IceCube

La Palma
15 years of MAGIC

June 27, 2018

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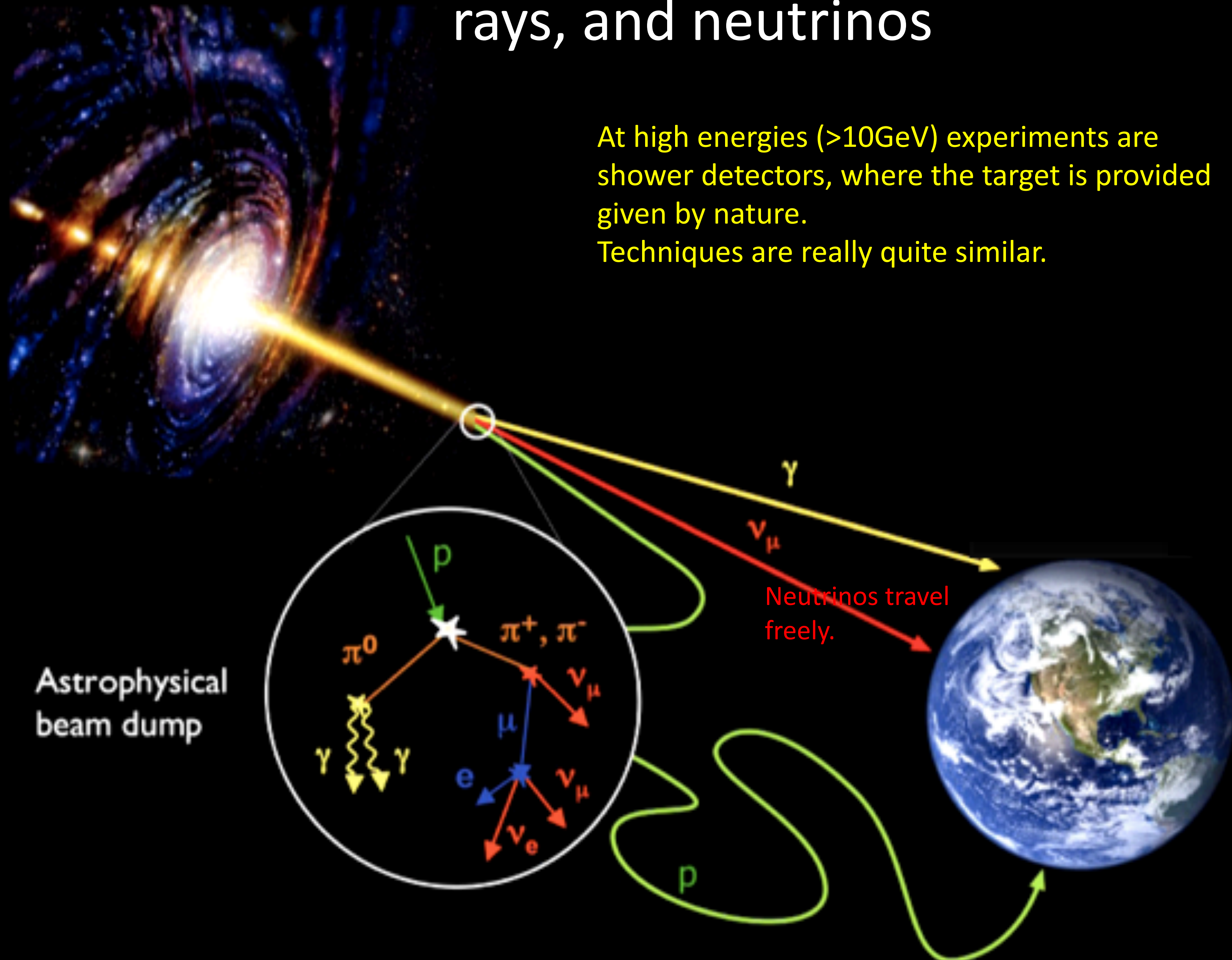
University of Wisconsin-Madison

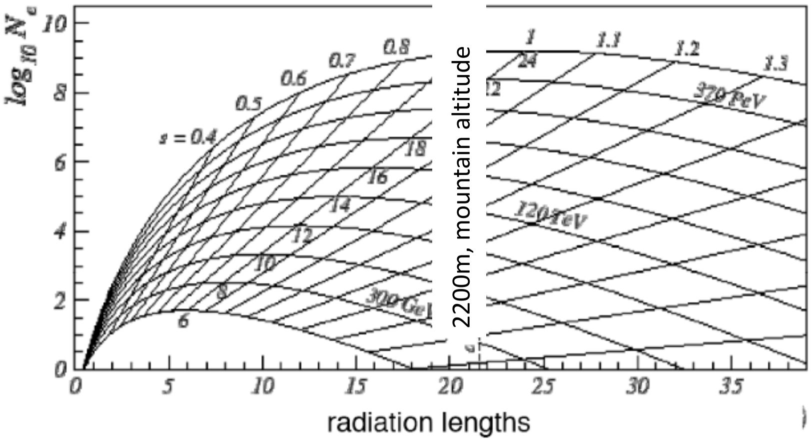
Icecube results for the IceCube collaboration

Detection of cosmic rays, gamma rays, and neutrinos

At high energies (>10GeV) experiments are shower detectors, where the target is provided given by nature.
Techniques are really quite similar.



Shower development and modes of observation: Tail catchers and fully active calorimeters



Rossi, 1965

Cherenkov, fluorescence, radio detectors can see whole shower.

Particle detectors on ground are tail catchers (or shower max samplers if energy or altitude high enough)

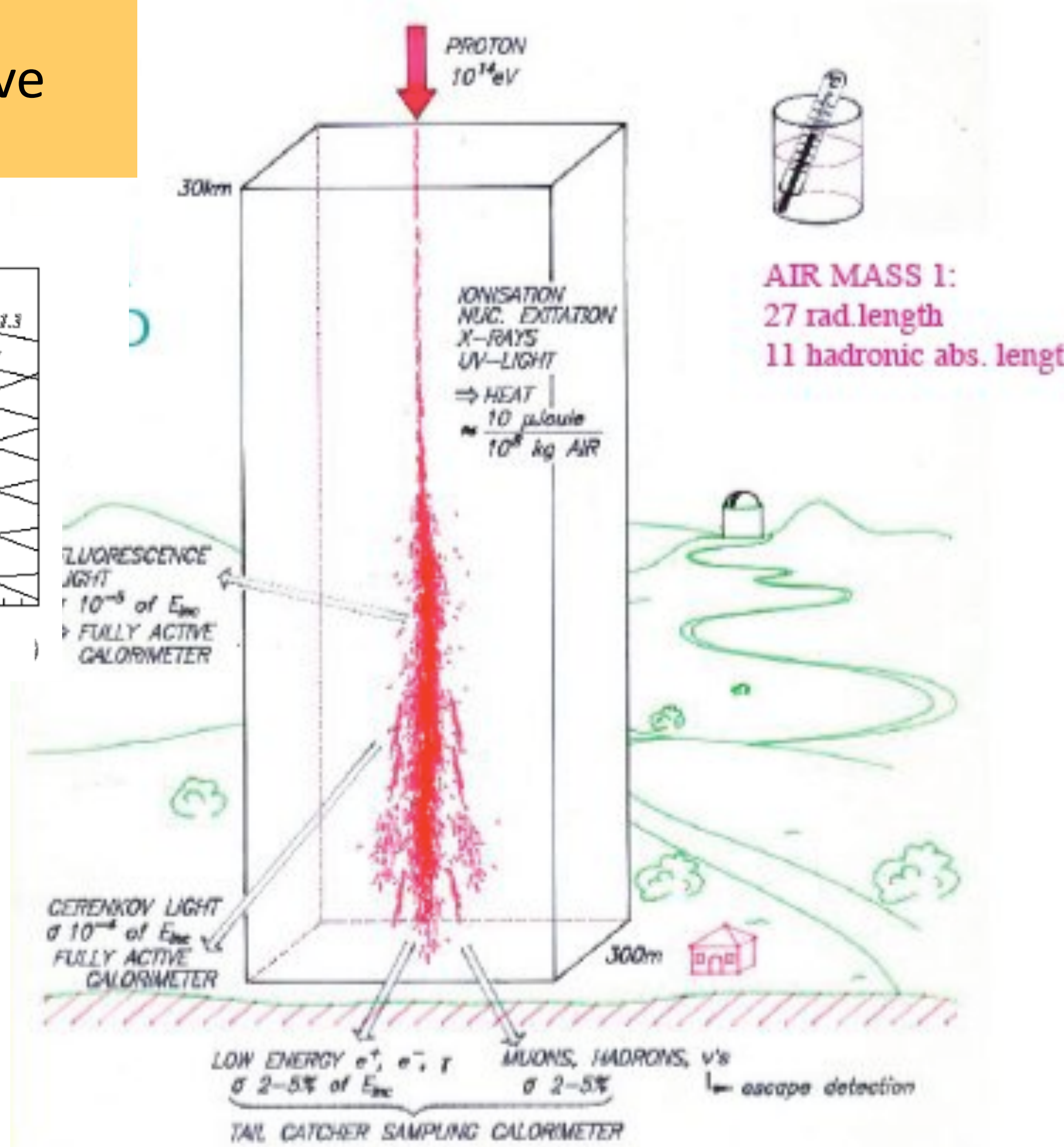
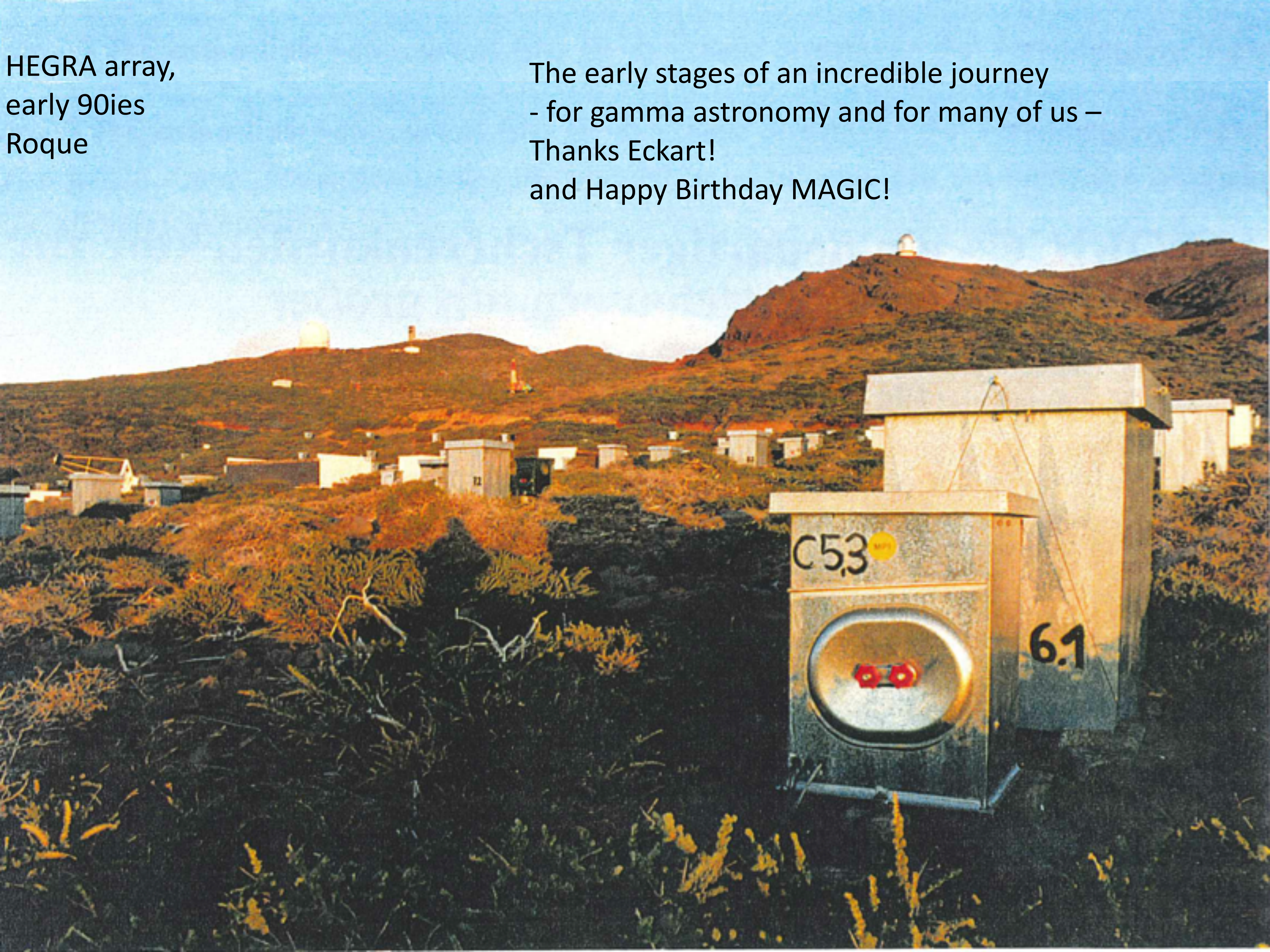
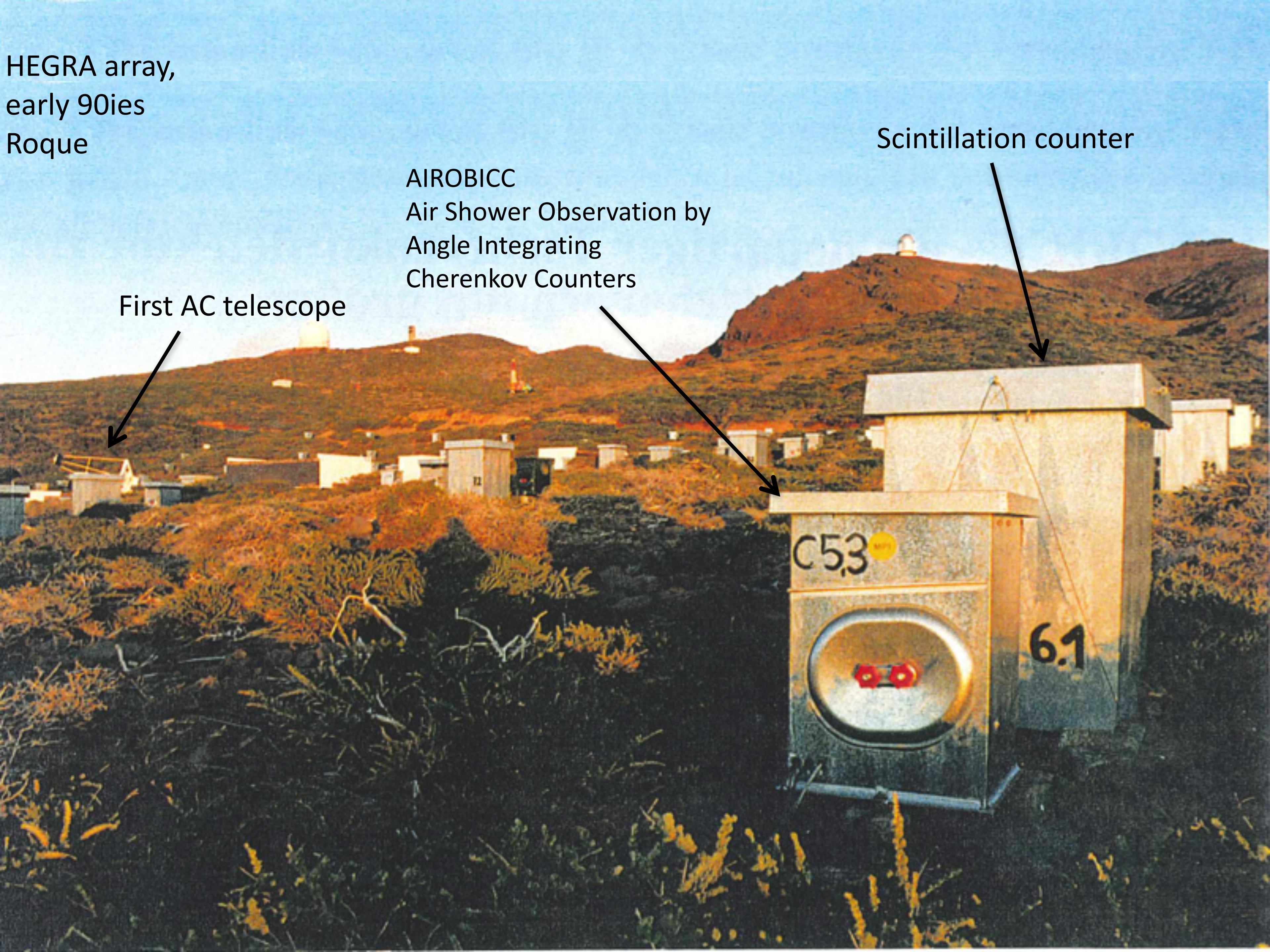


Figure: E. Lorenz

HEGRA array,
early 90ies
Roque

The early stages of an incredible journey
- for gamma astronomy and for many of us –
Thanks Eckart!
and Happy Birthday MAGIC!




HEGRA array,
early 90ies
Roque
Scintillation counter
AIROBICC
Air Shower Observation by
Angle Integrating
Cherenkov Counters
First AC telescope
C53
6.1

HEGRA array,
early 90ies
Roque

AIROBICC
Air Shower Observation by
Angle Integrating
Cherenkov Counters

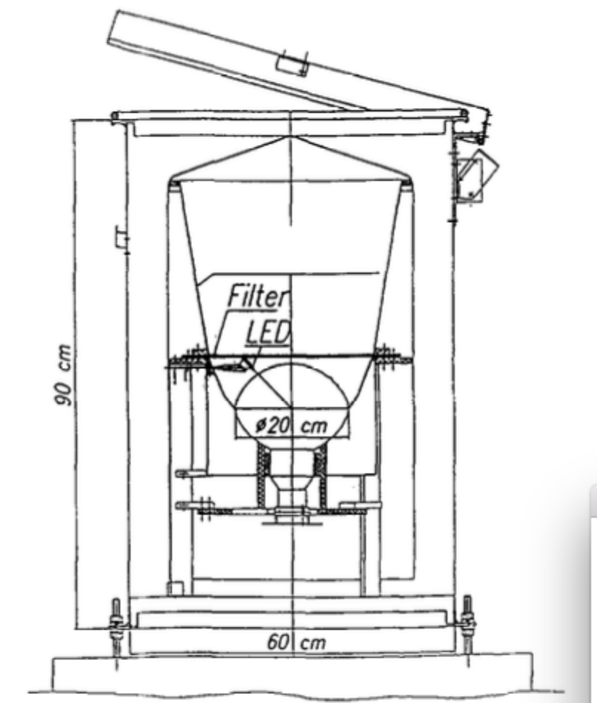
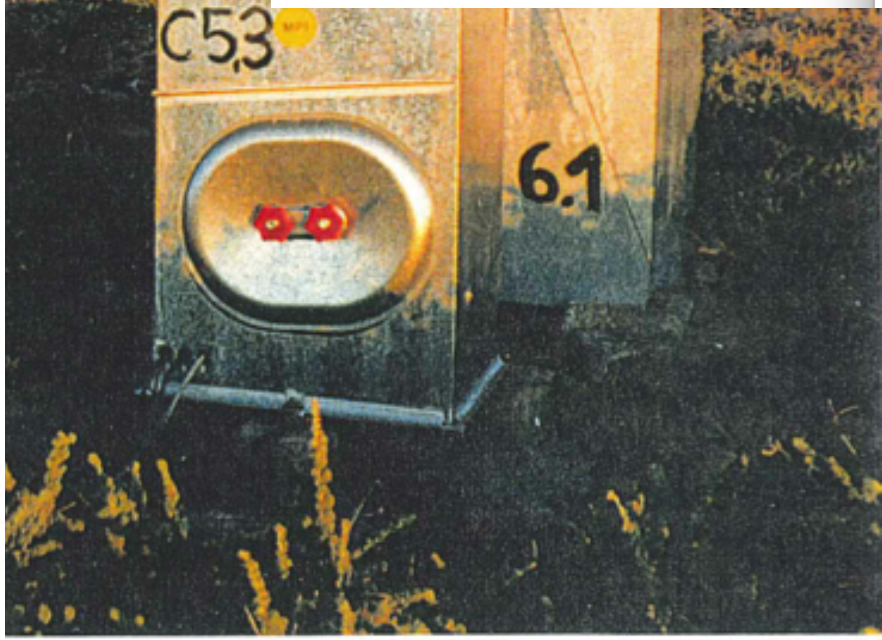
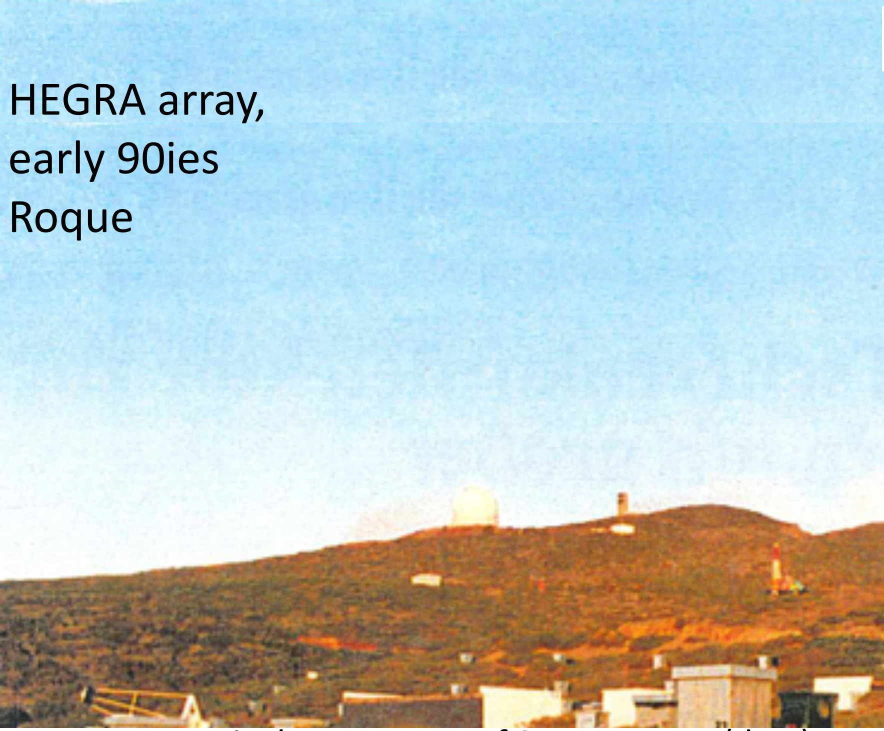


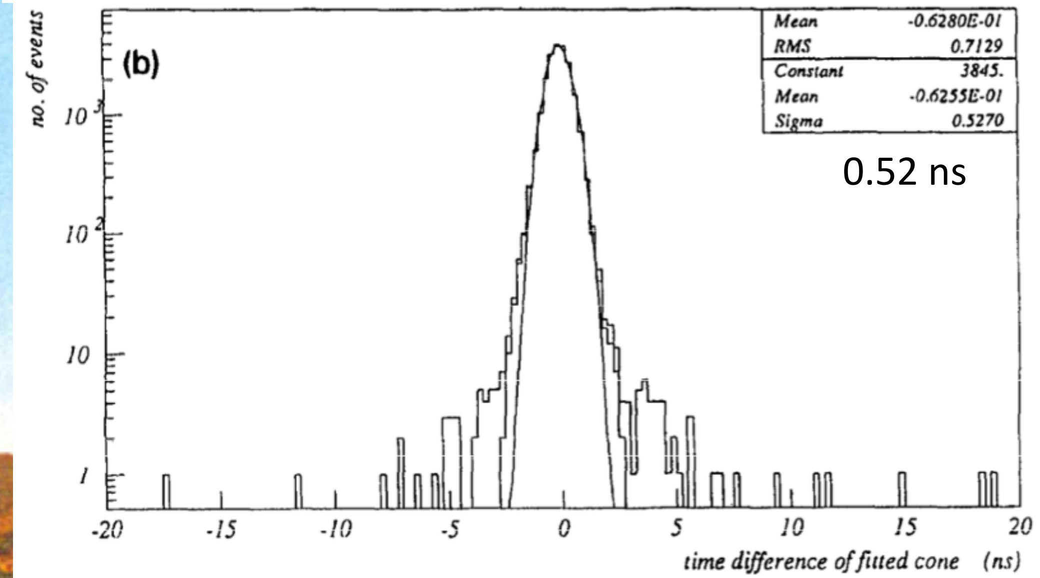
Fig. 5. Sectional drawing of an AIROBICC hut. The protecting lid is shown in a half opened position.



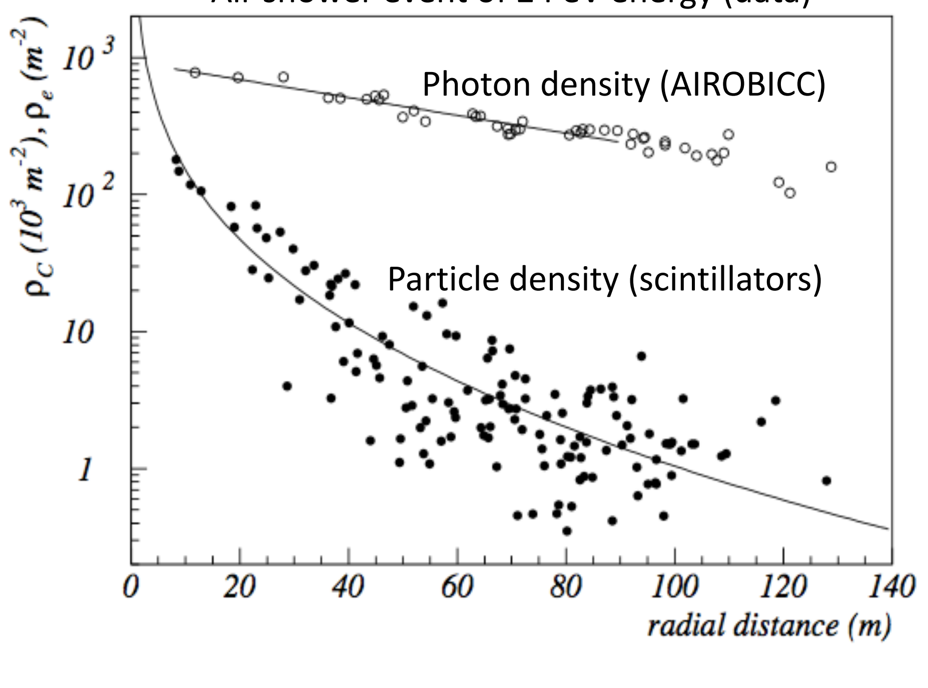
HEGRA array, early 90ies Roque

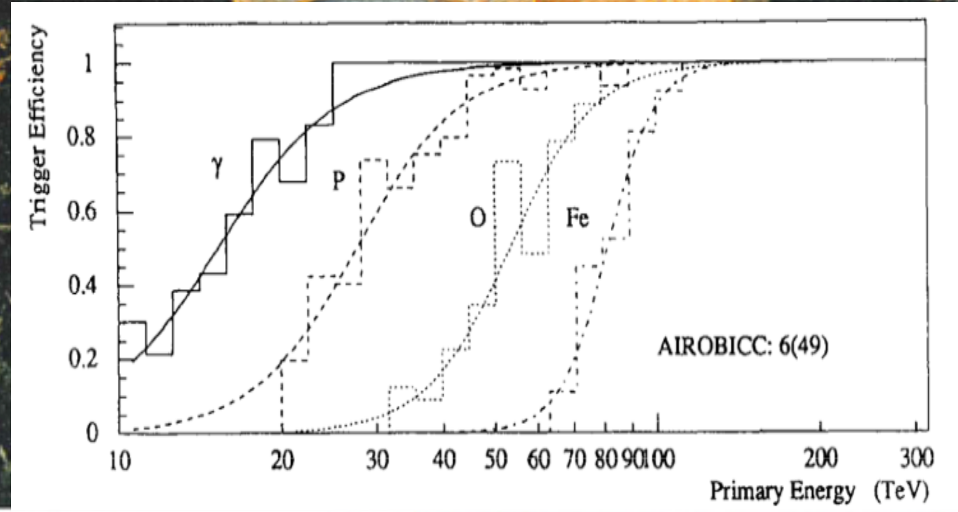


Time spread of measured arrival times vs cherenkov cone fit



Air shower event of 2 PeV energy (data)





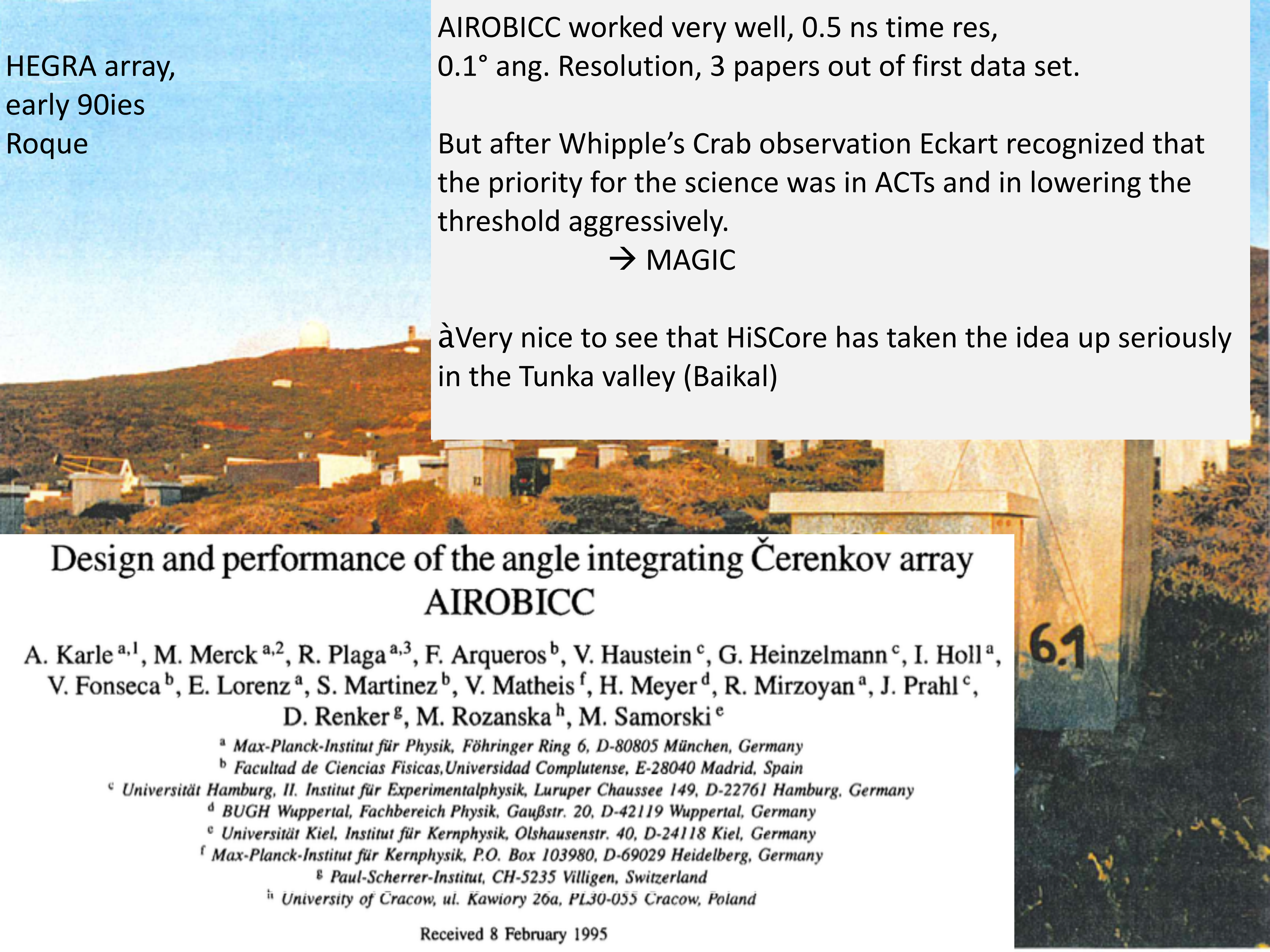
HEGRA array,
early 90ies
Roque

AIROBICC worked very well, 0.5 ns time res,
0.1° ang. Resolution, 3 papers out of first data set.

But after Whipple's Crab observation Eckart recognized that the priority for the science was in ACTs and in lowering the threshold aggressively.

→ MAGIC

àVery nice to see that HiSCore has taken the idea up seriously in the Tunka valley (Baikal)



Design and performance of the angle integrating Čerenkov array AIROBICC

A. Karle [a,1], M. Merck [a,2], R. Plaga [a,3], F. Arqueros [b], V. Haustein [c], G. Heinzelmann [c], I. Holl [a], V. Fonseca [b], E. Lorenz [a], S. Martinez [b], V. Matheis [f], H. Meyer [d], R. Mirzoyan [a], J. Prahl [c], D. Renker [g], M. Rozanska [h], M. Samorski [e]

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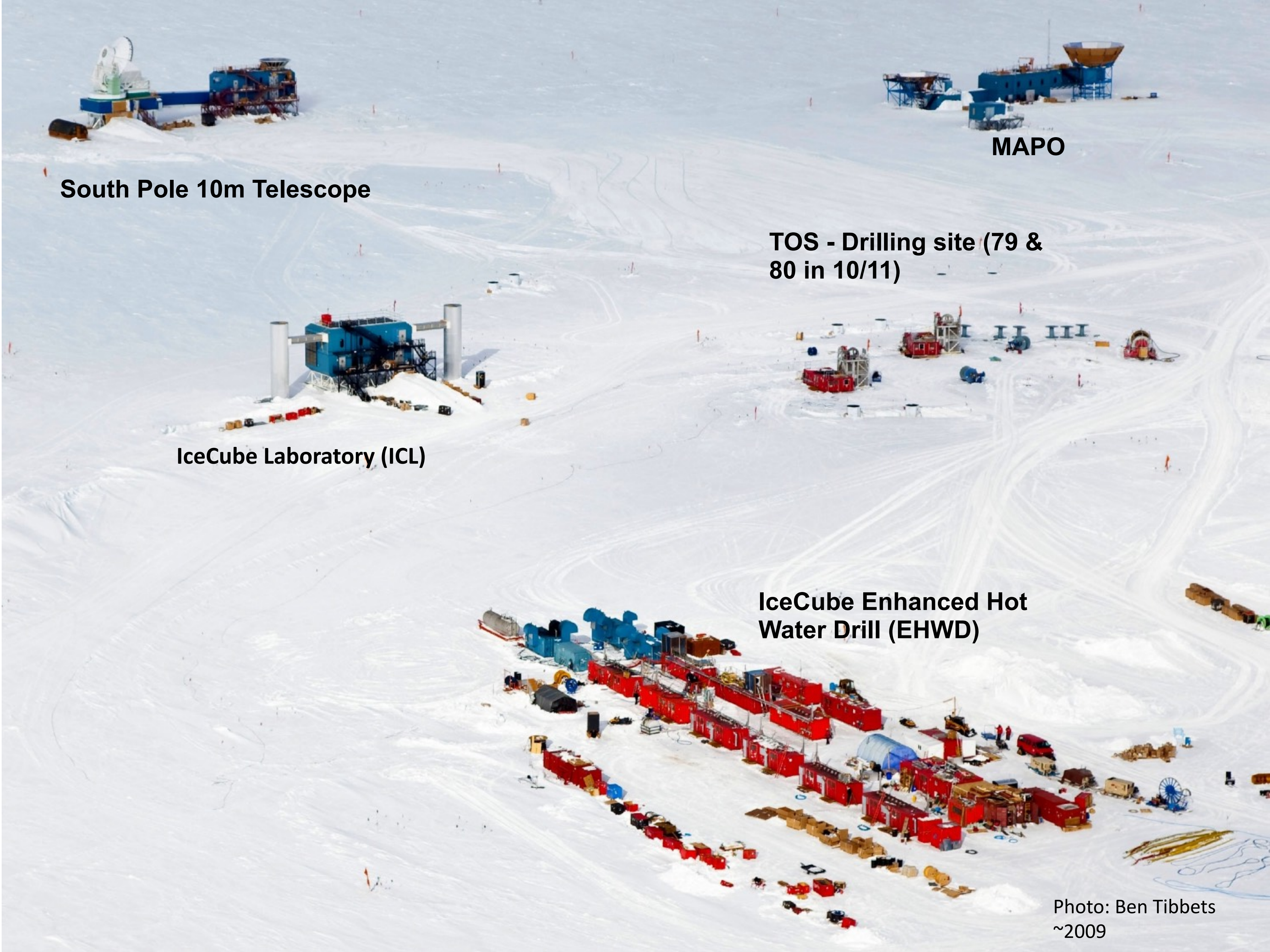
[f] Max-Planck-Institut für Kernphysik, P.O. Box 103980, D-69029 Heidelberg, Germany
[g] Paul-Scherrer-Institut, CH-5235 Villigen, Switzerland
[h] University of Cracow, ul. Kawiory 26a, PL30-055 Cracow, Poland

Received 8 February 1995

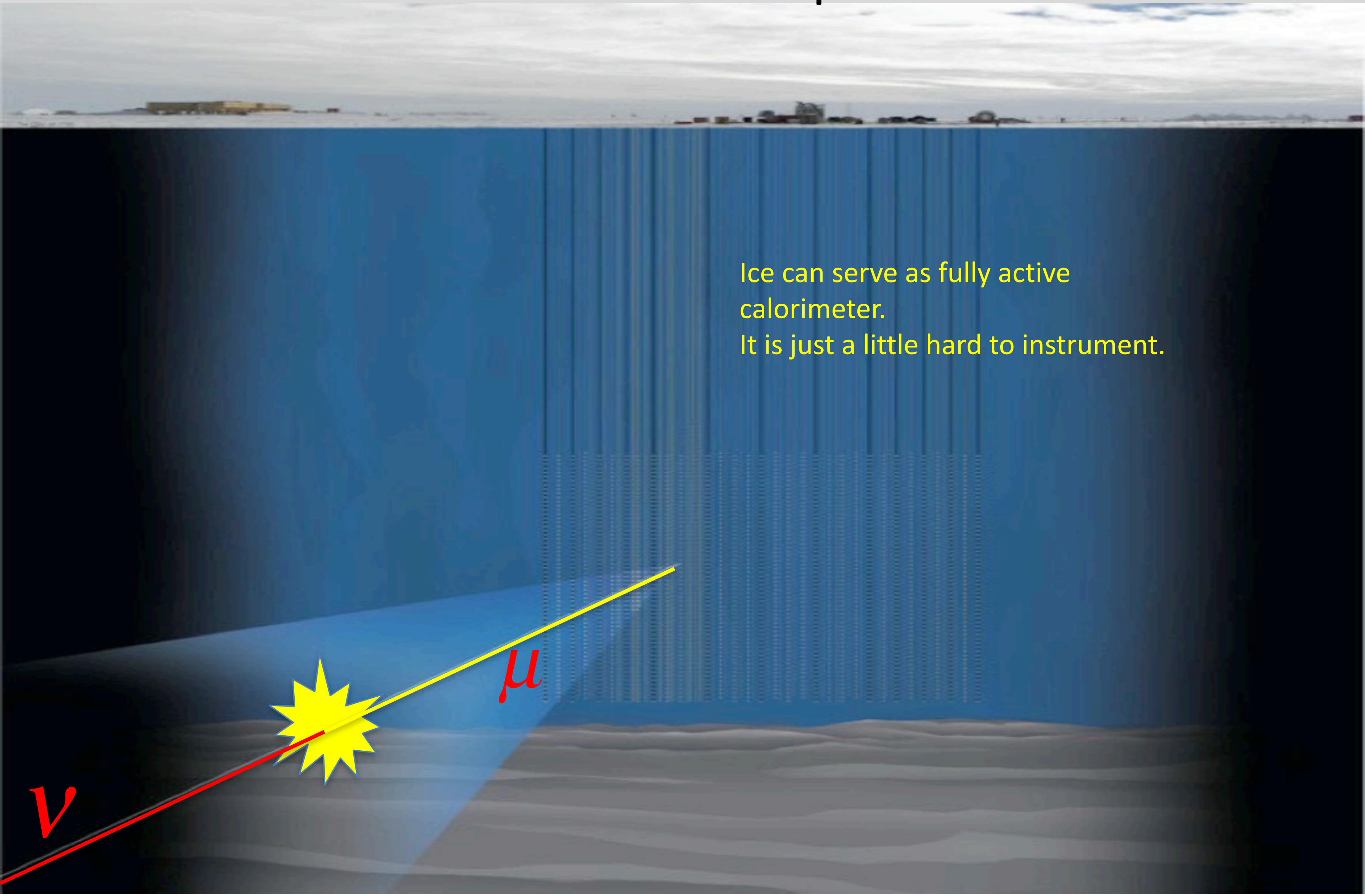
1999/2000: AMANDA-II drill site


South Pole 10m Telescope
MAPO
TOS - Drilling site (79 & 80 in 10/11)
IceCube Laboratory (ICL)
IceCube Enhanced Hot Water Drill (EHWD)
Photo: Ben Tibbets ~2009

AMANDA and IceCube deployments

Season	Campaign	Cum Sensors	Cum Strings	Depth	Neutrinos/yr	resolution at 100TeV
1992	exploratory activity	few small PMT		shallow depth	0	
1993						
1994	AMANDA-A	80	4	800-1000m	0	
1995						
1996	AMANDA-B4	86	4	1500-1950	2 (unpubl.)	
1997	AMANDA-B10	206	6/10	1500-1950	100	4 deg
1998						
1999	AMANDA-II	306	3/13	1500-1950		
2000	AMANDA-II	677	6/19	1500-1950	1000	2 deg
2001						
2002						
2003/2004	IceCube prep.					
2004/2005	IceCube 1	60	1/1	1450-2450m		
2005/2006	IceCube 9		8/9	1450-2450m		
2006/2007	IceCube 22		13/22	1450-2450m	14000	~0.7 deg
2007/2008	IceCube 40	2400	18/40	1450-2450m		
2008/2009	IceCube 59		19/59	1450-2450m	35000	
2009/2010	IceCube 79		20/79	1450-2450m	>50k	~0.4 deg
2010/2011	IceCube 86	5160	7/86	1450-2450m	>50k	

Cherenkov detection works also for neutrino telescopes in ice



IceCube Neutrino Observatory

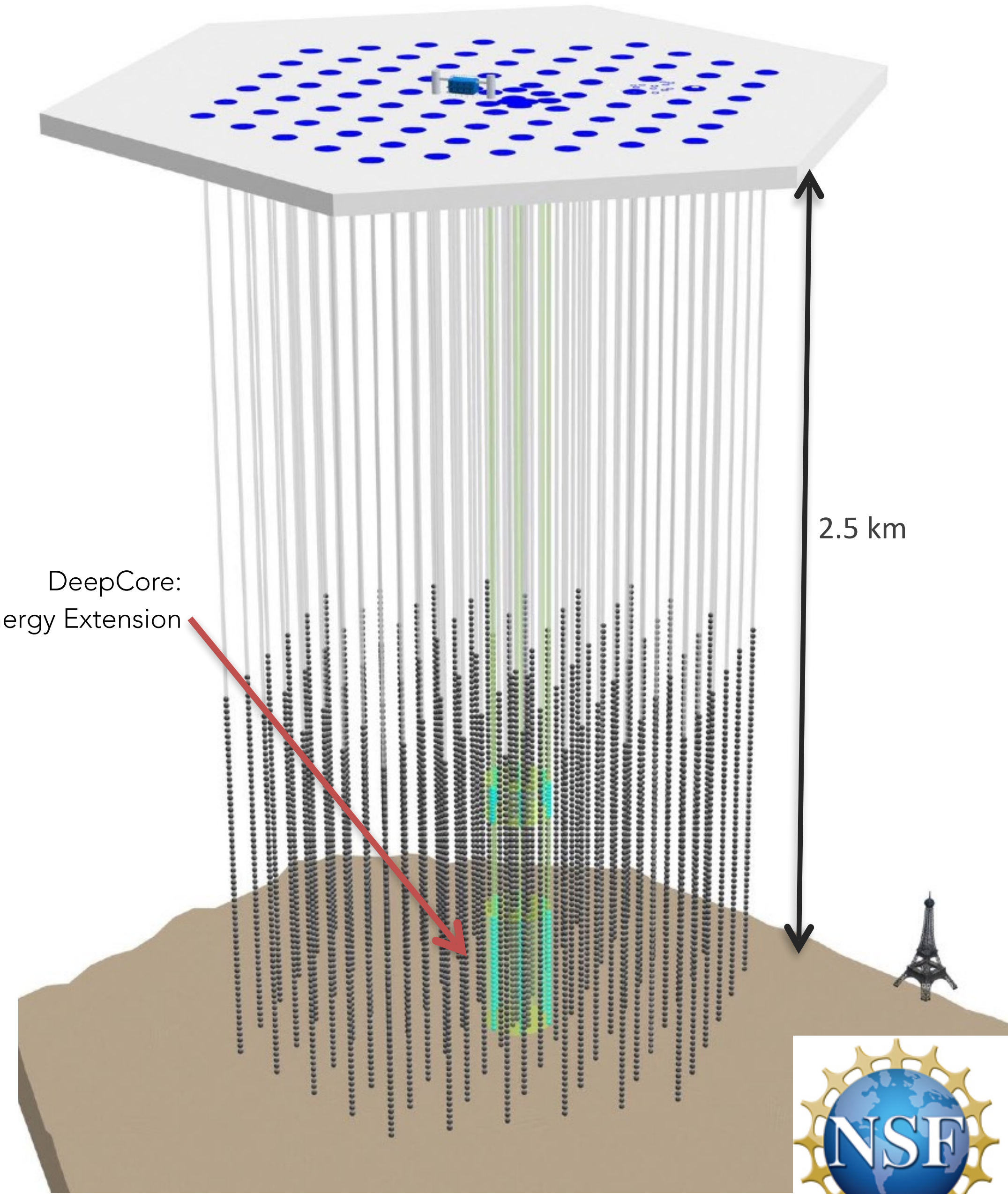
86 strings

60 Optical Modules per string

5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

Began full operations May 2011



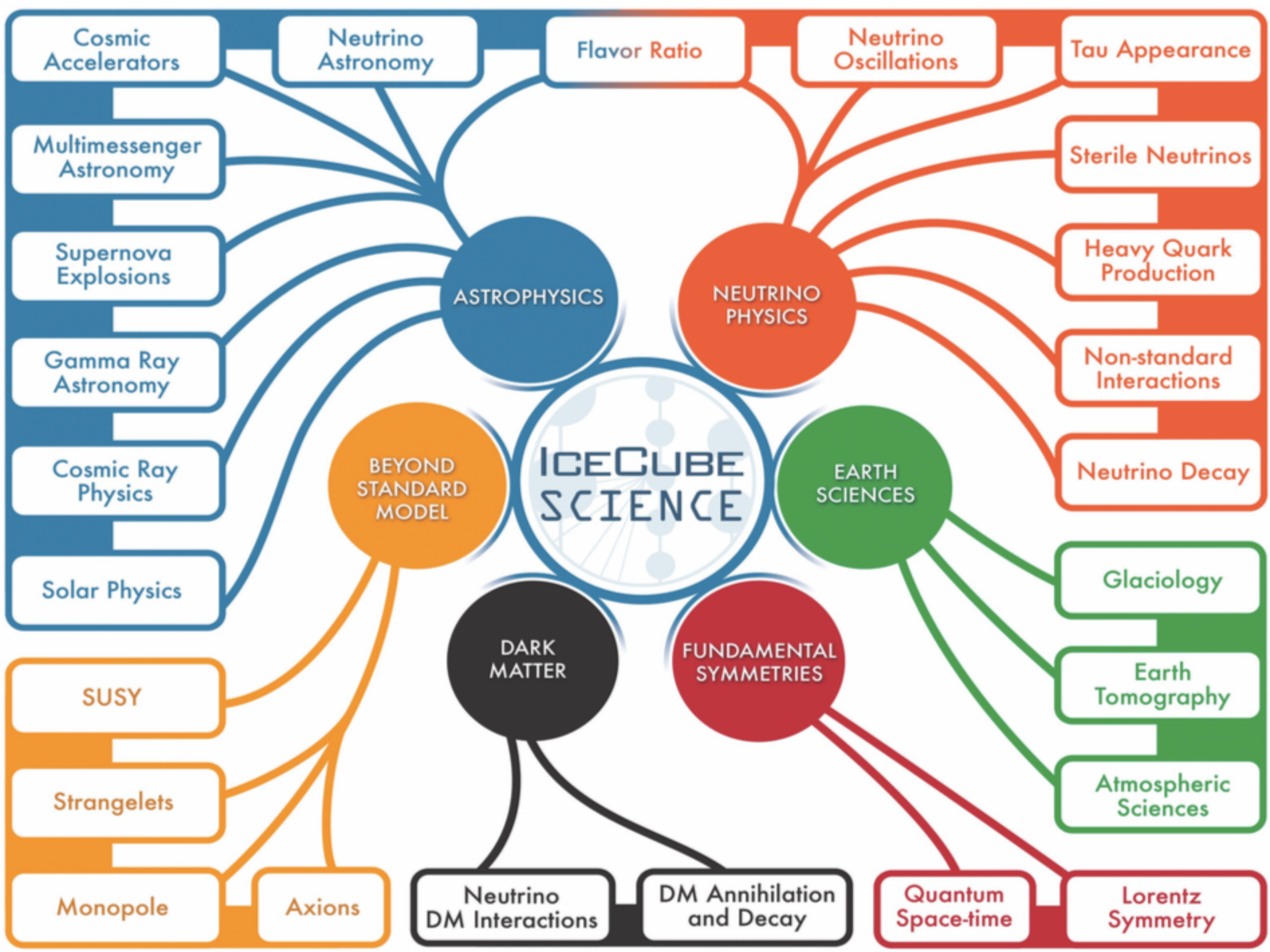
Highly stable operation.

Since 2016: livetime > 99.5%

clean-uptime 97-98%

(analysis-ready,
full-detector data)

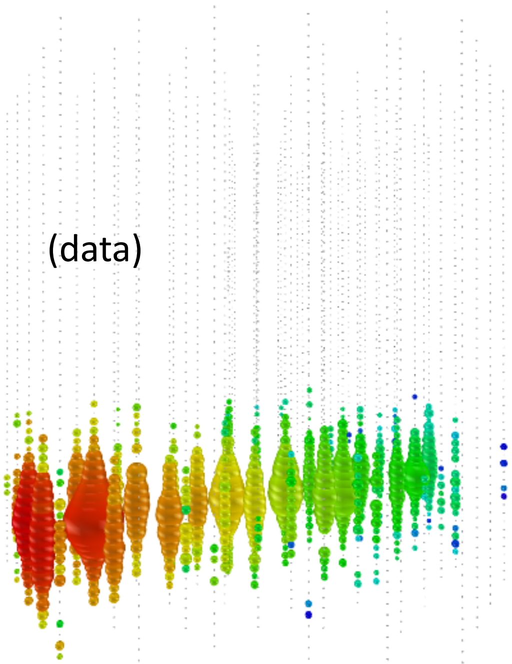
IceCube

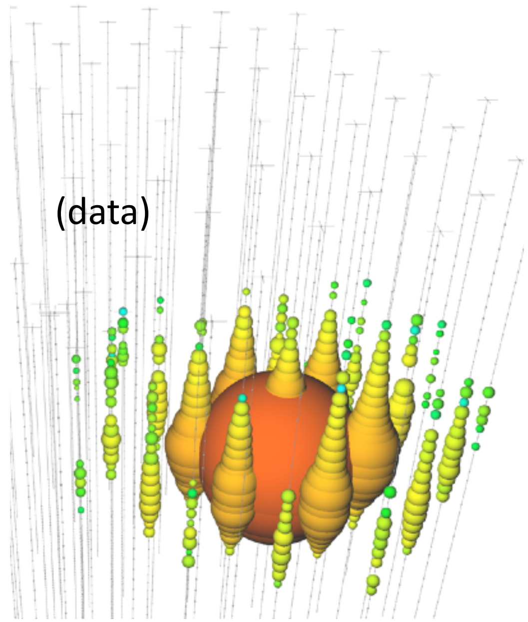


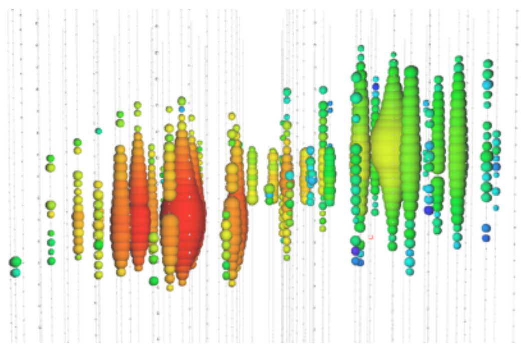
Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
ASTROPHYSICS
NEUTRINO PHYSICS
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
BEYOND STANDARD MODEL
ICECUBE SCIENCE
EARTH SCIENCES
Neutrino Decay
Solar Physics
Glaciology
DARK MATTER
FUNDAMENTAL SYMMETRIES
SUSY
Earth Tomography
Strangelets
Atmospheric Sciences
Monopole
Axions
Neutrino DM Interactions
DM Annihilation and Decay
Quantum Space-time
Lorentz Symmetry

Types of events and interactions

Charged-current ν_μ	**Neutral-current / ν_e**	**Charged-current ν_τ**
(data)	(data)	(simulation)







Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

0.3° above 100 TeV

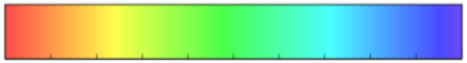
Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10-15° angular resolution (above 100 TeV)
Working on improving that.

"Double-bang"

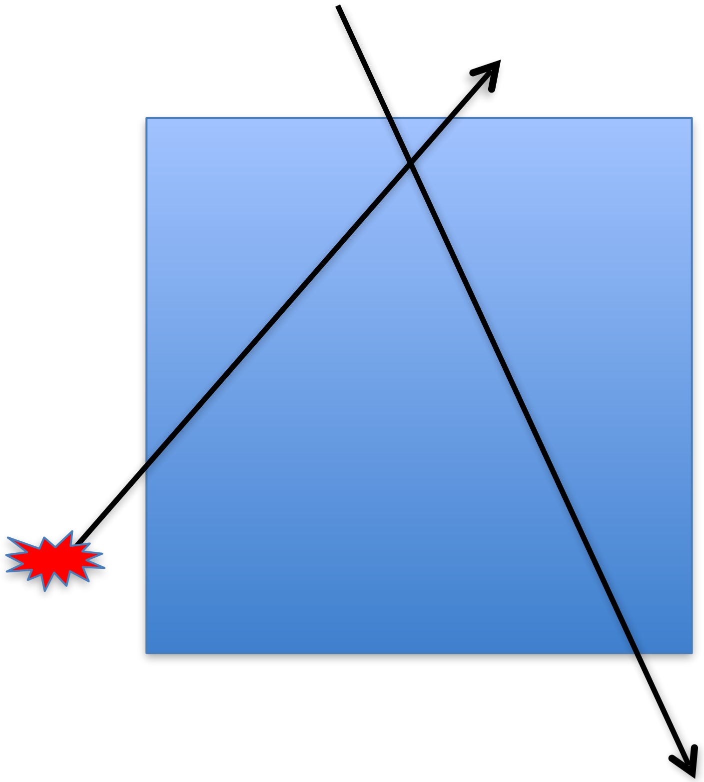
(none observed yet: τ decay length is 50 m/PeV)

ID: above~ 100 TeV (two methods)

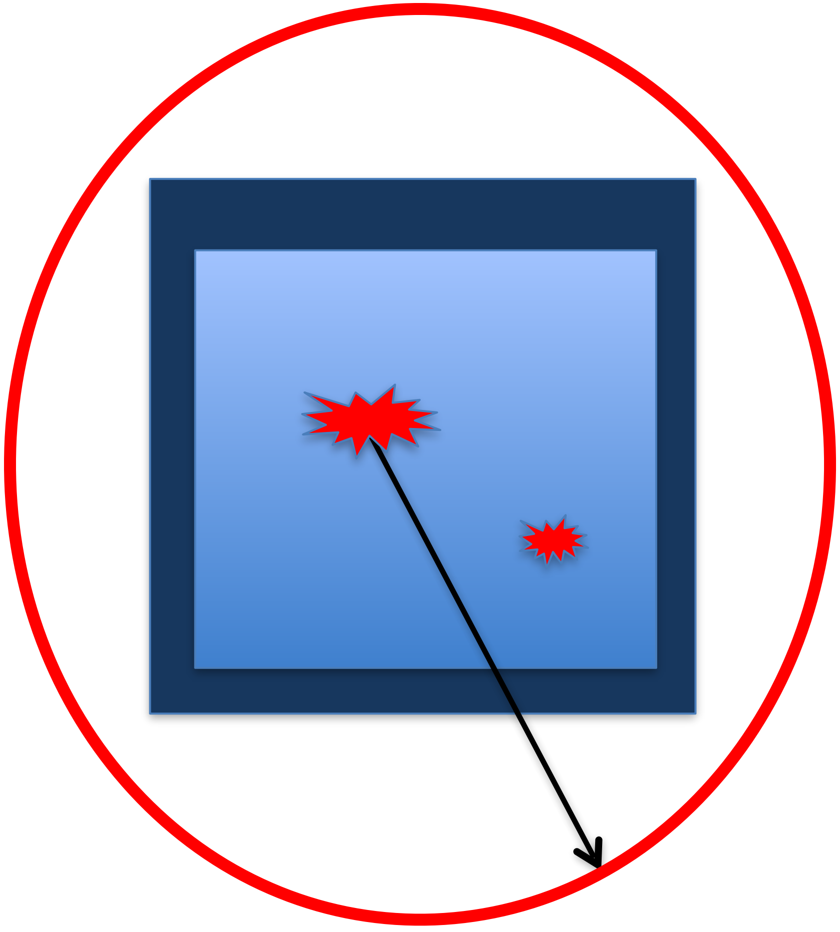
Early  Late

Event selection strategies

Throughgoing muons



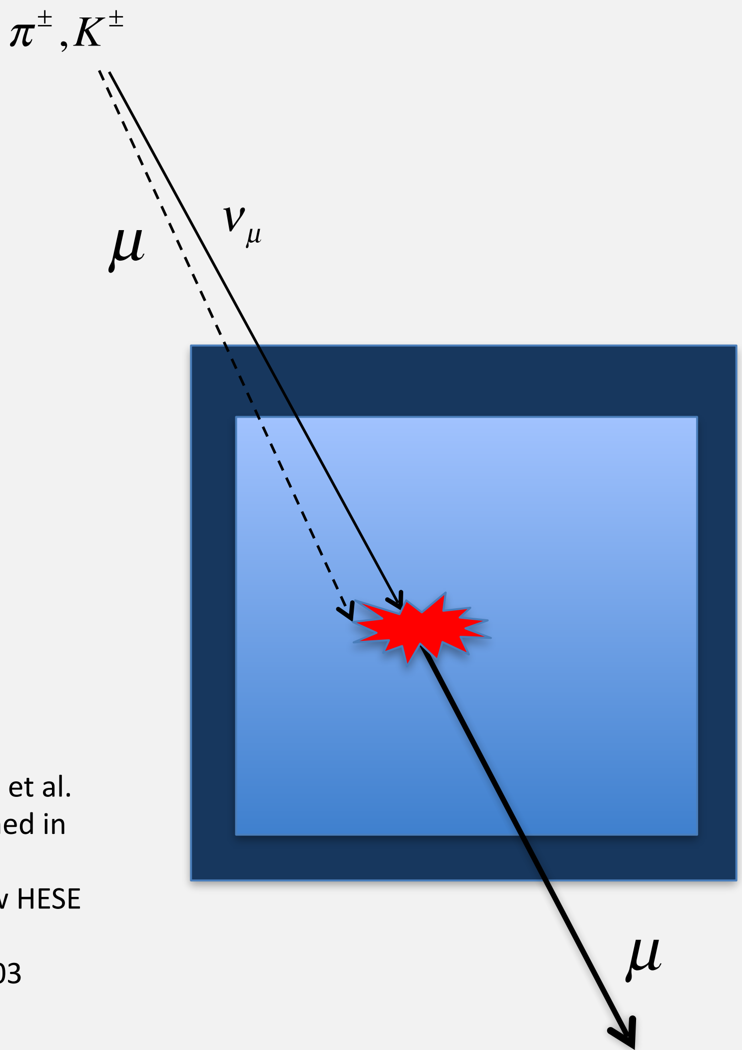
Events with contained vertex



Neutrino self veto –
Rejecting cosmic ray muons AND atmospheric neutrinos

for zenith angles < 60° and above some energy (10 to 30 TeV)

- "Atmospheric neutrinos" are generated in cosmic ray air showers.
- Above some neutrino energy, ~100 TeV, these neutrinos will likely be accompanied by one or more muons from parent air shower.
- Those muons can be used to veto atmospheric neutrino background.



Works also for electron neutrinos.

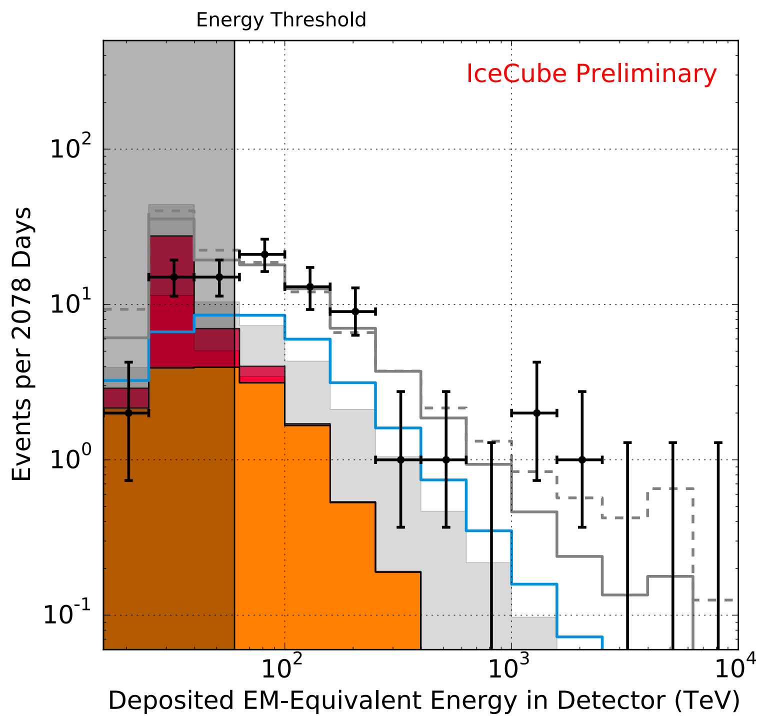
Suggested by Schoenert et al.
Phys.Rev. D79 (2009) 043009
arXiv:0812.4308

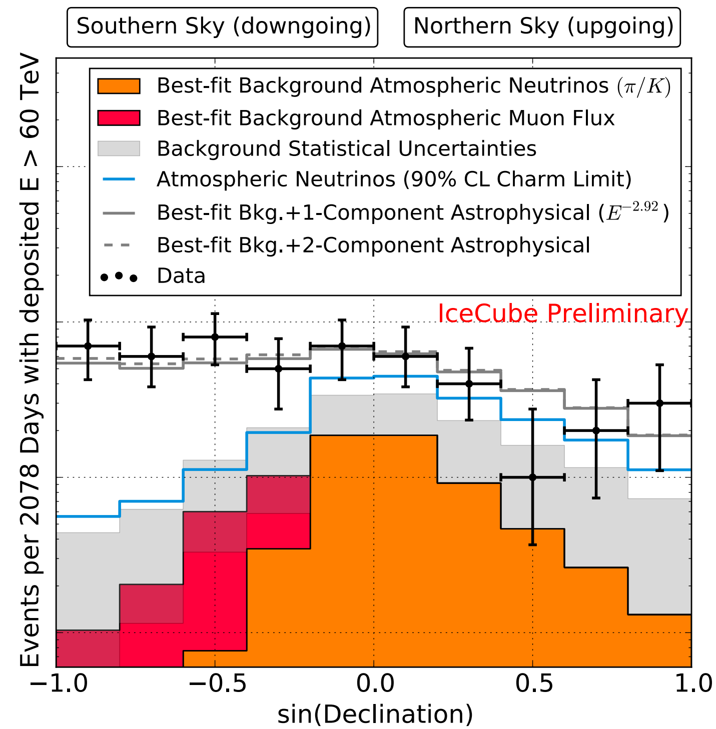
T. Gaisser, K. Jero, AK and J. v. Santen
arXiv:1405.0525

New work by T. Yuan, Arguelles, et al. largely agrees veto levels assumed in IceCube analysis.
Updated method applied in new HESE results
https://arxiv.org/abs/1805.11003

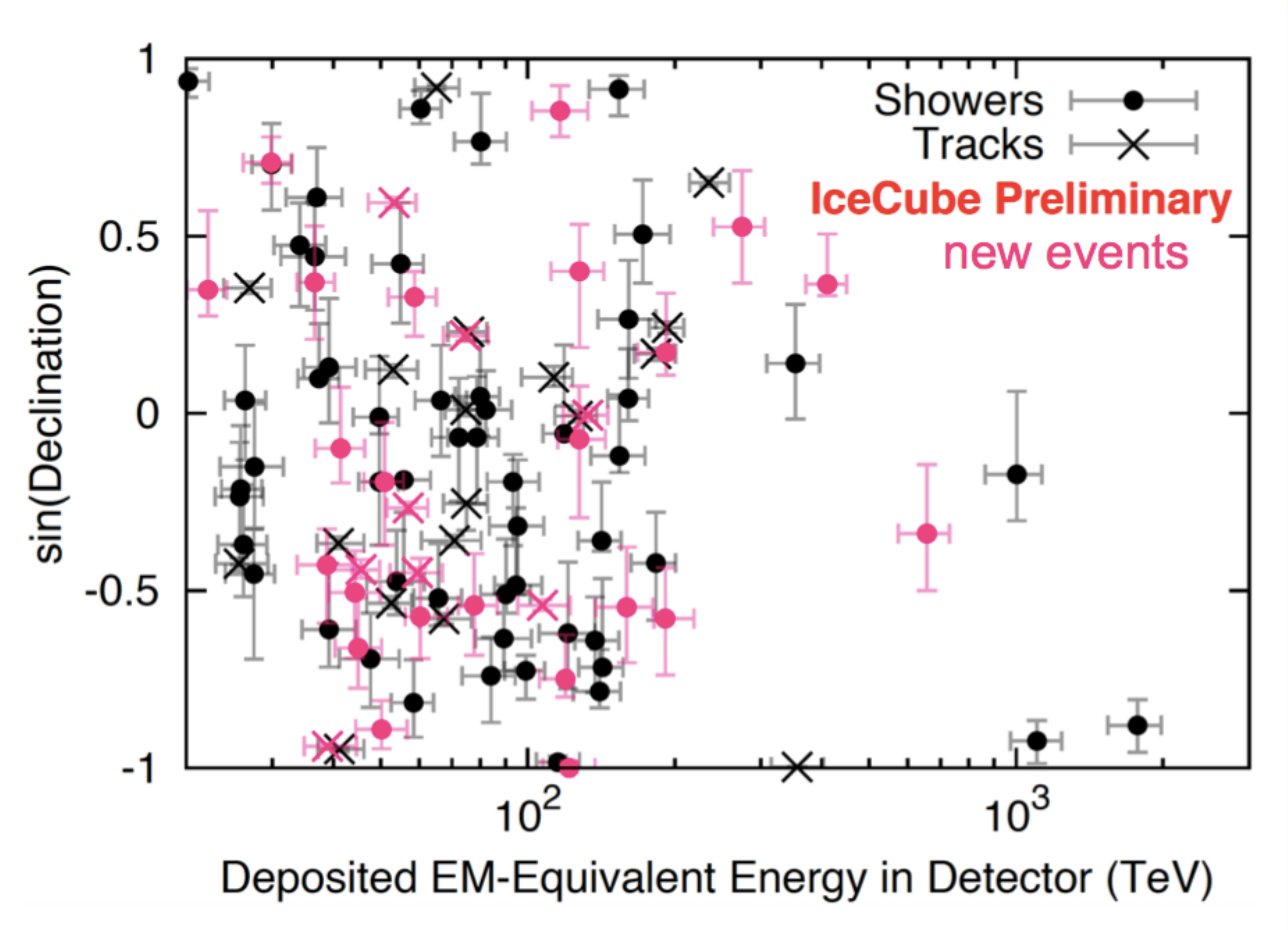
6-yr astrophysical

- Best-fit: $\phi = 2.46 \pm 0.8 \times 10^{-18}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1} , $\gamma = -2.92 \pm 0.3$
- Background-only hypothesis rejected by $\sim 8\sigma$



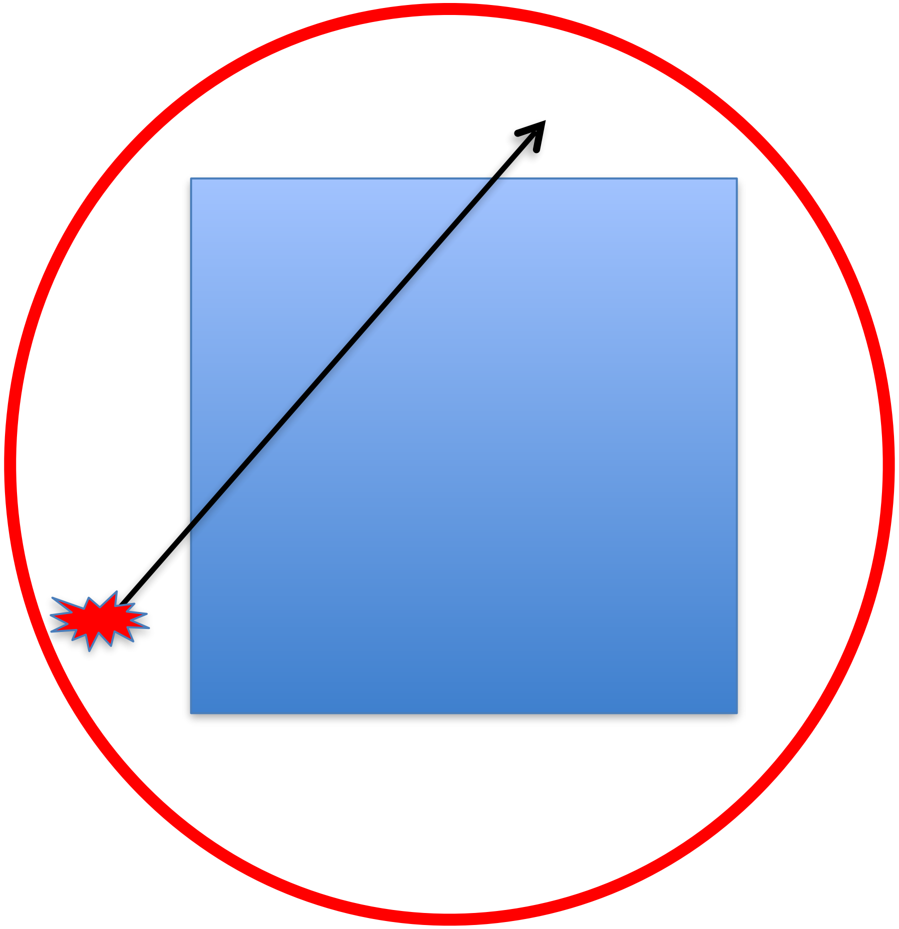


7.5 years of events with contained vertex (HESE)

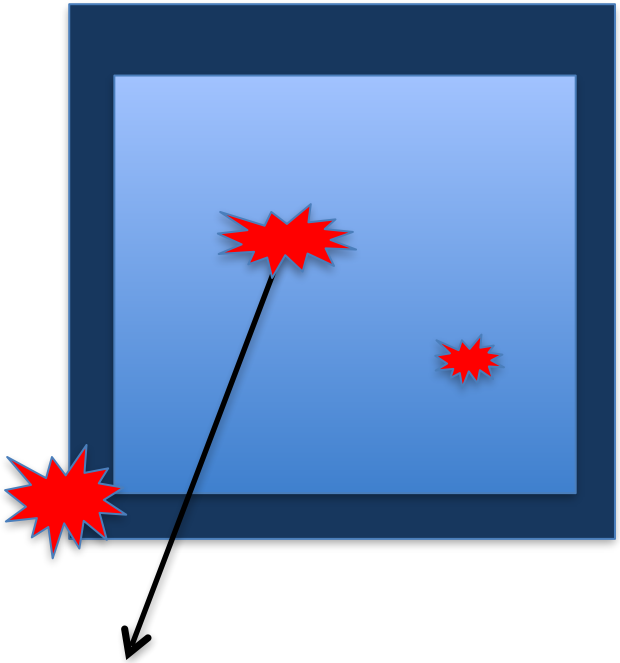


Event selection strategies

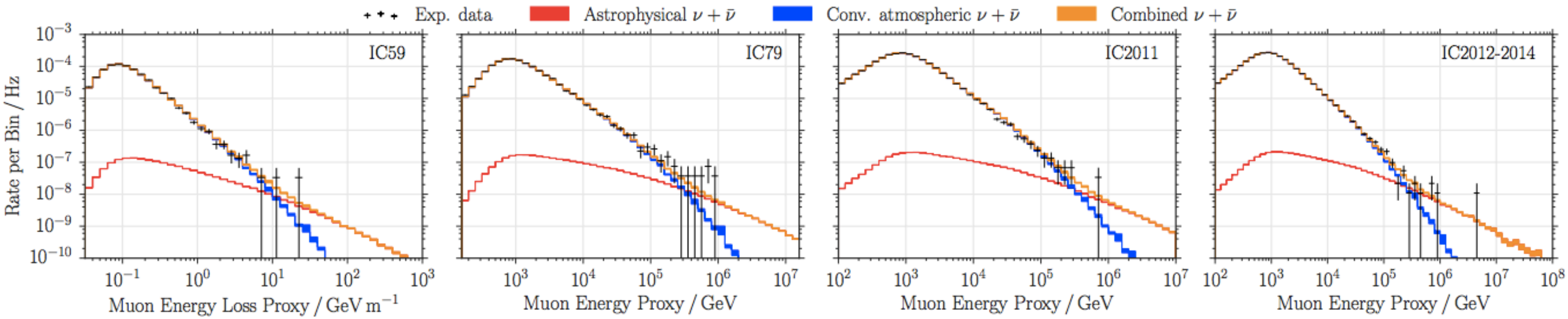
Throughgoing muons,
upgoing



Events with contained vertex



Diffuse Flux with upgoing muon neutrinos (6 years)



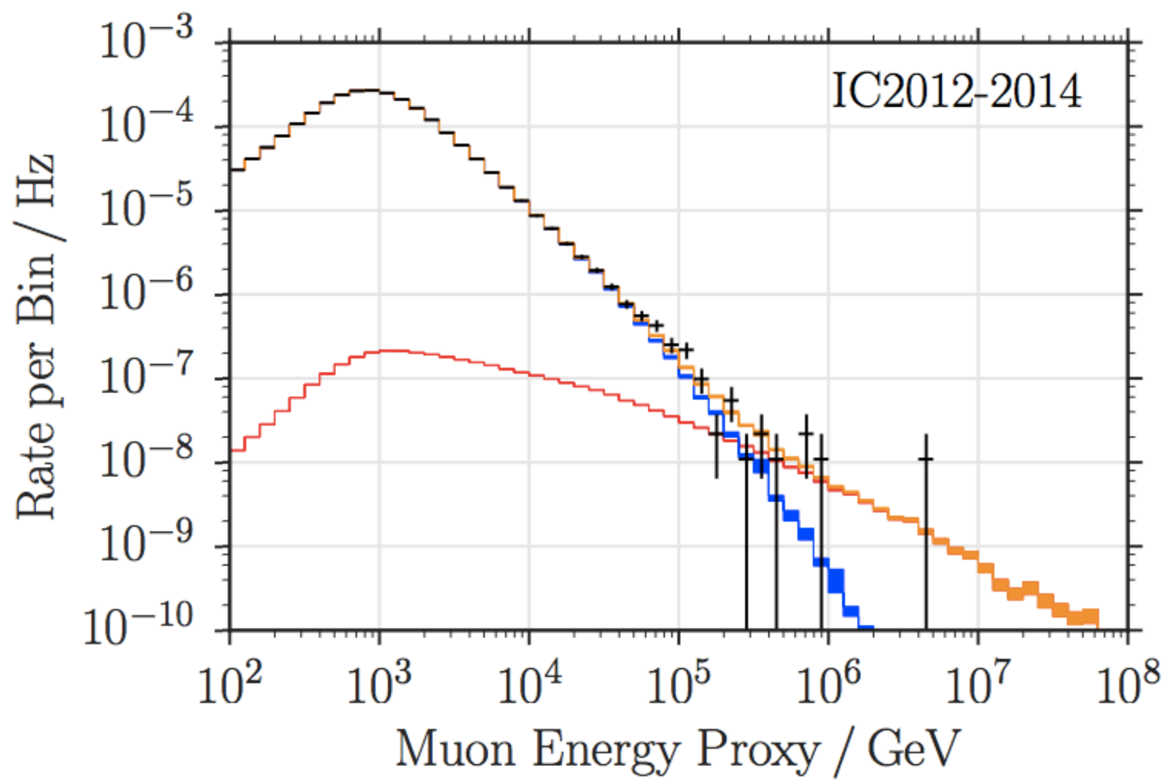
Upgoing or Horizontal track =
Earth-filtered

350 000 events in 6-year analysis

Estimated 99.7% pure
muon-neutrino sample

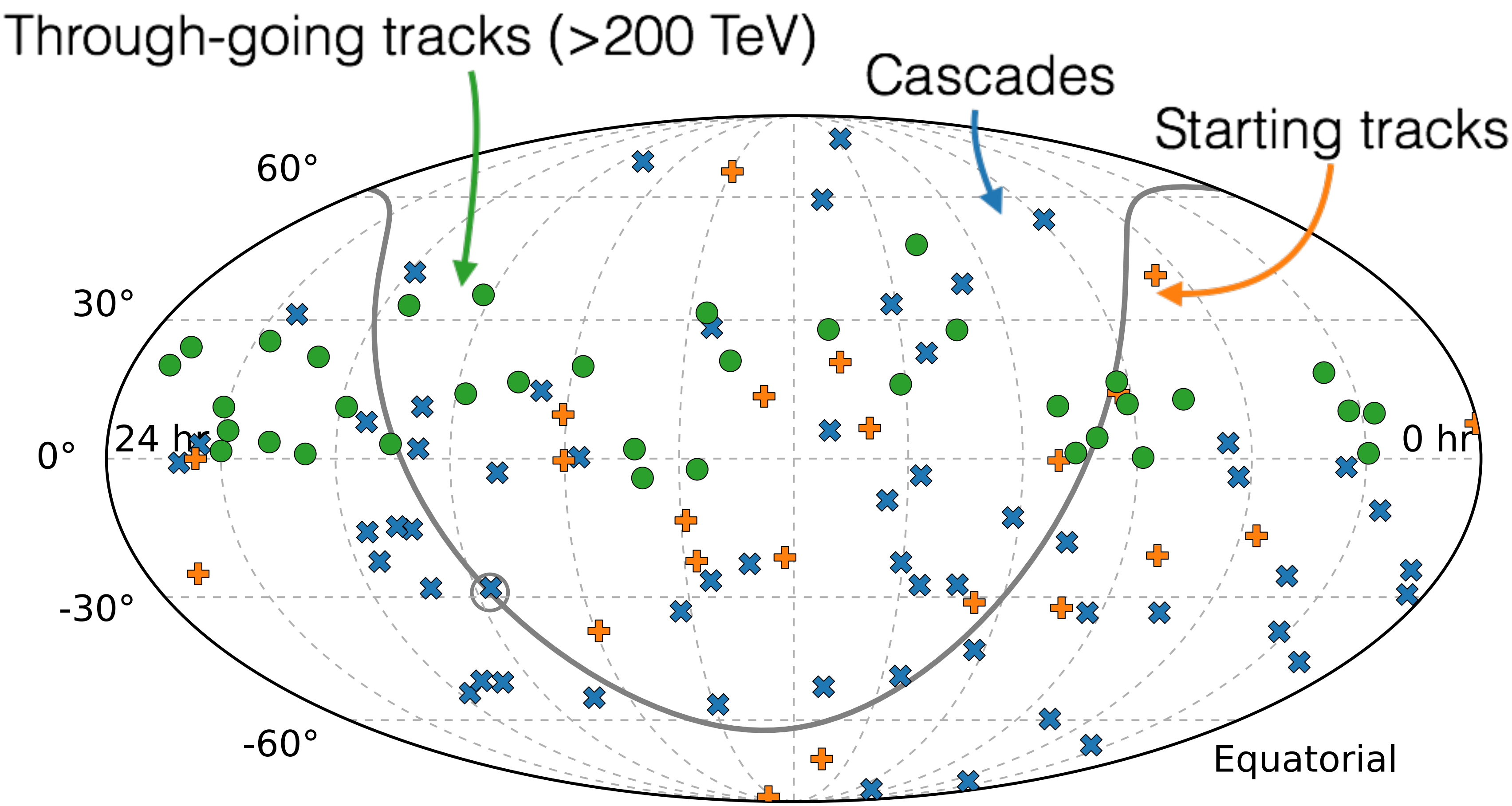
5.6**σ** for astrophysical flux

- Astrophys. J. 833 (2016) 1, 3
- also Haack (IceCube C.), ICRC 2017



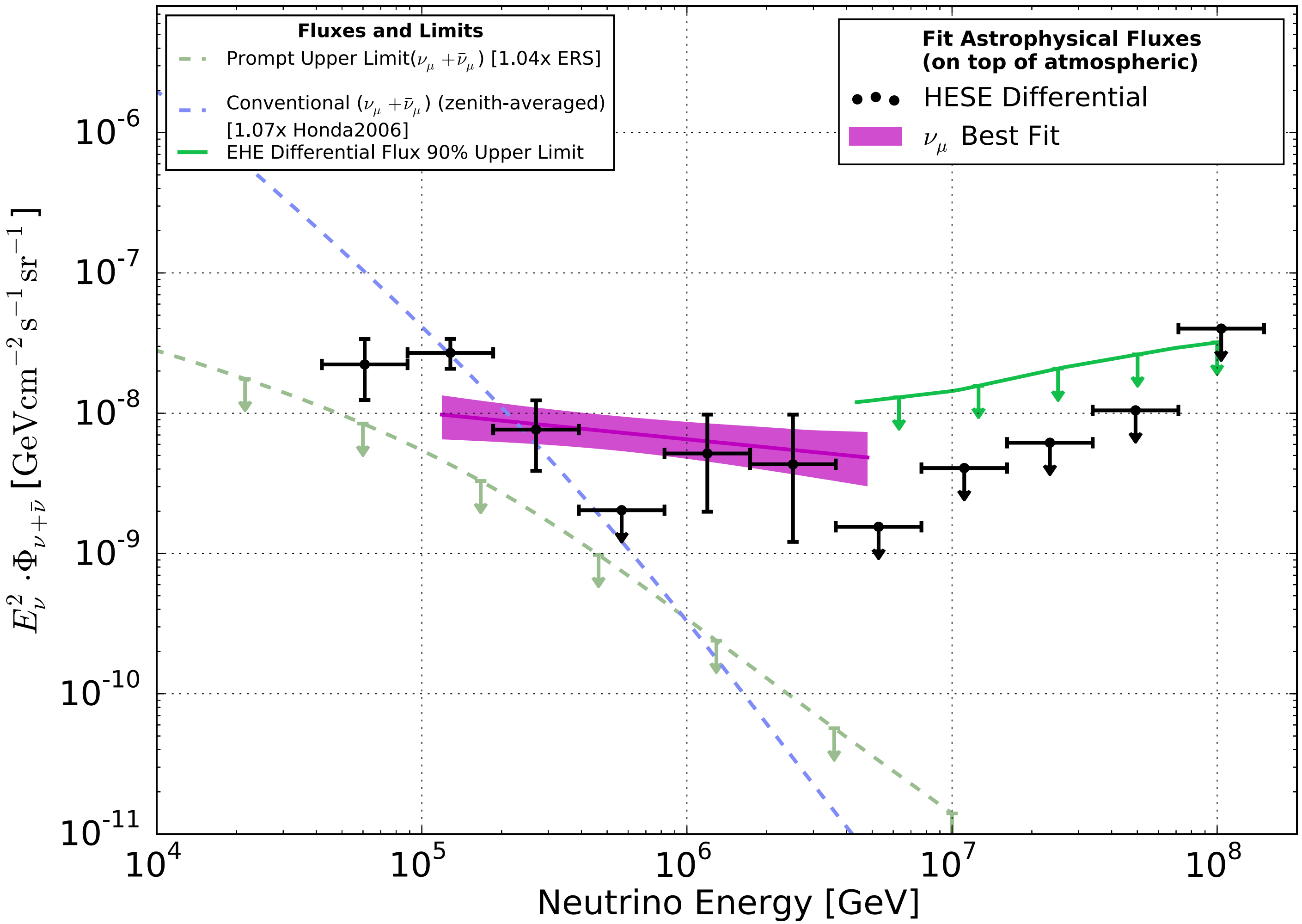
Events with reconstructed energy > 200 TeV (more than 50% of events are astrophysical)

Events from above event selections with energy cut.



6 years of data (ICRC 17)

Energy spectrum with these event samples: 1.) upgoing muon neutrinos 2.) contained vertex events



N. Wandkowsky, IceCube, Neutrino 2018

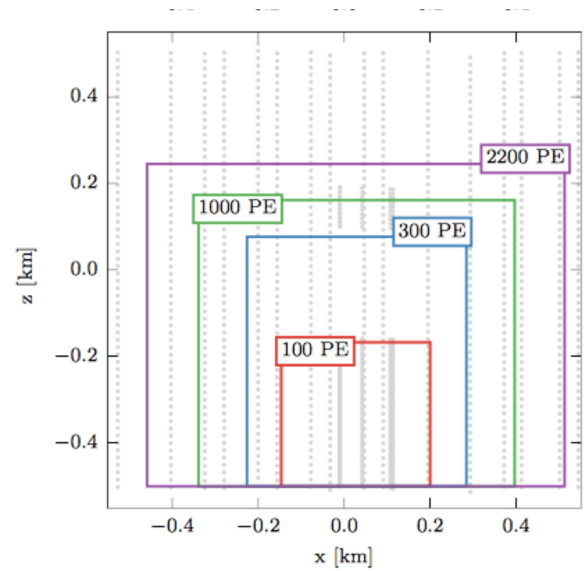
New event selections at “low” energies (<100 TeV)

From High to Medium energy: Part 1 - MESE

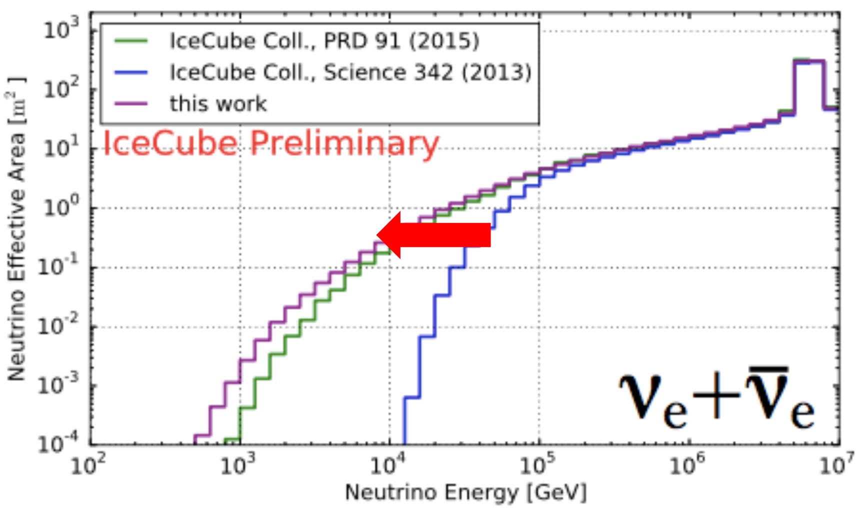
High energy: > 100 TeV (astro dominates atmospheric)
Low energy: 5 – 100 TeV

Follow-up analysis to arxiv.org/1410.1749

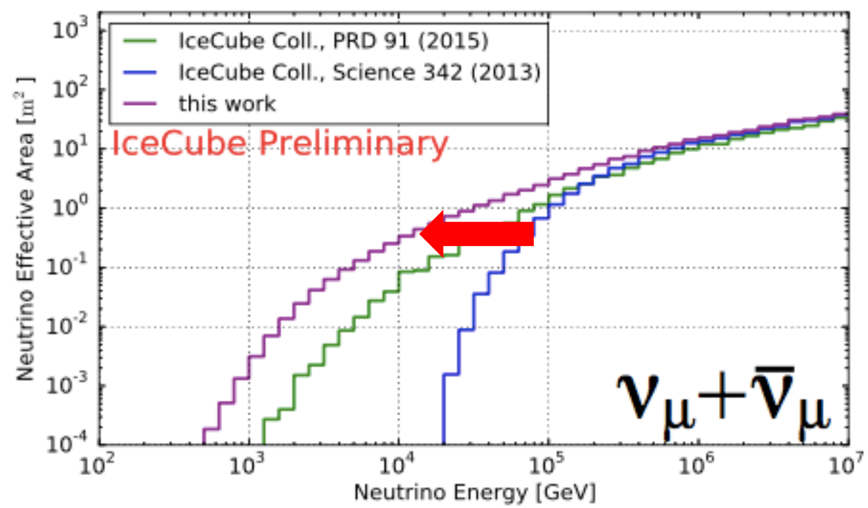
- 2 years → 7 years
- and optimized



Neutrino effective area



Neutrino effective area

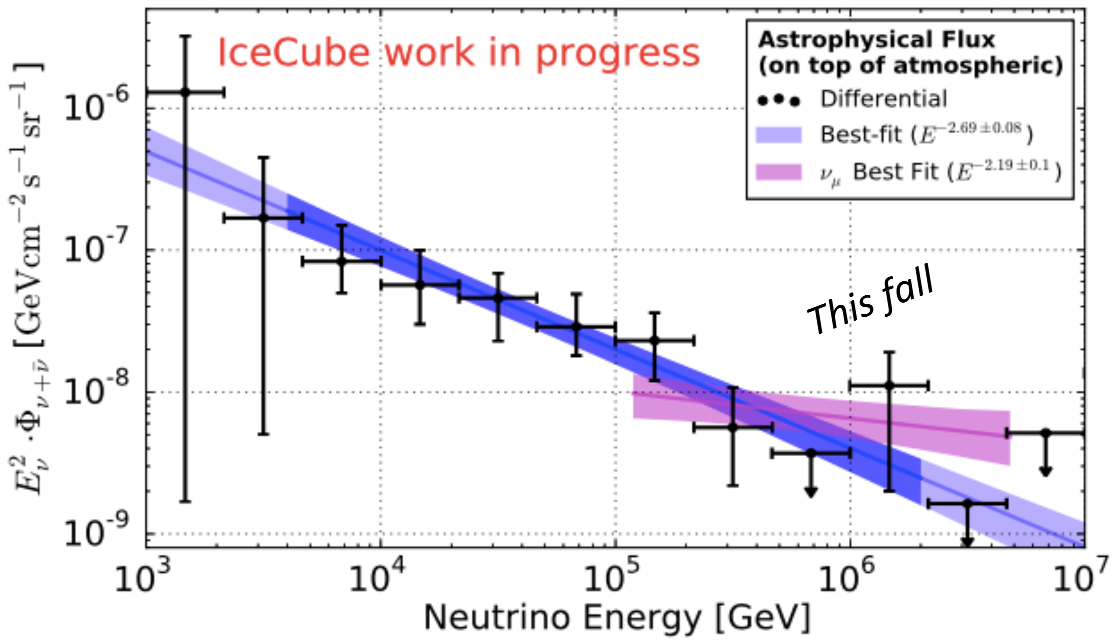


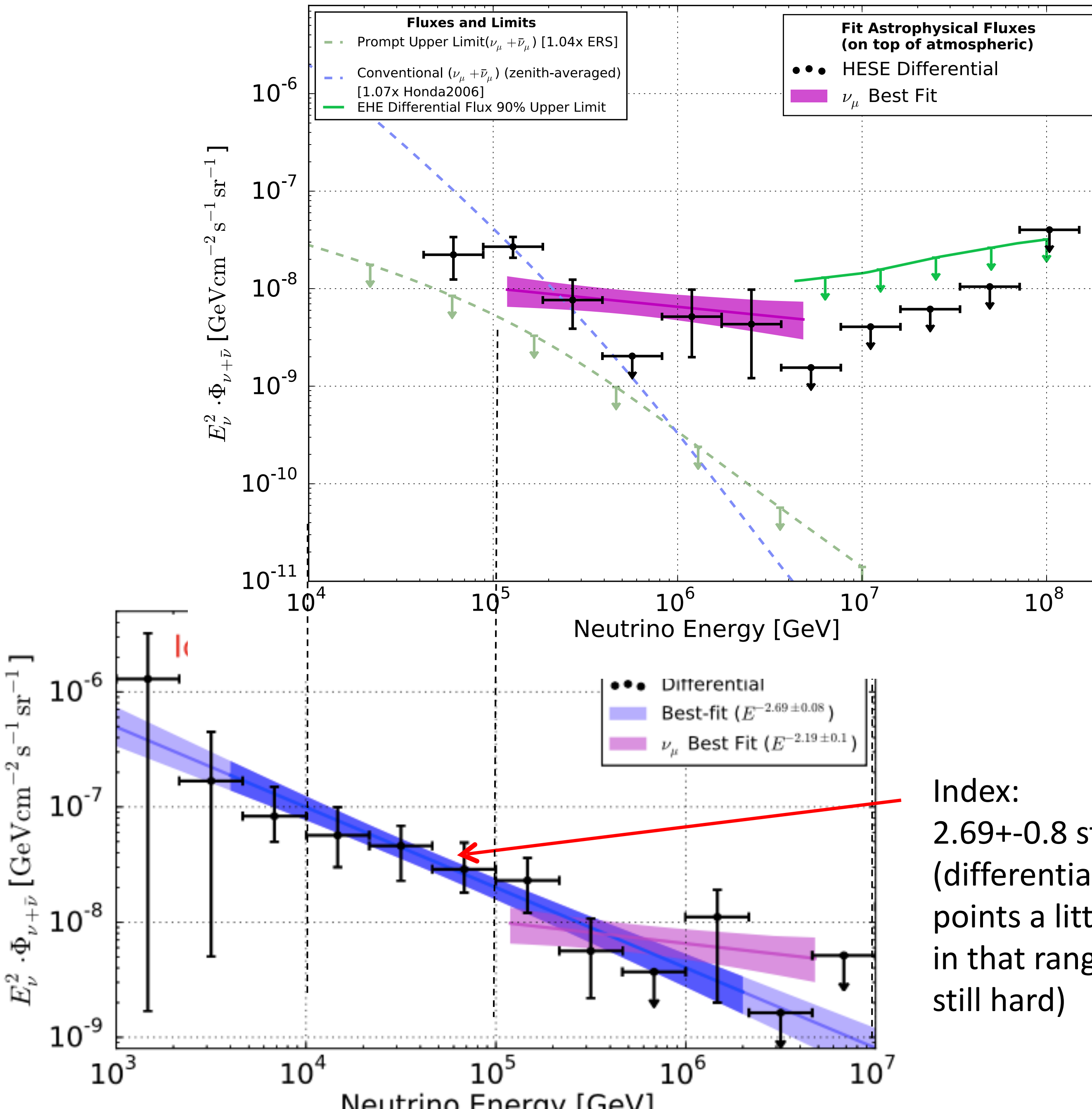
Low-threshold starting events (2010-2016)

7-yr unfolding

Systematics not included yet!

- Unfolding to neutrino energy:
  - assume isotropic flux, ν_e:ν_μ:ν_τ=1:1:1, ν:$\bar{\nu}$=1:1
  - compatible with through-going muons in sensitive energy range





Index:
2.69+-0.8 stat only
(differential data
points a little softer
in that range, but
still hard)

From High to Medium energy: Part 2 - ESTES

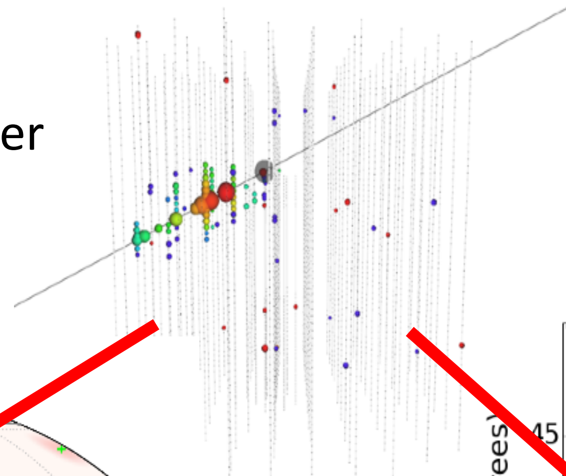
Self veto optimized for starting muon tracks.

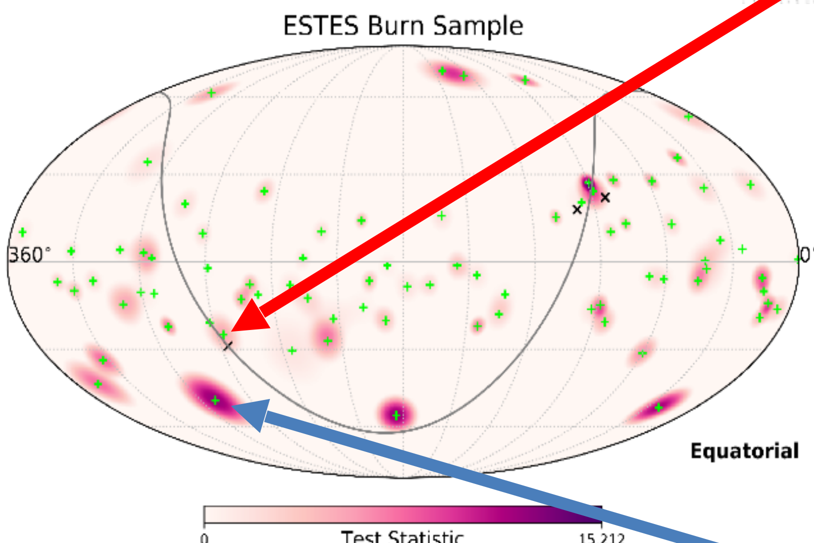
High purity astrophysical nu_mu events at ~10 TeV!

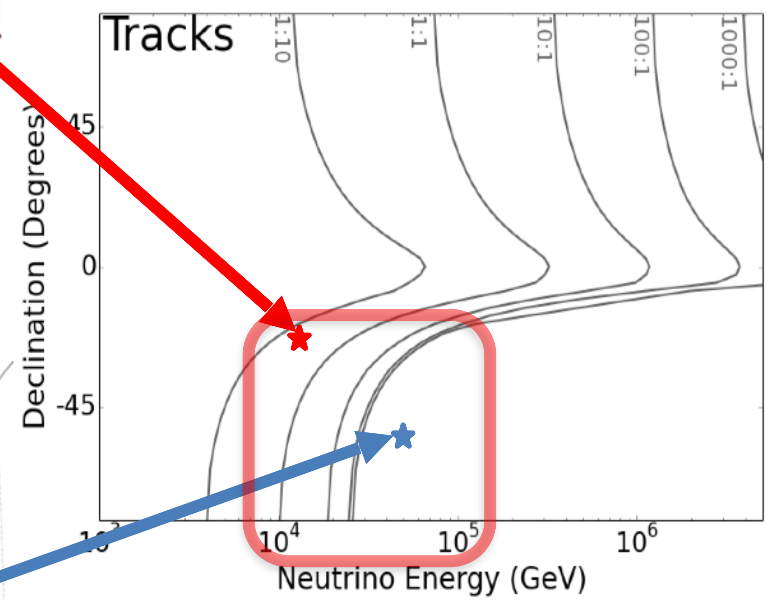
10% of data unblinded for inspection ("burnsample")

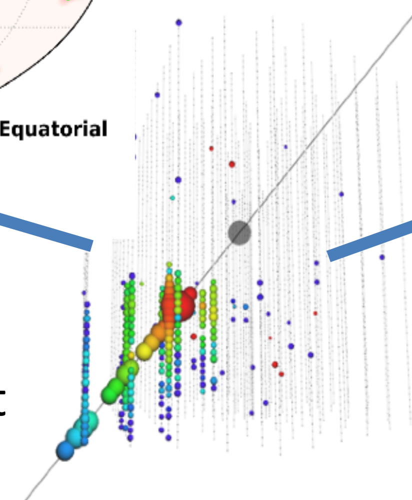
Expect 20 to 100 events in southern sky in 10 years depending on spectrum.

Event near Galactic Center









Highest Energy Event

From High to Medium energy: veto is only way

These new and lower energy event selections are being scrutinized for possible systematics.

The currently seen steep spectrum (2.7), if confirmed, into the 10 TeV range would result in significant tension of several models with diffuse Fermi photon flux.

→ Problem for models with calorimetric cosmic ray reservoirs that produce photons and neutrinos alike, eg starburst galaxies.

Two veto methods are possible:

self veto as discussed

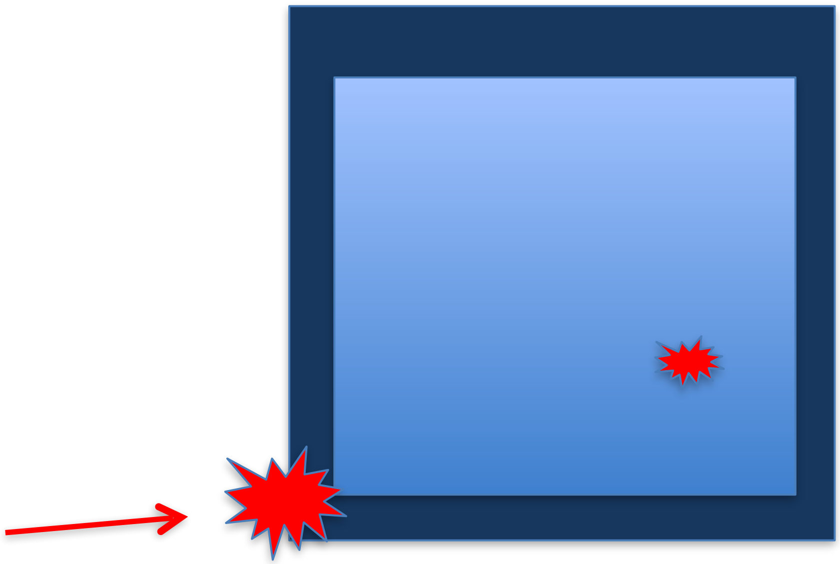
surface detector veto detectors

(like IceTop, but need lower threshold)

New event selections at high energies

Adding partially contained events at E > 1PeV

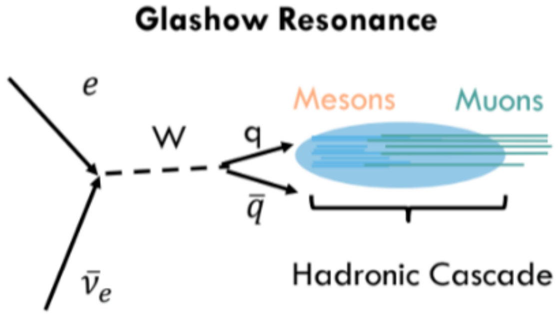
Events with
PARTIALLY contained vertex



Can double the effective volume at high energies, even more beyond 10 PeV.

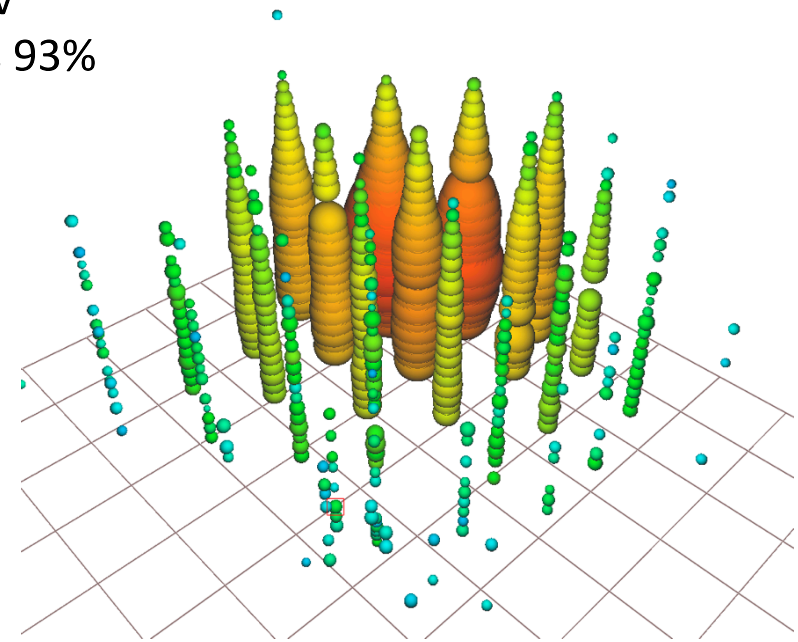
Analysis requires painstaking effort to ensure backgrounds are understood.
Background determination relies to a higher degree on simulations than in diffuse searches discussed above.

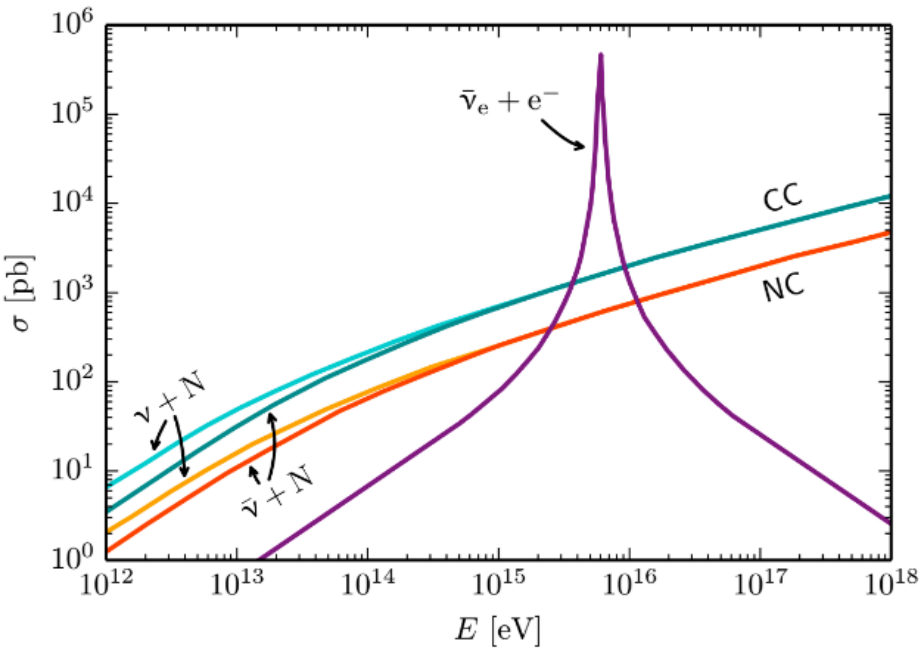
Observation of a 5.9 PeV event



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

Work in progress





Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

Potential hadronic nature of this ev

Potential hadronic nature of the event still Under study

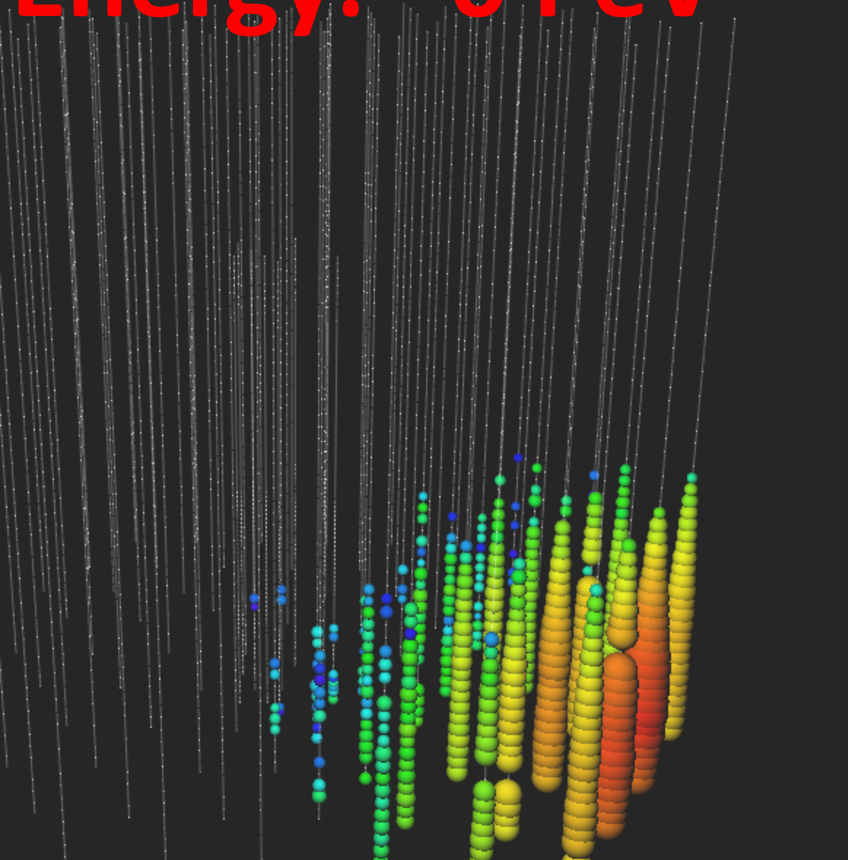
Slide courtesy: I. Taboada, Neutrino 2018

A neutrino event near Glashow resonance?

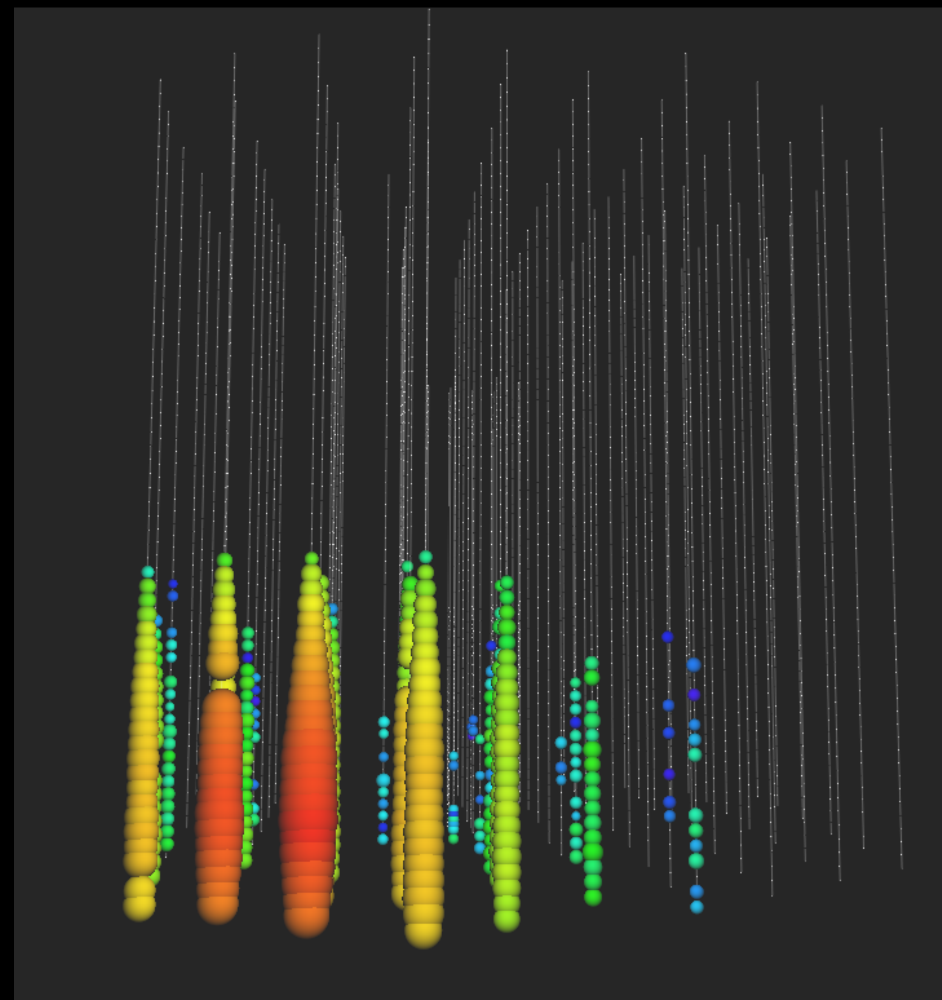
Interesting event found in expanded search.

Charge: 200,000 photoelectrons

Energy: ~6 PeV

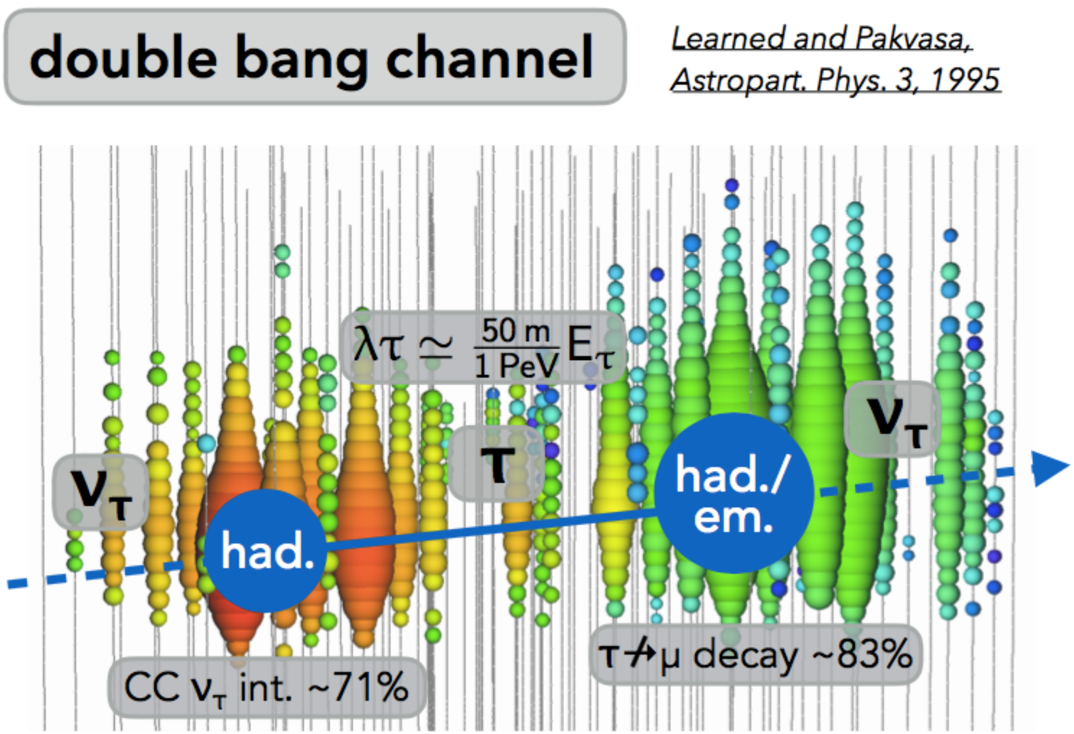


Ref: ICRC 2017, L. Lu (IceCube C.)



Tau neutrino search - Flavor ratio

Usner et al. (IceCube Coll.), ICRC 2017



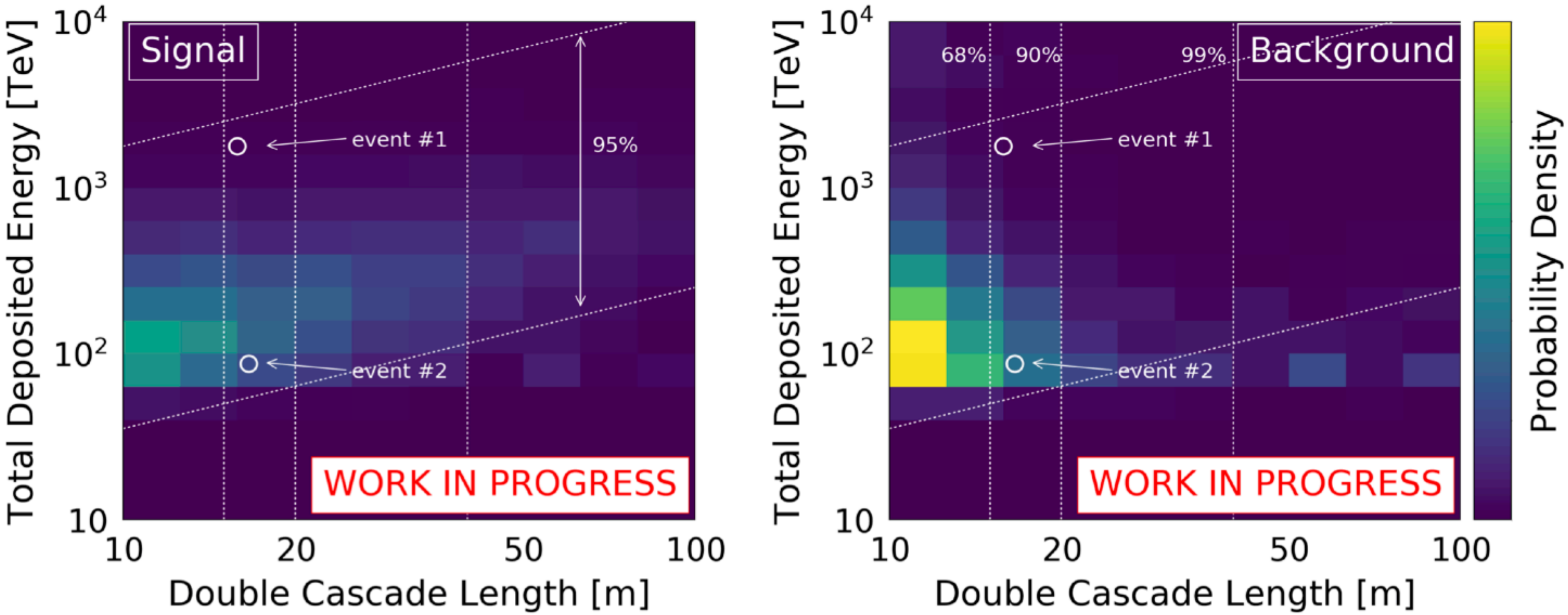
simulated double bang event with ~10 PeV neutrino energy

Decisive observable:
Decay length

Resolution (E > 200 TeV): 3 m

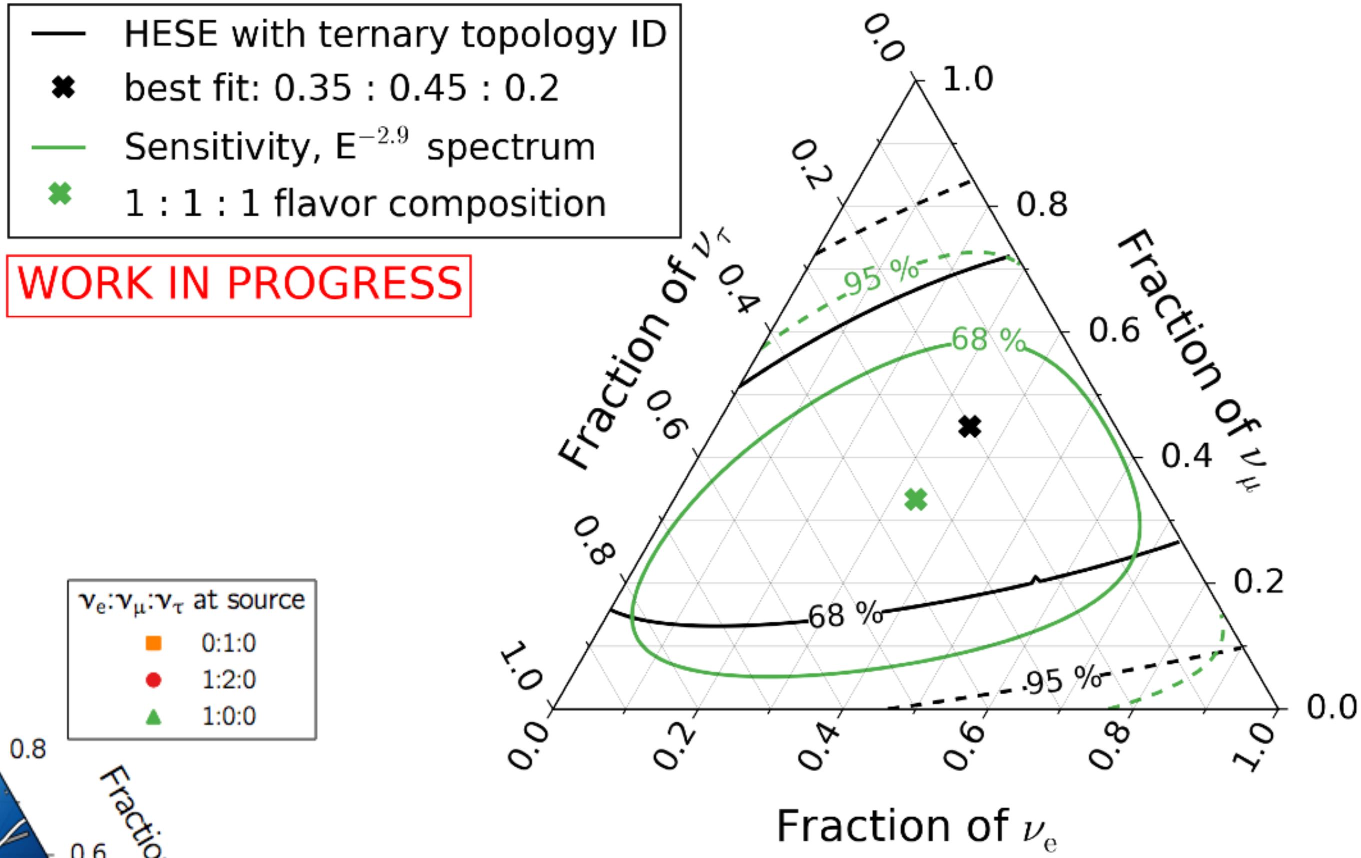
Can accept events with decay length > 10m

Tau neutrino search – flavor ratios

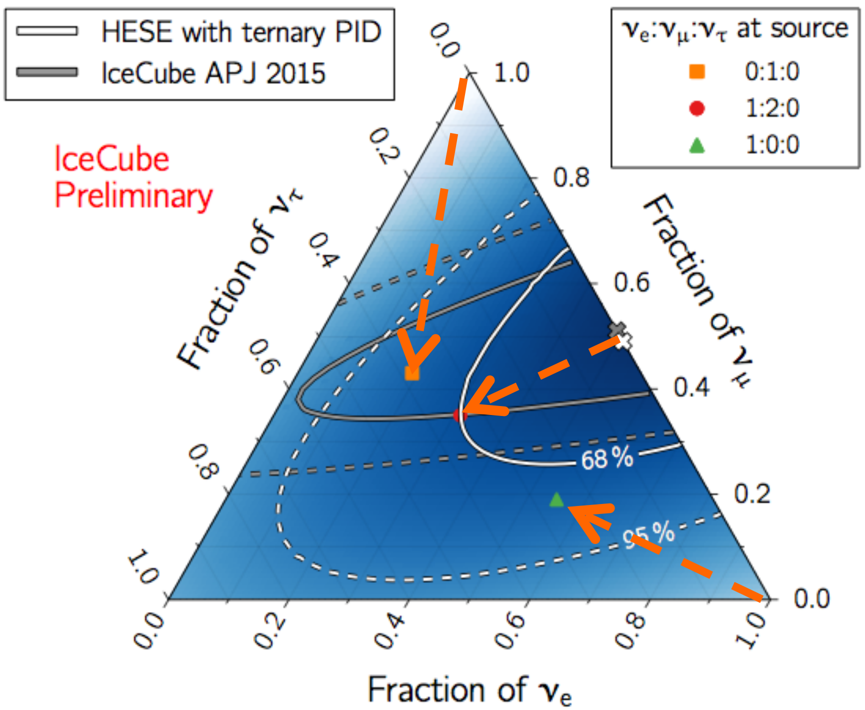


Neutrino 2018:
Poster #174 Stachurska et al. (IceCube)
Poster #176 Meier et al. (IceCube)

Tau neutrino search – flavor ratios



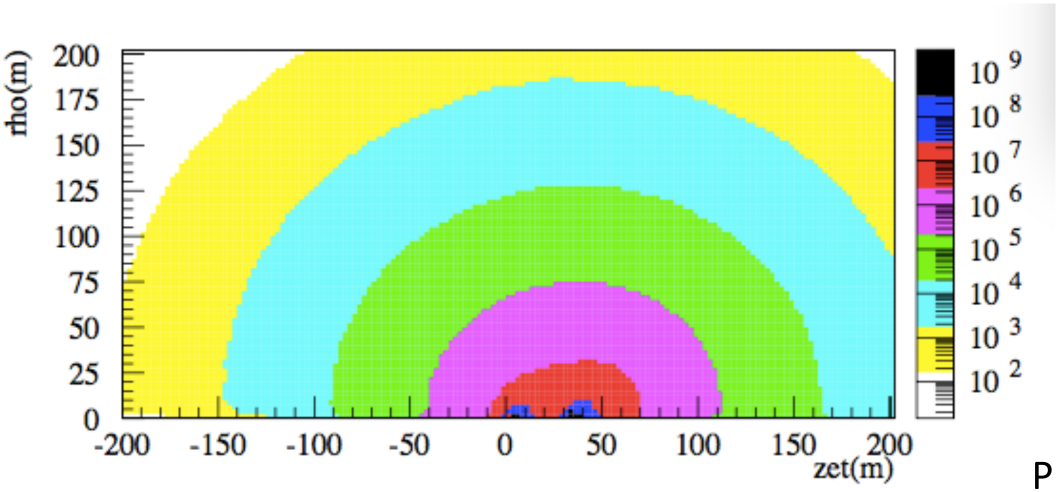
Previous result:



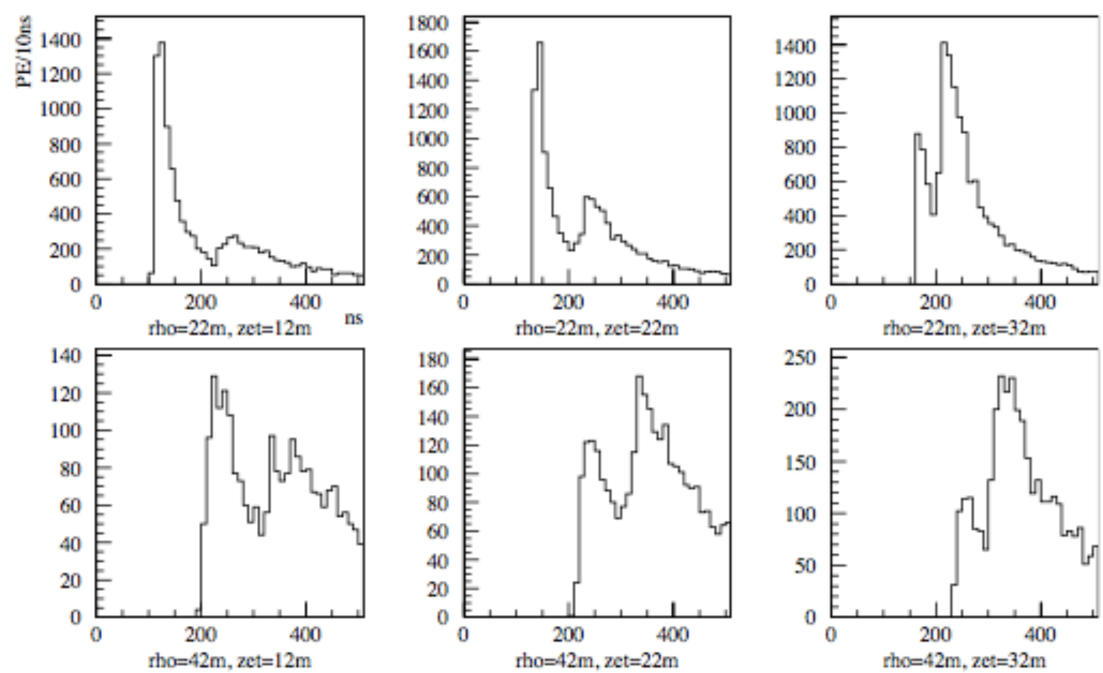
Usner et al. (IceCube Coll.), ICRC 2017

Tau neutrinos can be produced by decay of heavy mesons in atmosphere (prompt neutrinos, ~0.7 events) or by cosmic neutrinos oscillating on their long travel.

Simulation of a tau event



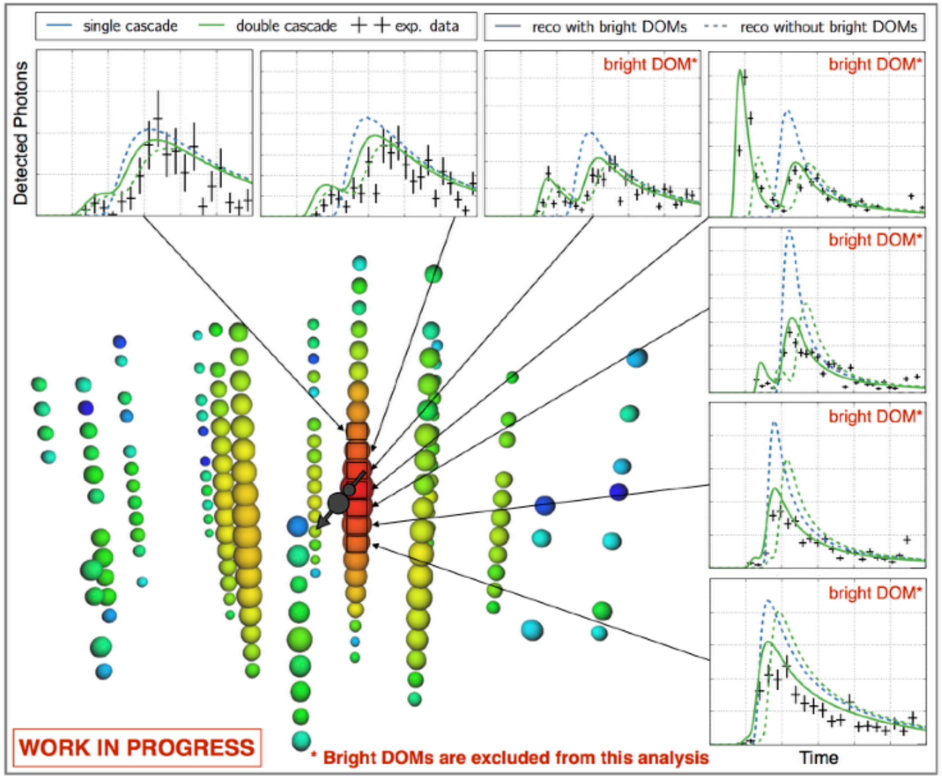
PMT signals with characteristic double pulse structure for some events.

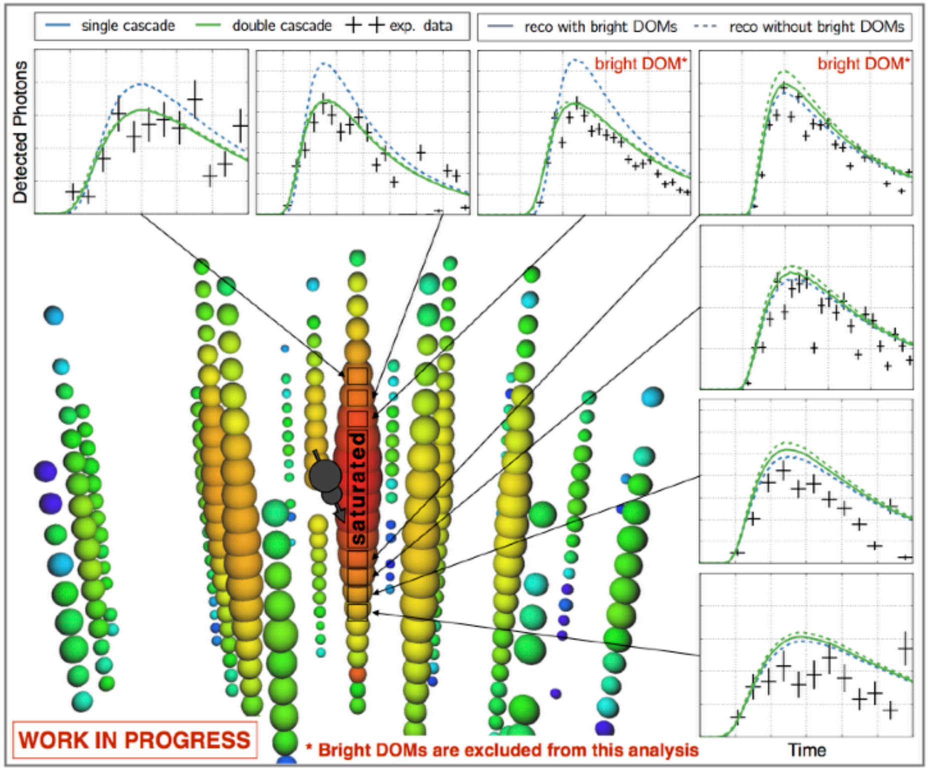


Energy: 600 TeV
Decay length: 30m

Backgrounds being investihated:
Eg
Nu_mu interaction with a brem
Throughgoing mu

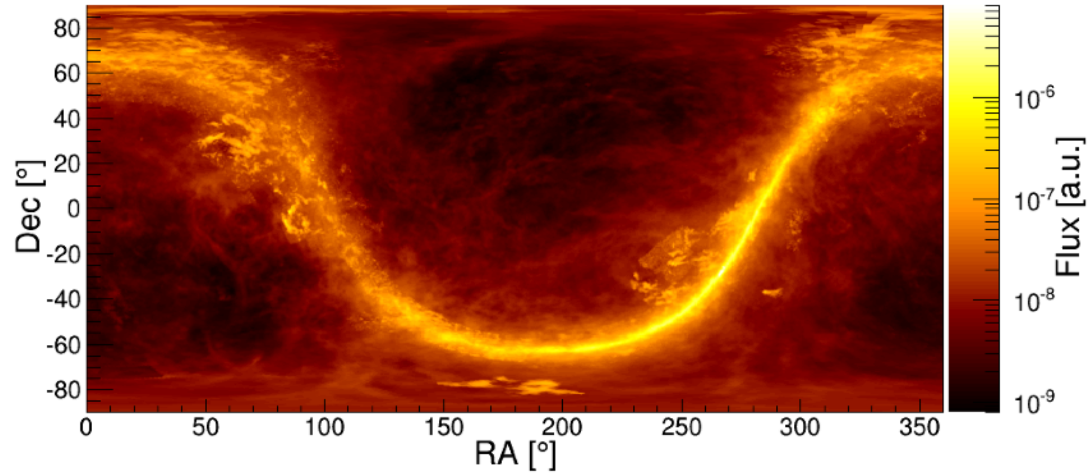
Tau neutrino search:
Identification two double cascade event candidates



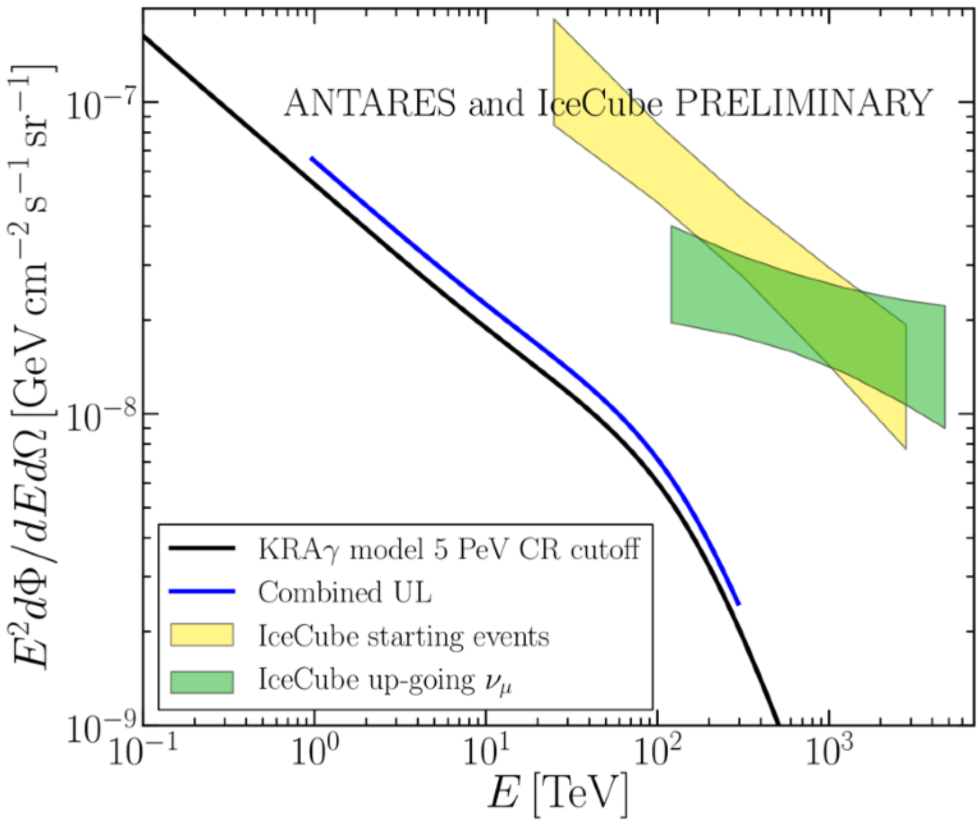


Two events in 7.5 years of data.
Background of 0.7 events.
Detailed study of events using waveform information in progress.

What fraction of the cosmic neutrino flux comes from the Milky Way?



KRA-γ (50 PeV cutoff) template



Only a small fraction Observed neutrino flux is of galactic origin (< 14%)

Compared to best fit spectrum in this energy range ($E^{-2.5}$ flux)

arXiv:1707.0341

What fraction of the cosmic neutrino flux comes from classes of extragalactic sources?

Gamma Ray Bursts

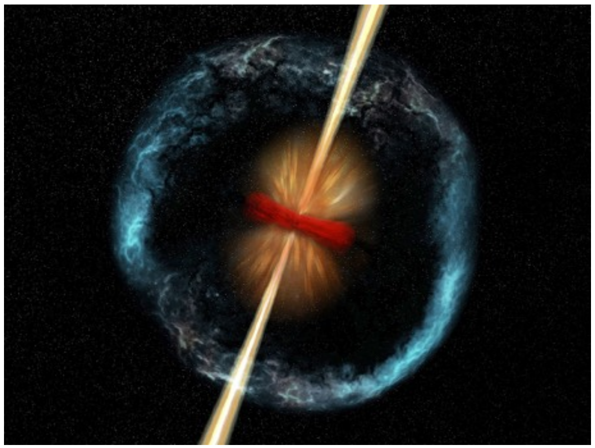


Illustration credit: NASA/CXC/M.Weiss

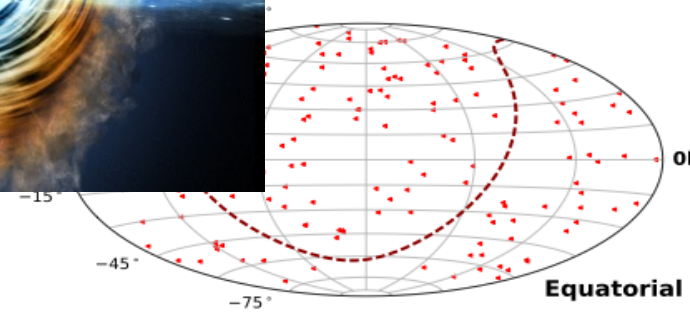
807 GRB's monitored for prompt neutrino emission at TeV to PeV energy range

Stacked GRB analysis: < 1% from prompt neutrinos

Ref: arxiv: 1702.06868

Fermi Blazars

AGN with supermassive black hole, with Jet pointing at us.



Fermi reports that ~85% of the gamma rays from the "diffuse" gamma ray flux originate from such blazars.

Stacked catalogue analysis: only a smaller fraction <27% of neutrinos from this catalogue.

(eg some assumptions, eg energy spectrum apply)

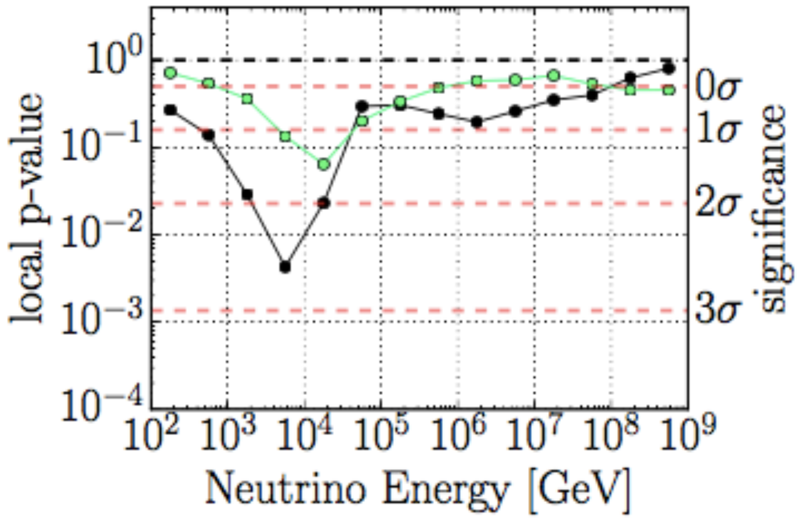
Ref: - Astrophys. J **835**, 45 (2017)

- ICRC 2017, Huber for IceCube C.

Blazar stacking

Population	p-value	
	γ-weighting	equal weighting
All 2LAC blazars	36% (+0.4σ)	6% (+1.6σ)
FSRQs	34% (+0.4σ)	34% (+0.4σ)
LSPs	36% (+0.4σ)	28% (+0.6σ)
ISP/HSPs	> 50%	11% (+1.2σ)
LSP-BL Lacs	13% (+1.1σ)	7% (+1.5σ)

Pre-trial significance vs energy for All 2LAC catalogue



Note also mild upward fluctuations in all channels. (TXS is part of ISP/HSP)

This analysis integrates all events.

New stacking analysis underway that will be sensitive to flaring sources.

Blazars: See: M. Huber, IceCube C. at ICRC 2017; Astrophys.J. 835 (2017) no.1, 45

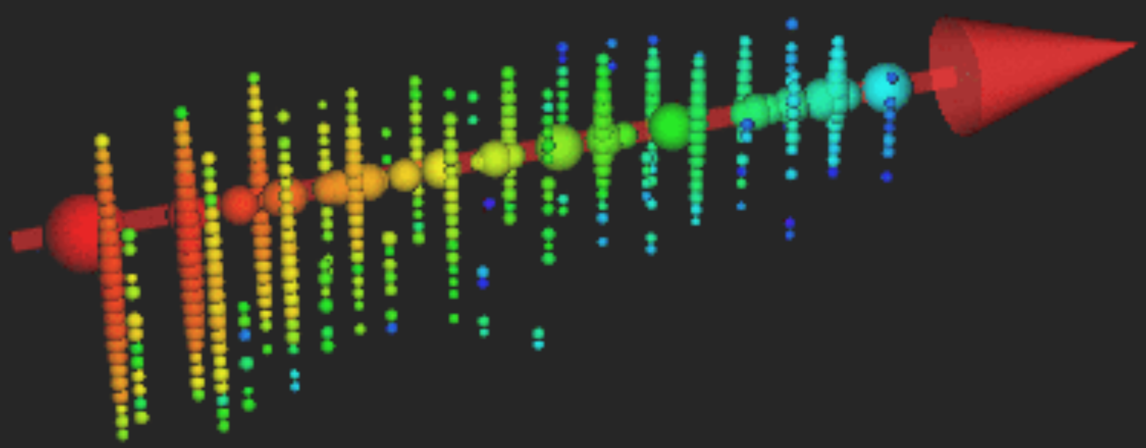
Realtime time multimessenger astronomy: IC170922a

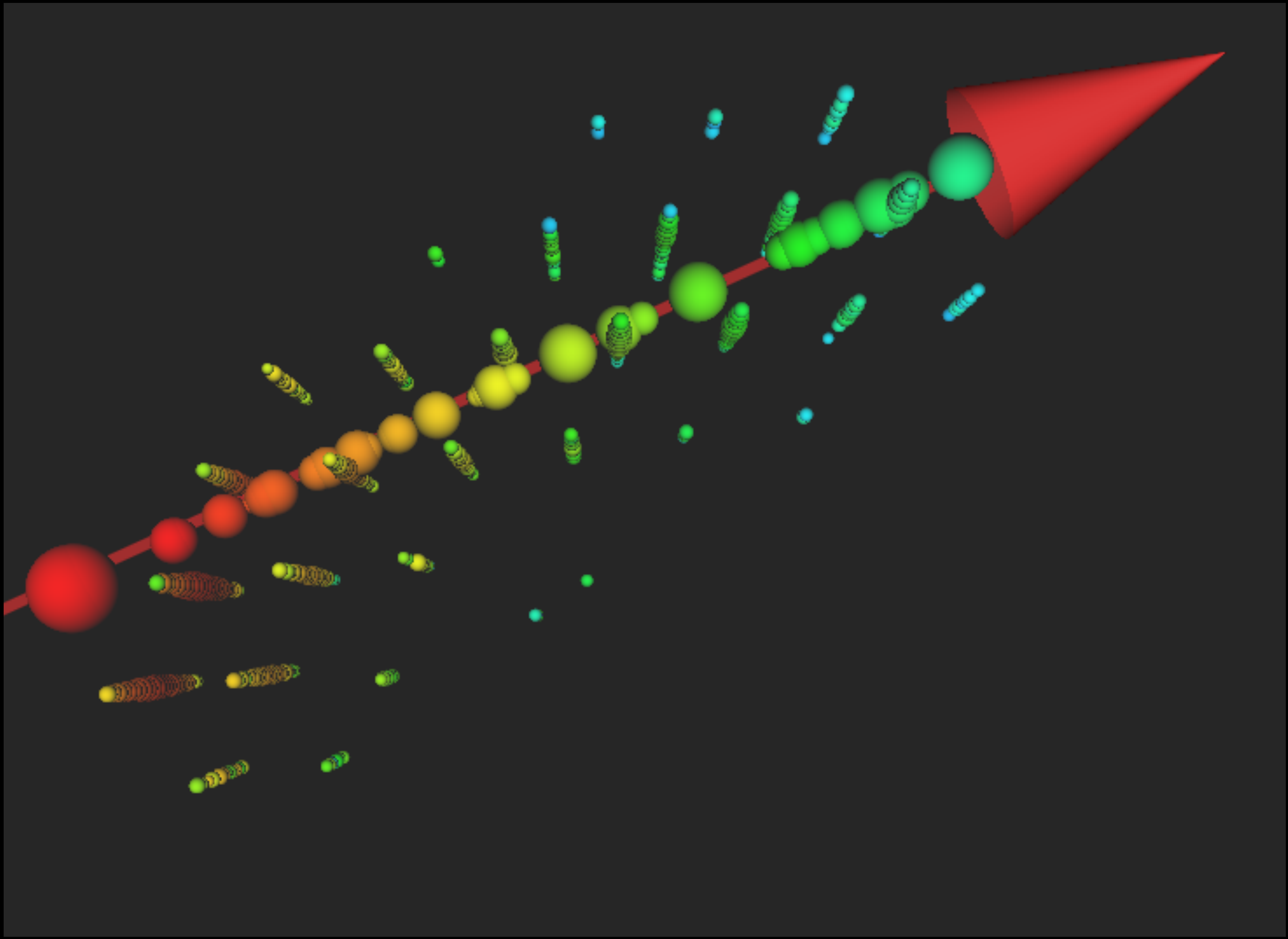
Example event: IC170922
September 22, 2017
Charge: 5700 photoelectrons

Neutrino Energy: 290 TeV (most probable)

Alert was sent ~40 sec after interaction!!!

The event is a very nice muon track.
Throughgoing with more than 1 km contained track length.
Almost horizontal: sweet spot for angular resolution (many strings participate in fit)
Still upgoing, 5 deg, can never be atmos muon.
Robust energy assessment.
A detected significant energy loss outside detector does not enter the energy fit (for robustness).





IceCube-170922A - Fermi-AGILE-GBM - MAGIC

Date: 22 Sept 2017

RA: 77.43° (-0.80°/+1.30° 90% CL)
Dec: 5.72° (-0.40°/+0.70° 90% CL)

Energy (prelim. reported est.): > 120 TeV

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy
neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube
<blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss
(University of  Maryland) report on behalf of the IceCube
Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy
event with a high probability of being of astrophysical origin.
The event was identified by the  Extremely High Energy (EHE)
track event selection. The IceCube detector was in a normal
operating state. EHE events typically have a neutrino
interaction vertex that is outside the detector, produce a muon
```

Date: 28 Sept 2017

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Date: 4 Oct 2017

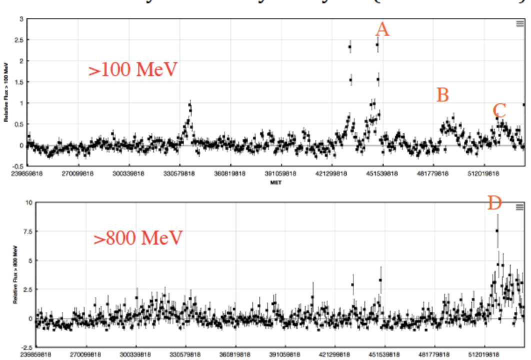
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

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

FAVA TXS 0506+056

'Fermi All-sky Variability Analysis' (Abdollahi+17)



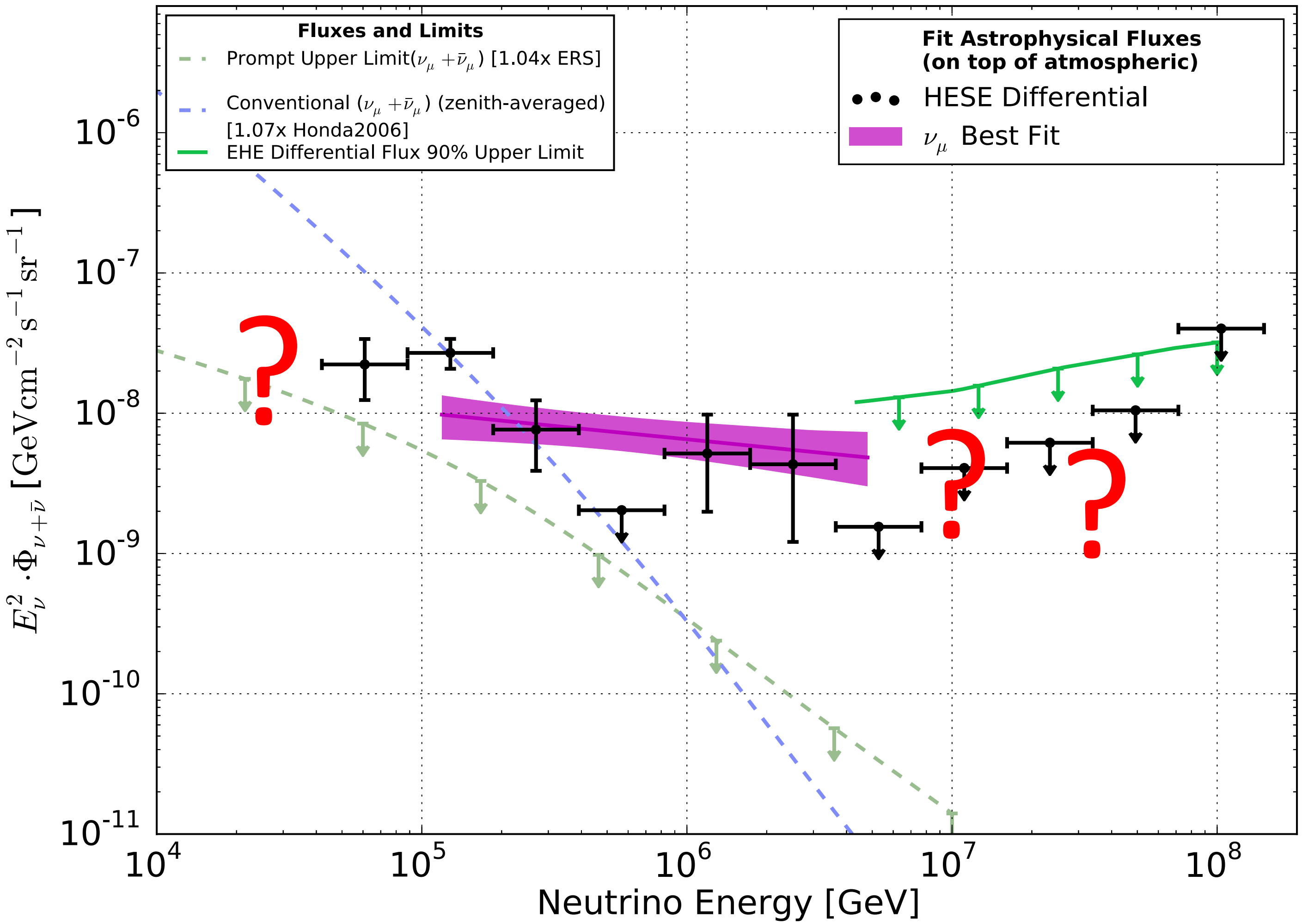
$Z = 0.3365 \pm 0.0010$
(Paiano+ 2018 ApJ, 854)

Related

- **10845** Joint Swift XRT and NuSTAR Observations of TXS 0506+056
- **10844** Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
- **10840** VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
- **10838** MAXI/GSC observations of IceCube-170922A and TXS 0506+056
- **10833** VERITAS follow-up observations of IceCube neutrino event 170922A
- **10831** Optical photometry of TX0506+056
- **10830** SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
- **10817** First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
- **10802** HAWC gamma ray data prior to IceCube-170922A
- **10801** AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
- **10799** Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
- **10794** ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
- **10792** Further Swift-XRT observations of IceCube 170922A
- **10791** Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
- **10787** H.E.S.S. follow-up of IceCube-170922A
- **10773** Search for counterpart to IceCube-170922A with ANTARES

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

How does the neutrino flux extend at higher energies?



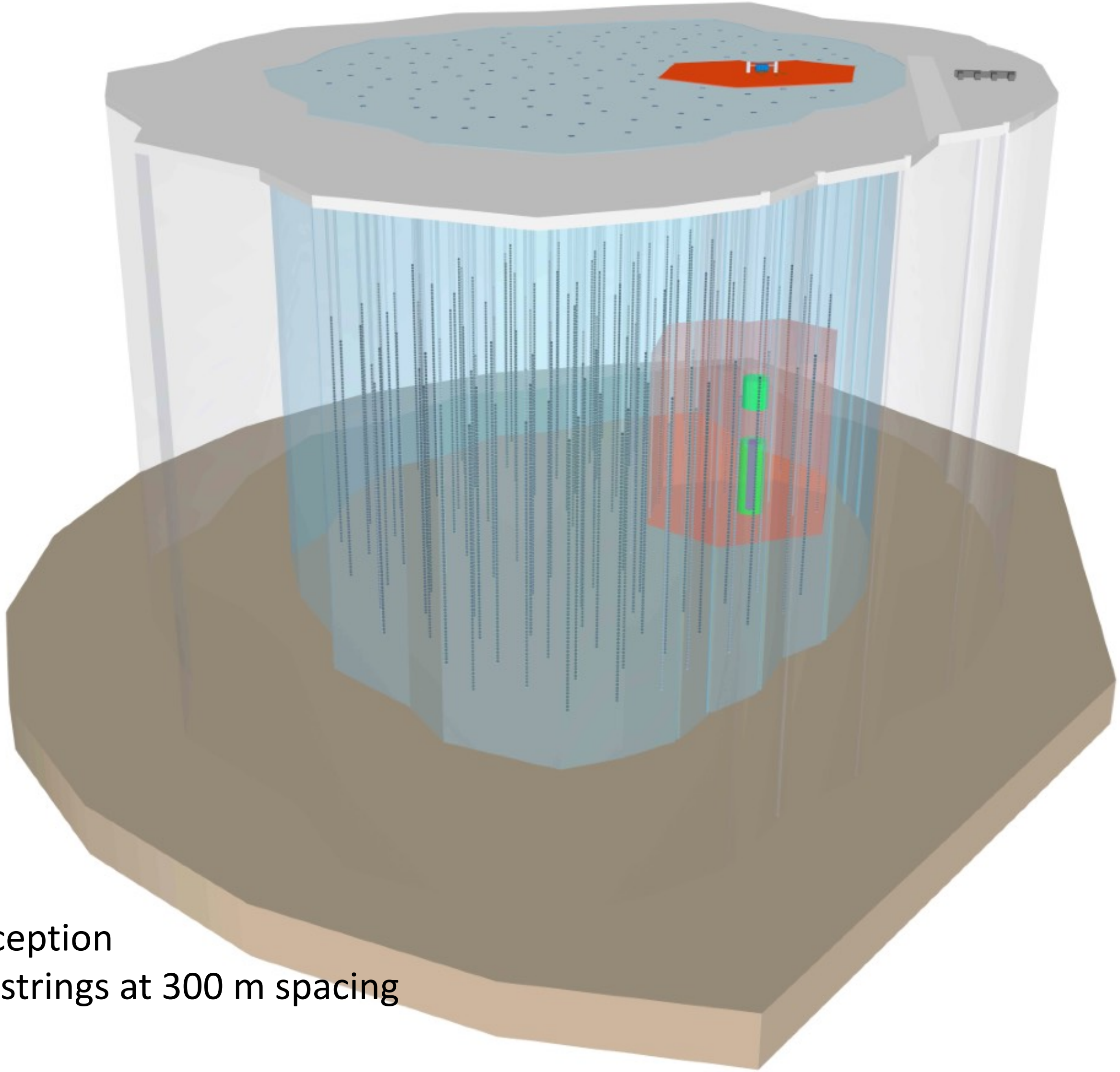
N. Wandkowsky, IceCube, Neutrino 2018

IceCube-Gen2

The next Generation IceCube: from discovery to astronomy

Multi-component observatory:

- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- Low energy core (~PINGU like)



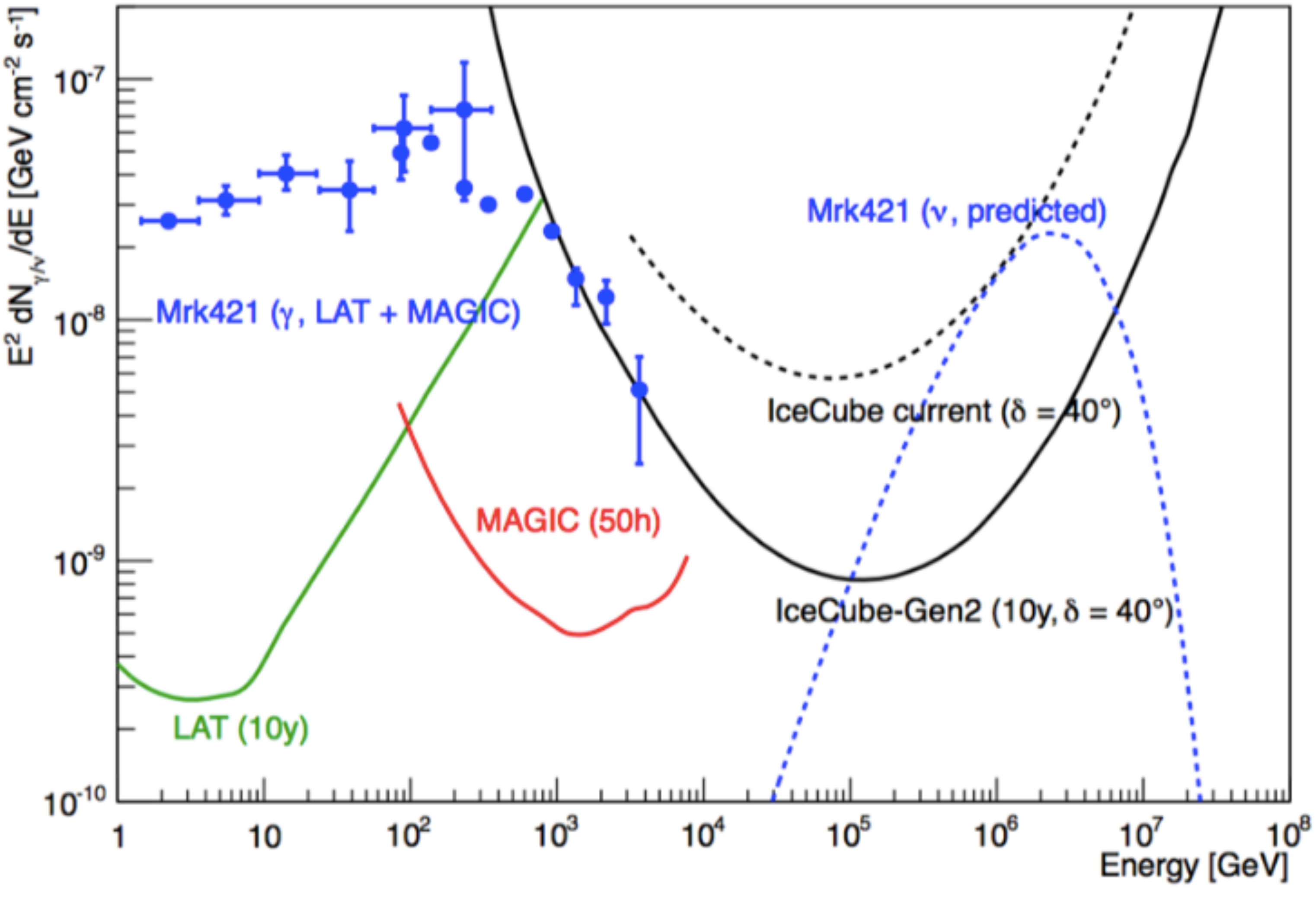
Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase of contained event rate at high energies.

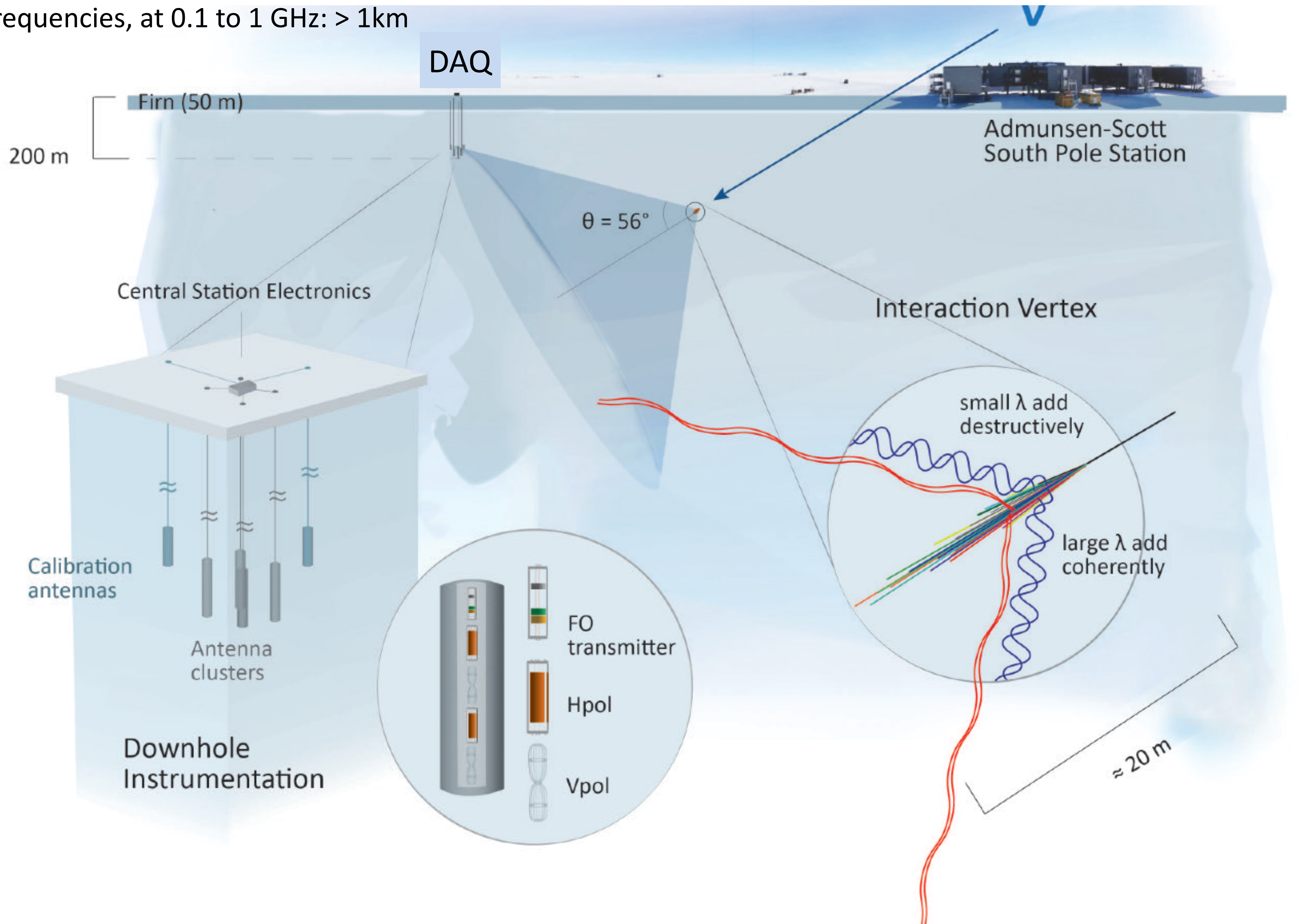
Artist conception
Here: 120 strings at 300 m spacing

Point source sensitivity example: Mrk421



The radio detection method of ultra high energy neutrinos via Askaryan signal

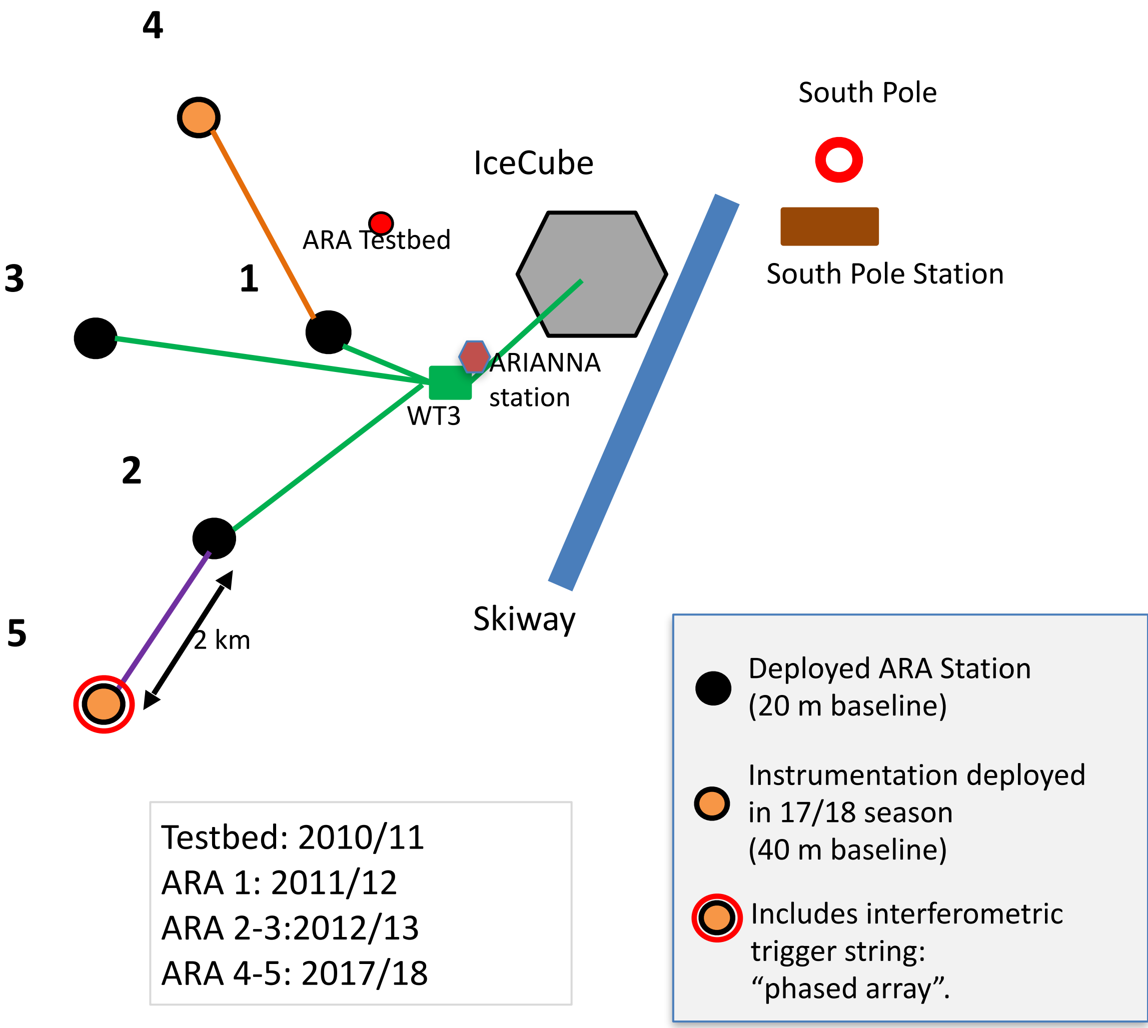
radio frequencies, at 0.1 to 1 GHz: > 1km



Askaryan Radio Array: 2017/18 upgrade

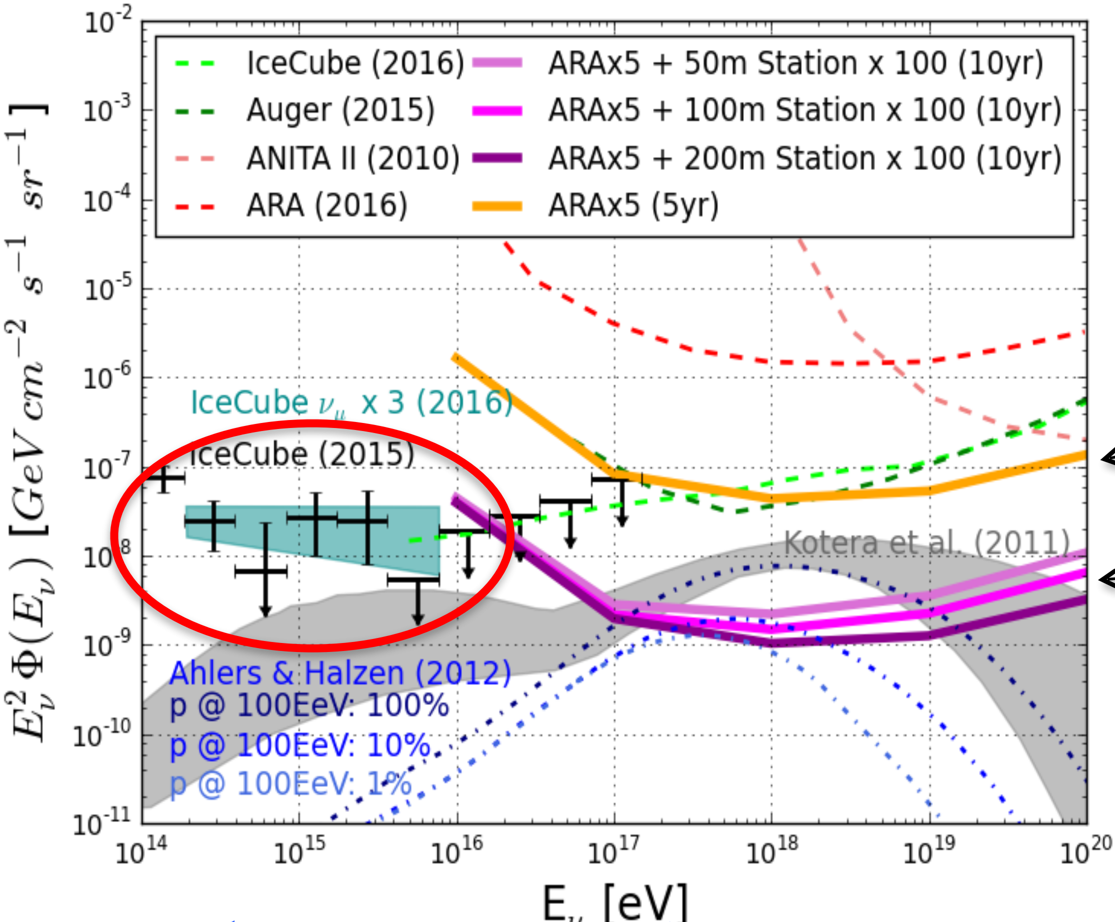
1. Major maintenance on stations 1, 2 and 3.
2. Repaired power system

   (now just passive cables to IceCube lab)
3. Deployed 2 new stations (40m baseline up from 20m)
4. Deployed Phased Array in ARA station 5. Integrated in trigger and readout.



Testbed: 2010/11
ARA 1: 2011/12
ARA 2-3:2012/13
ARA 4-5: 2017/18

Neutrino astronomy at highest energies



Published limit based on 8 months of data (arxiv:1507.08991)

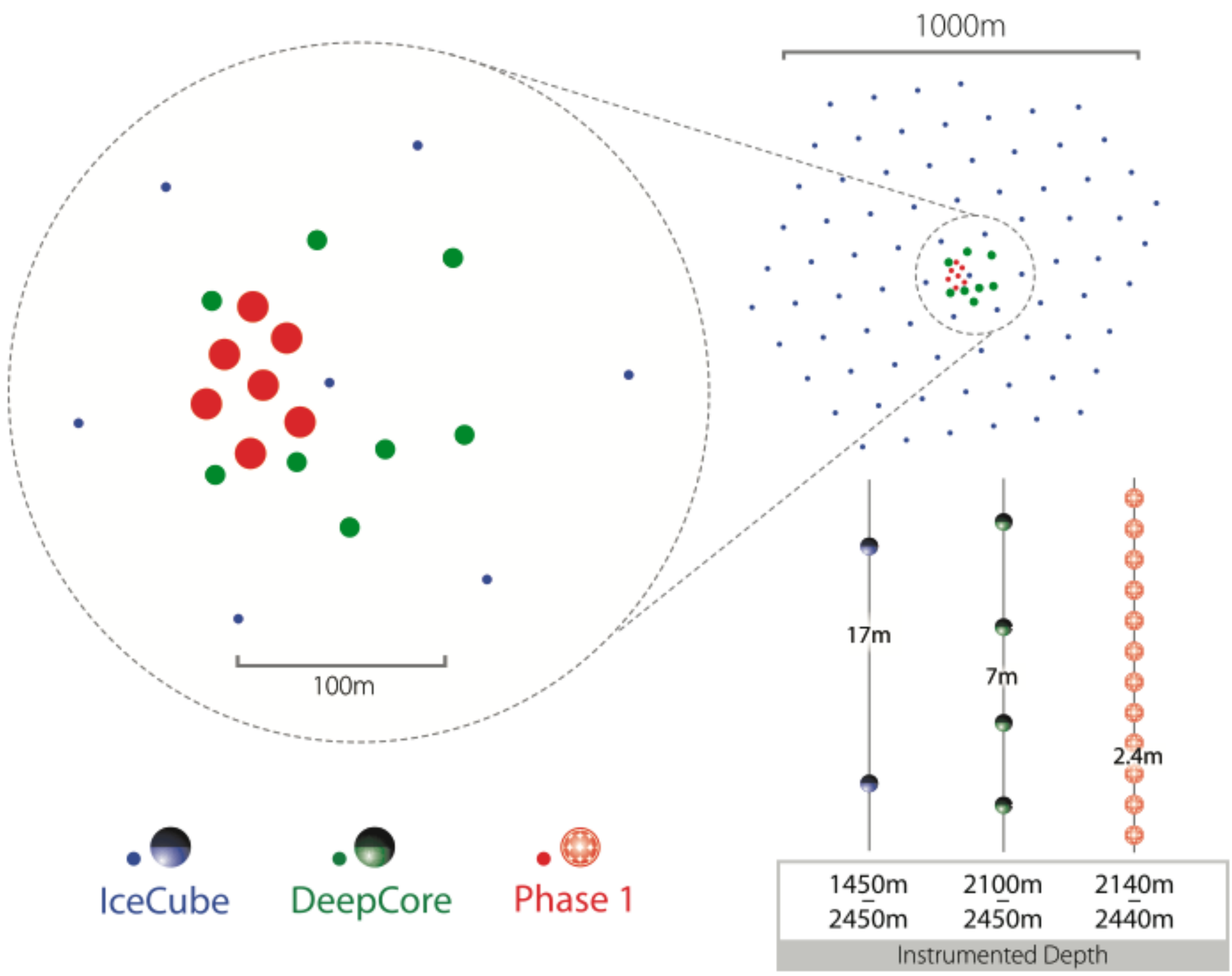
Sensitivity of ARA5 (5 yrs)

Sensitivity of Next generation radio detectors (ARA 100 scale)

IceCube-Gen2 optical
High statistics
resolve sources
Multi-messenger
astronomy

Energy coverage of next
radio neutrino detector.
Spectrum, sources, GZK,
alerts

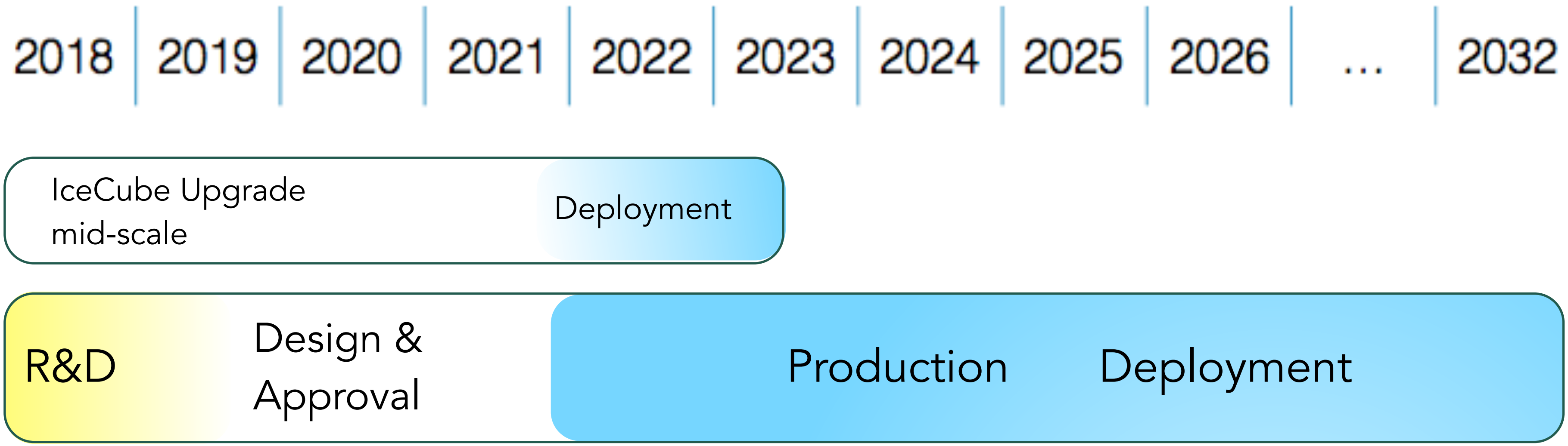
IceCube Upgrade (a step towards Gen2)



Science goals:

- ν_μ disappearance
- ν_τ appearance
- Precise calibration of IceCube optical properties and DOM response

IceCube Gen2 schedule



The IceCube Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
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 has discovered astrophysical neutrinos

- Starting to quantify their properties
- Data analysis continues to improve (calibration and reco)
- Alert program leads to exciting multimessenger observations.
- IceCube-Gen2 will take us from discovery to precision science.
  - IC upgrade as first step towards that

Thank you!
And thanks for the opportunity to come back to where to where it all started for me!