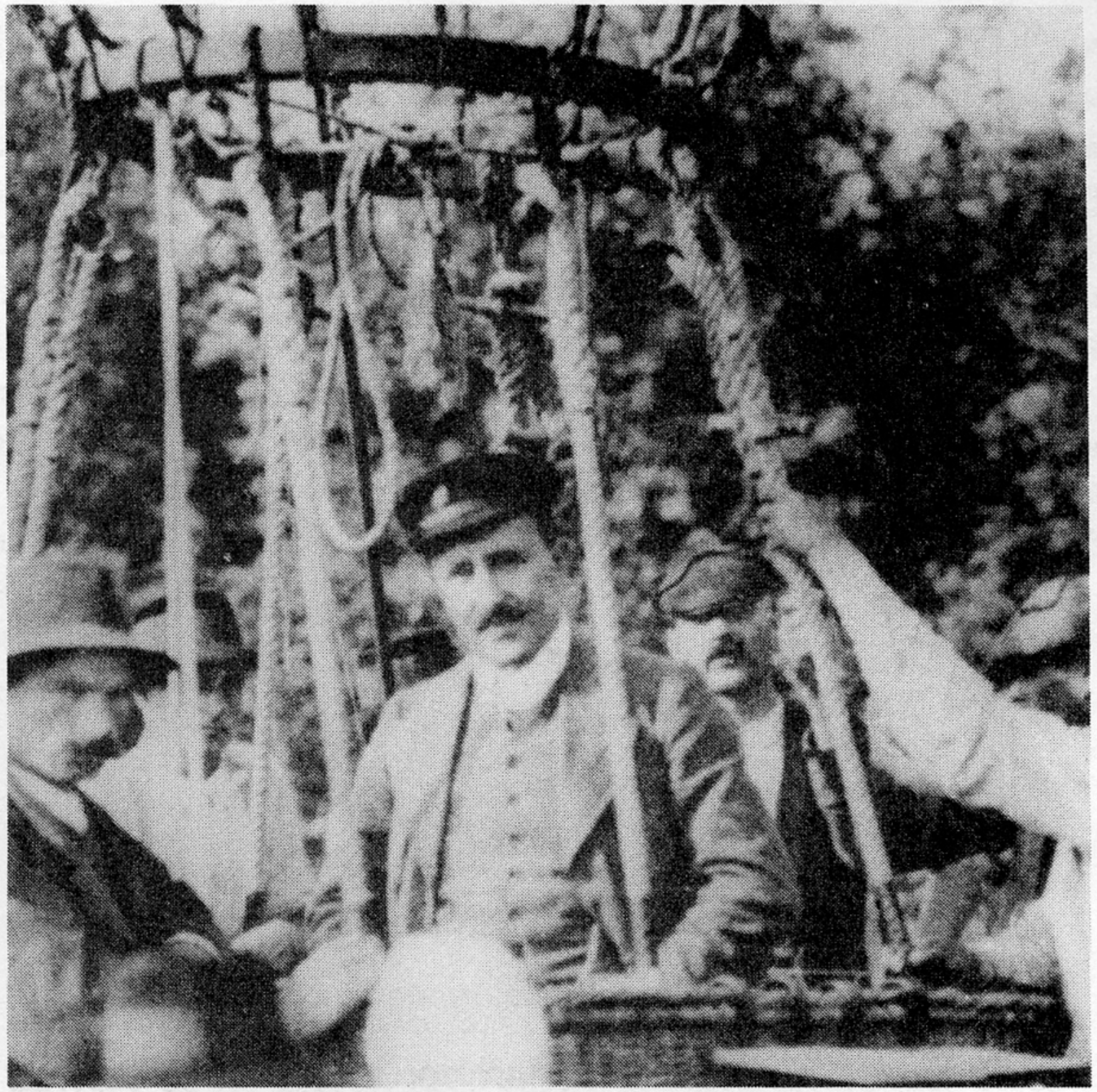
July 11, 2018

Lectures

- This lecture
  - Motivation
  - Neutrino Detection
  - Introduction to Neutrino Telescopes
    - The IceCube Neutrino Telescope and it's science program

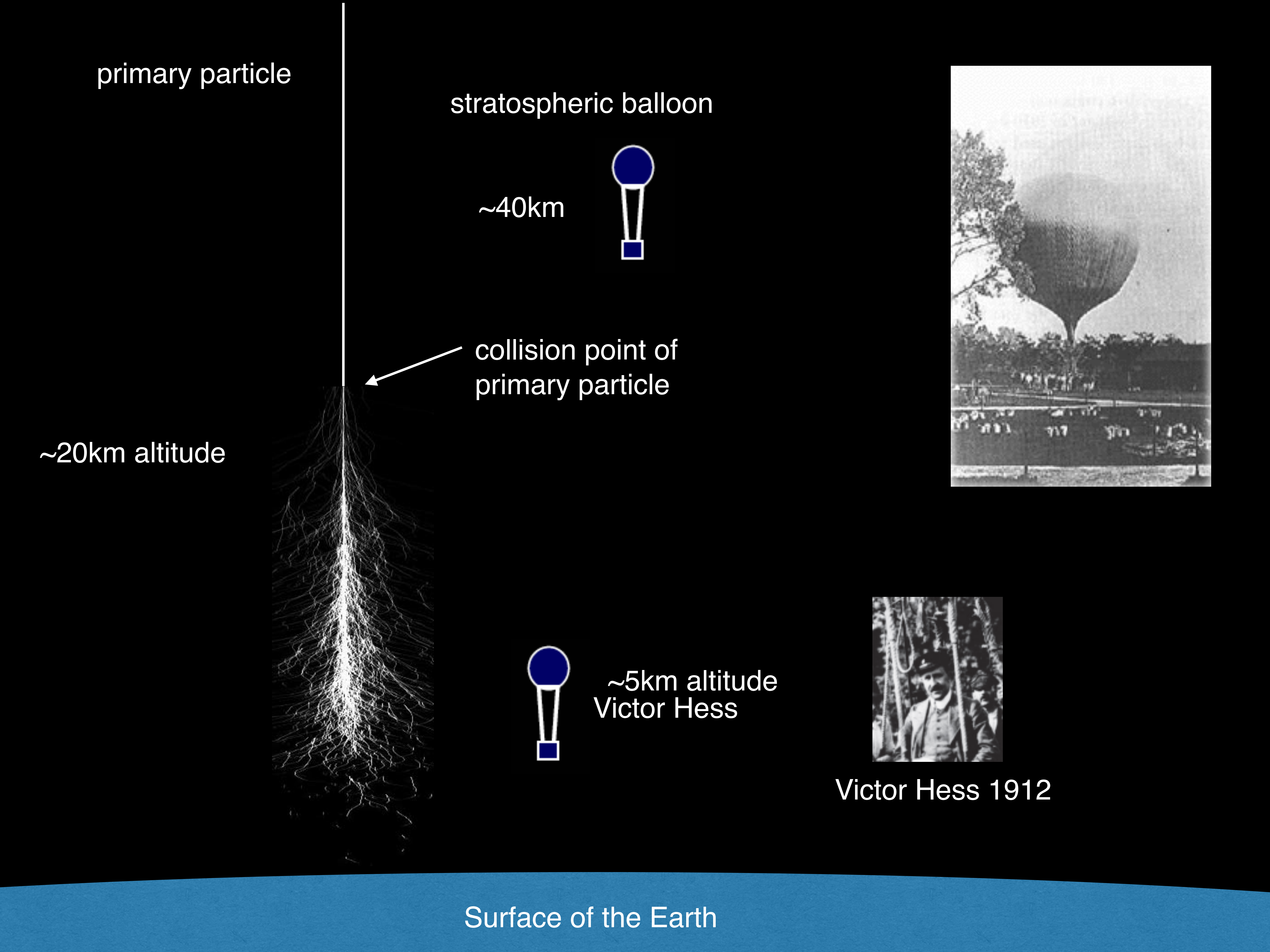
The Cosmic Ray Mystery

Victor Hess

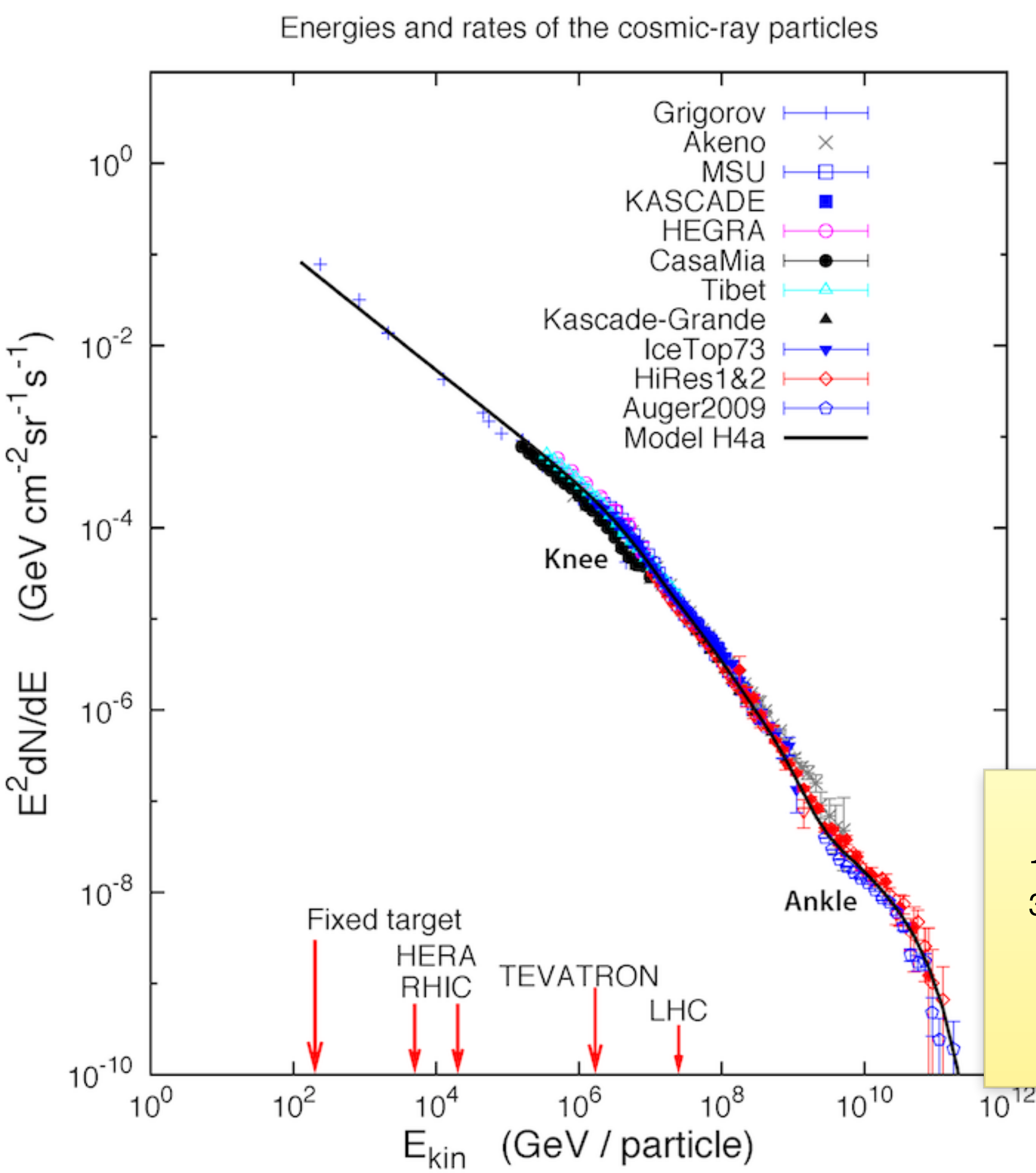


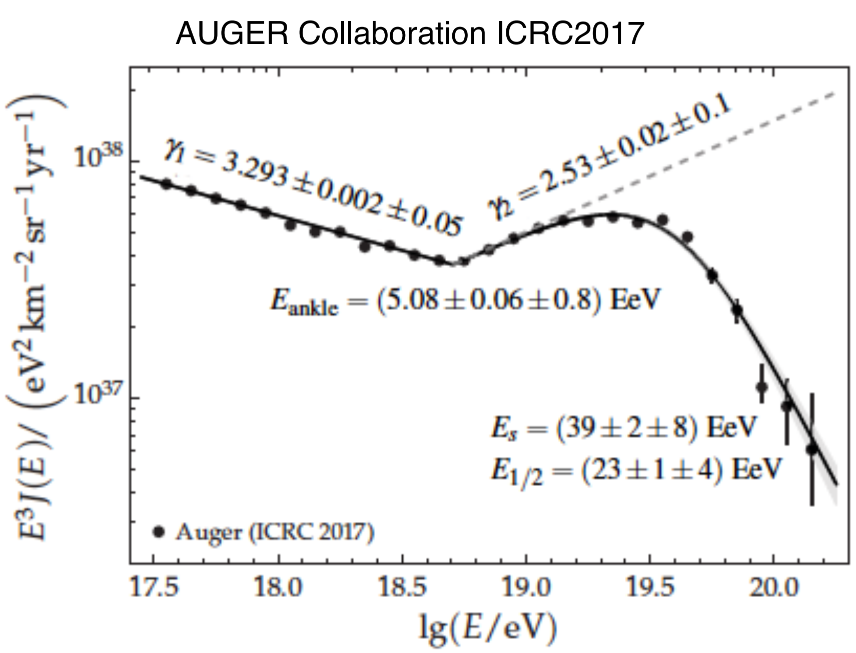
Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

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

Cosmic rays

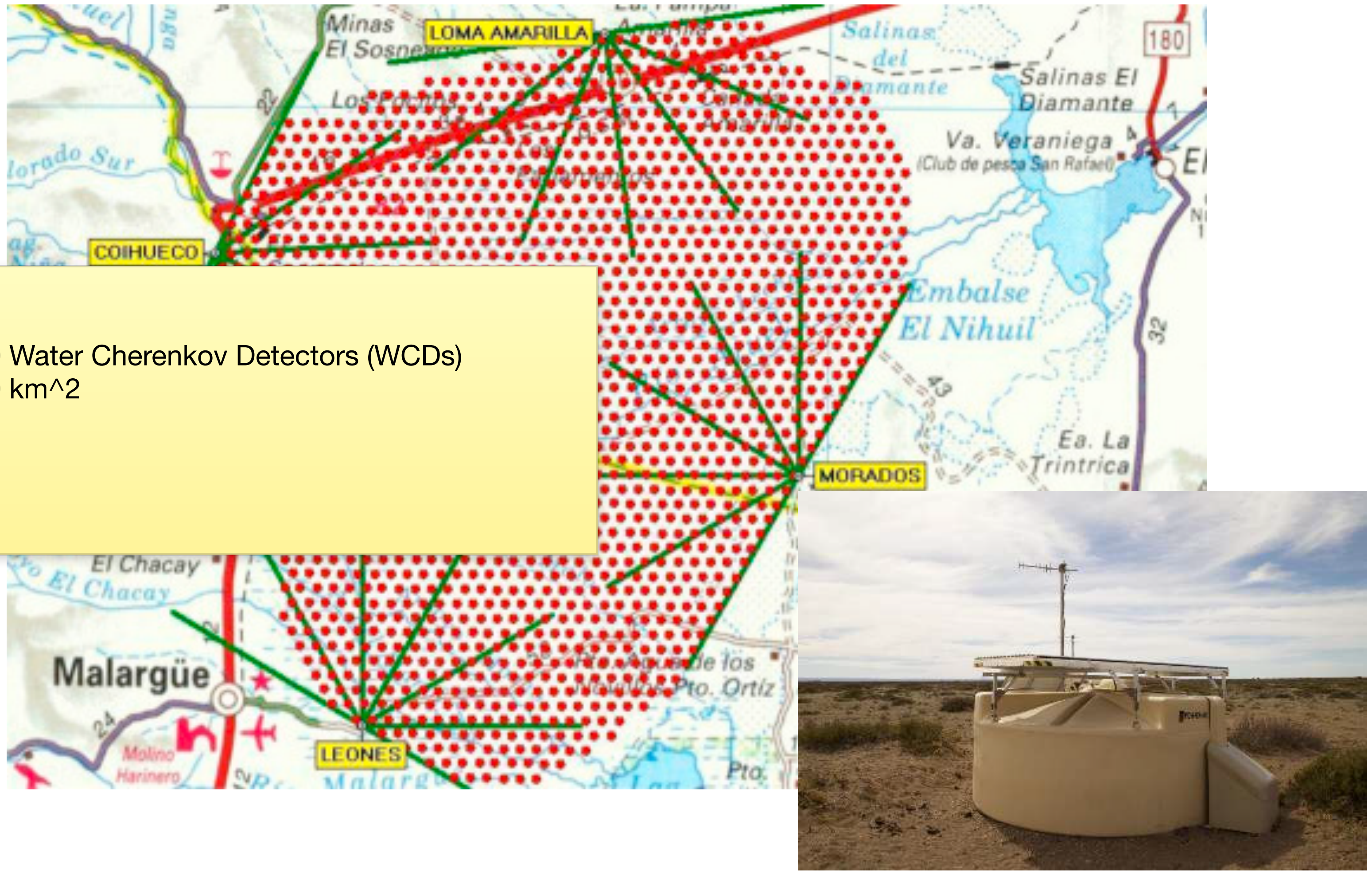




Cosmic rays have been observed with energies up to 10^{20}eV (100EeV) or 10^7 LHC beam energies

AUGER

Malargüe, Mendoza



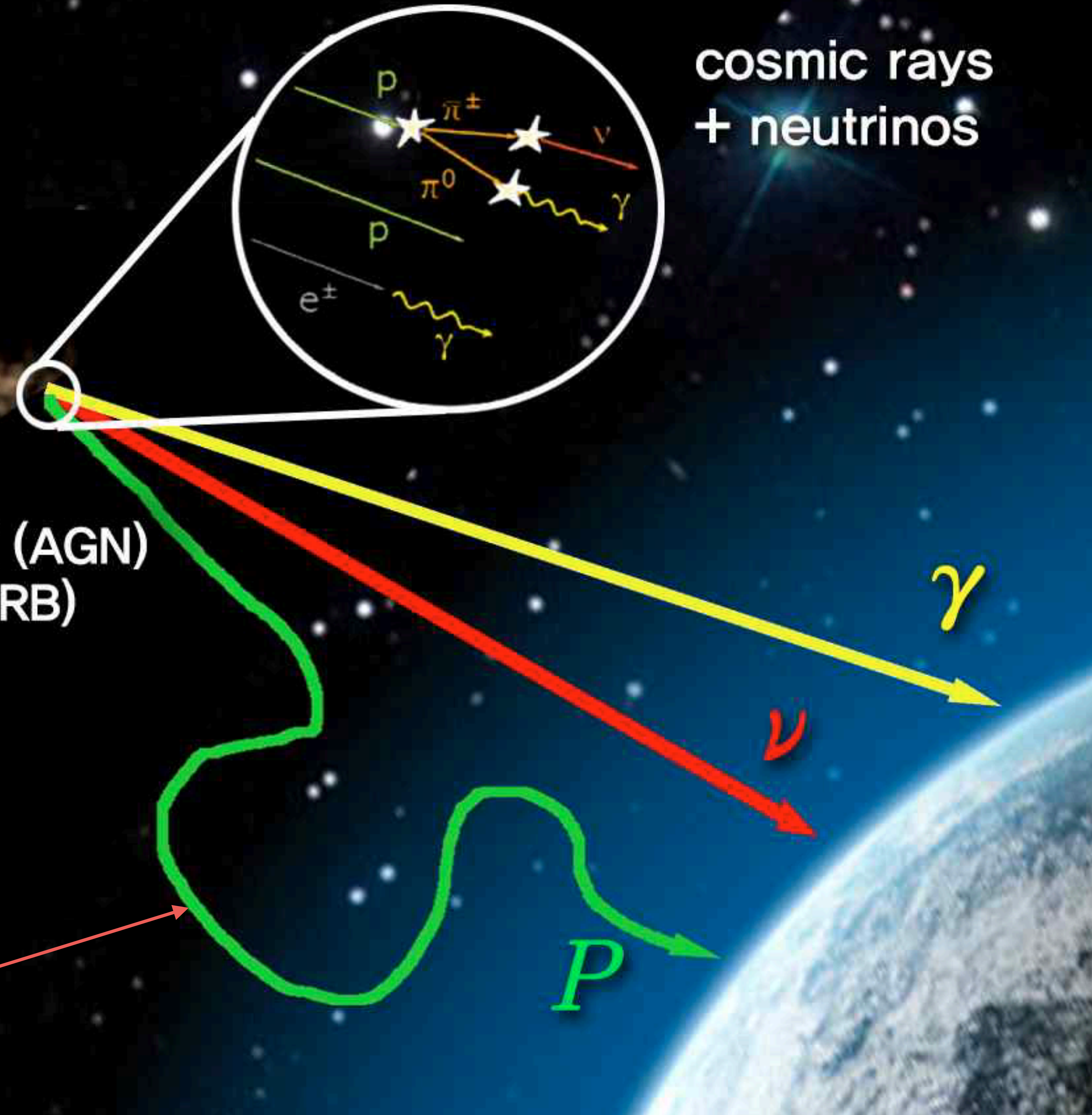
1600 Water Cherenkov Detectors (WCDs)
3000 km^2

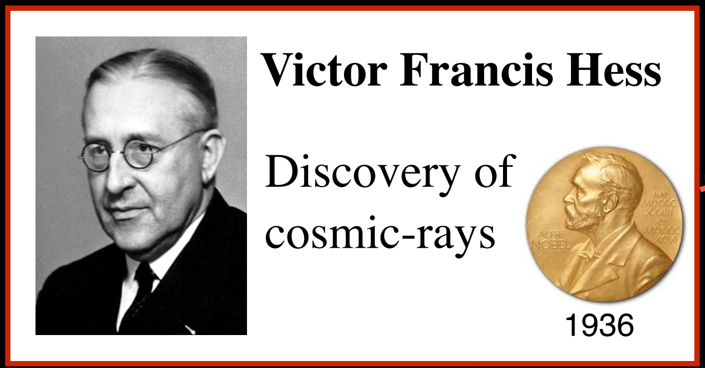
- Cosmic ray spectrum extremely well measured (TA, Auger, …)
- Where are they coming from ?
- What cosmic sources accelerate these particles to energies well beyond that reached at LHC ?

Astrophysical Messengers

Cosmic Ray Sources

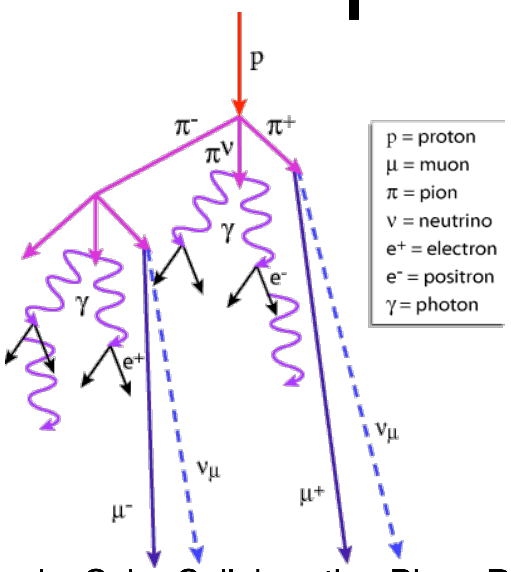
- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB)
- Supernovae (SN)
- Galaxy Clusters
- Unknown





Sources of High Energy Neutrinos

Atmospheric Neutrinos

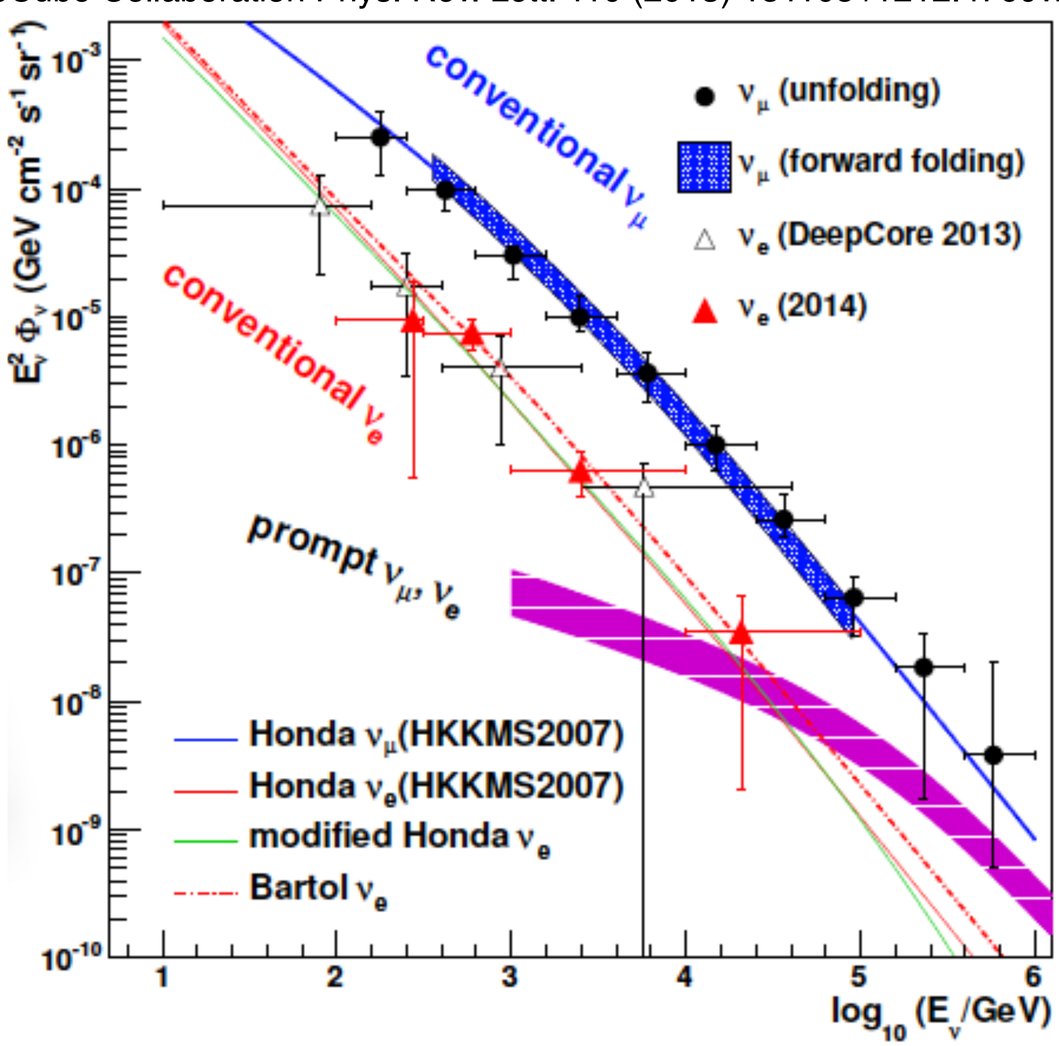


Cosmic rays interact in the upper atmosphere:

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

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

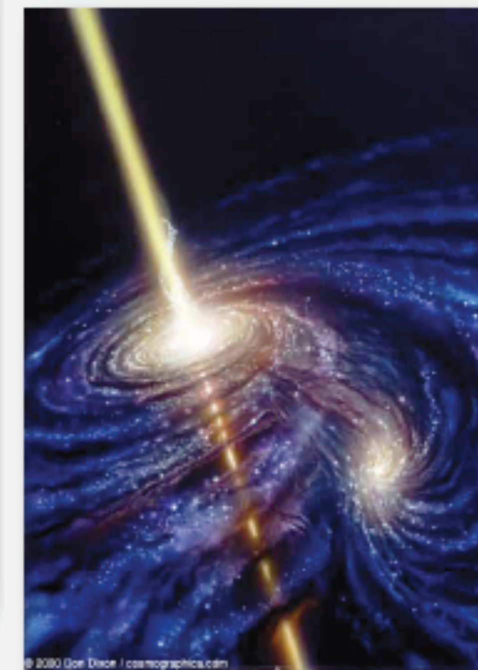
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



Astrophysical

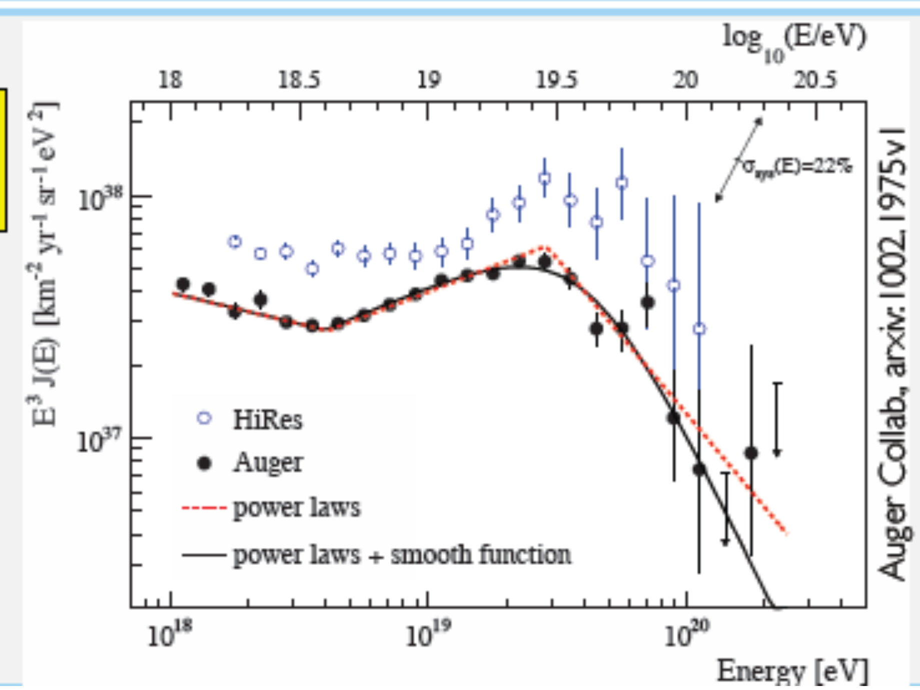
$p + (p,\gamma) \rightarrow \pi^\pm \rightarrow \nu$

Active Galactic Nuclei



Gamma-ray Bursts

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



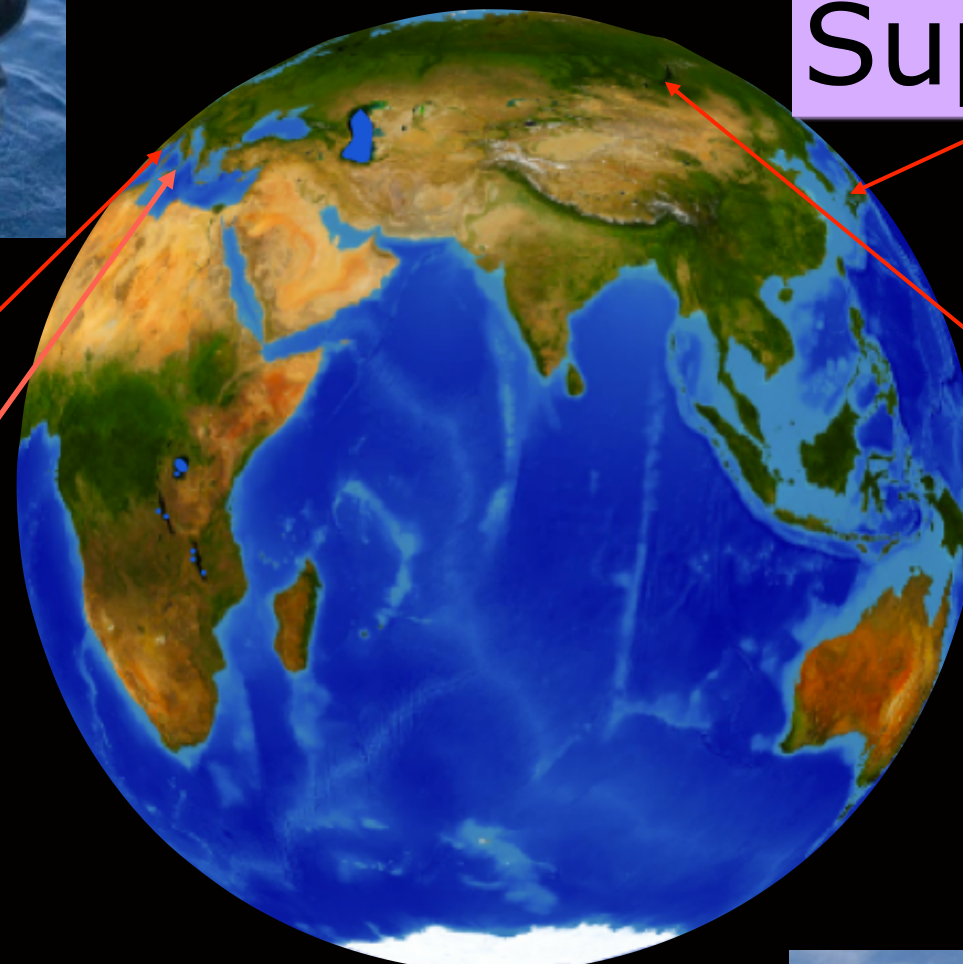
Auger Collab, arxiv:1002.1975v1

Neutrino Telescopes

Water Cherenkov Neutrino Detectors

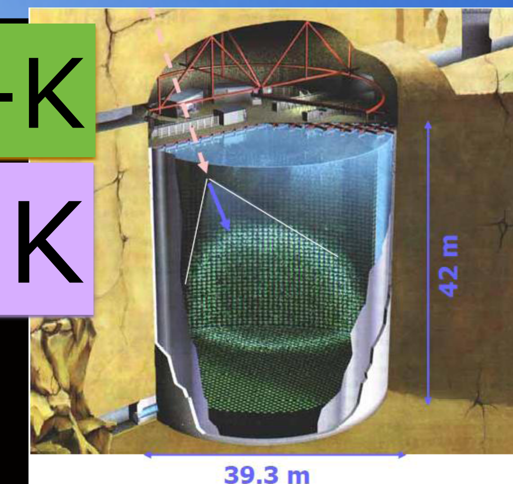
ANTARES

KM3Net ORCA



Hyper-K

Super-K



Lake Baikal

GVD

IceCube

Gen2/PINGU

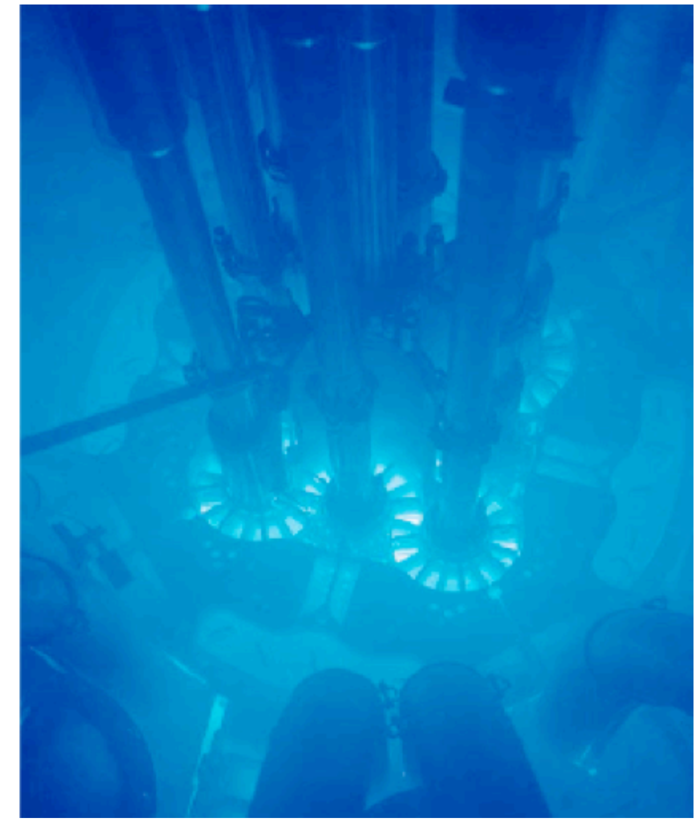
Active

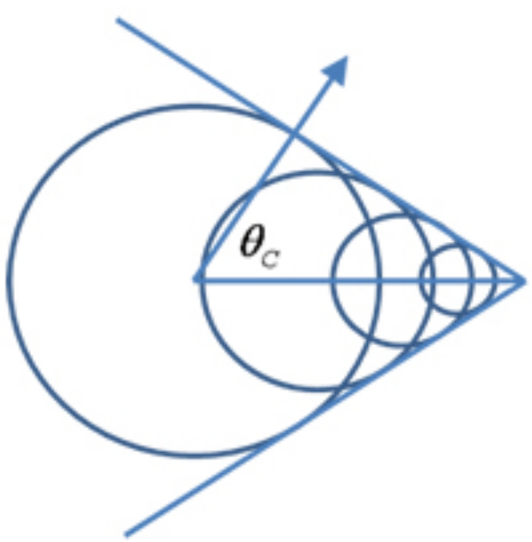
Construction

Planned

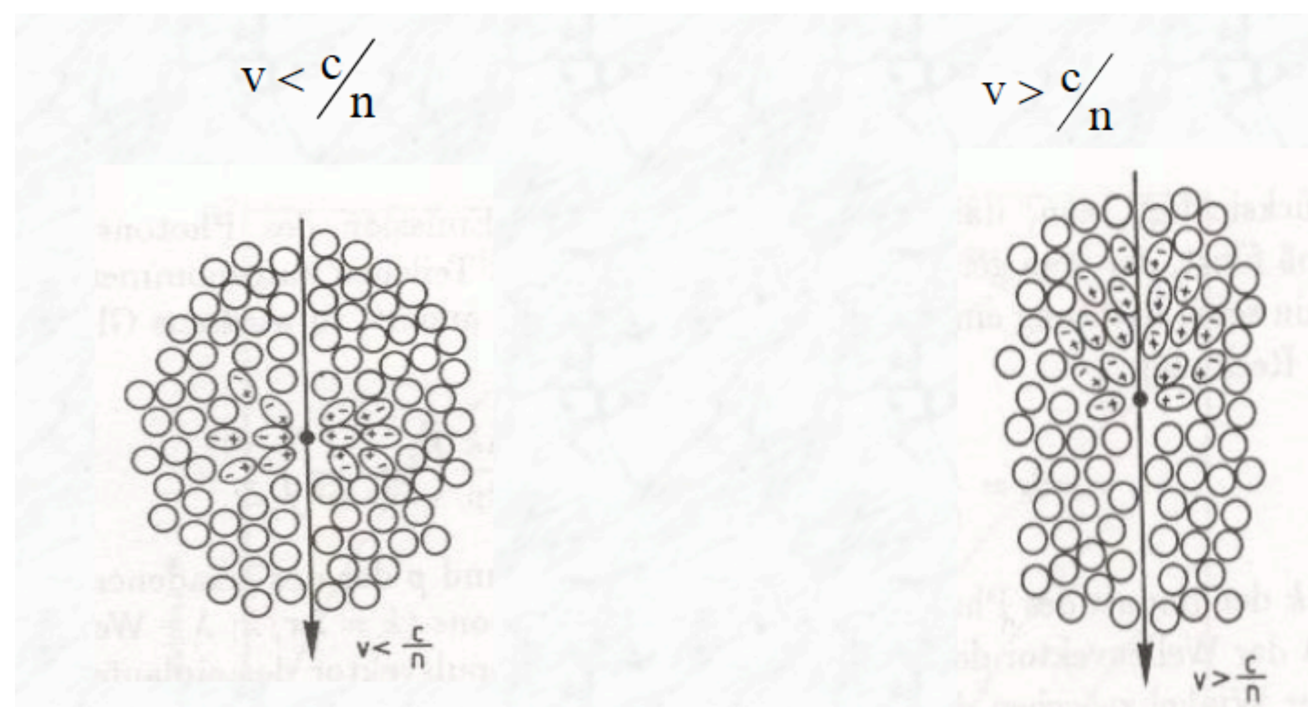
Cherenkov light in water/ice

- 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°

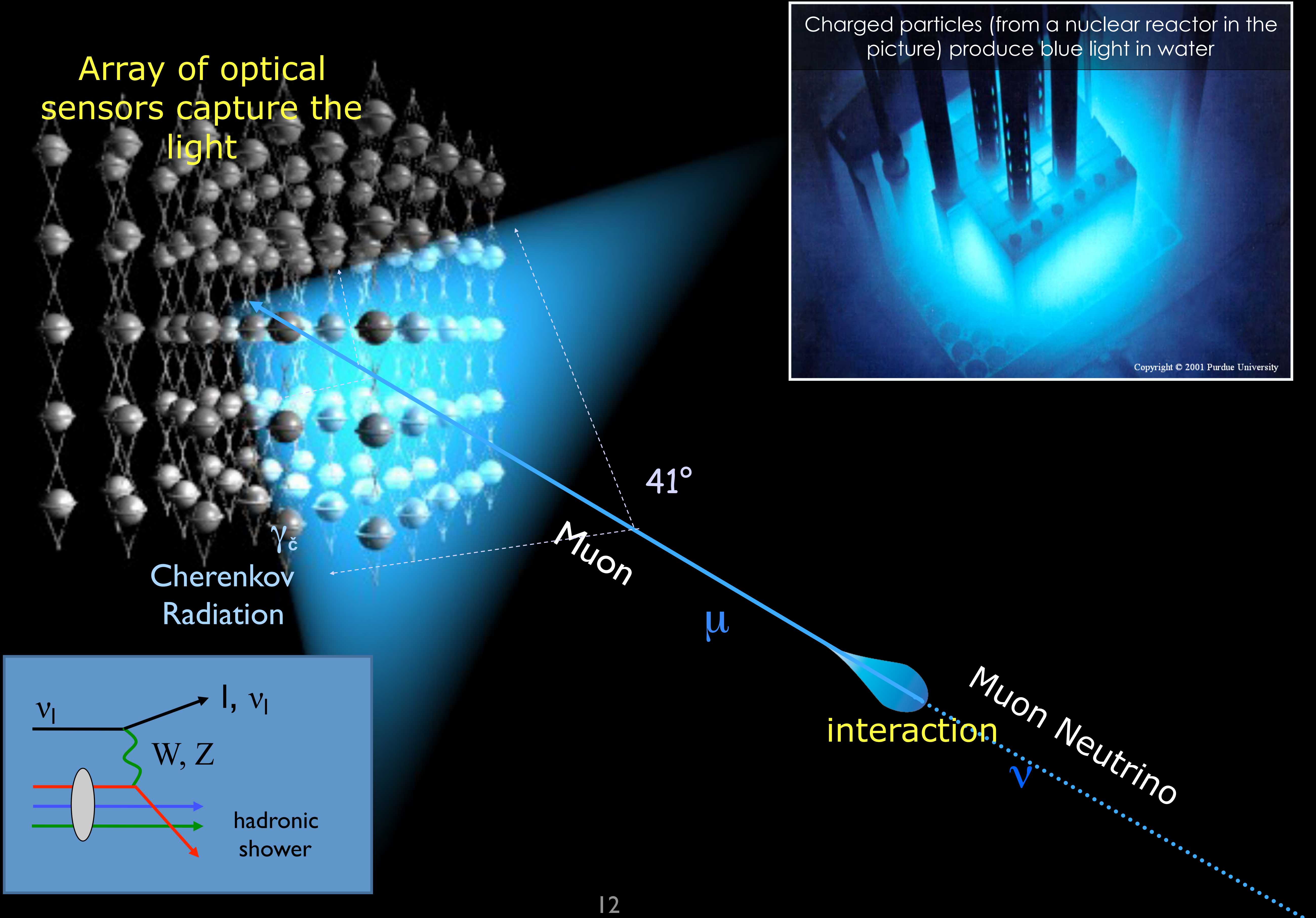


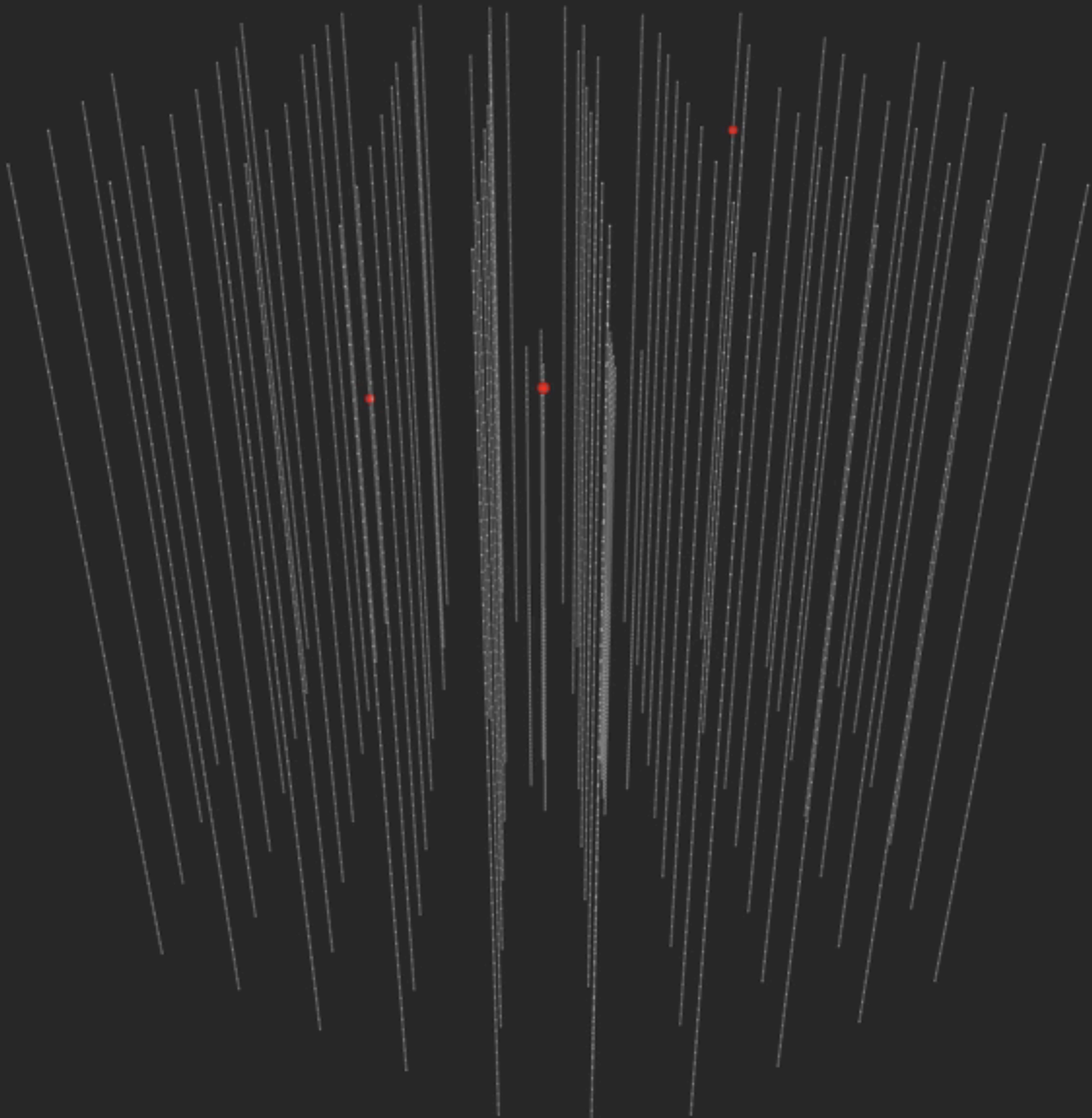


$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$



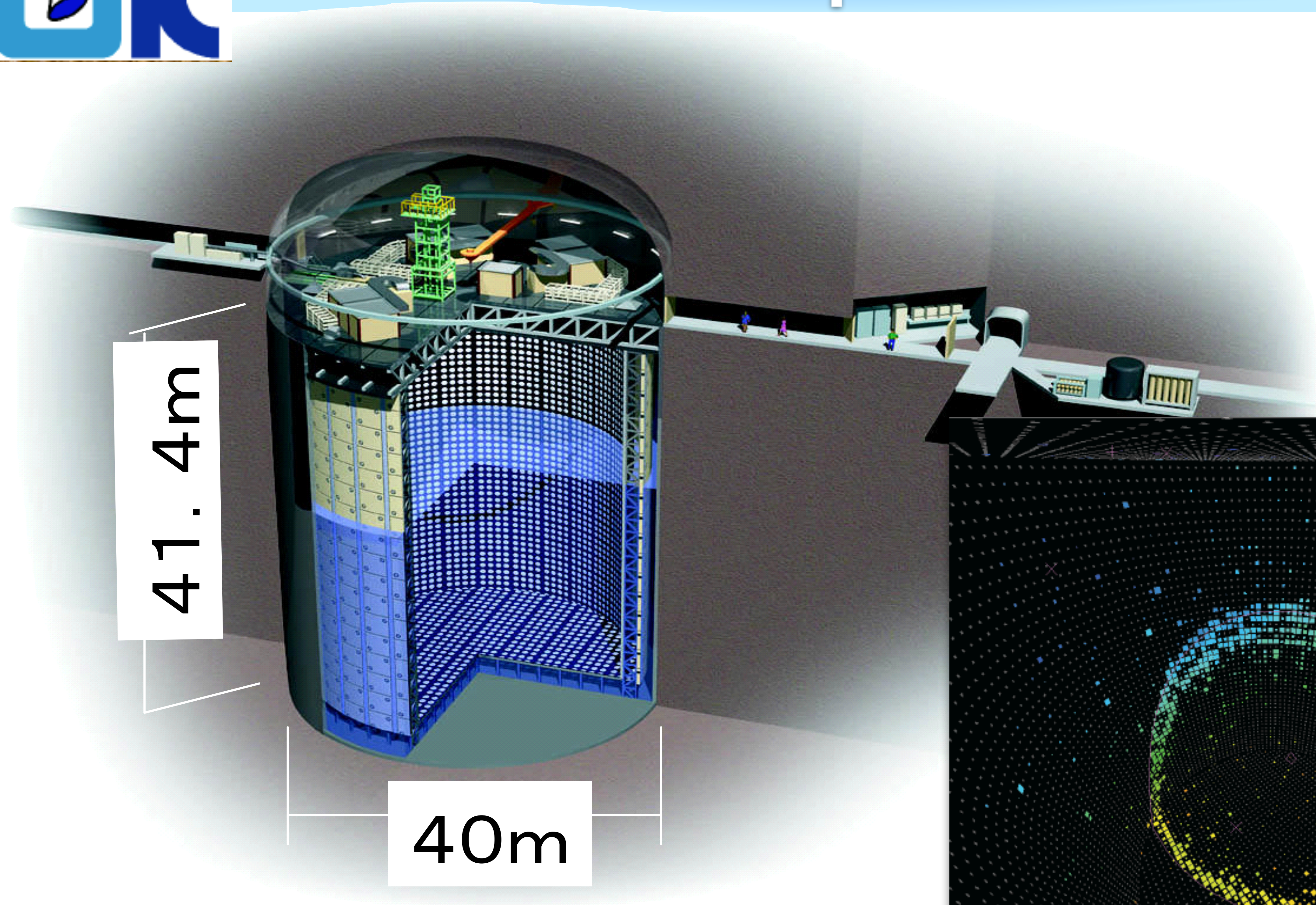
Principle of an optical Neutrino Telescope

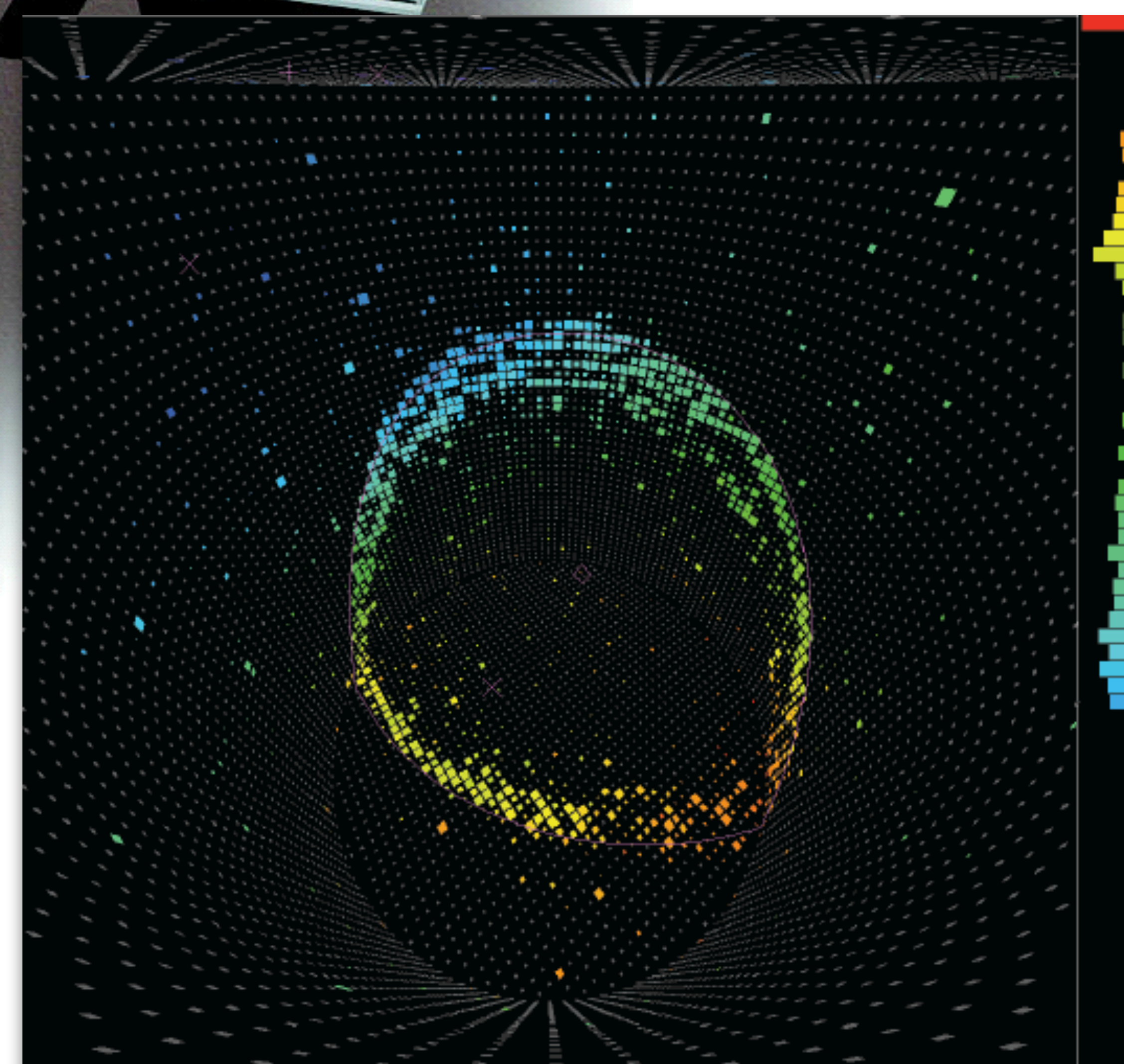




Neutrino Interactions and Detection (High Energies)

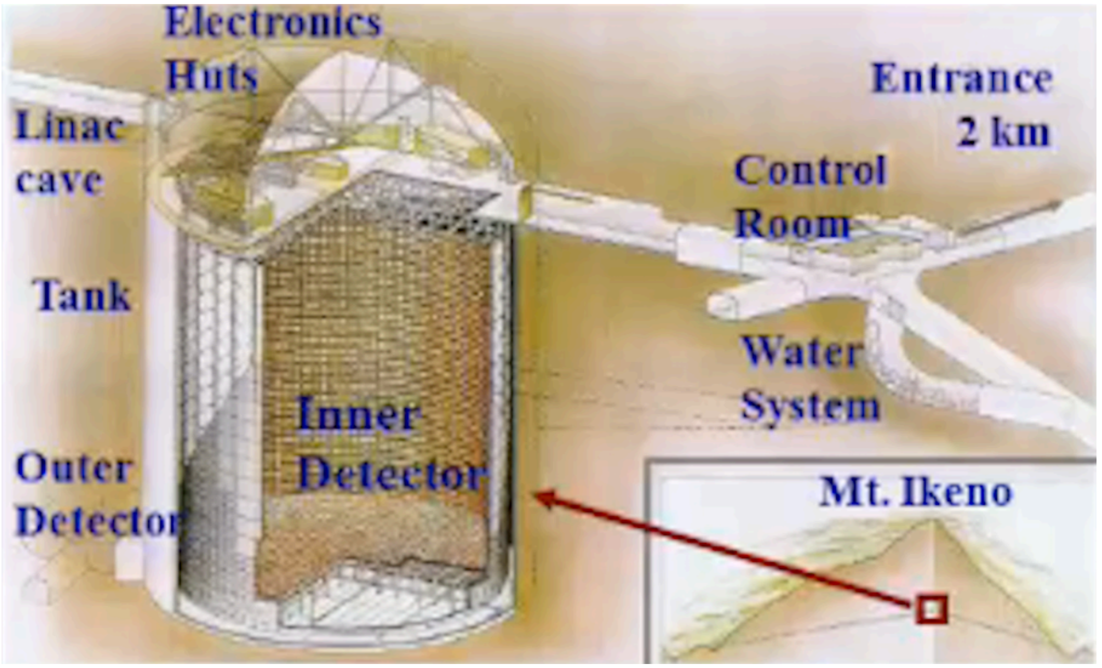
Super-Kamiokande

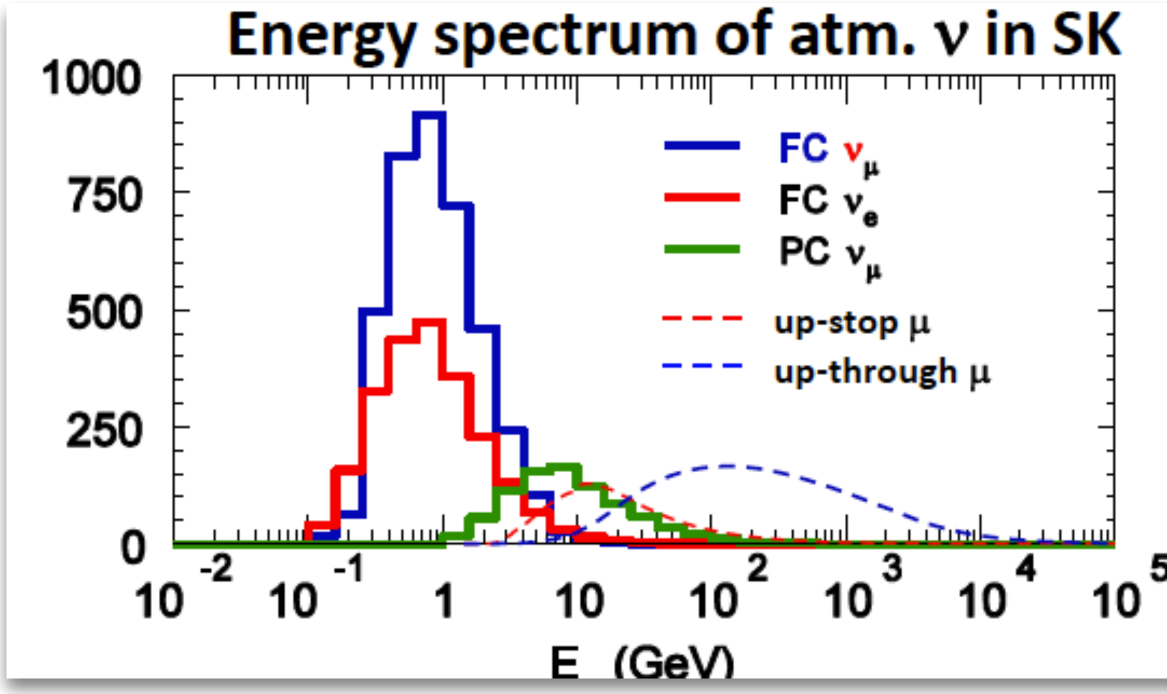




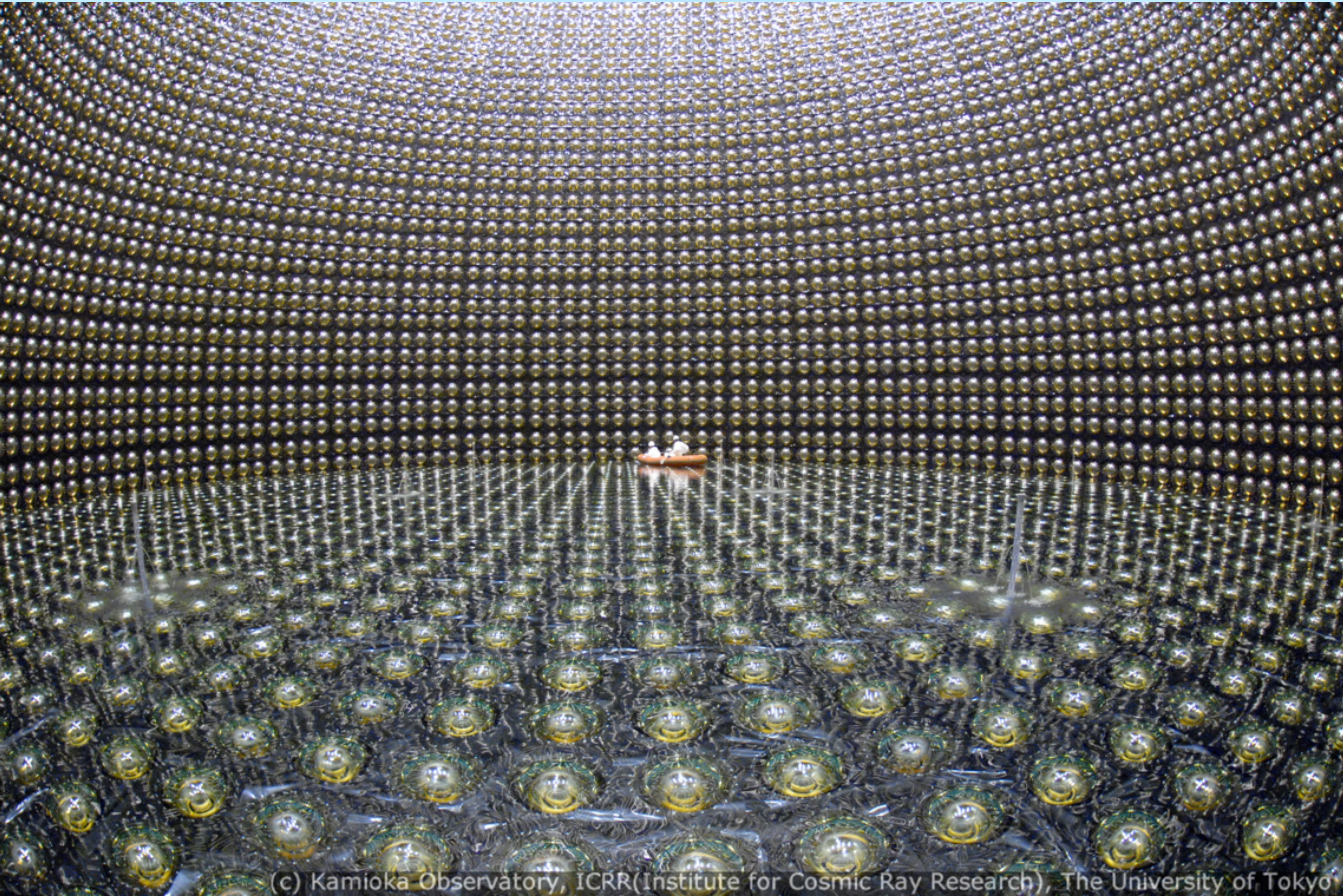
Super-Kamiokande

- Operating since 1996
- 50,000 ton ring-imaging water Cherenkov detector
- Inner detector 11,000 x 20"PMTs
  - 40% photo coverage
- Outer detector 1,885 x 8"PMTs
- In Mozumi mine of Kamioka Mining Co, near Toyama Japan
  - ~1000m of rock overburden to block cosmic rays

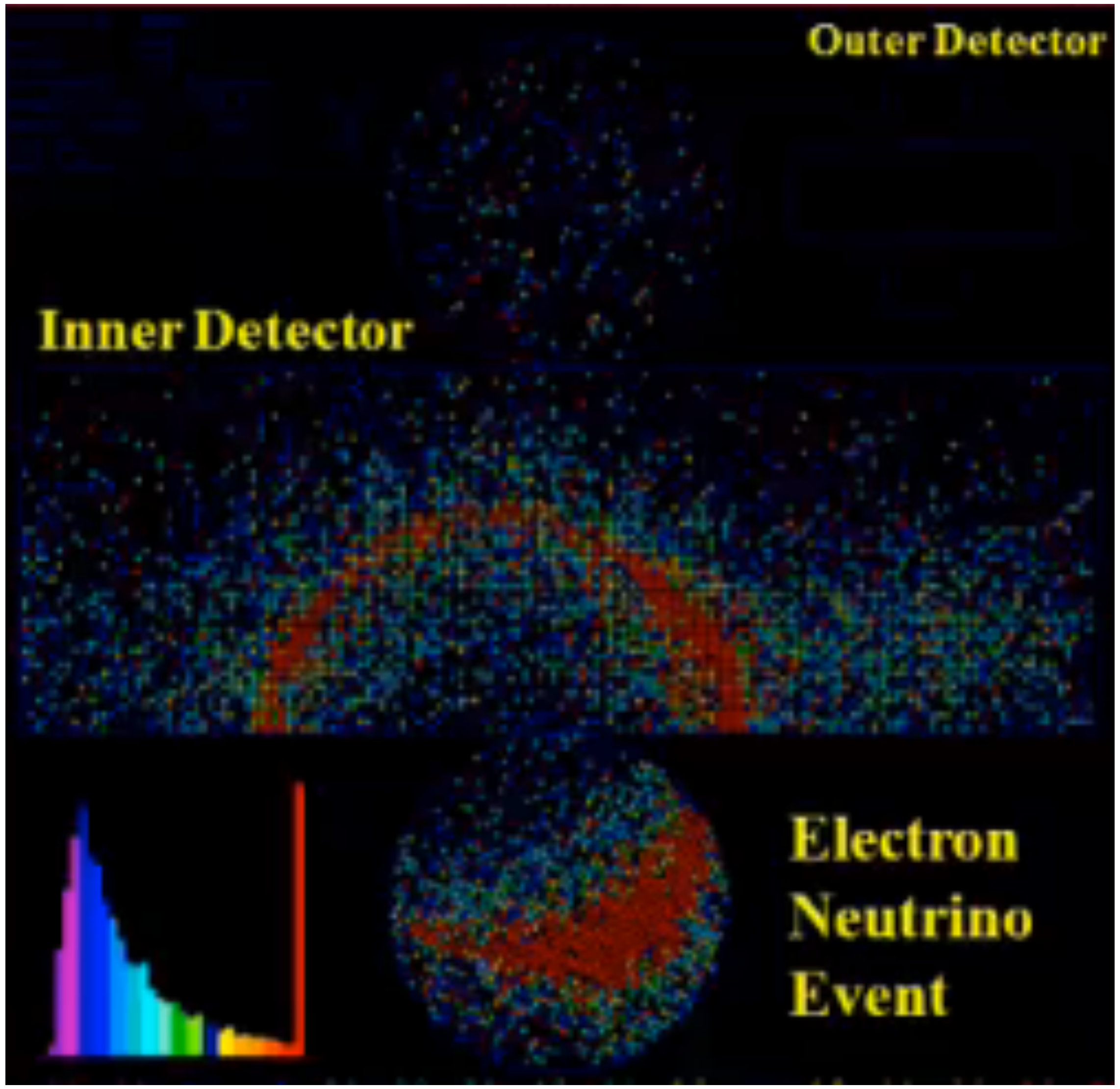


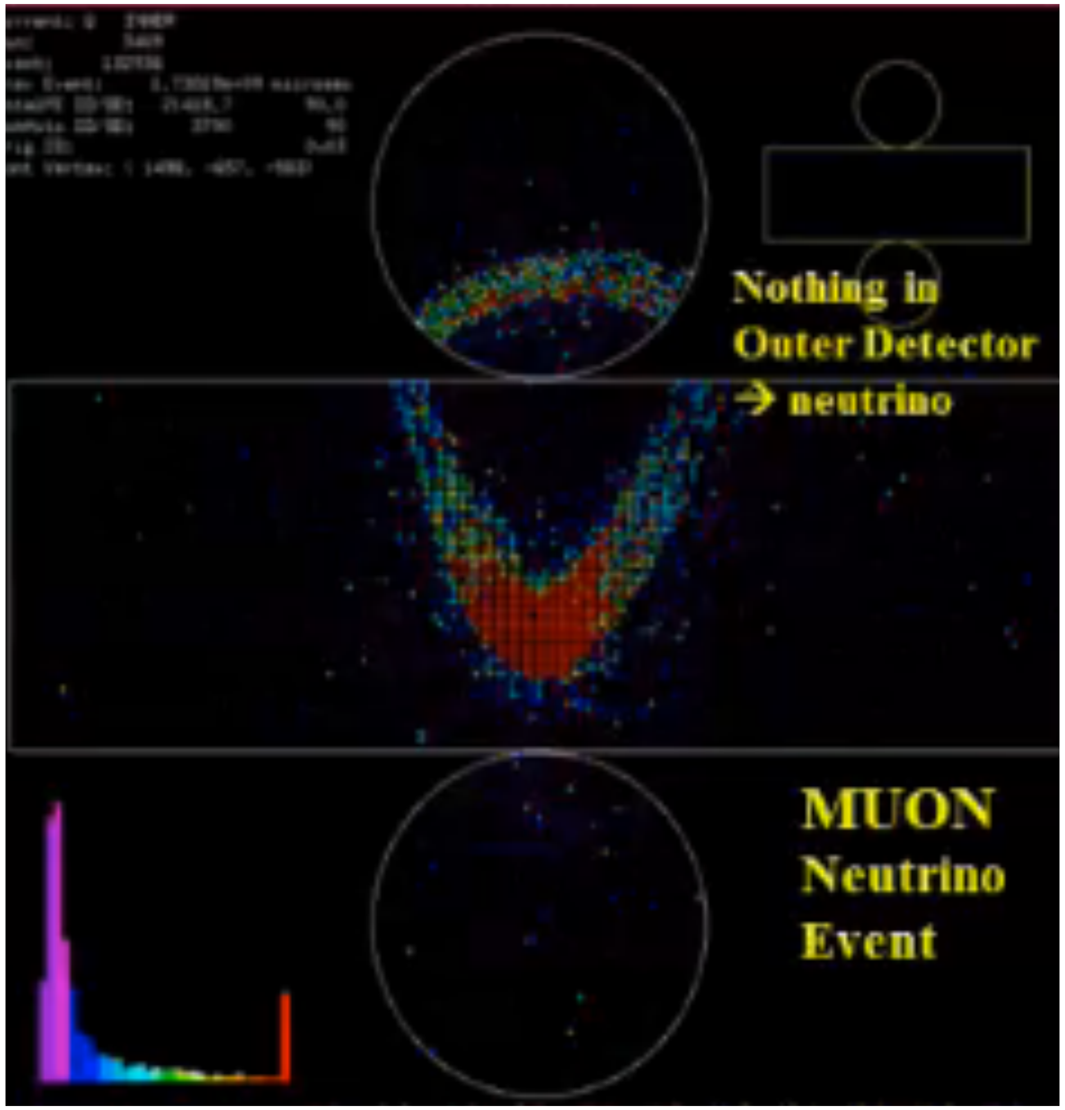


Polishing PMTs while filling the water



Particle Identification

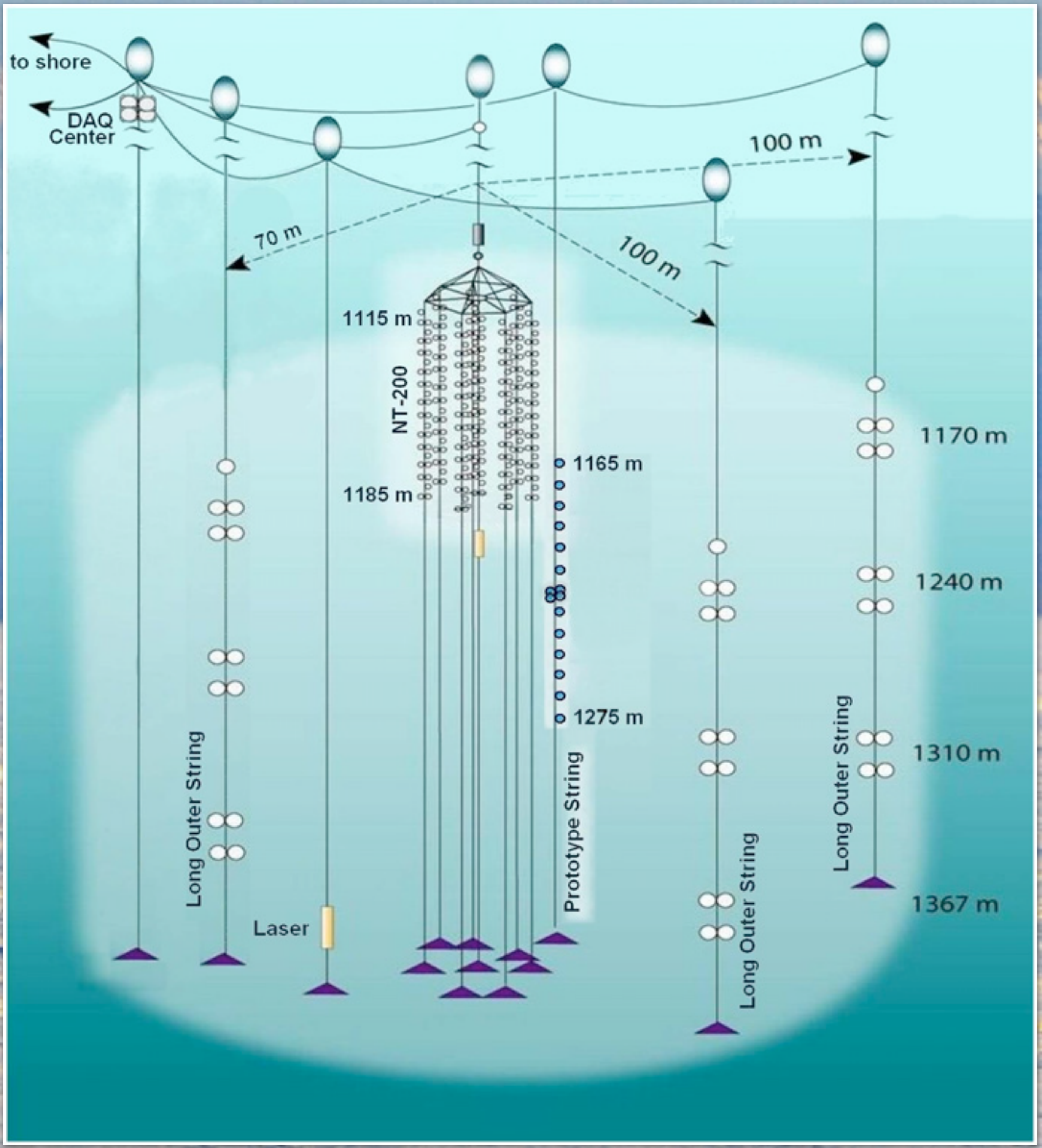




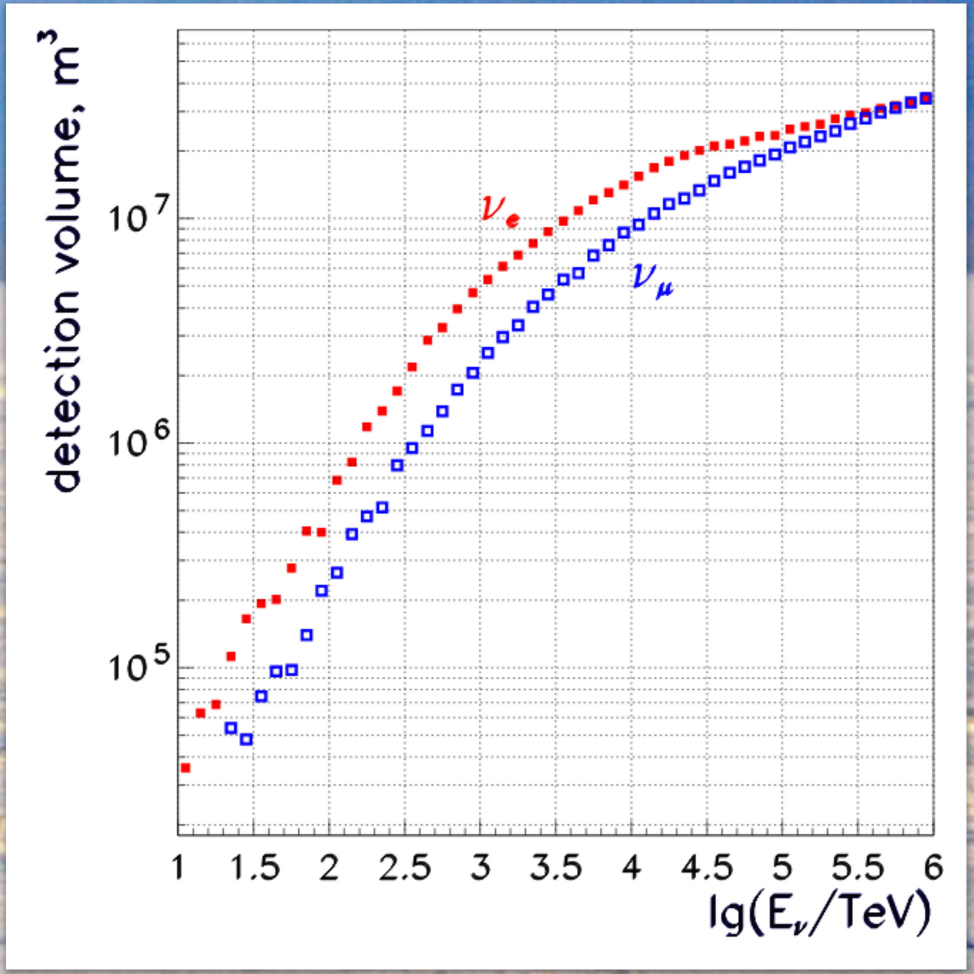
- Electron scatters in water and produces fuzzy Cherenkov ring
- Muon travels straight and produces sharp ring

Lake Baikal

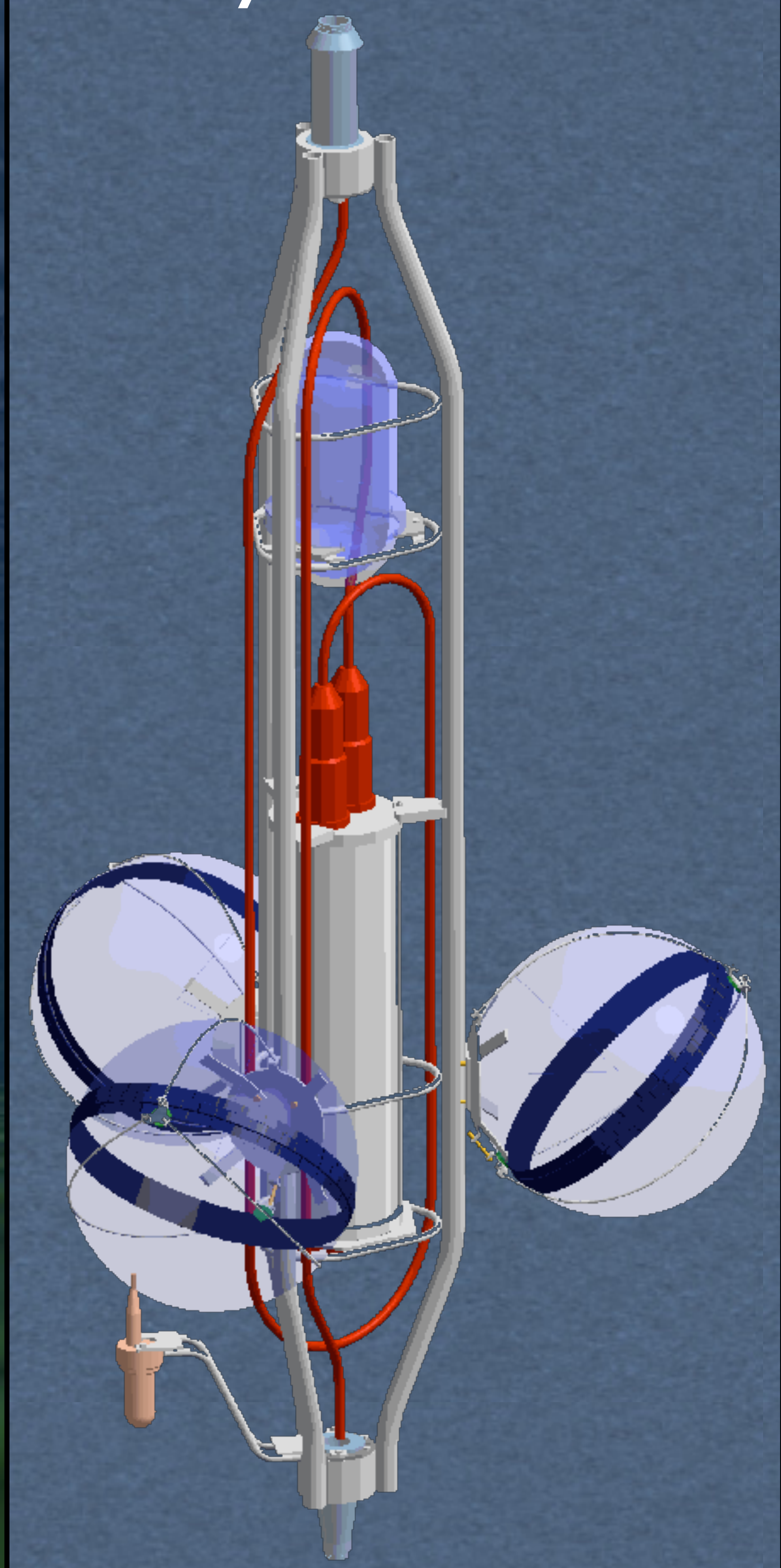
arXiv:astro-ph/0609743



228 PMTs
~0.1MT Volume

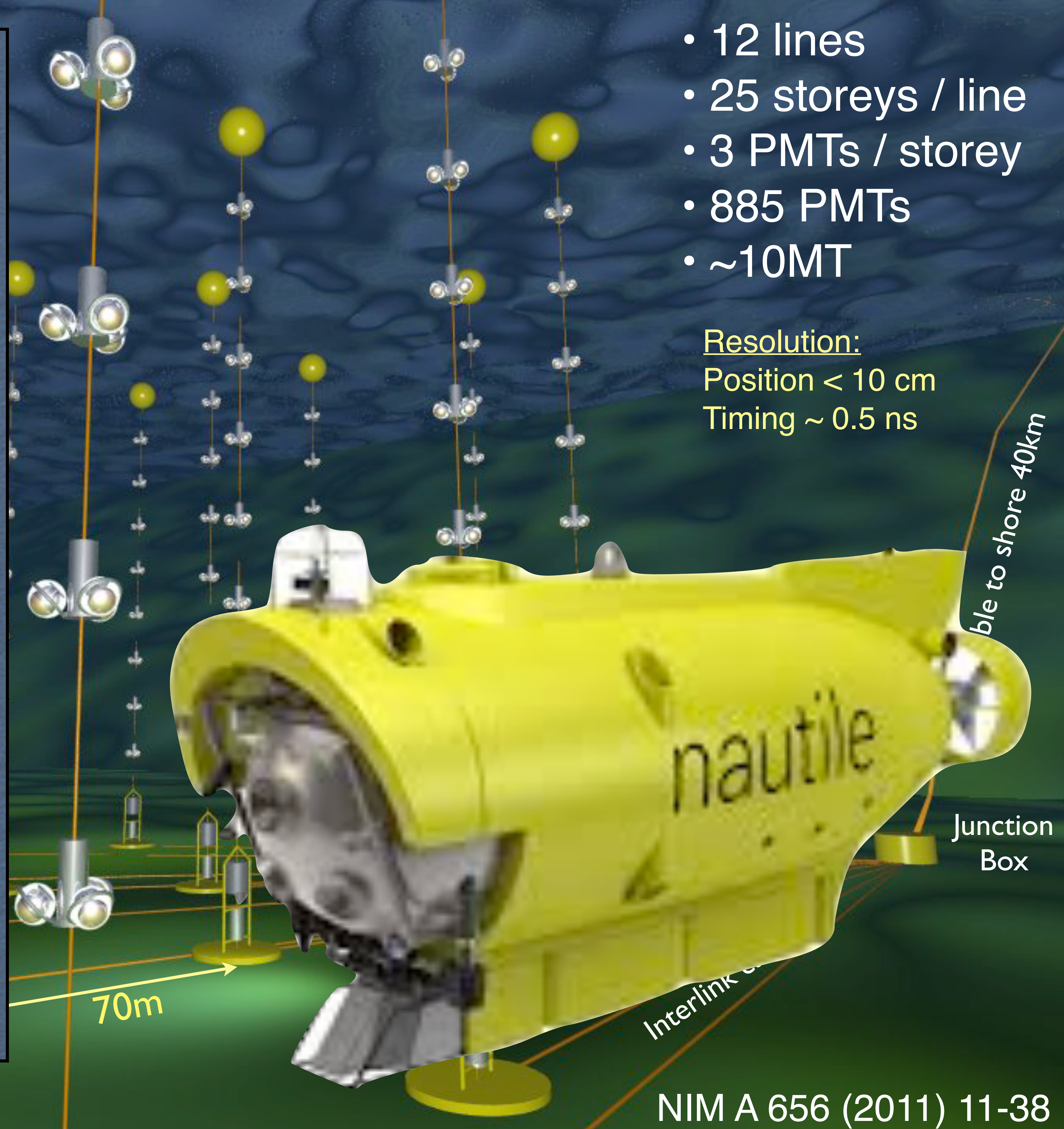


Storey with 3OMs



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

Resolution:
Position < 10 cm
Timing ~ 0.5 ns



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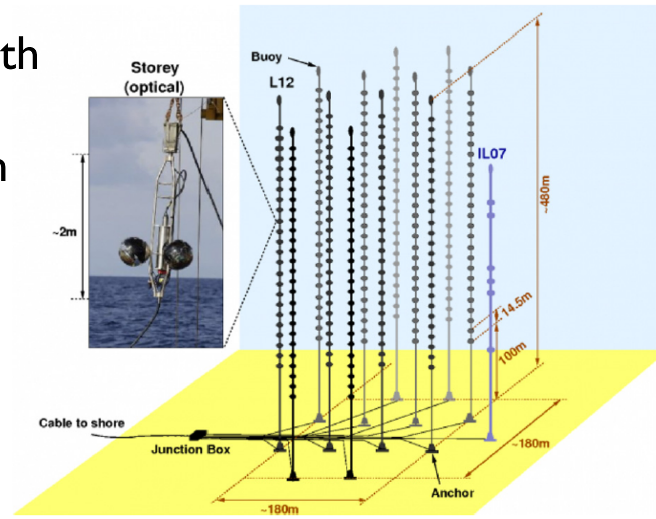
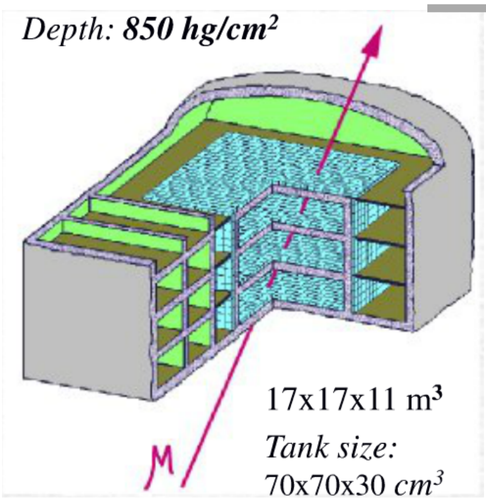
NIM A 656 (2011) 11-38

Neutrino Telescopes / Detectors

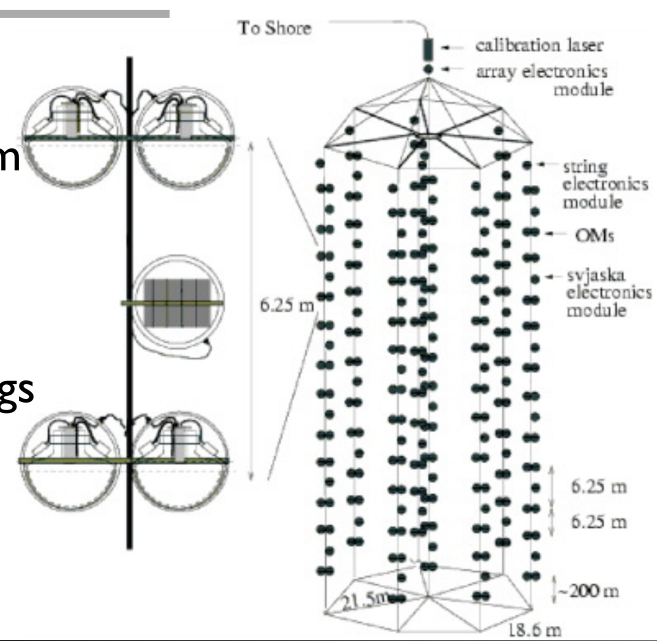
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



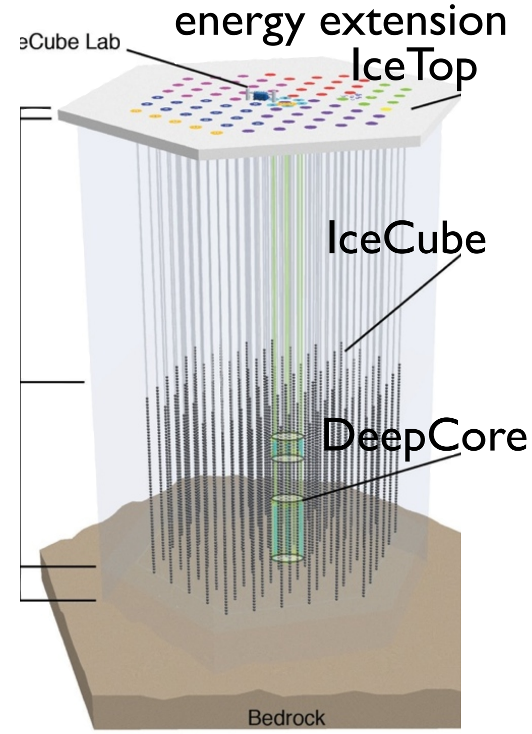


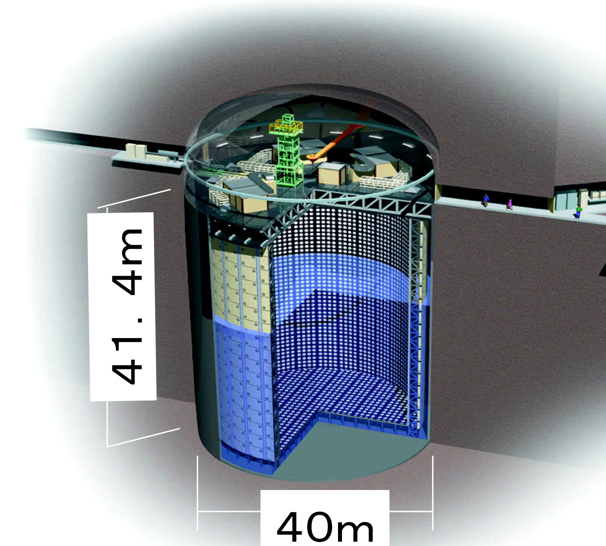
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension





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

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
SWITZERLAND
Université de Genève
UNITED KINGDOM
University of Oxford
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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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
90°
SOUTH POLE
1. 2008

How to get there ?

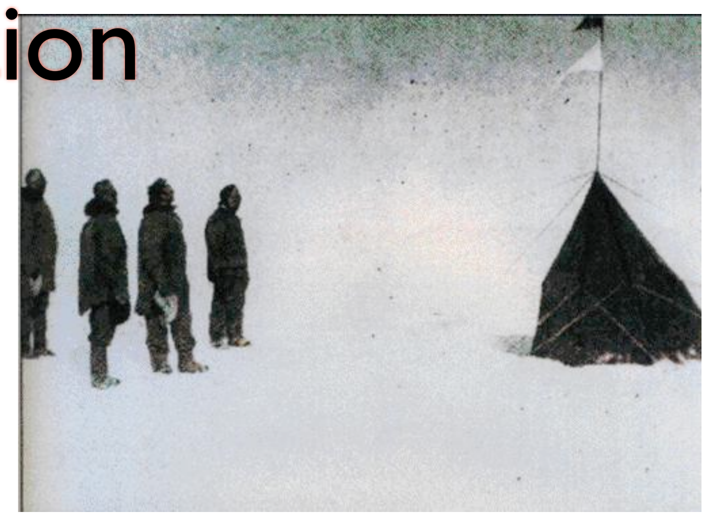
Arrival

Research/Expedition Team

Travel

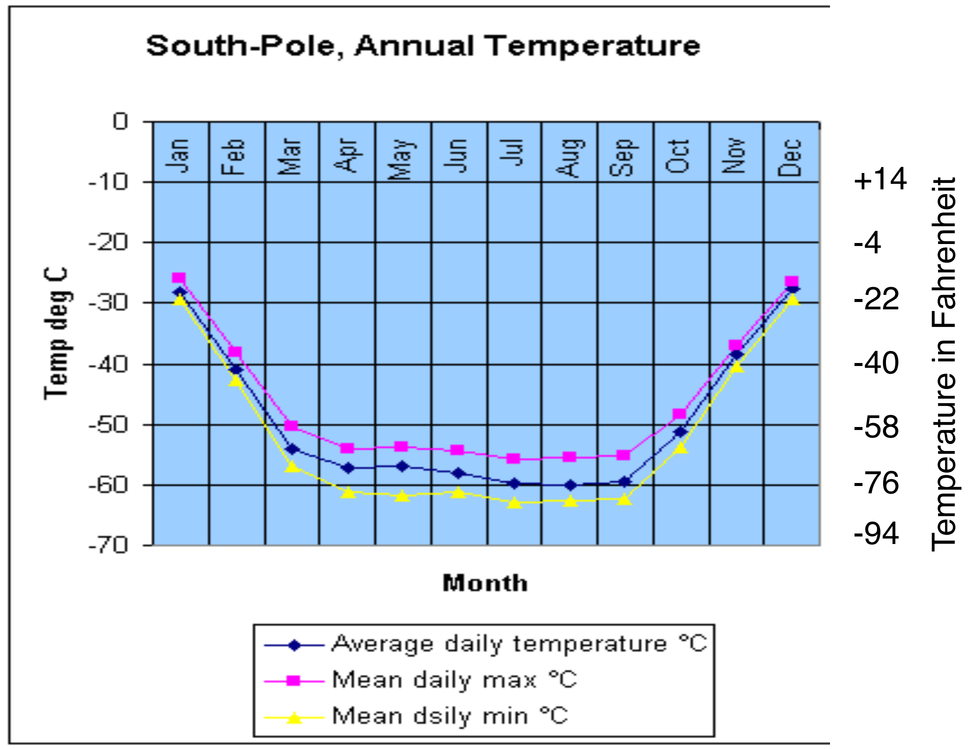
Conduct Experiments

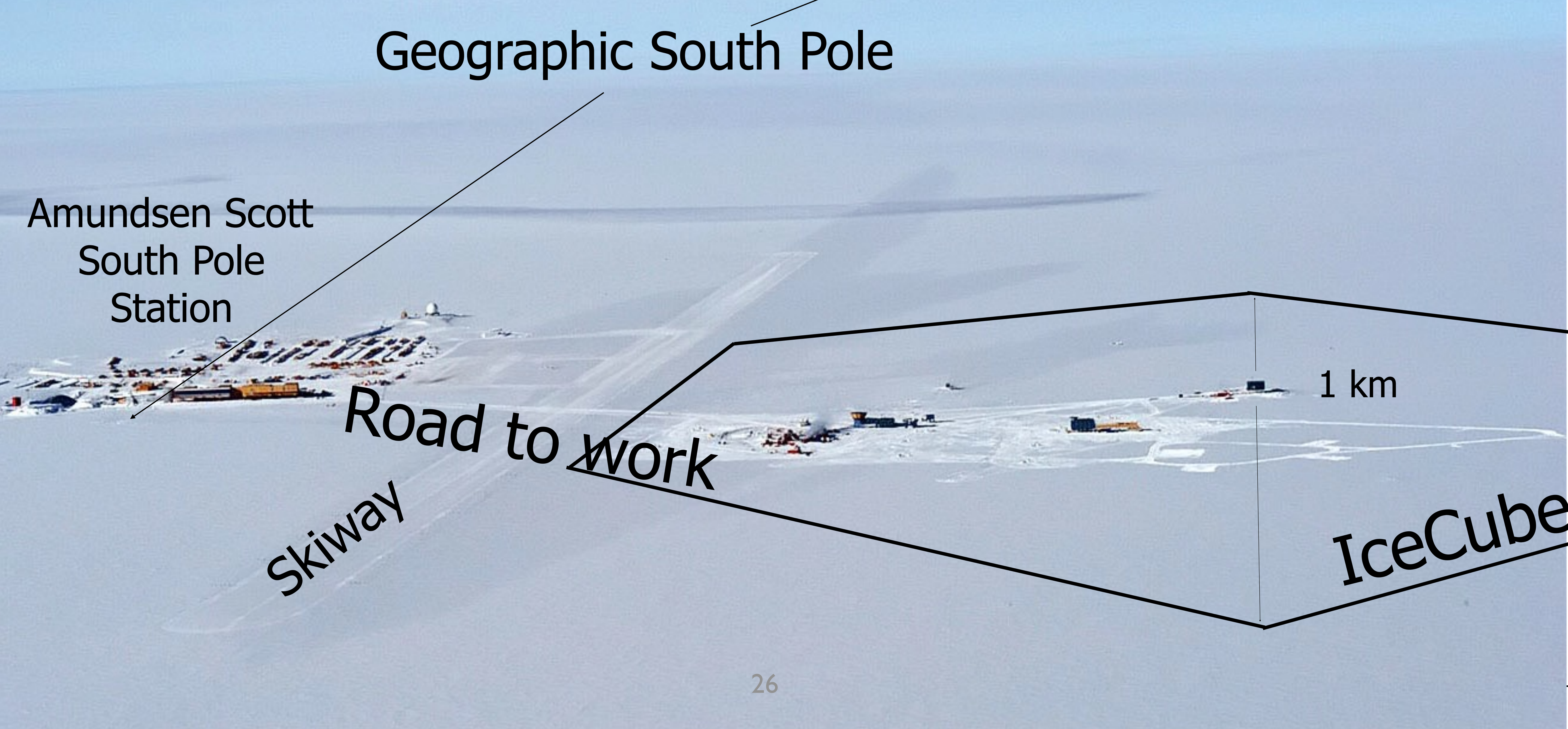
Station



Lasting Memories

Laboratory at the South Pole





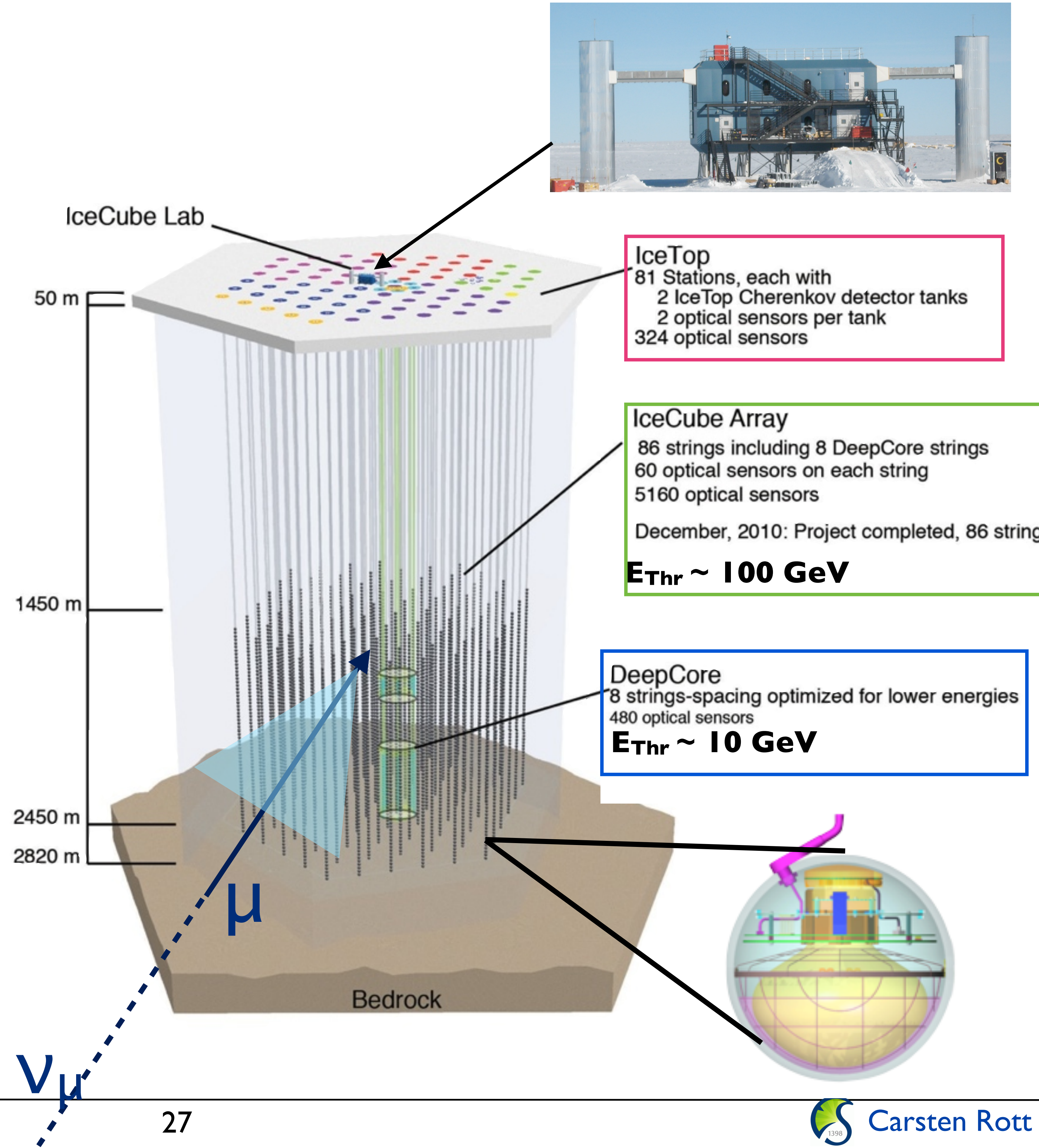
The IceCube Neutrino Telescope

- 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.〉

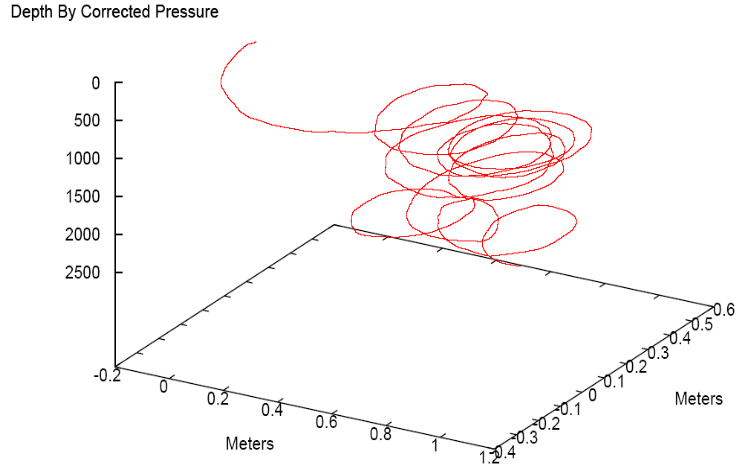
"한국 '세계적 리더' 될 좋은 기회"

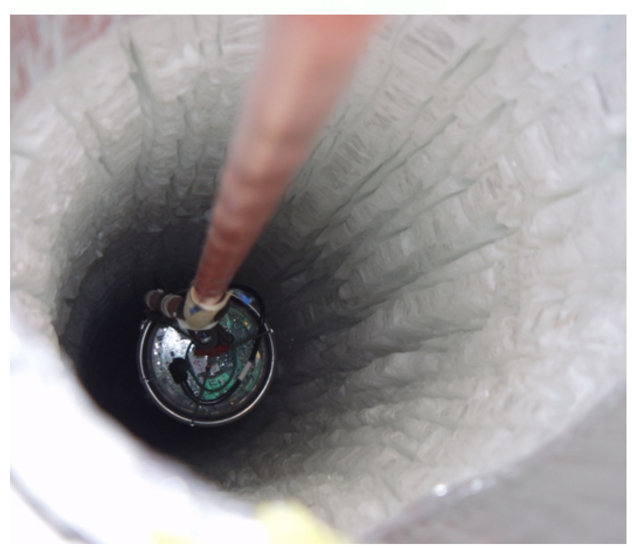
기초과학 투자 의지 활발, 한국에 새 연구 터전 둥지.. 연구자·학생 영입해 연구

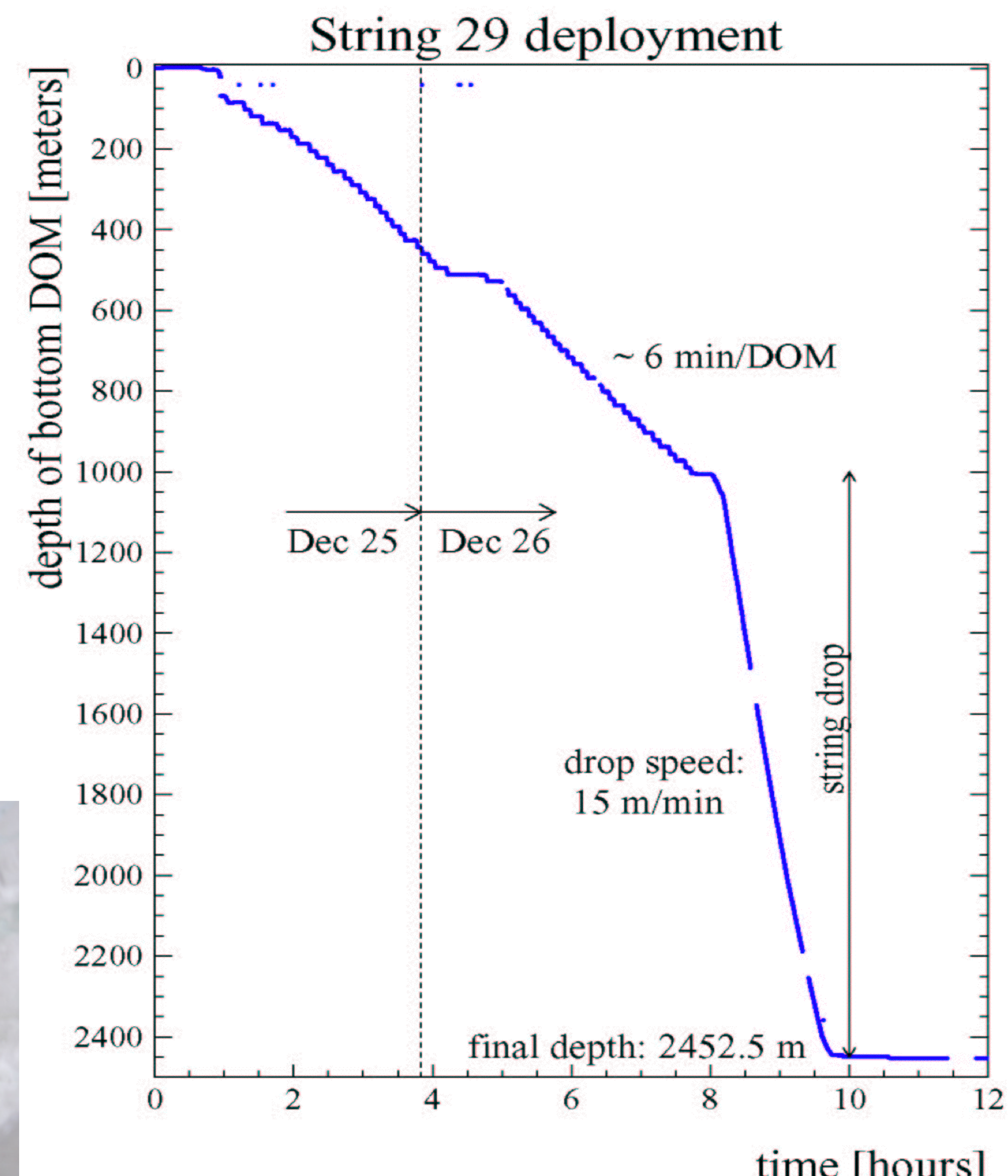


Drilling & Deployment

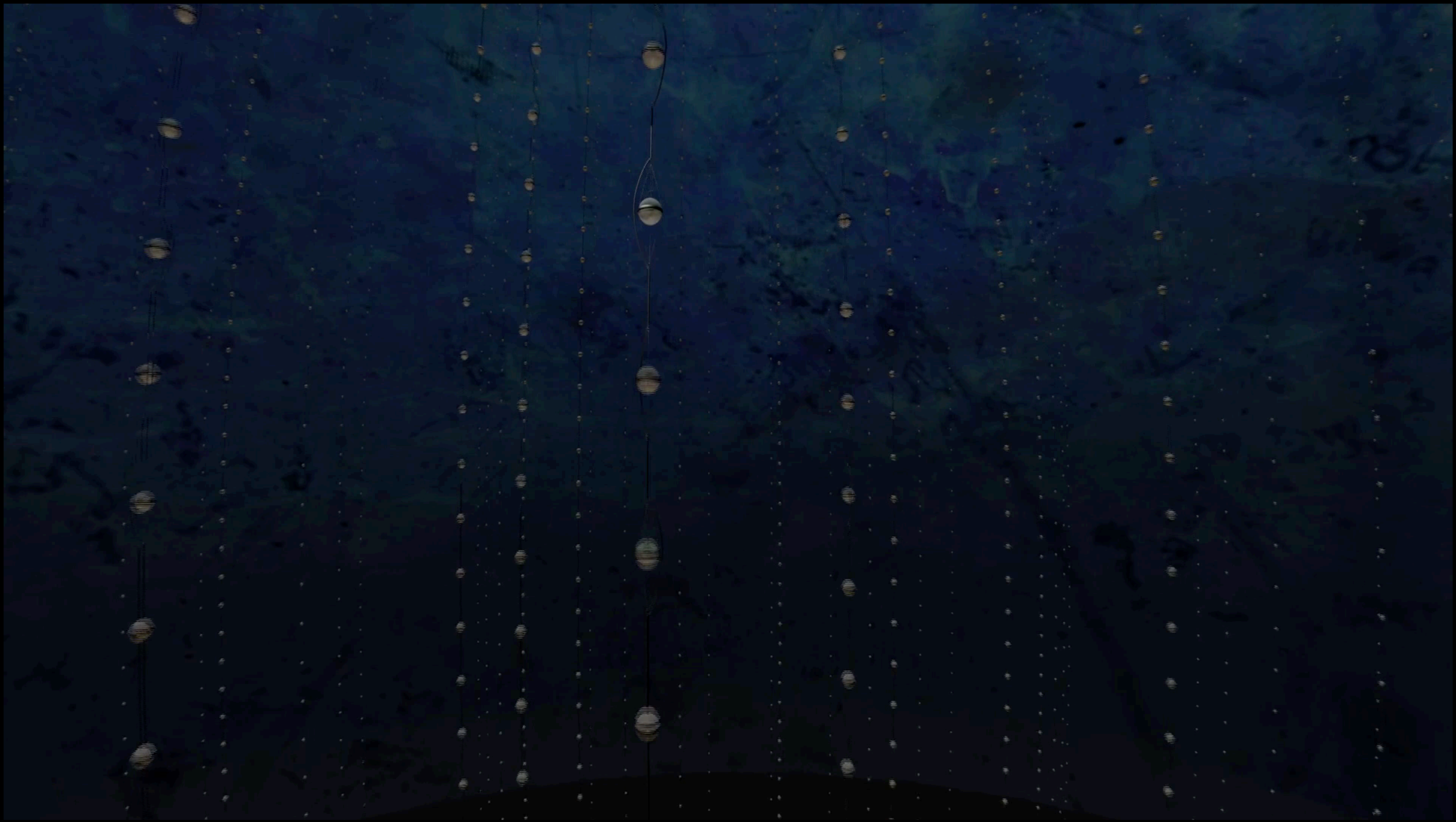
- Hole size ~60cm
- Depth ~2.5km
- Straight to 1m





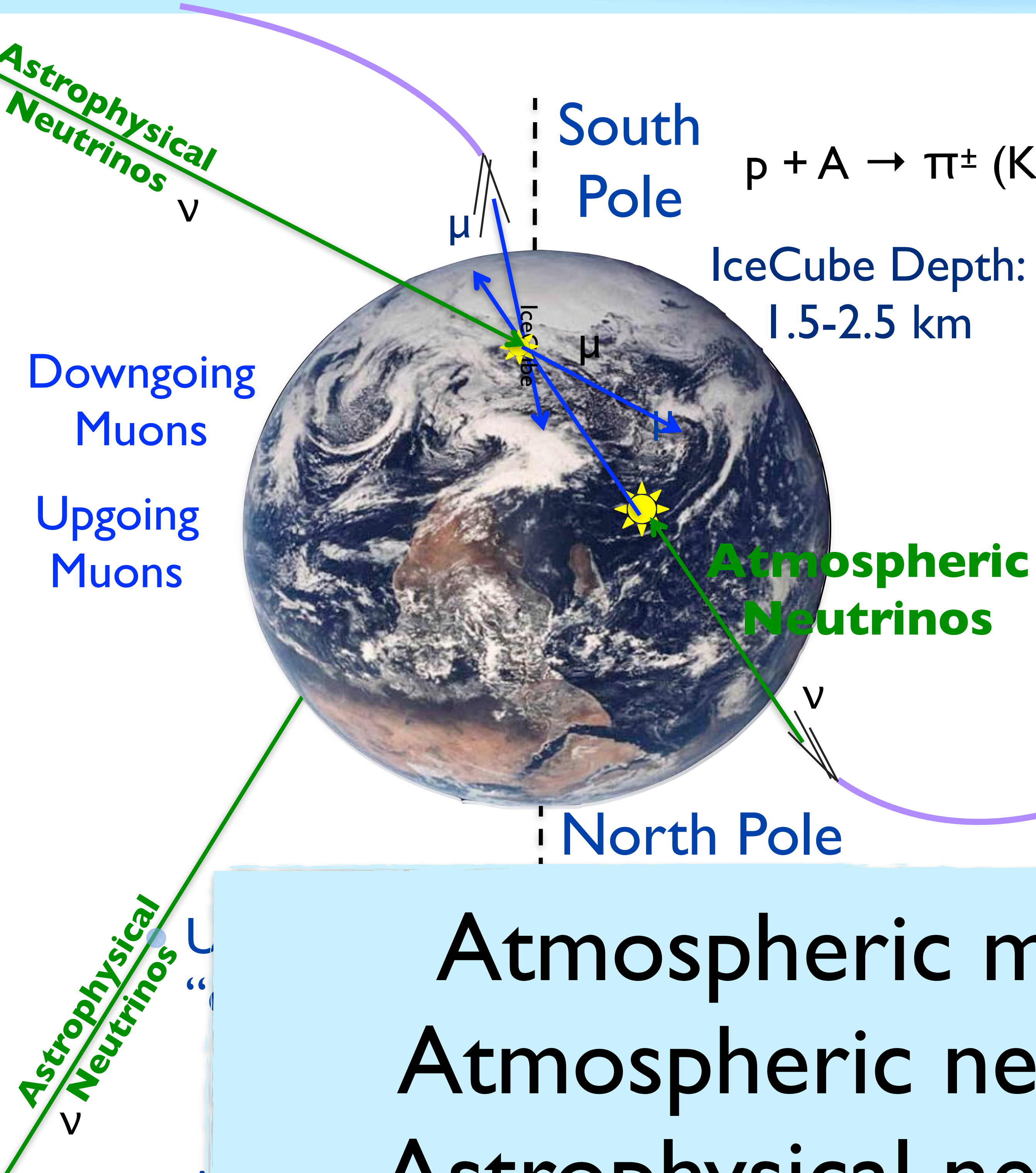


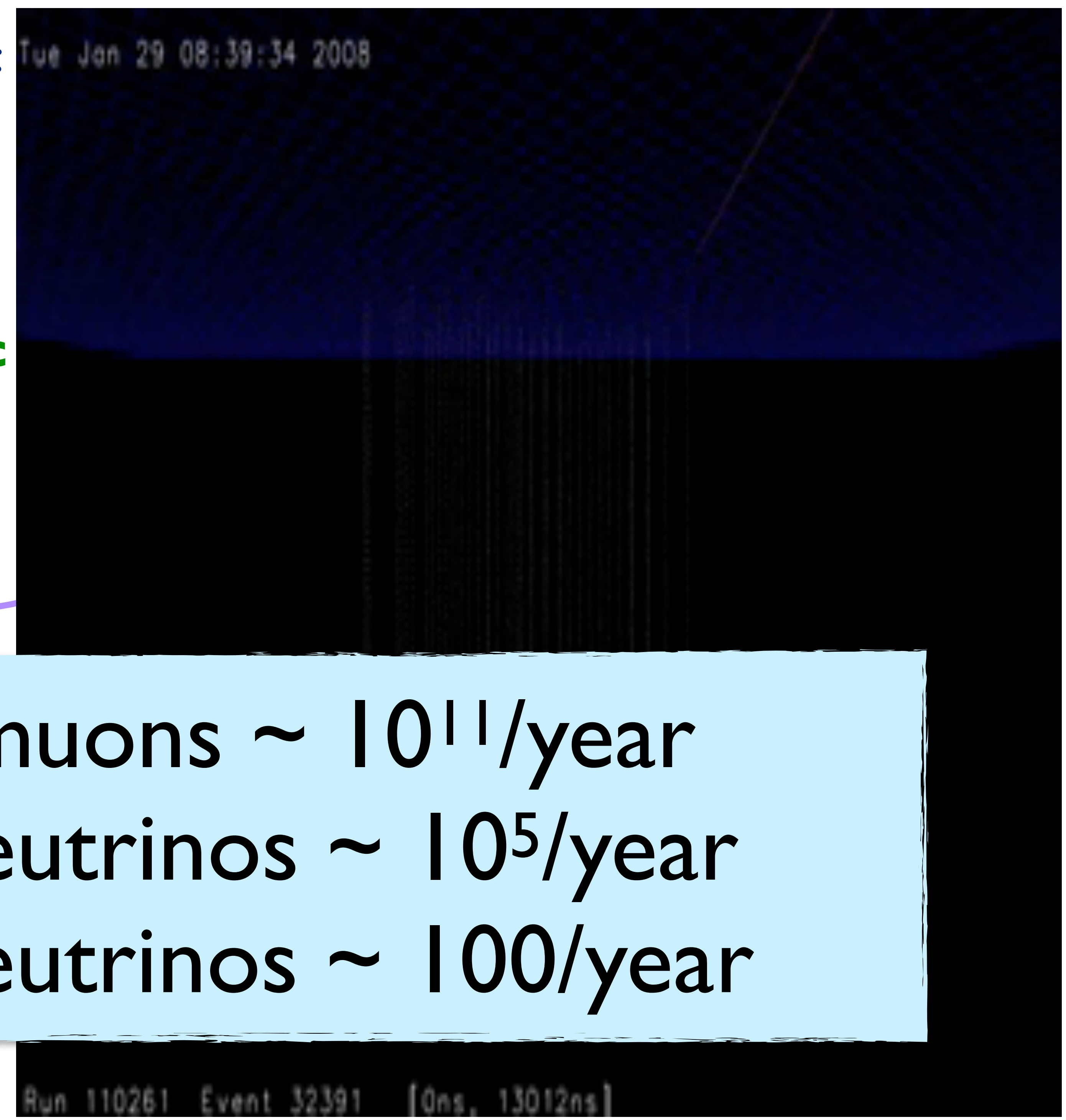
Drilling to 2500 m < 40h
String deployment ~ 12h



Signals in IceCube

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





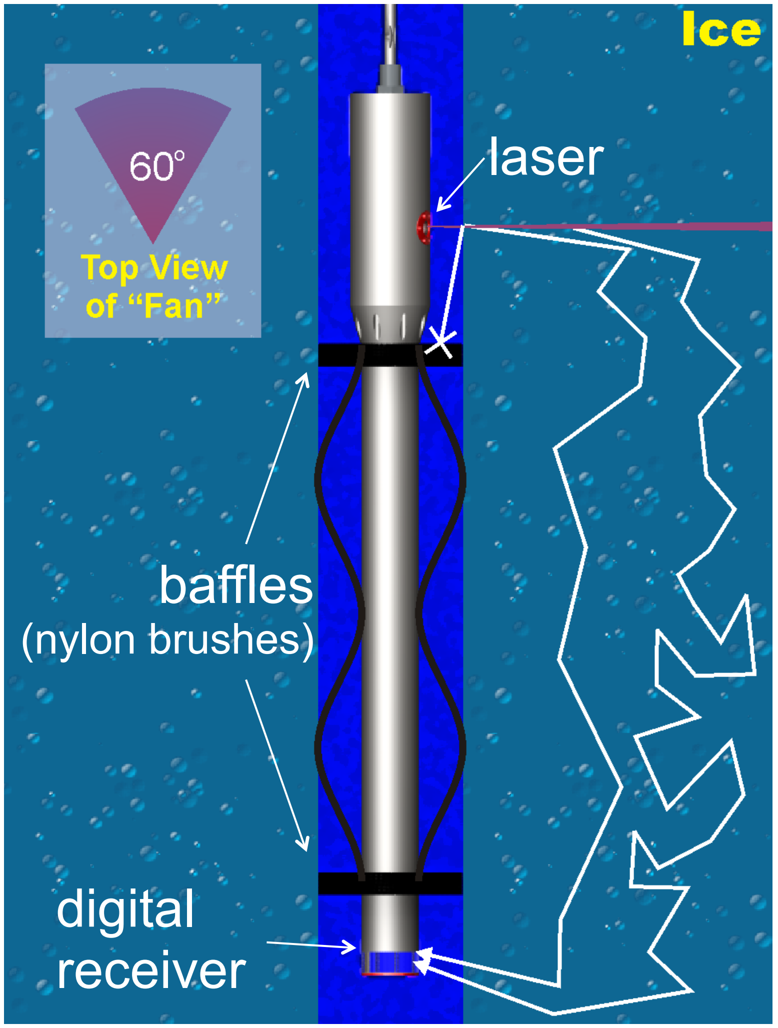
Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^{5}/year

Astrophysical neutrinos ~ 100/year

extra terrestrial neutrino fluxes

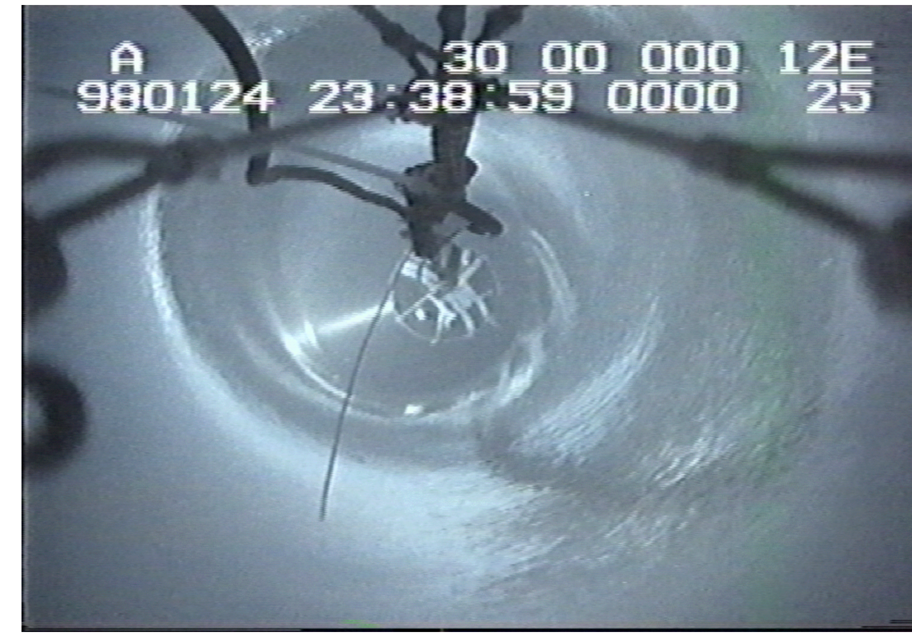
The Ice

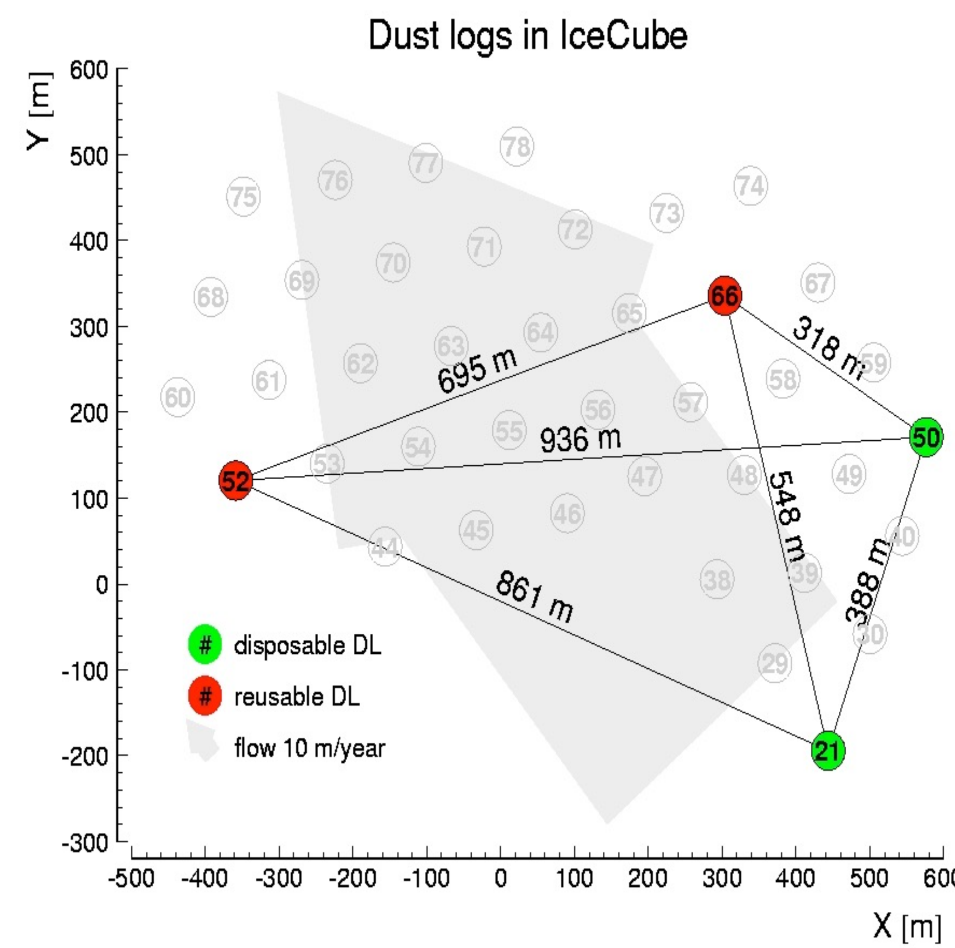


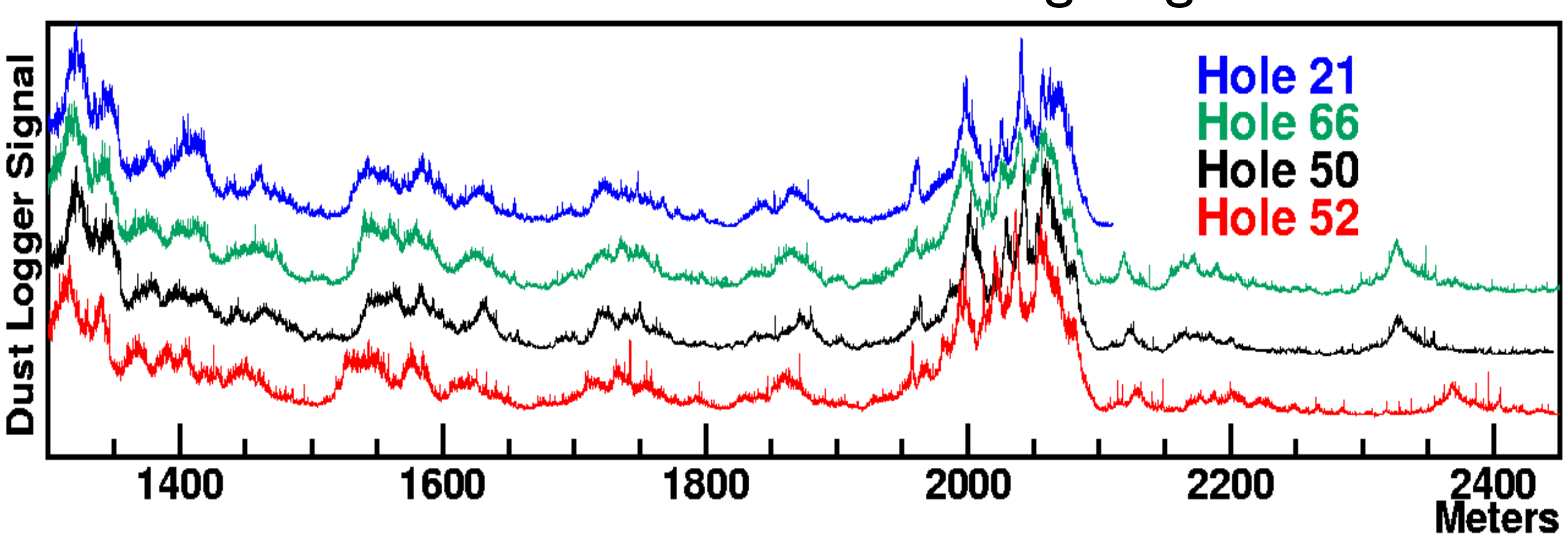
Major calibration efforts resulted in a very precise understanding of the ice surrounding the IceCube detector

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

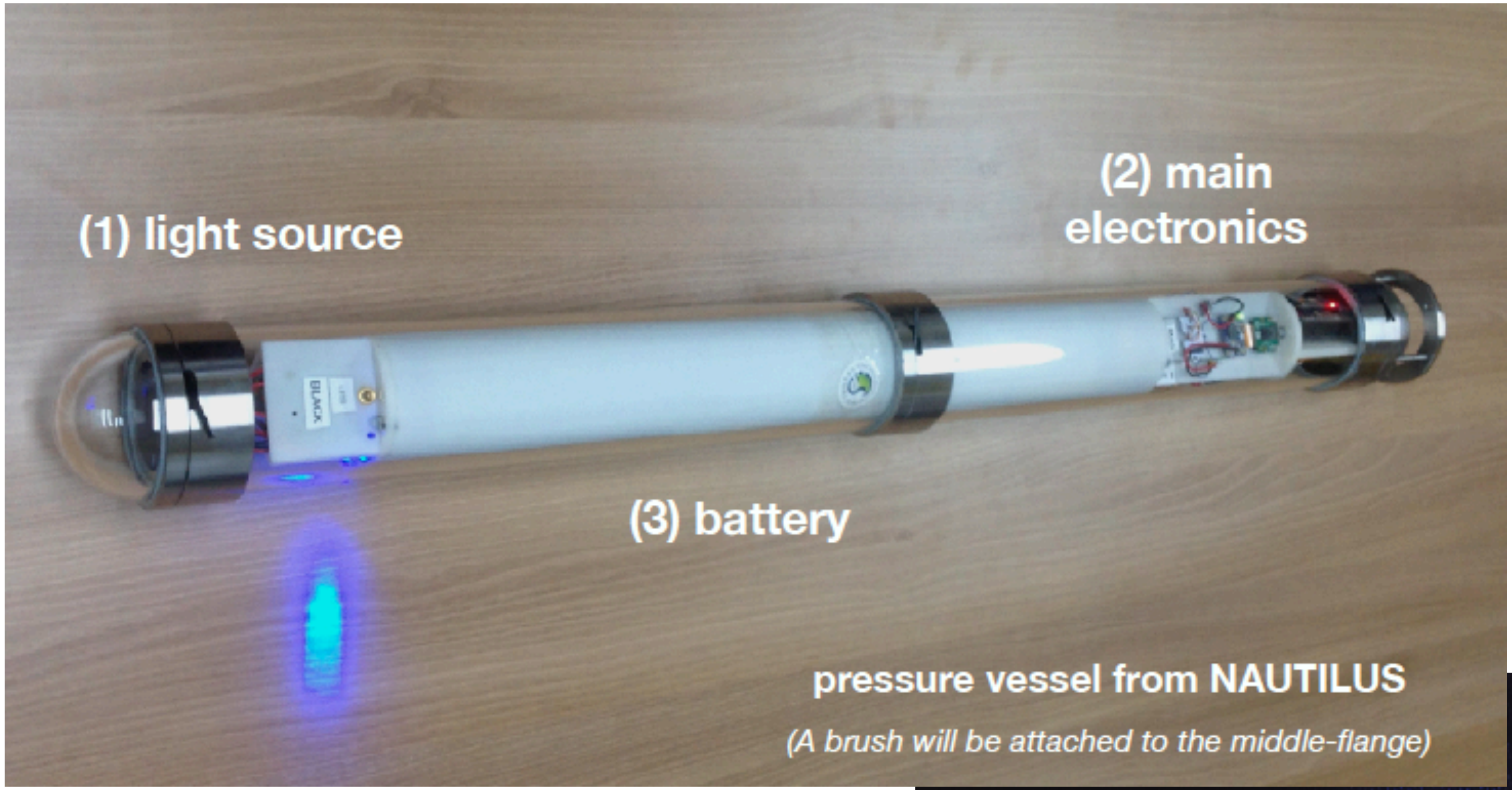
absorption length ~ 210m
scattering length ~20-40m



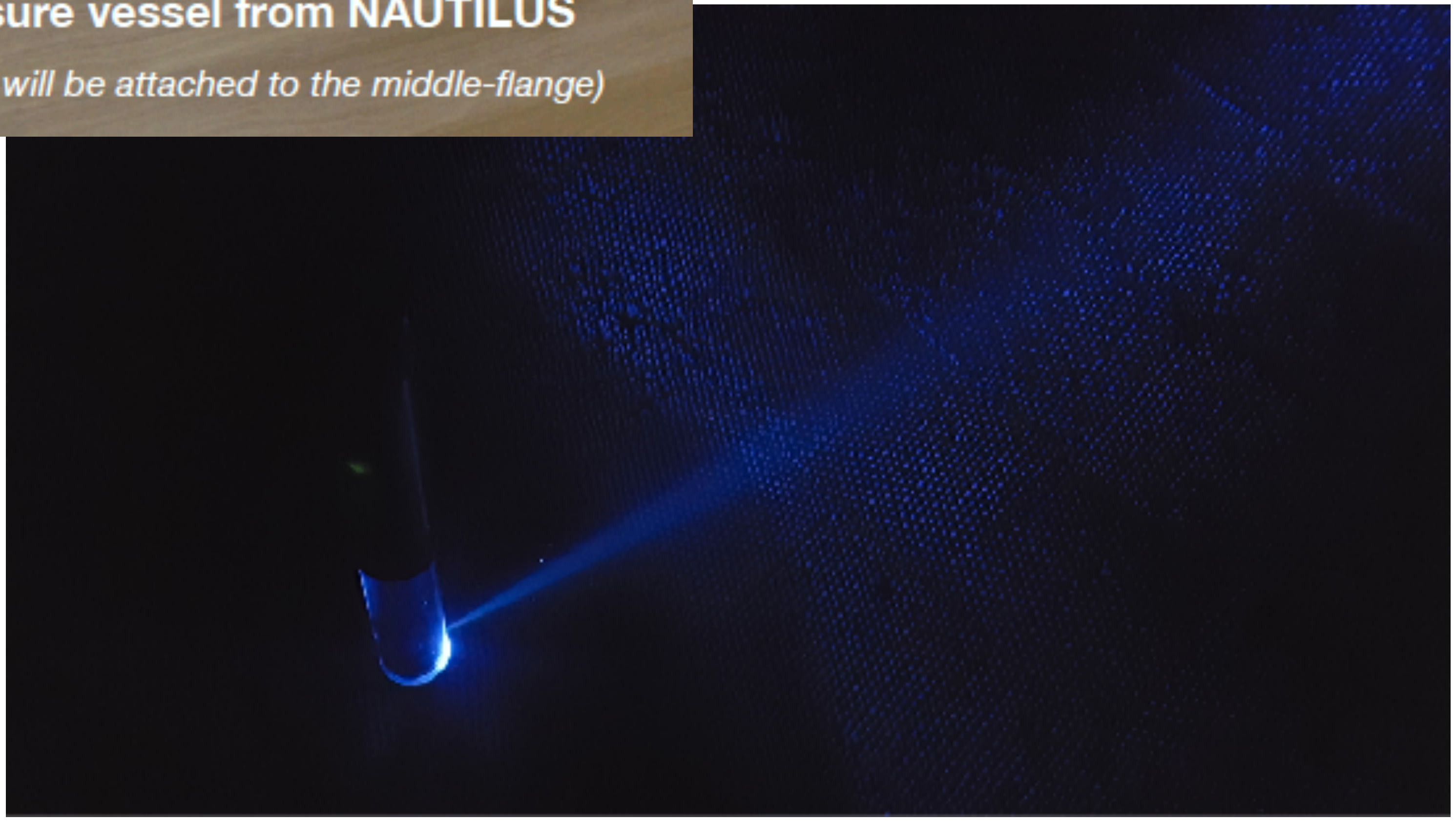




SKKU SPICE Core Camera System



- Camera system to measure anisotropy in the ice
- Use drill hole near the IceCube detector site

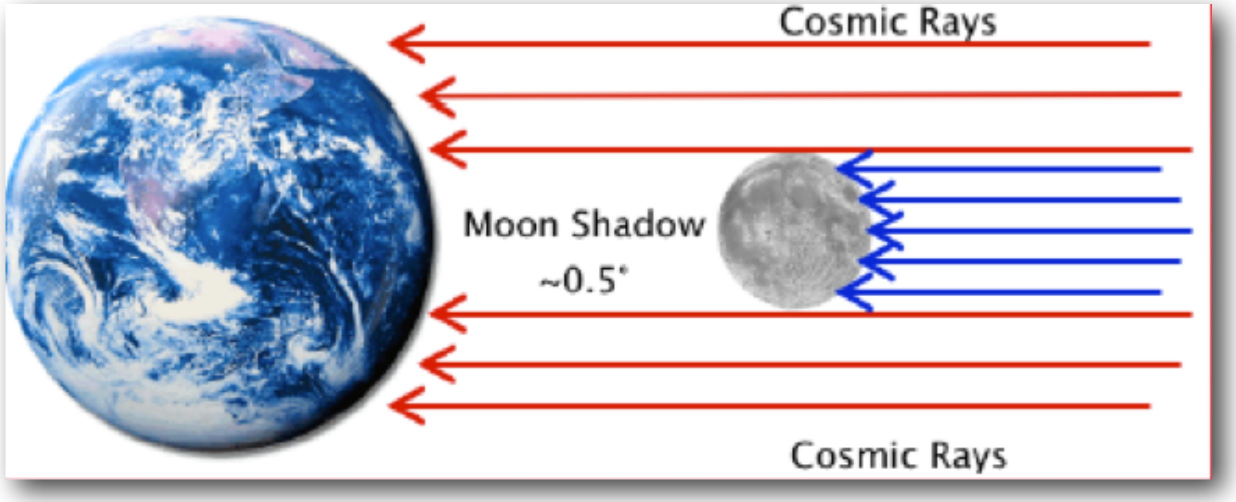


- Camera system to be deployed at the end of this year
- Platform to test camera systems for integration into next-generation optical sensor modules

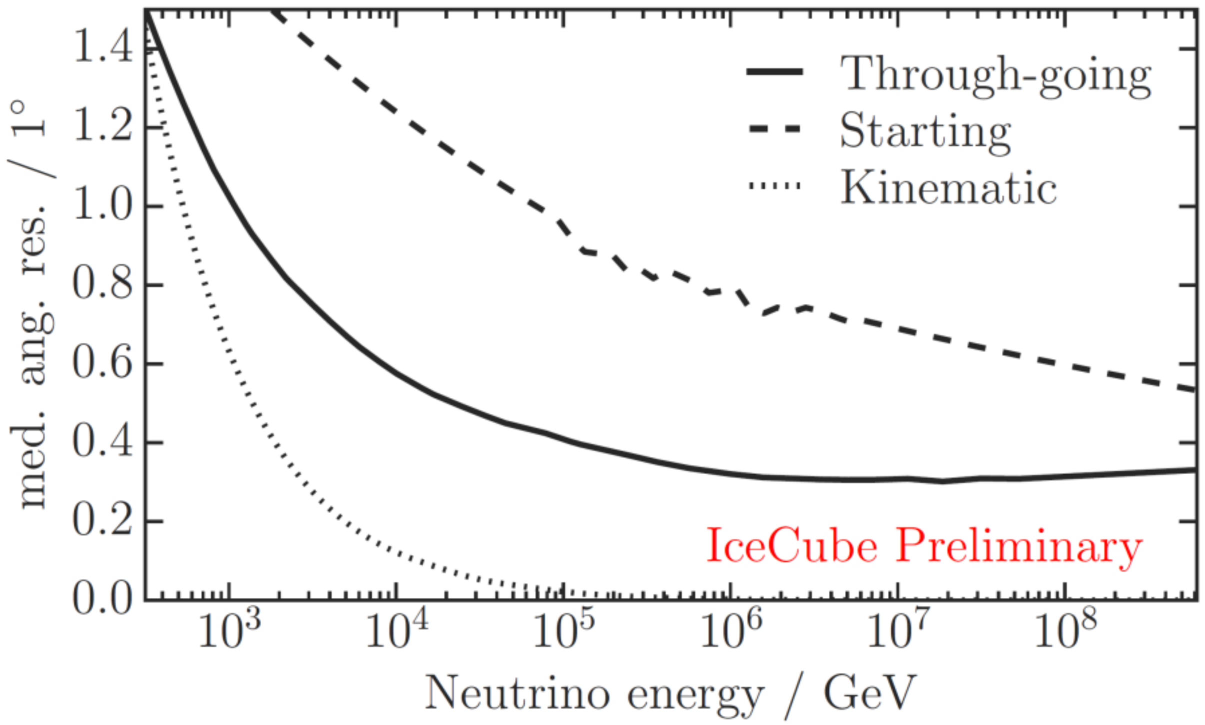
Calibration and Performance

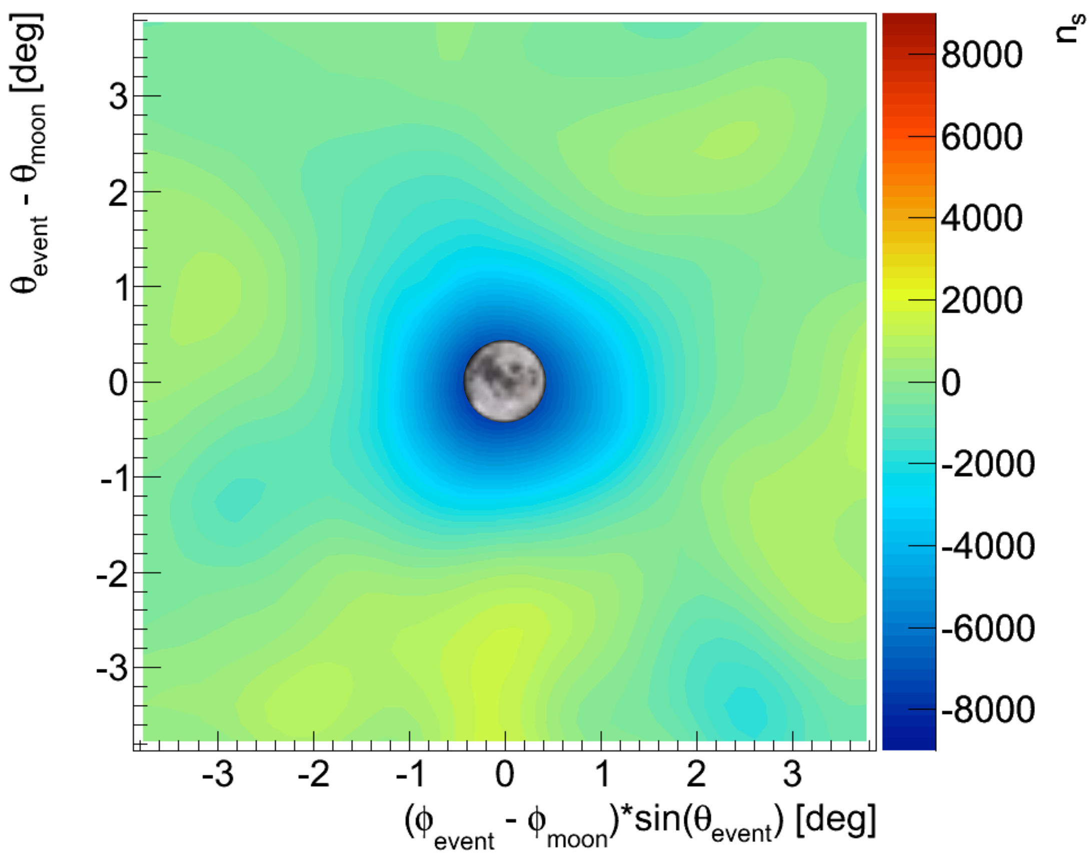
- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - Moon Shadow
  - Atmospheric Neutrinos
  - Minimum-ionizing Muons

Physical Review D89 (2014) 102004



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



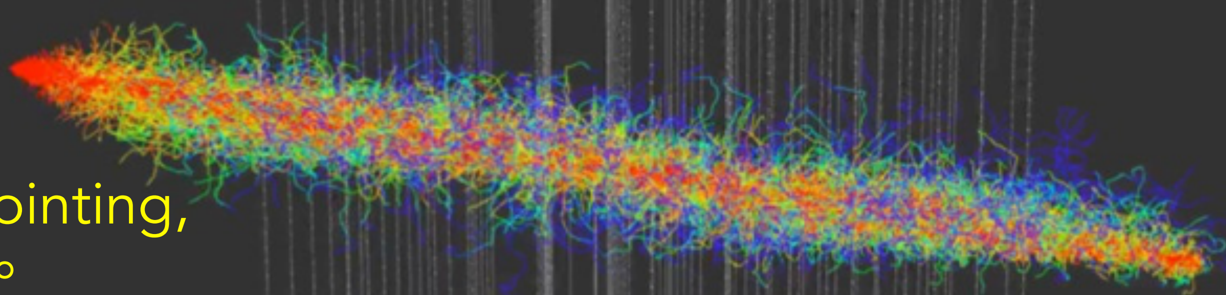


Event Topologies in IceCube

Track topology

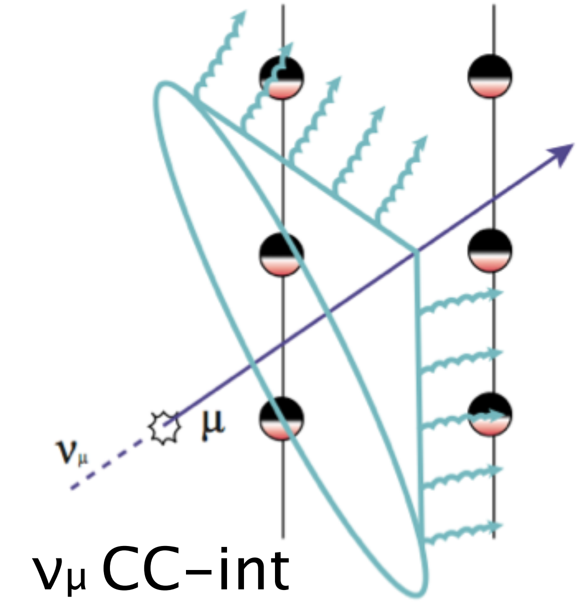
(e.g. induced by muon neutrino)

CC: ν_μ



Good pointing,
0.2° - 1°

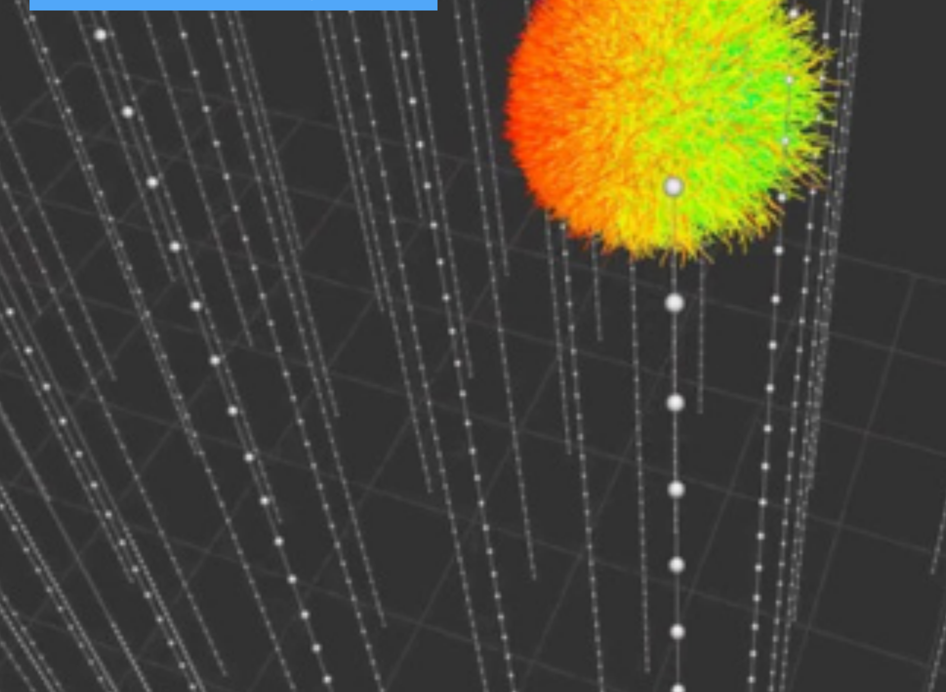
Lower bound on energy for through-going events



ν_μ CC–int

CC: ν_e ν_τ

NC: ν_e ν_μ ν_τ

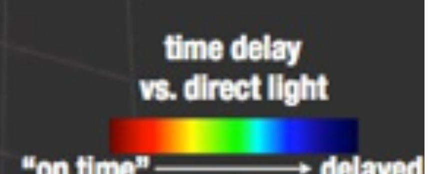


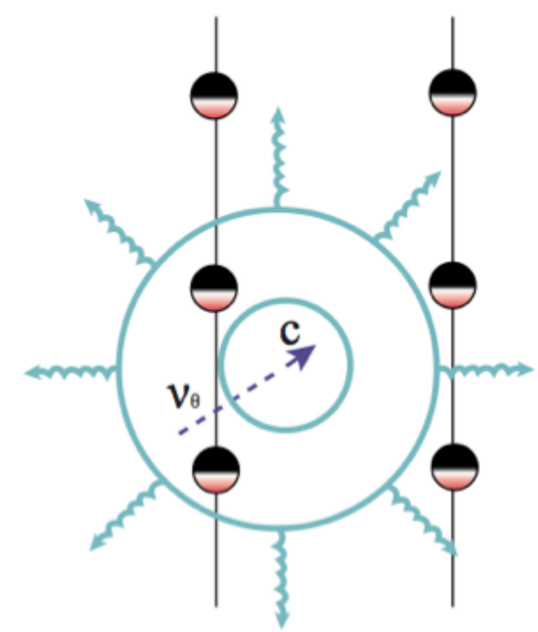
Cascade topology

(e.g. induced by electron neutrino)

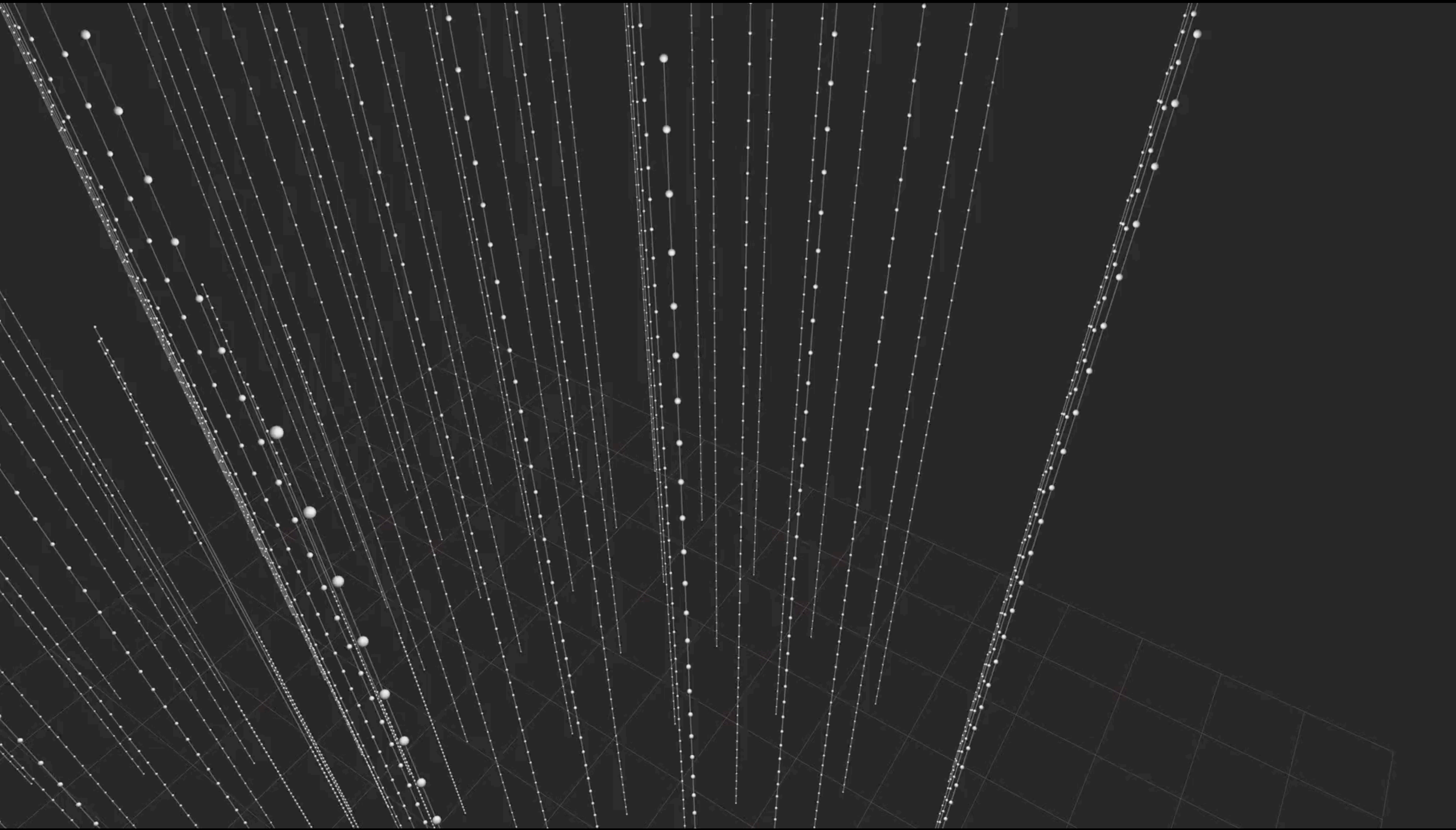
Good energy resolution, 15%

Some pointing,
10° - 15°





ν_e ν_τ CC–int & ν_i NC–int



Color indicates on-time or delayed

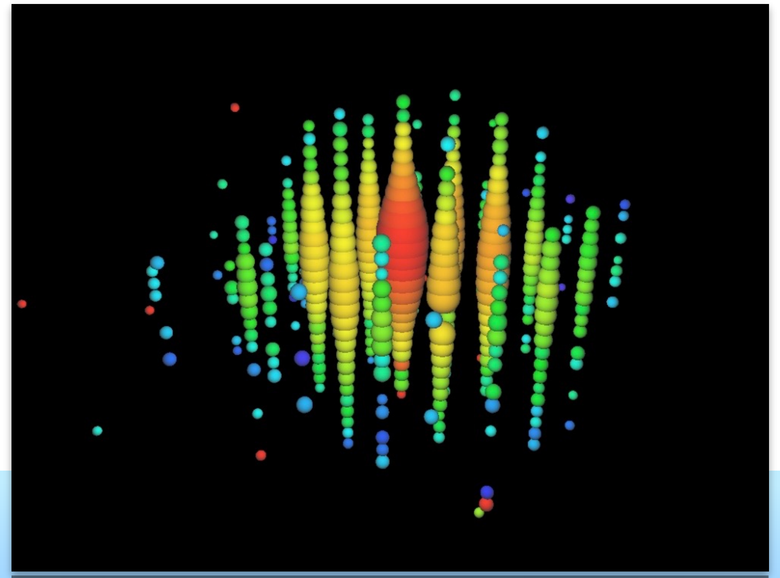
Selected Results and Science Program

IceCube Observations

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



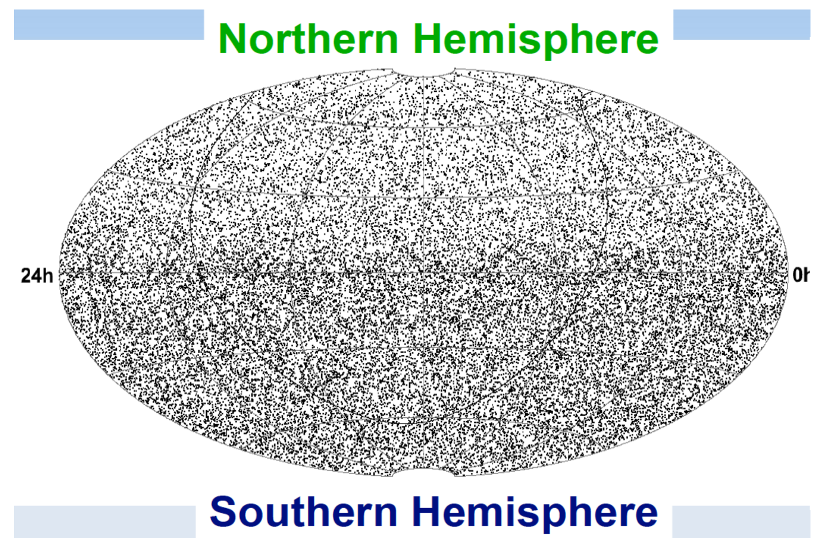
Astro-physical Neutrino Search

Finding Astrophysical Neutrinos

- How to overcome the large atmospheric neutrino background
- We need to rely on statistical methods to pick out neutrinos from this mess
  - Do neutrinos cluster anywhere in space, time, or arriving in coincidence with astronomical events or objects ?
  - Do we see any spectral features ?

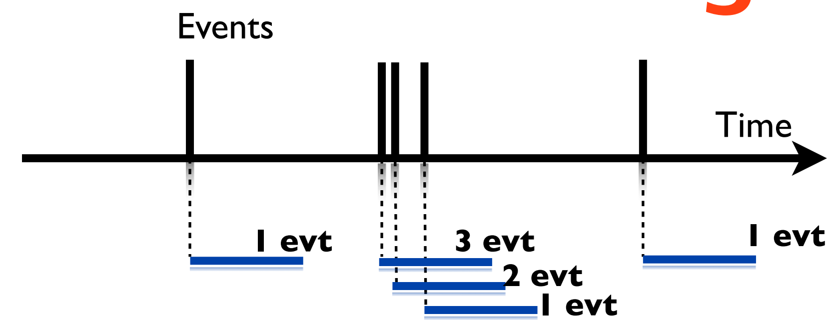
1. Point Source

single dominant source



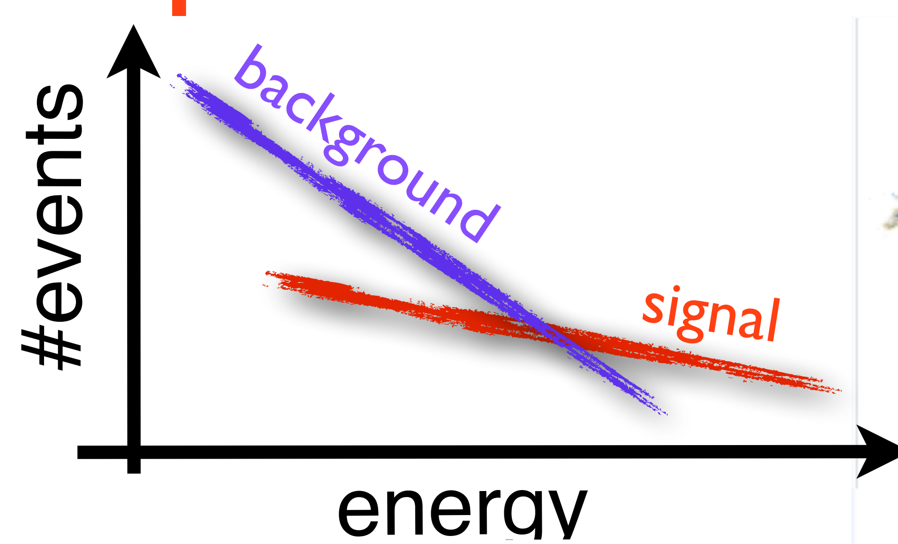
2. Time clustering

transient source

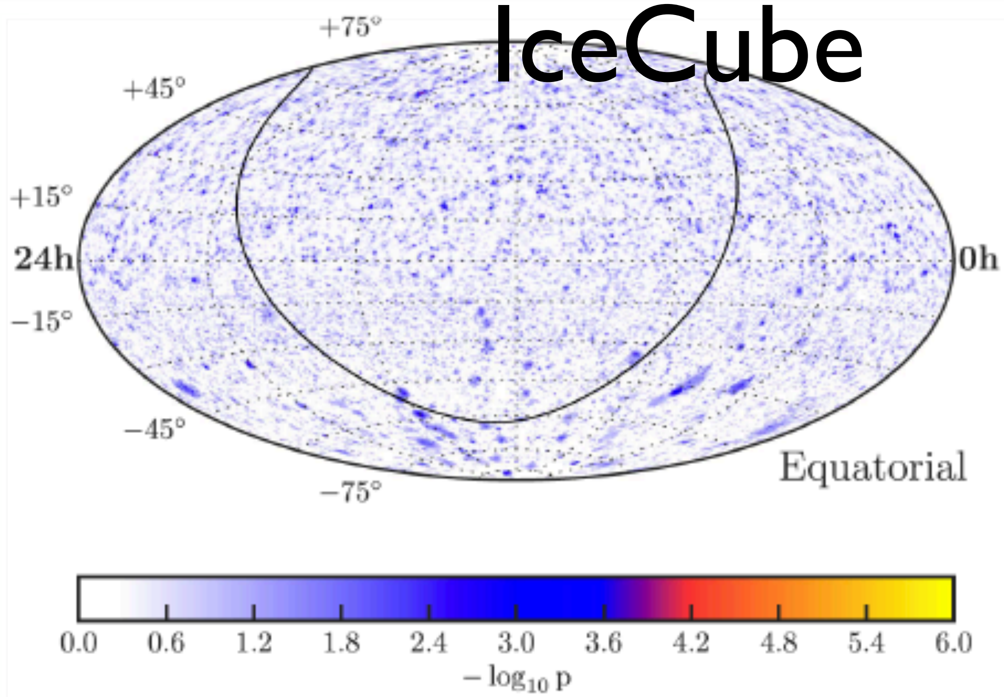


3. Spectral feature

cumulative flux



Point Source Search

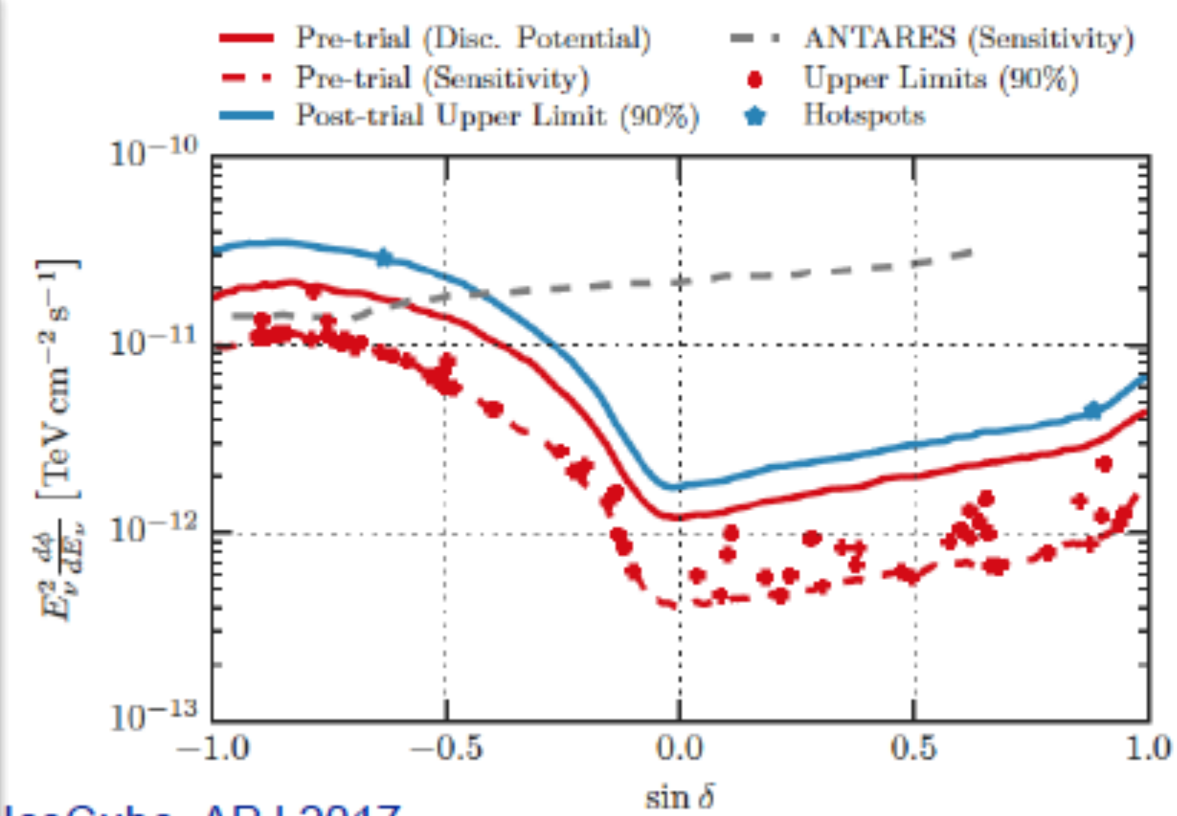


No significant PS reported

No correlation with list of 74 sources in both hemispheres. Galactic & Extragalactic

Most recent data periods:
~80k northern hemisephere evt/yr (atm ν)
~35k southern hemisepher evt/yr (atm μ)
~200 starting tracks. Southern sky

ApJ 835 (2017) 151



IceCube, APJ 2017

IceCube Searched for

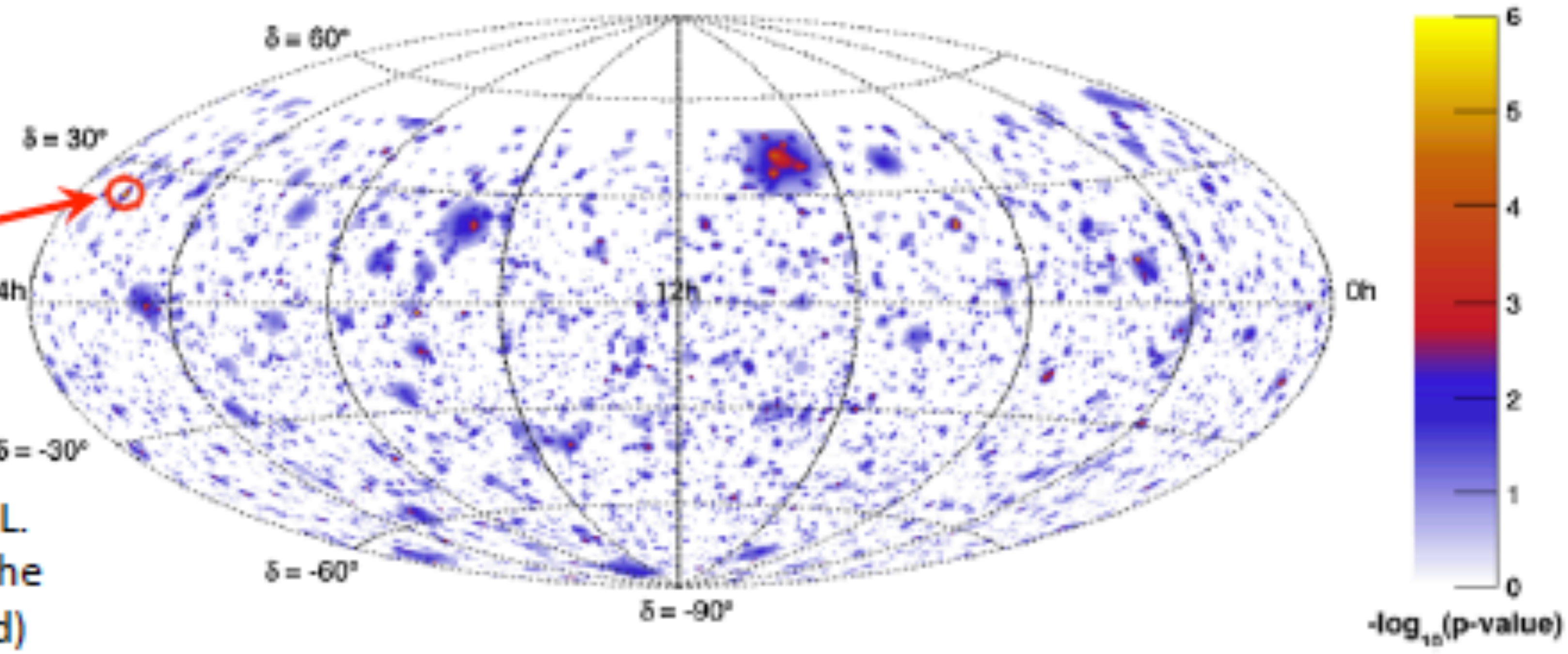
- point sources
- extended sources
- catalog of sources
- diffuse Galactic emission

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

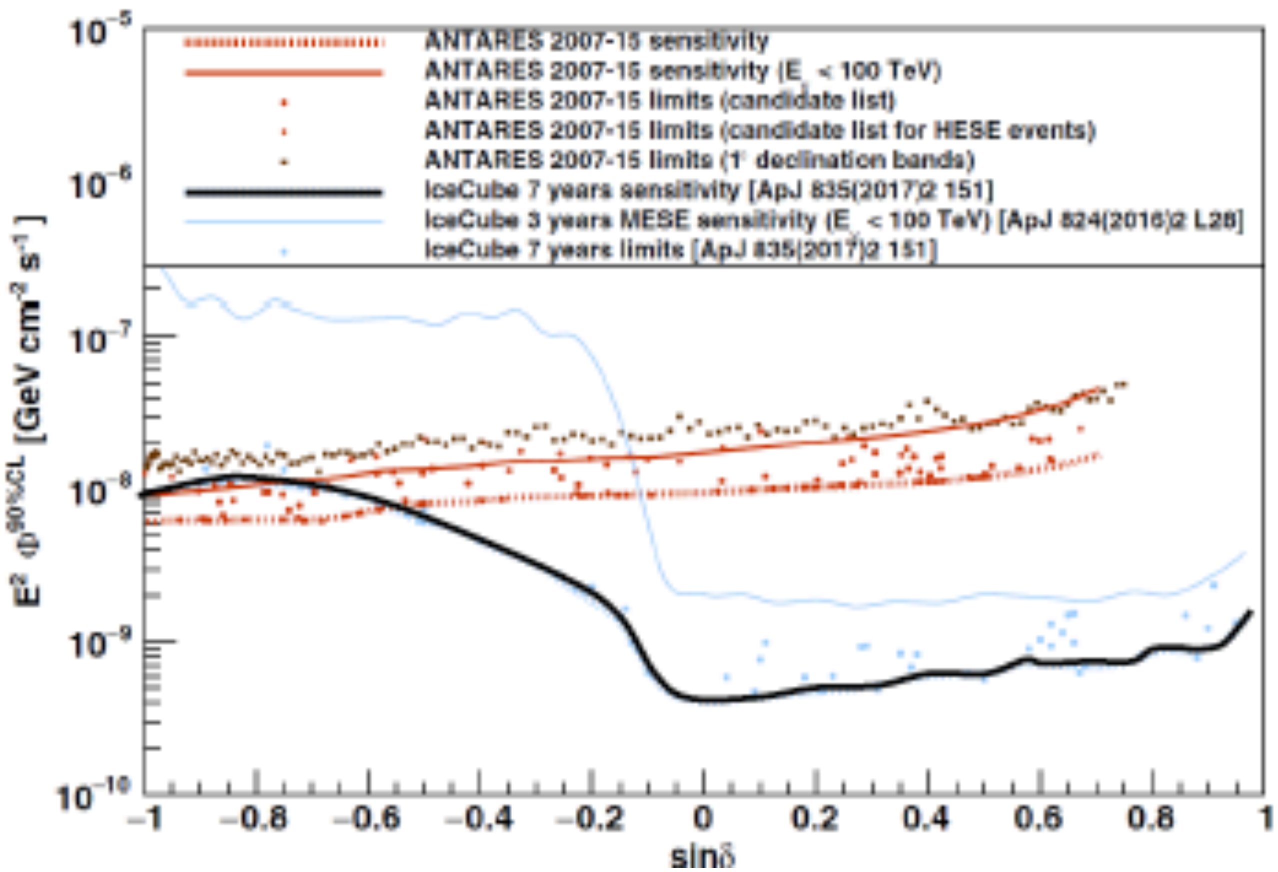
ANTARES Point Source Search

Most significant cluster c
the full-sky search (1.9σ
post-trial significance)
α = 343.8° δ = 23.5°

Sky map in equatorial coordinates of pre-trial p-values



Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)



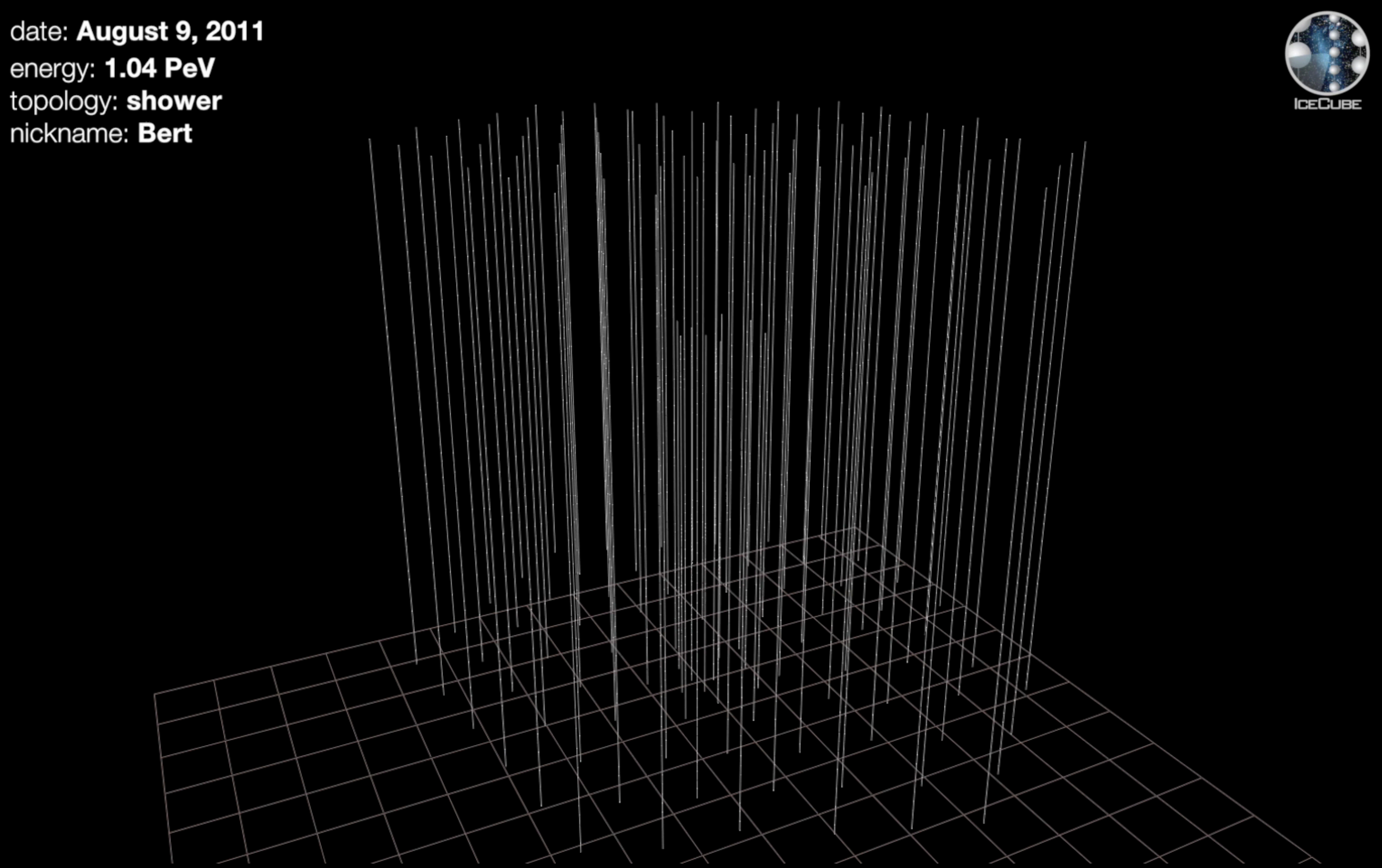
Phys. Rev. D96 (2017), 082001

ANTARES is the most sensitive instrument for a large fraction of the southern sky below 100 TeV

IceCube is the most sensitive instrument in the northern sky and a fraction of the southern sky

t. of Tech. 16

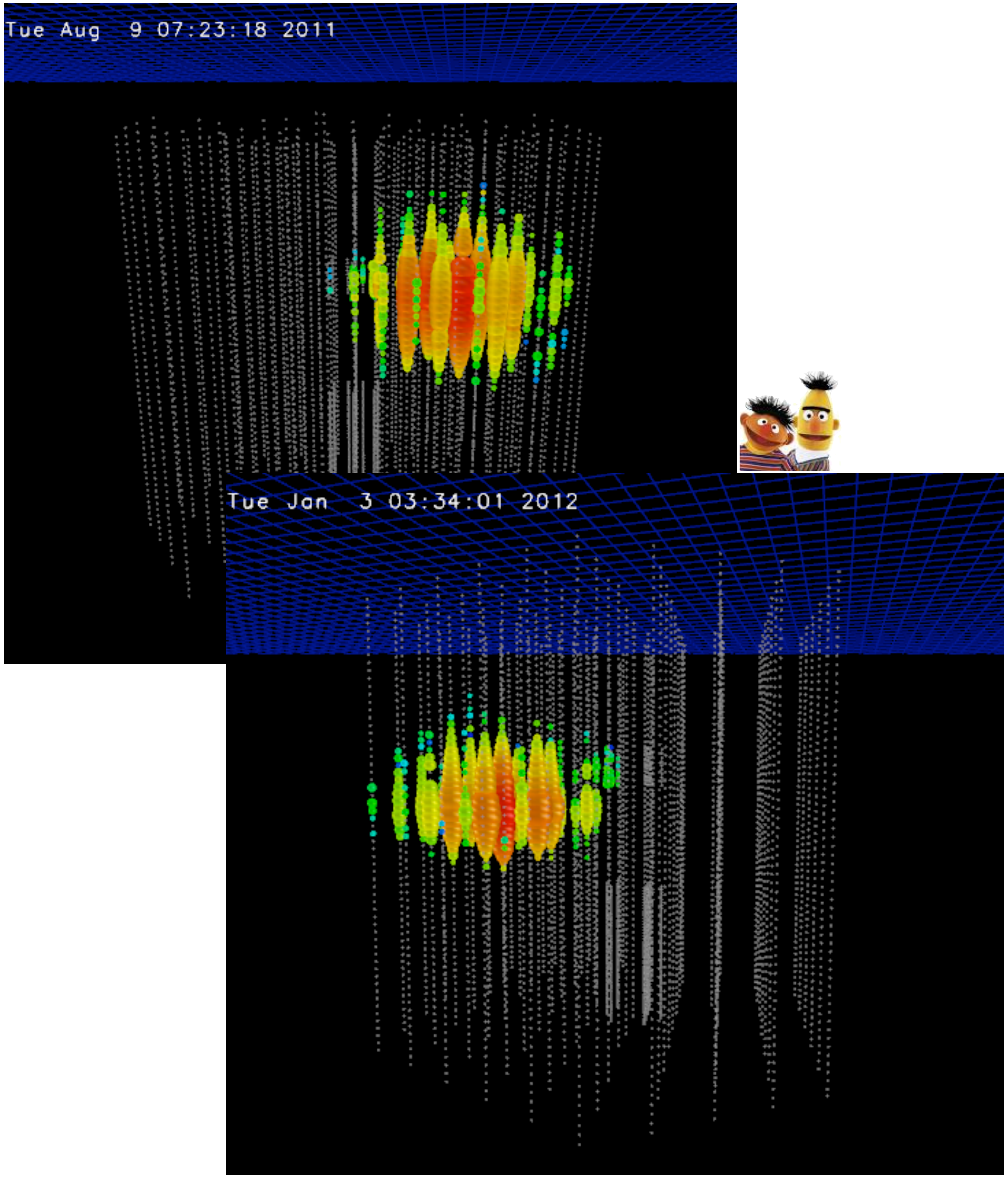
A cosmic neutrino interacts INSIDE the detector: it is too energetic to be produced in the atmosphere



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

Search for highest energy neutrinos

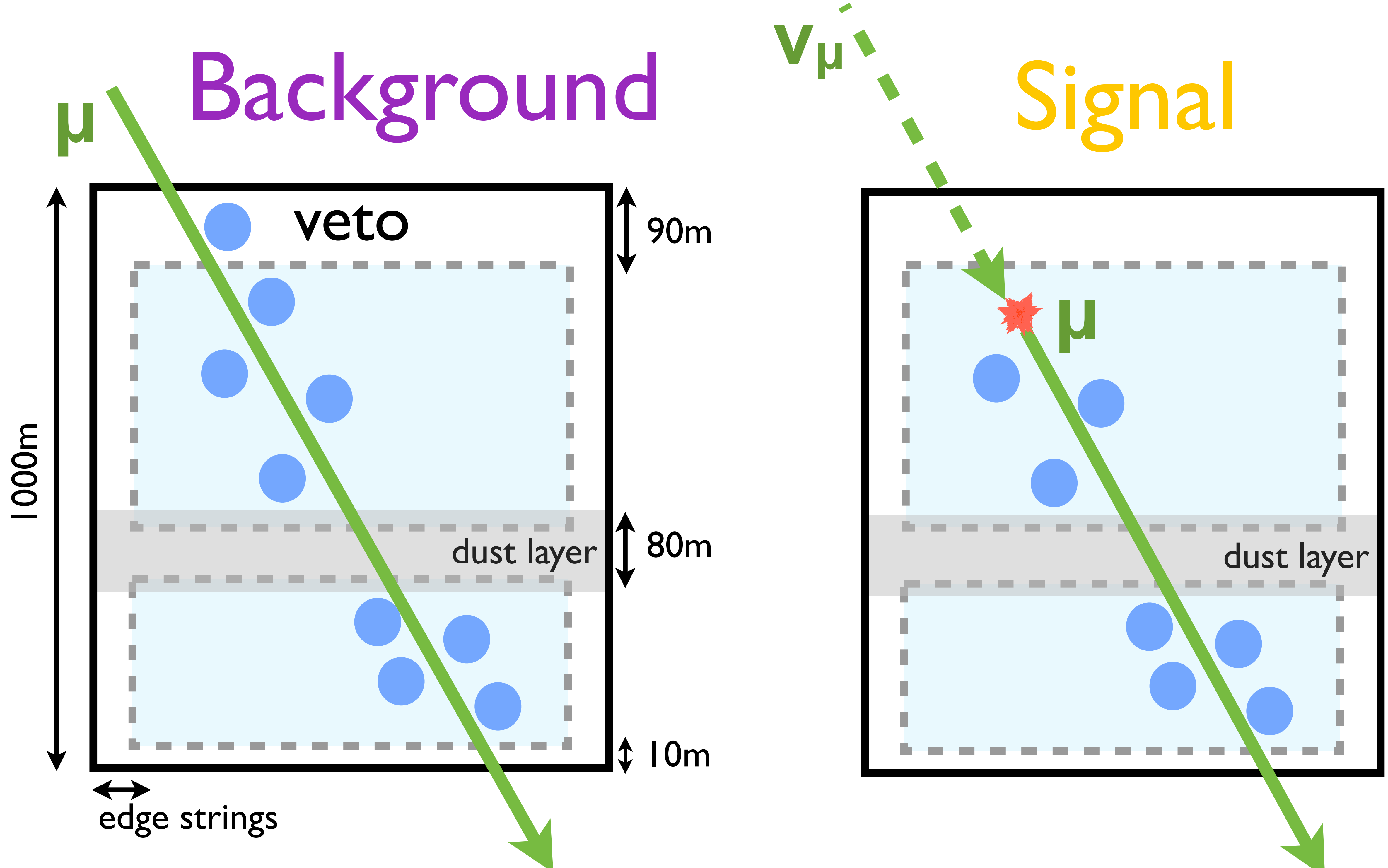
IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356



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

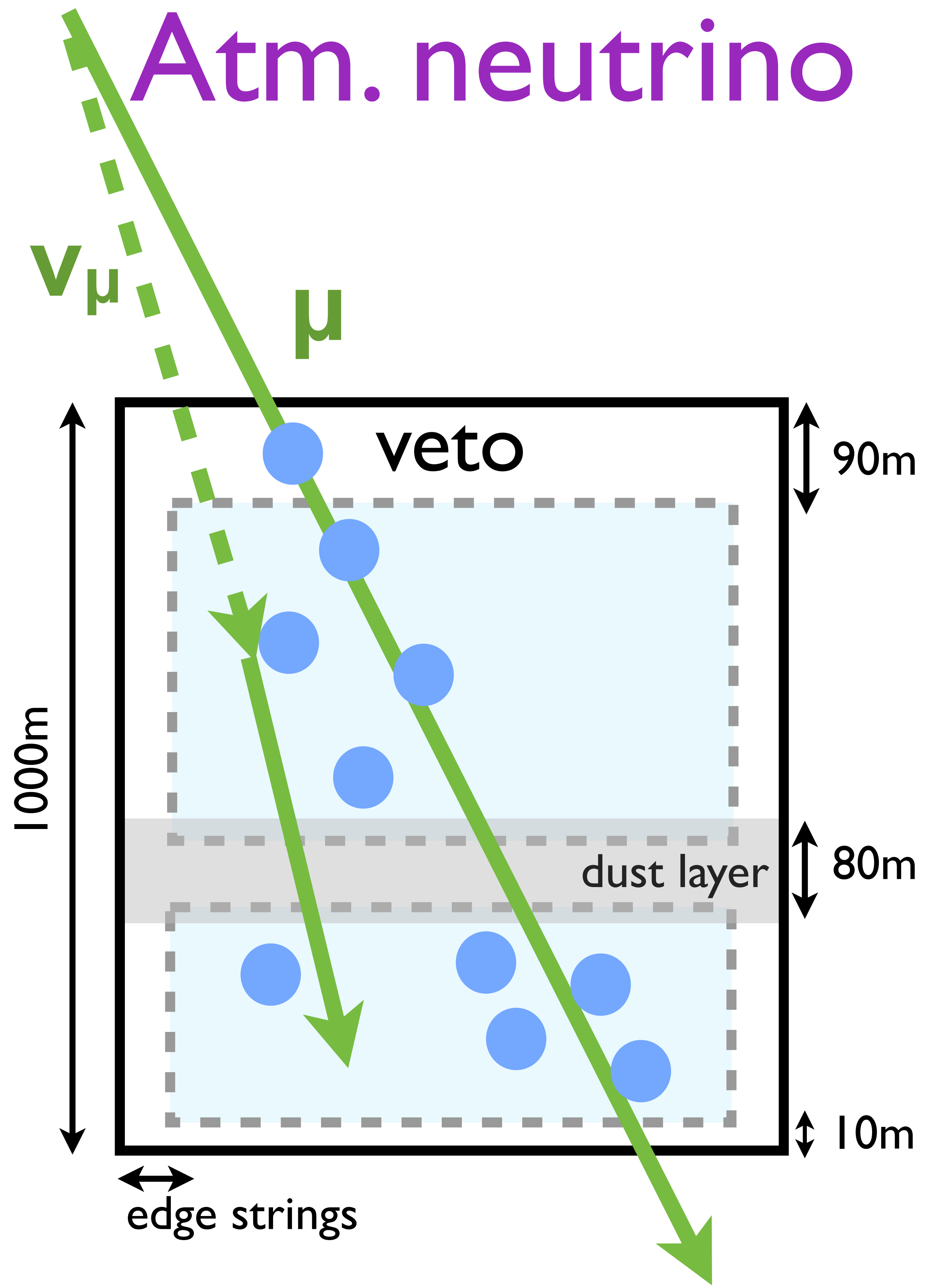
- Ernie ~1.15 PeV (~1.9 $\cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~1.7 $\cdot 10^{-4}$J)
- Topology of the events - cascades
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

- Probe the energy region of about 30TeV to 1PeV, all flavors and all directions, by vetoing down-going high-energy muons with the outer layer of IceCube

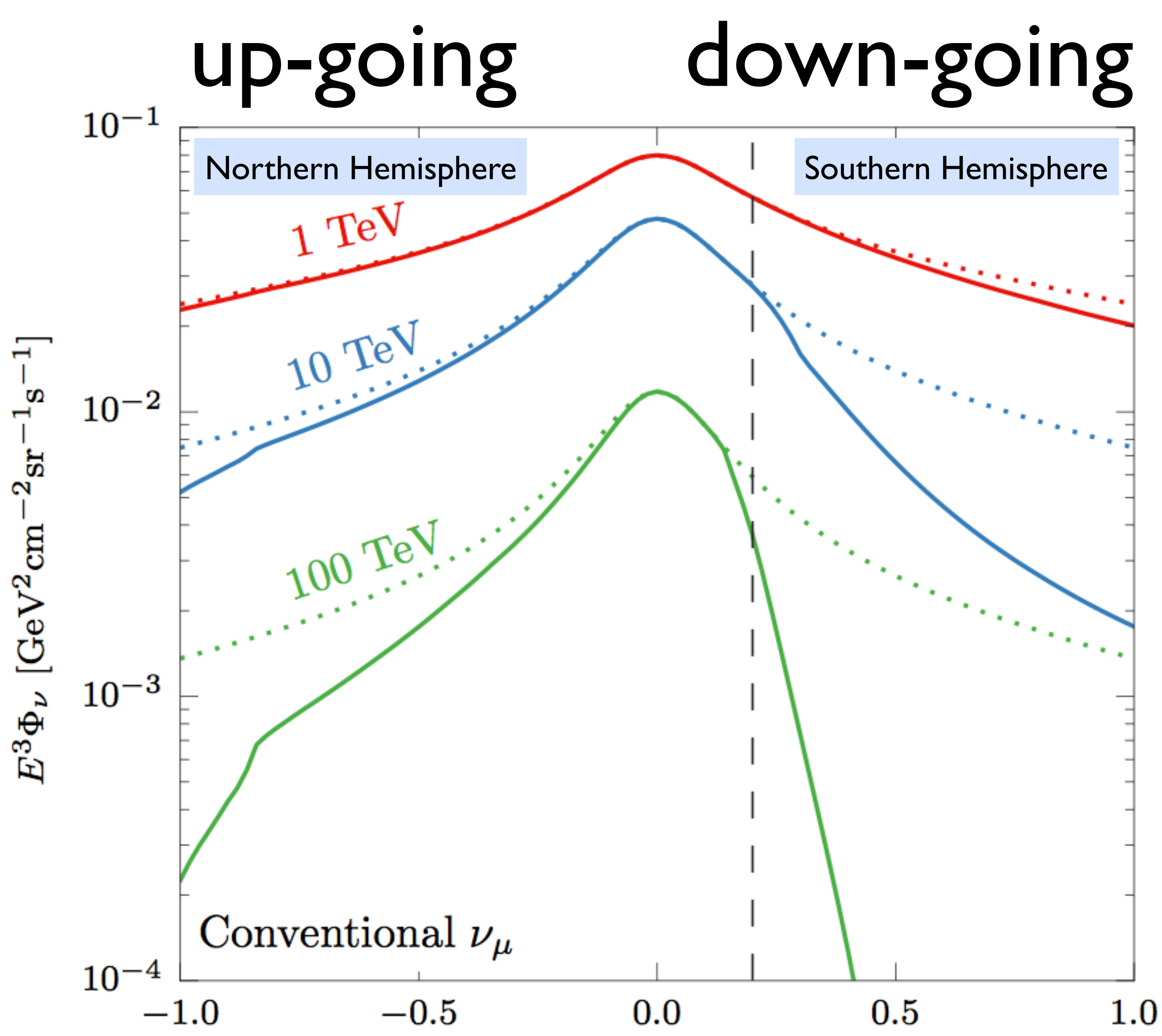


IceCube Collaboration **Phys.Rev. D91 (2015) no.2, 022001** (arxiv:1410.1749)

Veto and Self-veto

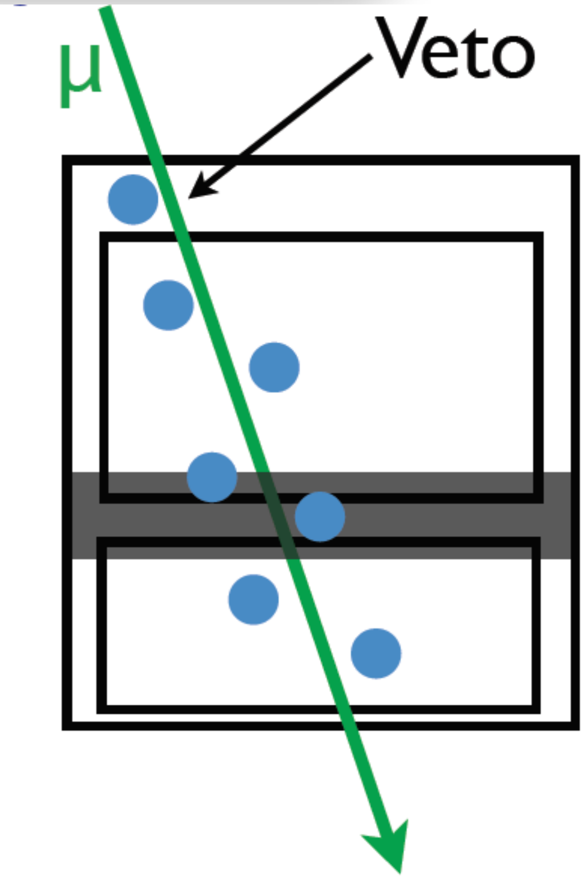


Down-going high-energy neutrinos can be nearly background free identified as astro-physical neutrinos

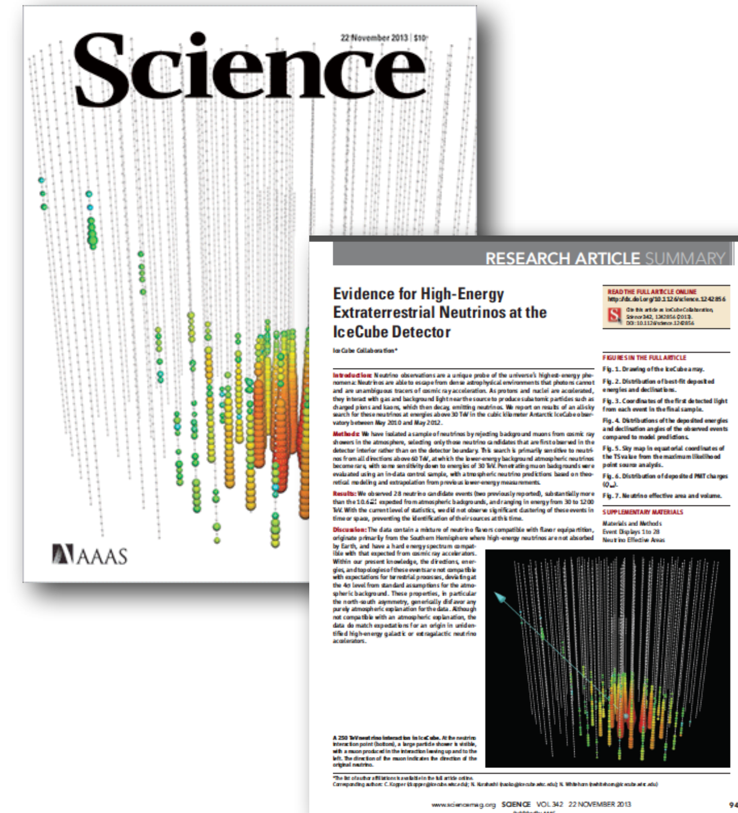


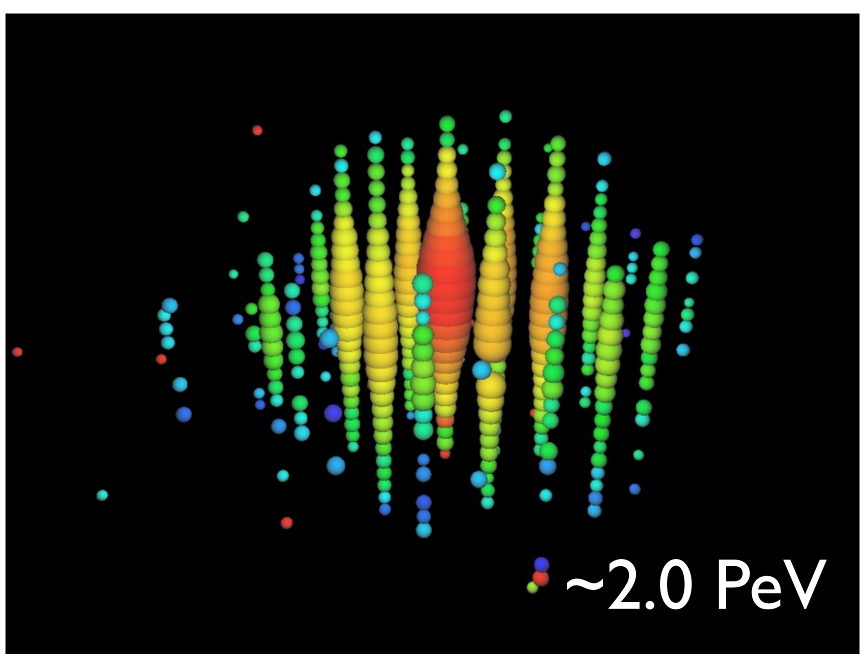
Observation of high-energy astrophysical neutrinos

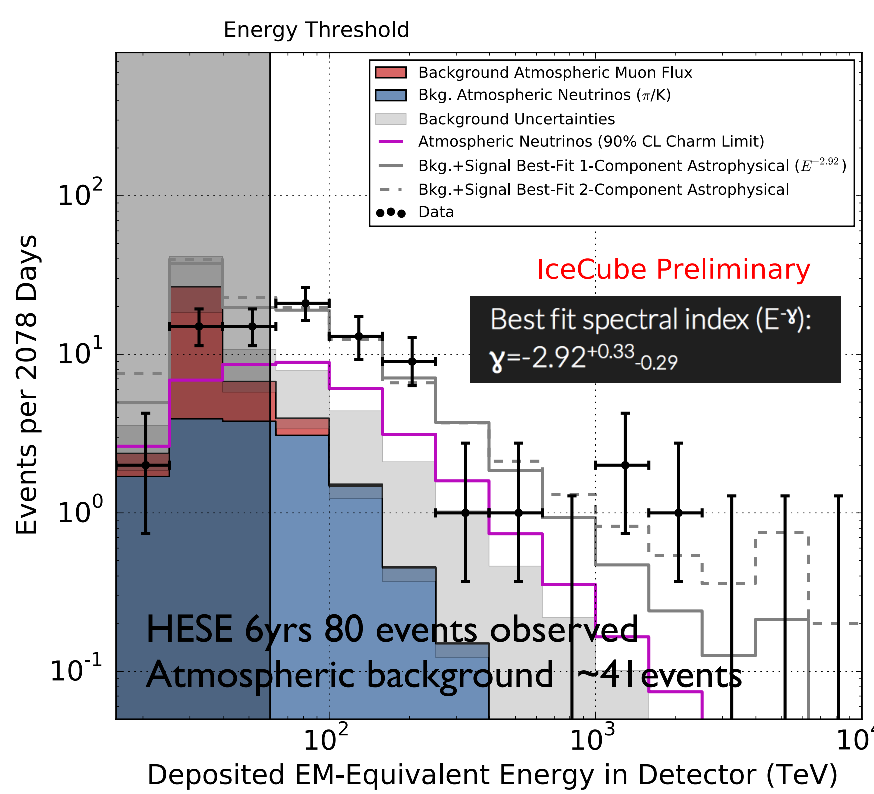
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

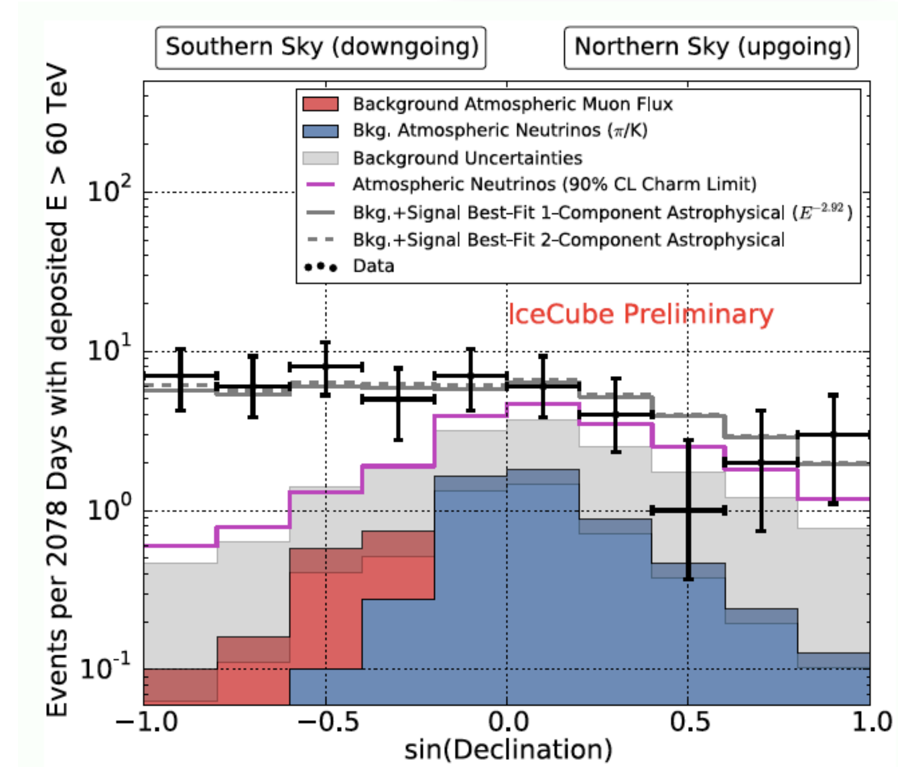


- Search for High-Energy Starting Events (HESE)
  - Efficient reject atmospheric backgrounds
  - Discovery of astrophysical neutrinos







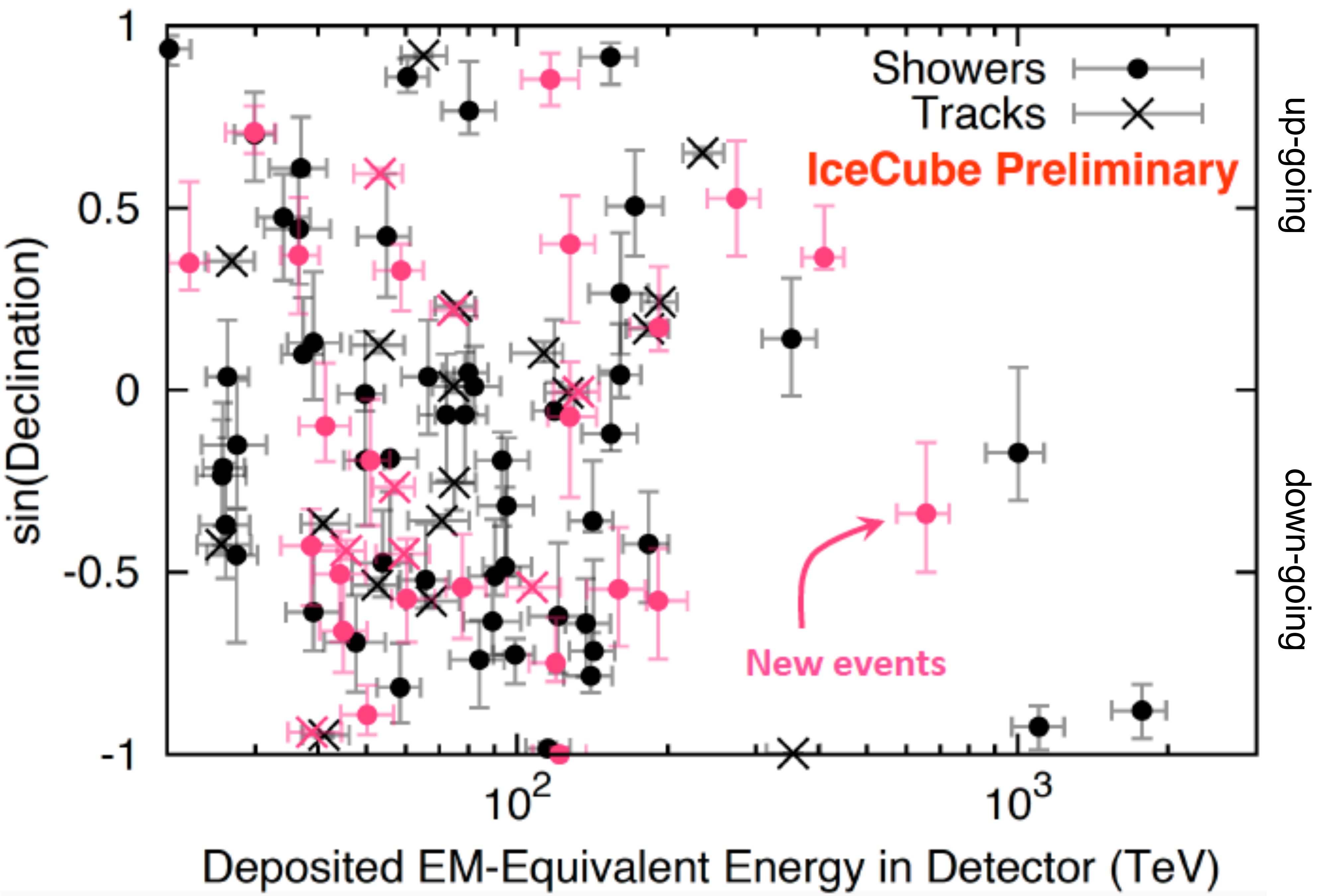


NEUTRINO
2018
Heidelberg
4–9 June

HESE7.5yrs results

High-Energy Starting Events (HESE) – 7.5 yr

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



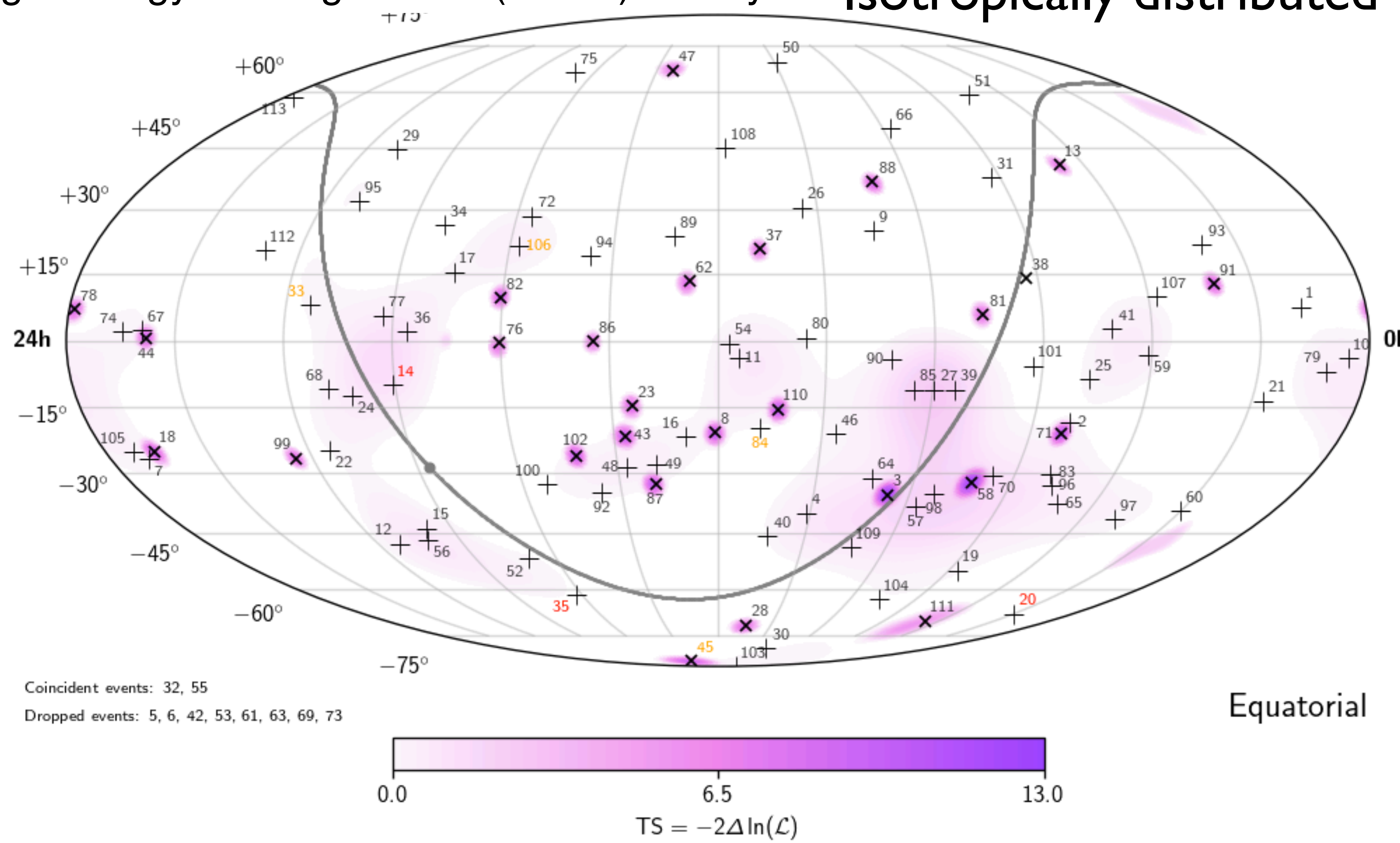
Prior result 6 years ICRC 2017 arXiv:1710.01191
Updates to calibration and ice optical properties
103 events, with 60 events >60 TeV
→Changes to RA, Dec, energy

Arrival directions (highest energy events)

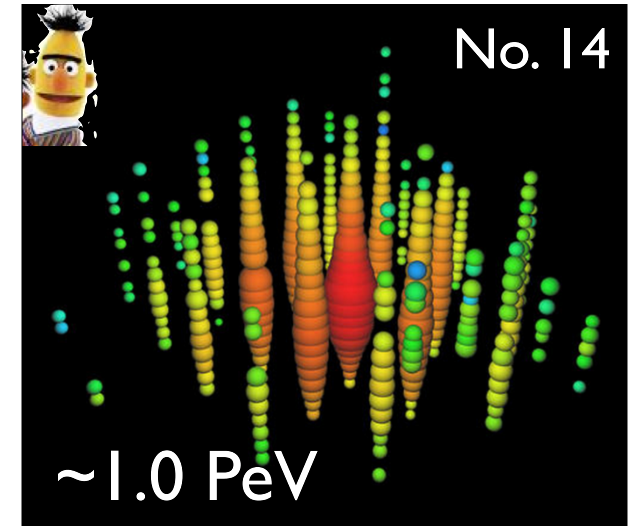
IceCube Collaboration, *Science* 342, 1242856 (2013)

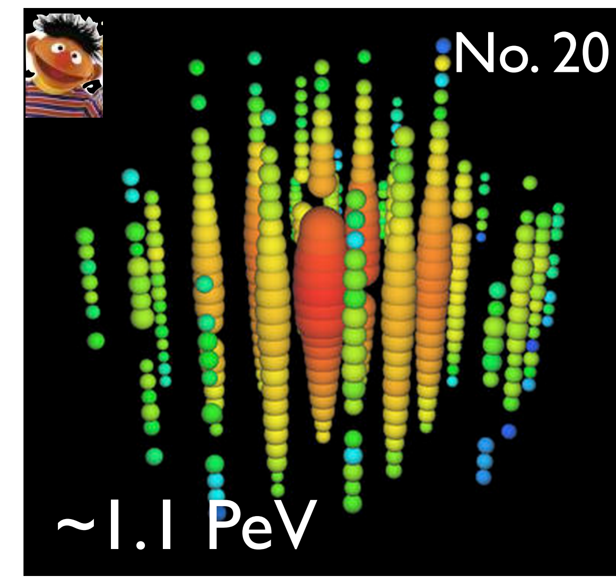
High-Energy Starting Events (HESE) – 7.5 yr

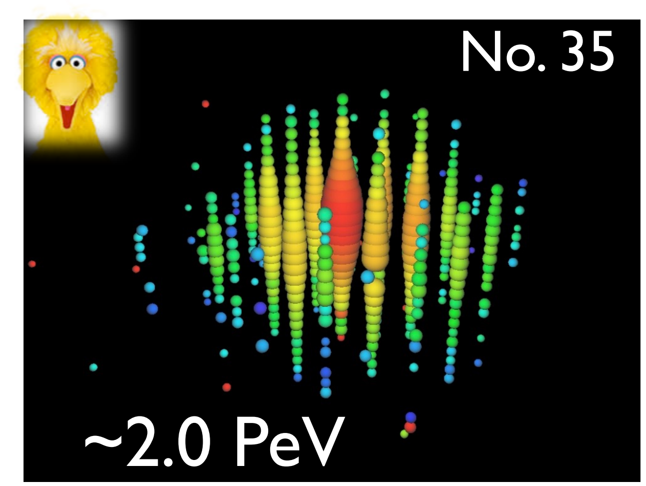
Isotropically distributed



$E < 300$ TeV   300 TeV $< E <$ 1 PeV   1 PeV $< E$



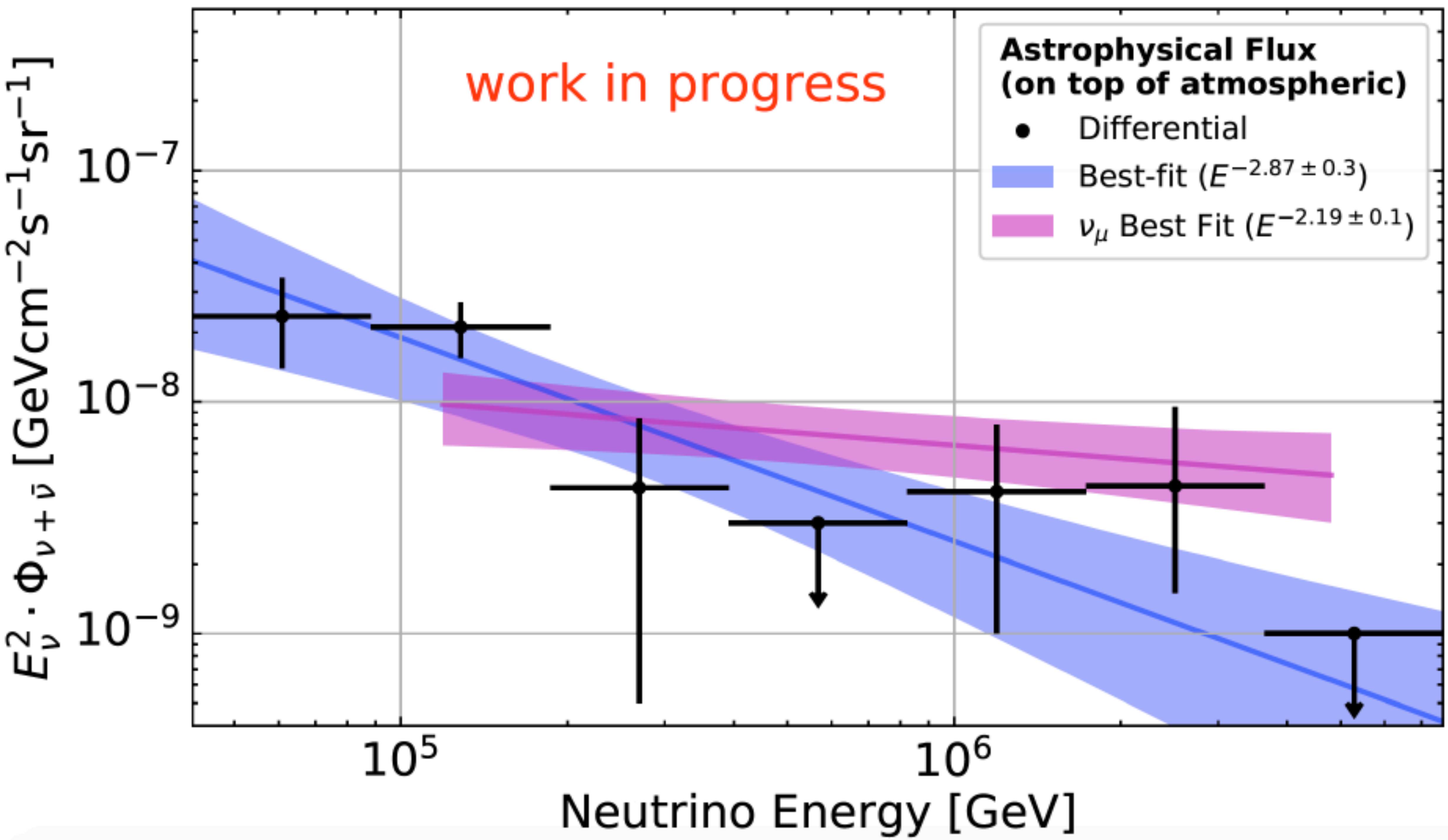




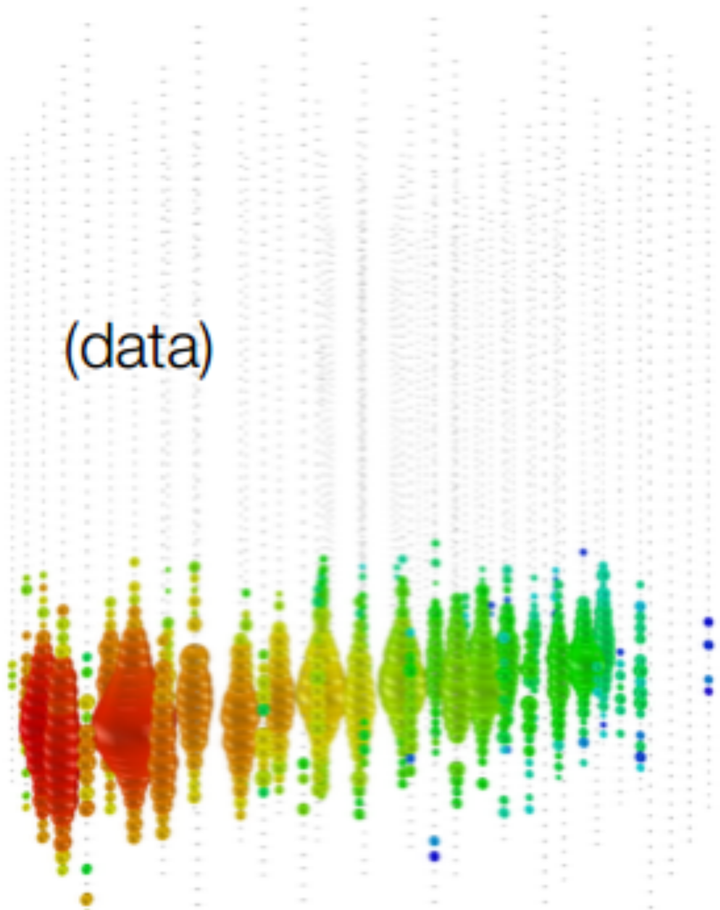
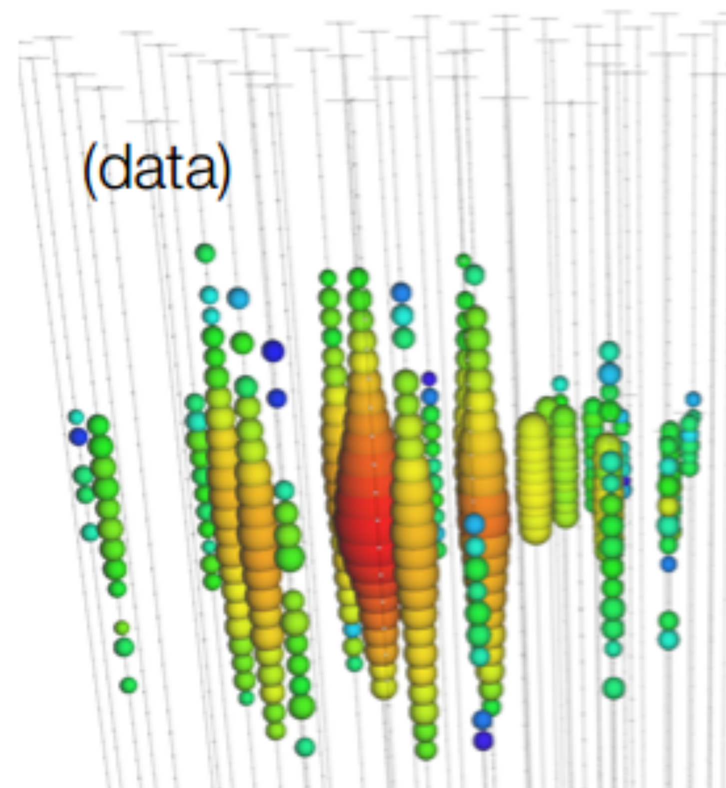
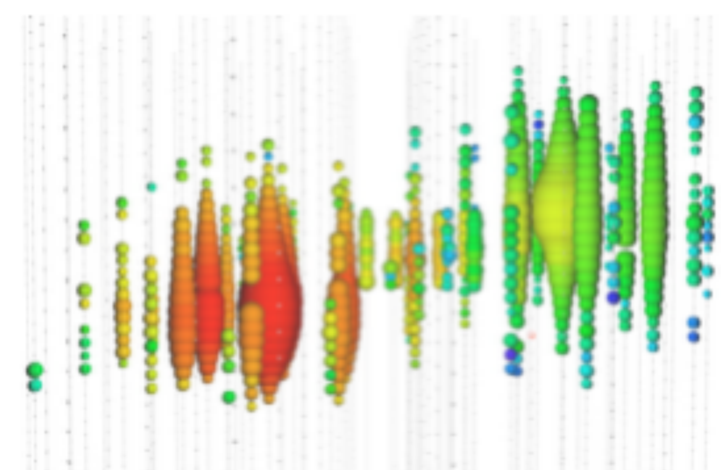
No evidence for point sources, nor a correlation with the galactic plane

Neutrino energy spectrum

High-Energy Starting Events (HESE) – 7.5 yr

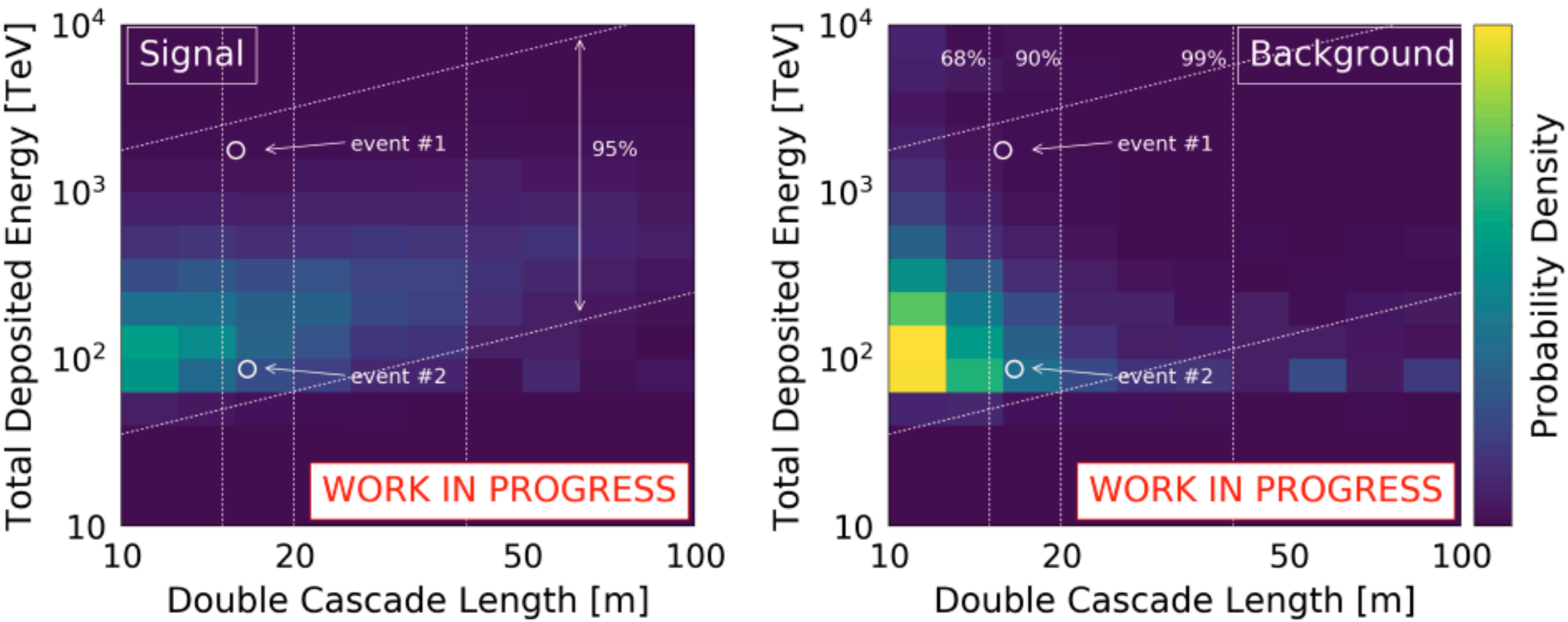


Event topologies

Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ
		
Up-going track	**Isolated energy deposition (cascade) with no track**	**“Double-bang”**
Factor of ~2 energy resolution < 1 degree angular resolution	**15% deposited energy resolution 10 degree angular resolution (above 100 TeV)**	**(none observed yet: τ decay length is 50 m/PeV)**

Early  Late

High-Energy Starting Events

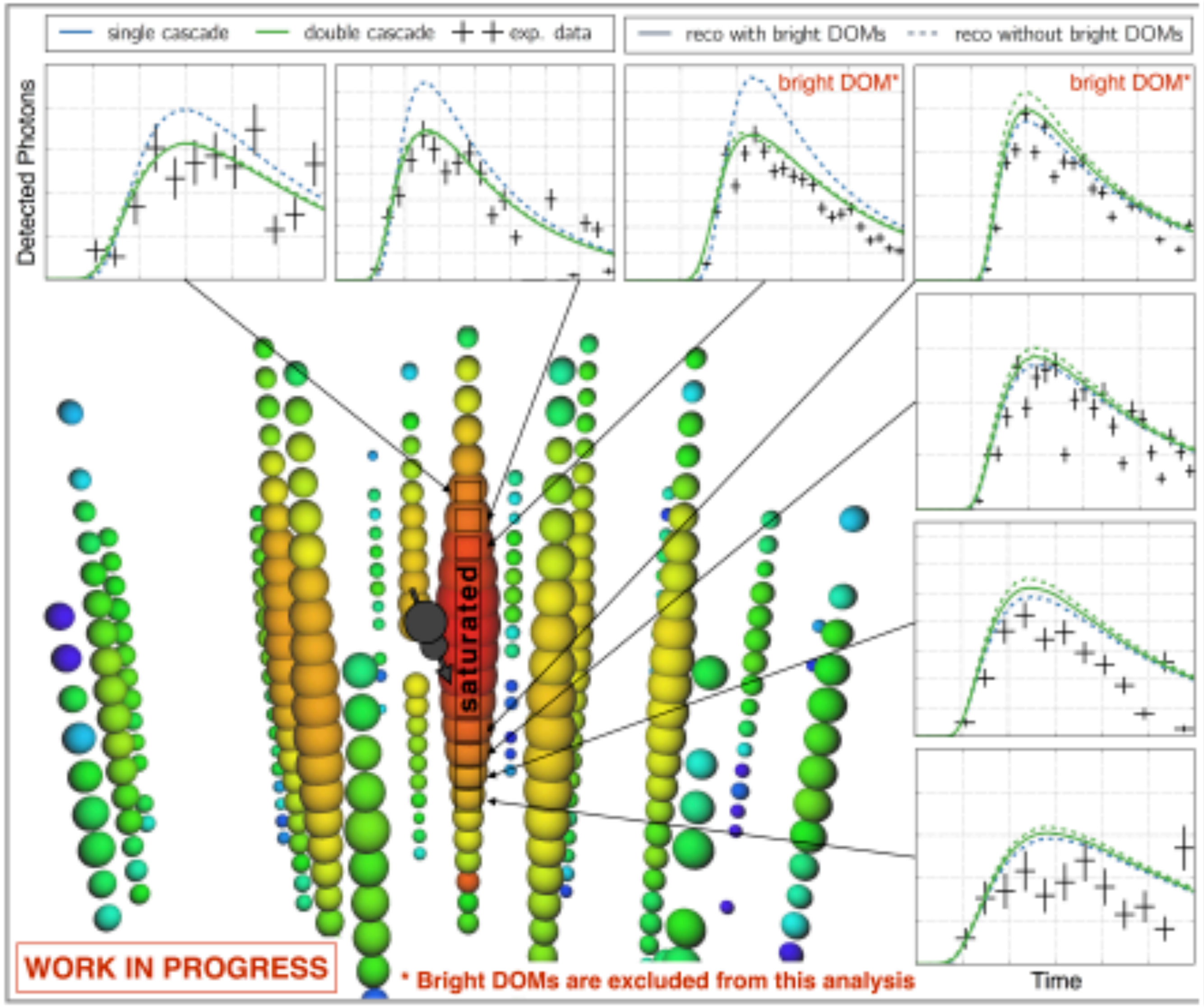


Two double cascades have been identified

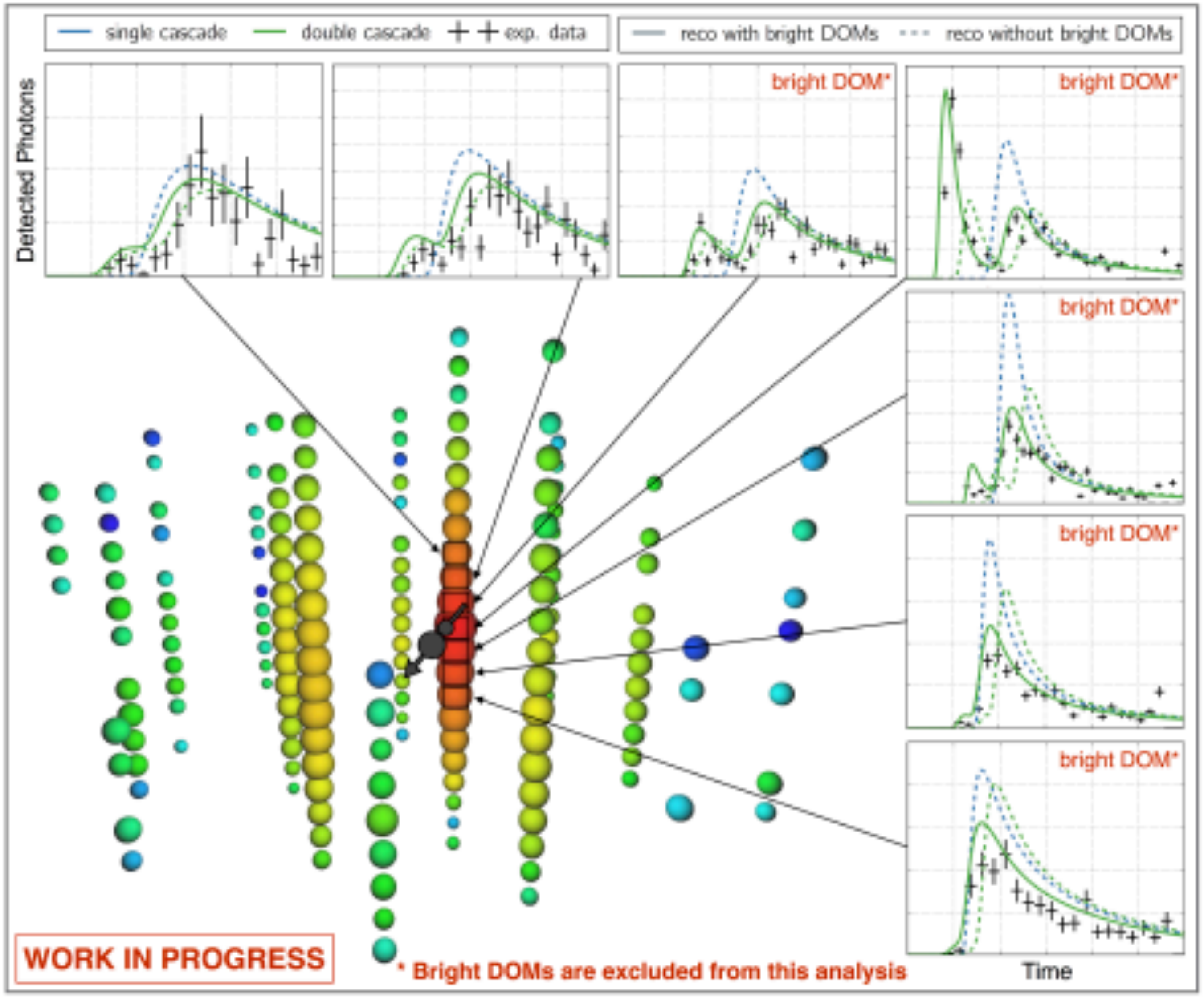
Double cascades can arise from ν_τ or mis-identified bckg (astro ν/ atm).

Separate study of tauness of the double cascade events ongoing

HESE 7.5yrs Tau Search



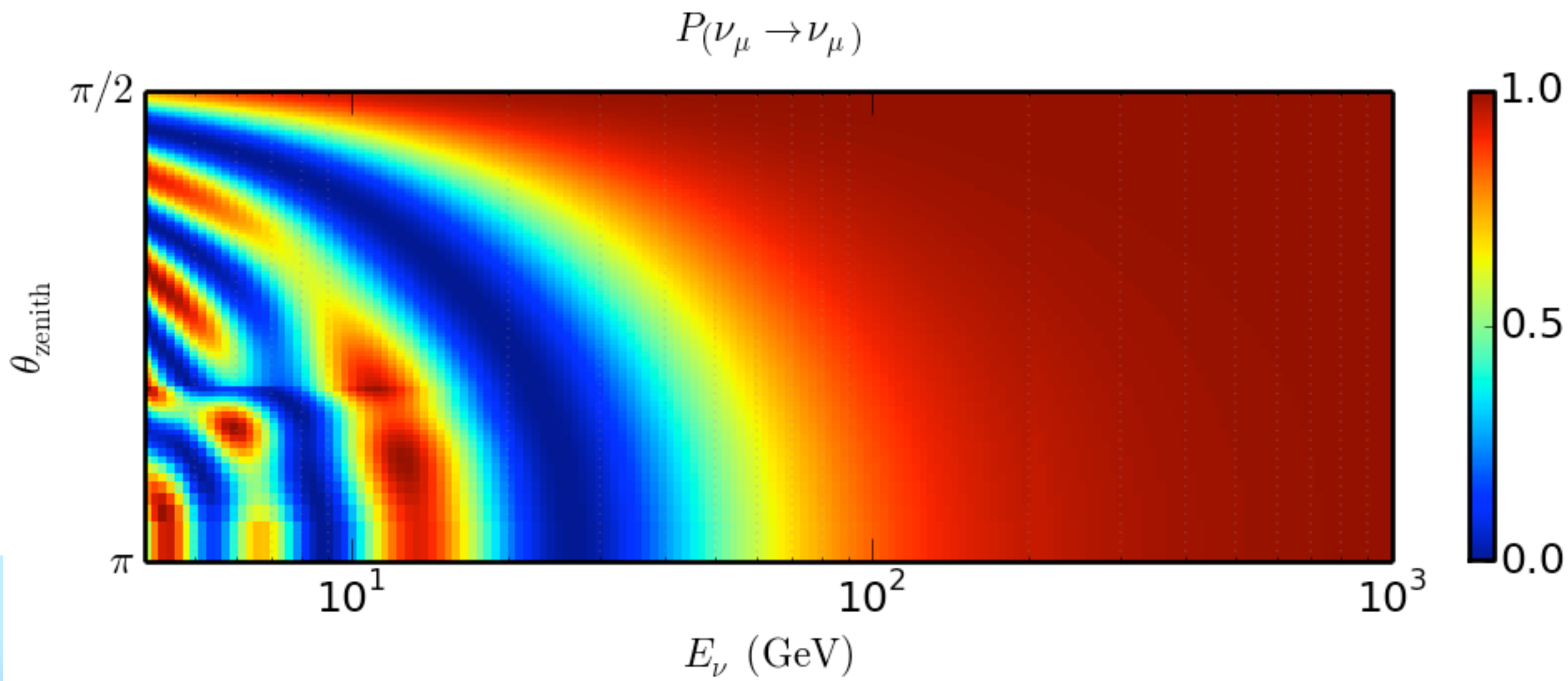
Double cascade Event #1



Double cascade Event #2

"Bright" DOMs not used in reconstruction

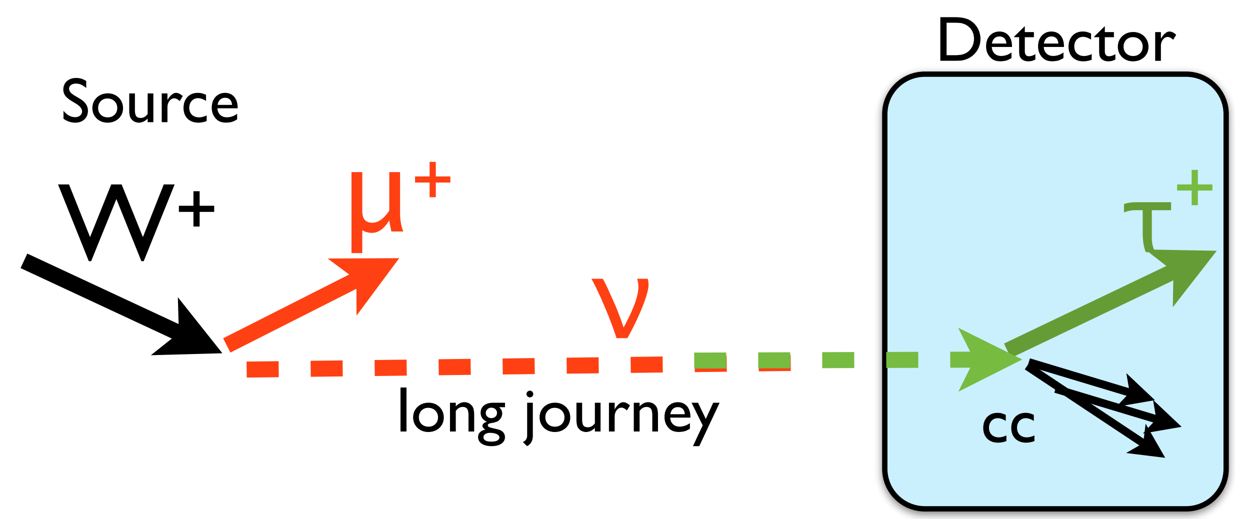
Direction and two reconstructed cascades shown in dark gray

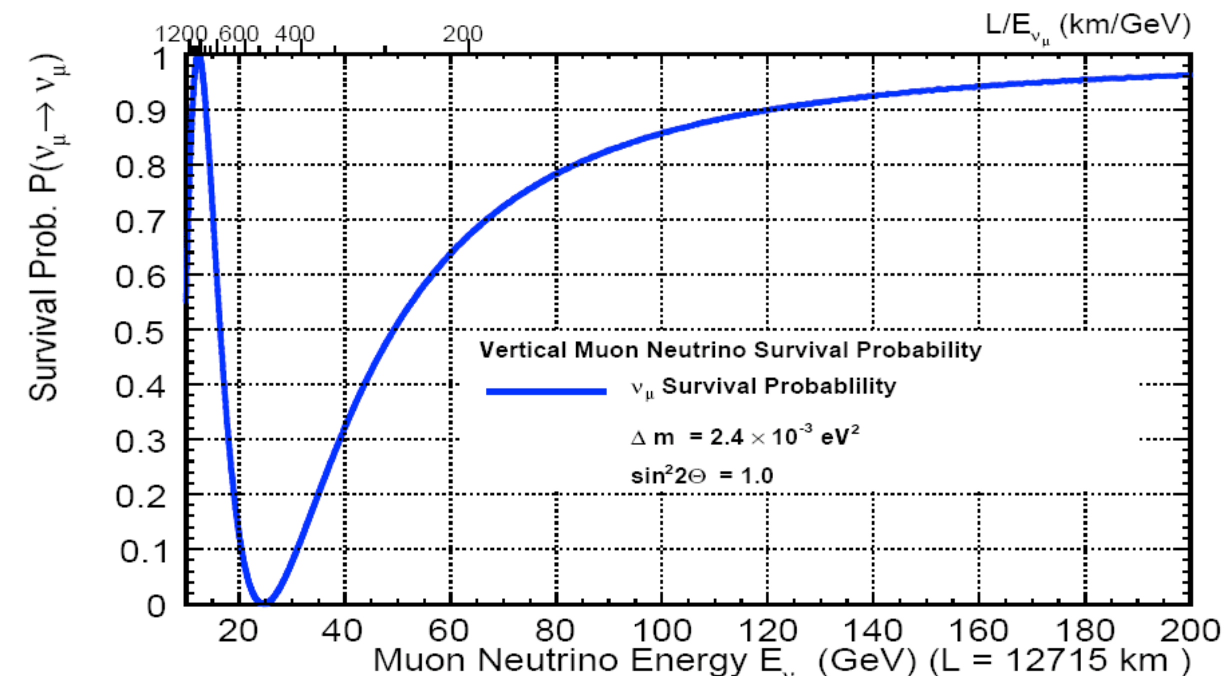


Neutrino Oscillations in IceCube

Neutrino Oscillations

- Neutrinos come in three different flavors: ν_e, ν_μ, ν_τ
- A neutrino created as one flavor can change into a different flavor
- This phenomenon (neutrino oscillations) depends on the energy of the neutrino and the distance traveled
- It further depends on the "potential" the neutrino travels through





$$P(\nu_\alpha \to \nu_\beta) = 4 \sin^2\theta \cos^2\theta \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

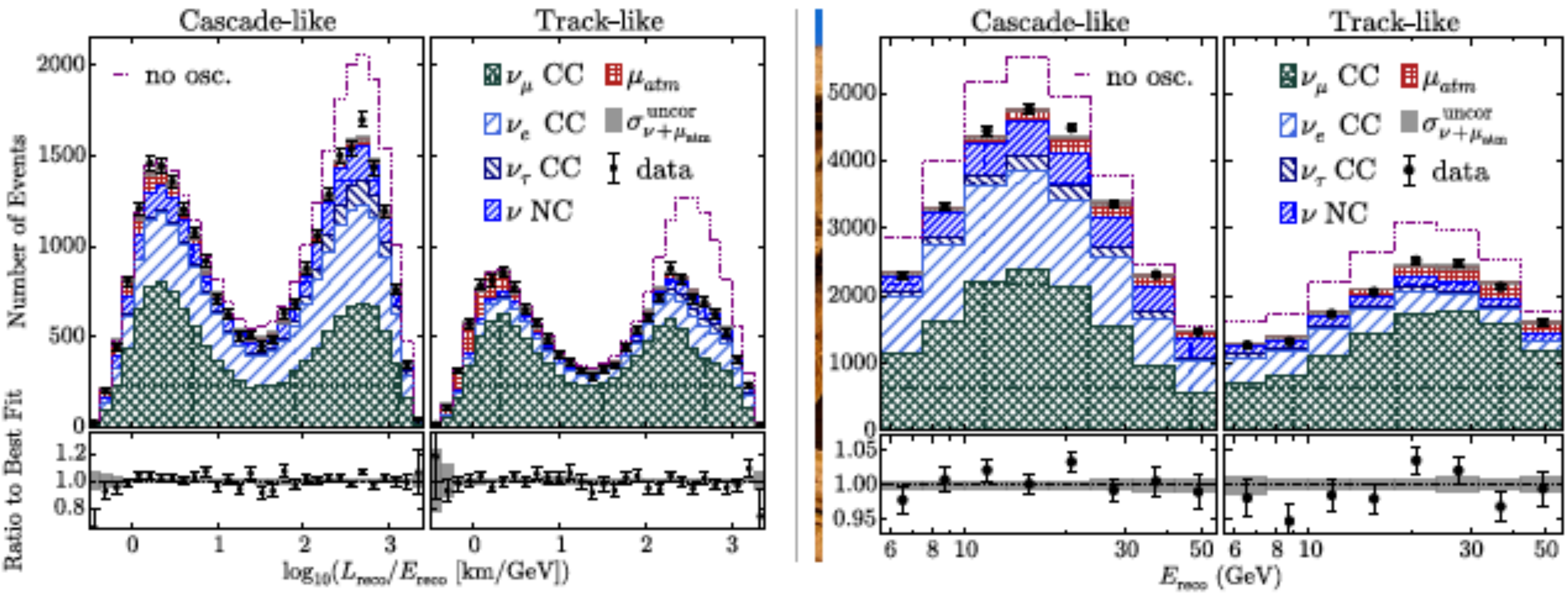
oscillation probability

oscillation parameters

energy

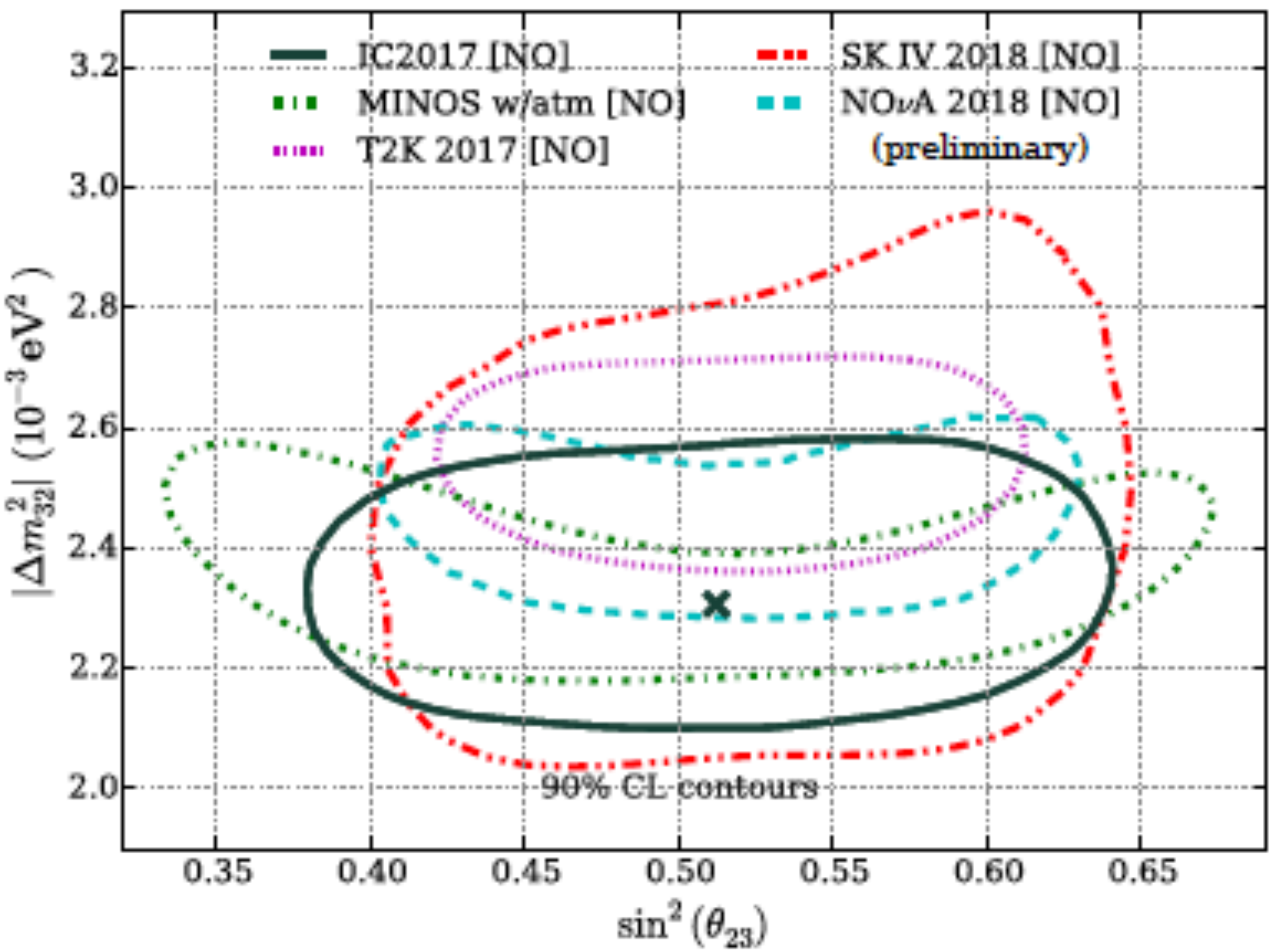
distance

M. Aartsen et al. (IceCube), *Phys. Rev. Lett.* 120, 071801 (2018)



- Analysis histograms projected to 1D for visualization
  - Down-going and cascade events useful for disentangling systematic effects
  - Particle ID (ν_μ CC event tagging) poor at low energies – important to correct for disappearance of untagged ν_μ CC events in cascade sample!

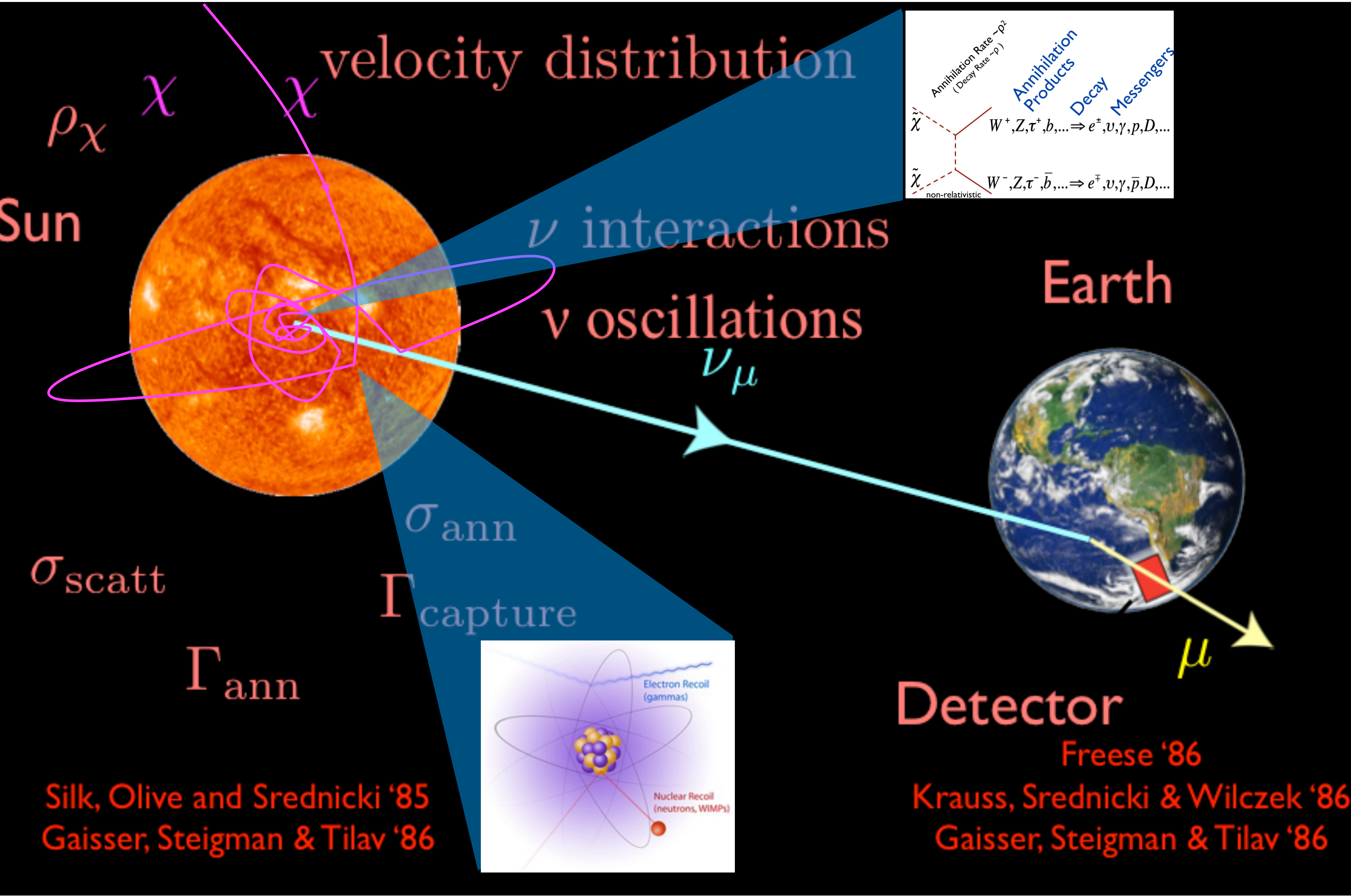
M. Aartsen et al. (IceCube), *Phys. Rev. Lett.* 120, 071801 (2018)



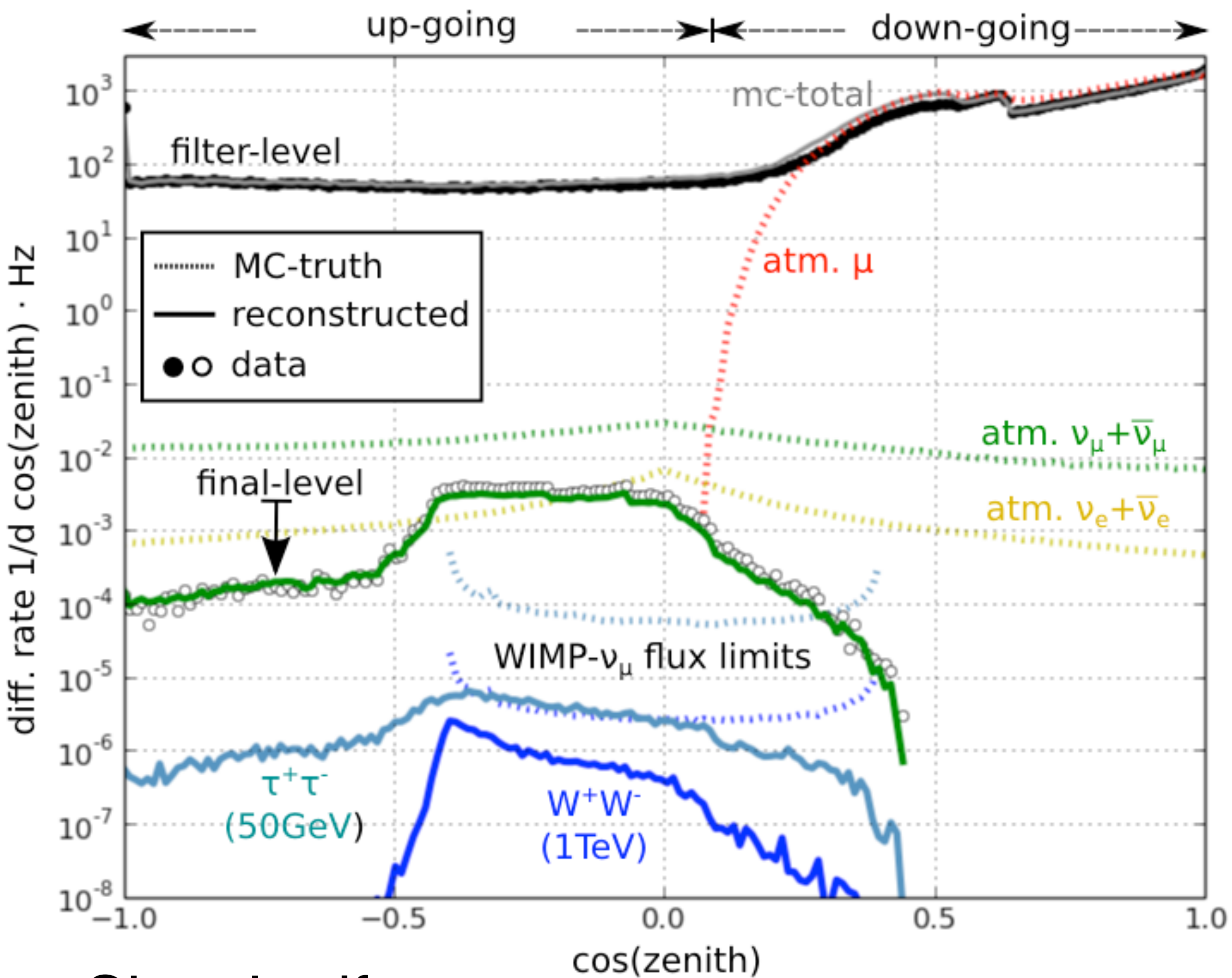
- 1,022 days live time 2012-14
- 41,599 events (full-sky)
  - 15,138 track, 26,461 cascade events
  - E_ν reconstructed from muon range plus cascade energy
  - Est. 5.2% atm. μ BG
- Best fit $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$, $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2
  - Most precise atmospheric measurement, highest energy range (constraints primarily from 15-50 GeV neutrinos)

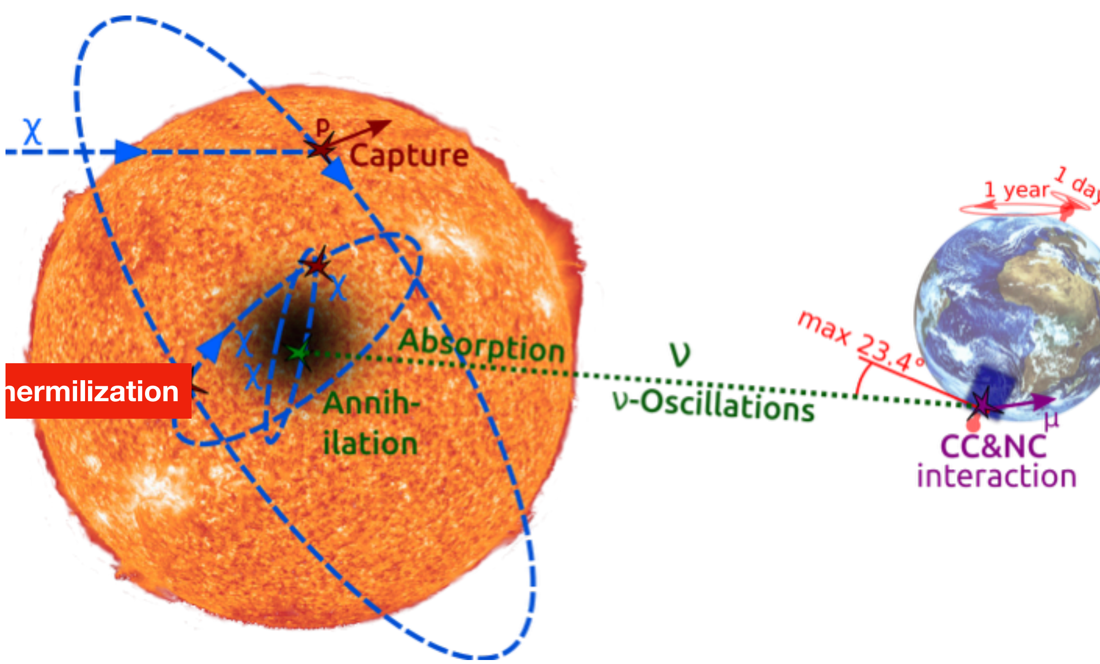
Search for Dark Matter

Solar Dark Matter



Search for Dark Matter in the Sun





Signal pdf:

Spectral part

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

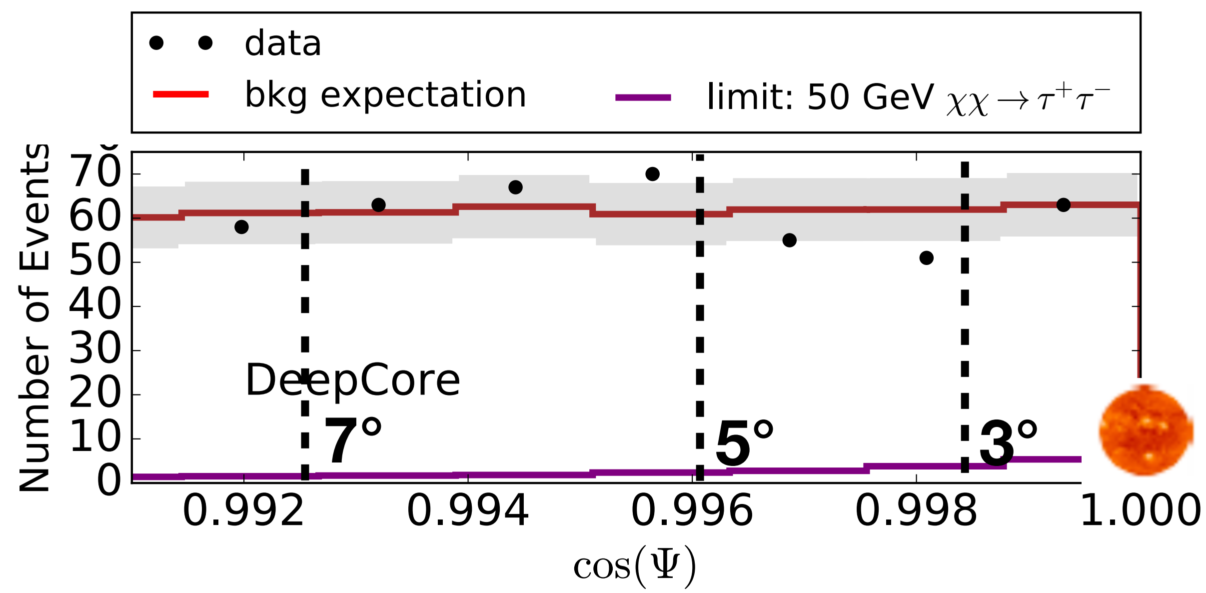
Monovariate Fisher Bingham distribution from directional statistics

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

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

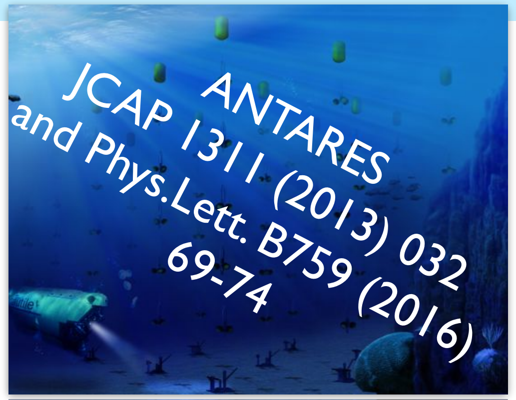
Observed events

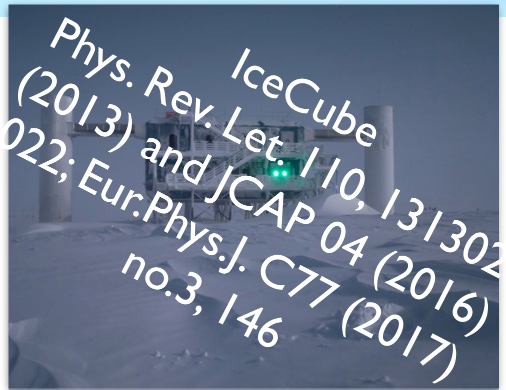
IceCube Eur.Phys.J. C77 (2017) no.3, 146

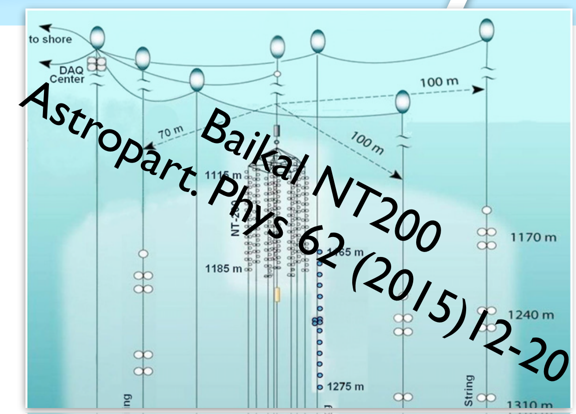


- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Observed events consistent with background only expectations

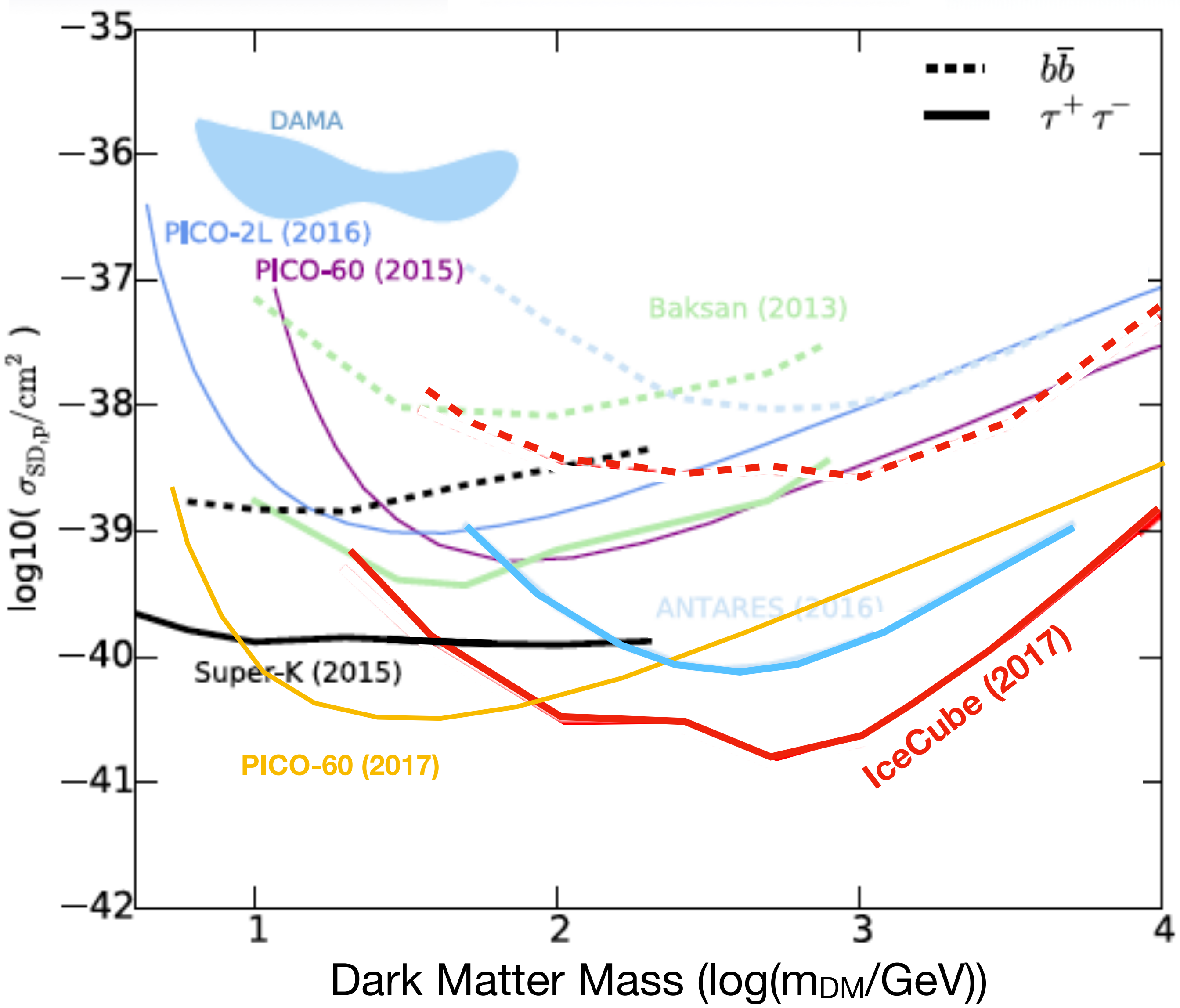
Solar Dark Matter Summary



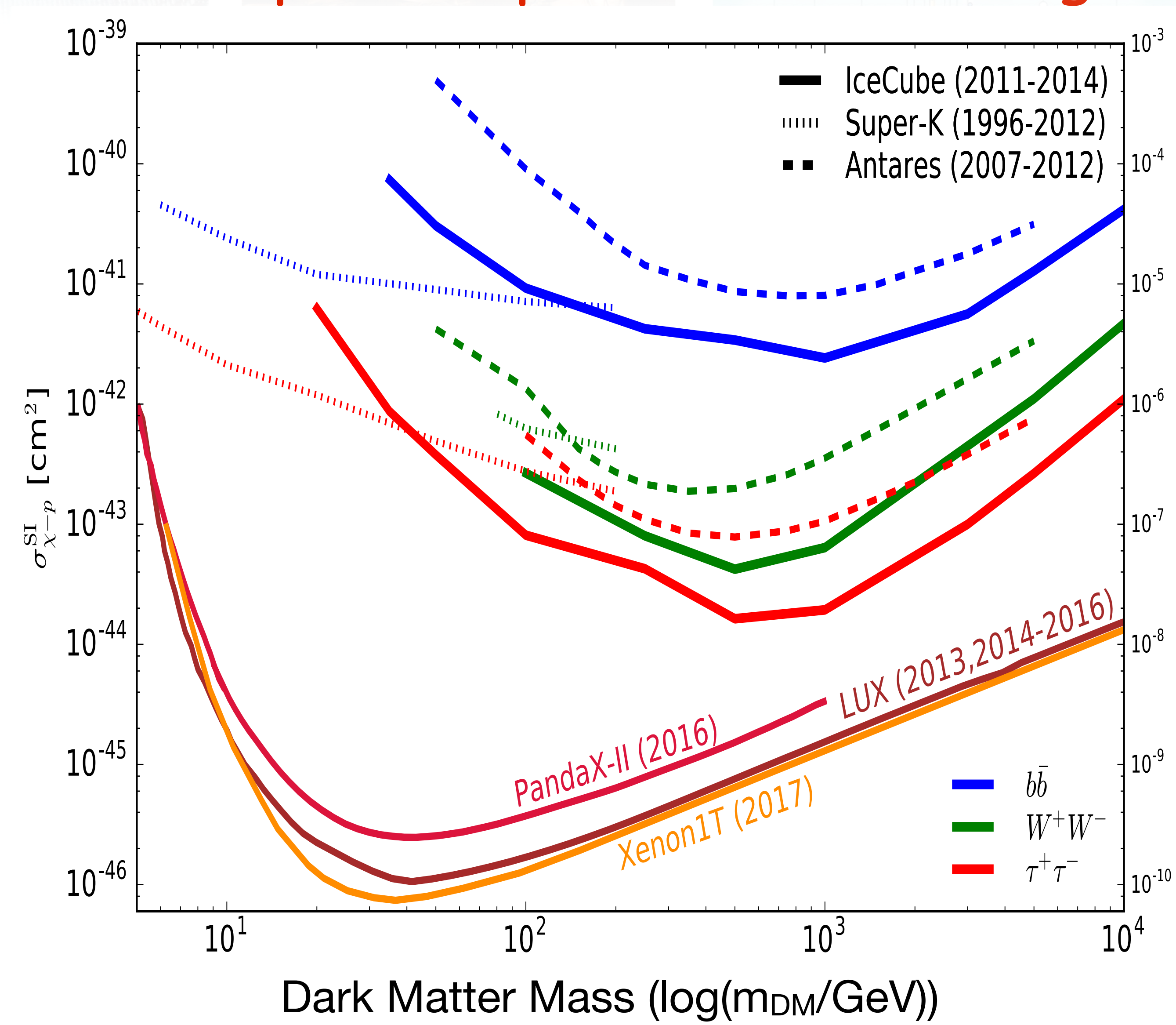




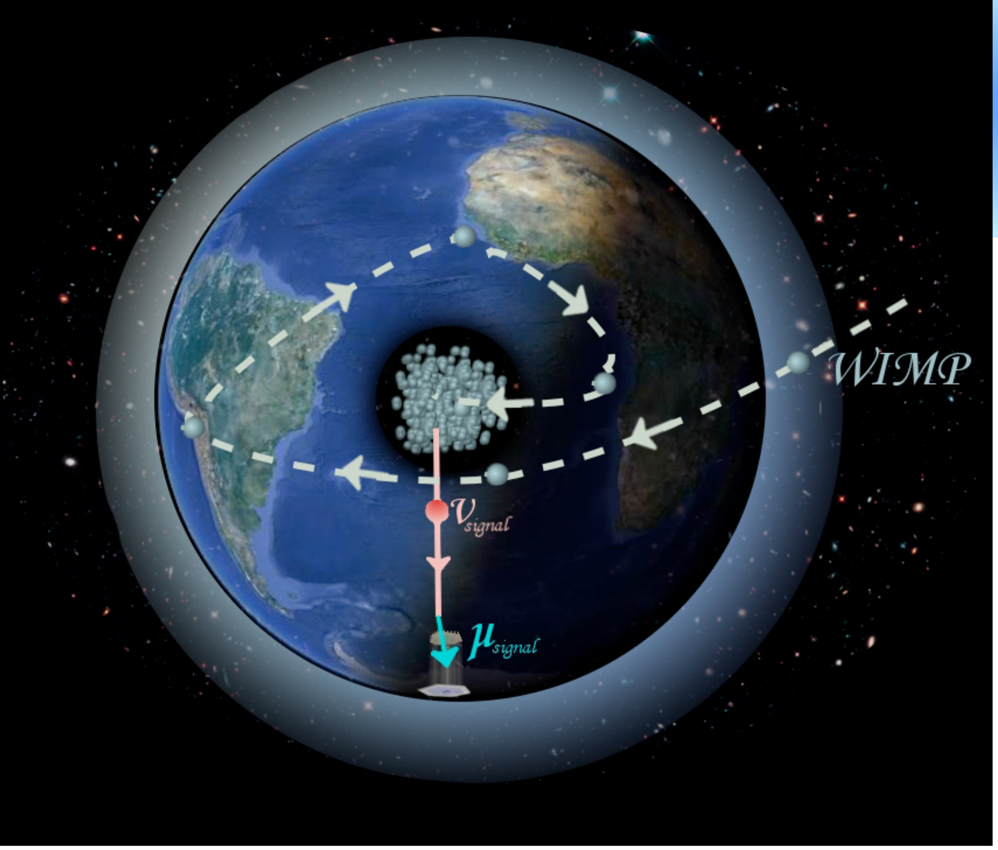
Spin-dependent scattering



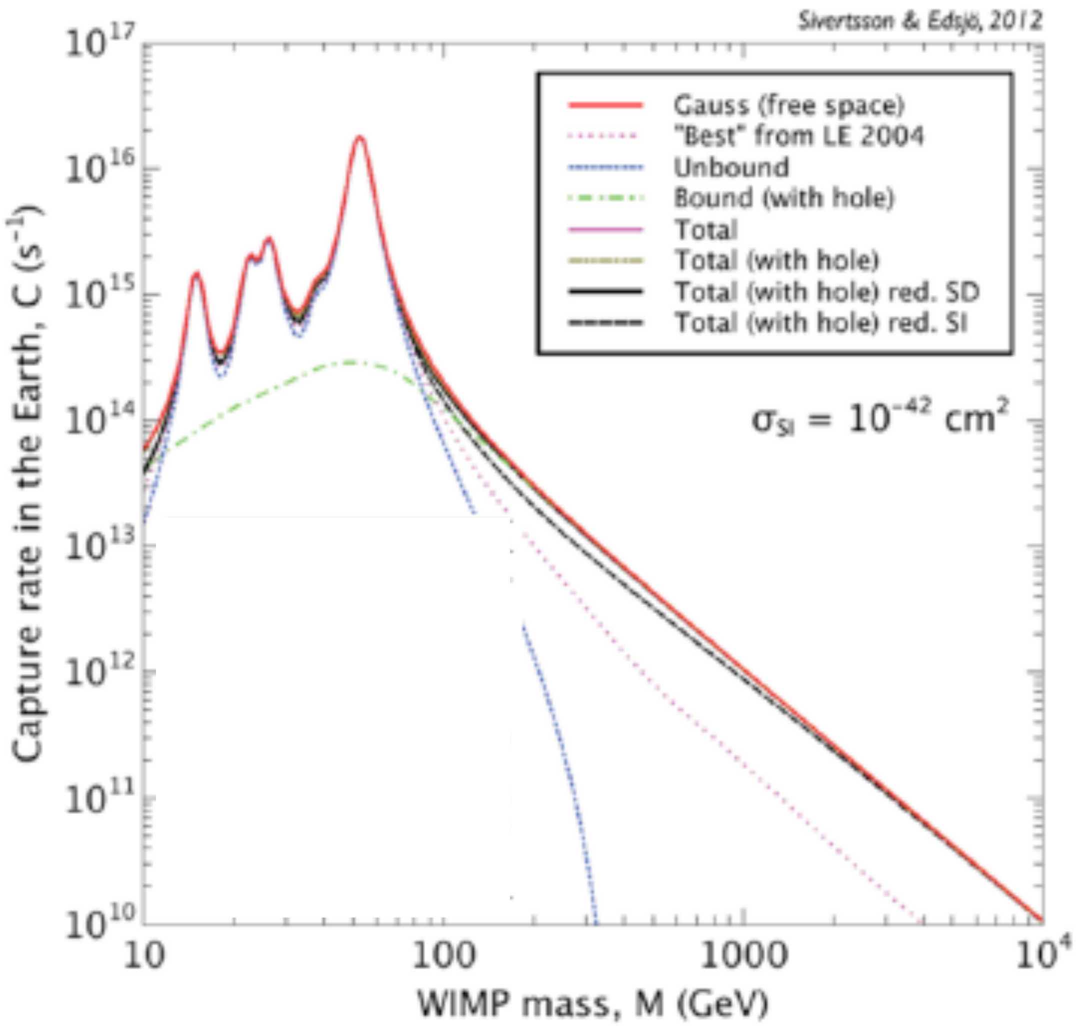
Spin-independent scattering

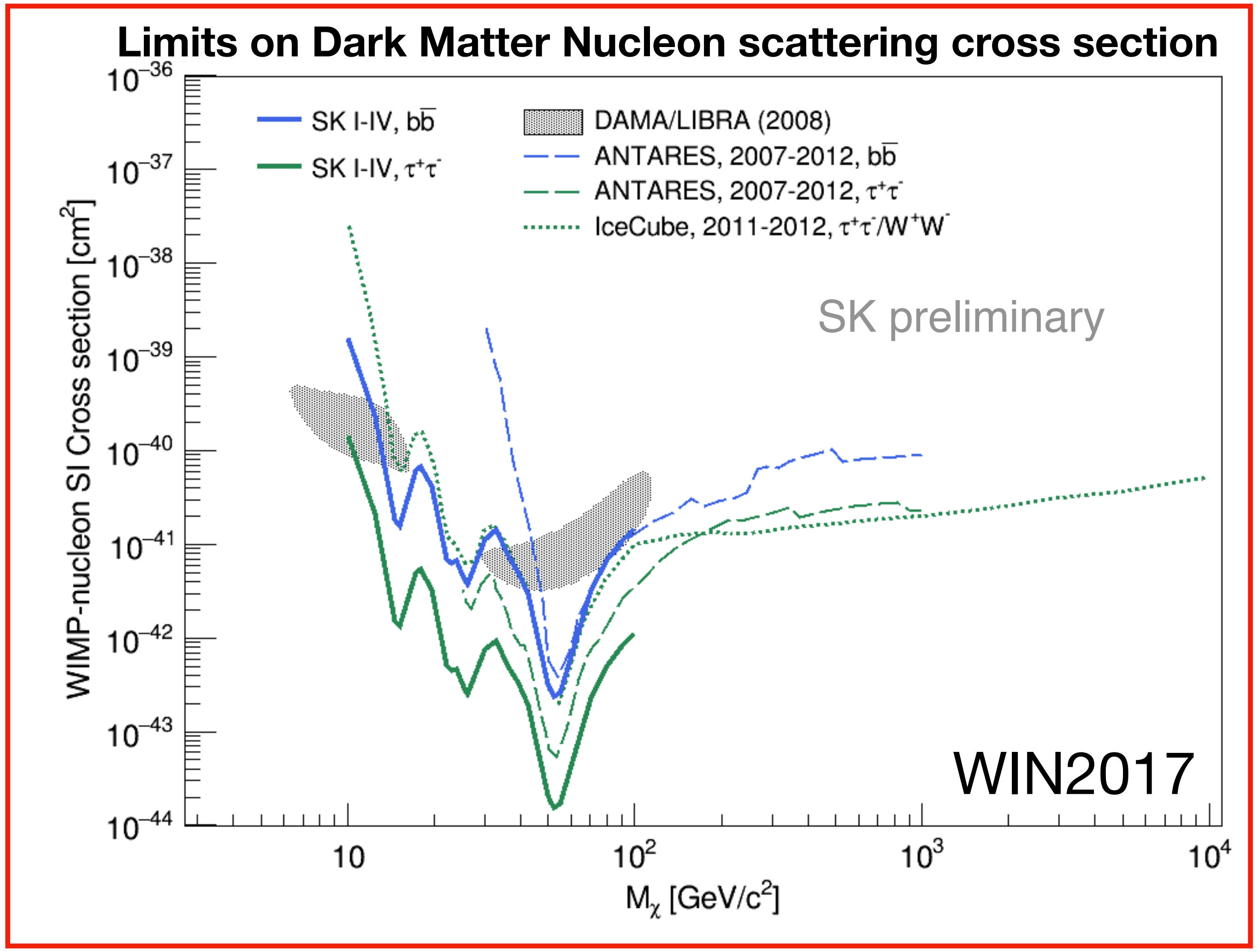


Earth WIMPs

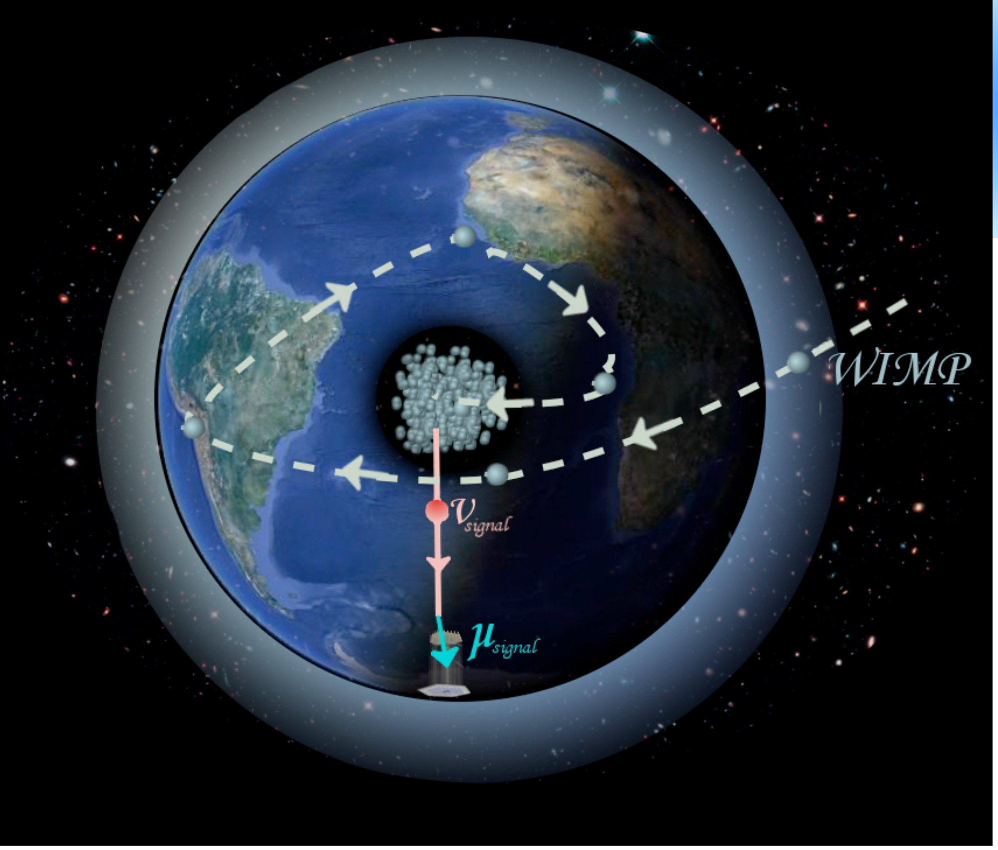


- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- No off-source region

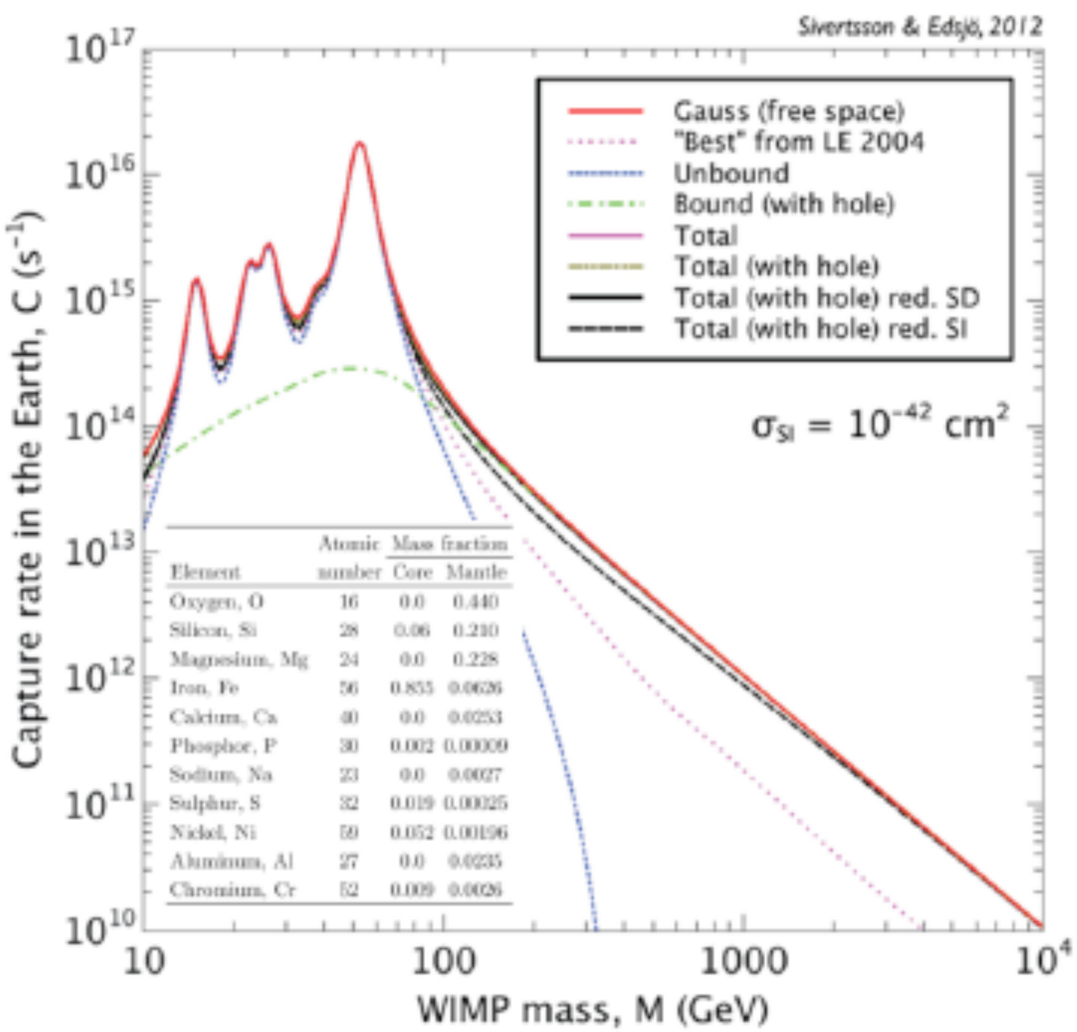




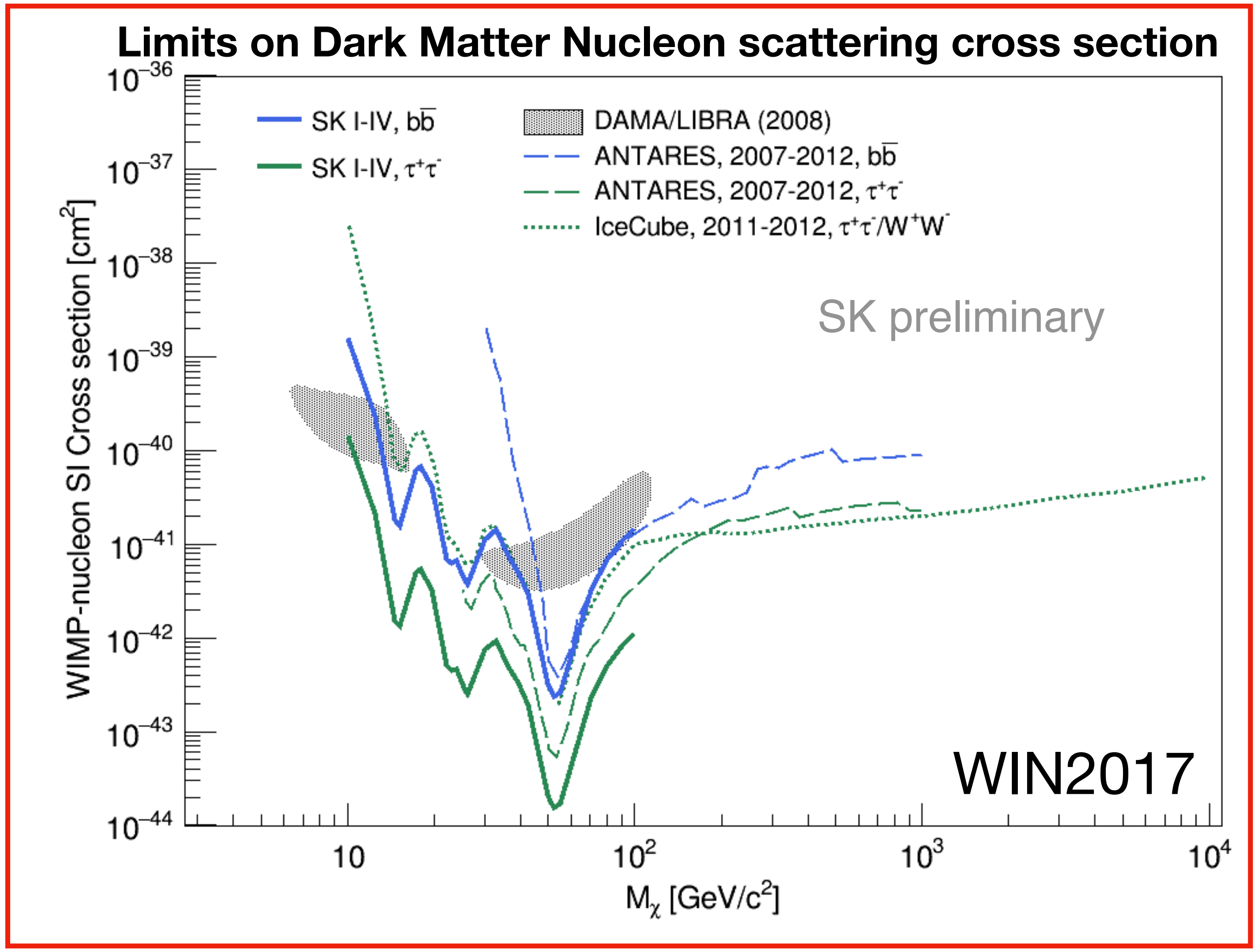
Earth WIMPs



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



Element	Atomic number	Mass fraction Core	Mass fraction Mantle
Oxygen, O	16	0.0	0.440
Silicon, Si	28	0.06	0.210
Magnesium, Mg	24	0.0	0.228
Iron, Fe	56	0.855	0.0626
Calcium, Ca	40	0.0	0.0253
Phosphor, P	30	0.002	0.00009
Sodium, Na	23	0.0	0.0027
Sulphur, S	32	0.019	0.00025
Nickel, Ni	59	0.052	0.00196
Aluminum, Al	27	0.0	0.0235
Chromium, Cr	52	0.009	0.0026



Summary

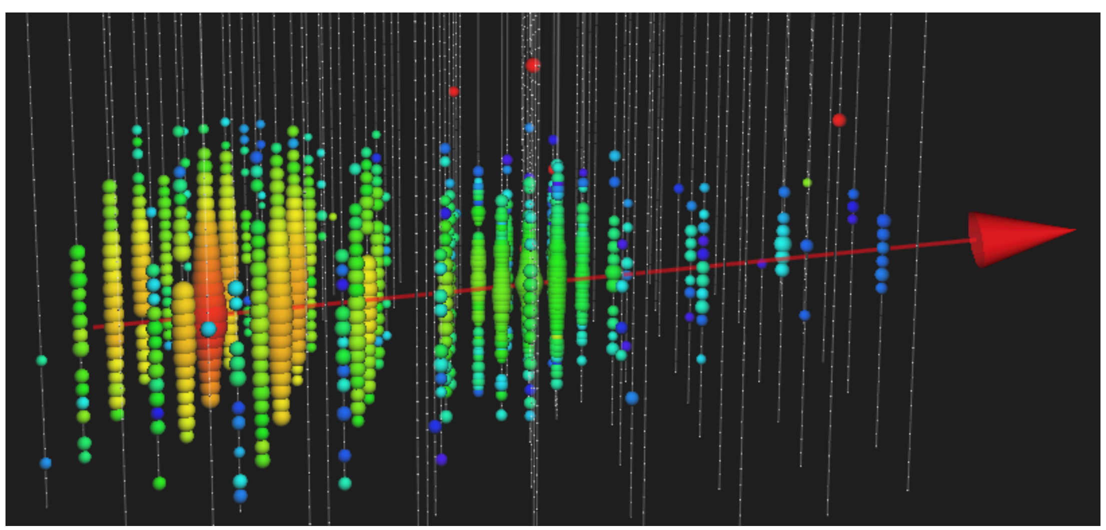
- Neutrino Telescopes are multipurpose experiments with a very diverse science program
- Detection of high-energy astrophysical neutrinos have opened up a new window to the Universe
- The origin of the highest energy neutrinos (and cosmic rays) remains a mystery

Thanks !

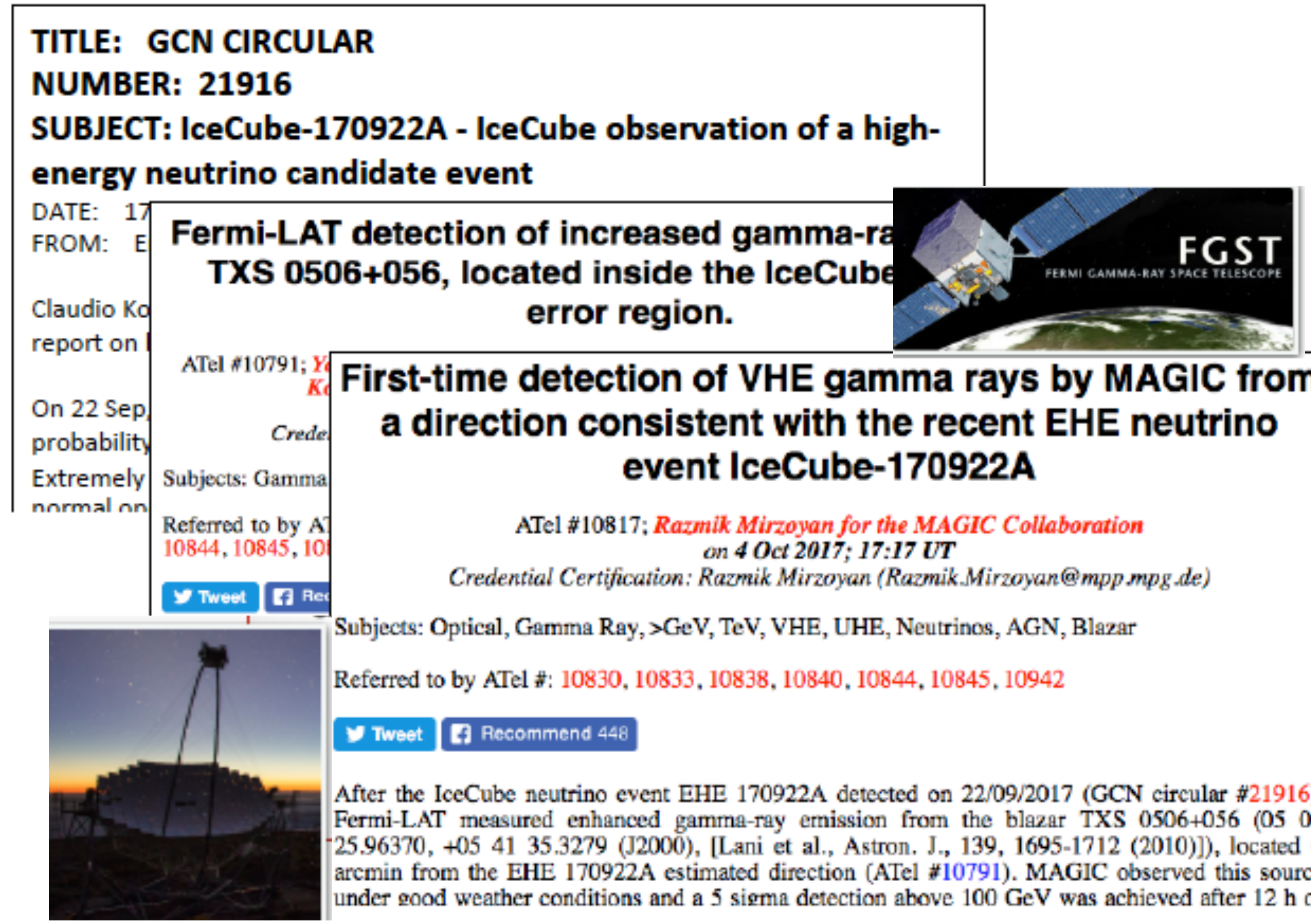
Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056

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



First public ν Alert: IceCube-160427



- 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

Work in progress … more information soon