Cosmic Neutrino Searches with IceCube

Aya Ishihara
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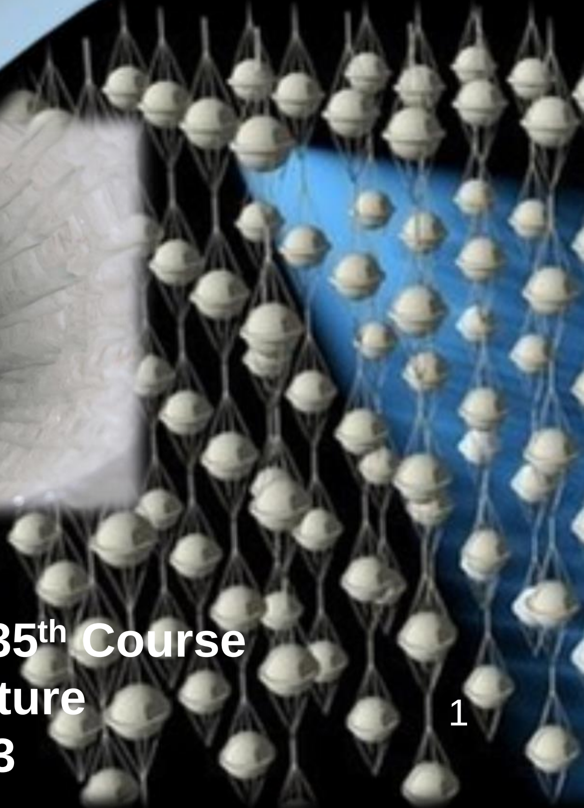
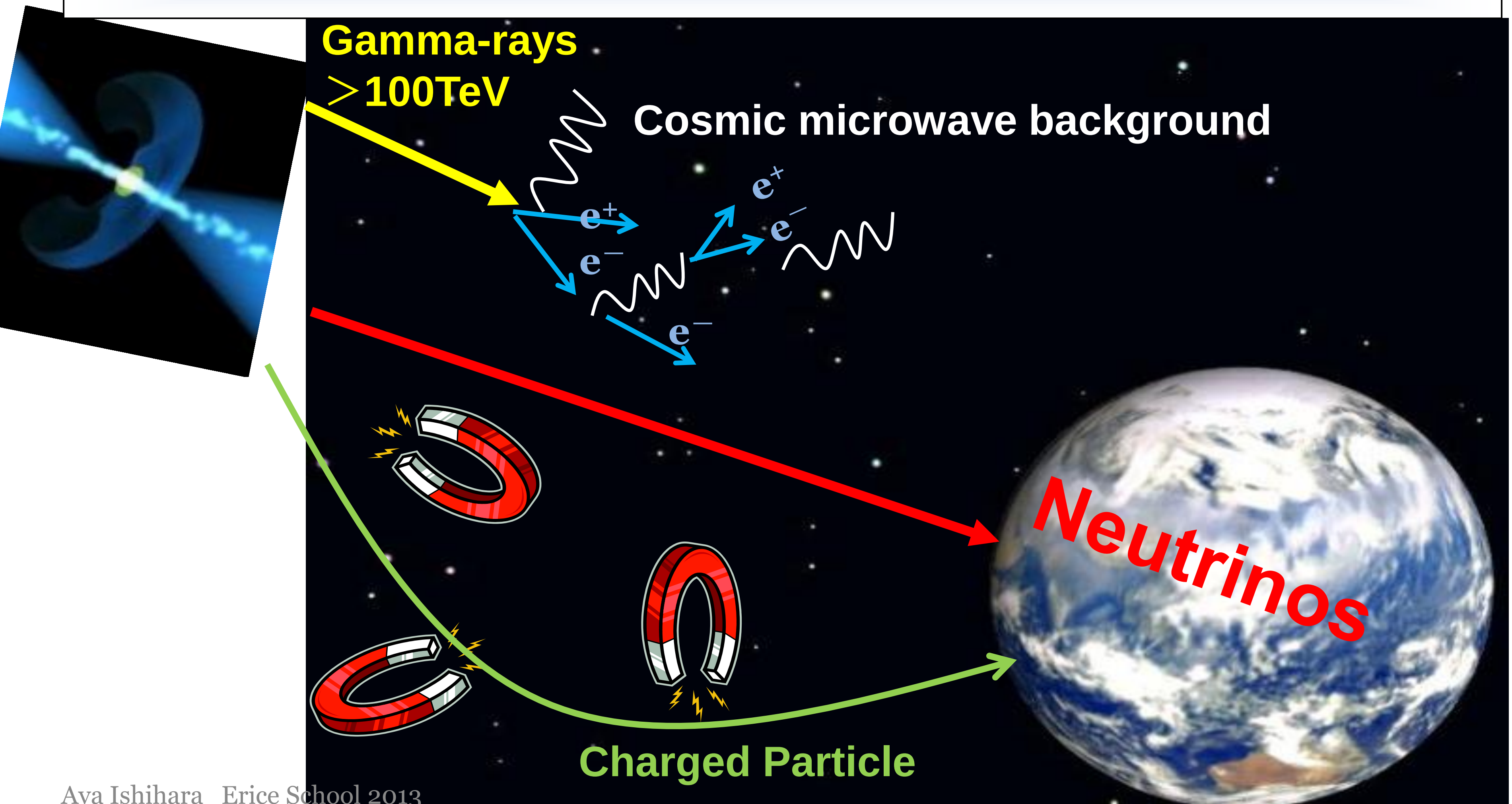


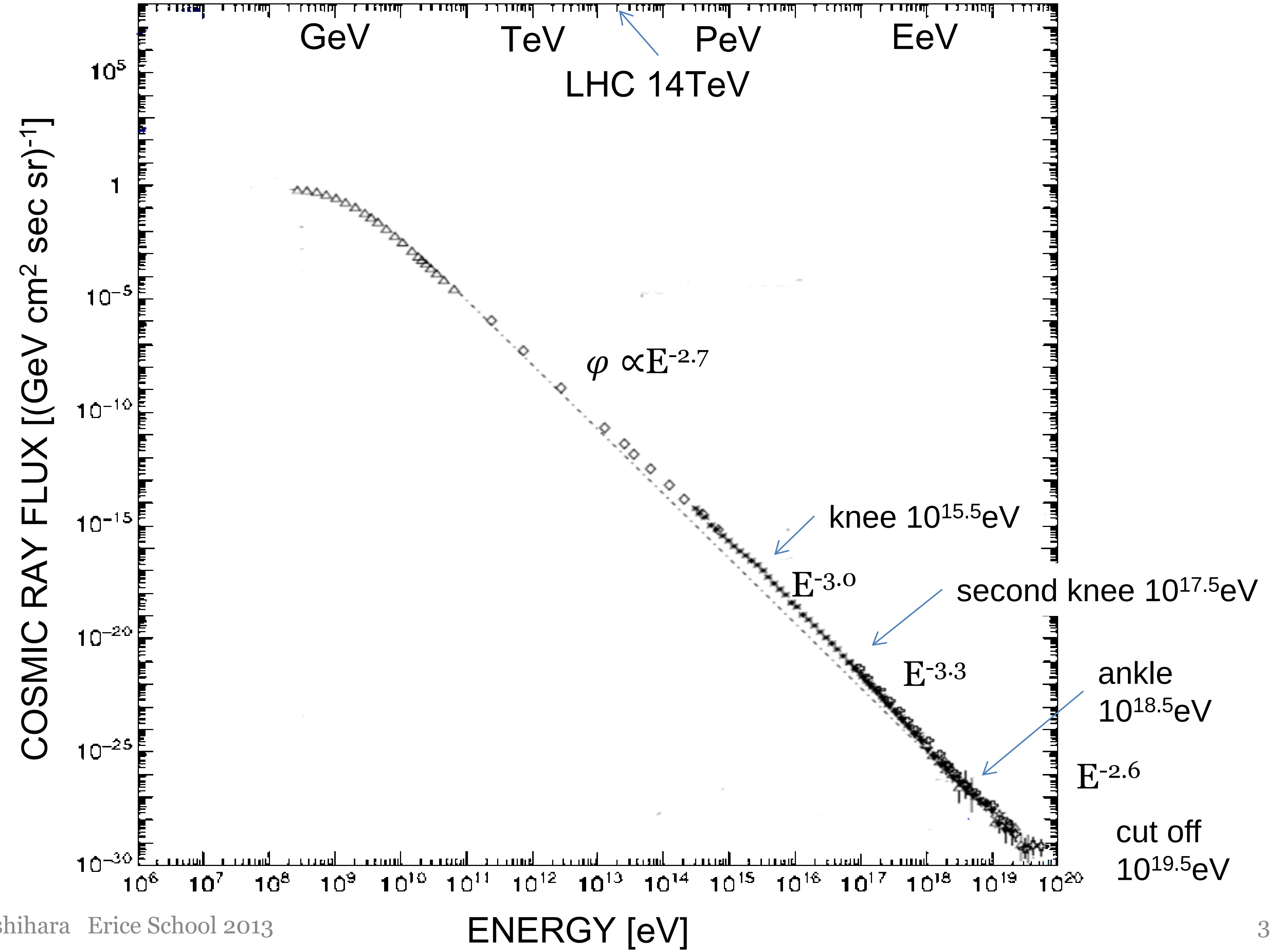
International School of Nuclear Physics 35th Course
Neutrino Physics: Present and Future
Erice Sicily September 21, 2013

Why Cosmic Neutrinos?

- Cosmic-rays (proton or nuclei) are charged particles of which trajectories are bend by unknown magnetic field
- Gamma-rays loose their energy via interaction with cosmic-microwave background
  - typically 100k light years (diameter of our galaxy) at ~PeV (10^{15}eV)
  - gamma-rays are produced by both electrons and hadrons. hard to distinguish



Extremely-high energy emission in the Universe



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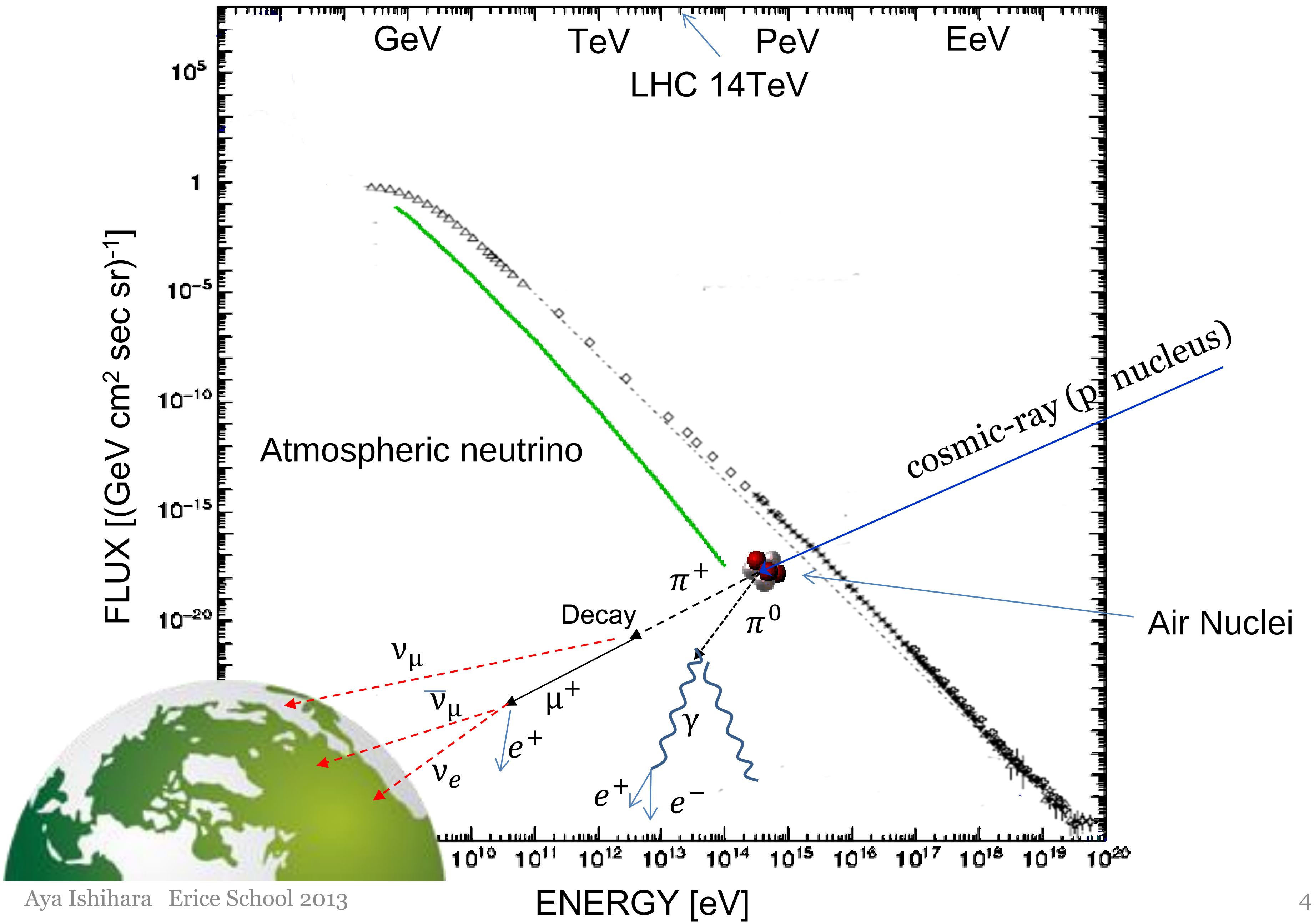
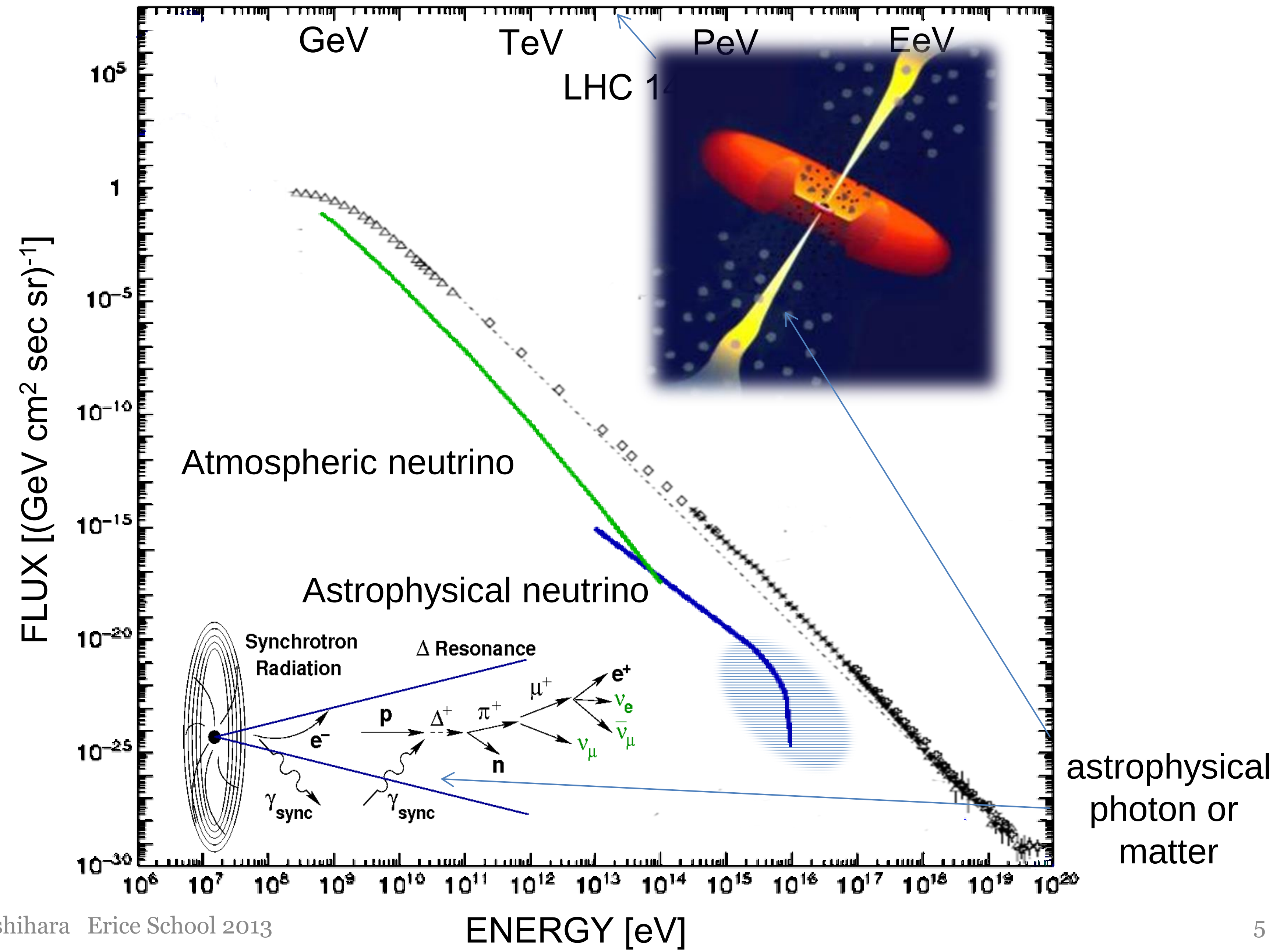
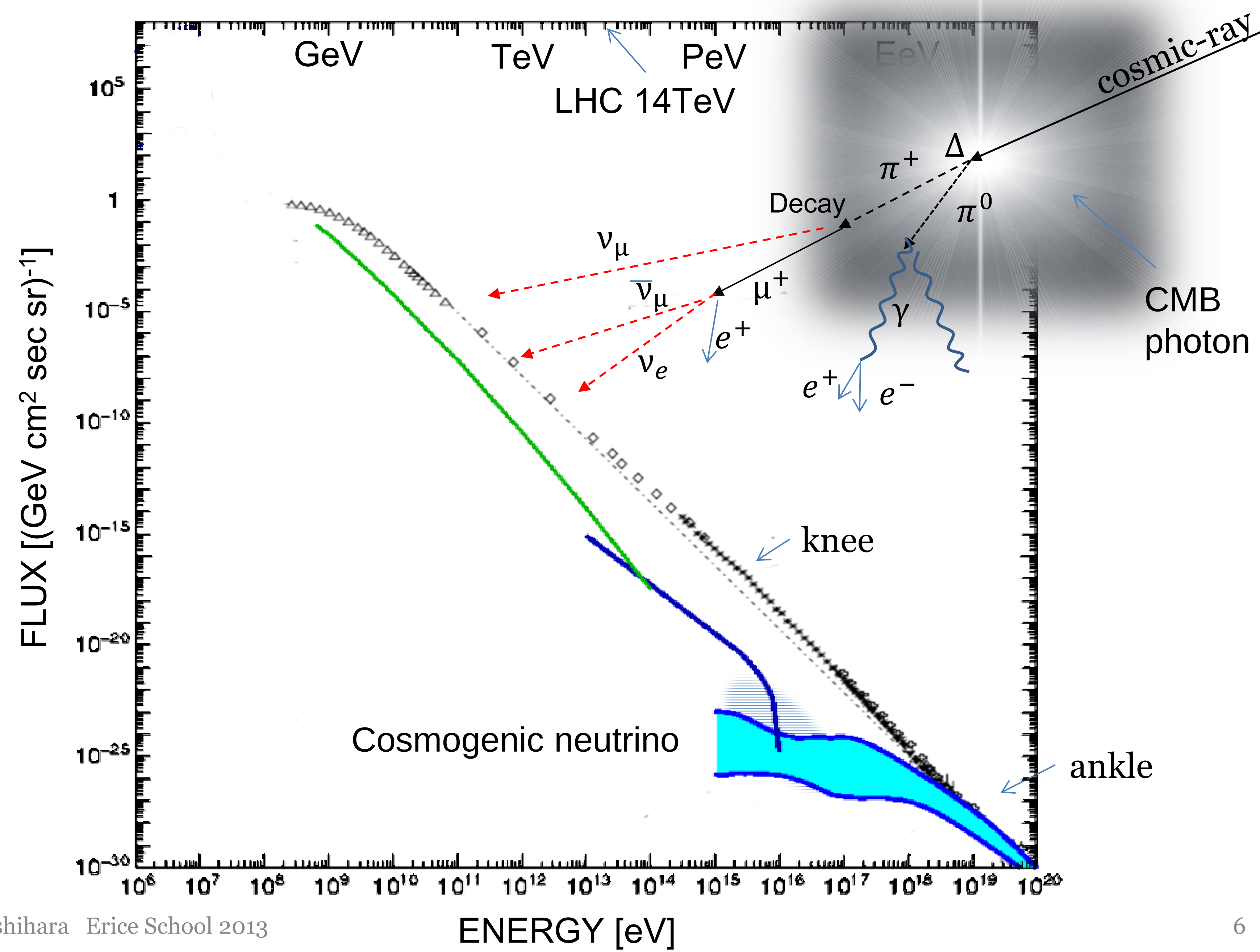


Extremely-high energy emission in the Universe



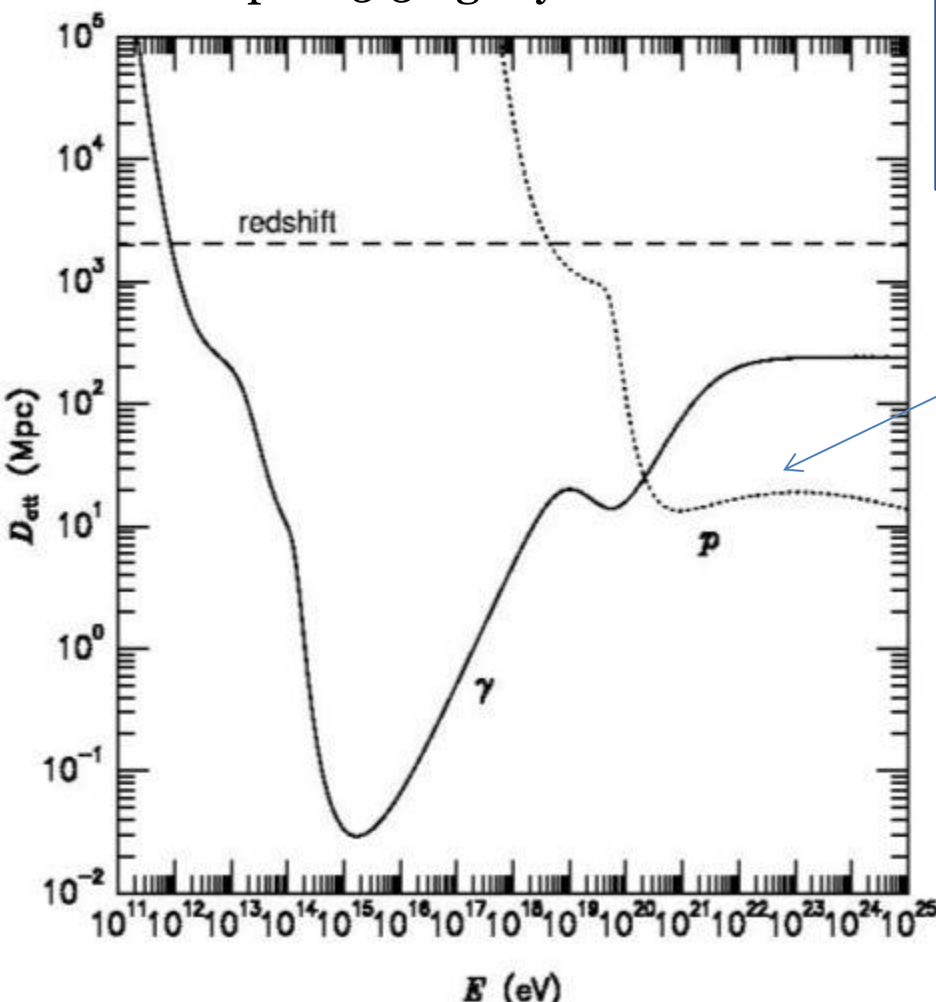
Extremely-high energy neutrinos in the Universe

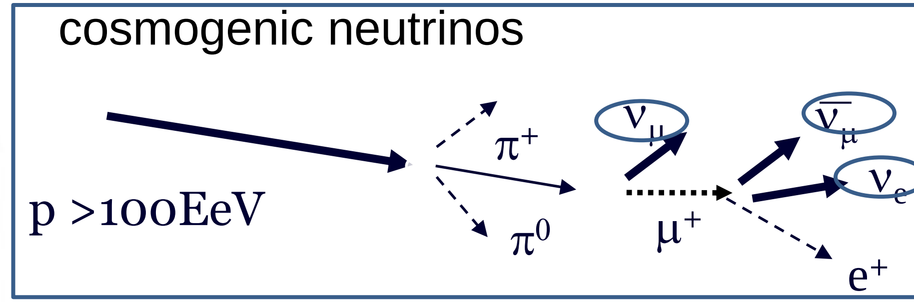


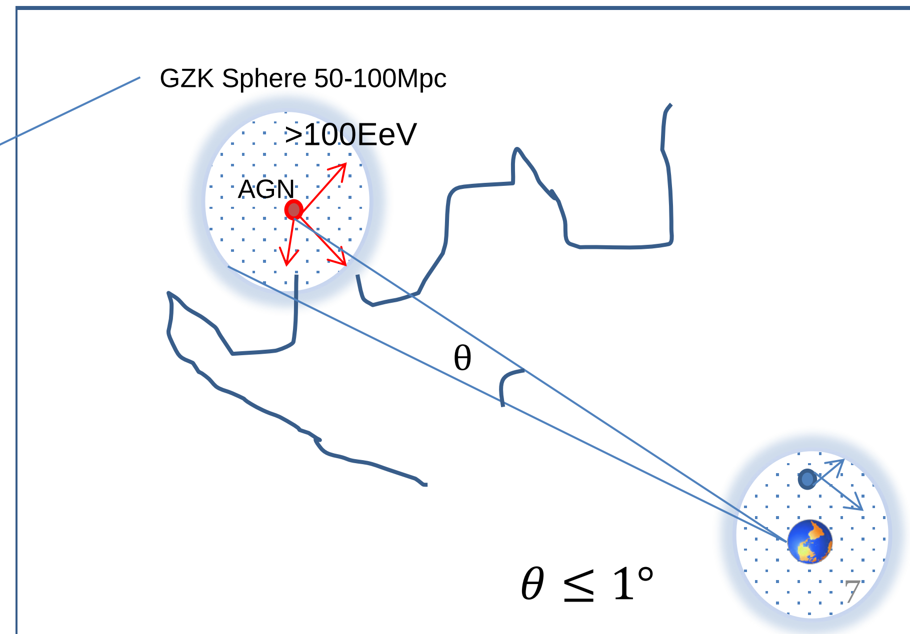
What the EHE neutrinos tells about the Universe

cosmogenic ν induced by the off-source (<50Mpc) interactions of cosmic-ray and CMB photons via GZK (Greisen-Zatsepin-Kuzmin) mechanism

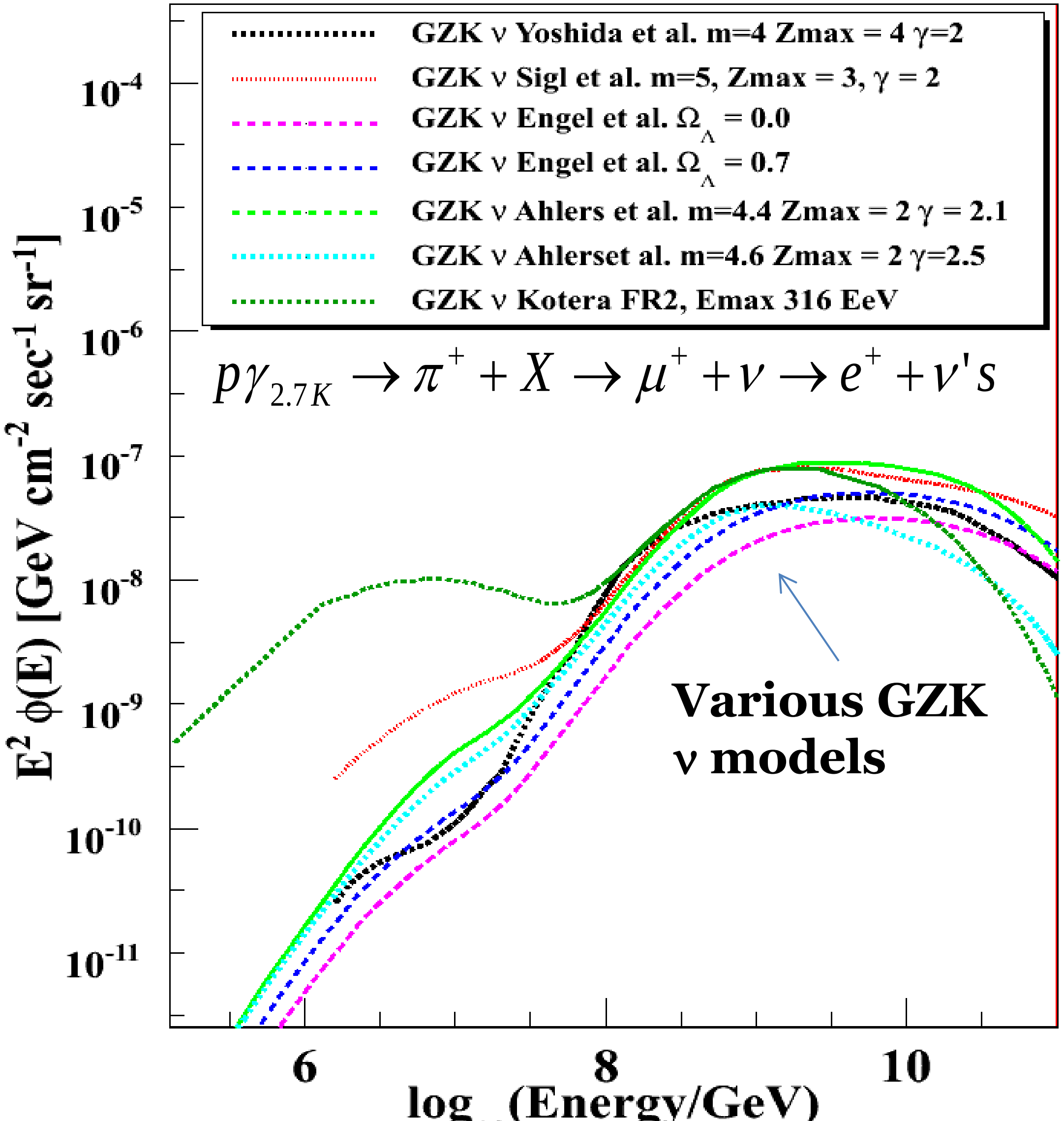
1 pc ~ 3.3 light years







What the EHE neutrinos tells about the Universe not accessible otherwise



- Location of the cosmic-ray sources
- Cosmological evolution of the cosmic-ray sources; intensity reflects the contributions from the sources in a high redshift region
- Cosmic-ray spectra at sources: the highest energy of the cosmic-rays $\mathbf{E}_{\mathbf{max}}$ and spectral slope
- Composition of the cosmic-rays

Plus

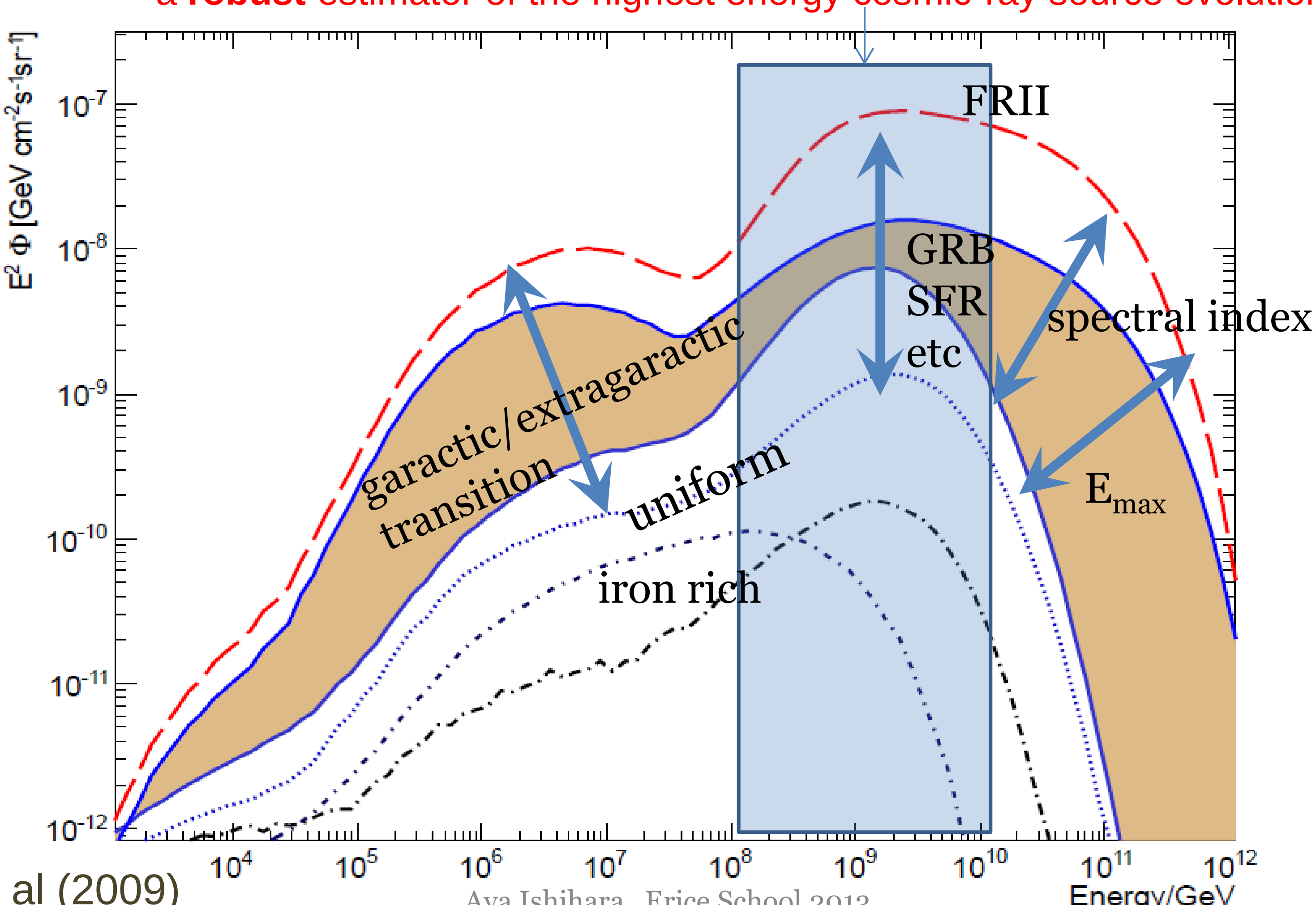
- Particle physics beyond the energies accelerators can reach

Cosmological neutrino flux shape carry a lot of information about the cosmic-ray origin

IceCube has a limited energy region sensitive to the cosmogenic neutrinos, we are sensitive to cosmological evolution not the other parameters

IceCube's view of the cosmogenic neutrinos

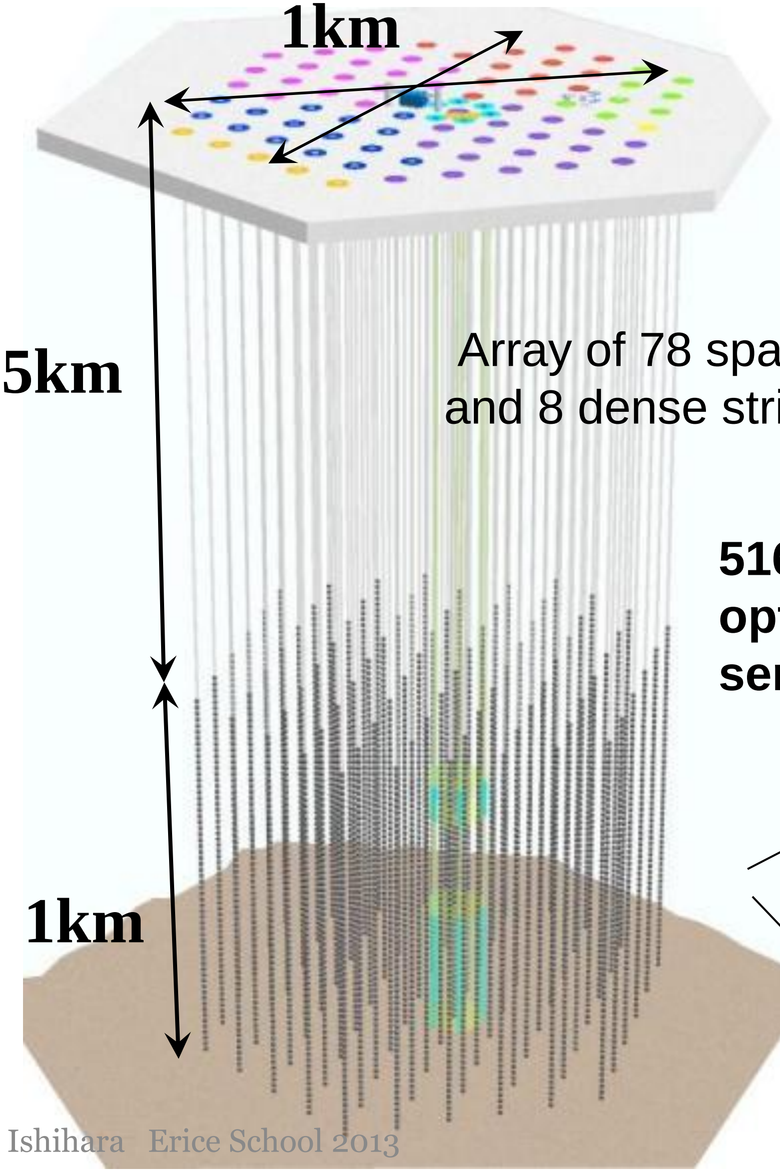
a **robust** estimator of the highest energy cosmic-ray source evolutions



Kotera et al (2009)

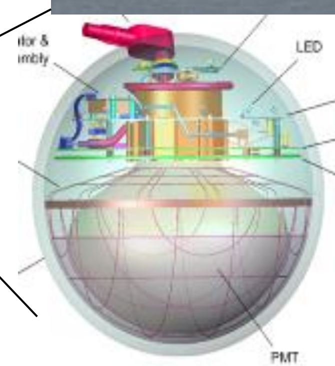
The Largest Neutrino Detector in the world:

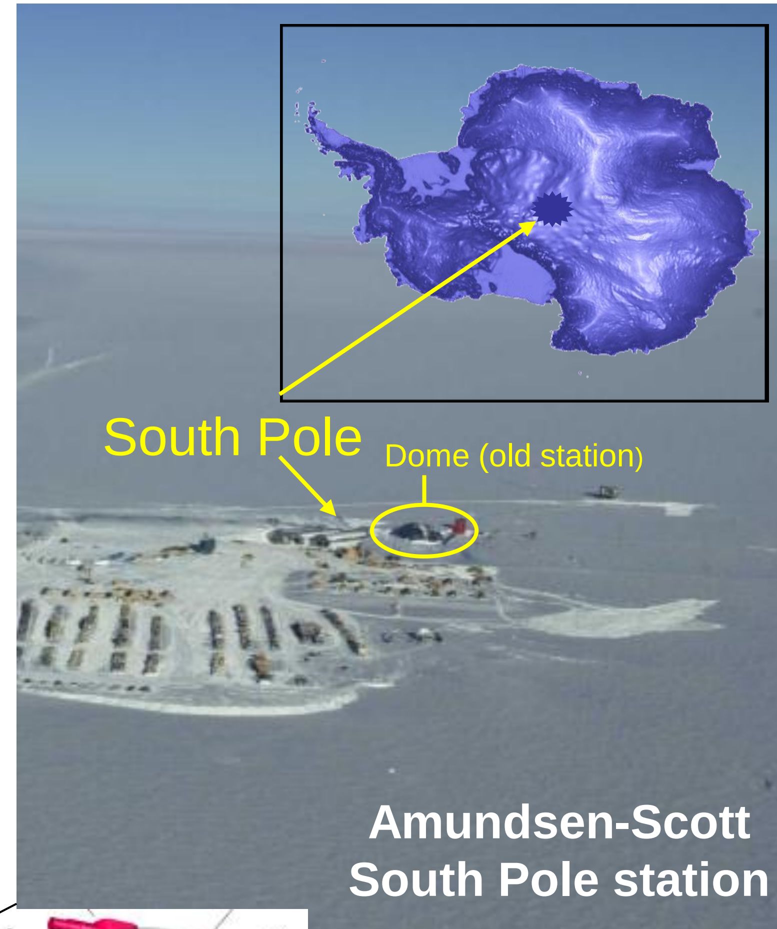
The IceCube Detector



Array of 78 sparse and 8 dense strings

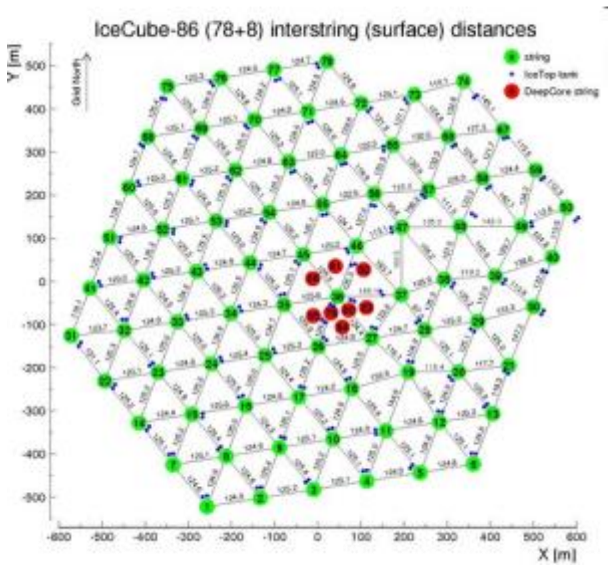
5160 optical sensors



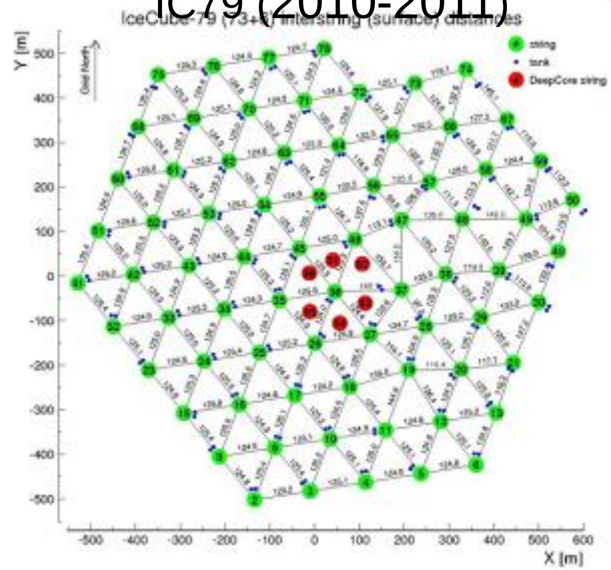


IceCube Construction and Runs

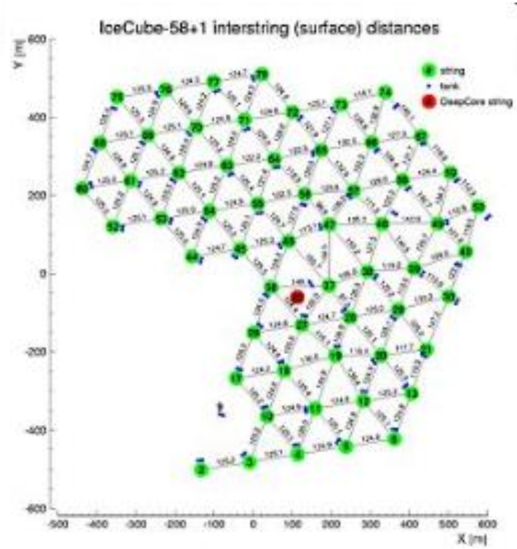
IC86 = full IceCube (2011~)



IC79 (2010-2011)



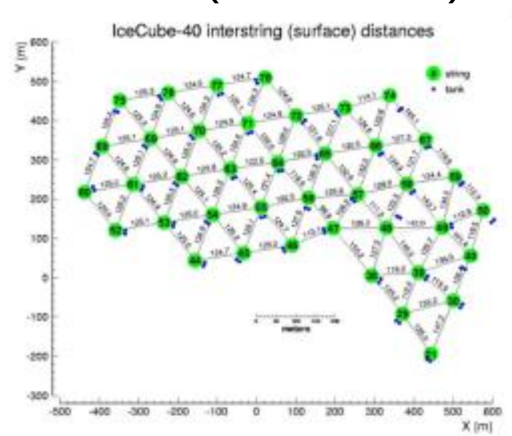
IC59 (2009-2010)



Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per day)
IC40	2008-09	375 days	1100	~40/ day
IC59	2009-10	350 days	1900	~70/ day
IC79	2010-11	320 days	2250	~100/day
IC86-I	2011- 2012	360 days	2700	~120/day
IC86-II	2012- 2013	360 days	2700	~120/day
IC86-III	2013-	TBD	2700	~120/day

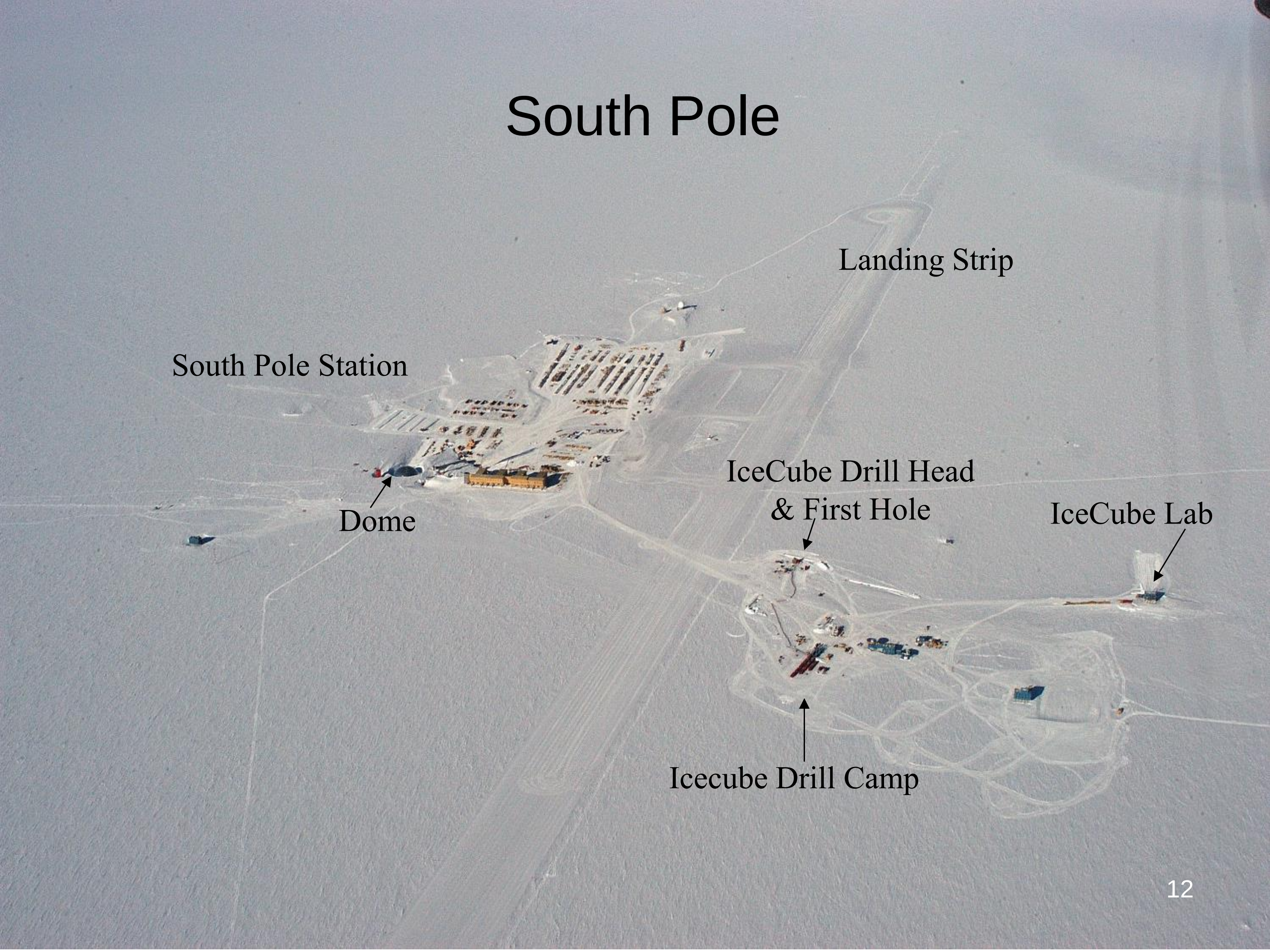
This talk (IC79, IC86-I)

IC40 (2008-2009)



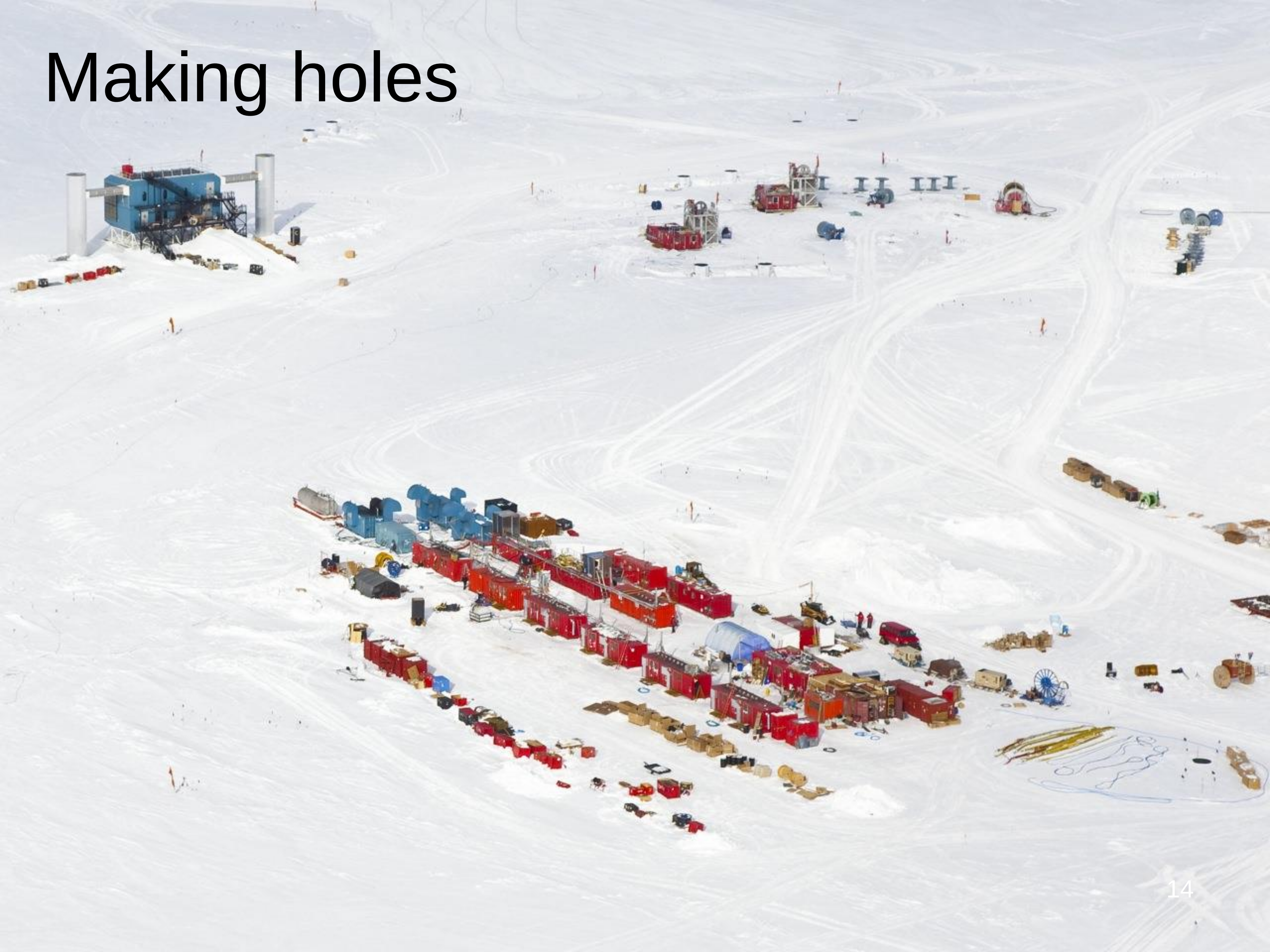
Very stable full operation since May 2011

South Pole

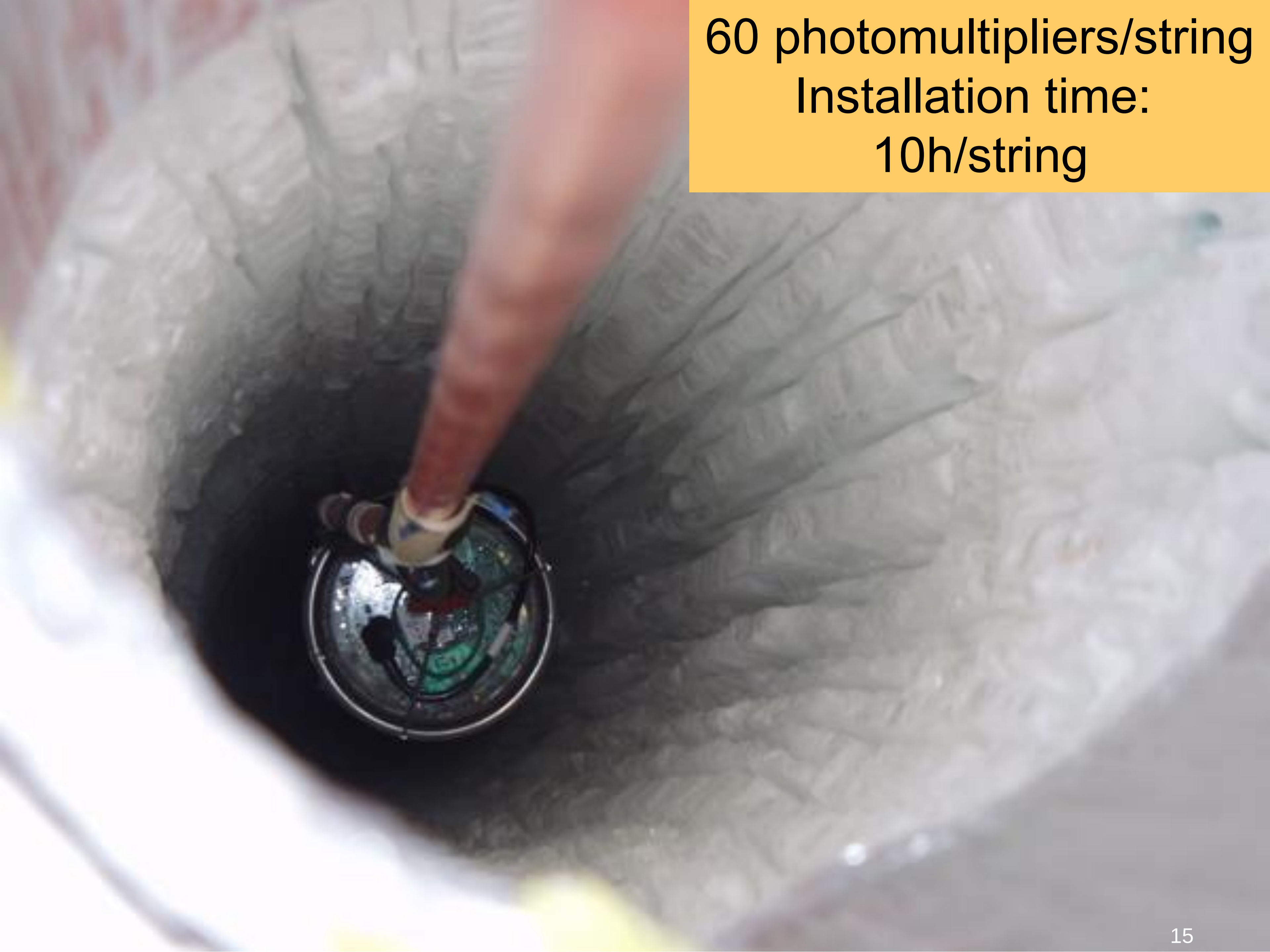

Landing Strip
South Pole Station
Dome
IceCube Drill Head
& First Hole
IceCube Lab
Icecube Drill Camp

The IceCube LAB

Making holes

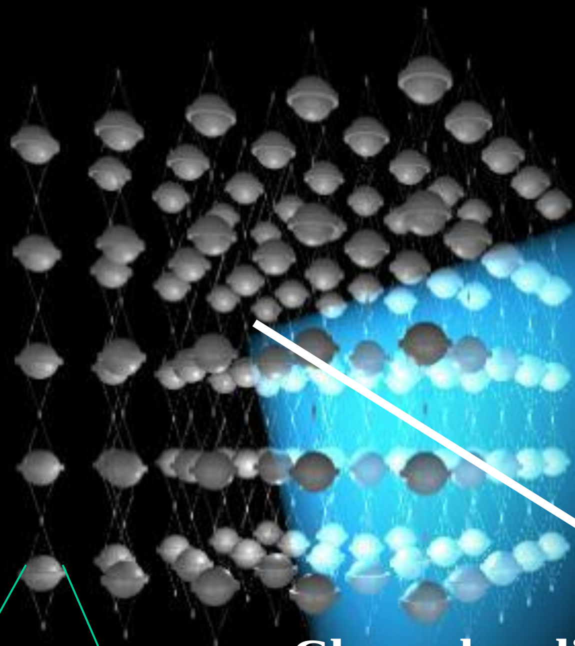


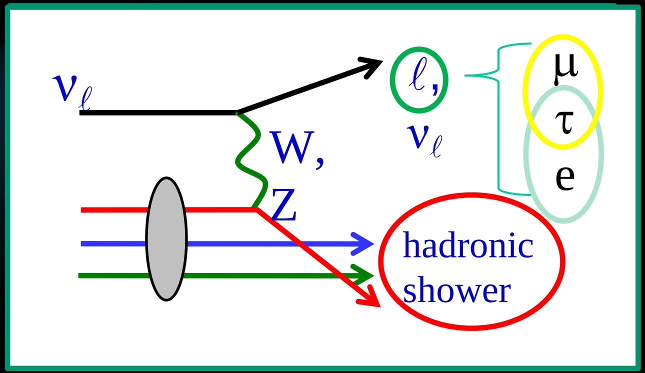
60 photomultipliers/string
Installation time:
10h/string



Detection Principle

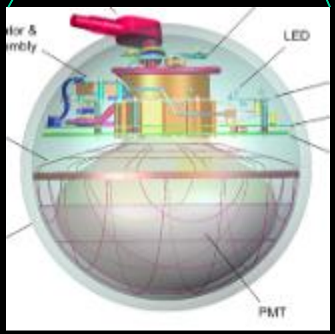
Dark and transparent material





μ, τ or cascades

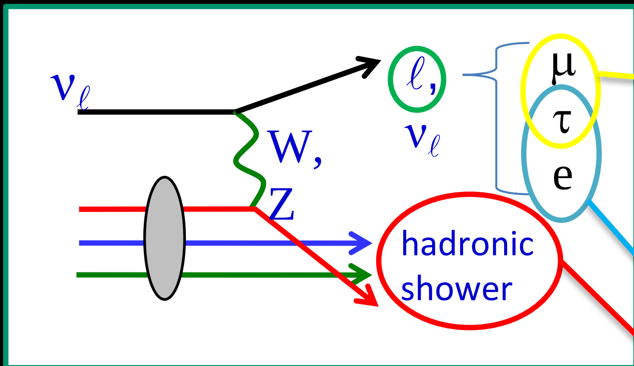
Cherenkov light

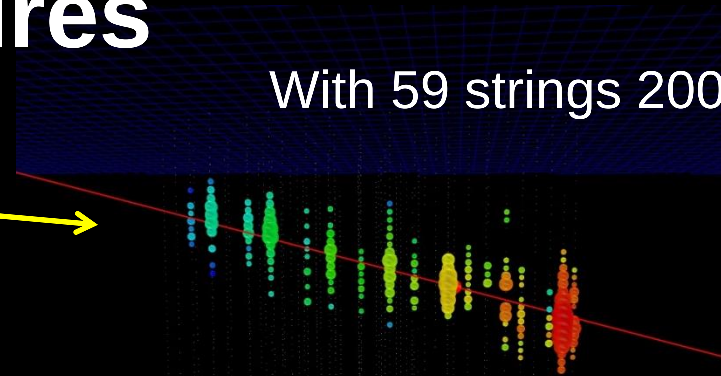


An array of
photomultiplier tubes

ν

IceCube event signatures

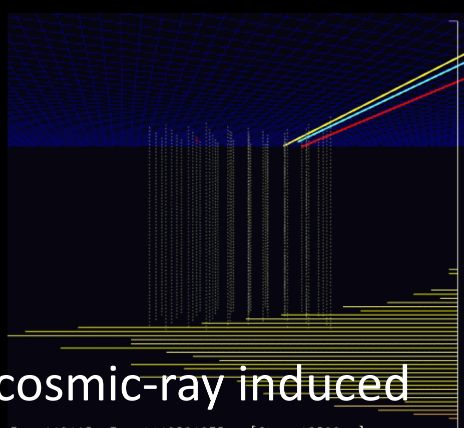




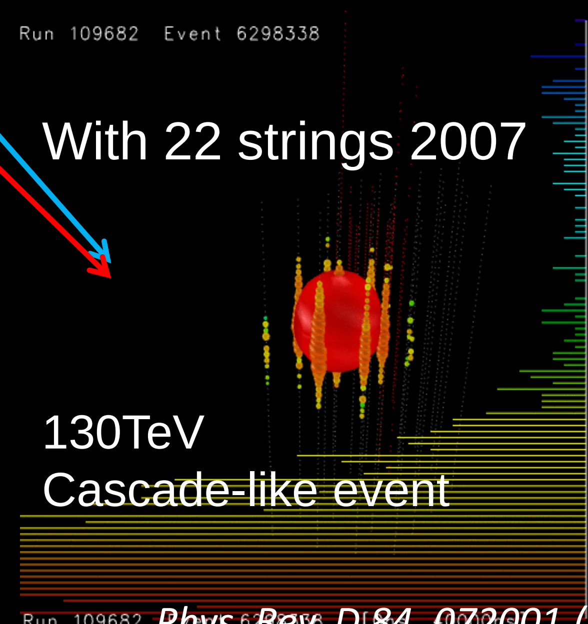
With 59 strings 2009

～100TeV up-going muon track event

With 40 strings, 2008 Dec



high energy cosmic-ray induced atmospheric muon bundle event



With 22 strings 2007

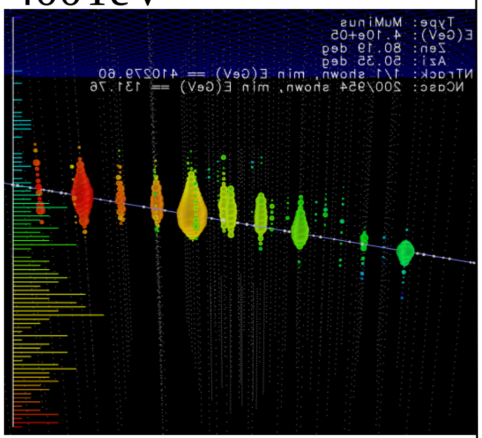
130TeV Cascade-like event

Phys. Rev. D 84, 072001 (2011)

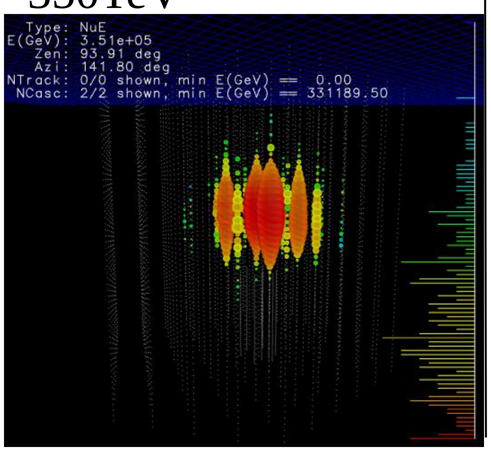
‘Brightness’ is the signature for UHE neutrinos

below ~PeV, upward-going tracks and cascade-like topology is important

400TeV



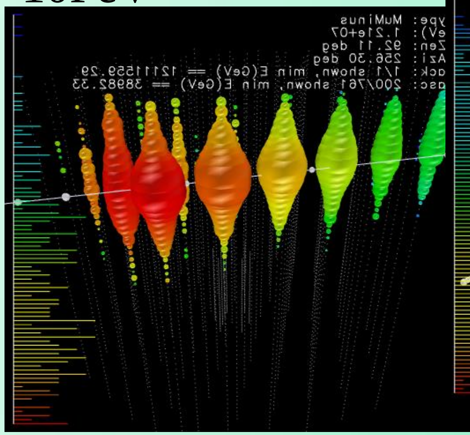
350TeV



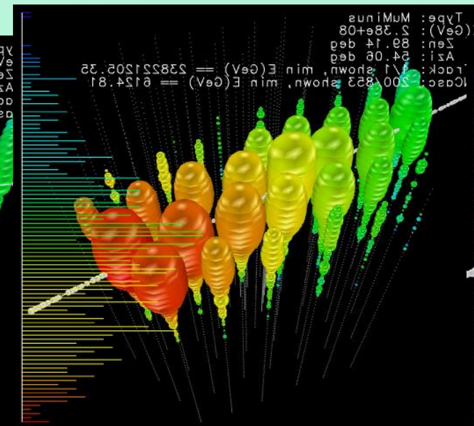
‘Very bright’ is an important feature

A brightness condition can select both type of events

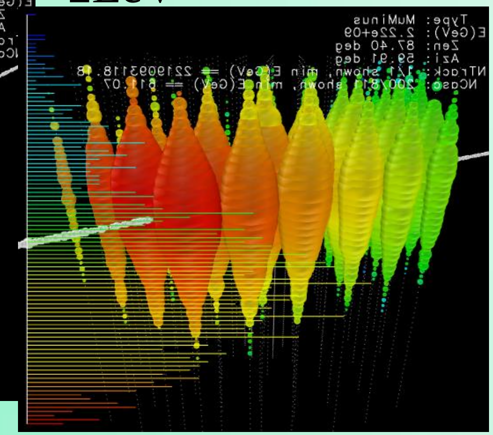
10PeV



200PeV



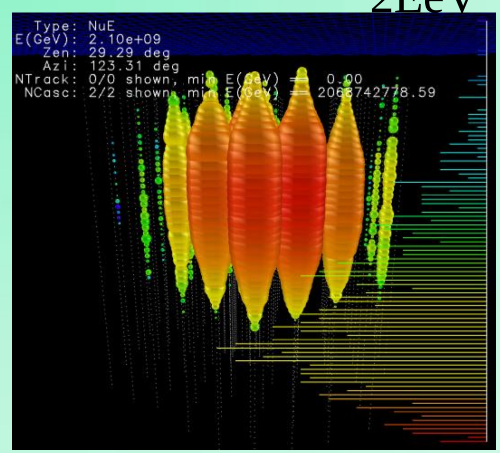
2EeV



$$-\left\langle \frac{dE}{dX} \right\rangle = \alpha + \beta E$$

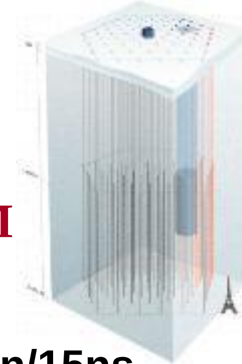
- NPE is the number of photoelectron signals measured by IceCube detector

2EeV



from MC simulation

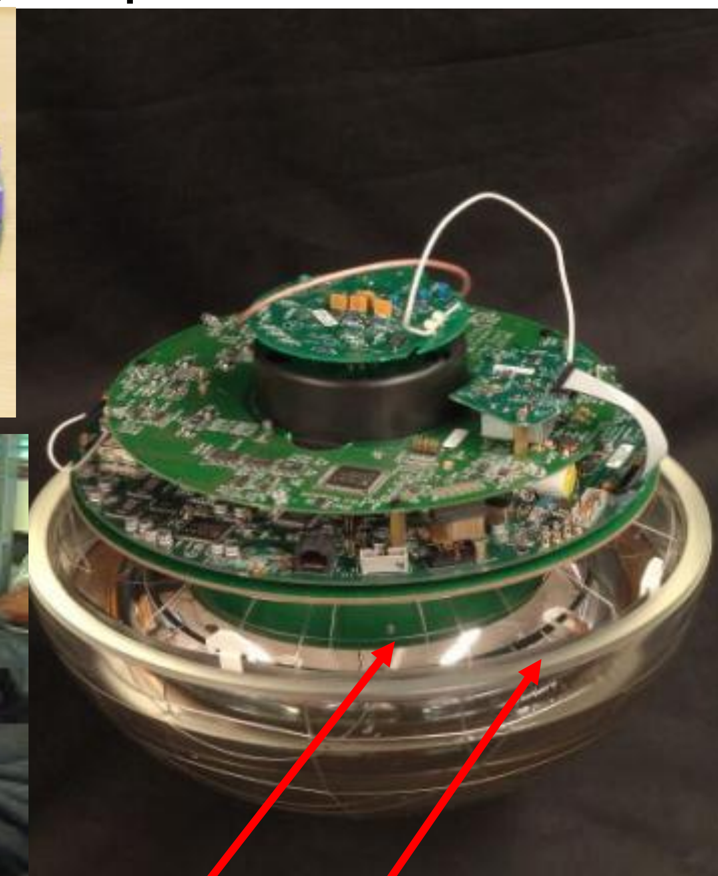
Digital Optical Module



- **PMT: 10 inch Hamamatsu**
- **Power consumption: 3 W**
- **Digitize at 300 MHz for 400 ns with custom chip**
- **40 MHz for 6.4 μs with fast ADC**
- **Flasherboard with 12 LEDs**
- **Local HV**

Waveforms, times digitized in each DOM

- **Dynamic range 500 photoelectron/15ns**

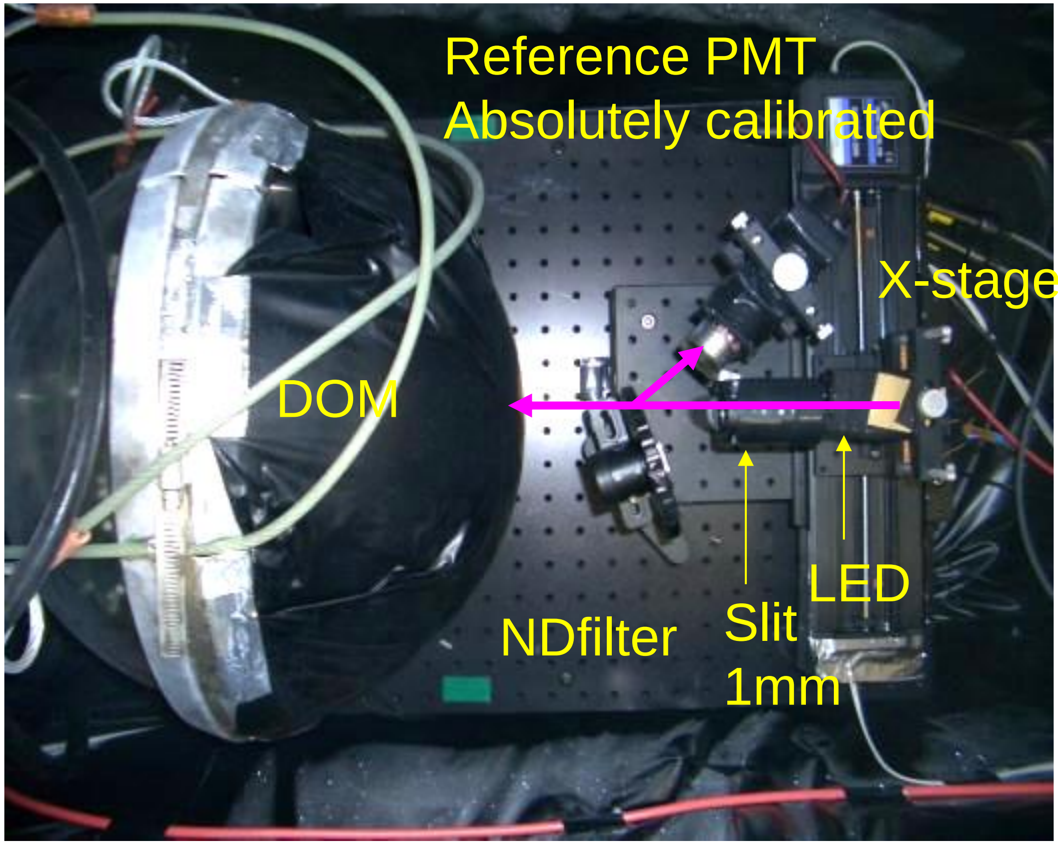


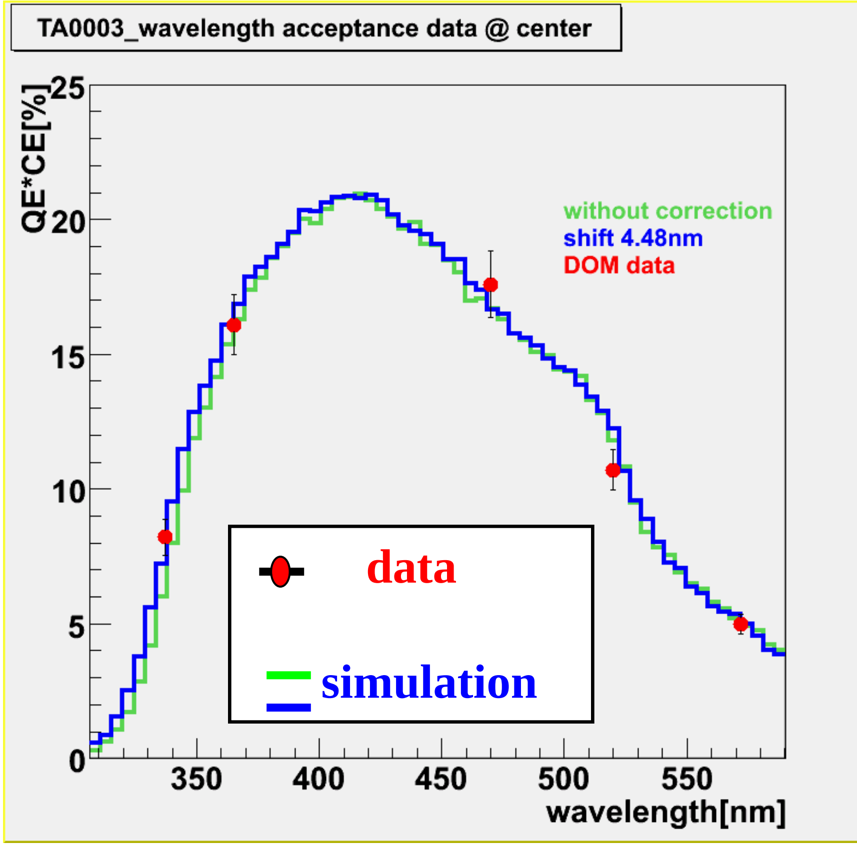
Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
Time calibration resolution = 2 nsec

25 cm PMT
33 cm Benthosphere

Absolute Calibration of DOMs

QE × CE Absolute calibration





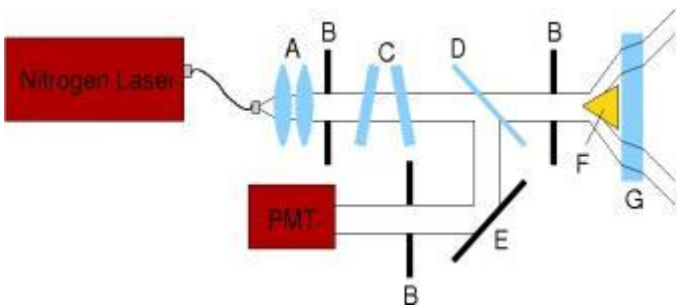
Reflectivity : 14.5%±0.73
Transmission : 50.7%±2.54

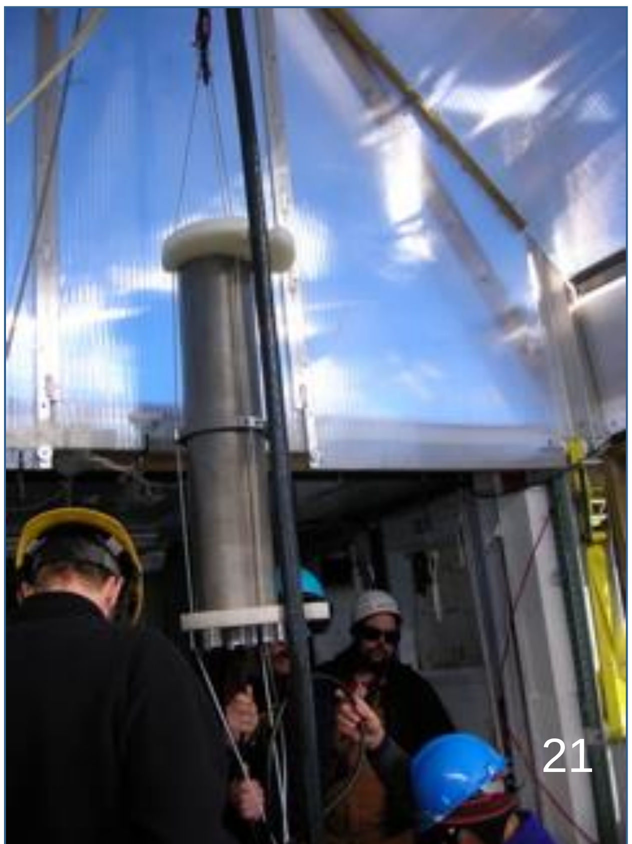
Nuclear Instruments and Methods A, 618 (2010)

In-*situ* Absolute Calibration

Calibrated light source: Standard Candle

- **in-situ calibrated N_2 pulsed laser**
- **light wavelength 337 nm**
- **at 100% intensity generates $4x10^{12}$ photons per pulse emitted at 41^o**
- **output adjustable between 0.5% ~ 100%**

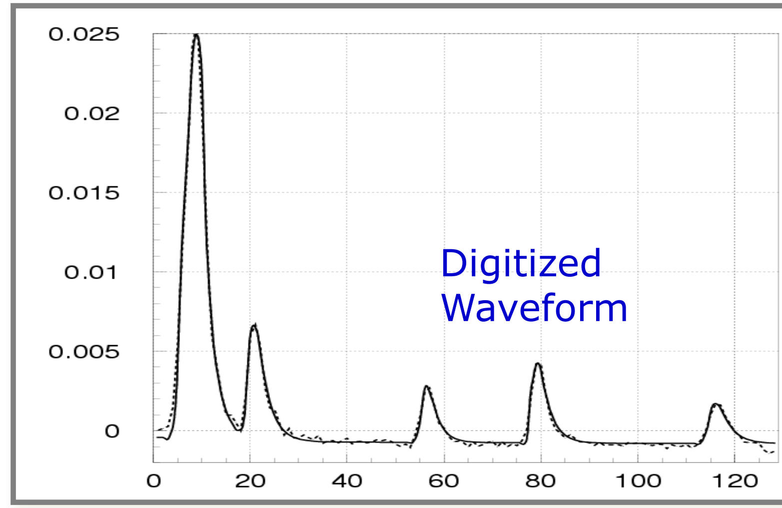


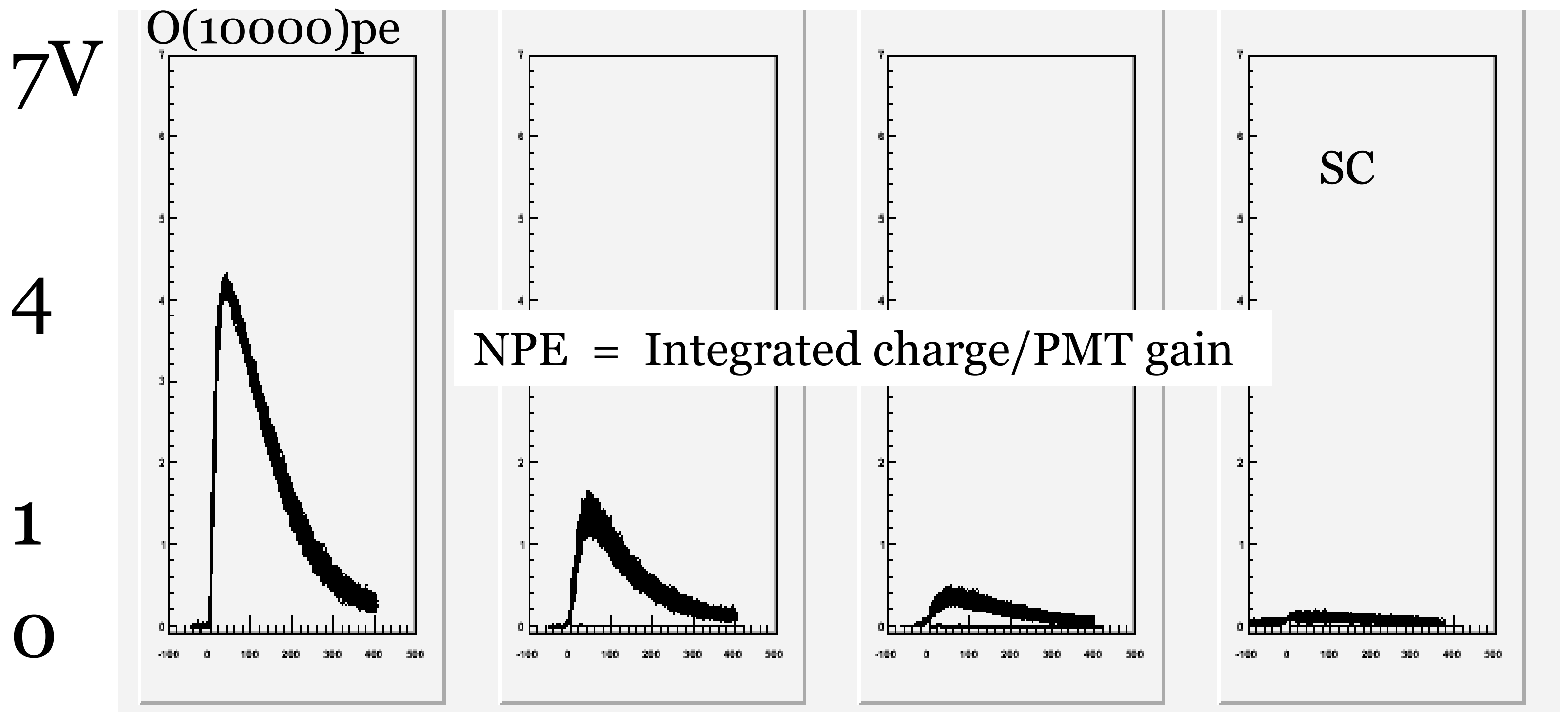


Waveform examples from spe to 10,000 pe

25 cm PMT

single pe level

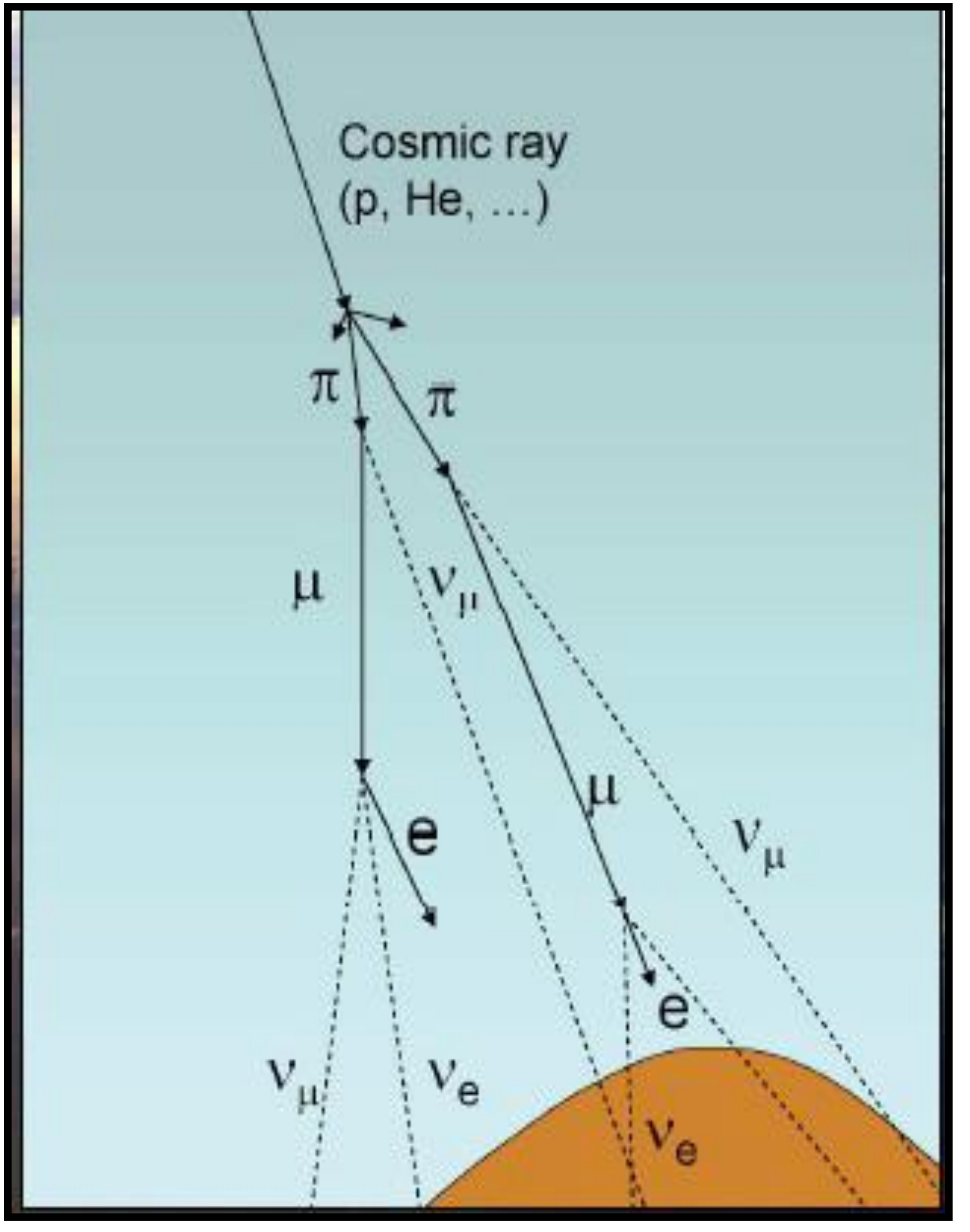




NPE = Integrated charge/PMT gain

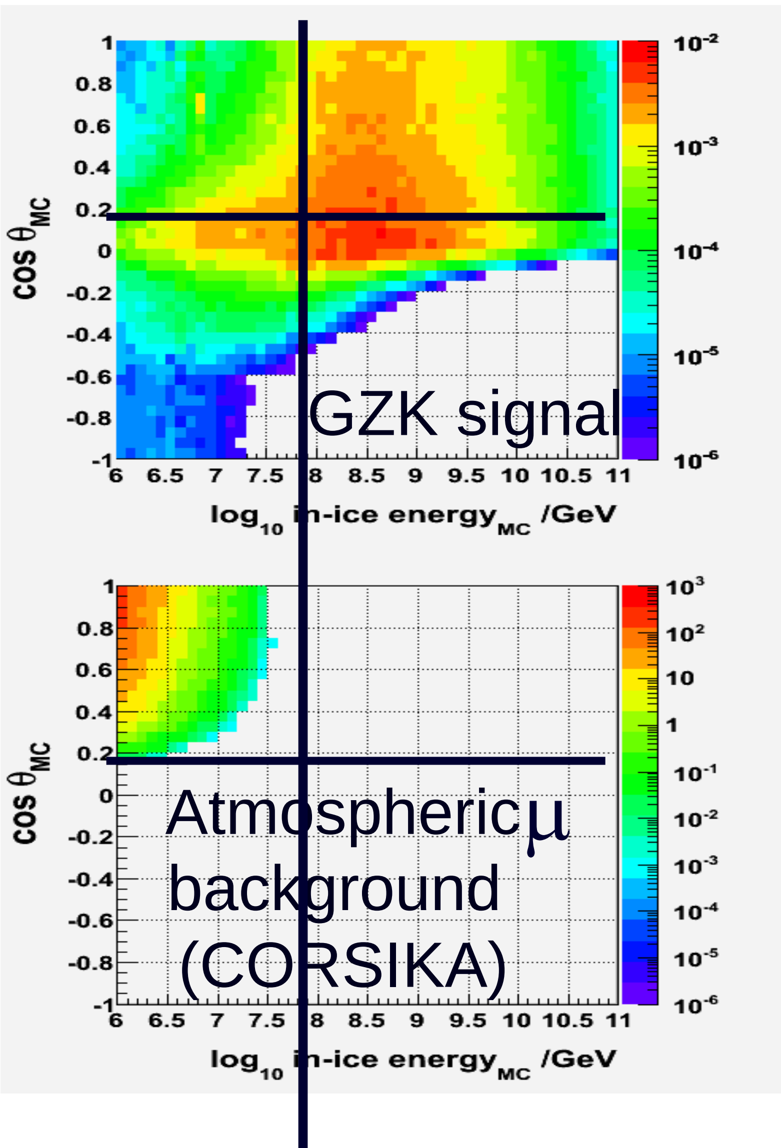
Background

Atmospheric muons
(downward going,
more energetic and
dominant in number)
and
Atmospheric
neutrinos
(full angle, less
energetic, smaller in
rate)



Aya Ishihara

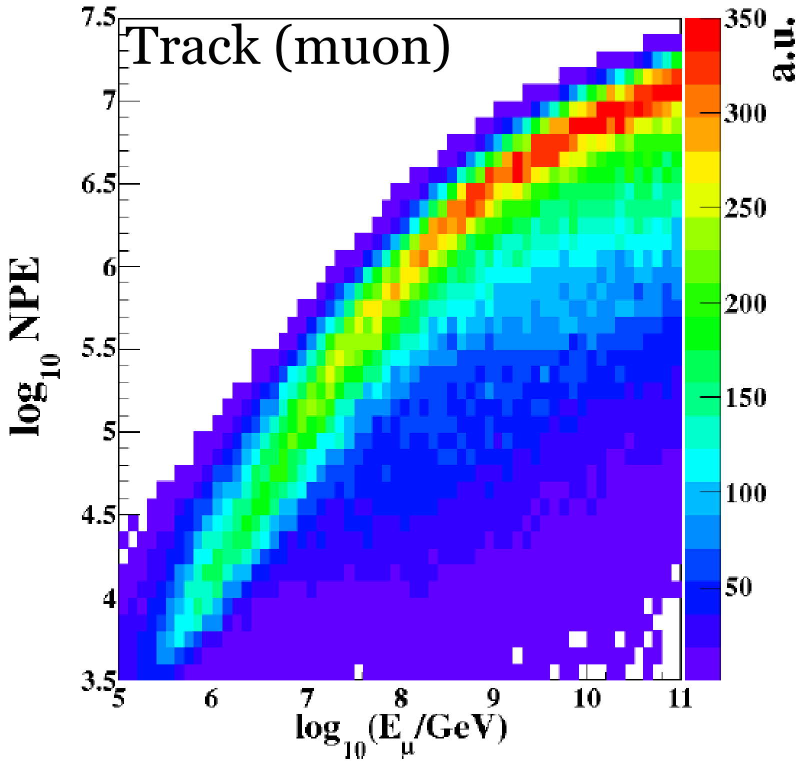
Atmospheric muon background rejection

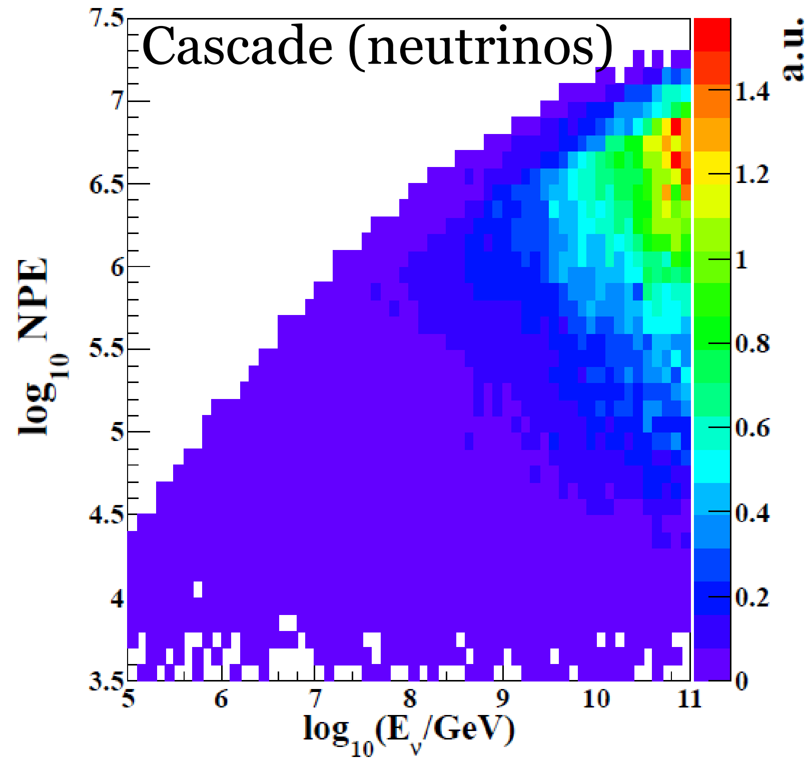


Background energy smaller than signal

Background muons are vertical downward-going while signal comes near horizon

The Energy–Brightness relation

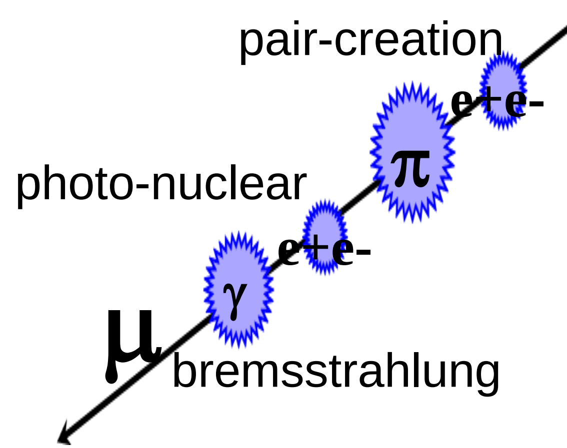




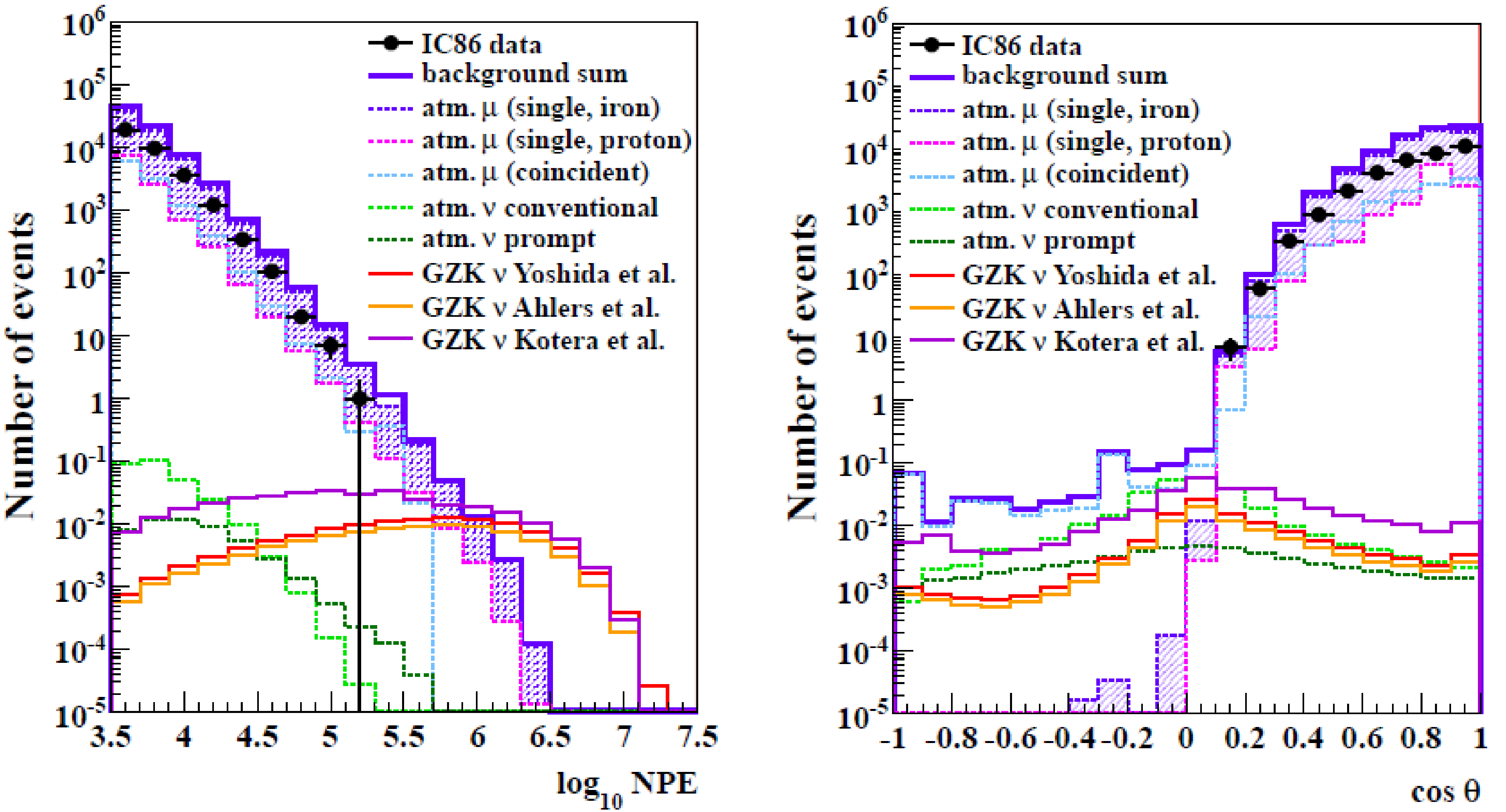
- NPE is the number of photoelectron signals measured by IceCube detector

$$-\left\langle \frac{dE}{dX} \right\rangle = \alpha + \beta E$$

Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)



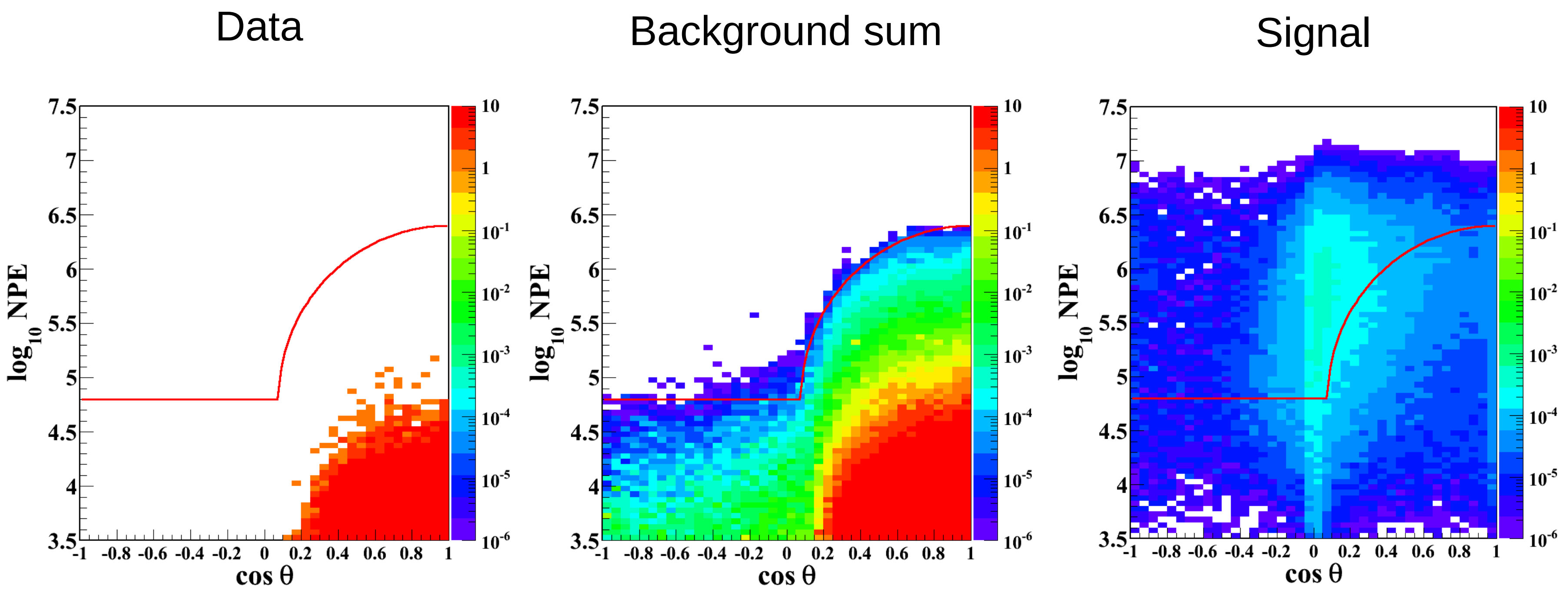
Brightness and zenith angle distributions



NPE = Integrated charge/PMT gain

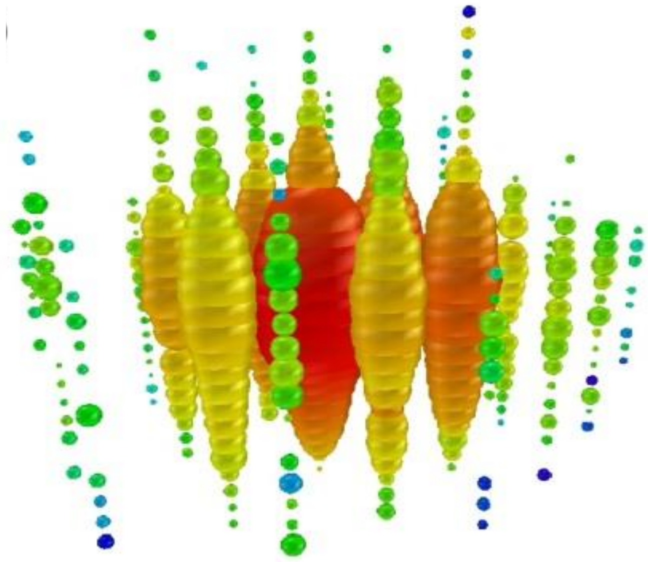
Analysis Level NPE vs ZA

IC86



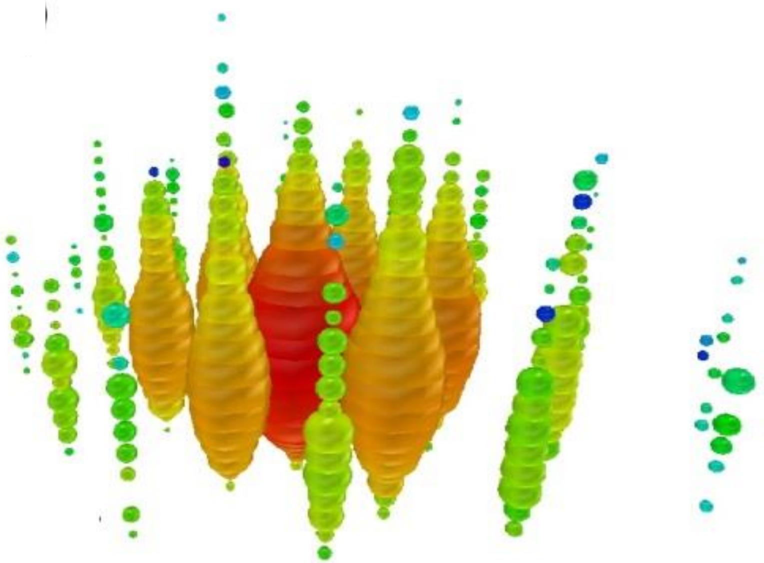
Open the box - Observation of 2 events

Run118545-Event6373366
NPE 6.9928×10^4
GMT time: 2011/8/8 12:23:18



1.0PeV

Run119316-Event36556705
NPE 9.628×10^4
GMT time: 2012/1/3 9:34:01



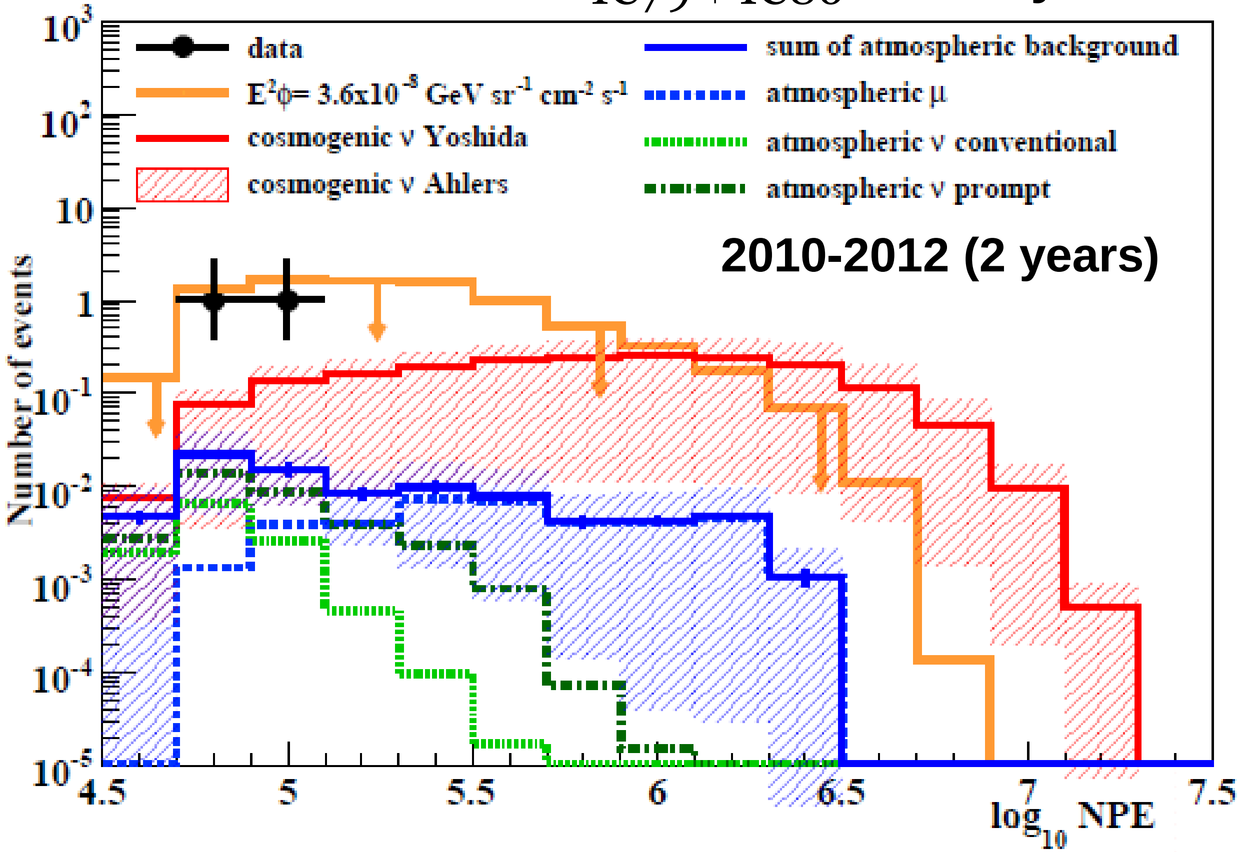
1.1PeV

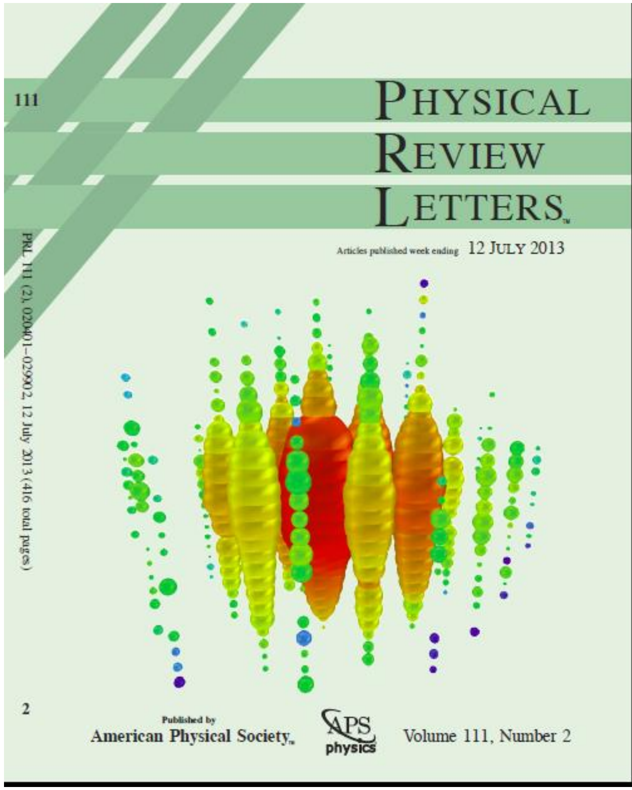
Extremely high energy neutrino search above PeV

- ν_e:ν_μ:ν_τ=6:1:2 at 1PeV, 3:4:2 at 10PeV, 2:5:3 at 100PeV
- 2..8sigma excess over $0.08^{+0.04}_{-0.06}$ events of atmospheric BG

IC79+IC86

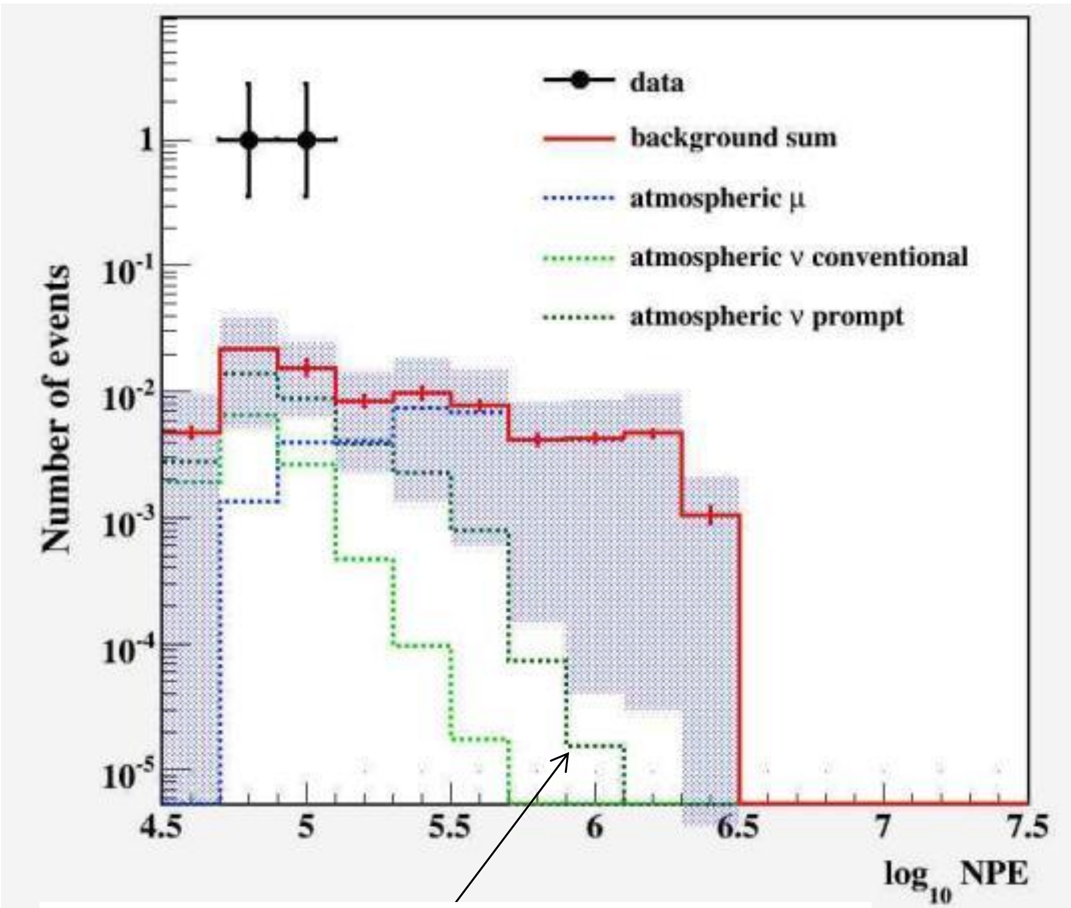
Phys. Rev. Lett. 111, 021103 (2013)





Number of photoelectrons: NPE ∝ Visible Energy

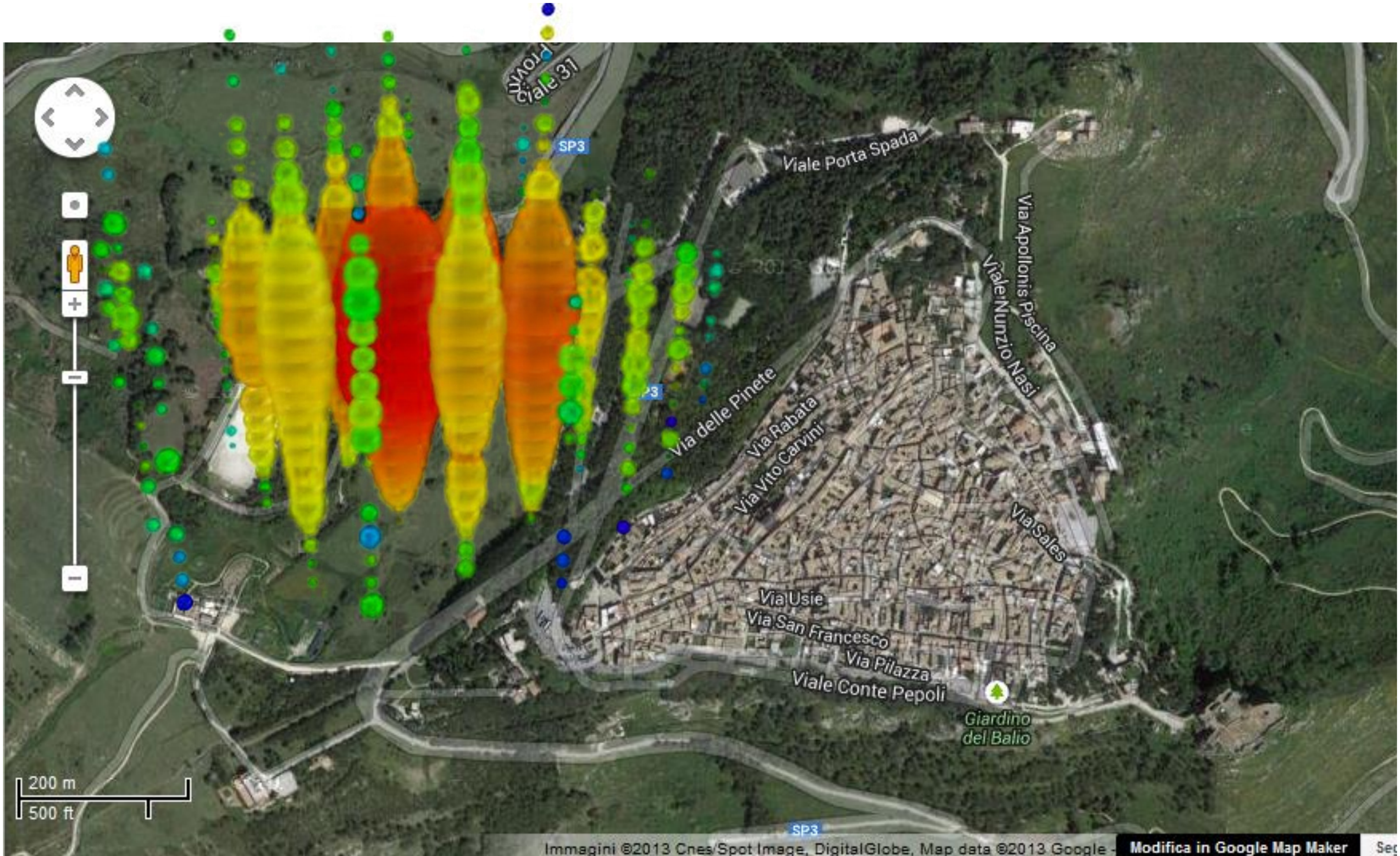
Background and systematics



The largest uncertainty is on the prompt (charm) ν model (a factor of 2 in pQCD model, up to a factor of 5 from nonpQCD)

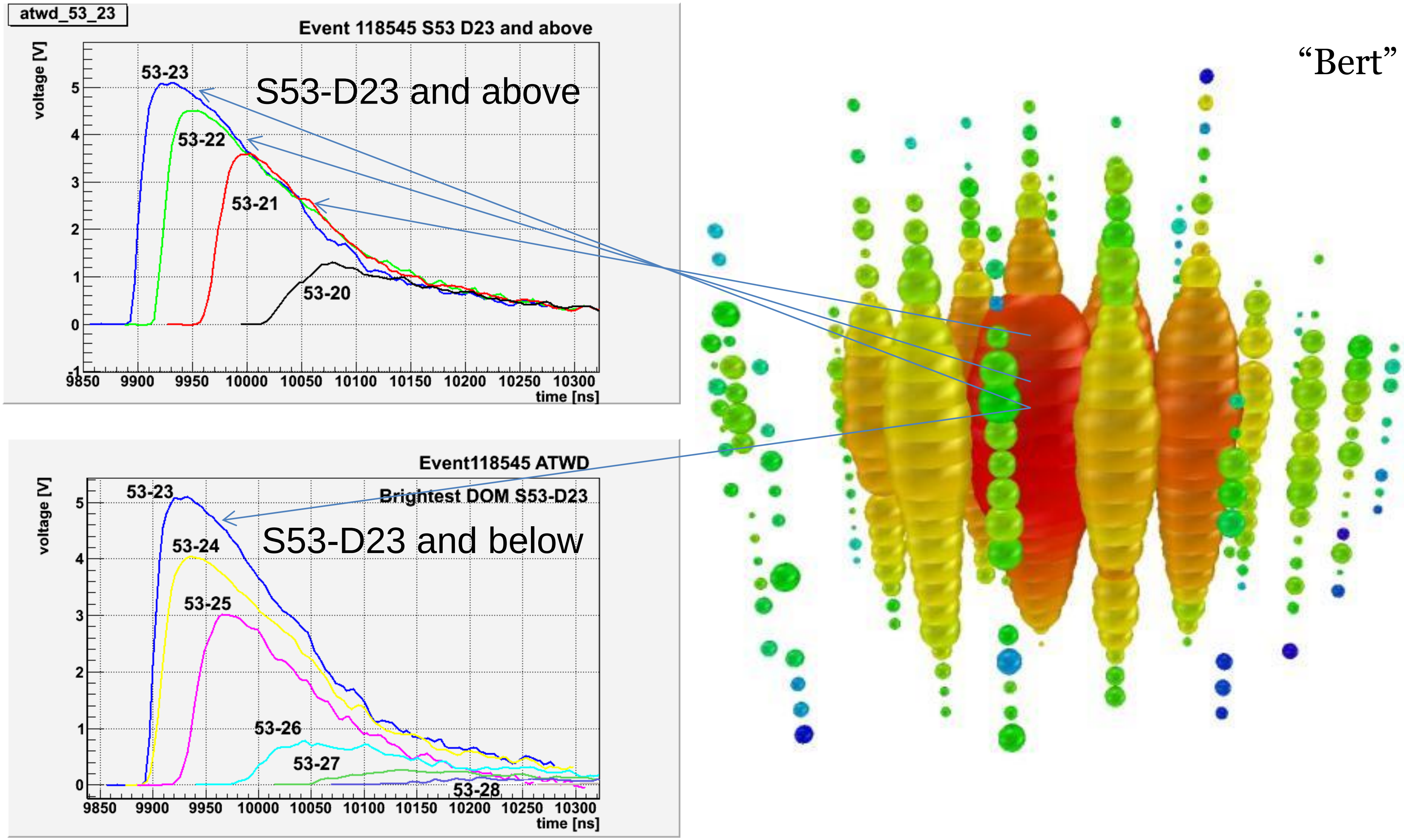
Sources	conventional Atm. μ, ν(%)	prompt (%)
Statistical error	±7.3	±1.1
DOM efficiency	+63.7, −30.8	+21.3, −18.9
Ice property and detector responses	−48.0	−29.8
Cosmic-ray flux variation	+24.0, −39.0	±30.0
Cosmic-ray composition	−61.0	
Hadronic interaction	+13.5	
nu yield from cosmic-ray nucleon	± 3.5	
Total	±7.3(stat) +69.5−92.5(sys)	±1.1(stat) +36.8−46.4(sys)

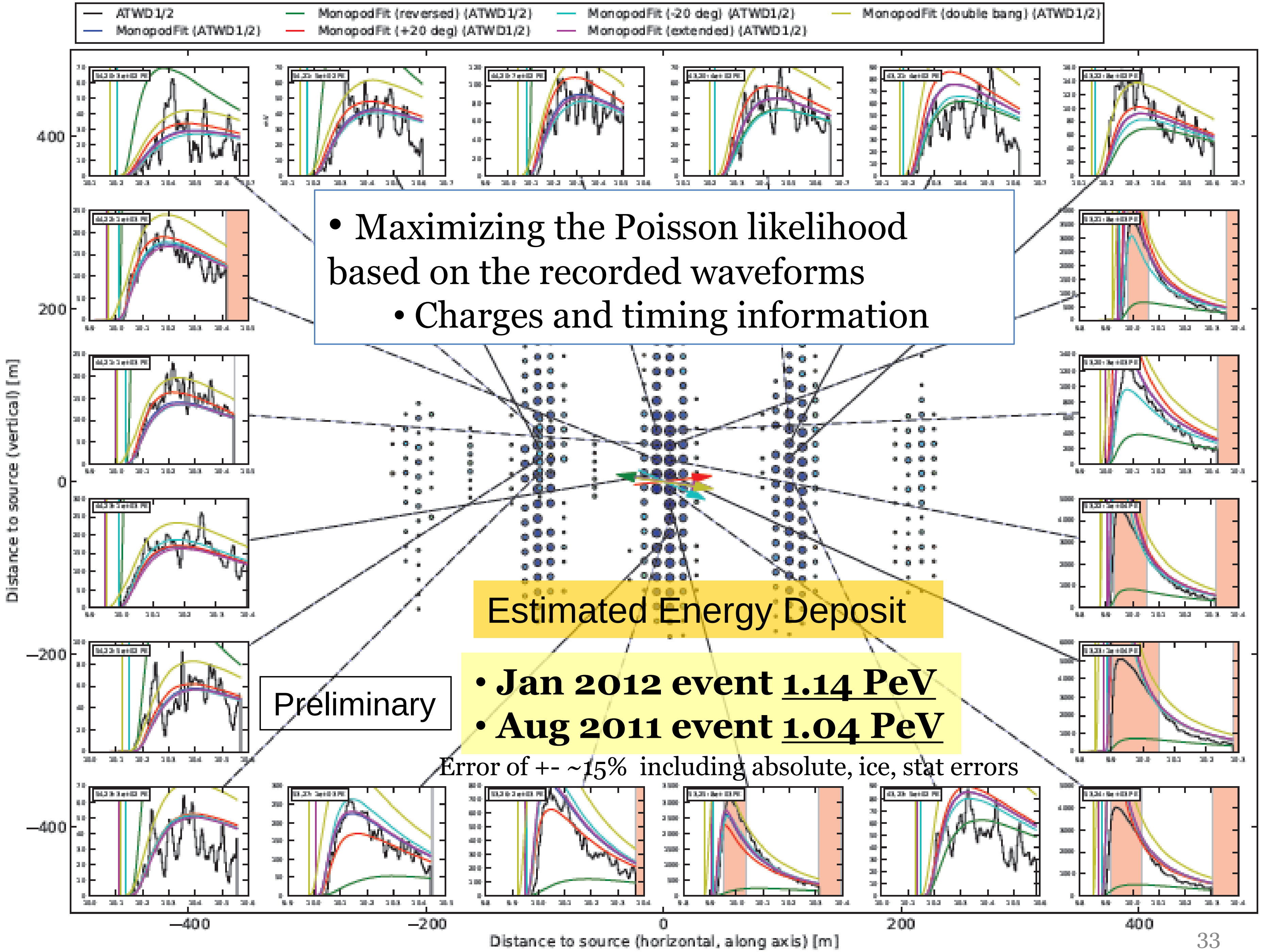
Scale the event with Erice



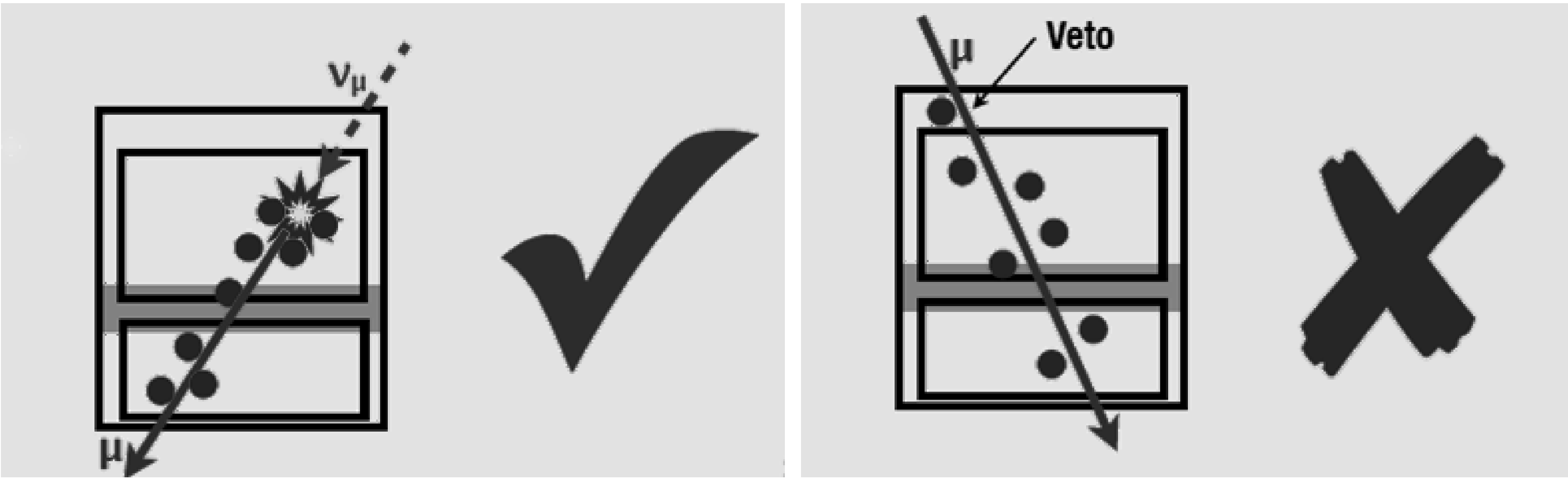
Event from Aug-2011

Calibrated ATWD waveforms above and below the highest charged DOM (S53-23)



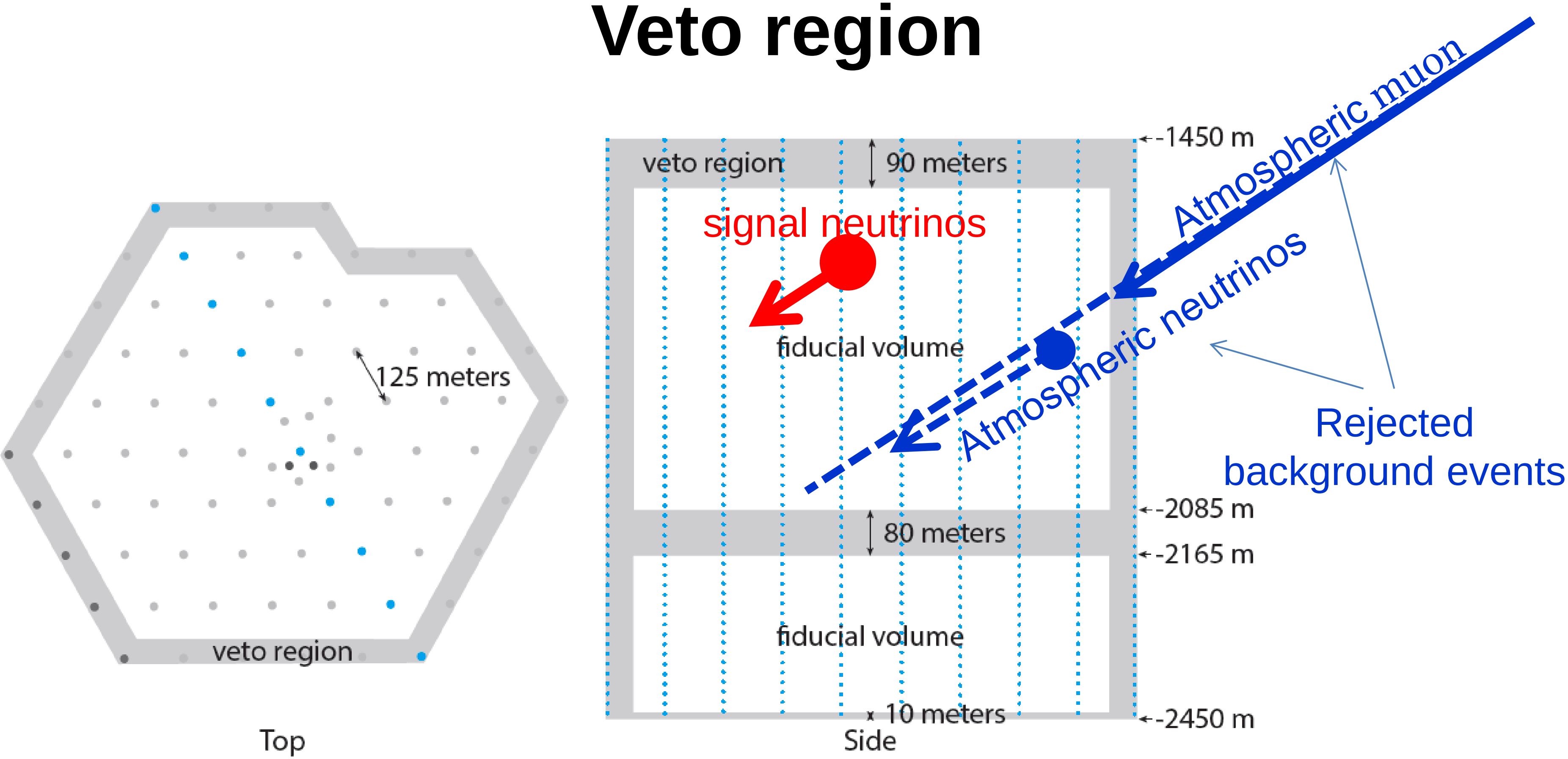

ATWD1/2
MonopodFit (ATWD1/2)
MonopodFit (reversed) (ATWD1/2)
MonopodFit (+20 deg) (ATWD1/2)
MonopodFit (-20 deg) (ATWD1/2)
MonopodFit (extended) (ATWD1/2)
MonopodFit (double bang) (ATWD1/2)
• Maximizing the Poisson likelihood based on the recorded waveforms
• Charges and timing information
Estimated Energy Deposit
Preliminary
• Jan 2012 event 1.14 PeV
• Aug 2011 event 1.04 PeV
Error of +- ~15% including absolute, ice, stat errors
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400

Starting Event Search (cascade+starting track)



- Followup analysis on the UHE cascade-like events
- Atmospheric muon/neutrino background largely reduced by vetoing events with initial photons in outer layers
- Events with NPE > 6000 (the case for EHE, NPE > 60000), sensitivity extended down to 30TeV

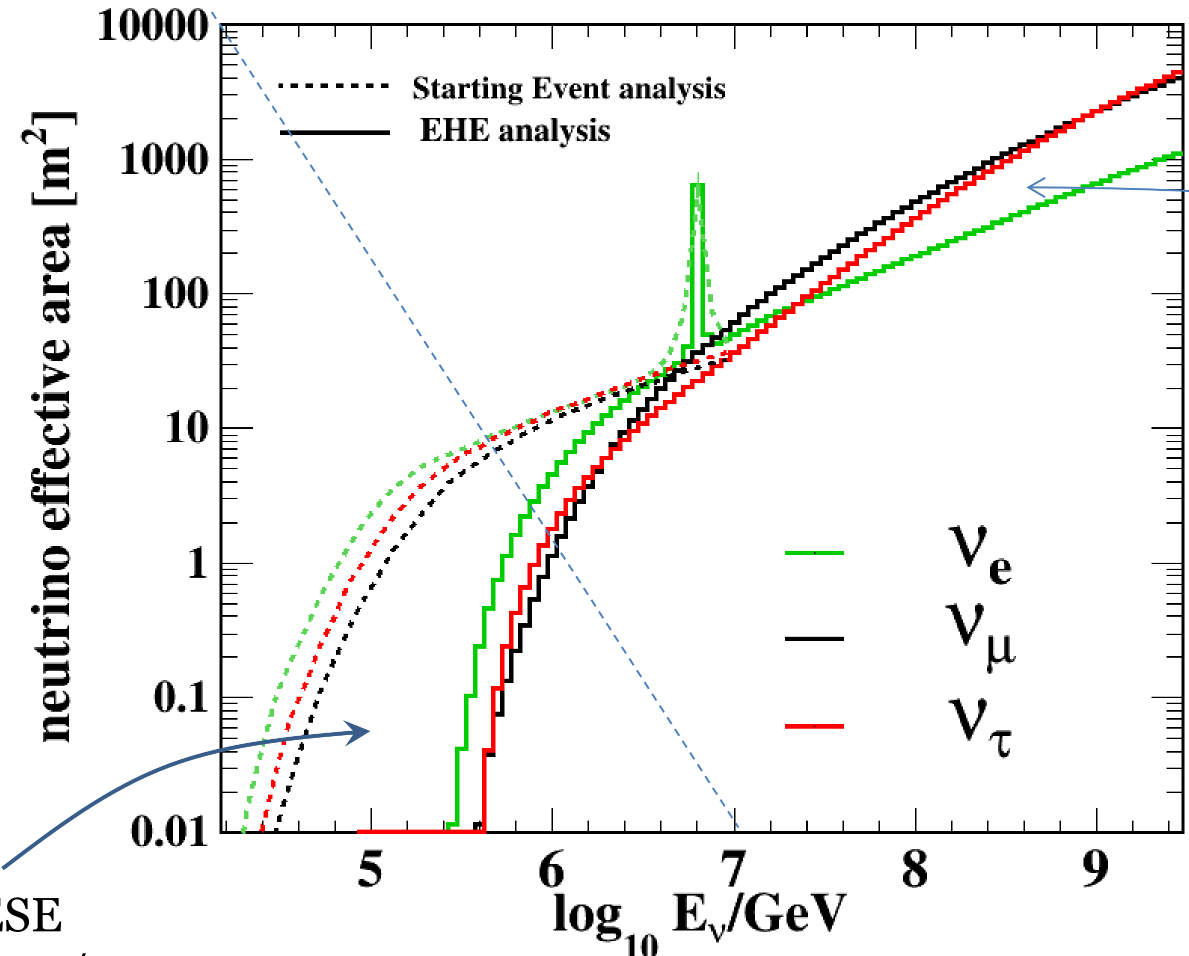
Veto region



- Down-going atmospheric neutrinos are also reduced by vetoing atmospheric muon events

Effective Areas
Propositional to expected event rates

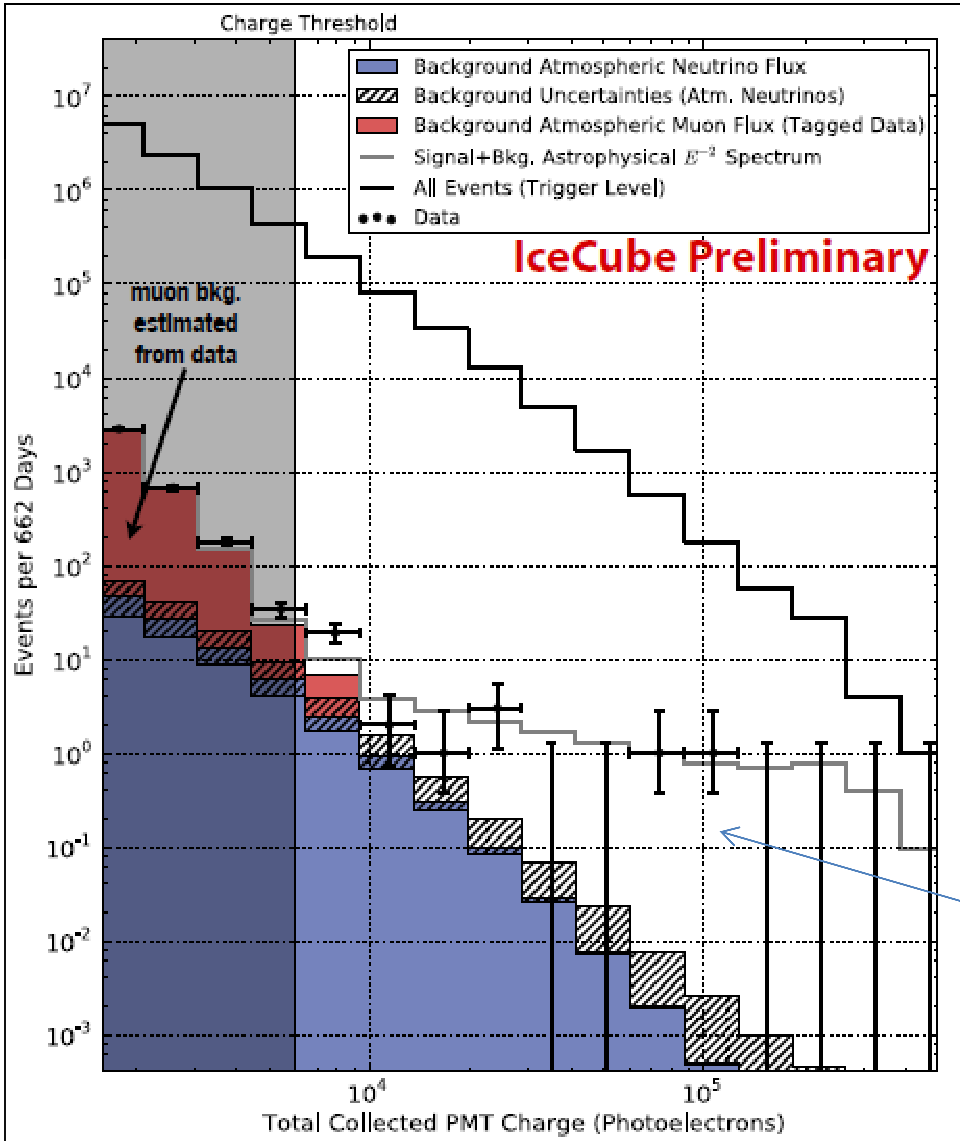
Area x ν flux x 4π x livetime = event rate



EHE
0.04 BG events/year

HESE
6 BG events/year

Starting Event NPE Distributions

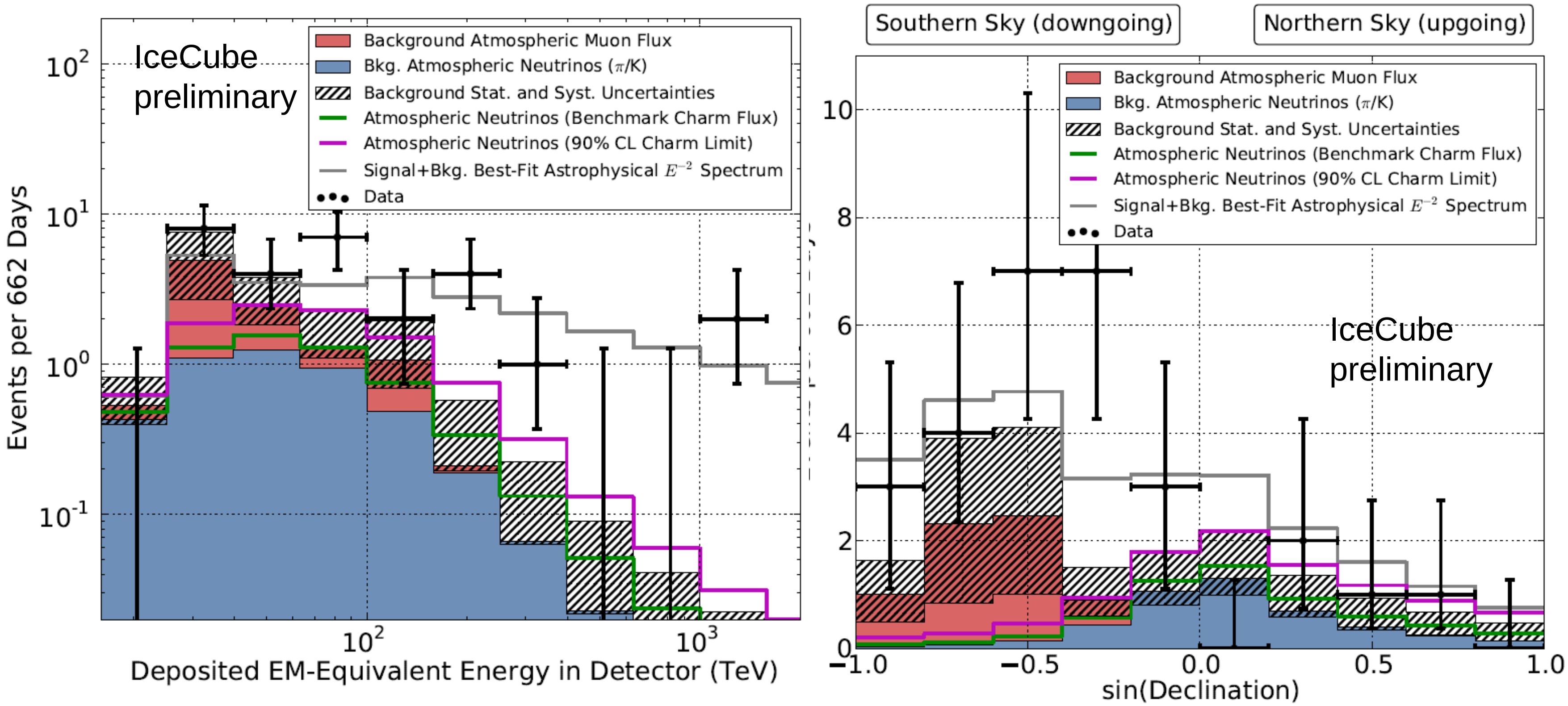


2010-2012 (2 years)

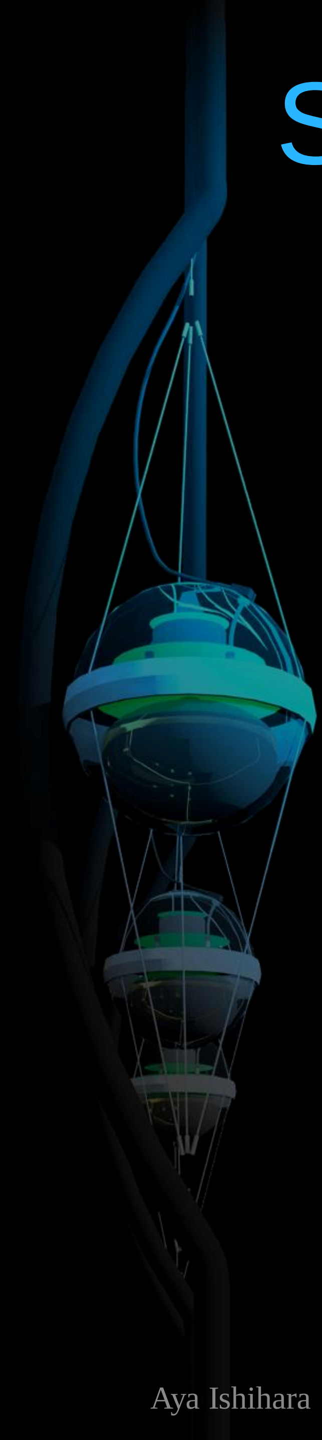
- 26 new events found (19 cascades, 7 with tracks)
- over background expectation of 12 +/-4 atmospheric muons(6±3) and atmospheric neutrinos(6±2)
- no new events near the PeV region but deviation from background only hypothesis observed

Already observed two events

Extraterrestrial neutrino search with starting events



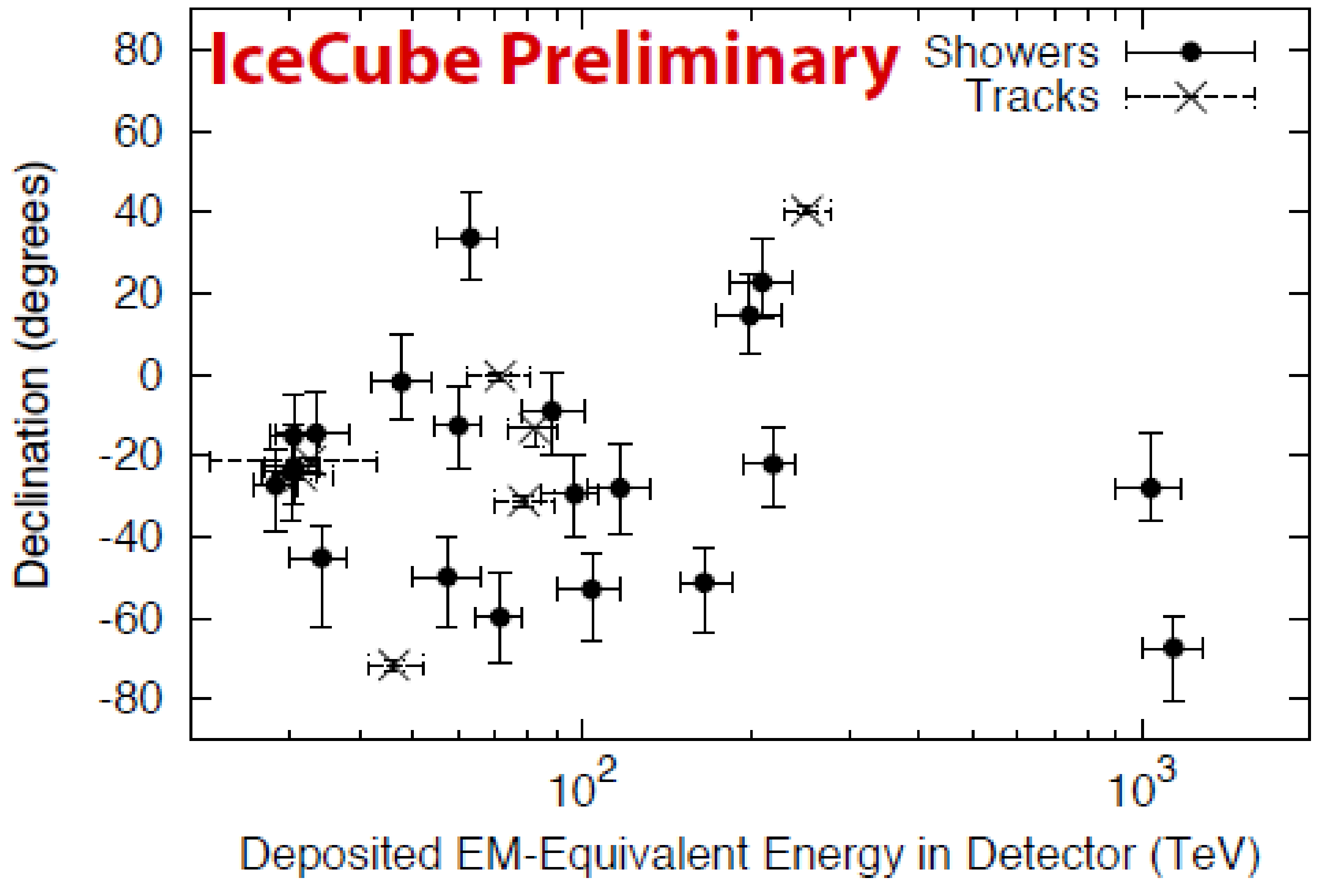
- **Inconsistent with background only model** at 3.3σ for 26 events and 4.1σ with 28 events combined (preliminary)
- Event features (reconstructed energy, zenith angle, vertex positions and topology) **consistent with background + astrophysical ($\phi_{astro} \propto E^{-2}$) fluxes**
- **Best fit results** $E^2\phi$=3.6x10-8 [GeV cm-1 s-1 sr-1] with a hard cut off at 1.6PeV
  - Need to be evaluated with adding more statistics soon!



Summary

- Two year data analysis in search for the neutrinos above PeV and a followup analysis using veto method were performed
- They reject background only hypothesis at 4.1σ
- Expected signal distribution from the observation are consistent with isotropic, flavor 1:1:1, $\varphi \propto E^{-2.2\sim-2.0}$
- We are studying the different channels, showing consistent results so far
- In a phase transition from discovery to measurement

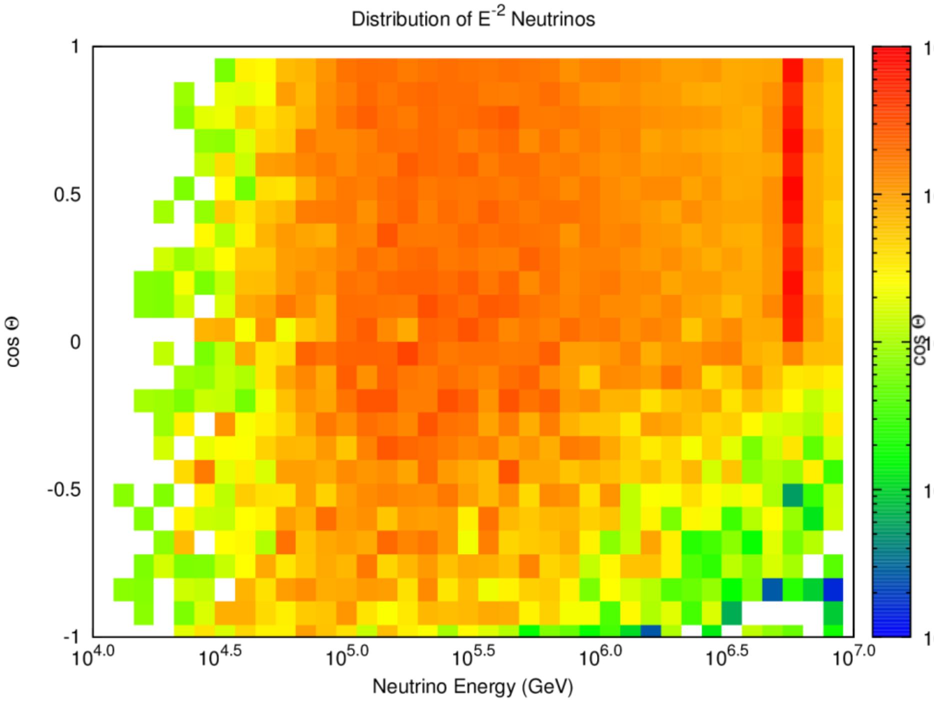
Energy, declination and topology



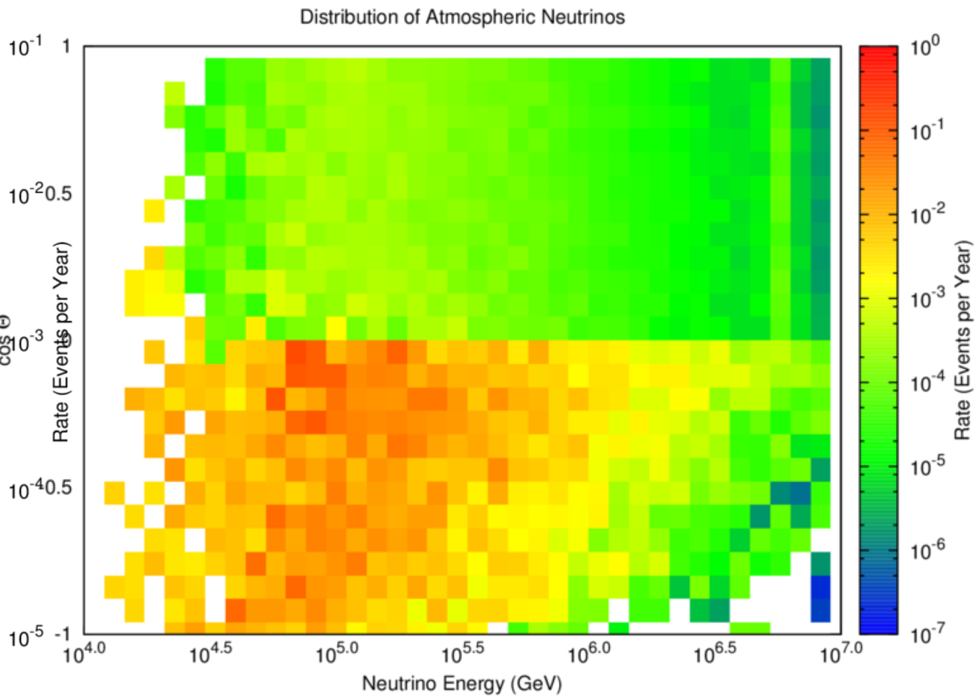
Up-Down Asymmetry

expected Energy vs cos θ distributions

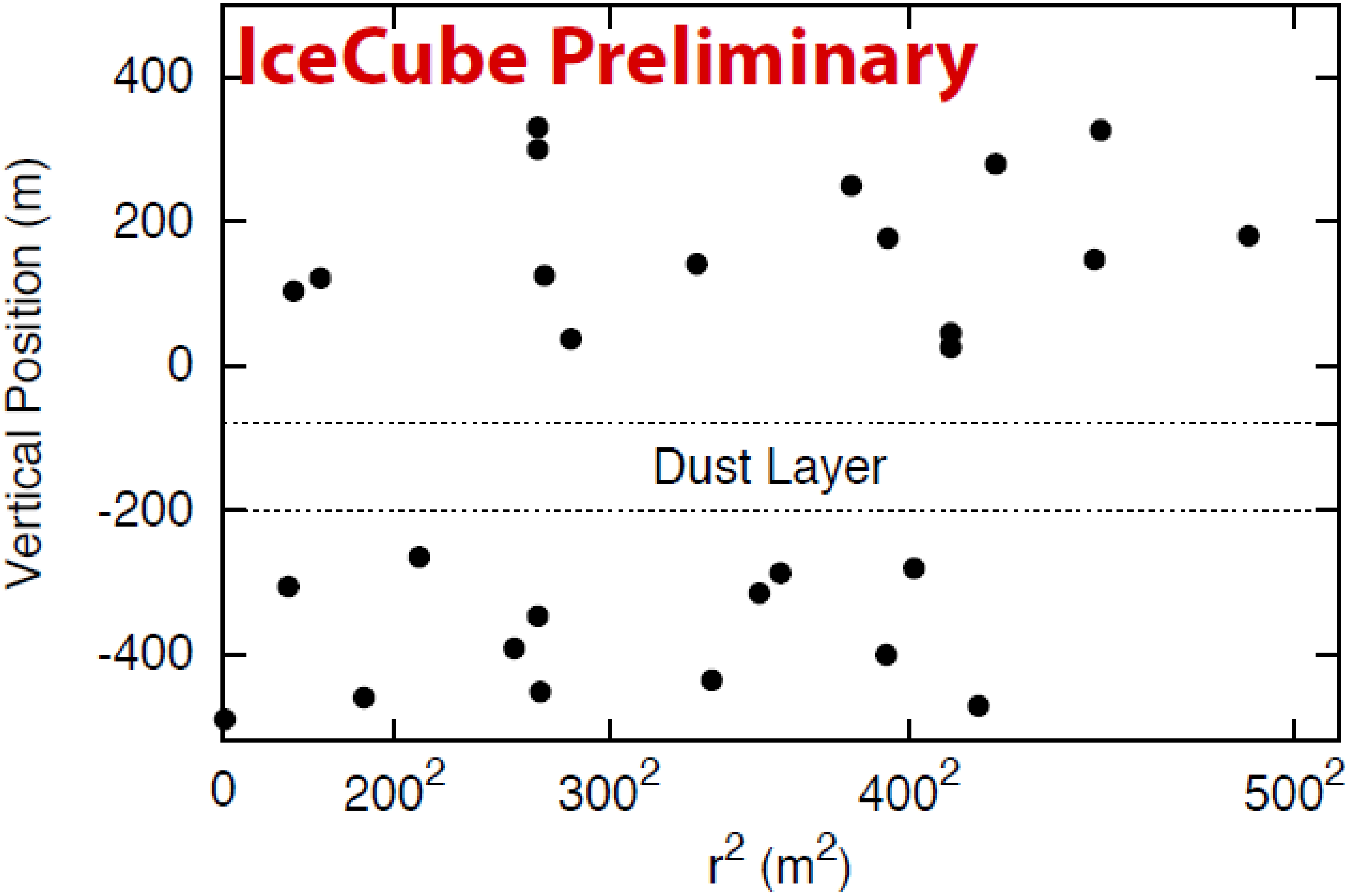
signal



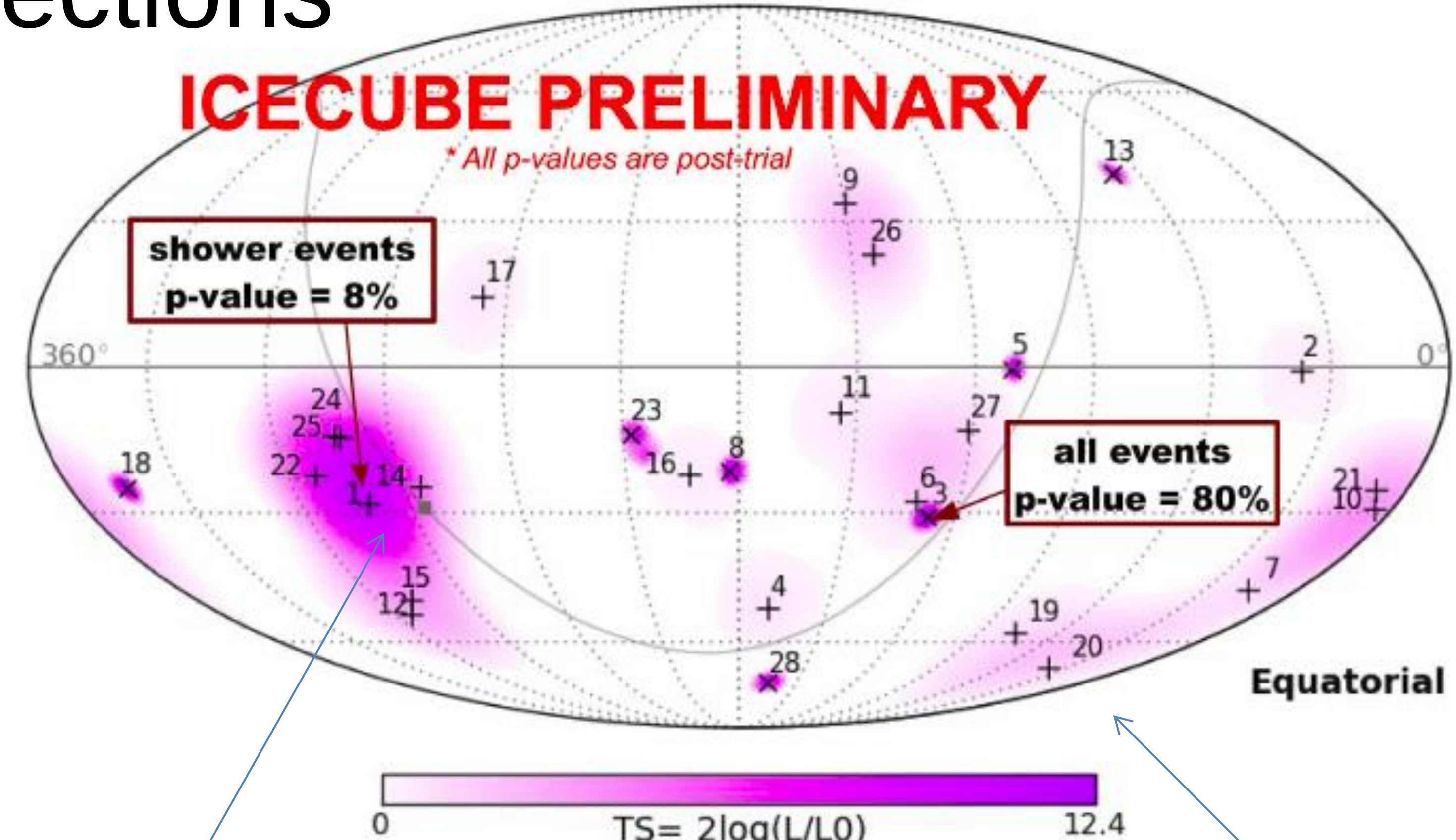
atmospheic neutrinos



Vertex positions



Directions



1.04PeV

1.14PeV

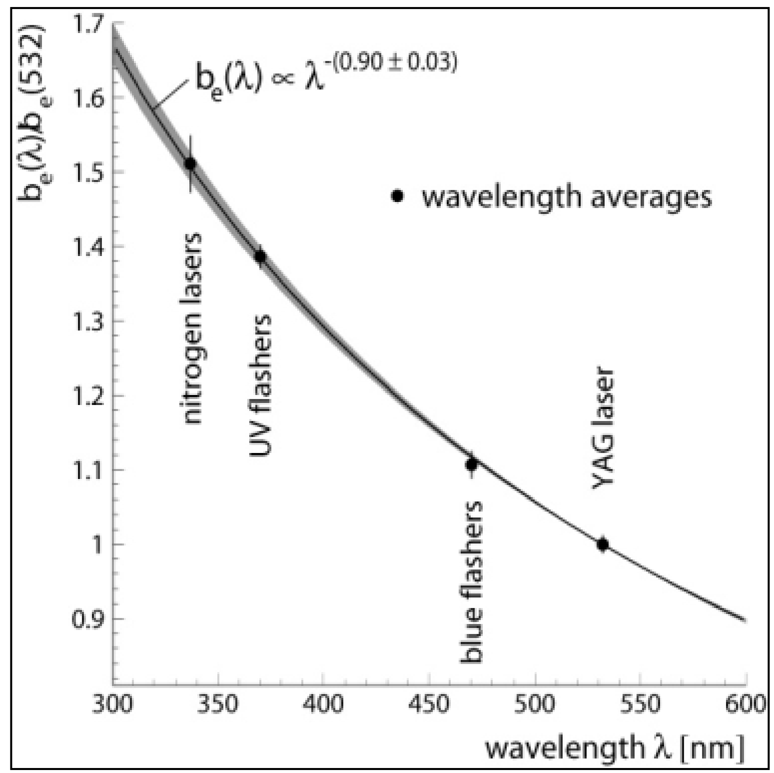
p-values	All 28 Events	21 Cascade Events
Cluster Search	~80%	8%

What causes scattering in the ice?

- In the ***shallow ice***, scattering is predominantly caused by air bubbles.
- In the deeper ice, ***below 1400 m***, the bubbles have converted to non-scattering air hydrate crystals, so-called clathrates, and scattering is caused by **dust**.
- This dust has four main components: mineral grains, salt, acids, and soot. Scattering is mainly caused by the mineral grain component.

The wavelength dependence of the scattering coefficient is described (in the wavelength range 300-600 nm) by a power law:

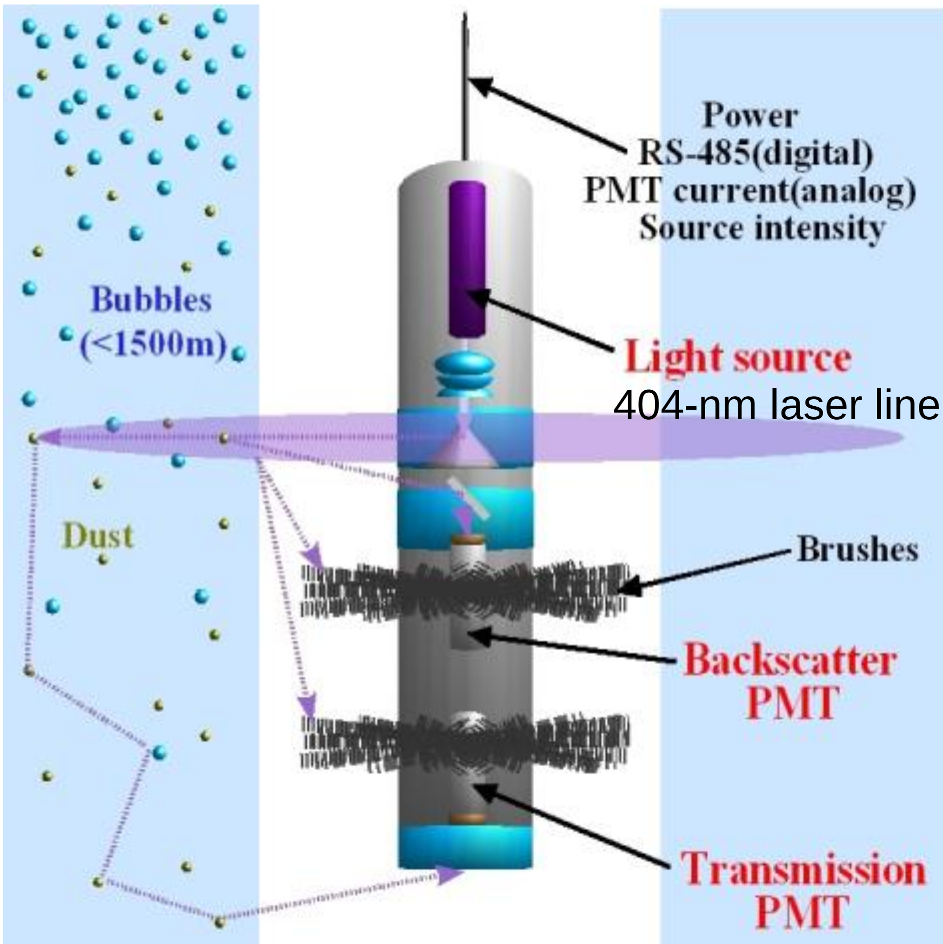
This power law was fitted to pulsed data at 4 wavelength for IceCube.



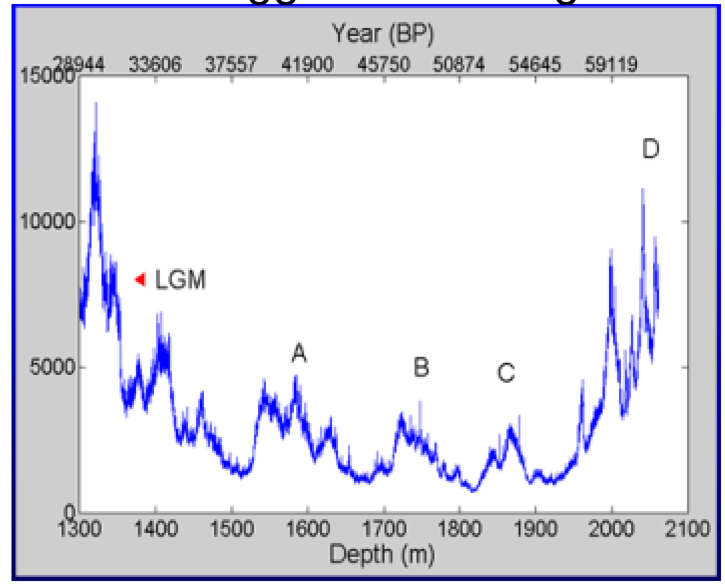
Absorption is caused by dust and the ice itself.

Dust Logger

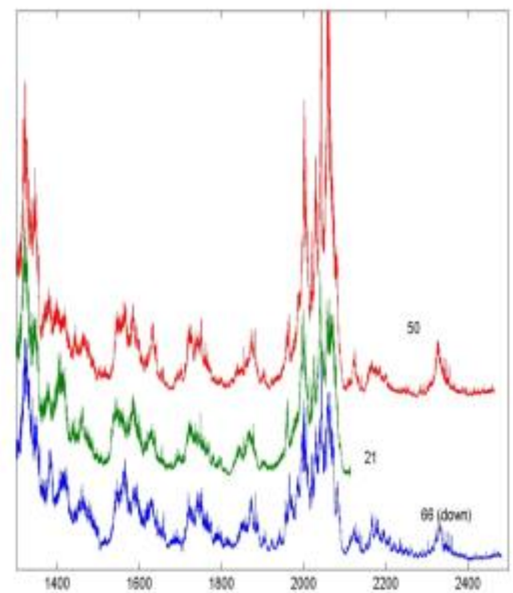
Since scattering is caused by **dust**.
It is important to understand



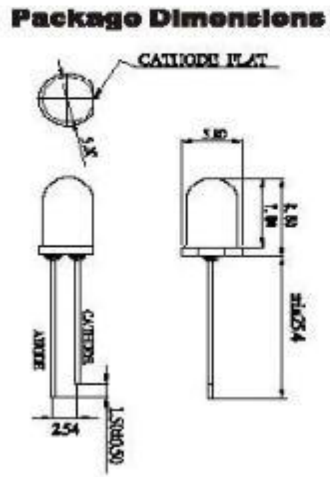
dust logger data string 21

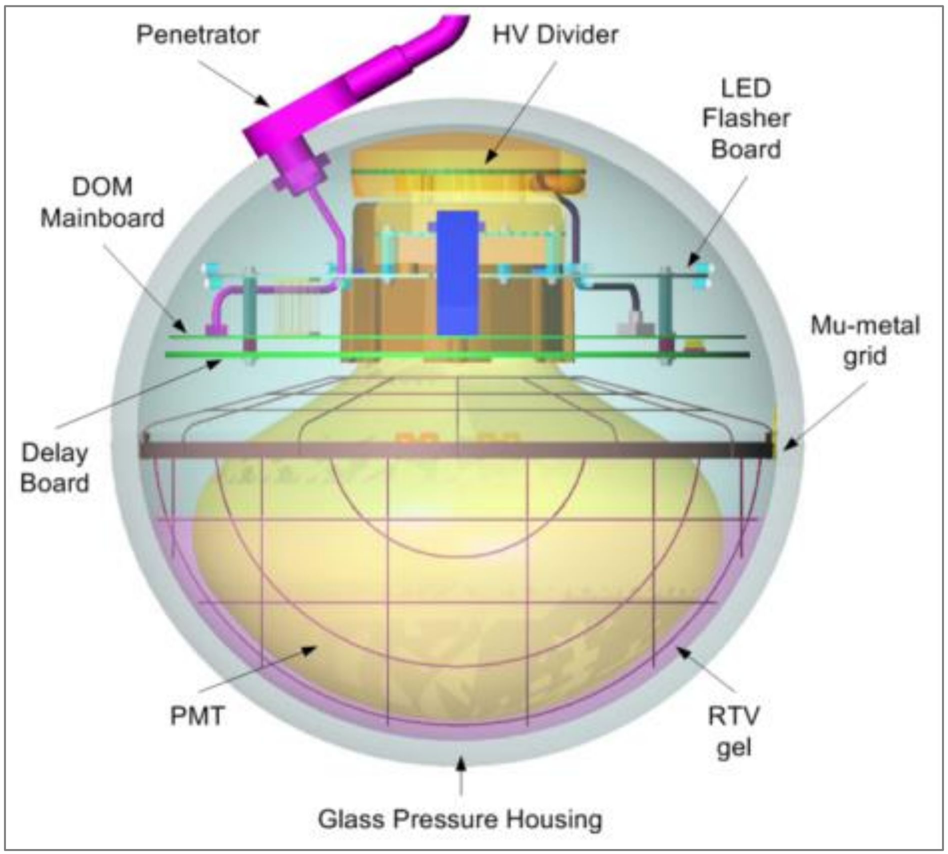


dust logger data of multiple location

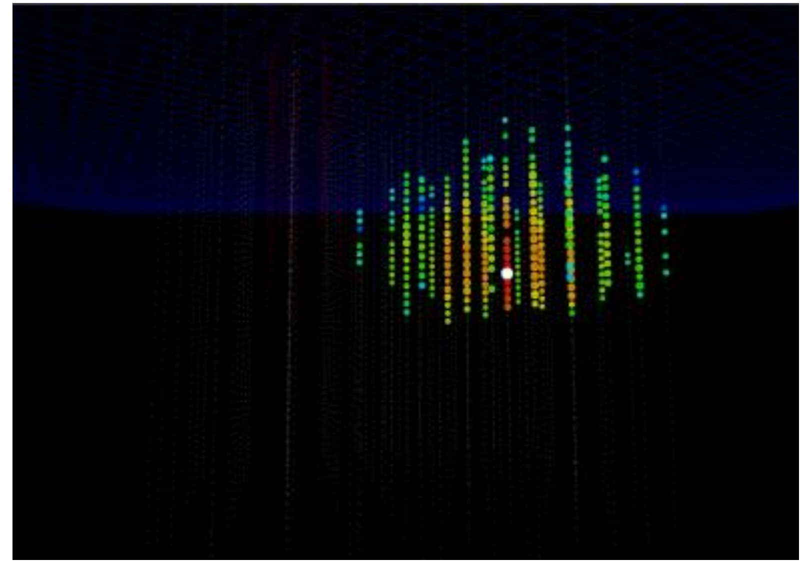


Flasher on the every DOM

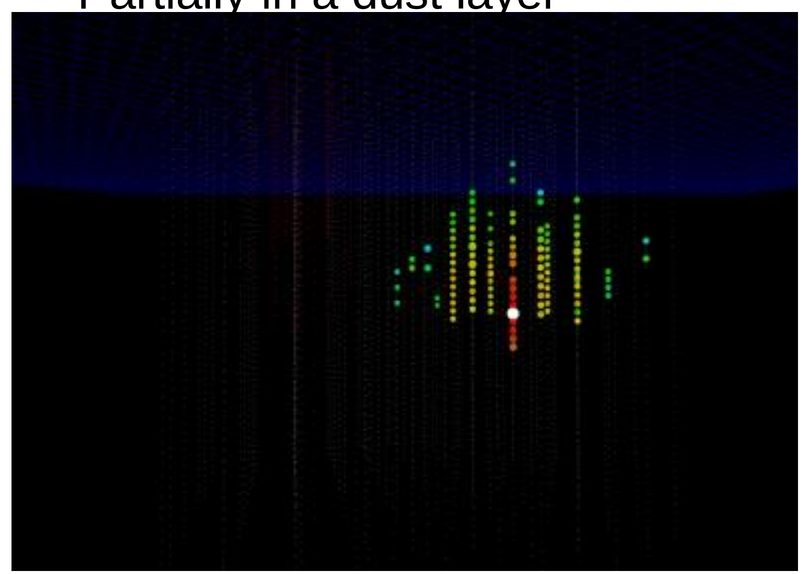




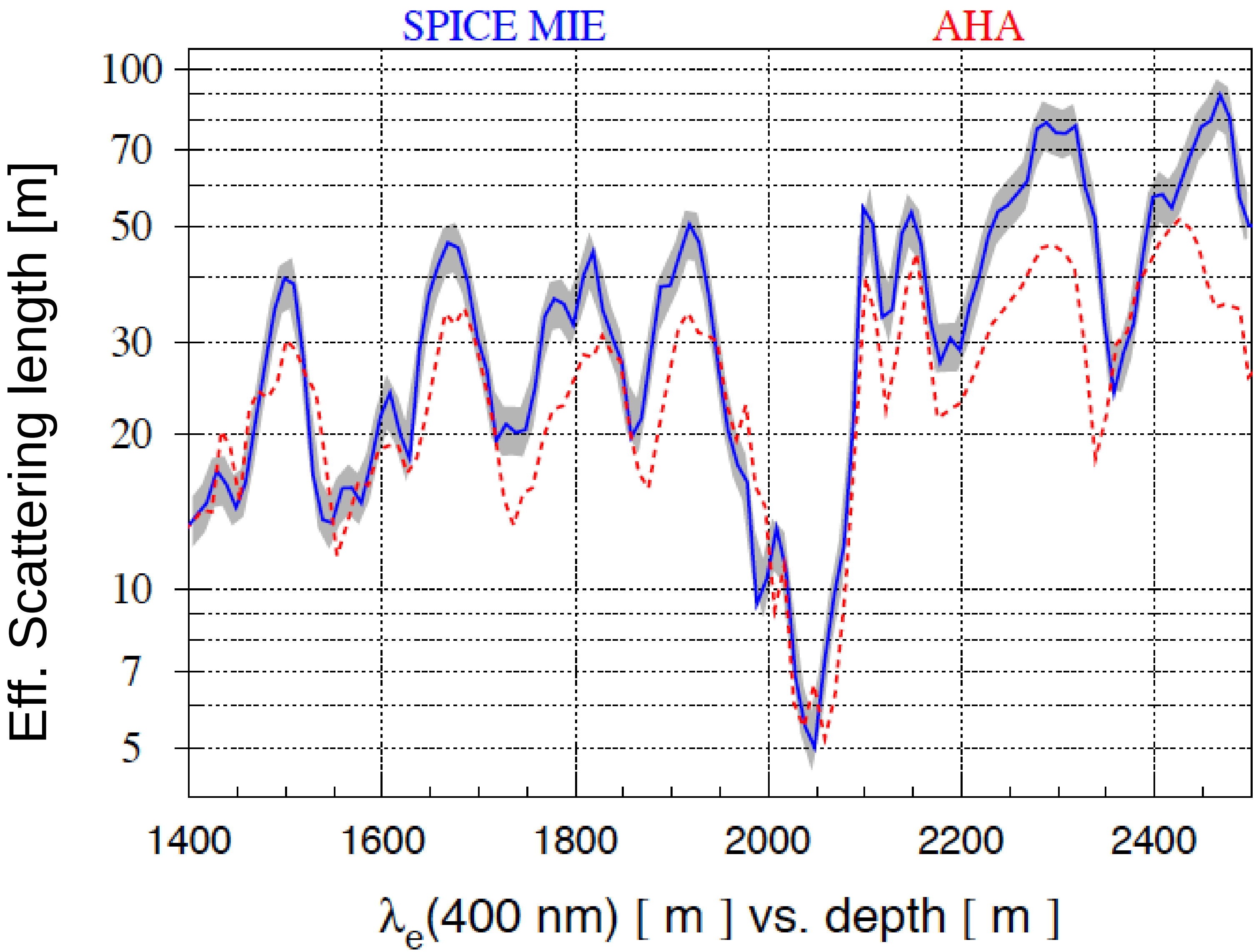
Above a dust layer



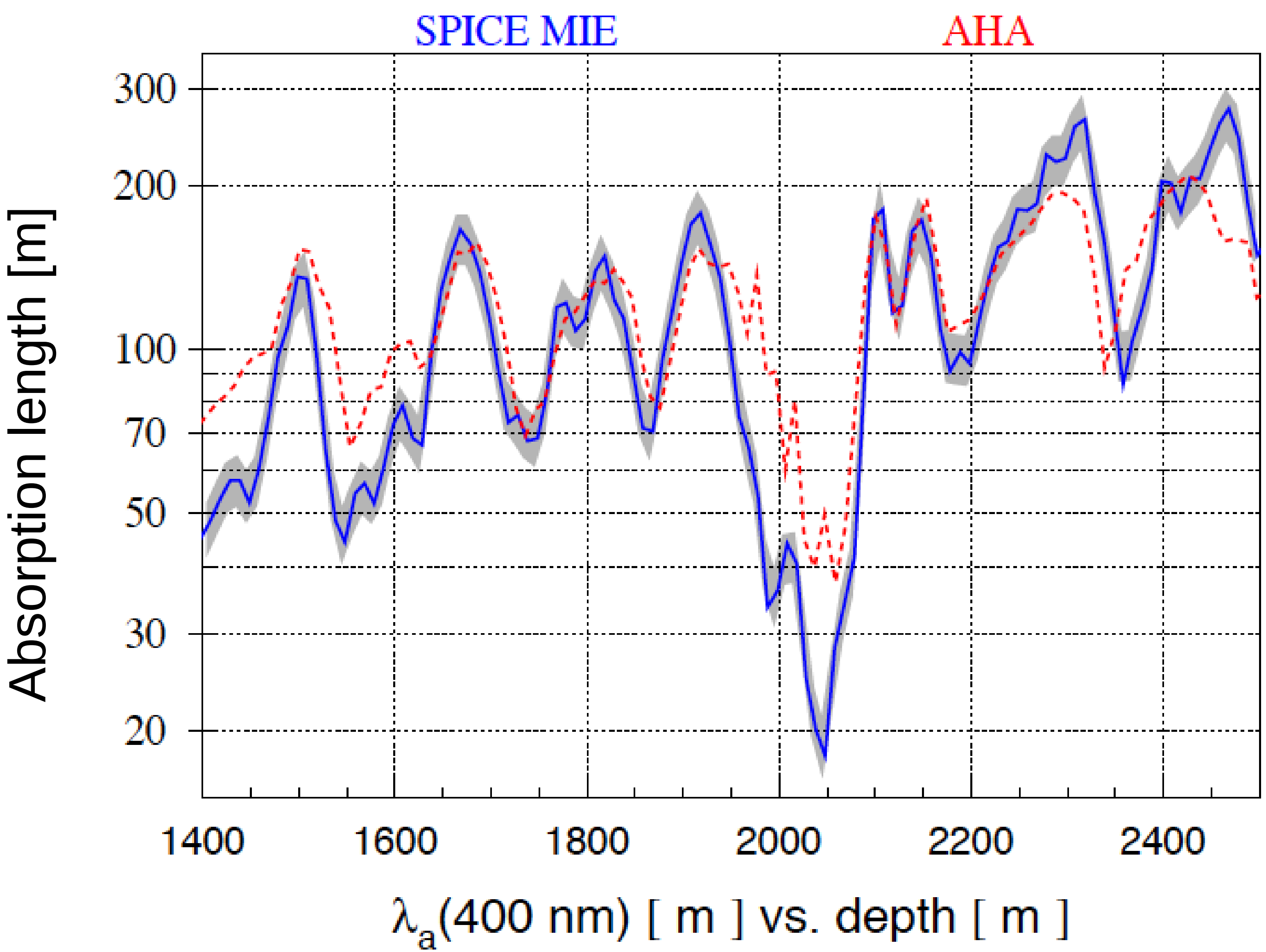
Partially in a dust layer



The Ice is very clear
Effective scattering length vs Depth



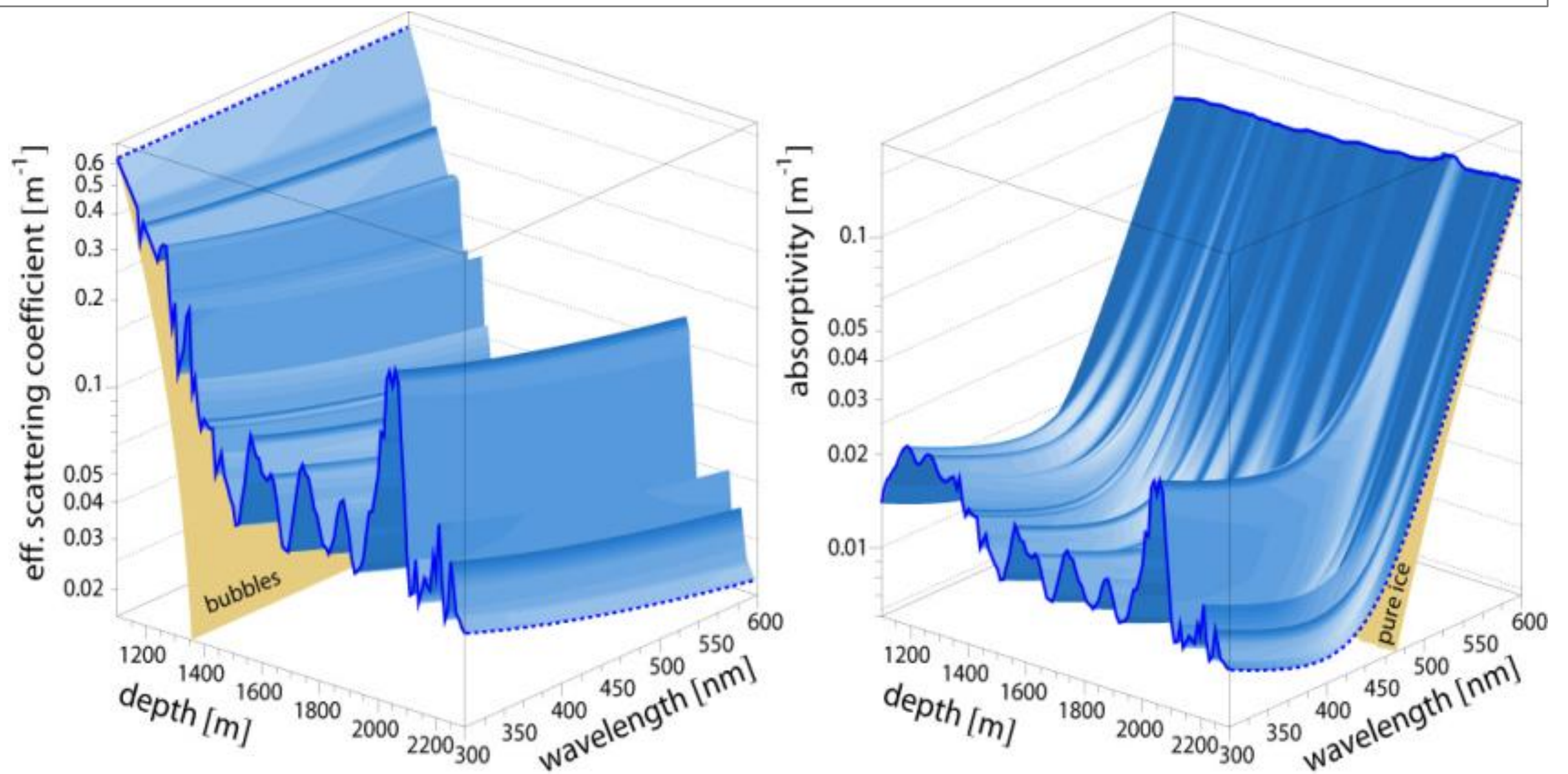
Absorption length vs Depth



Optical Properties

- Combining all the possible information
- These features are included in simulation
- We're always be developing them

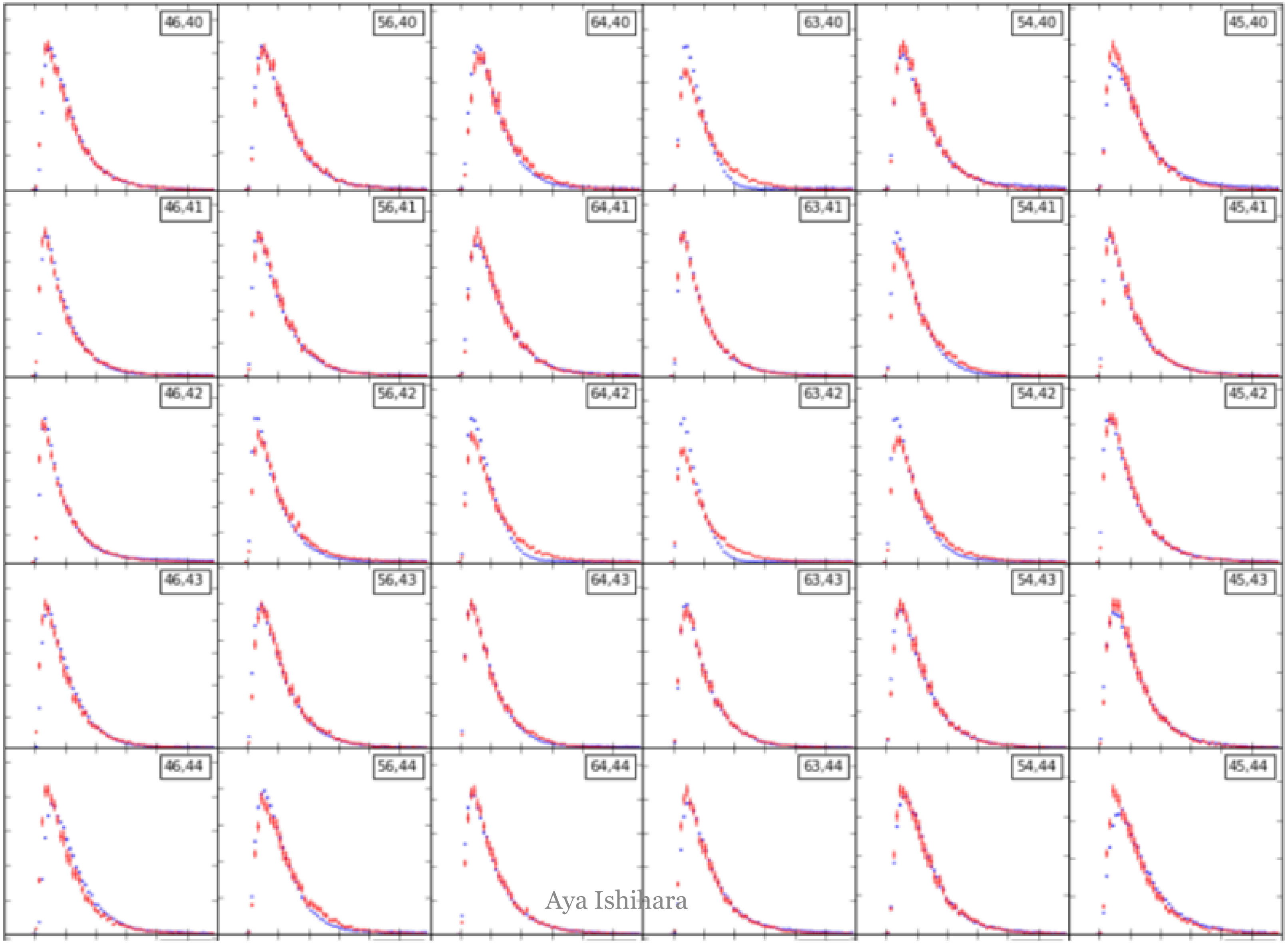
Nature never tell us a perfect answer but obtained a satisfactory agreement with data!



Checks of non saturated region

Red:data
Blue:MC

Comparisons of normalized waveforms in non saturated region (shape = photon timing)



High Energy Veto Method