High Energy Neutrinos

J. Brunner
CPPM

Content

- Motivations

- The experiments

- Atmospheric neutrinos

- Extraterrestrial neutrinos
  - Diffuse flux seaches
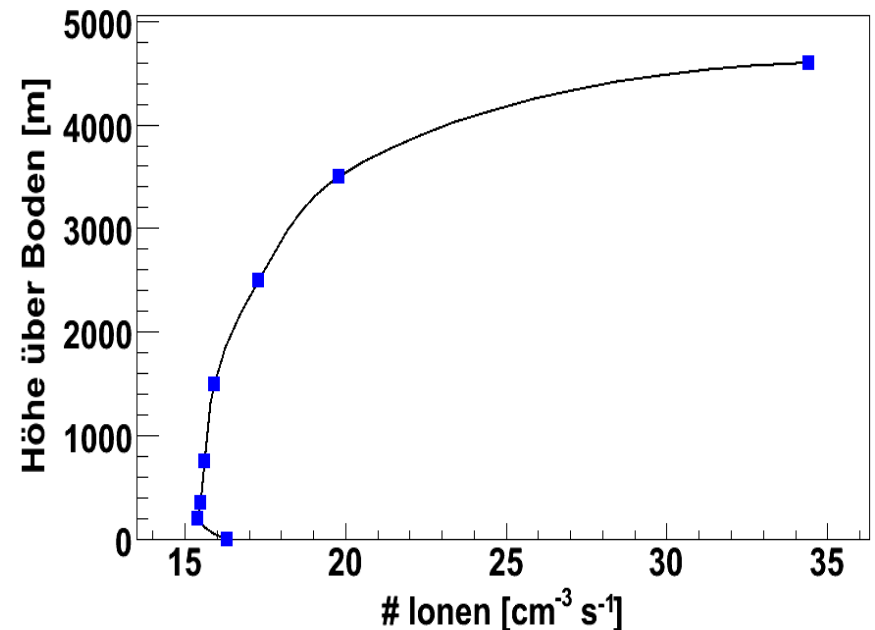 - Point source searches
  - Transient point sources

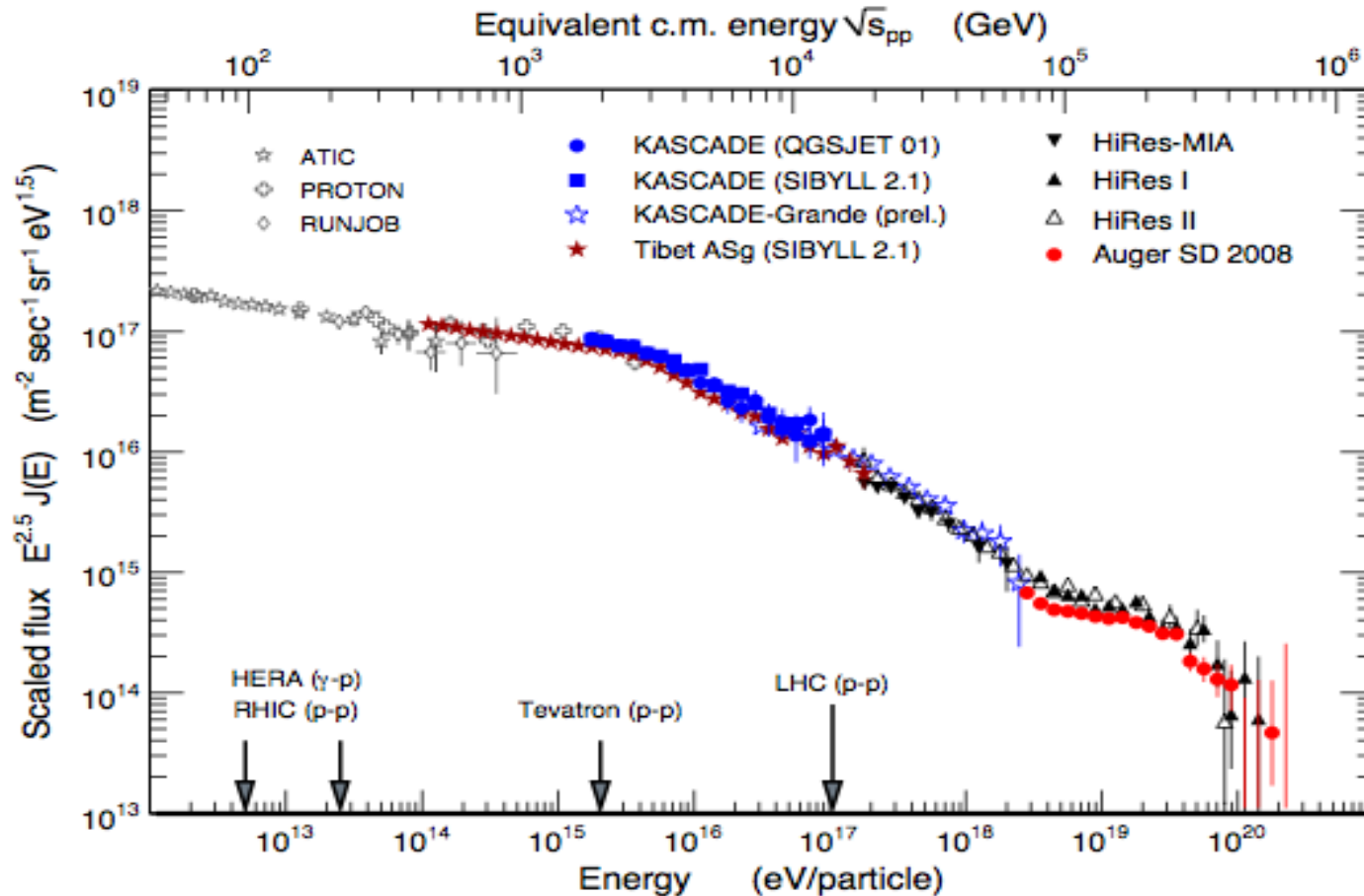# 1912: Discovery of cosmic rays (Victor Hess)

https://indico.desy.de/conferenceDisplay.py?confId=4213

- **Balloon experiments**
  - **Hess, Kolhörster**

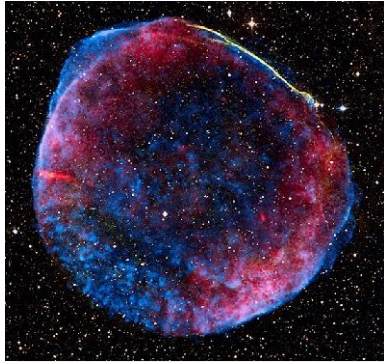Measurements Victor Hess (1912)
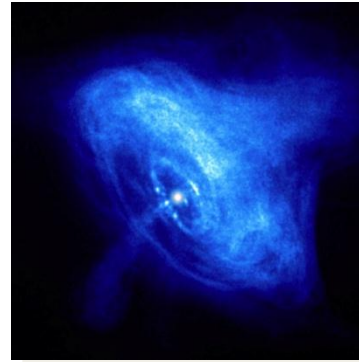
Victor Hess

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What and where are the accelerators ?

The high-energy universe

supernova remnants
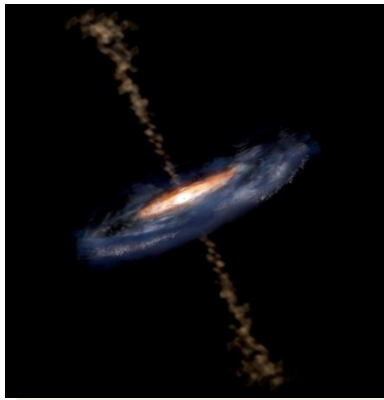(SN1006, optical, radio, X-ray)
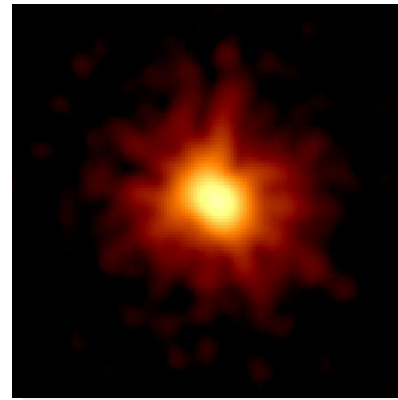
pulsars
(Crab, X-ray, Chandra)

Galactic

**active galactic nuclei**
(artist's view)

gamma-ray bursts
(GRB 080319B, X-ray, SWIFT)

Extra-Galactic

Acceleration mechanism

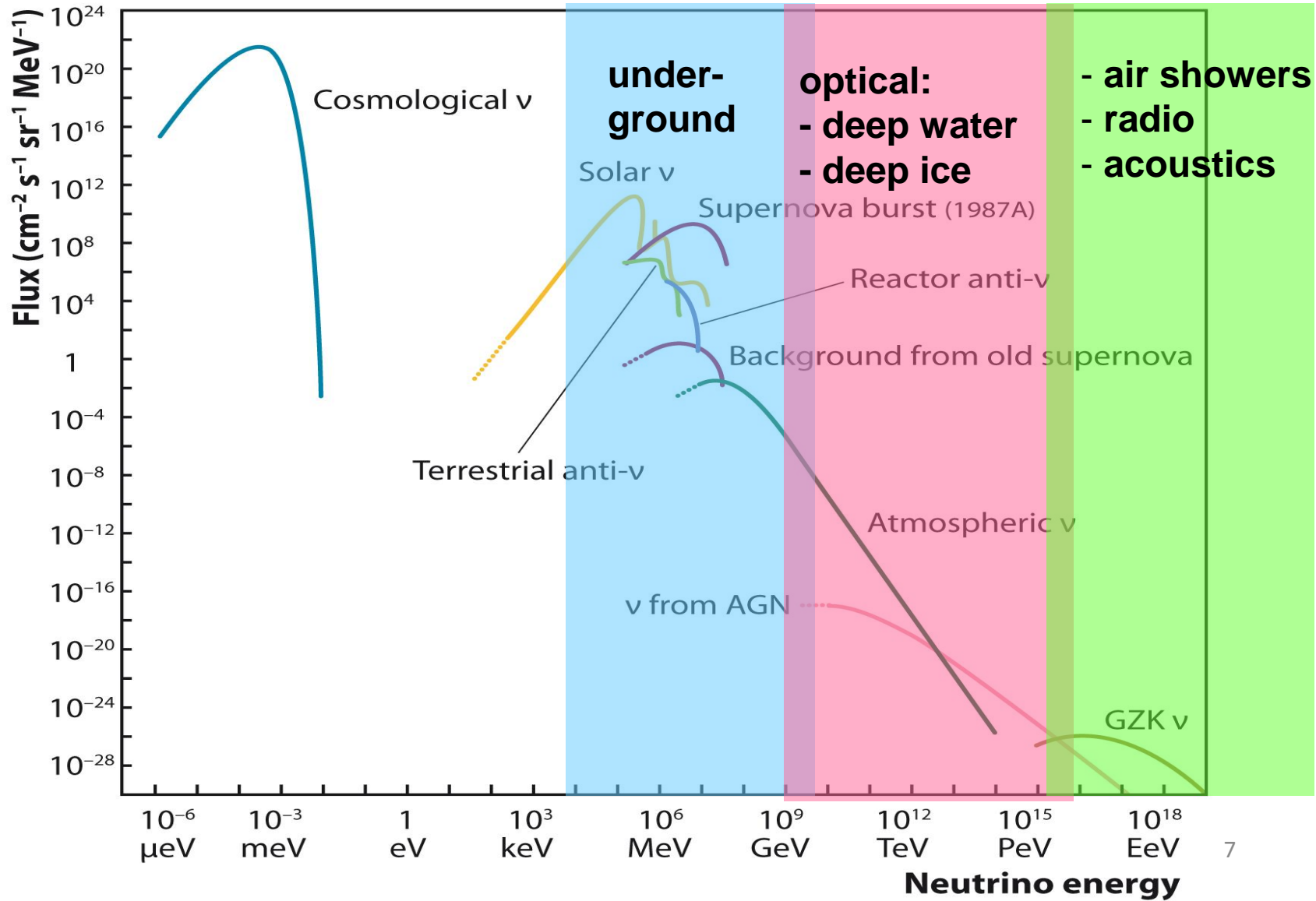- Fermi acceleration in shock waves
- Produces power law spectra
- Maximal energy controlled by
  - Magnetic field
  - Size of cosmic accelerator
  - Relativistic speed of shock wave
- Promising candidates: GRBs

Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)
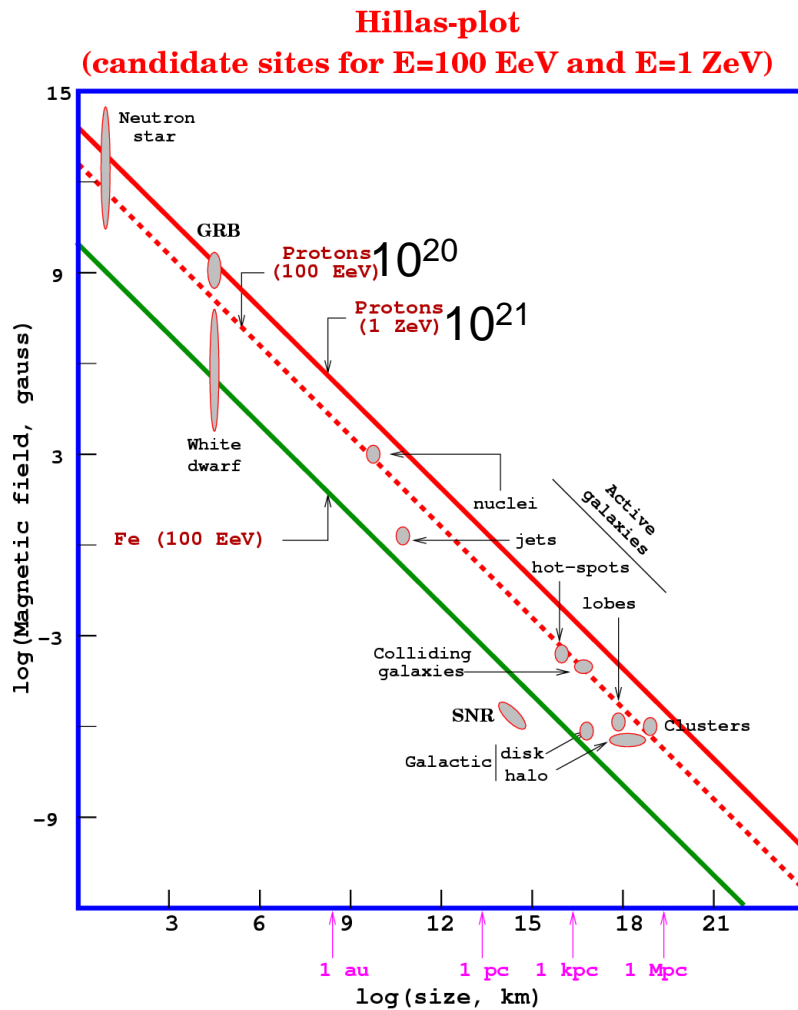
$E_{max} \approx ZBL$ (Fermi)

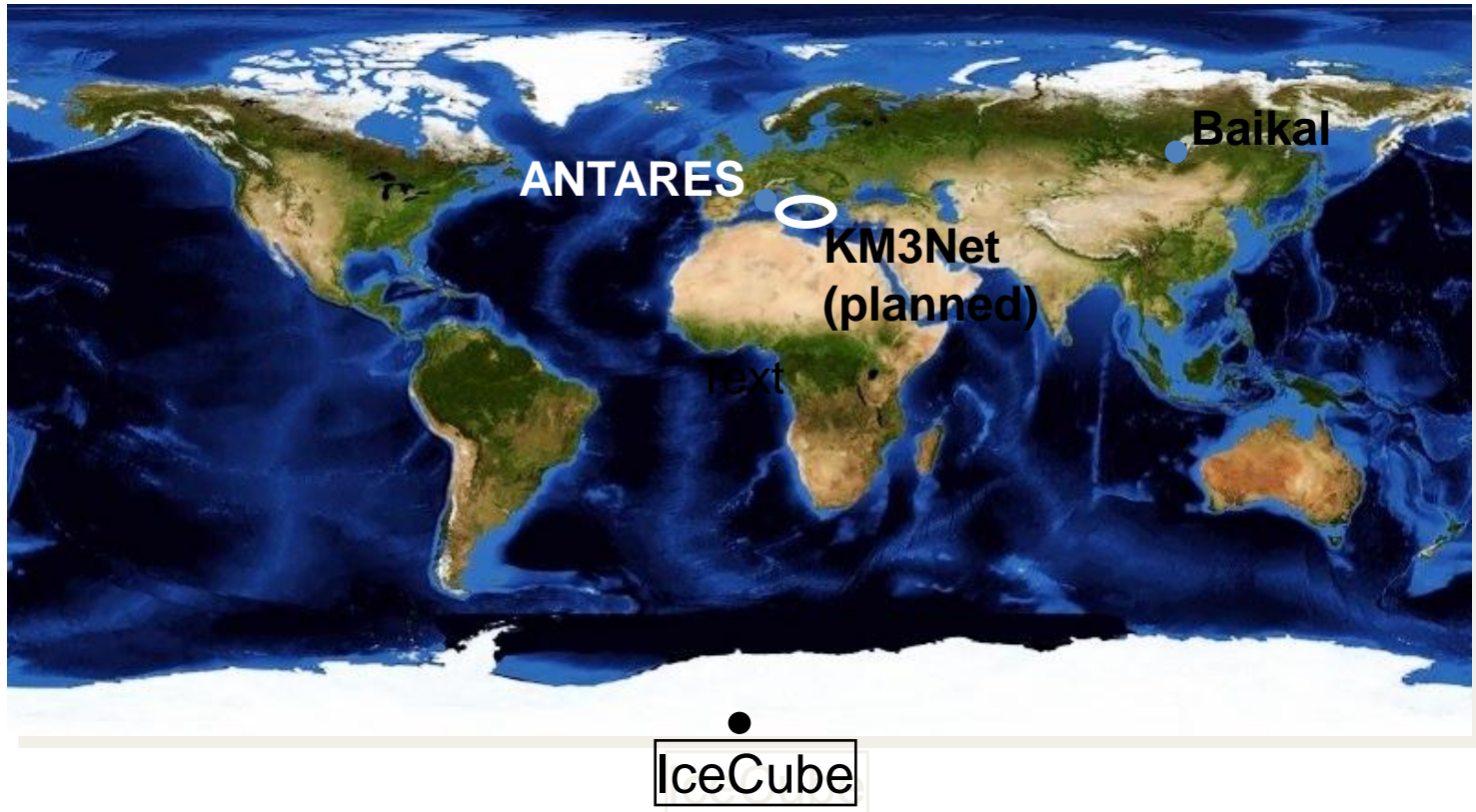$E_{max} \approx ZBL\,\Gamma$ (Ultra-relativistic shocks-GRB)
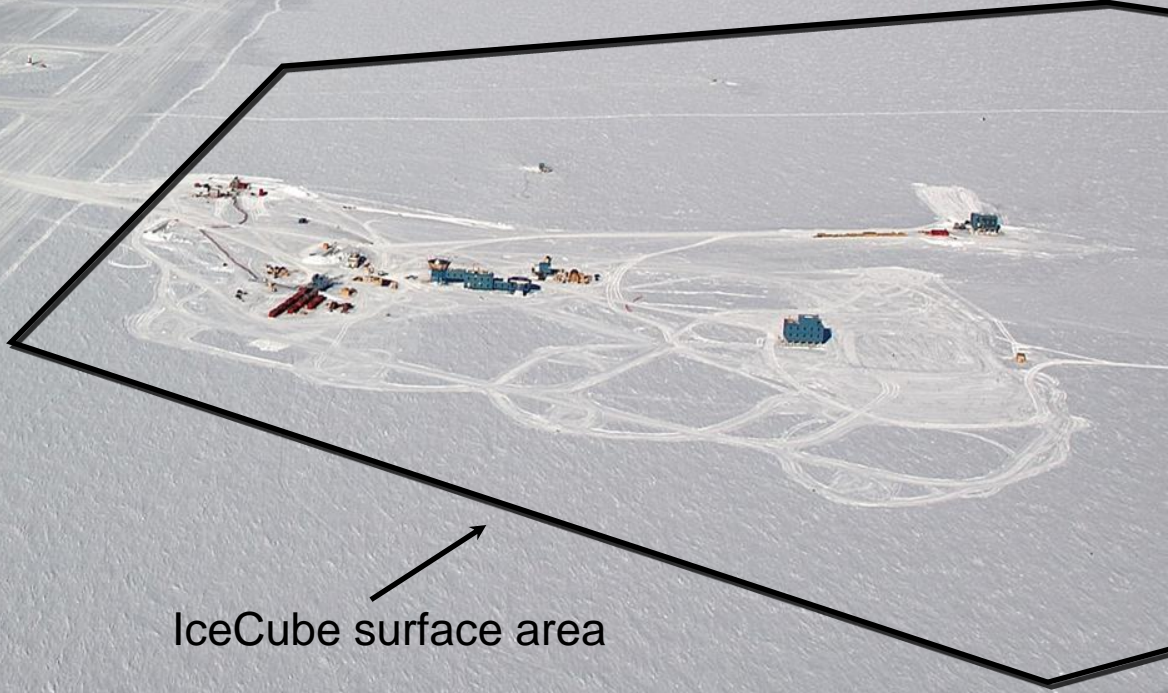
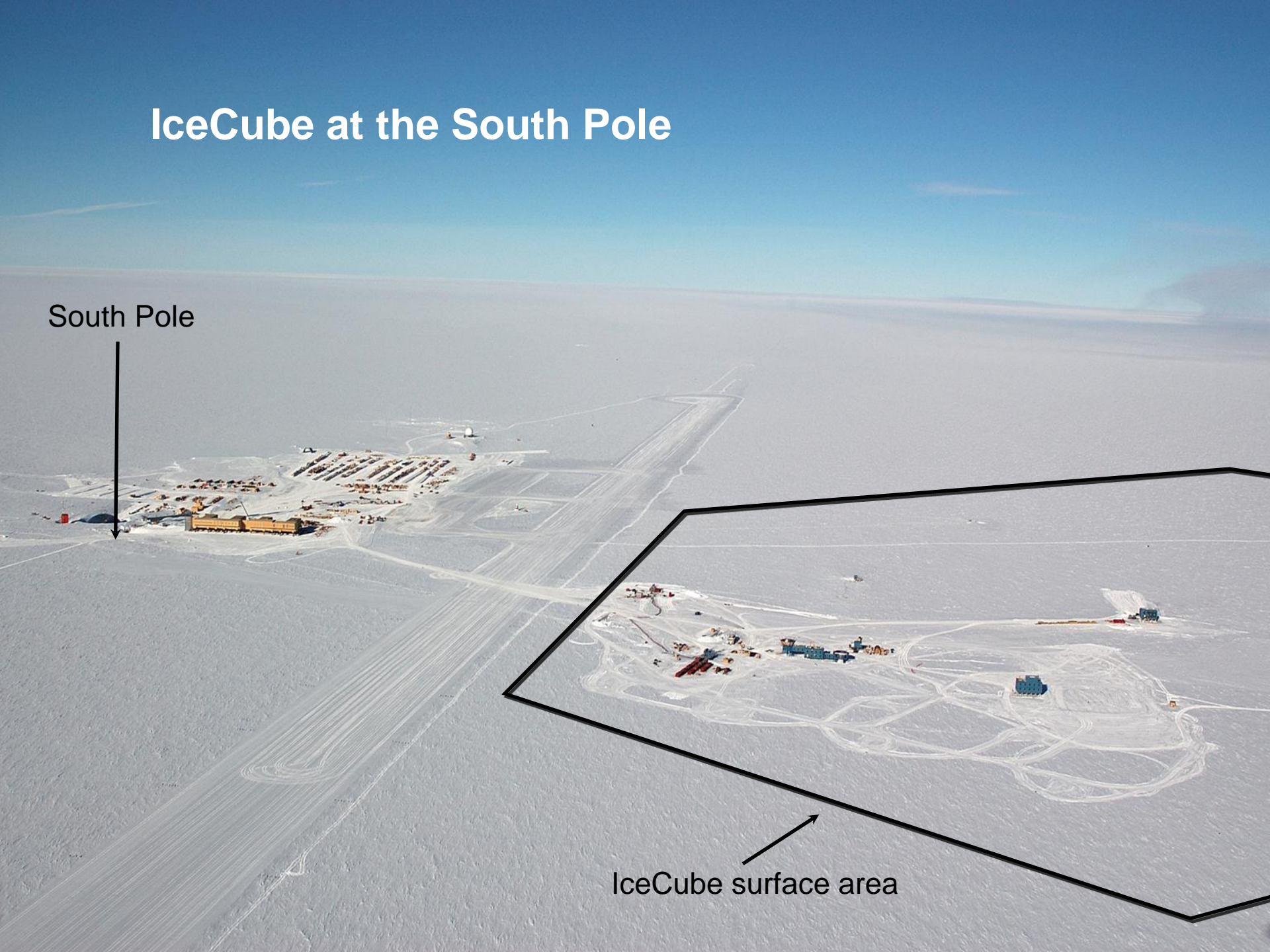# Fluxes of (cosmic) neutrinos

The Devices

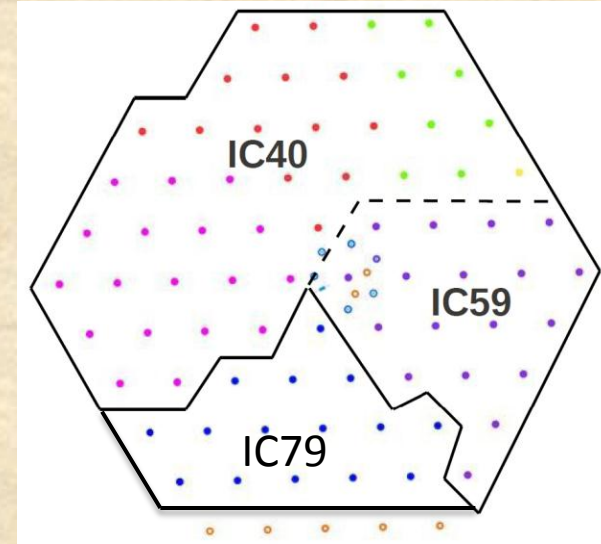# Neutrino Telescope Projects

IceCube at the South Pole

South Pole

IceCube surface area

IceCube Detector

Detector Completion Dec 2010

IceCube Lab

50 m

IceTop
81 Stations, each with
    2 IceTop Cherenkov detector tanks
    2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

1450 m

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

2450 m
2820 m

Bedrock

IC40

IC59

IC79

9 strings   (2006)
22 strings   (2007)
40 strings   (2008)
59 strings   (2009)
79 strings   (2010)
86 strings   (2011)

G. Sullivan
ν-2012 Kyoto

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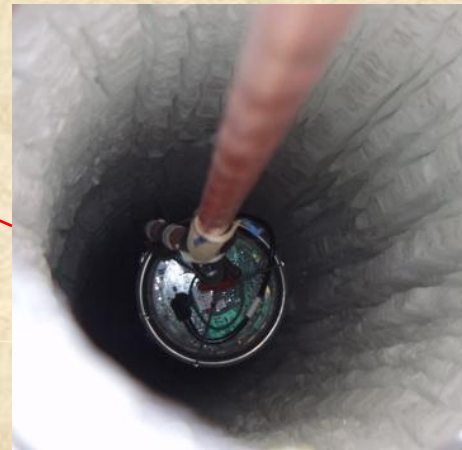
The ANTARES Site & Infrastructure

IFREMER Toulon Centre

TOULON
HYÈRES
LA SEYNE S-MER
ILES D'HYÈRES
Levant
Porquerolles
Port-Cros
200 m
2200 m
2400 m

40 km submarine cable
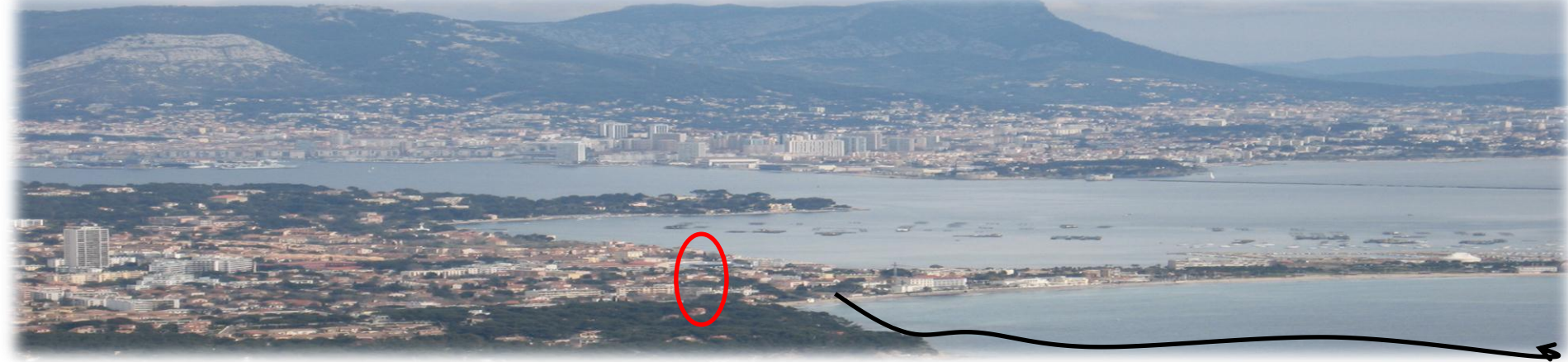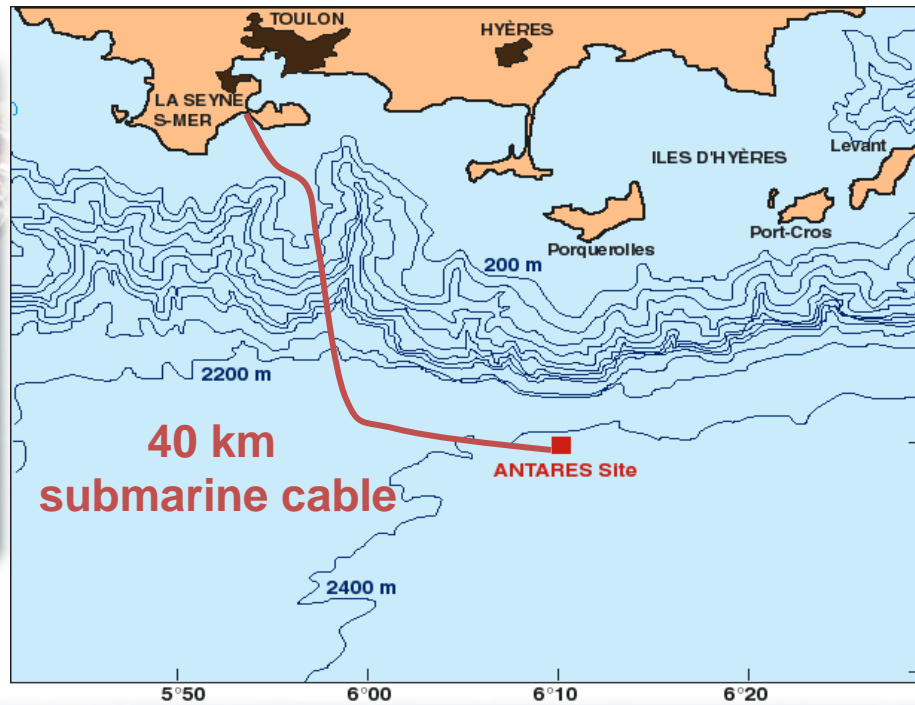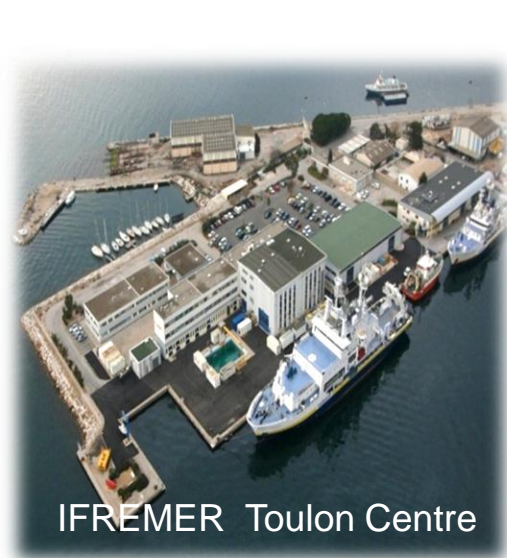
ANTARES Site

Shore Station

FOSELEV Marine

2006 – 2008: Construction of the Detector
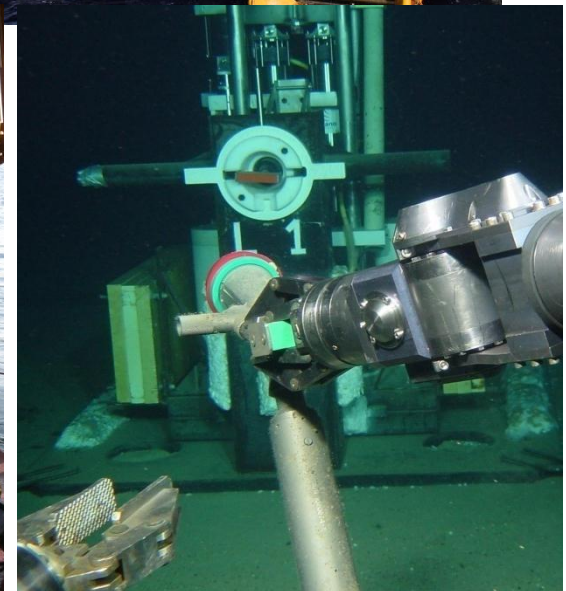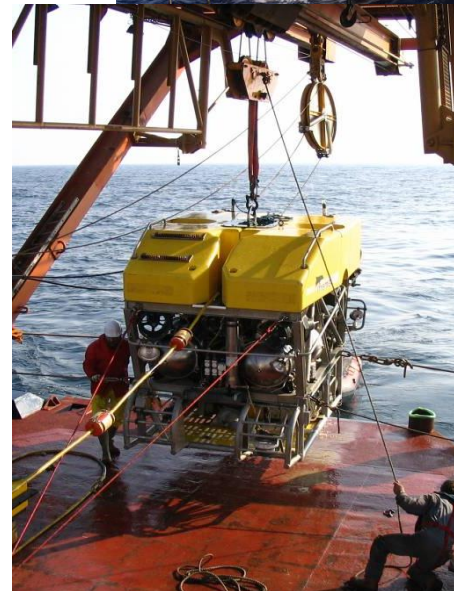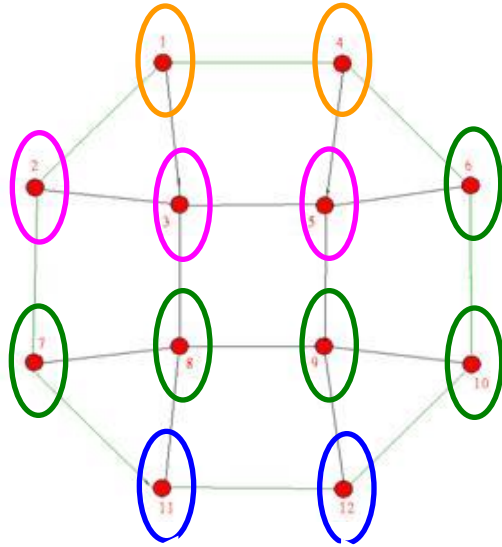
- **Junction box**   **2001**
- **Main cable**   **2002**
- **Line 1, 2**   2006
- **Line 3, 4, 5**   01 / 2007
- **Line 6, 7, 8, 9, 10**   12 / 2007
- **Line 11, 12**   05 / 2008

The ANTARES Detector

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

40 km to shore

450 m

70 m

Junction Box

Interlink cables
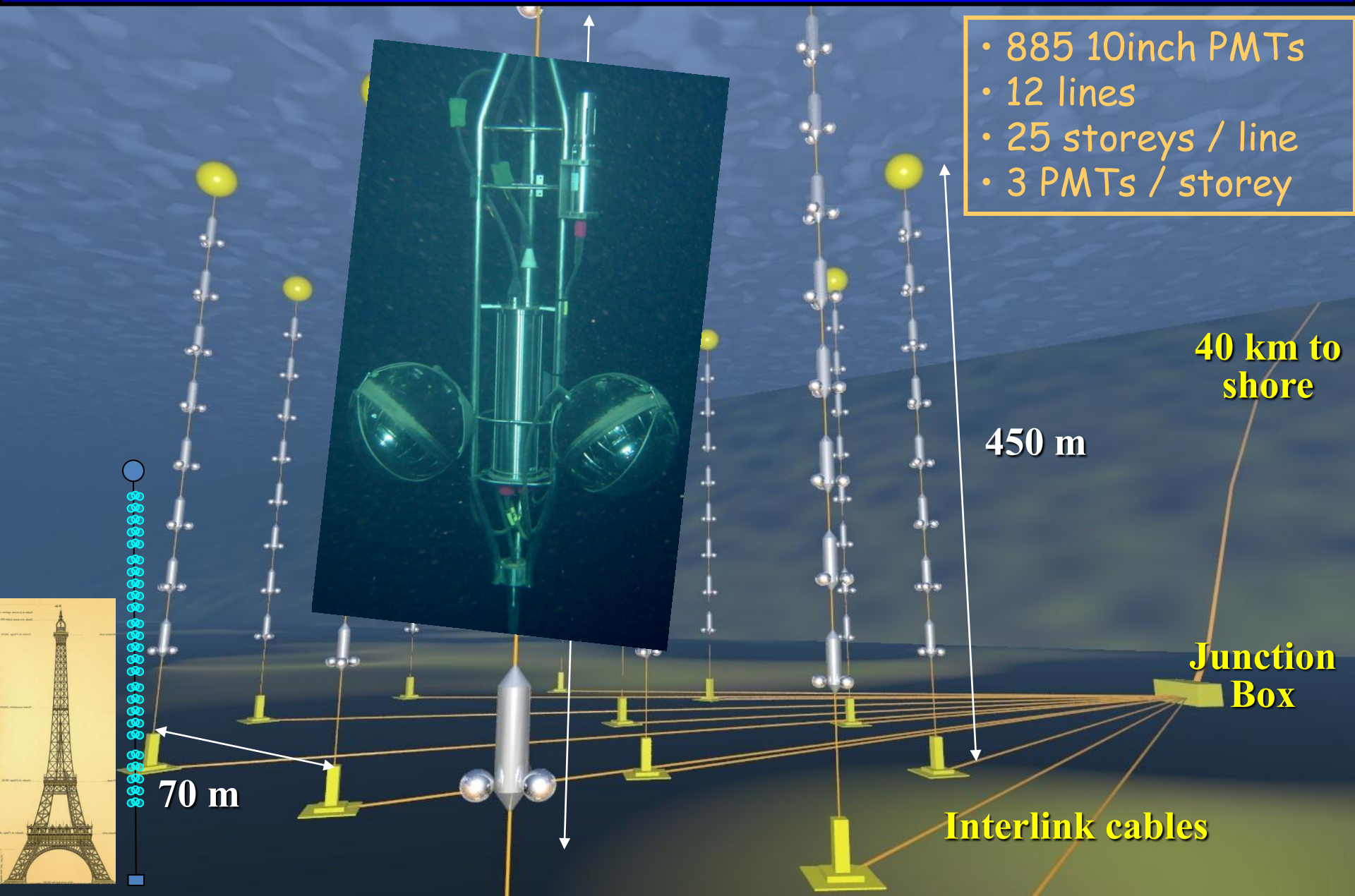
Atmospheric Neutrinos: standard candle and possible source of interesting physics

Muon tracks in the detector

- **Muons detected per year (IceCube/Antares)**

  – Atmospheric μ *
  7×10^{10} / 7×10^{8}

  – Atmospheric ν→μ **
  8×10^{4} / 2×10^{3}

  – cosmic ν→μ ~10

  - * 2000/20 per second
  - ** 1 every 6 min/5h

cosmic rays

p

μ

ν_μ

background

cosmic

ν_μ

atmosphere

ν_μ μ

p
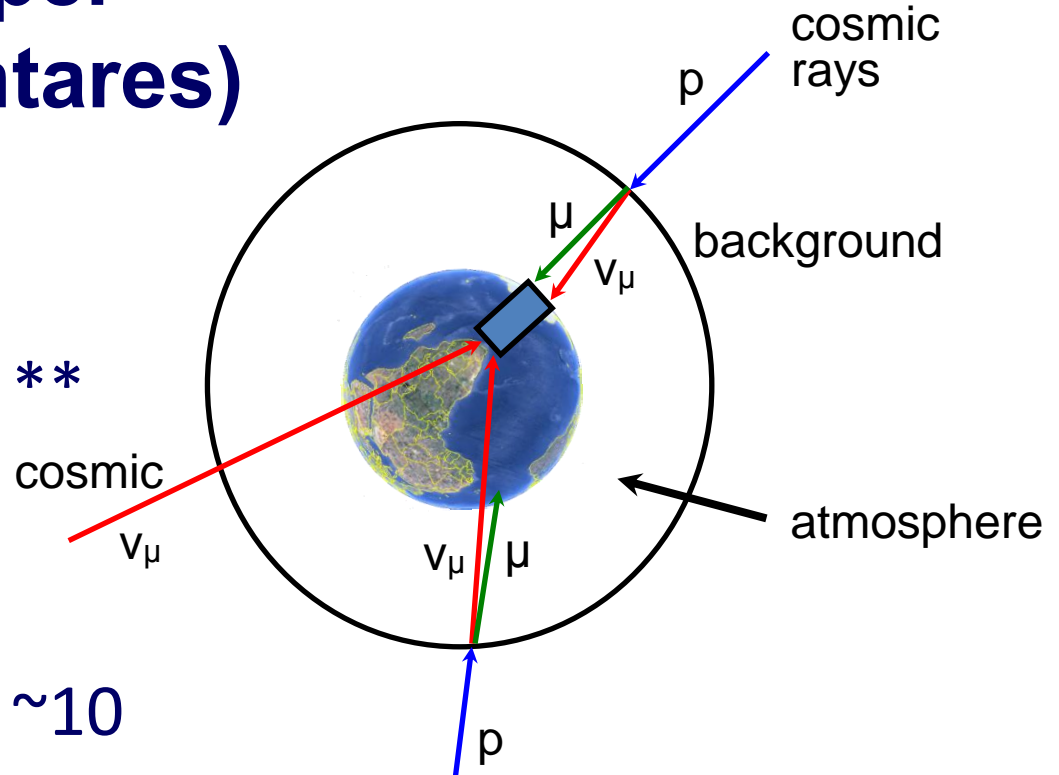
Some Events

reconstructed up-going neutrino:
detected in 6/12 detector lines:
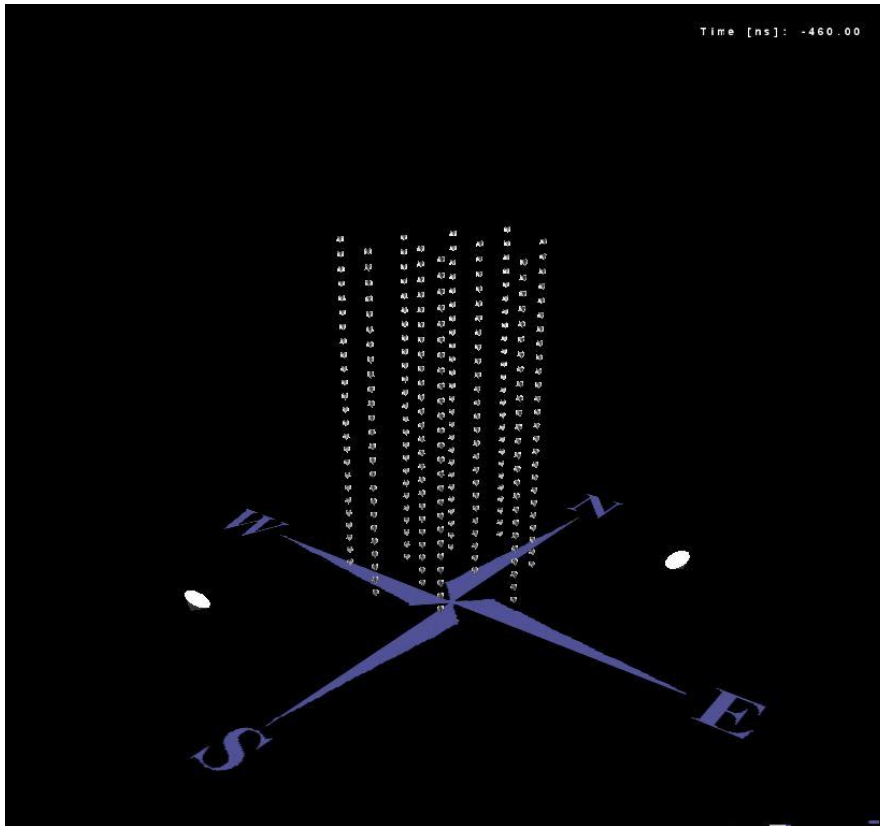
reconstructed down-going muon:
detected in all 12 detector lines:

upward μ from CC ν_μ interactions

ANTARES, clean sample of ν_μ isolated (2008)

Oscillations with Atmospheric Neutrinos

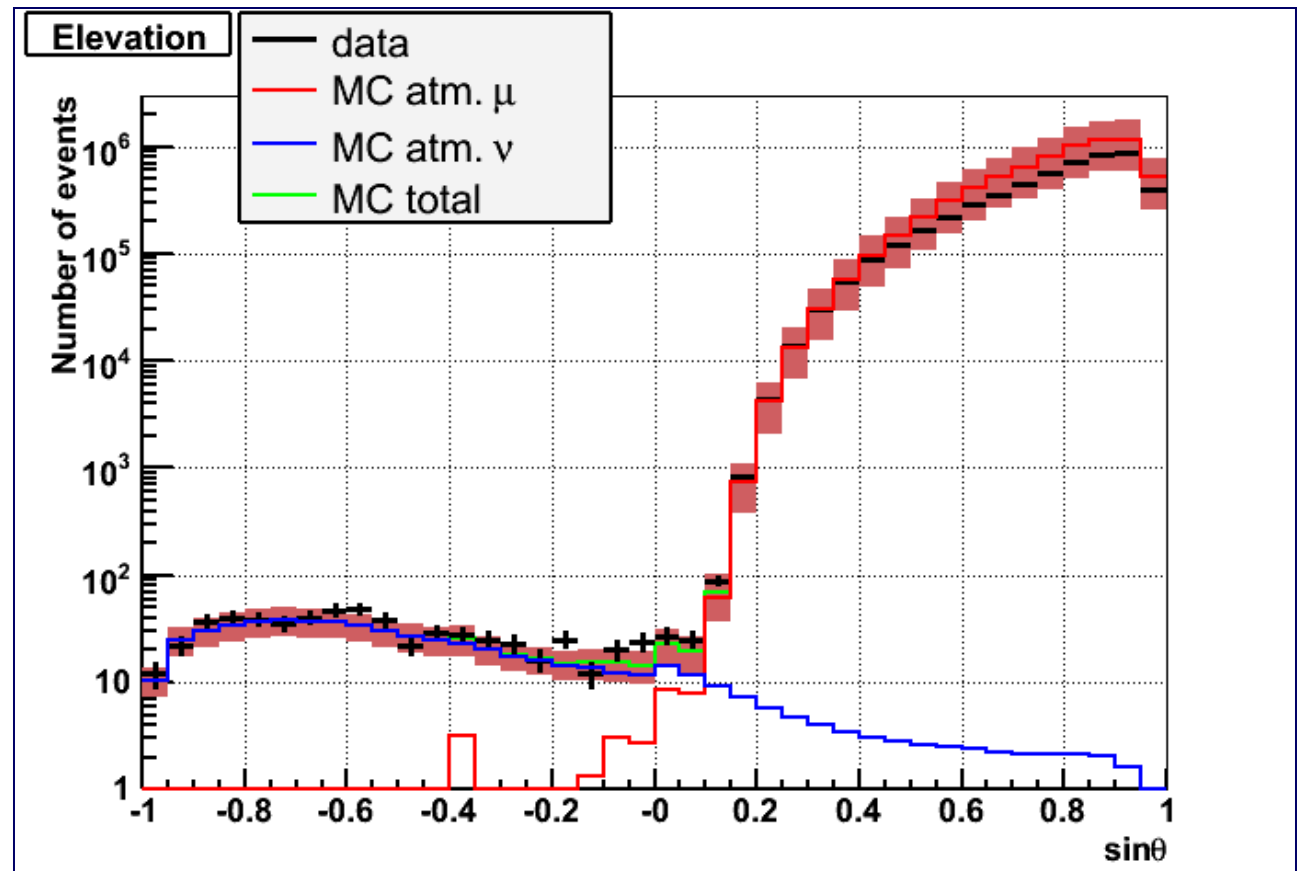$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\,\Delta m_{32}^2 \cos\Theta}{E_\nu}\right)$$

detector

atmosphere

$\cos\theta = 0.8$
$L = 25$ km (15 mi)

θ

$\cos\theta = 0$
$L = 500$ km (300 mi)

Earth

For upgoing tracks

L=2 R$_{Earth}$ cosΘ
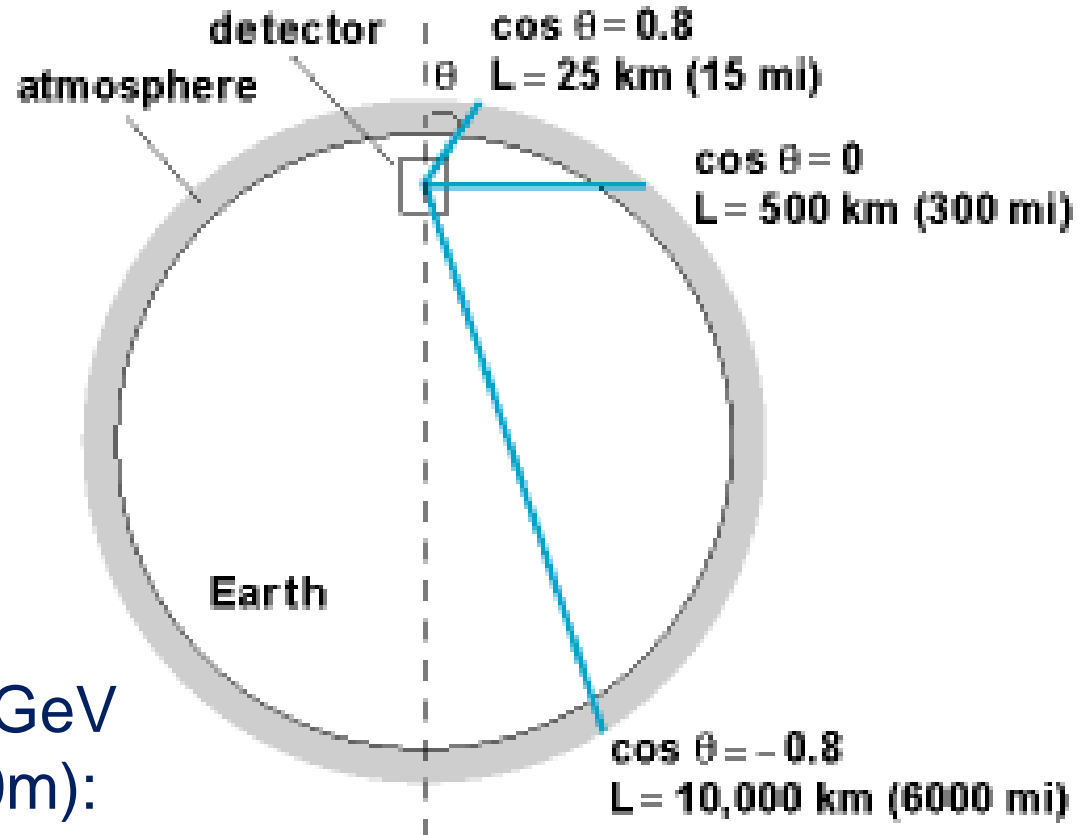
Oscillations maximal at 24 GeV
for vertical neutrinos (~120m):

$\cos\theta = -0.8$
$L = 10{,}000$ km (6000 mi)

Neutrino Oscillations in ANTARES

- ANTARES 2007-2010 data (863 days active time)
- Energy threshold 20 GeV corresponds to 8 storeys
- Muon energy from range : E(GeV) = Δz/5(m)/cosθ (lower limit)
- Zenith angle from track fit
- Clear effect of neutrino oscillations below 50 GeV
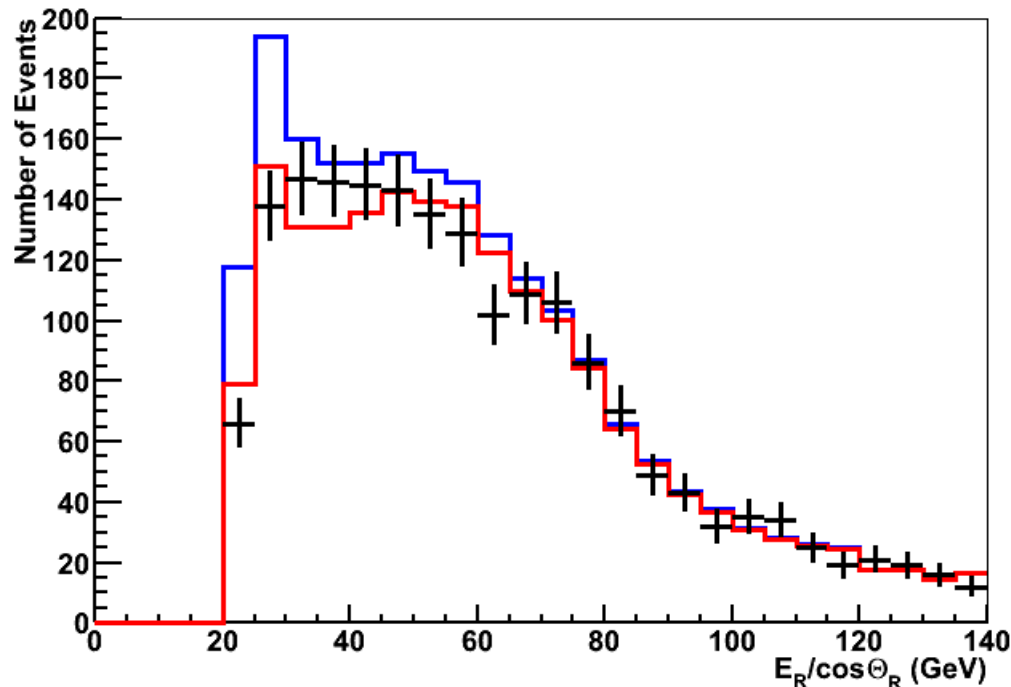
Neutrino Oscillations in ANTARES: Result

No oscillation: $\chi^2/NDF = 40/24$ (2.1%)

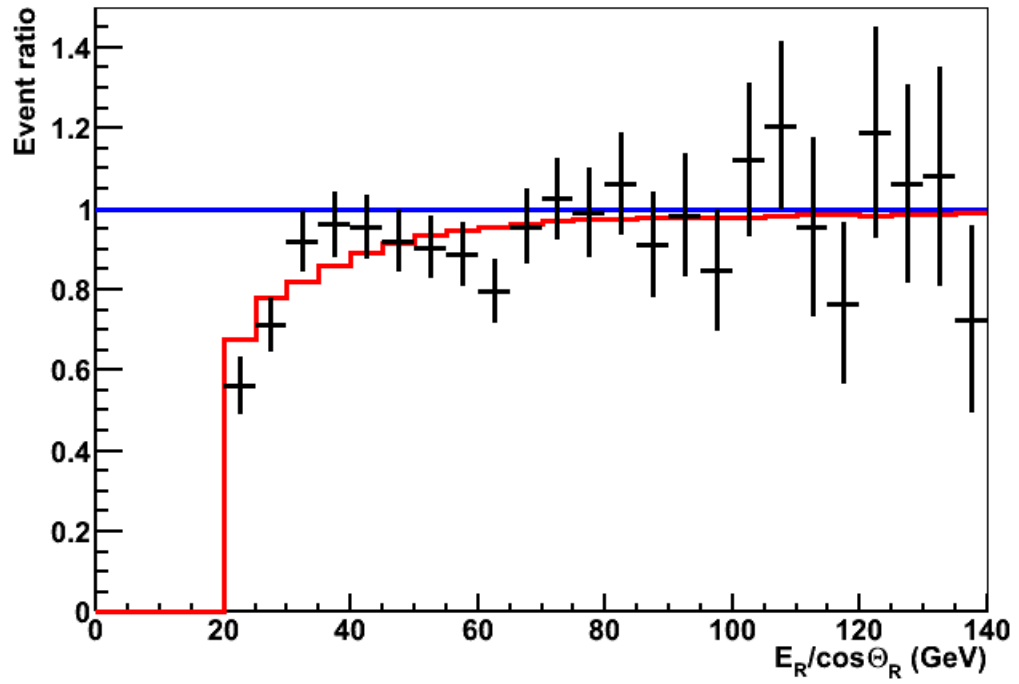Best fit: $\chi^2/NDF = 17.1/21$

$\Delta m^2 = 3.1\ 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.00$

$\varepsilon = 0.138$

$\eta = 0.143$

Neutrino Oscillations in ANTARES : Result
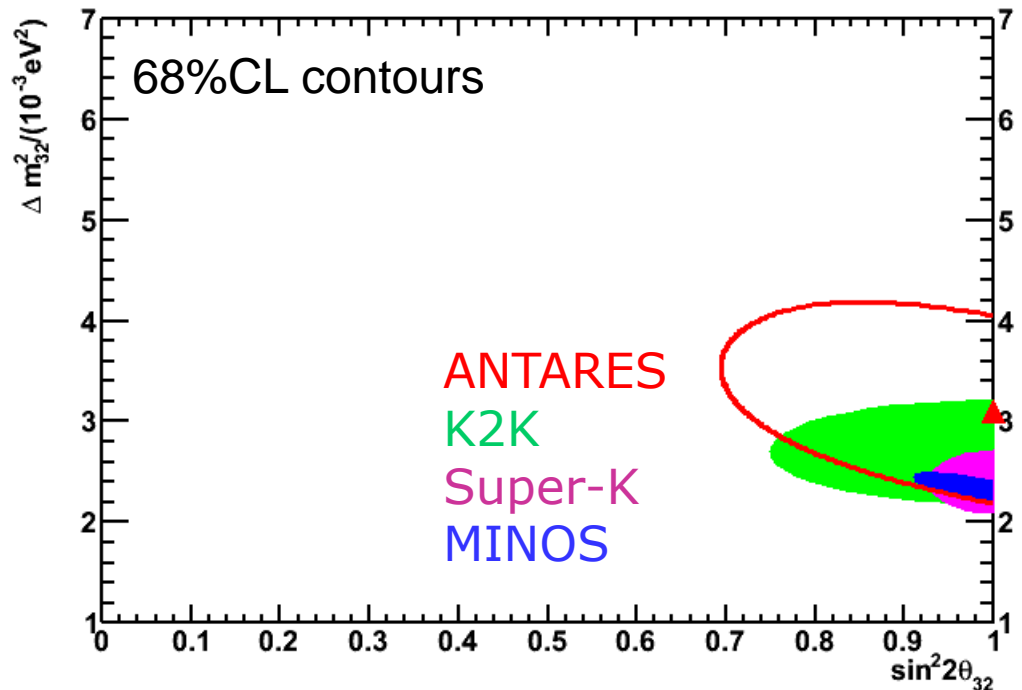
First measurement of oscillation parameters with high energy neutrino telescope

Refined measurement expected from DeepCore

68%CL contours

ANTARES
K2K
Super-K
MINOS

Assuming maximal mixing: $\Delta m^2 = (3.1\pm0.9)\ 10^{-3}\ eV^2$

Submitted to PLB (arXiv:1206.0645v1 [hep-ex])

Energy spectrum of atm. muon neutrinos
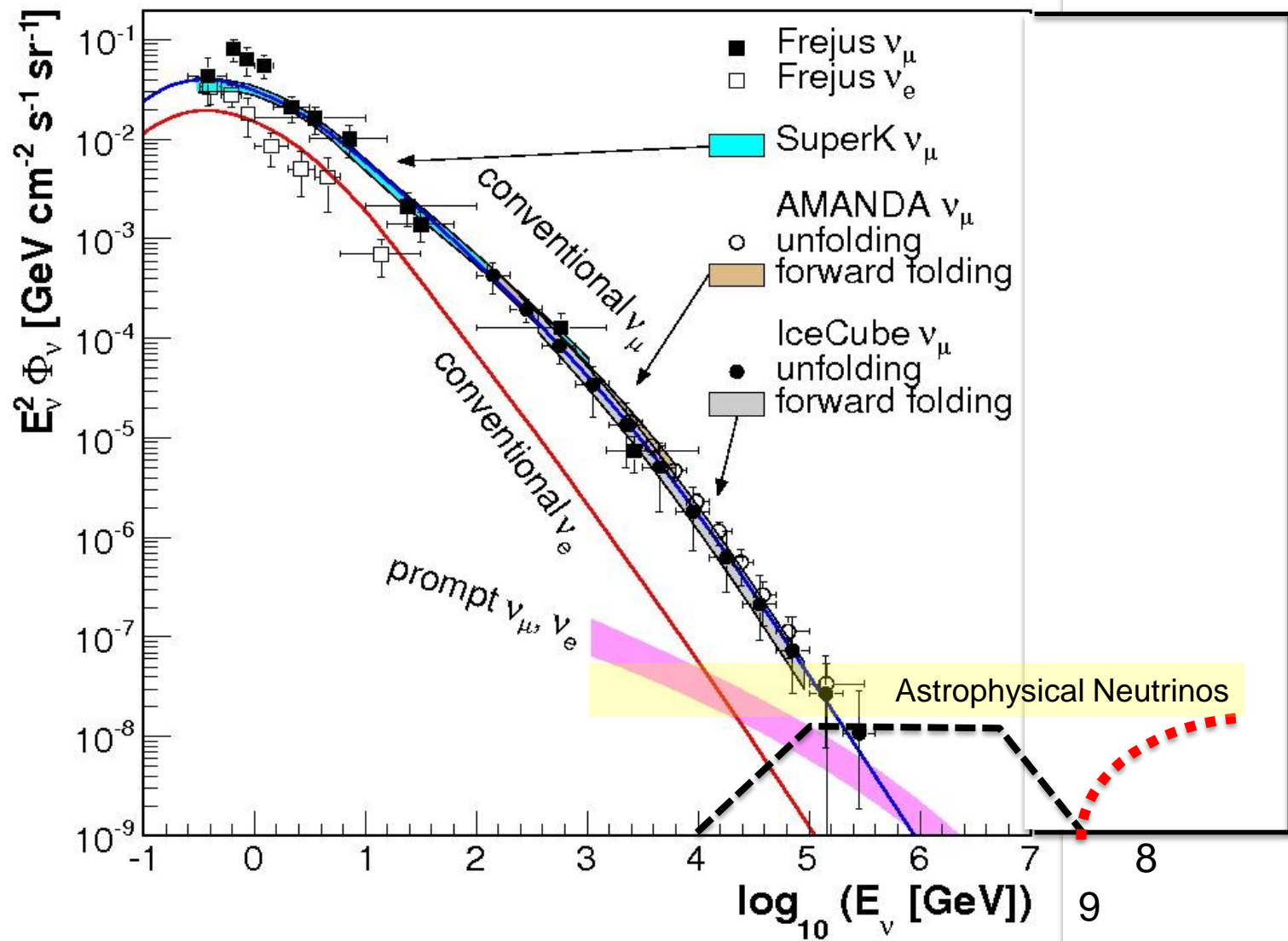
Diffuse Flux of Extraterrestrial Neutrinos

IC59 Diffuse ν_μ Search

Livetime: 348 days   Events: 21943

Legend:
- IC59 data
- conventional atmospheric neutrinos (Honda2006)
- conventional atmospheric neutrinos (best fit)
- prompt atmospheric neutrinos (best fit)
- astrophysical neutrinos E^{-2} (best fit)
- astrophysical neutrinos E^{-2} (90%CL upper limit)

Preliminary

ν_μ 90%CL: Φ_{lim} E^2 < 1.44 x 10^{-8} GeV sr^{-1} s^{-1}cm^{-2}

(y-axis)

$\log_{10}(dE/dx_{reco}$ [GeV/m])
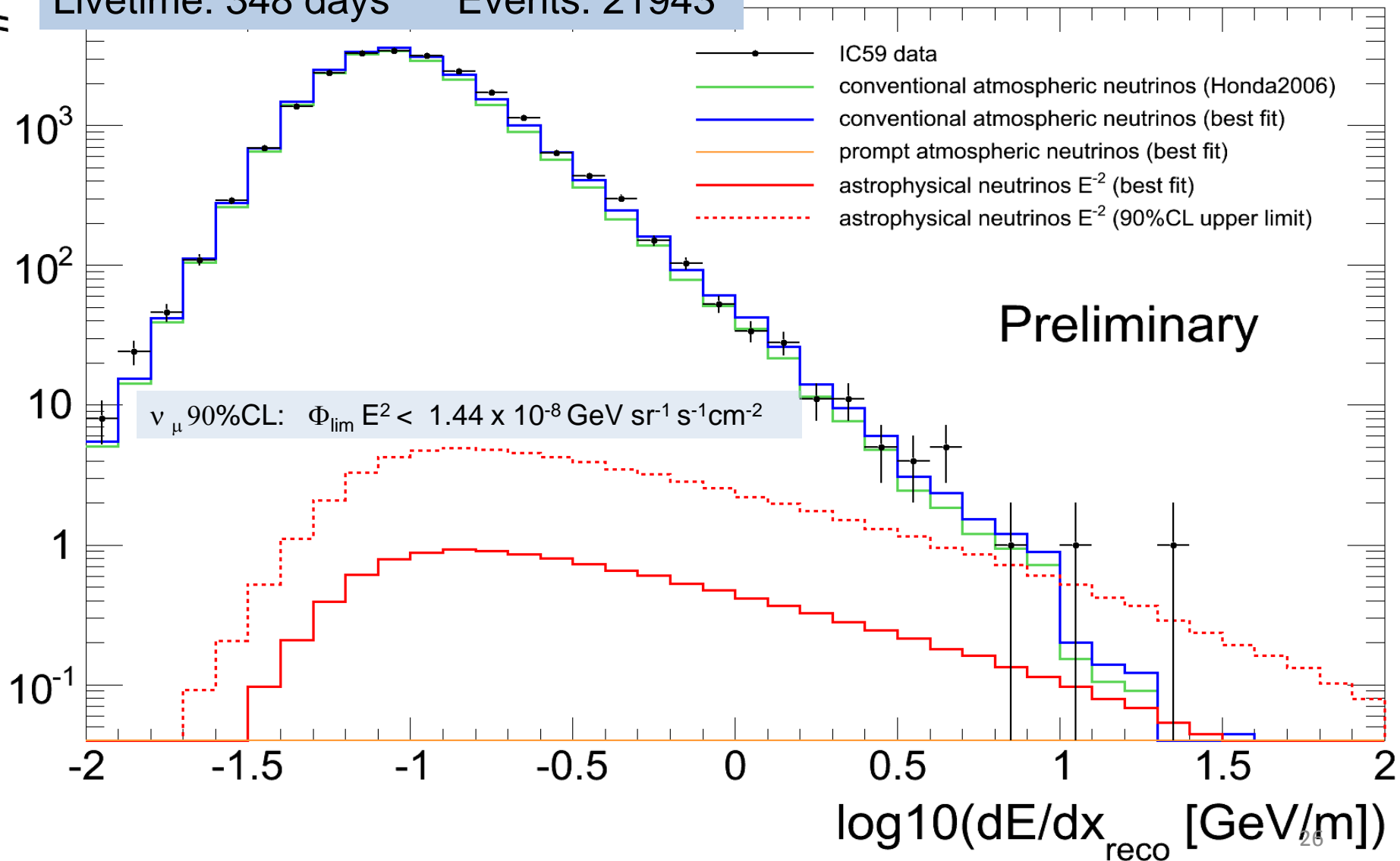
Current ν μ Diffuse limits (single flavor)
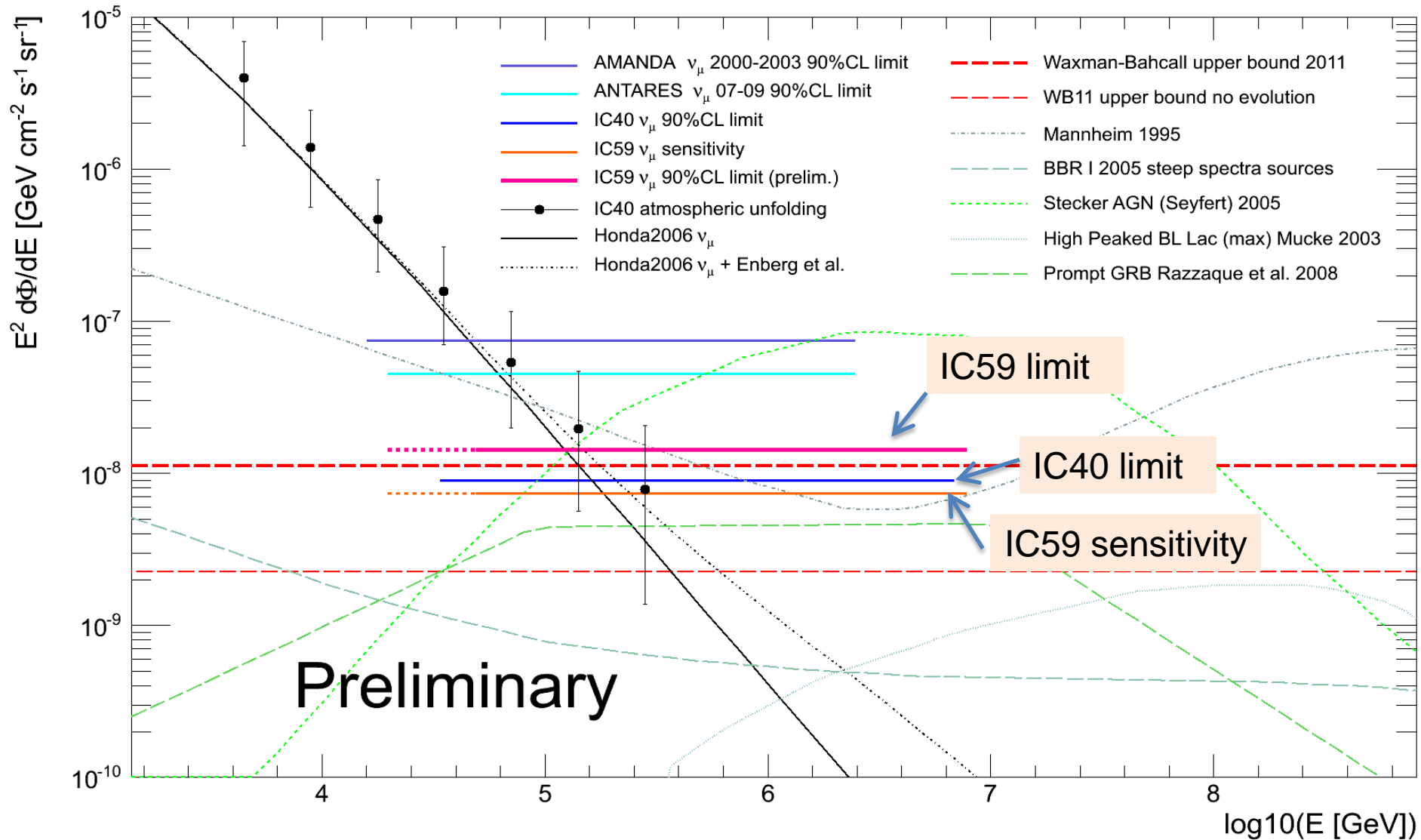
Ultra High Energy Events

A. Ishihara
ν-2012 Kyoto

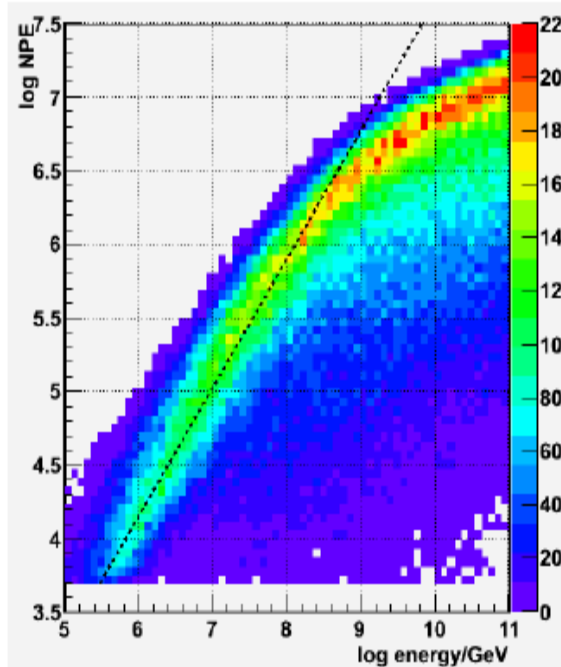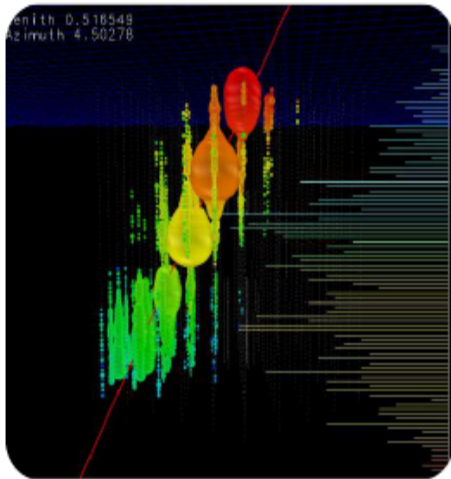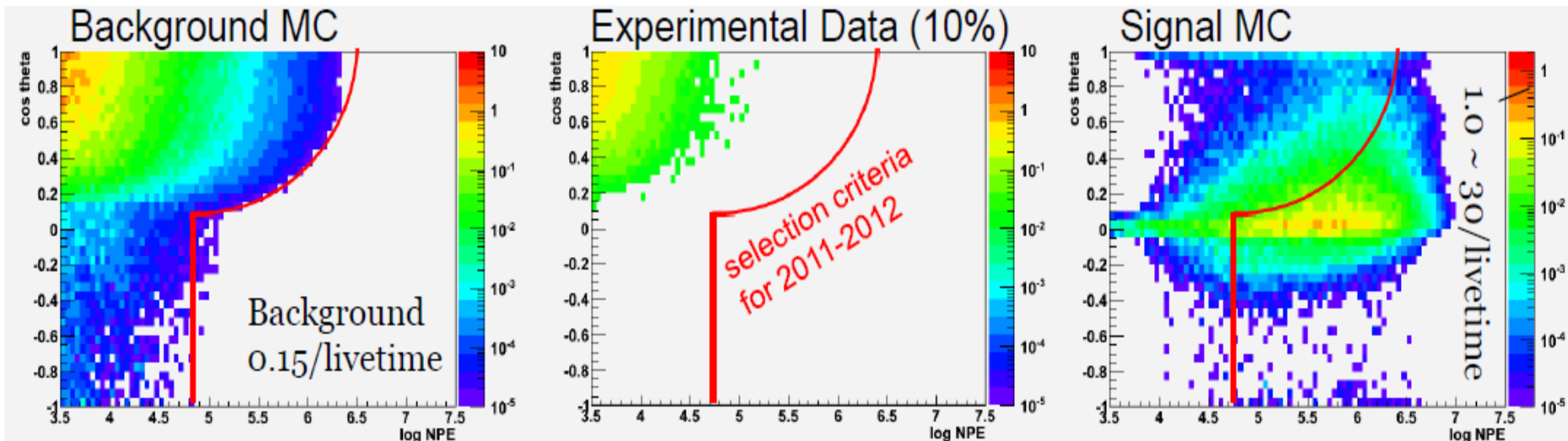Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

- Optimization based MC / MC verification based on 10% 'burned' experimental sample

Background MC

Background
0.15/livetime

Experimental Data (10%)

selection criteria
for 2011-2012

Signal MC

1.0 ~ 3σ/livetime

Two events passed the selection criteria

Run119316-Event36556705
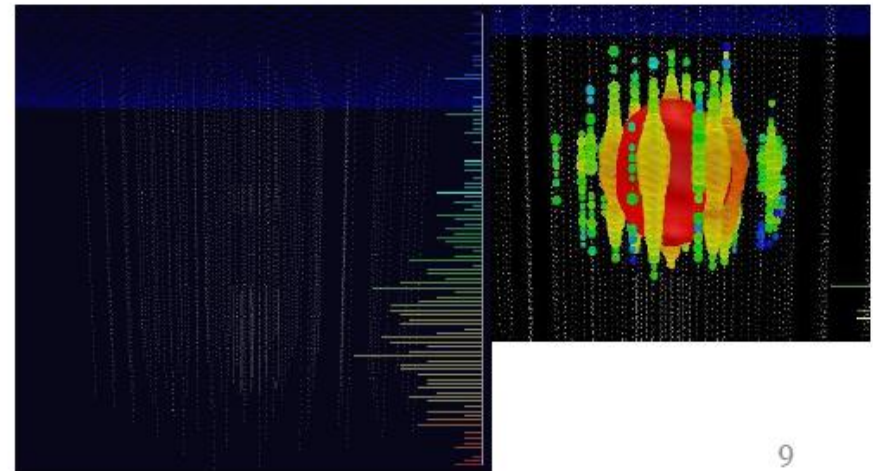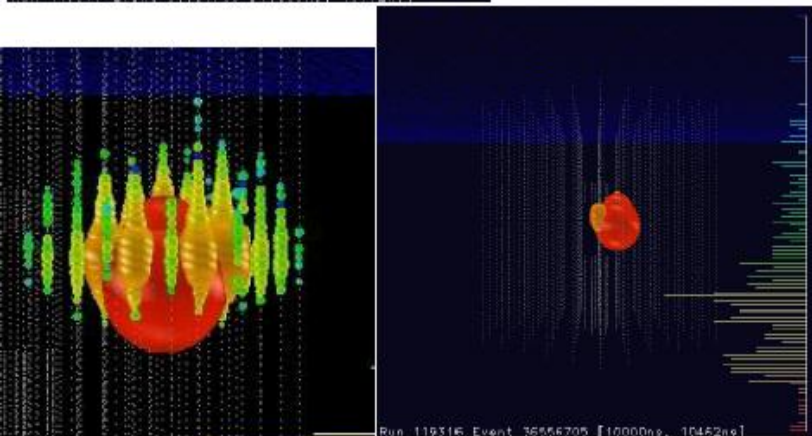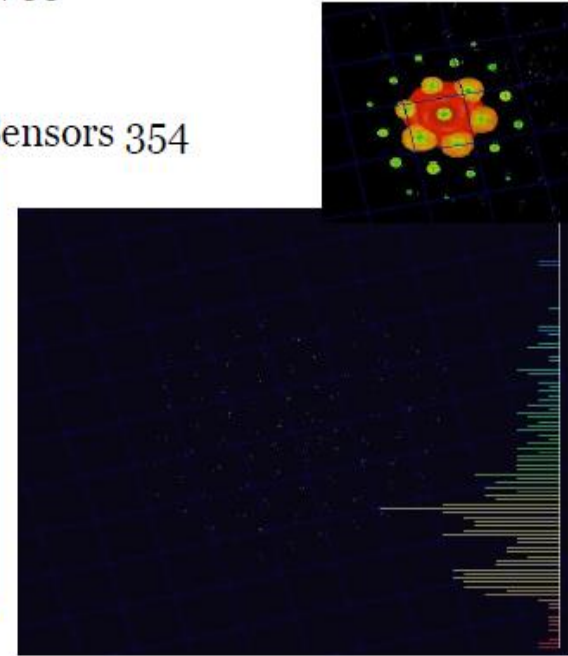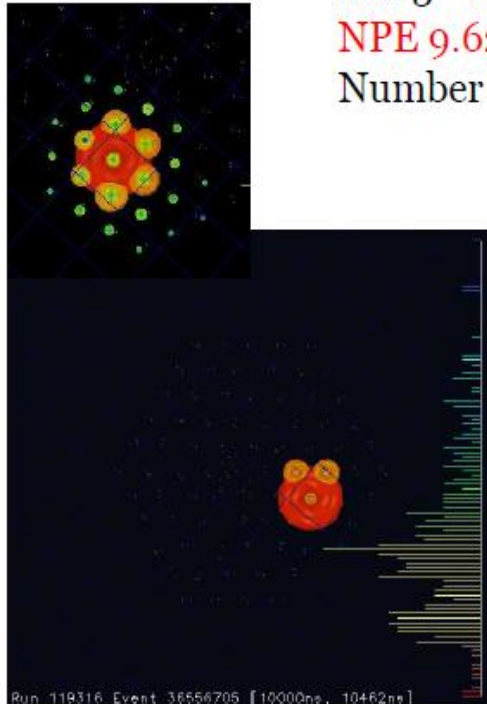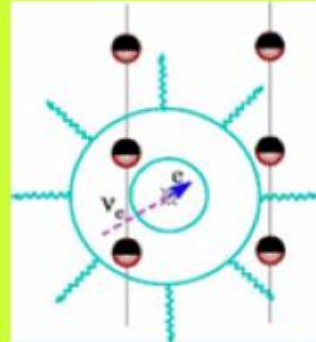Jan 3rd 2012
NPE 9.628x10^4
Number of Optical Sensors 312

Run118545-Event63733662
August 9th 2012
NPE 6.9928x10^4
Number of Optical Sensors 354

CC/NC interactions in the detector

MC

ν_e (cascade) simulation

9
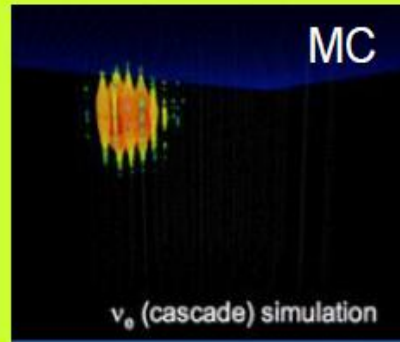
Event Brightness (NPE) Distributions 2010-2012

Legend:
- GZK ν Yoshida m=4 Zmax = 4 γ=2
- GZK ν Kotera FR2, Emax 316 EeV
- GZK ν Ahlers m=4.6 Zmax=2 γ=2.5
- $E^2\phi = 1 \times 10^{-18}$ GeV cm^{-2} sr^{-1} s^{-1}
- Background Total
- Atmospheric prompt ν Enberg std.
- IceCube 2010-2012 (673days) Preliminary

Preliminary

x-axis: $\log_{10}$ NPE

y-axis: Event rates / bin / livetime
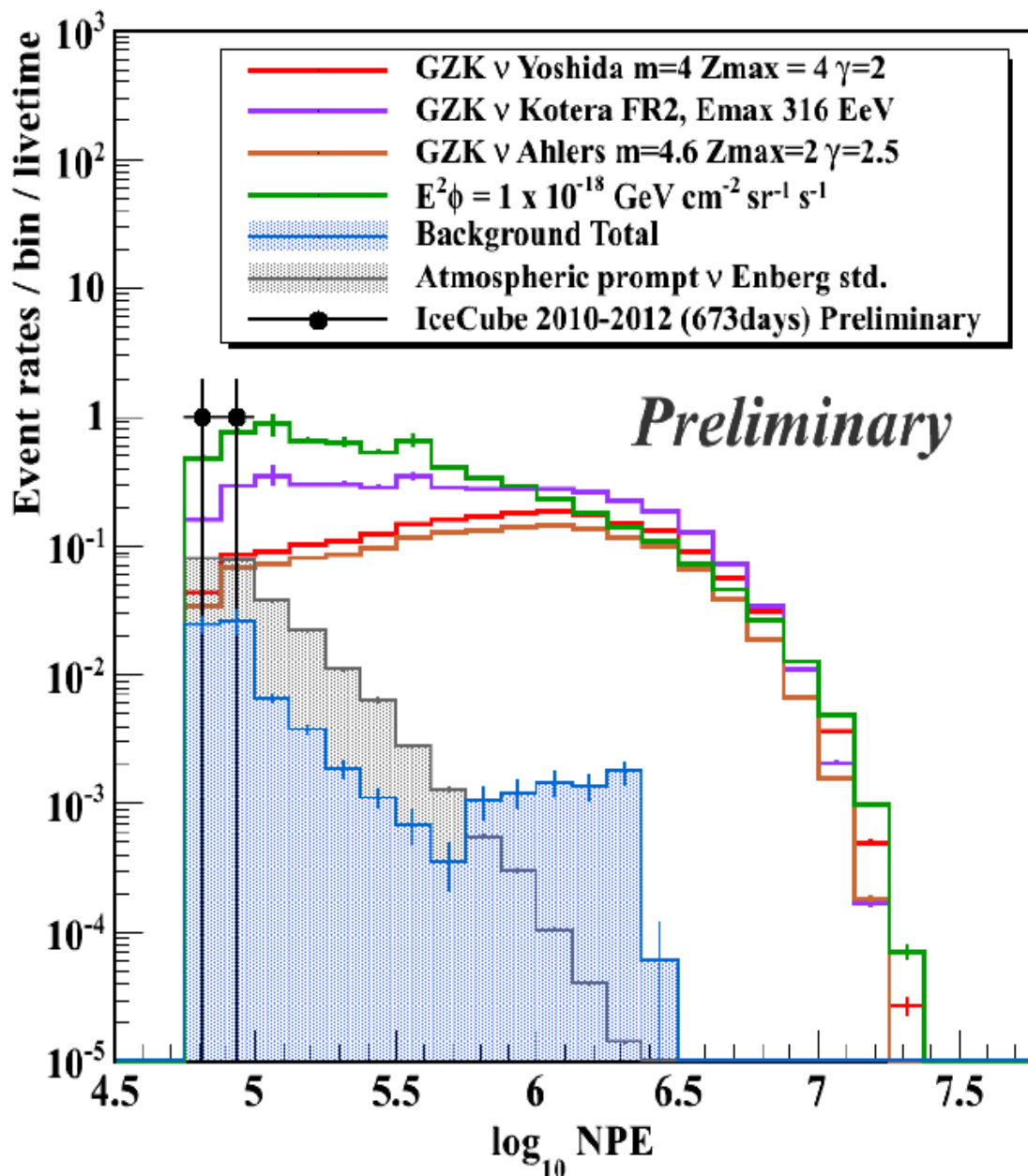
- Observed 2 high NPE events
- Near the NPE threshold

- Possibility of the origin includes
  - cosmogenic ν
  - on-site ν production from the cosmic-ray accrelators
  - atmospheric prompt ν
  - atmospheric conventional ν

A. Ishihara
ν-2012 Kyoto

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Point Sources Searches

Point Source Search in Skymap (IC40+59)

43339 up-going + 64230 down-going from 723 days

unbinned likelihood

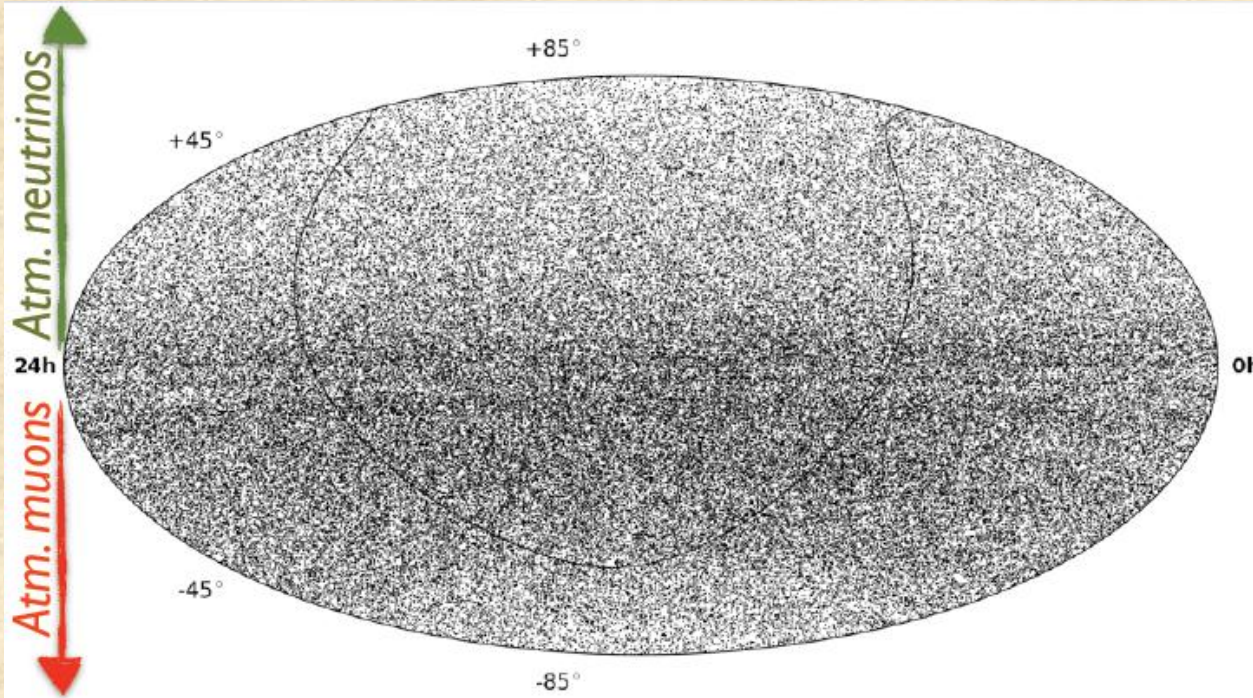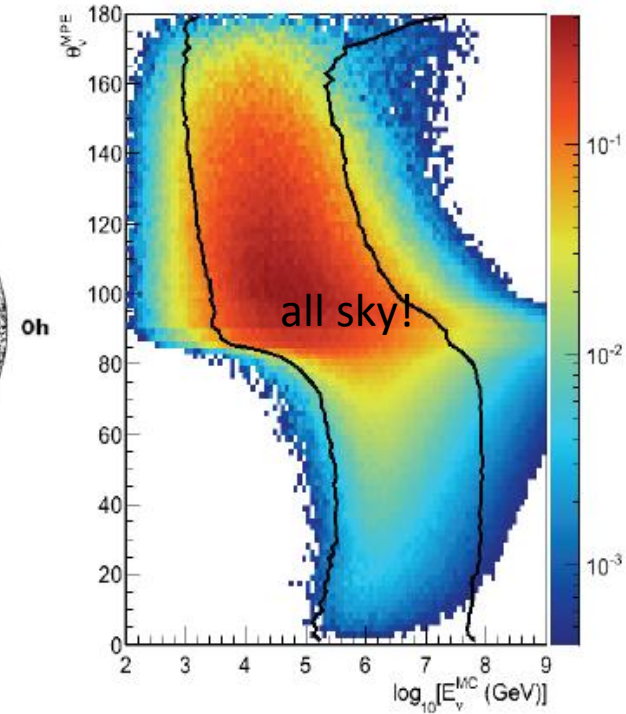$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

signal term contains angular and energy pdf

test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \text{p} - \text{value}$$

Skymap IceCube (IC40+59)

Northern hemisphere

atm. neutrinos

TeV − PeV

atm. muons

PeV − EeV

preliminary
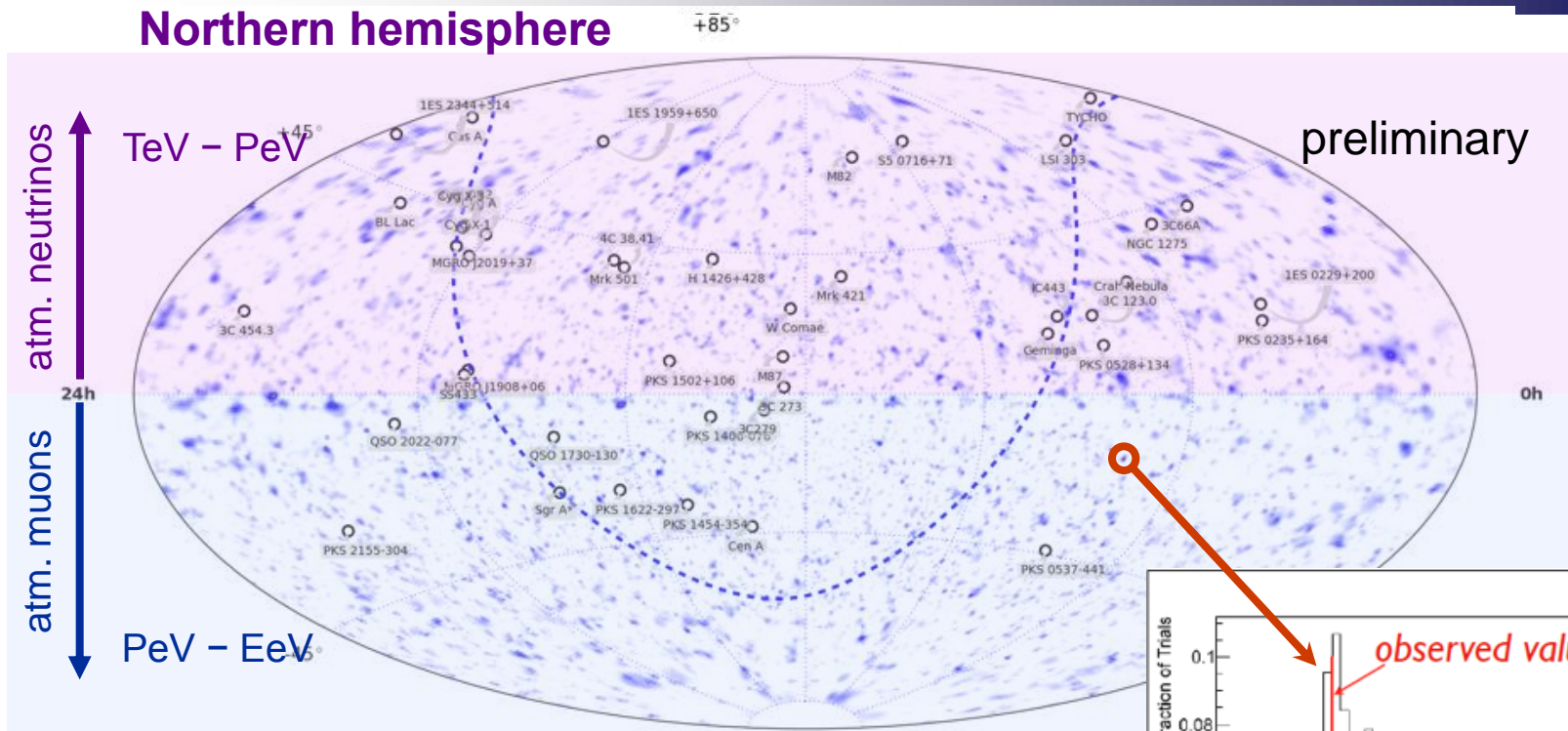
Southern hemisphere

- – **107,569 events** (30% upgoing, livetime 723 d)
- – **Source list:** 13 Galactic, 20 extragalactic
- **No significant excess**
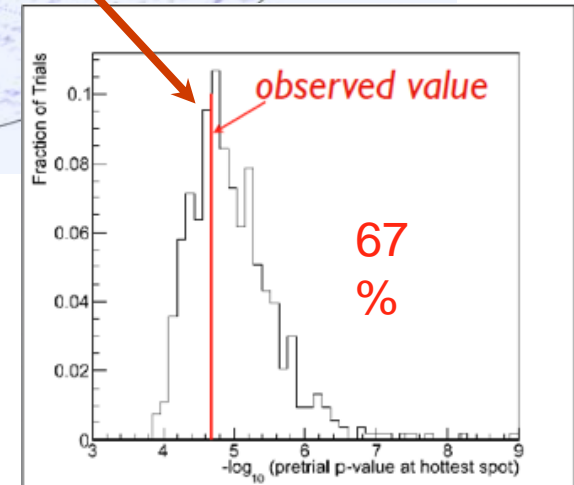
Full-Sky Search (2007-2010)

Sky map in equatorial coordinates

Most significant cluster at:
$\mathcal{RA}$= −46.5°,
δ= −65.0°

N_{sig} = 5
p-value = 0.026
Significance = 2.2 σ

Antares 2007-2010 preliminary

3°
1°

Result compatible with the background hypothesis

Candidate List Search – 90%CL Flux Limits
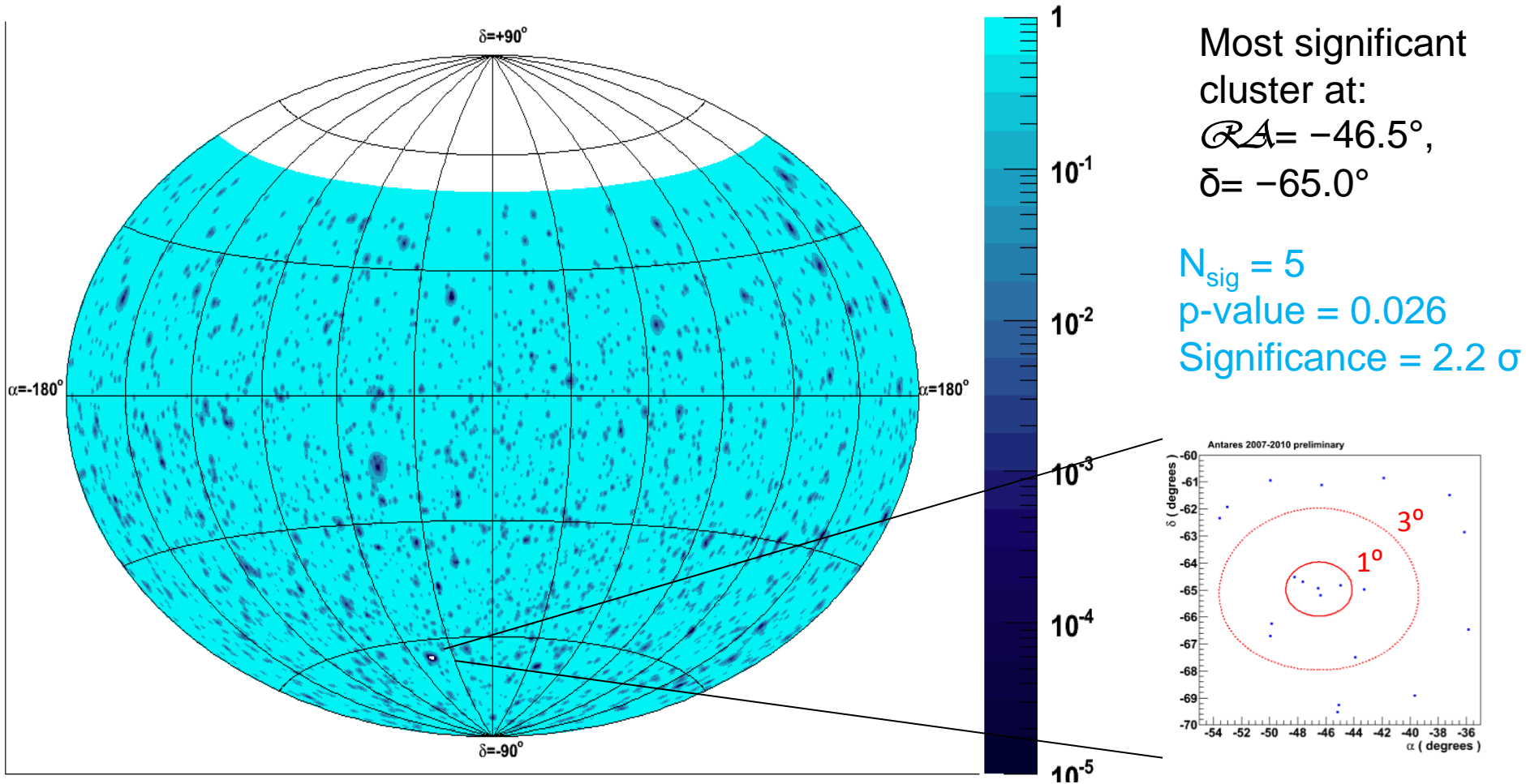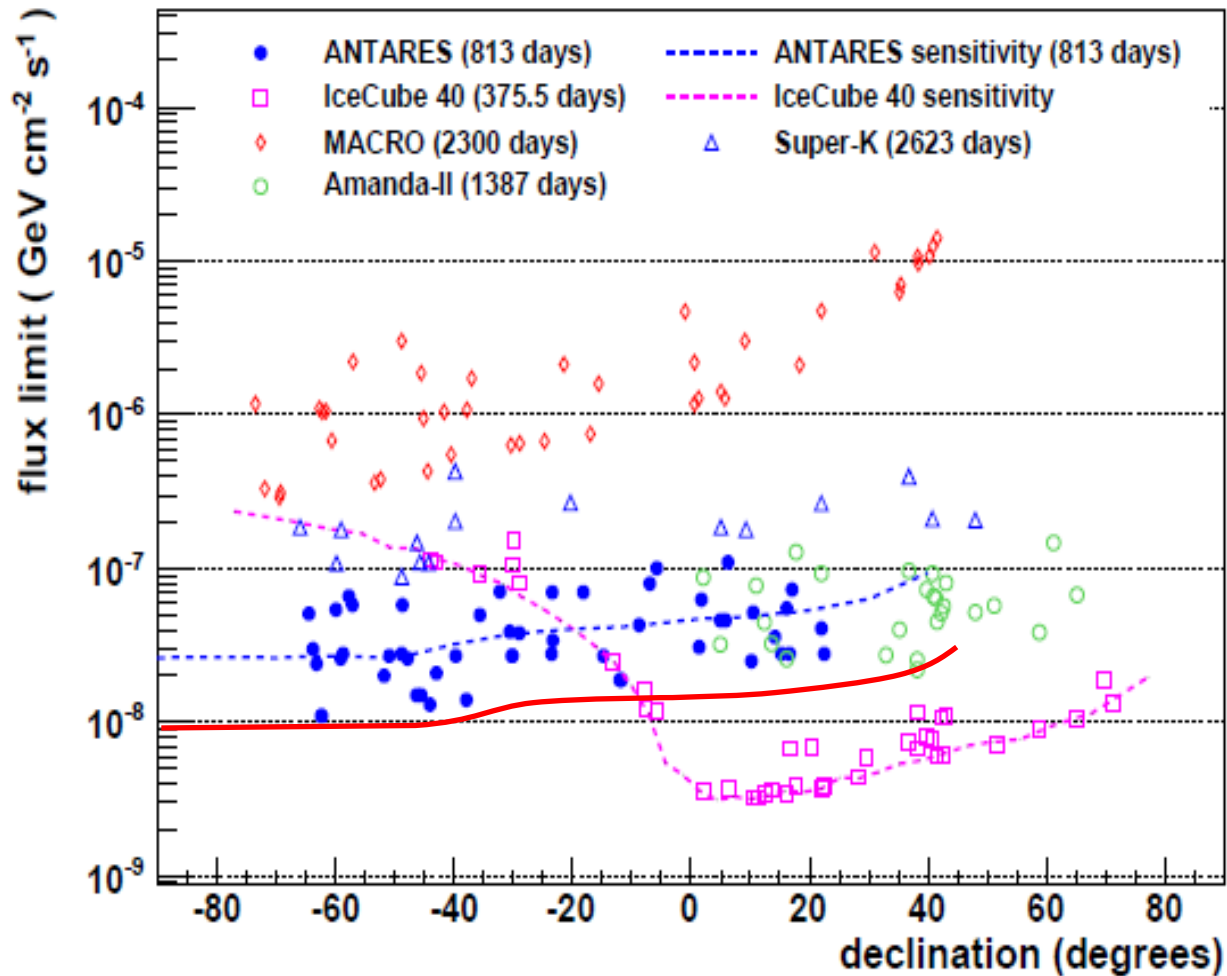

Assumes E^{-2} flux for a possible signal

ANTARES 2007-2010
813 days
× 2.5 improvement w.r.t. previous analysis

IC40 375 days

Combined analysis
IC40+IC59 : next plot

Transient Point Sources Searches

Fireball model

Off-Time | Always Blind
Precursor | On Time

1 hour | 10 min | 1 hour

time

110 s | T90

Internal Shock

Collisions betw. diff. parts of the flow

Jet — collapse — **Precursor** — Jet — **GRB** — **Afterglow**

$\approx 10^{13}$ cm | $> 10^{16}$ cm

X O R

γ

t ~ -10 →-100s

t ~ 0 → t90

t ~ t90 → ?
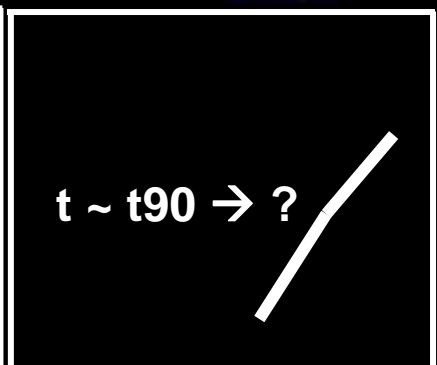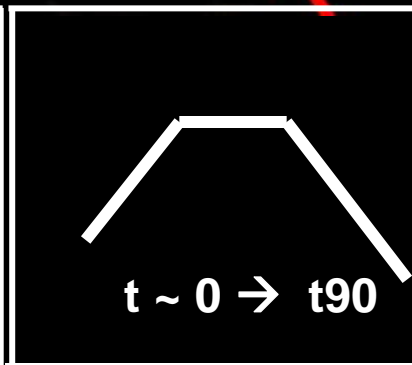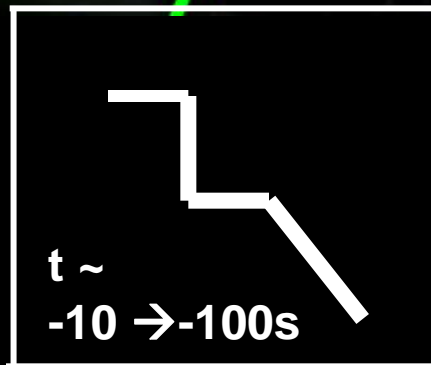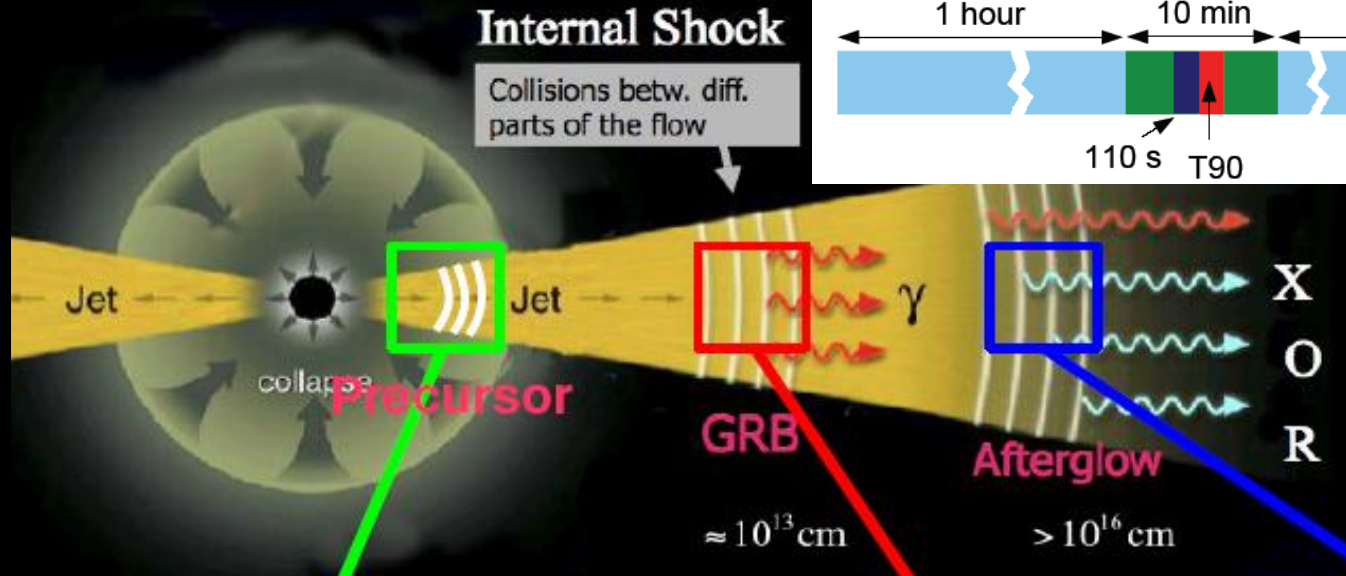
Energy

IceCube GRB search

- IceCube performed a stacked search for a neutrino signal in coincidence with observed GRB gamma signals
  - All Northern hemisphere GRB bursts are considered.
- Combination of spatial and time correlation yields very low background *(~Background Free Search)*
- Per-burst neutrino fluence and spectra are calculated based on the measured gamma-ray spectra. Parameterization of Guetta, et al. (Astropart.Phys. 20 (2004) 429-455)

Nature **Vol 484**, 351 (2012)
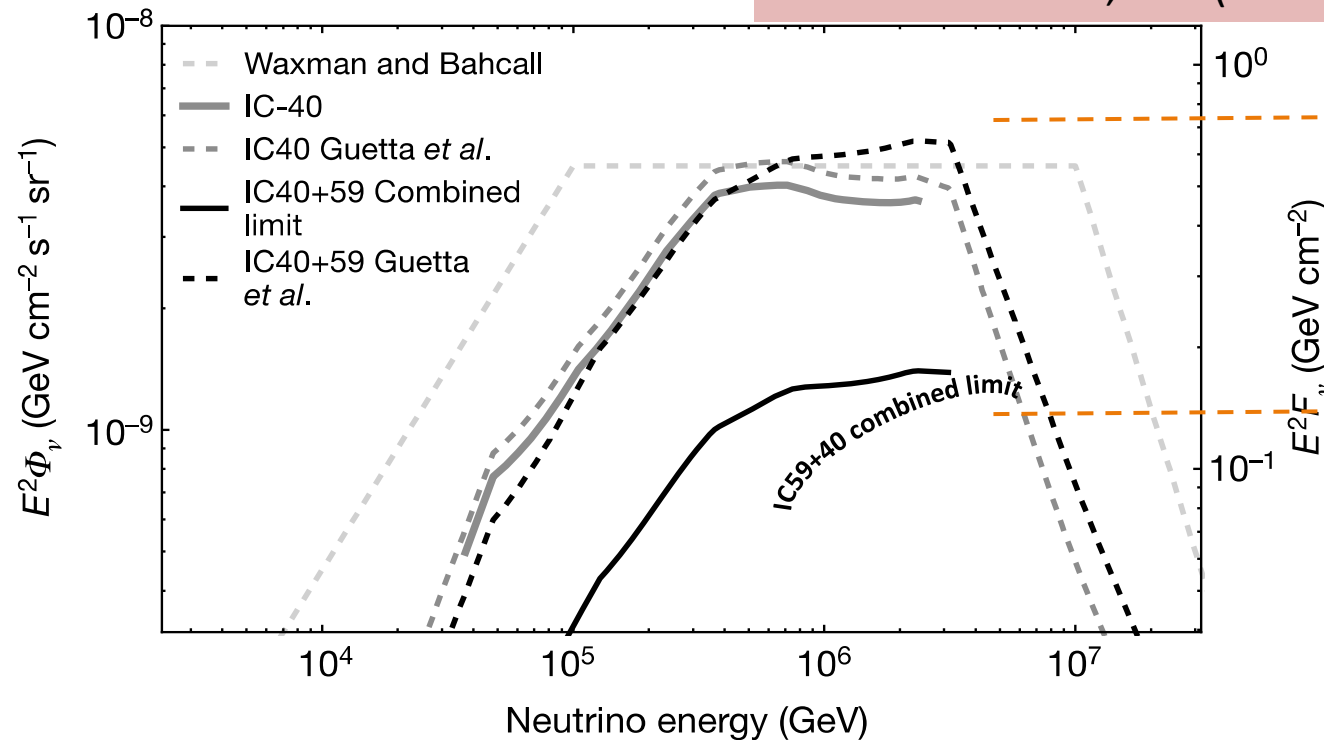
90% c.l. = 0.27 model

8.4 events expected
0 events observed

G. Sullivan
ν-2012 Kyoto

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IceCube GRB Summary

- Three successive seasons (IC 22, 40, 59) without a GRB neutrino discovery

- Combined (IC40, IC59) search results
  - Expect 8.4 events, see 0 → *0.27 Guetta et al prediction*

- ***Where are the neutrinos?*** → *Nature Paper*

- ***Do we already rule out GRB as The CR source?***
  - Input assumptions in modeled GRB neutrino flux
    - Bulk Lorentz factor, fraction of energy in electrons relative to protons, dynamics of time structure, **particle physics**

- Has generated activity in the theory of GRB's
  - Recalculations reduce predicted neutrino significantly

- IC79, 86 (~3x sensitivity of current limit) already recorded
  - IceCube sees ν's within "years" or rule out GRB as THE CR source

G. Sullivan
39
ν-2012 Kyoto

Summary

- IceCube and Antares are producing lots of interesting results
  - Astrophysics
  - Particle physics
- IceCube is opening the era of km^3 physics
- ANTARES most sensitive for Galactic sources
- Realistic models start to be challenged
- First high energetic astrophysical neutrino observation might by around the corner

END