Recent Developments in HE Neutrino Astronomy

Efforts, Achievements and Outlook

In Search of the Origin of the Cosmic Radiation

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Vulcano Workshop 2012 May 28 - June 2
Frontier Objects in Astrophysics and Particle Physics

Overview

- **The Cosmic Ray Puzzle, Progress & Status**
- **High & UHE Neutrino Telescopes & Results**
  - Optical Cherenkov Detector Matrices
  - AS Fluorescence (FE type) & Particle Detectors
  - Cherenkov Radio Detection (Antenna Arrays)
  - Acoustic Detector Matrices in Solids & Liquids
- **Future Giant Neutrino Detectors**
- **Concluding Remarks**

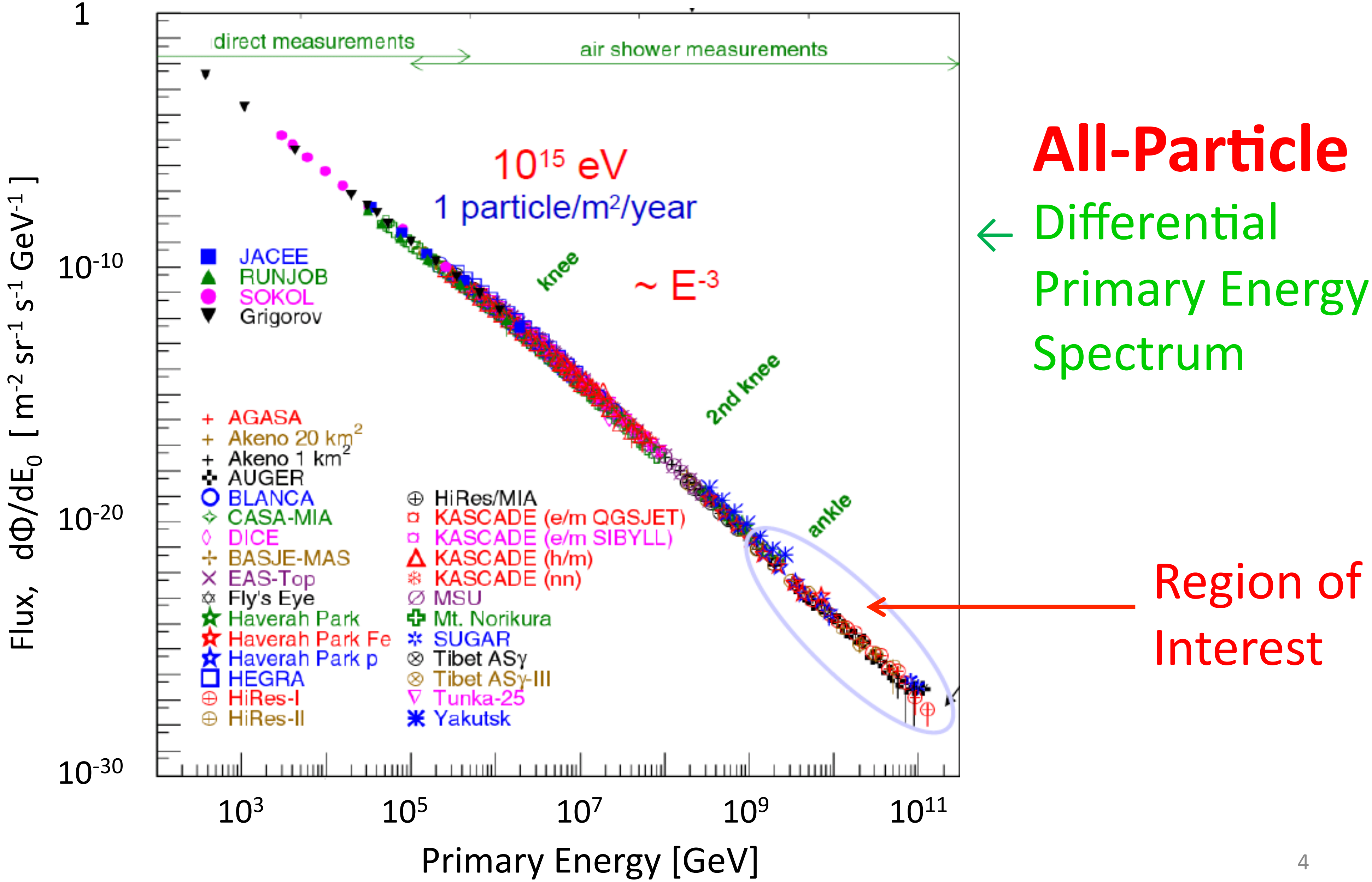
The Cosmic Ray Puzzle

Great progress has been made in recent years but 3 relevant questions remain:

- **Spectrum** and spectral features at the highest primary energies (dips, bumps and cutoff)
- **Composition** of the primary radiation (particles and quanta, energy dependence)
- **Location of the source(s),** unveil their nature, mechanism and association with known objects

Neutrino astronomy can yield part of answers

Current Status of UHE CR Physics

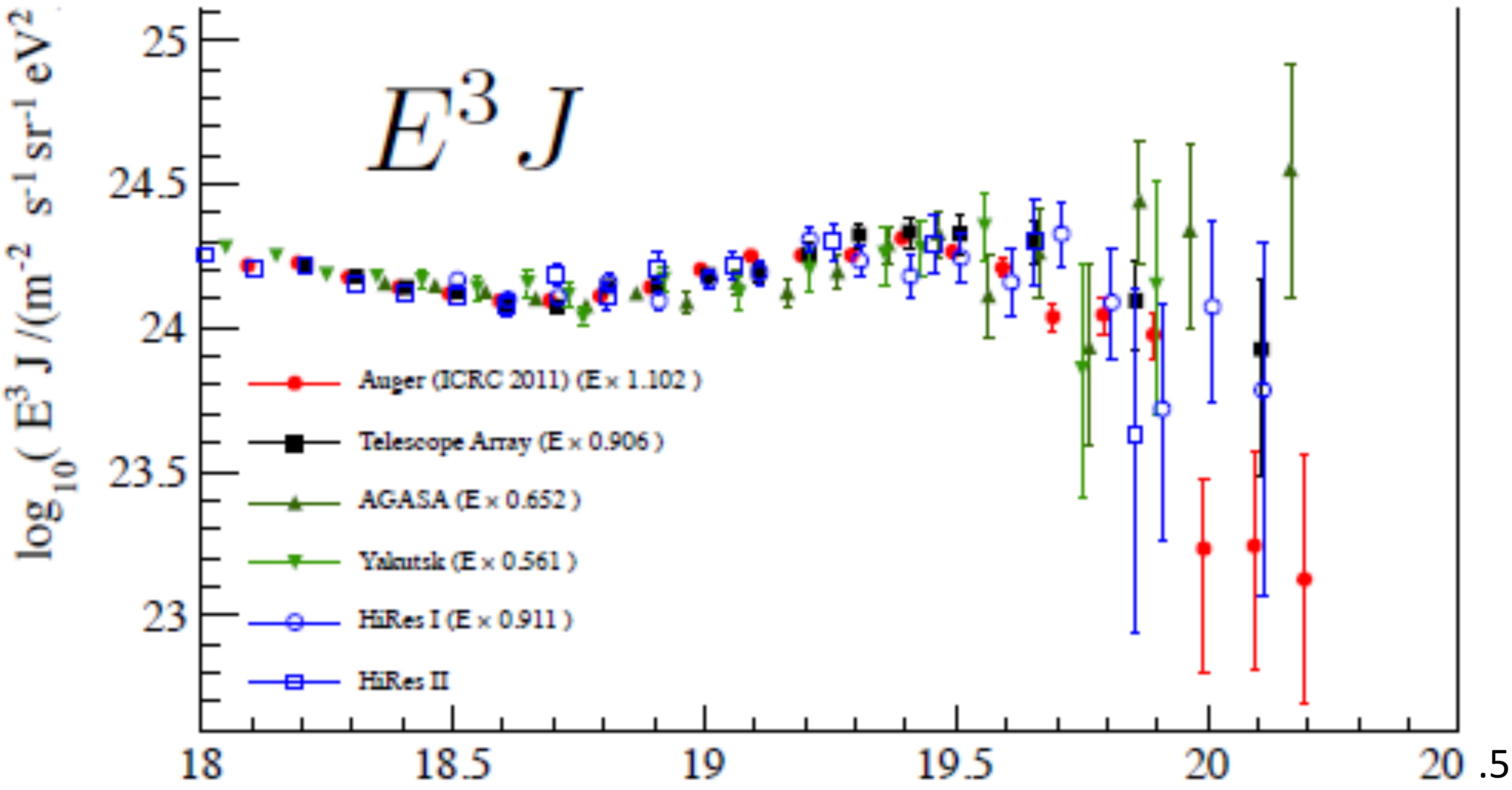


All-Particle

← Differential Primary Energy Spectrum

UHE Portion of Spectra, 6 Experiments

PAO, HiRes and TA are in agreement well within systematic errors below lg E = 19.5 eV



log$_{10}$ (E) [eV]

Search for UHE Cosmic Ray Sources

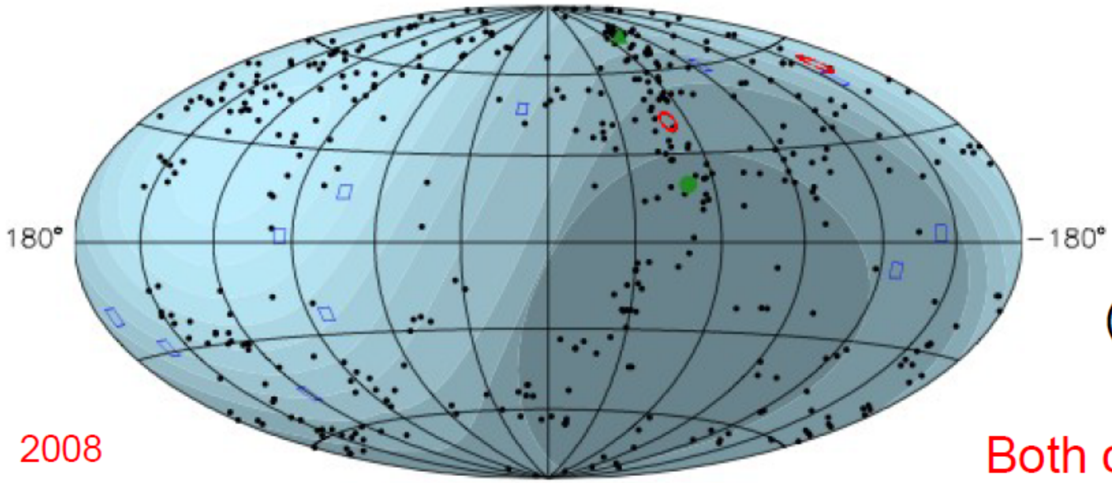
using multi-messenger approach

Hadrons, Photons, Neutrinos

- Anisotropies
- Point sources
- Diffuse sources
- Galactic and extragalactic magnetic fields
- Propagation aspects (rad. fields, dust, etc.)
- Nature of primaries is relevant (h, γ, ν)

Where do E>10 EeV Particles come from?

EAS Anisotropy at UHE



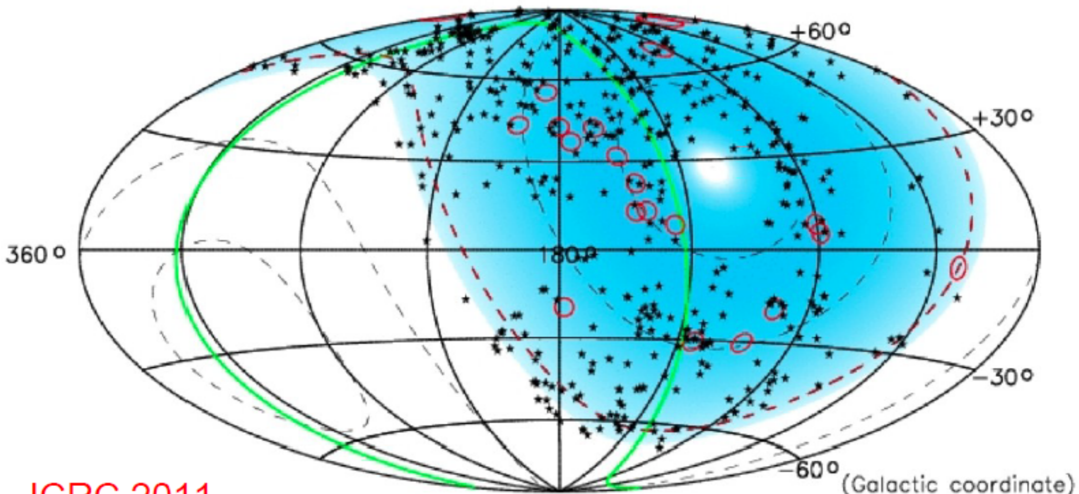
2008

HiRes

2 out of 13 correlate

(expect 3.2 if isotropic)

Both compatible with
Auger current anisotropy
(and also with
isotropy!)



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TELESCOPE ARRAY PROJECT

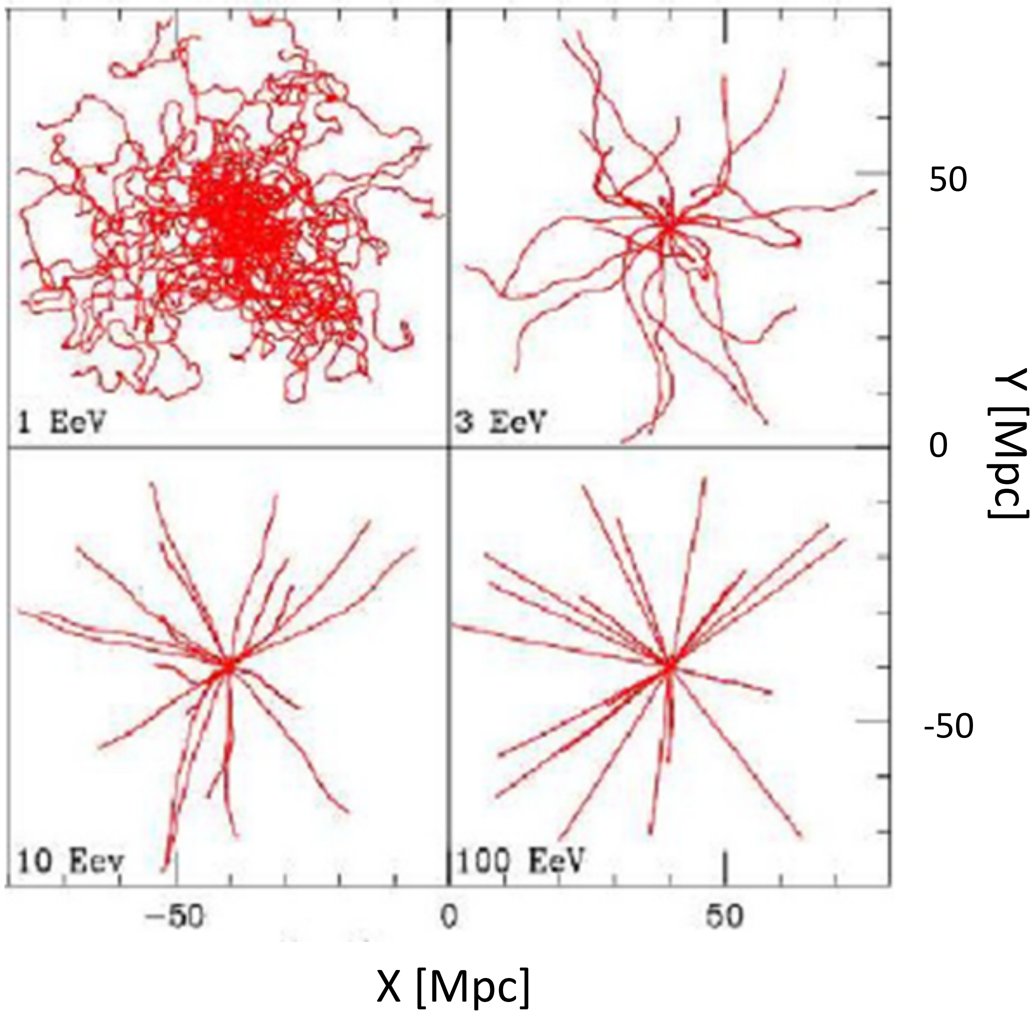
8 out of 20 correlate

(expect 4.8 if isotropic)

UHECR2012
Privitera

CR Source Blurring by Magnetic Fields

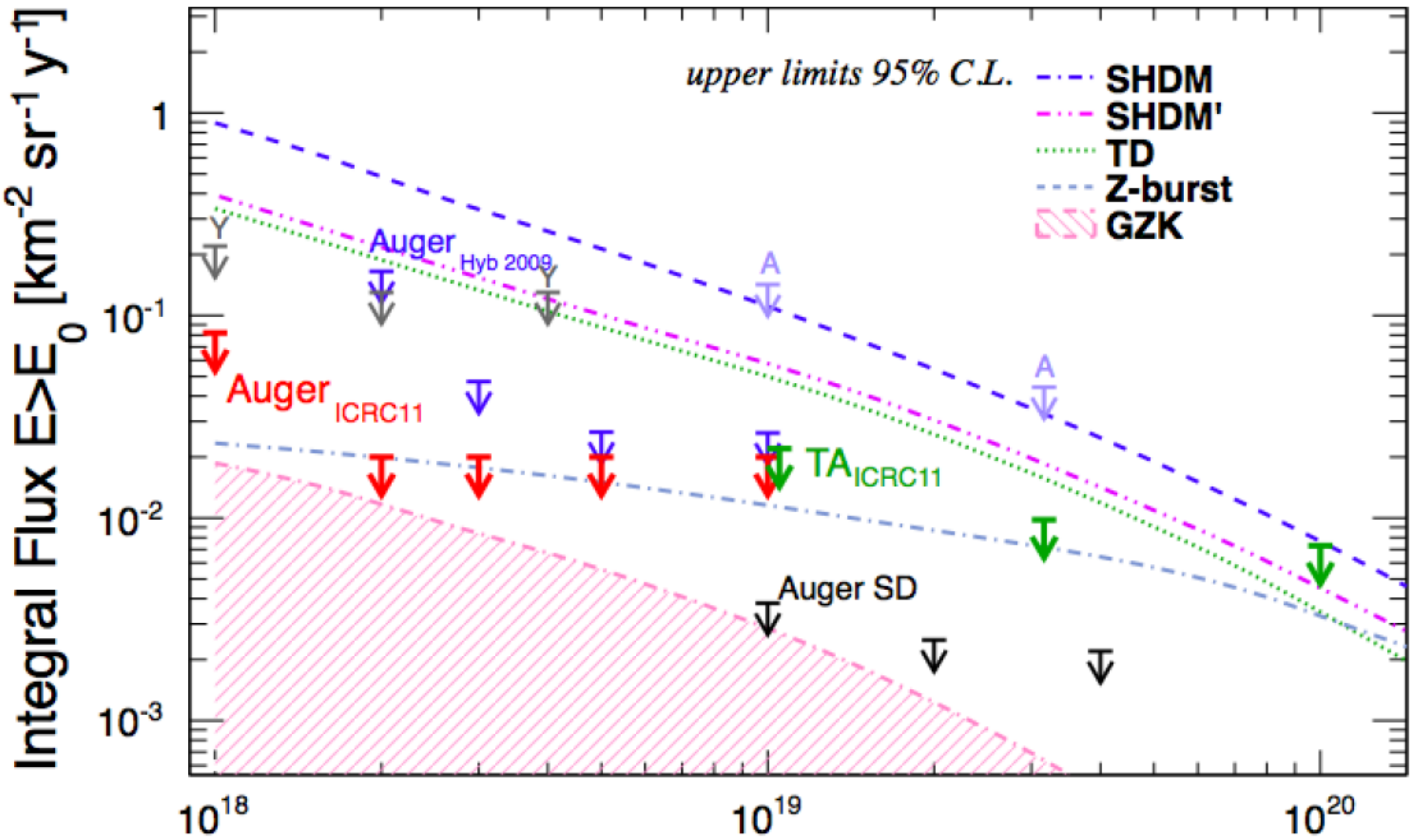
X-Y-projection of 3-D trajectories of primaries from point sources in field of 1 nG, randomly oriented with cell size 1 Mpc



Search for UHE CR Photon Sources

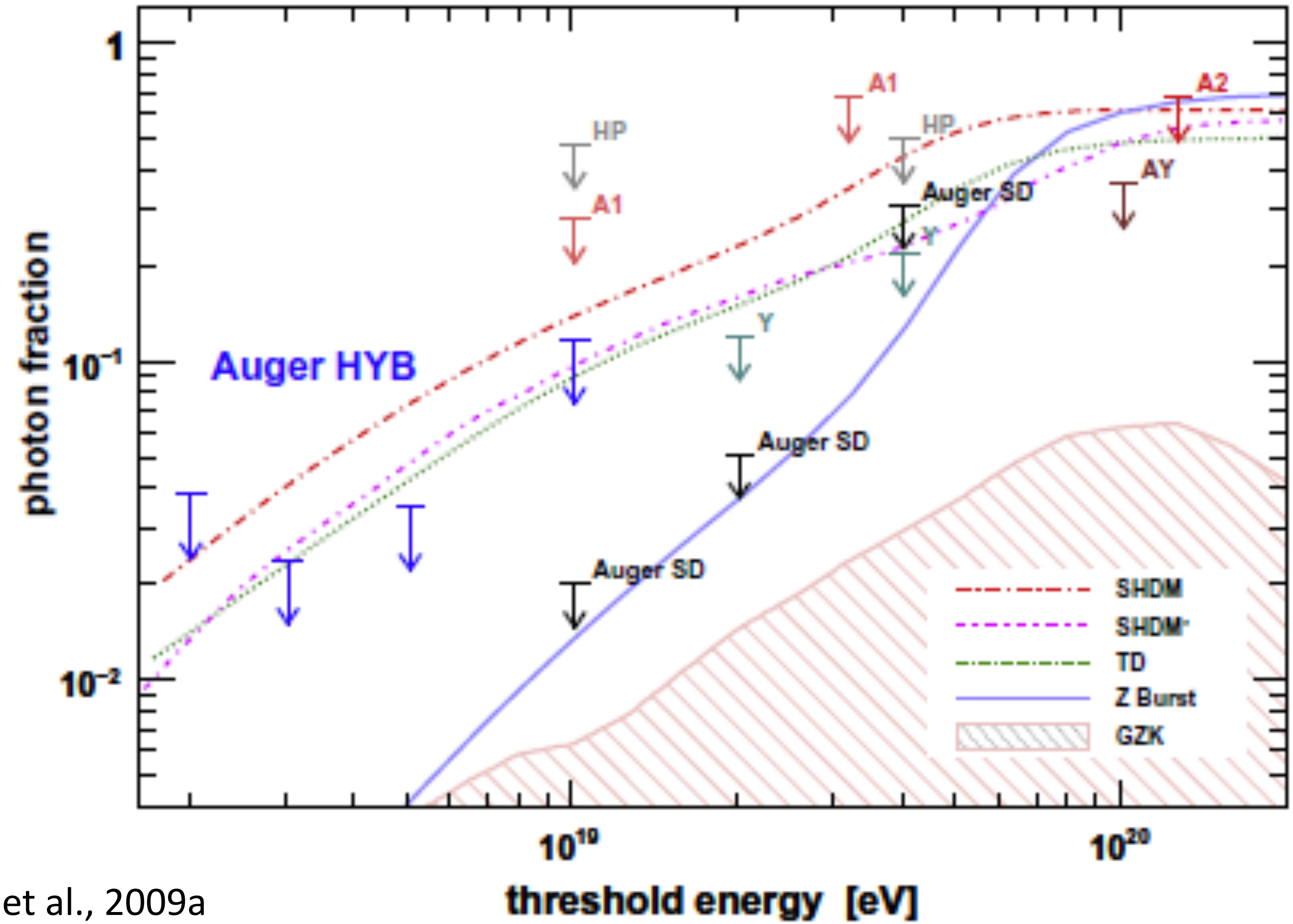
- Photons travel straight
- Point at source
- Identify e.m. activity (underlying hadronic?)
- Have reasonable cross section
- Can interact in transit
- Can produce pre-showering (magn. pair prod.)
- Detection by reaction only (reaction products)
- Produce e.m. (muon-poor) showers
- Detection with (dedicated) AS detectors

Upper Limits for UHE CR Photon Flux



Primary Energy [eV]

Upper Limits of UHE CR Photon Fraction

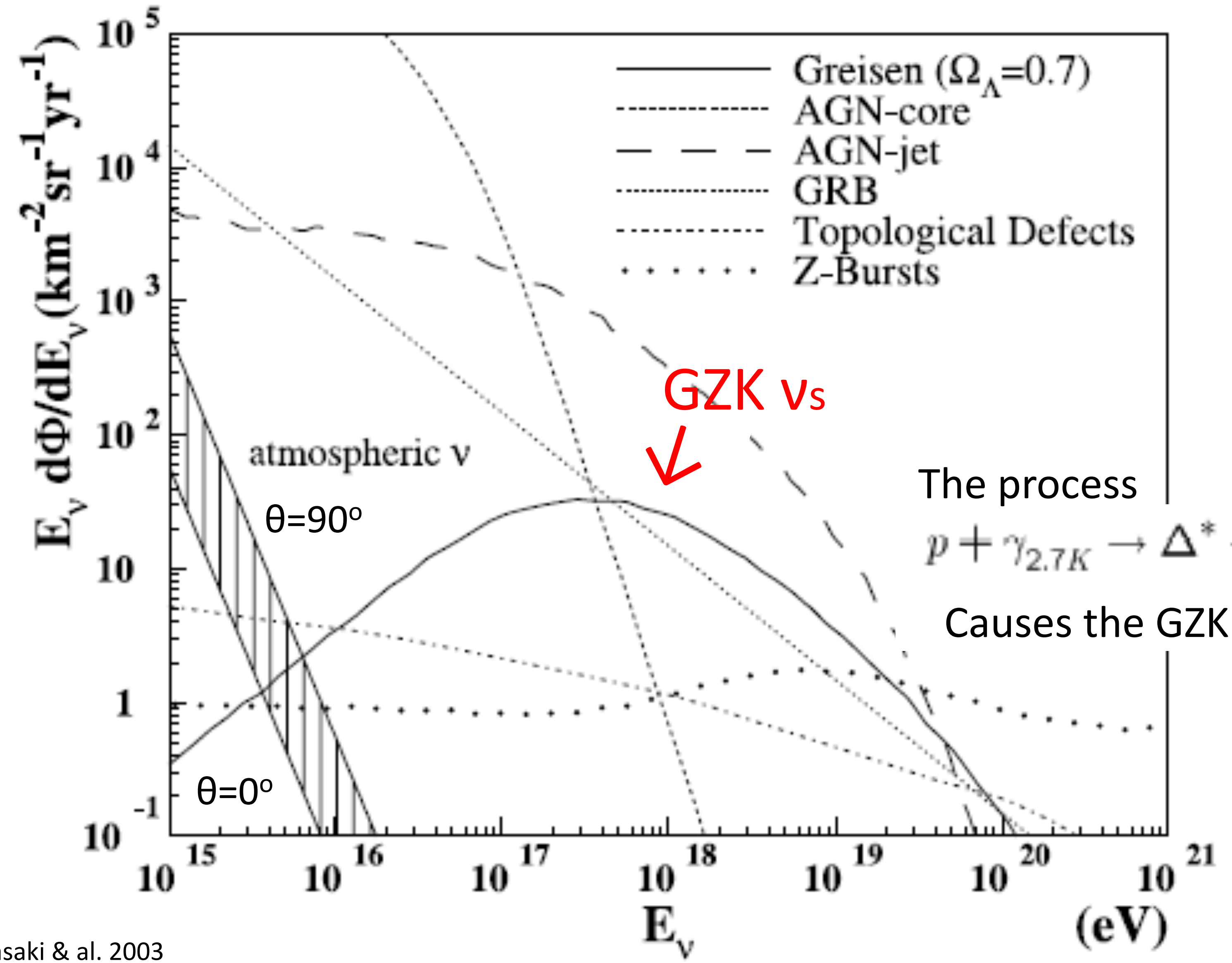


Abraham et al., 2009a

Search for UHE Astrophysical & Cosmogenic (GZK) Neutrinos

- Neutrinos travel straight & far from source
- Point at source
- Are subject to oscillations in transit
- Can identify locations of hadronic activity
- Detection by reaction only (reaction products)
- Have small energy dependent cross section
- Require huge detectors, good shielding
- Some reaction products produce air showers
- Need new detection concepts

Predicted Differential Intensity of Muon Neutrinos ($\nu_\mu + \overline{\nu_\mu}$) from Various Sources



The process

$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^\pm$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$

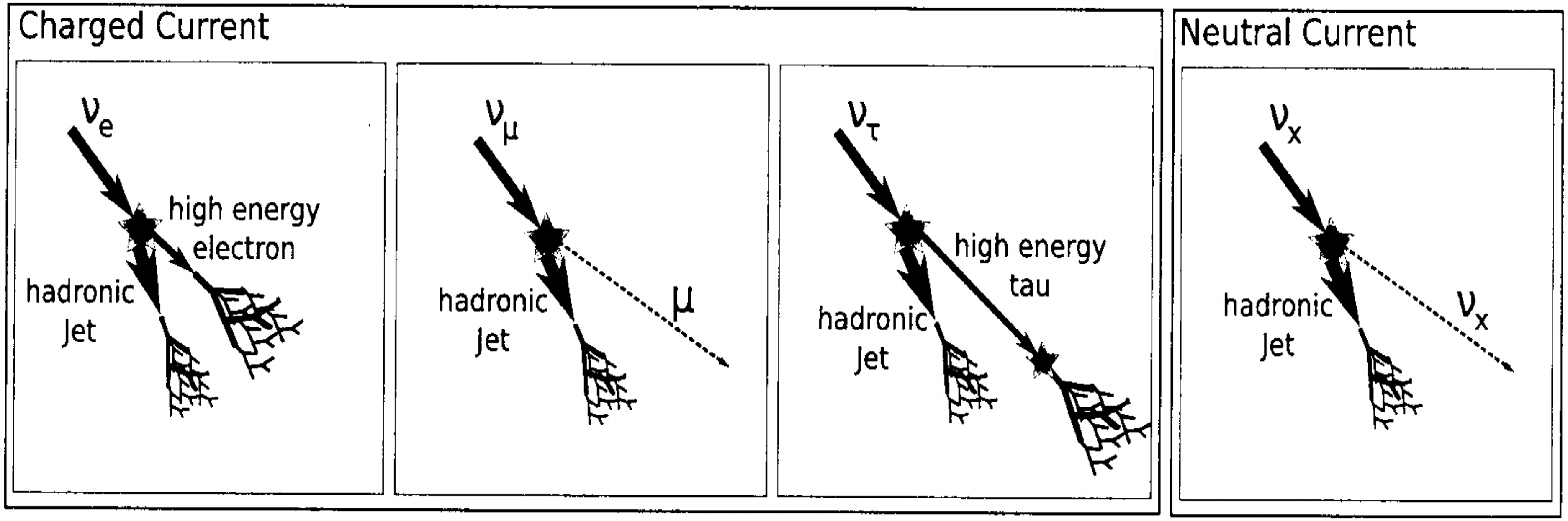
Causes the GZK effect

Sasaki & al. 2003

Neutrino Signatures and Detection

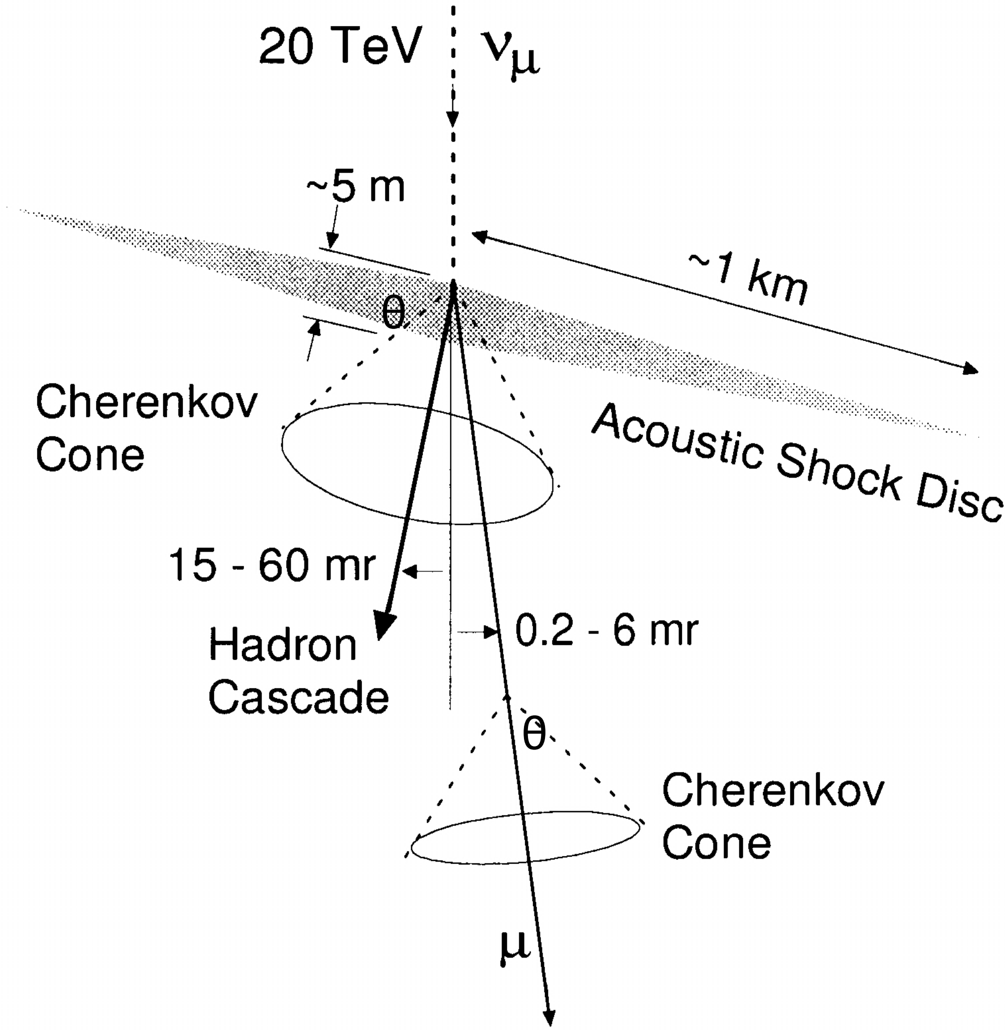
Detection via Neutrino Reactions only

Characteristics of neutrino reactions and type of reaction products are neutrino flavor specific



Effects of Neutrino Reactions in Target

Acoustic Shock, Optical and Radio Cherenkov Emission by Particles and Cascades (EM and Hadronic)



$\cos\theta = 1/\beta n$

$\beta_{th} = 1/n$

UHE Neutrino Telescopes

Neutrino Detection is via reaction products

Detector Requirements:

- Huge volume, heavily shielded.
- Detect, reconstruct, interpret muon trajectories (downward and upward going), energy estimate.
- Detect and interpret neutrino induced cascades.
- Good angular, spatial & multi-trajectory resolution.
- High background rejection.
- Suitable environment, location (sky coverage).

Detection Techniques

Optical Cherenkov trajectories in refractive media (water, ice) of ν-induced muons, tau mesons, EM and hadronic cascades (classical method). **Attenuation*: 25 m < L < 50 m**

Fluorescence and **Particles** in special, ν-induced AS (partly revisited old approach, +). **Attenuation*(FD): L >> 1 km**

Radio Cherenkov bursts generated by ν-induced EM showers and cascades in solids. (Successfully applied). **Attenuation*: L > 1 km**

Acoustic shocks in solids and liquids from sudden energy deposits by ν-induced compact cascades (in exploratory stage). **Attenuation*: L > 1 km**

**** in target medium; "threshold".***

Pioneering Efforts & Prototype Systems

- Early astrophysical neutrino searches were based on horizontal AS studies (using EAS arrays in the 1960s)

Optical Cherenkov Detection of HE Neutrino Events

in large bodies of water or ice

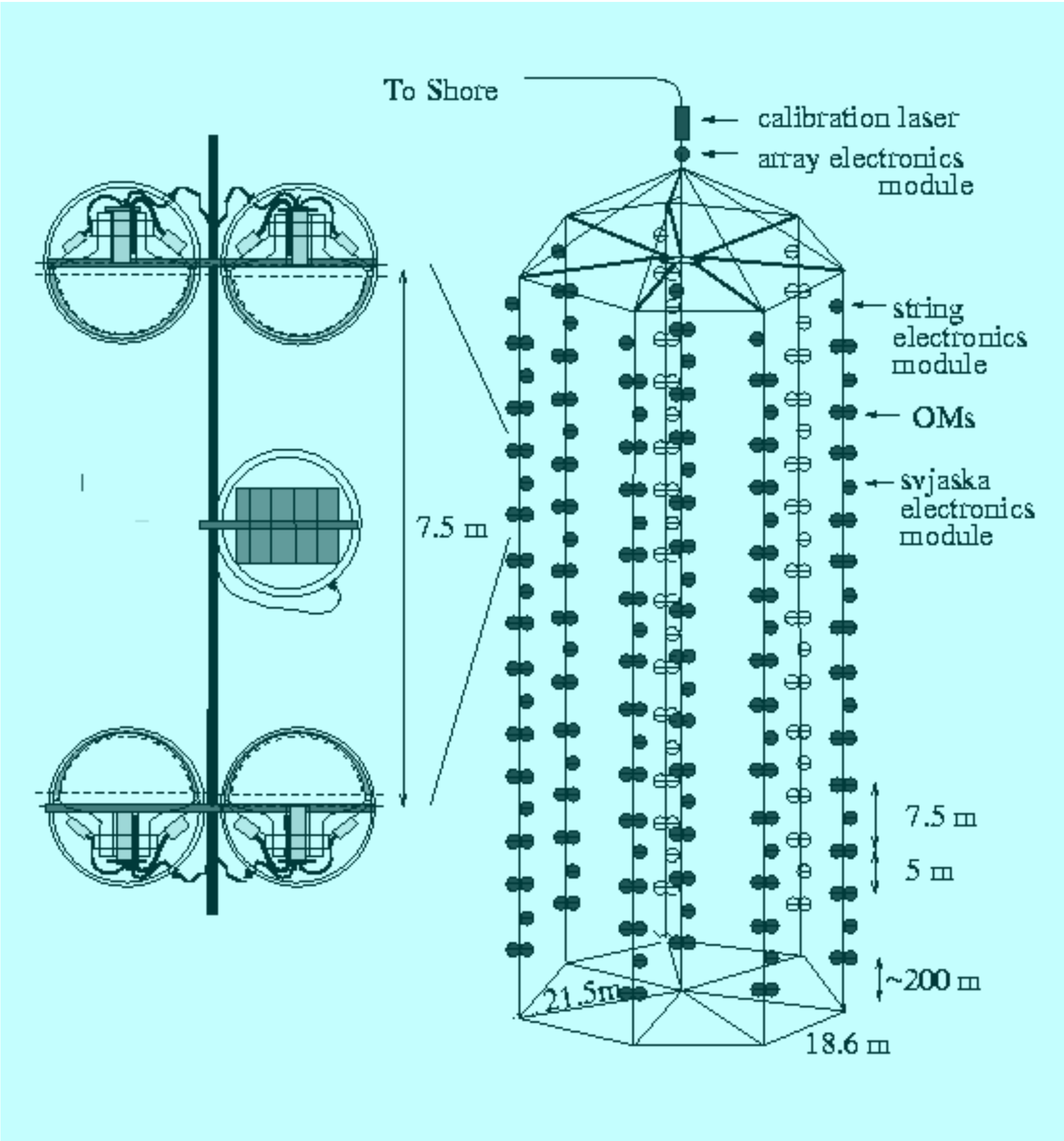
- DUMAND project and prototype set template for all optical arrays (early 1970 – 1995)
- Baikal project (early 1980s)
- In-Ice detection efforts (late 1980s)
- *Follow-up Projects:* NESTOR , NEMO, etc. (early 1990s)

Major Operating Optical Cherenkov Muon and Neutrino Telescopes

- Baikal (1993; NT200 1998 →)
- AMANDA (2003→)
- IceCube (40, 86 strings, 2011→)
- ANTARES (2007 →) Background!

Acoustic detection capability is being implemented on most installations or is in use on an exploratory level, partly combined with sonar telemetry matrix.

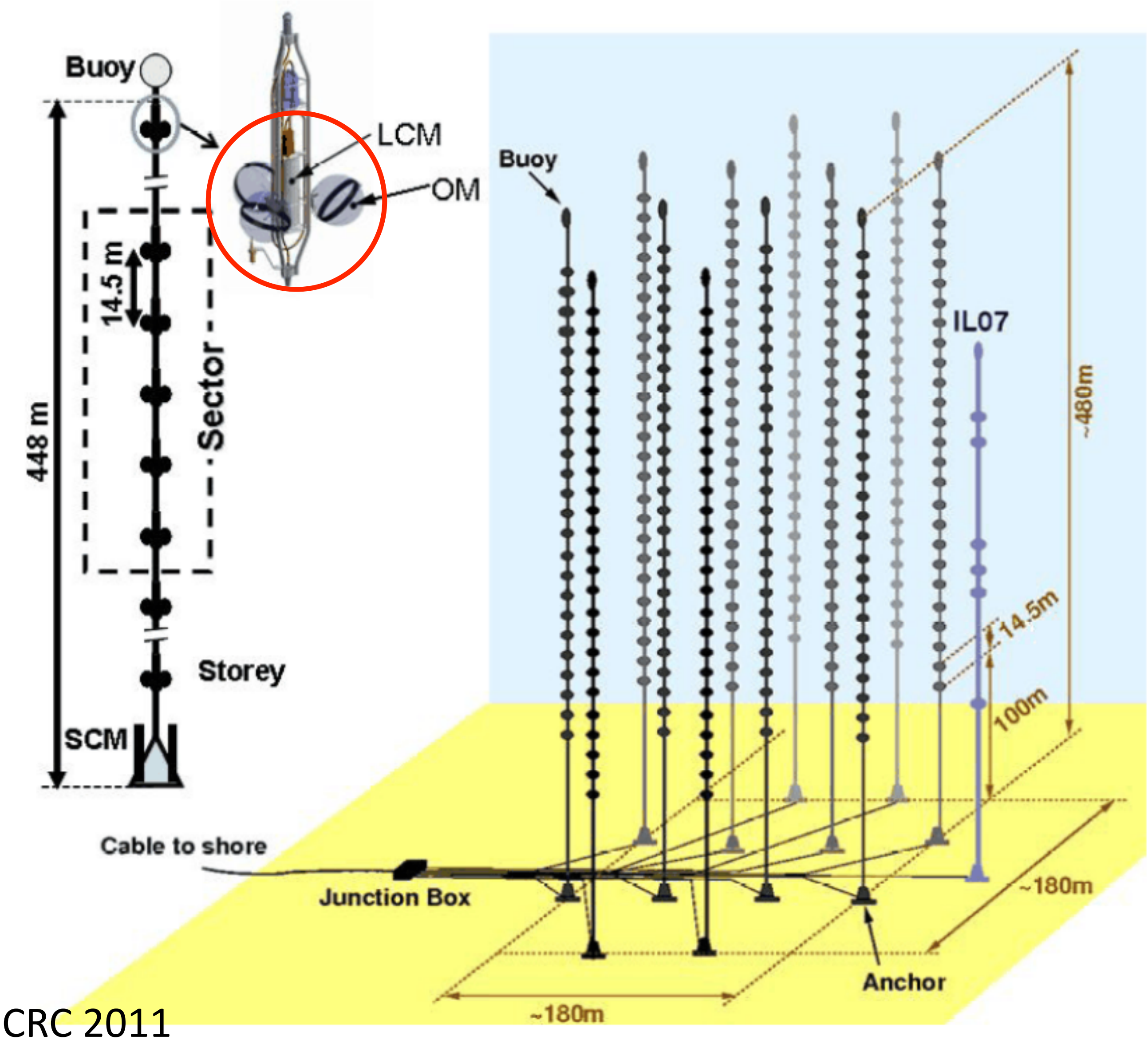
Baikal NT 200 Array



192 Optical Modules
8 Strings
5 M-tons enclosed
Depth >1100 m
Threshold ~10 GeV

ANTARES Telescope

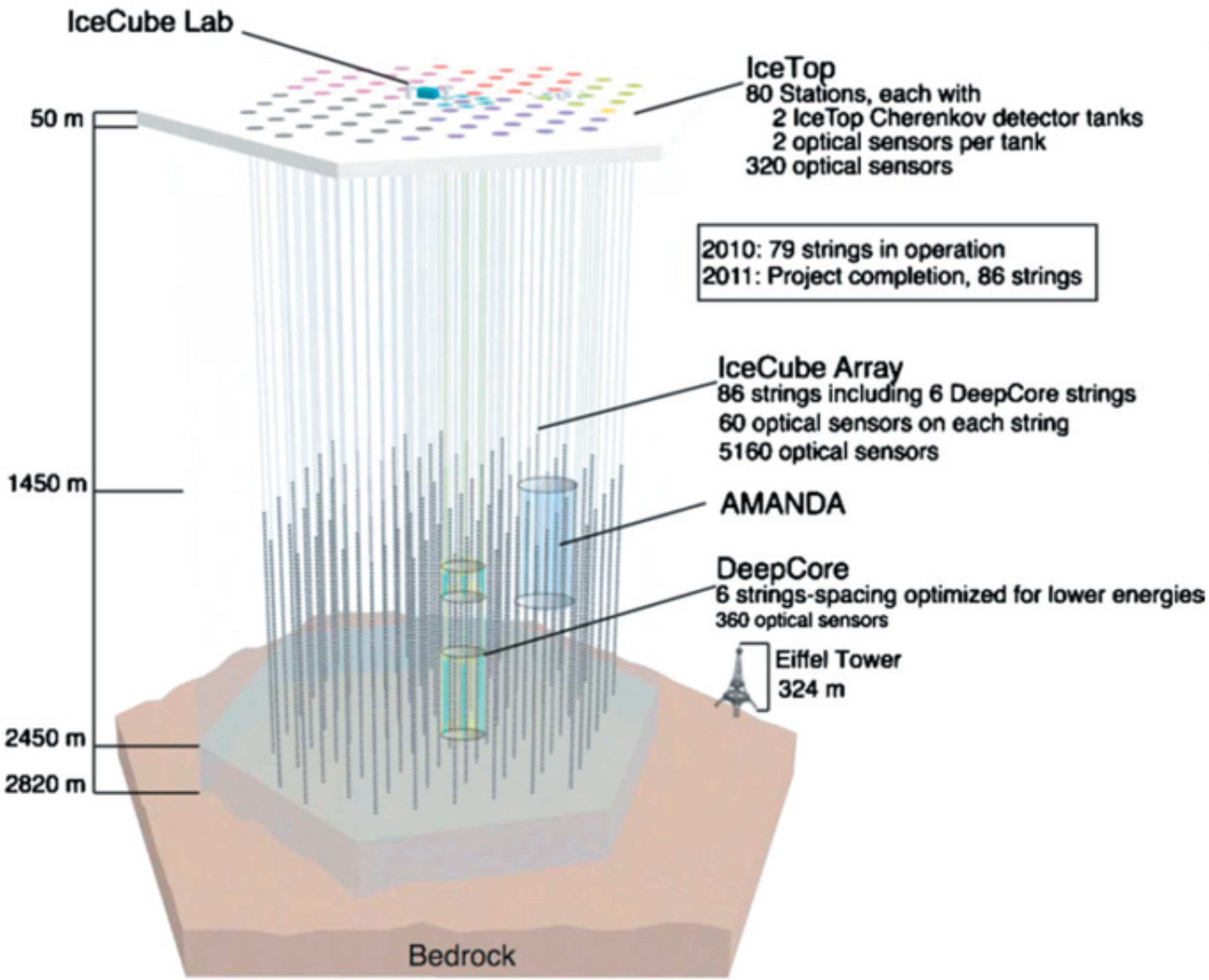
Depth 2475 m, 12 lines, 885 modules

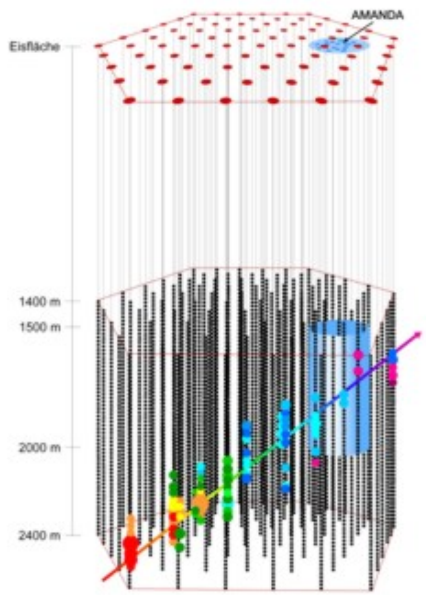


Attenuation Length:
37 m at 400 nm
55 m at 475 nm

High level of bioluminescence

IceCube (1 km^3)



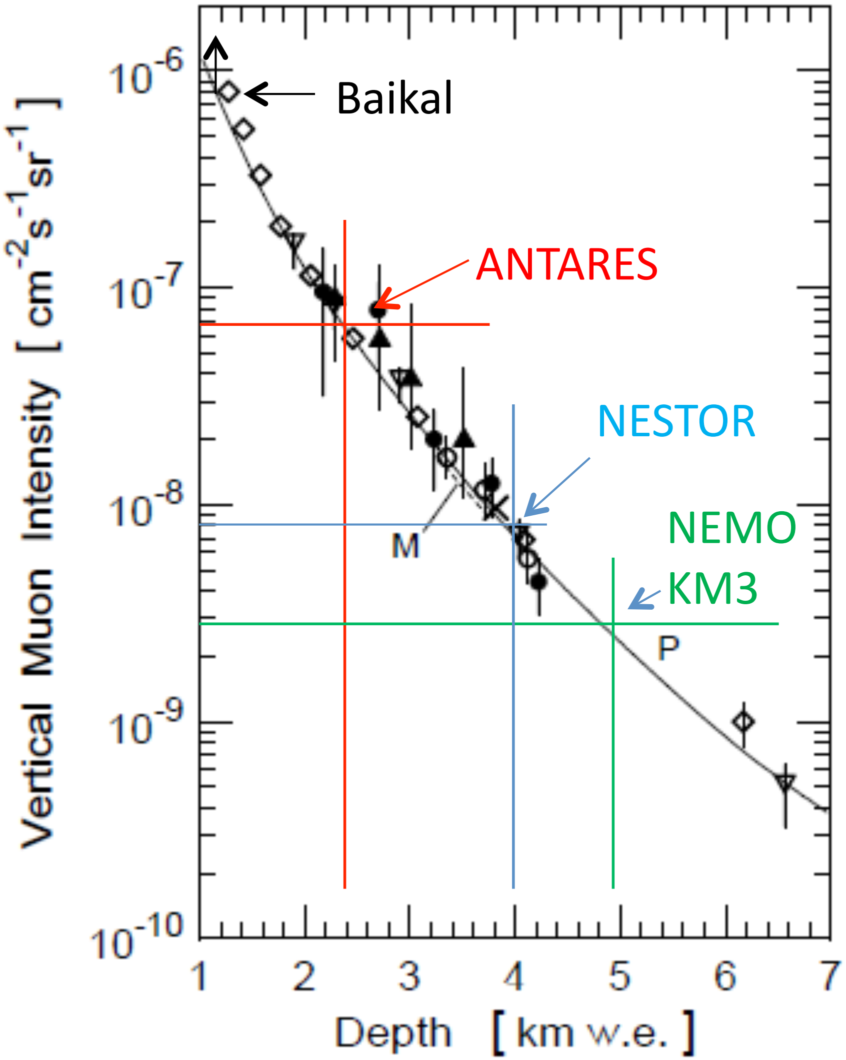


IceCube event

Problems Encountered:

Background, Technical, Environmental & Site

Muon Depth-Intensity



K40

Bioluminescence

Atmospheric muons

Atmospheric neutrinos

OM & matrix location survey

Target/Medium Properties:

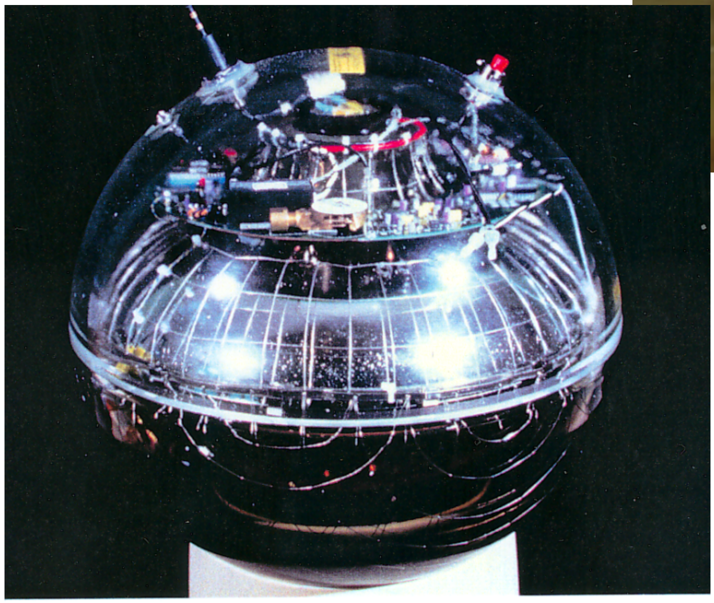
Transparency, Absorption

Scattering

Currents, Sedimentation

Biofouling

Evolution of Optical Detector Modules



DUMAND Single 15 in.
Phototube Optical
Detector Module

← KM3NeT Multi-Phototube
Optical Module Designs

↓

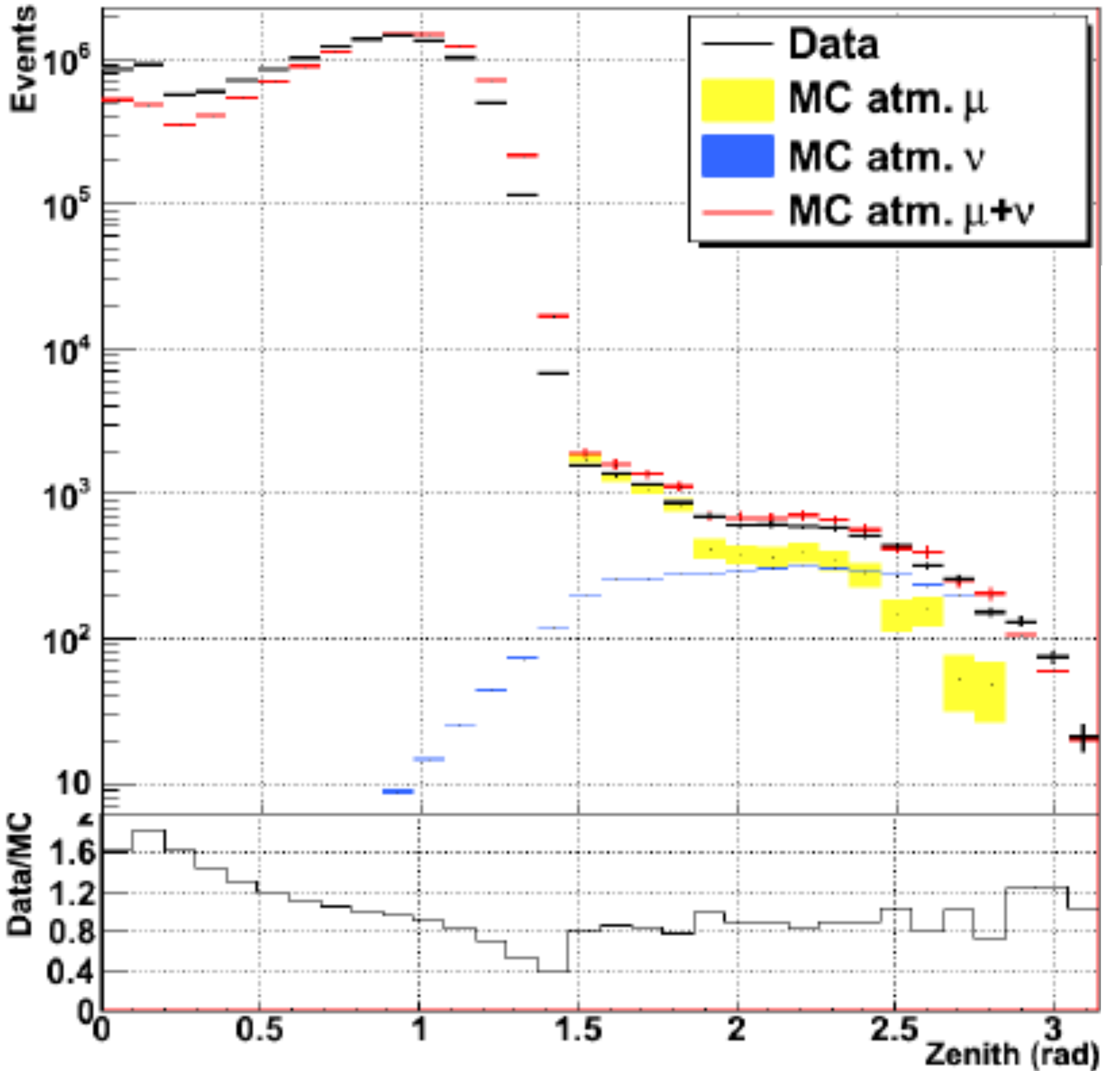
Achievements

Routine Measurements

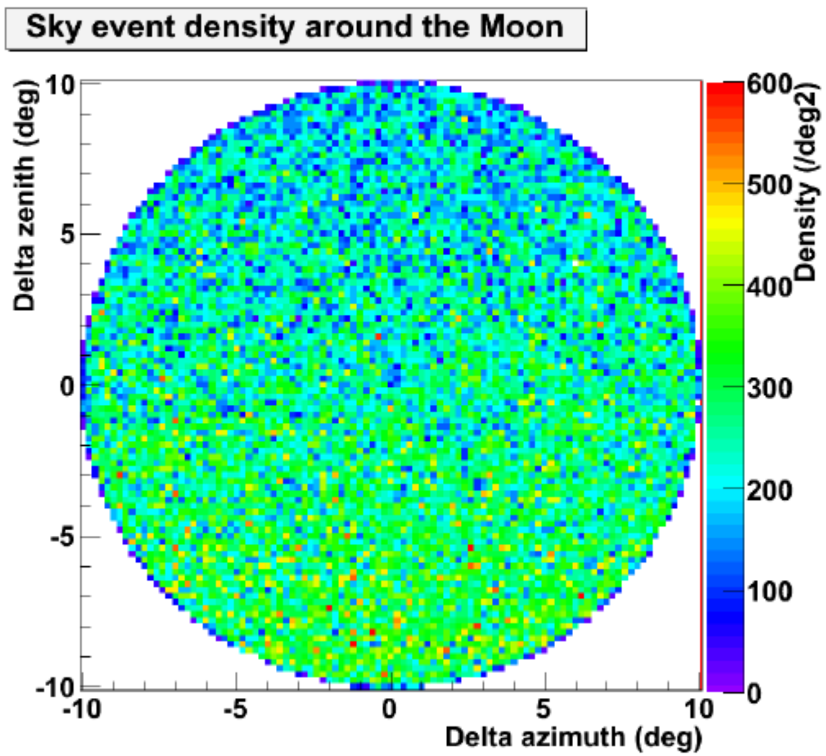
(Optical Neutrino Telescopes)

- Environmental data (currents, transparency, scattering, K40, bio-, chemoluminescence, sedimentation, dust layers in ice, etc.)
- Detector performance, matrix surveys
- Downward-going atmospheric muons
- Array energy calibration
- Moon shadow (angular resolution)
- Search for upward-going events

Antares Telescope: Zenith Angle Distribution of Muons & Neutrinos



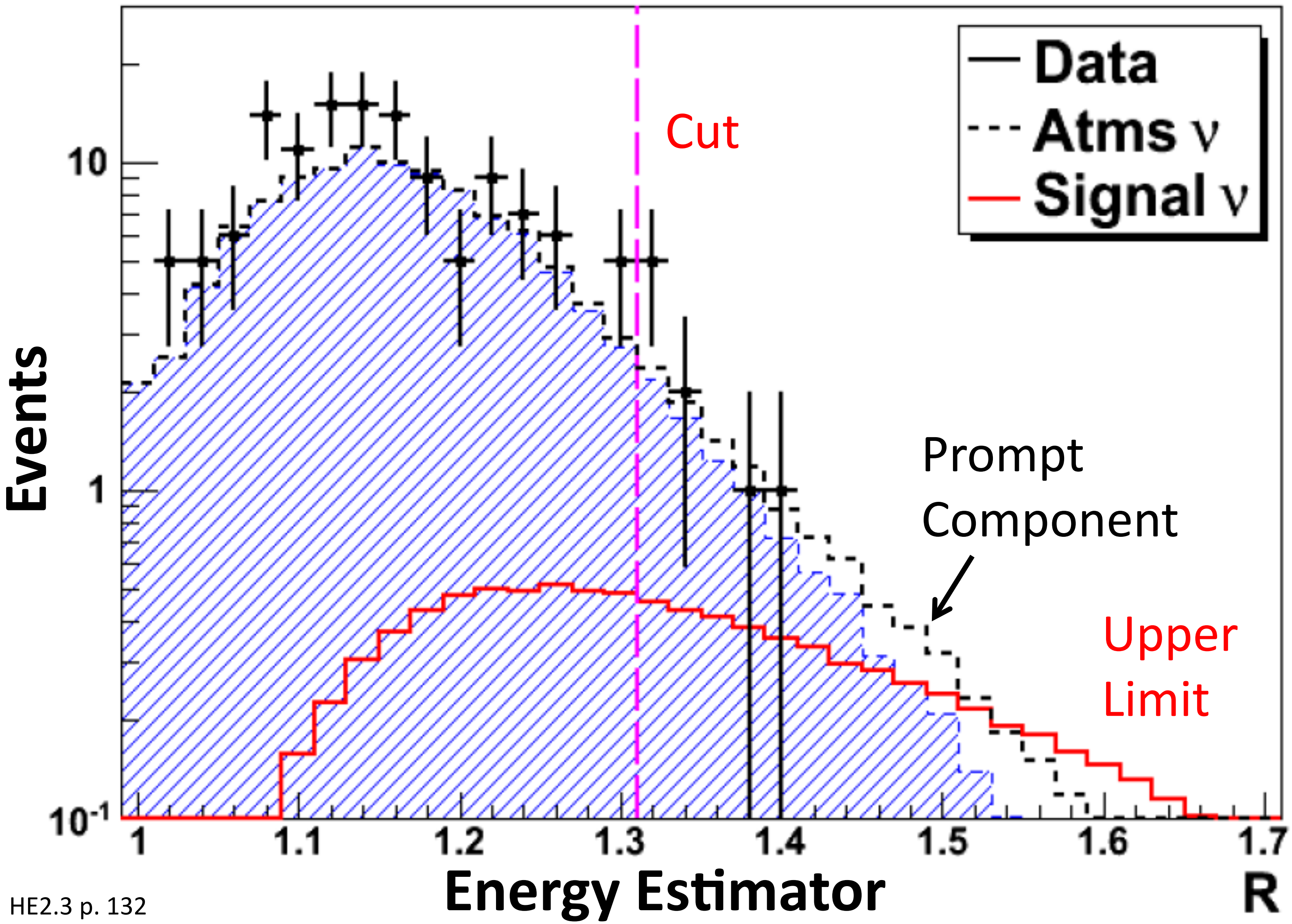
Moon Shadowing Exp.:
Moon radius 0.259°
Detector Resolution 0.4°
Observation 884 days



ICRC 2011 p. 114

ANTARES Telescope Data

Muon Energy Estimator



ICRC 2011 HE2.3 p. 132

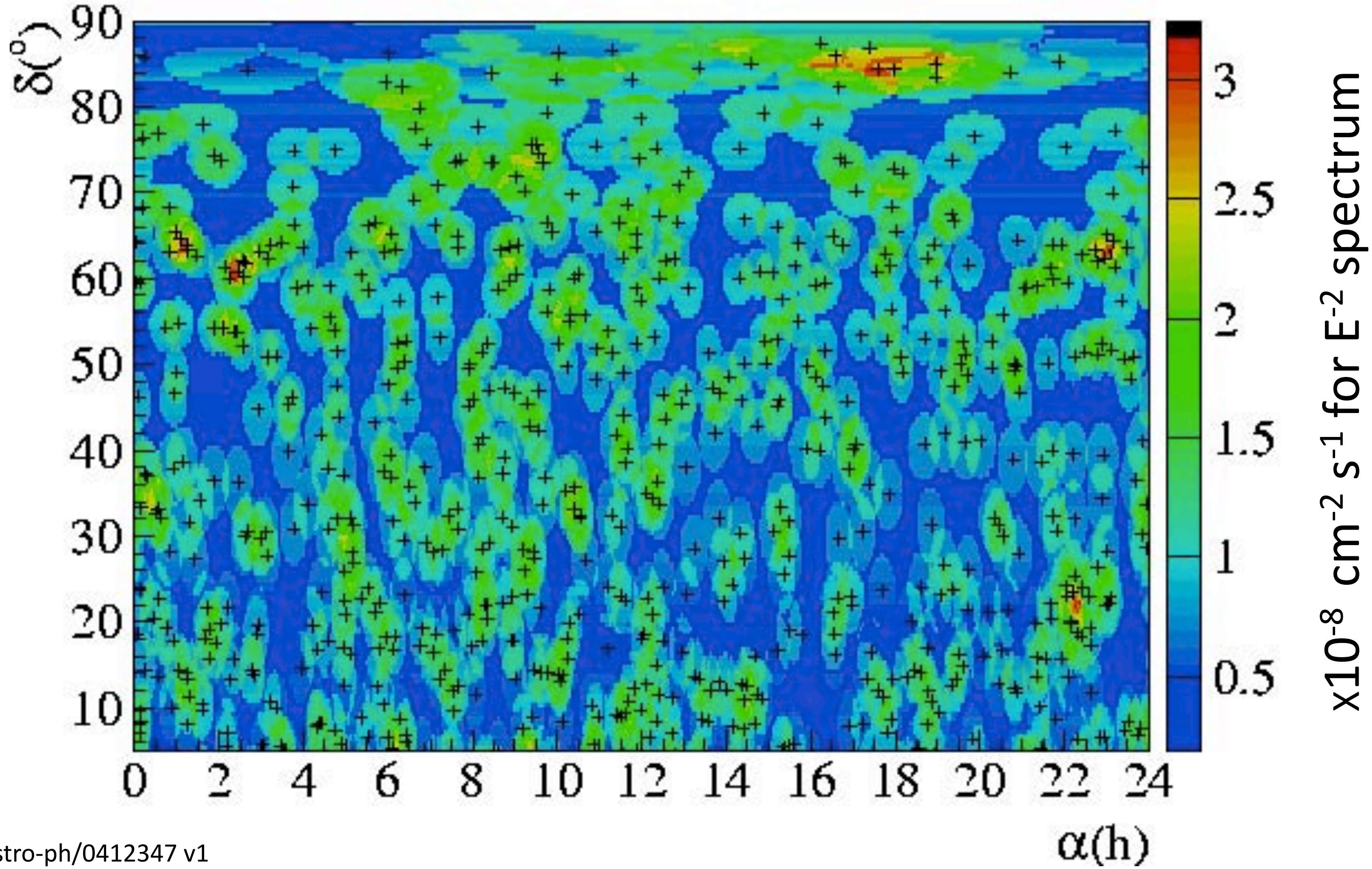
CR & Particle Physics Investigations
(Optical Neutrino Telescopes)

- Muon physics with atmospheric muons: energy loss, multi-muons, muon reactions, etc.
- Correlations with surface AS measurements.
- Atmospheric (upward) neutrino flux studies.
- Neutrino sky map.
- Neutrino induced particle showers, jets.
- DM, WIMP, etc. searches

AMANDA Neutrino Sky Map (E_ν >10 GeV)

Integrated flux recorded 2000-02 (90% CL)

677 OMs, depth 1500 - 2000 m, encl. vol. 0.016 km^3



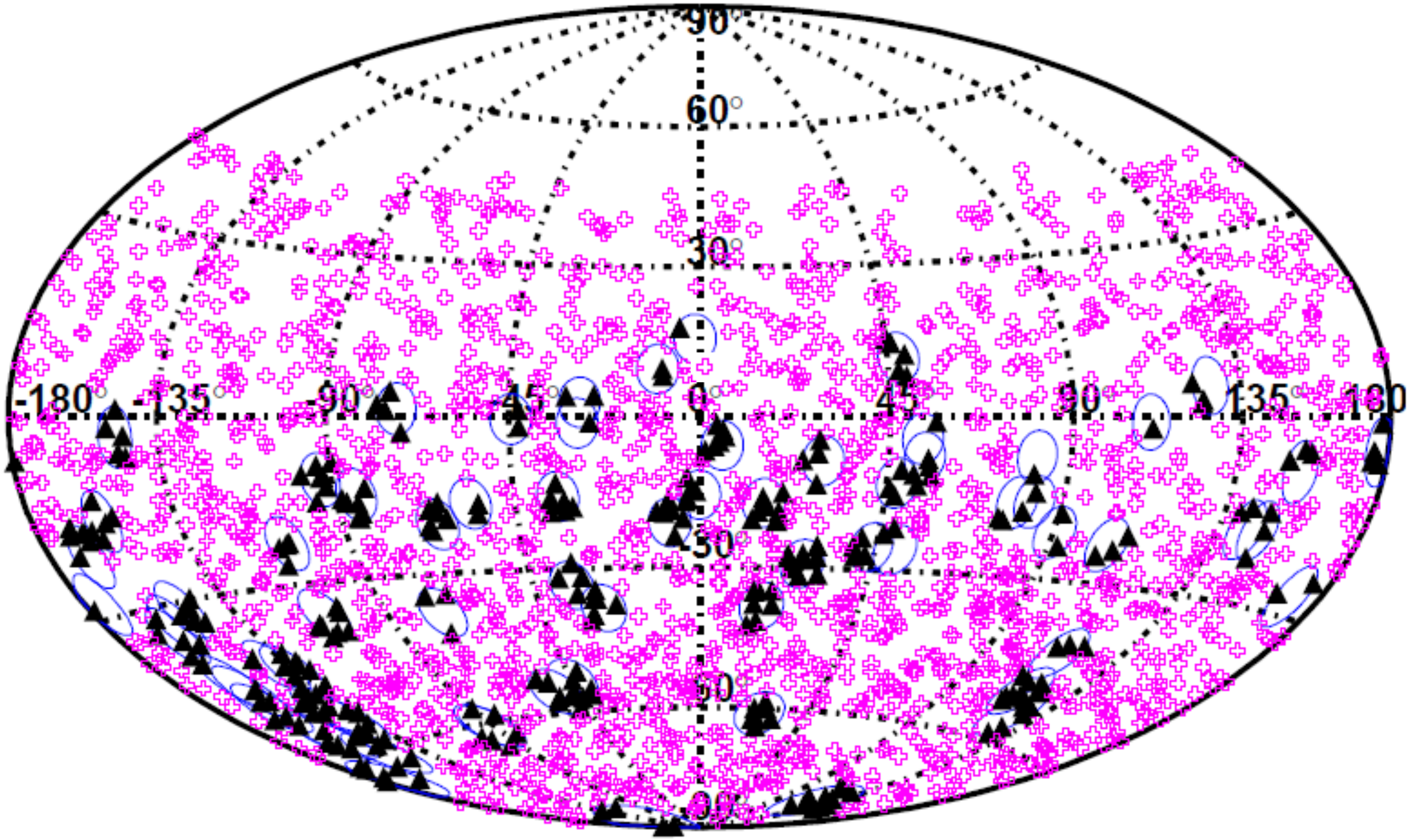
arXiv:astro-ph/0412347 v1

Astrophysical Measurements
(Optical Neutrino Telescopes)

- Neutrino point source searches: so far negative
- Diffuse AP ν flux searches: upper limits
- Cosmogenic and SN neutrino searches: neg. (u.l.)

- Various searches for correlations, etc.
- ν emission from blazars, GRB, X-ray sources
- Neutrino - gamma correlations
- Transient ν and optical follow-up
- All negative (upper limits)

Correlation between ANTARES Neutrino Events and UHE CR Auger Events

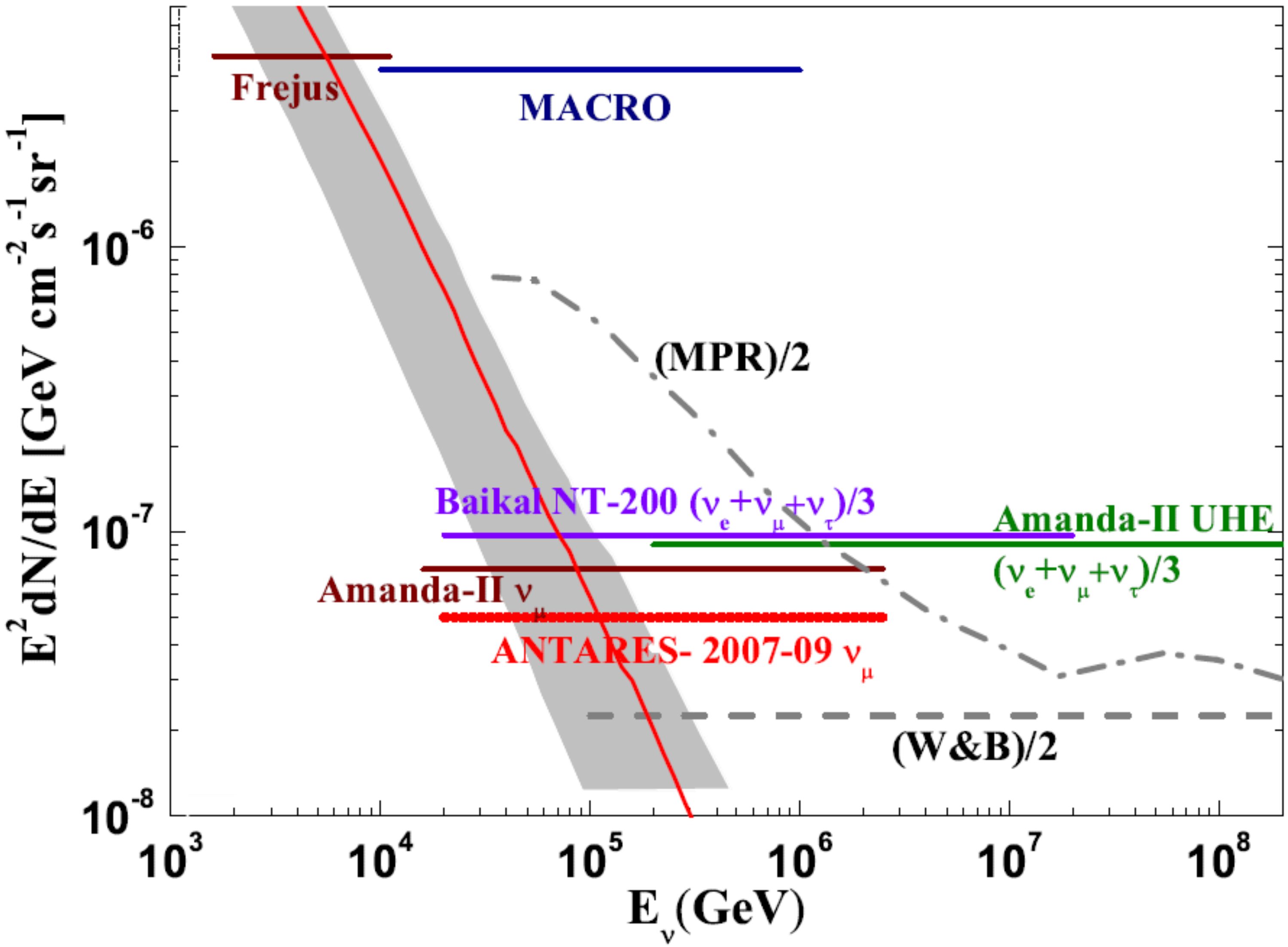


ν-events outside 4.9° of PAO UHE CR event centers.

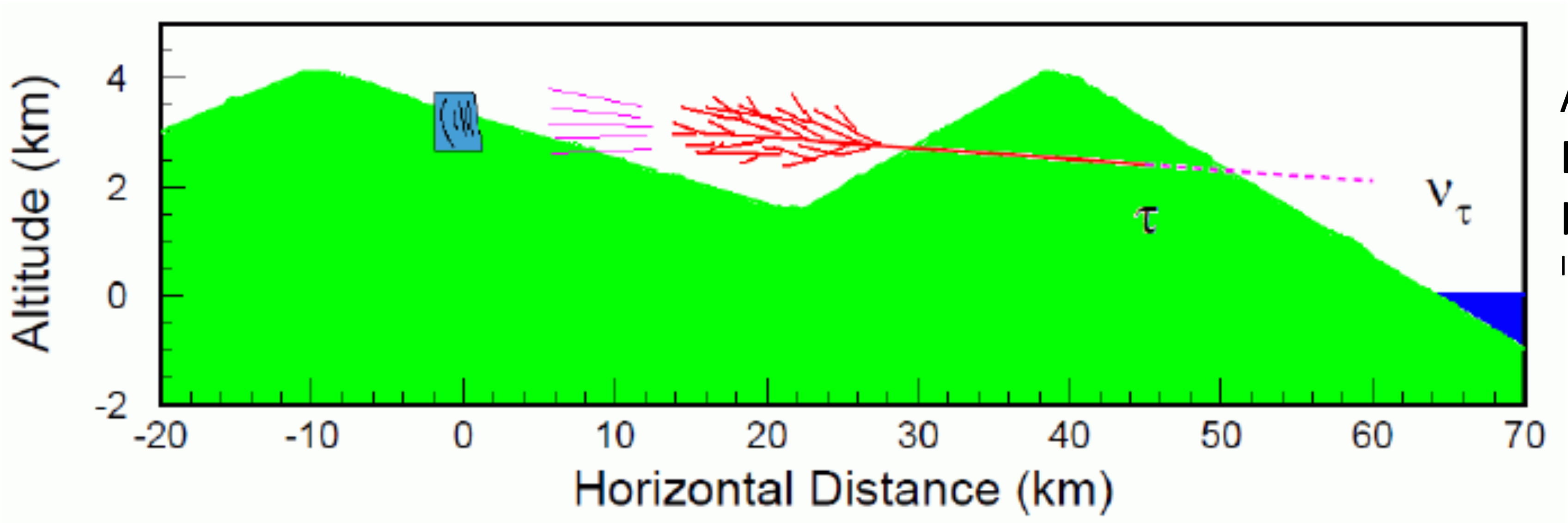
ν-events correlating with PAO UHE CR events.

ICRC 2011, HE2.3 p. 144

Upper Limits for E^{-2} Diffuse $\nu_\mu + \nu_\mu$ Spectrum from Different Experiments & Models



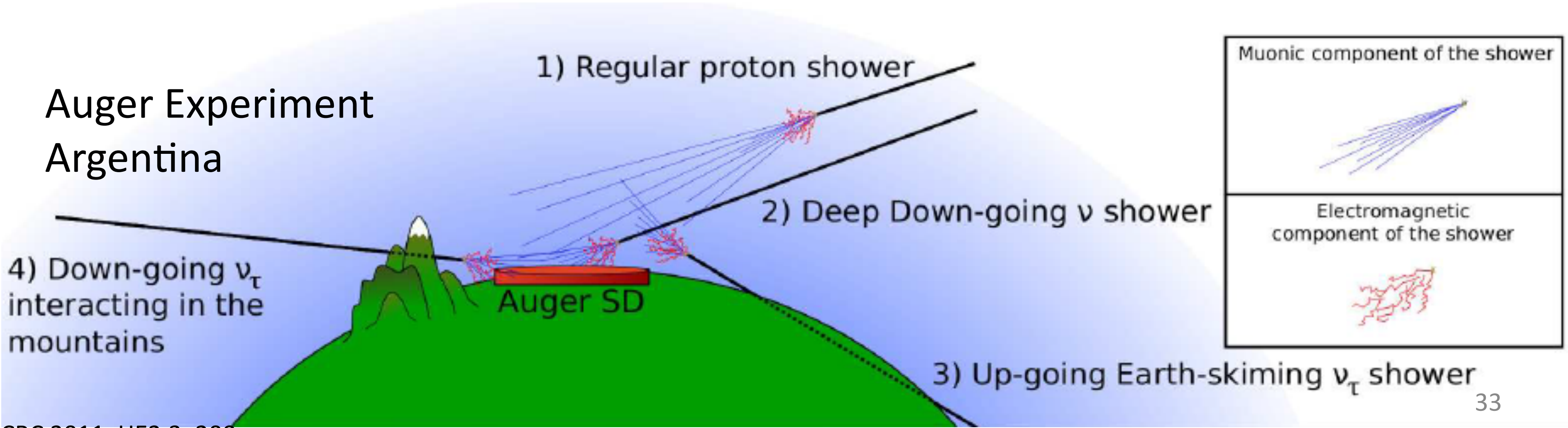
Air Shower based Neutrino Detection Experiments, incl. ν_τ Signature



ASHAR Exp. Hawaii

ICRC 2009, 313

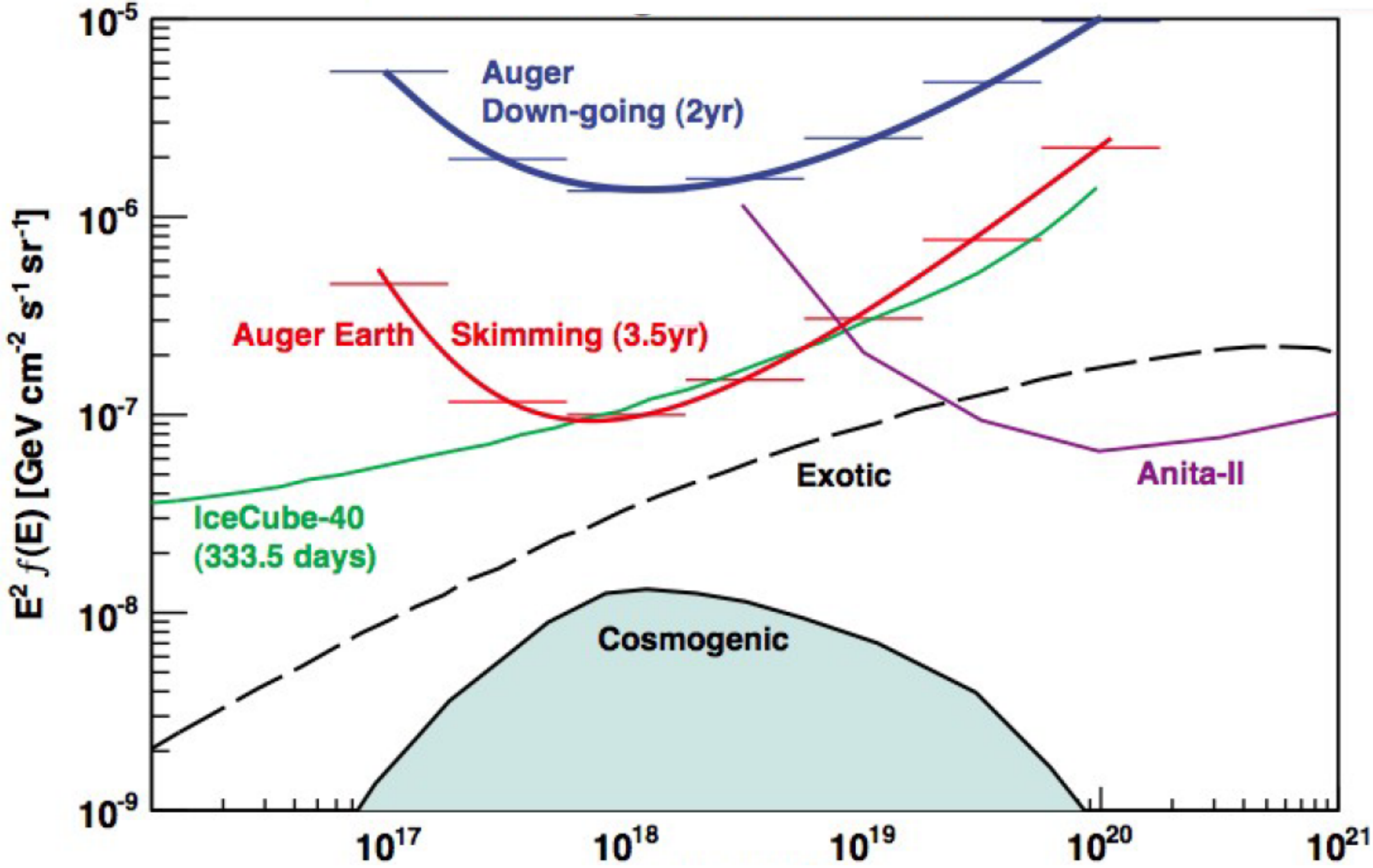
Auger Experiment Argentina



ICRC 2011. HE2.3, 200

Astrophysical Neutrinos, Upper Limits

90 % CL single flavor limits



Neutrino Energy [eV]

Radio Signatures of Neutrino Events

(of neutrino induced particle cascades)

Method originally explored for CR AS detection

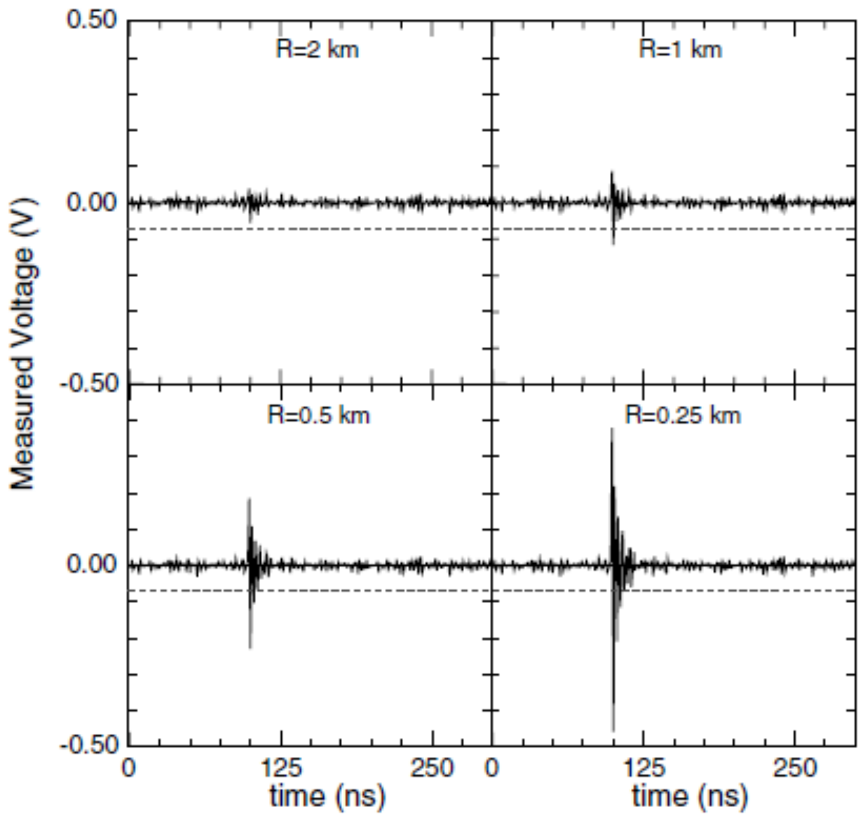
Radio generation mechanisms of cascades:

- Geo-synchrotron radiation } { require long track in
- Transverse current } { magn. Field, e.g., EAS
- Transition radiation — EAS on impact at ground
- **Cherenkov mechanism (negative charges excess in dense media; Askar'yan effect)**

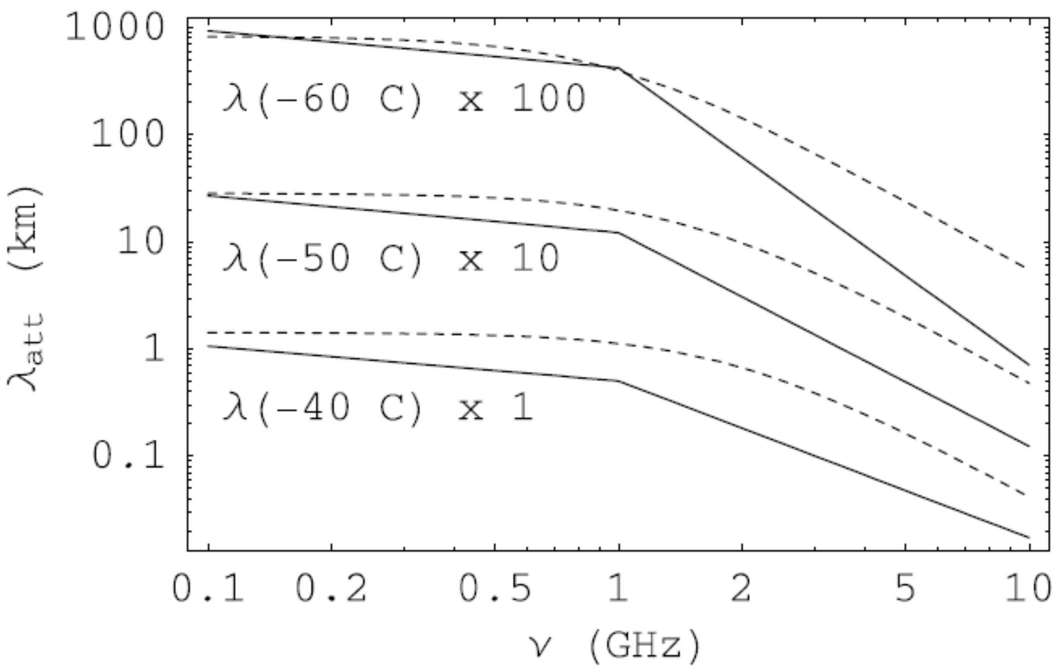
- Askar'yan (1961, 1962, 1965), developed basic theory, so-called Askar'yan mechanism.
- Saltzberg et al., 2001, accelerator-based experimental verification of process.

Typical Characteristics of Cascade-induced Radio Bursts in Ice

Typical Cherenkov Radio Bursts from 10 PeV Neutrino-induced Cascade in Ice

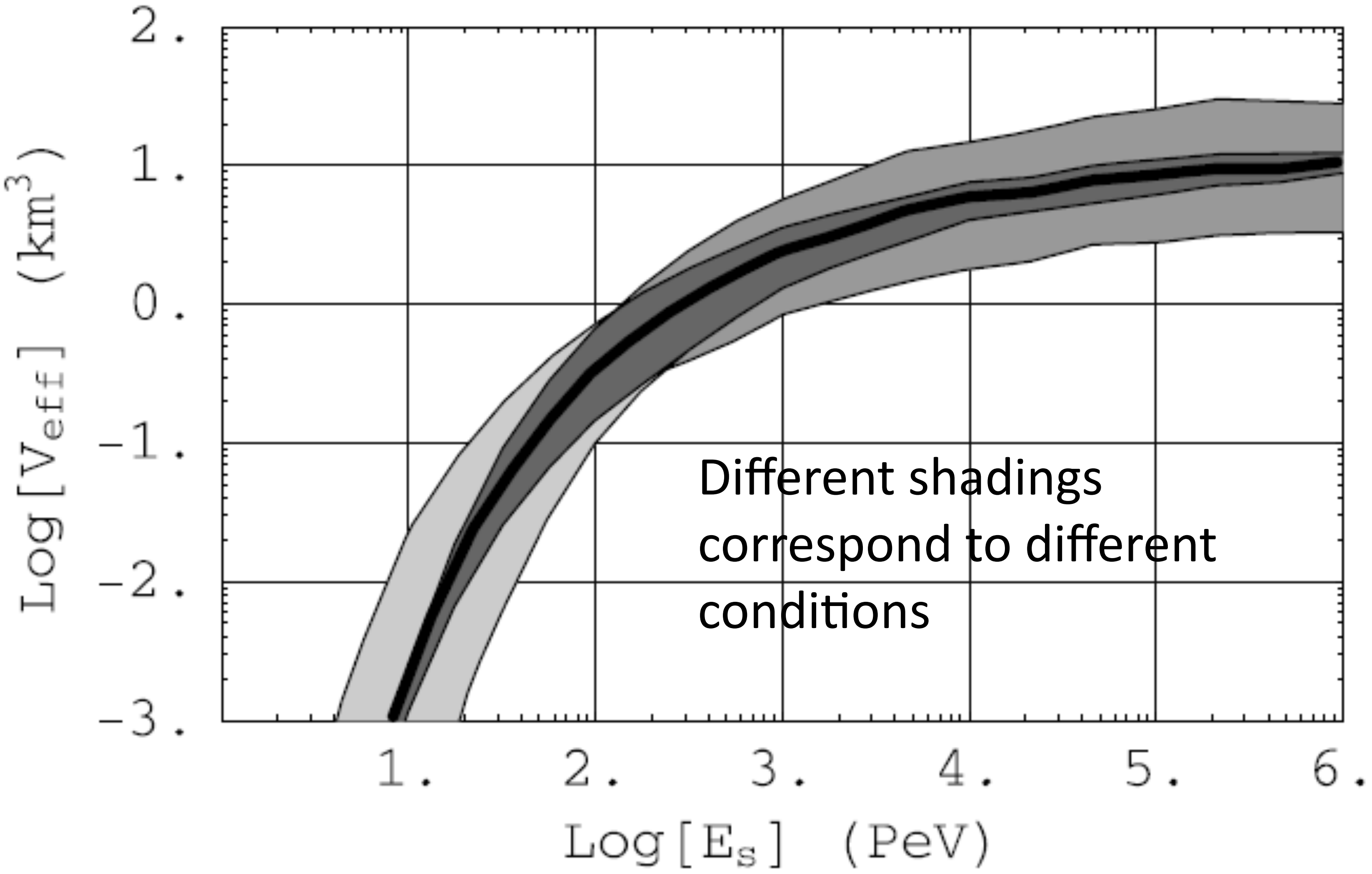


RF Attenuation Length in Ice v/s Frequency for Different Temperatures and Models



Kravchenko et al., 2003, RICE

Effective Volume v/s Event Energy Deposit for RICE Experiment



Kravchenko et al., 2003

Radio Detection of UHE Neutrinos

(and CR initiated Cascades)

Ground, Balloon & Space-Based Experiments

RICE *Radio Ice Cherenkov Experiment* (1995, 2003→)
Antennas in ice at Antarctica (200x200x200 m^3).

FORTE *Fast On-orbit Recording Transient Events* (2004)
Satellite based antenna viewing Greenland ice shelf.

GLUE *Goldstone UHE Neutrino Experiment* (2004)
Ground based radio astronomy dishes viewing Moon.

NuMoon *WSRT Obs. UHE Neutrino Experiment (2003)*
Ground-based radio astronomy dish viewing Moon.

ANITA *Antarctic Impulsive Transient Antenna (2003, 2008)*
Balloon-based antennas above Antarctic ice shelf.

Radio Detection of UHE νs (cont.)

Ground, Balloon & Space-Based

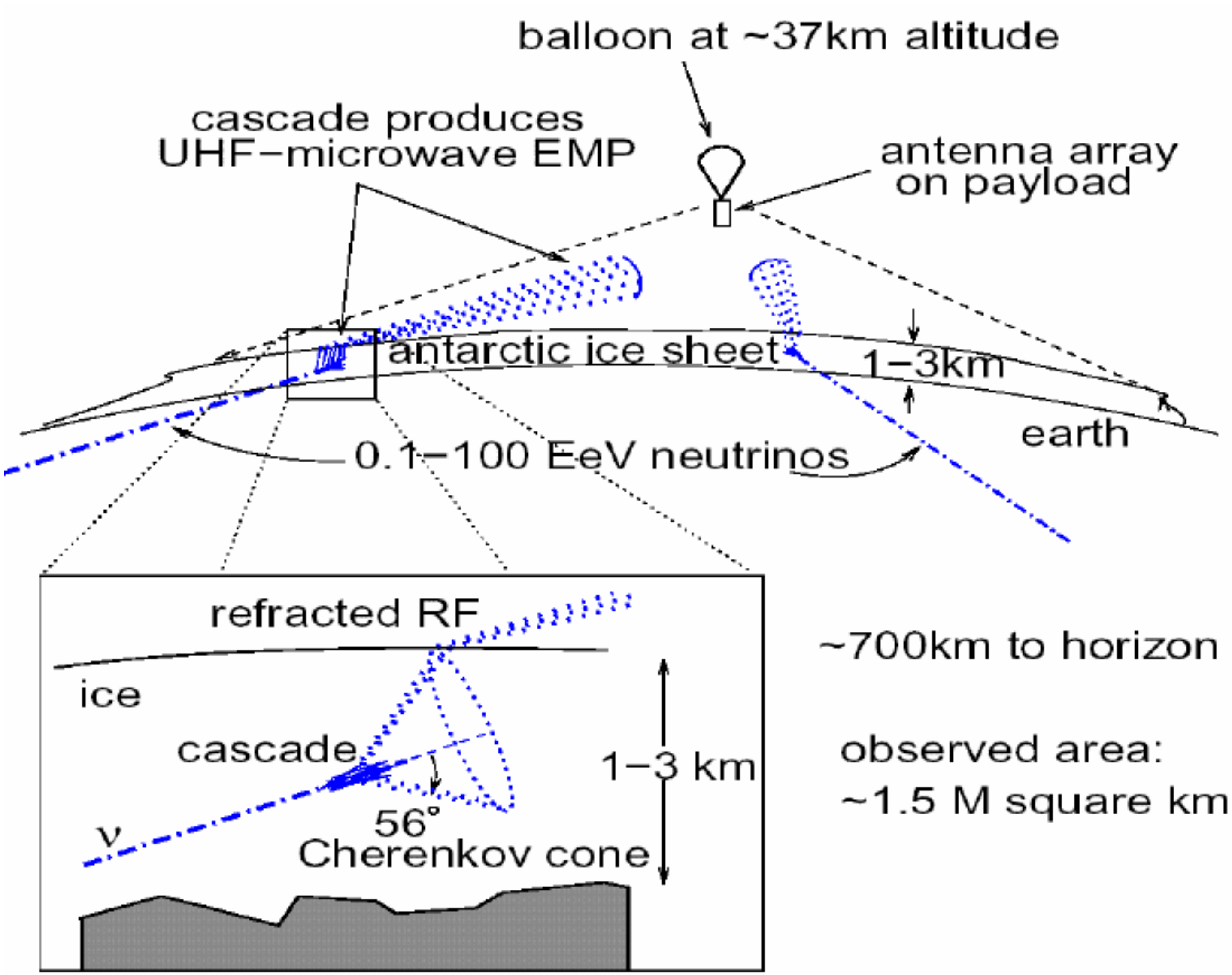
LUNASKA/ATCA *Lunar UHE Neutrino Astrophysics Square Kilometer Array / Australian Telescope Compact Array*.
Ground-based array of dipoles and dish antennas detecting Cherenkov radio emission of UHE lunar ν & CR events.

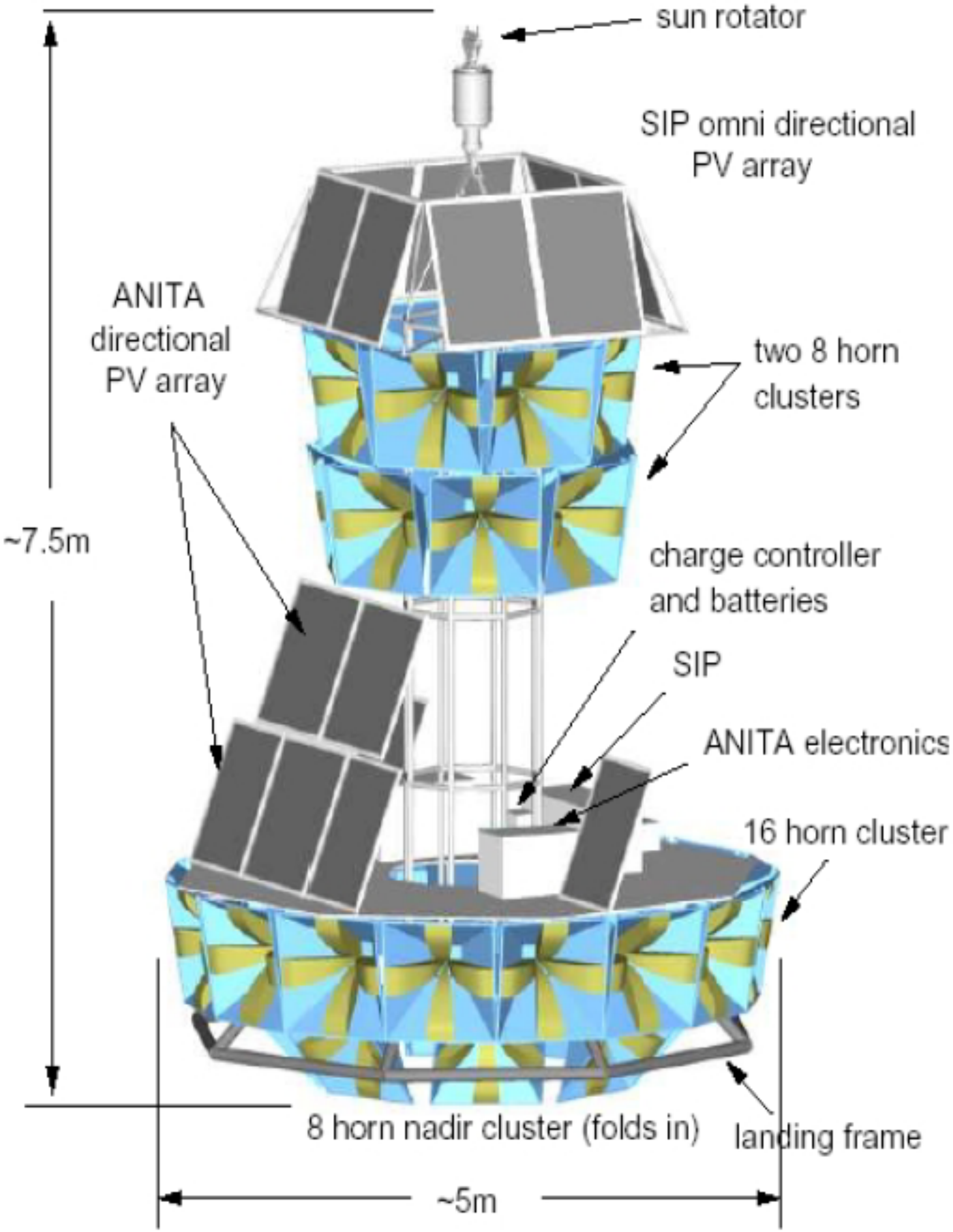
LOFAR *LOw Frequency Array*
As above but many sets distributed across Europe.

LORD *Lunar Orbiting Radio Detection*
Satellite based antenna viewing lunar surface.

ANITA Experiment

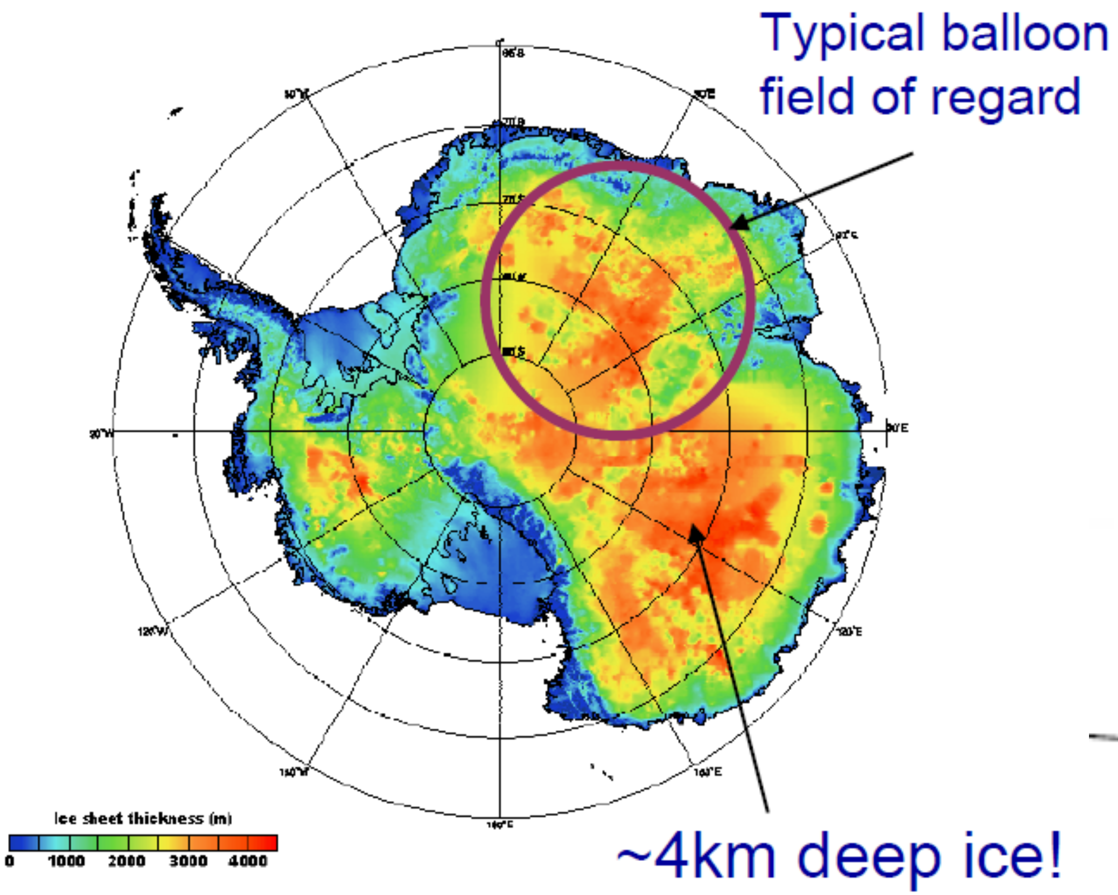
Balloon-bound Detection of Cherenkov Radio Emission from Ice



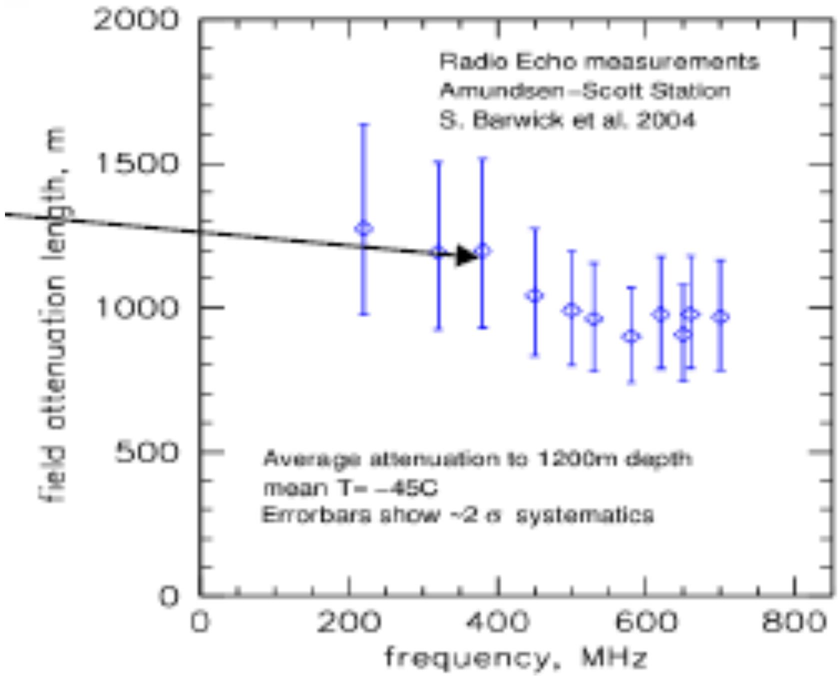


ANITA Balloon Suspended Instrument

ANITA Field of View over Antarctic Ice



RF attenuation length in ice v/s frequency



Effective "telescope" aperture:

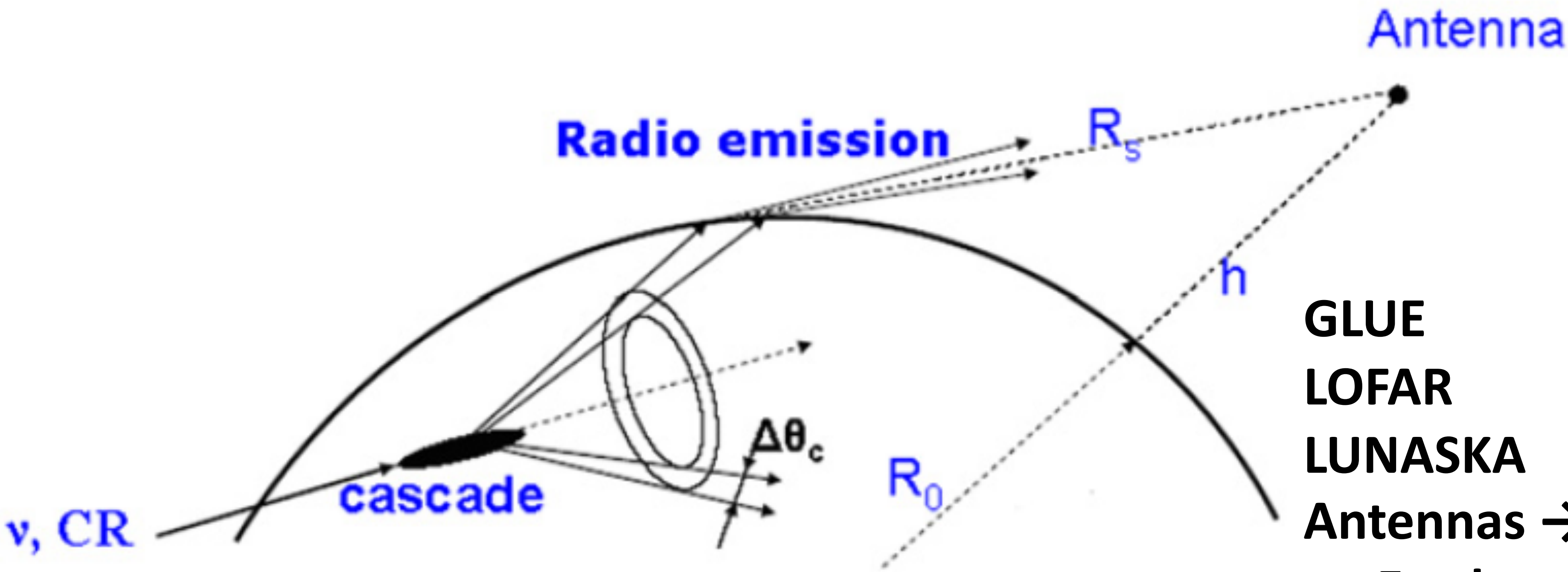
- ~250 km^3 sr @ 10^{18} eV
- ~10^4 km^3 sr @ 10^{19} eV

(compare to ~1 km^3 at lower E)

Varner 2005

LORD Experiment

Satellite based Cherenkov radio detection of ν & CR initiated cascades in lunar Regolith



GLUE
LOFAR
LUNASKA
Antennas → at Earth

LOFAR Experiment

Earth based huge Cherenkov radio antenna array to detect ν & CR initiated cascades in lunar Regolith

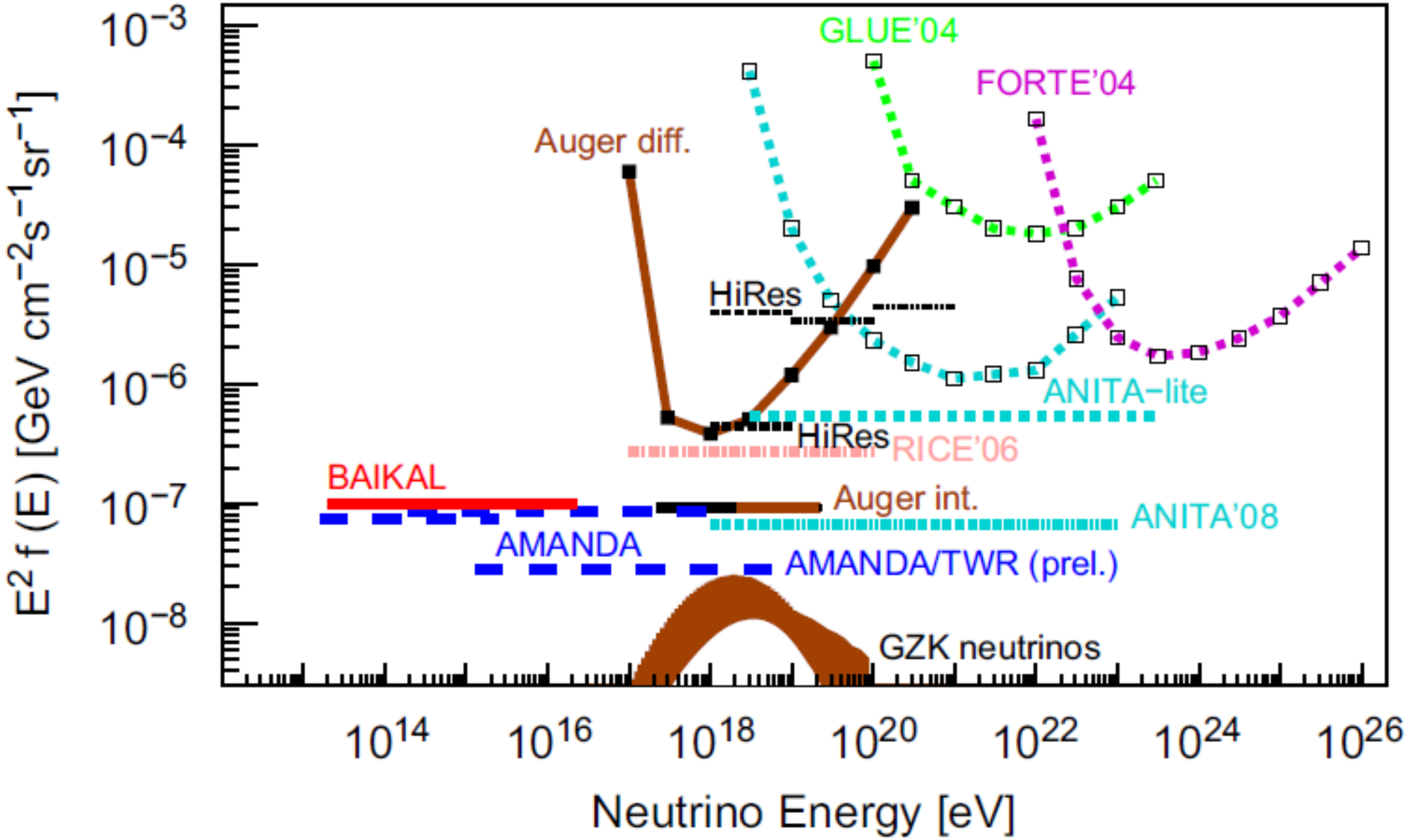
LOFAR Antenna Arrays & Radio Telescope

Site in the Netherlands

Differential & Integral U.L. Neutrino Flux

for E^{-2} diffuse neutrino spectrum.

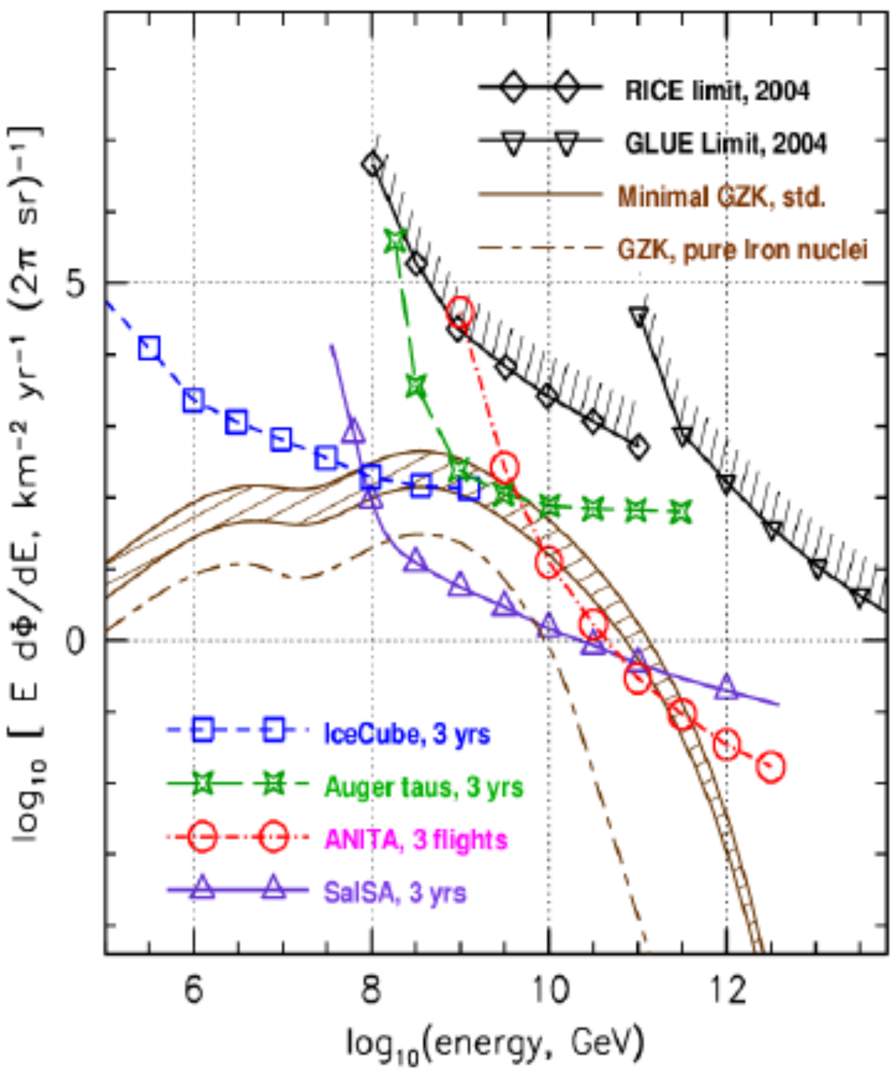
For PAO data ν_τ only, other data all flavors.



Gora et al., 2009 (PAO)

Existing Neutrino Limits 2006

& anticipated future sensitivities



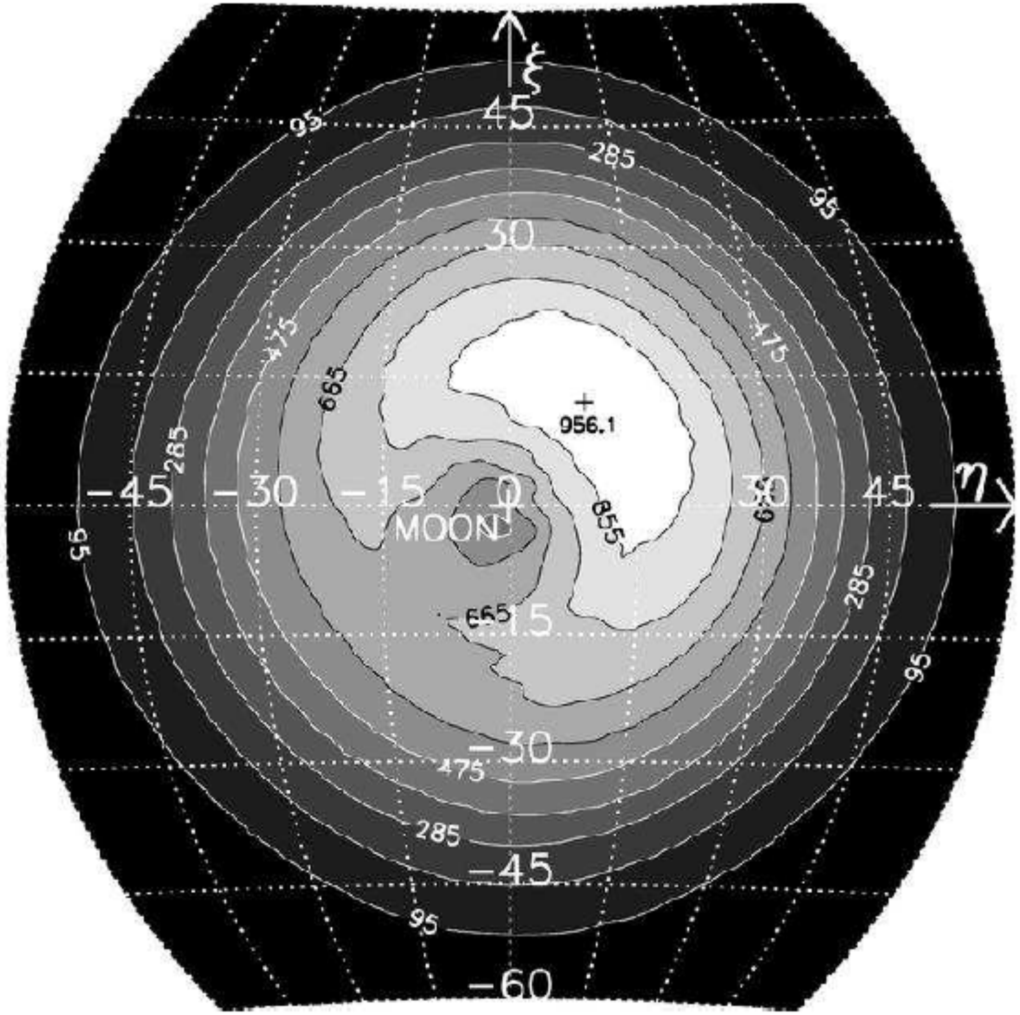
- RICE limits for 3500 hours livetime
- GLUE limits ~120 hours livetime
- ANITA sensitivity, 45 days total:
  - ~5 to 30 GZK neutrinos
- IceCube: high energy cascades
  - ~1.5-3 GZK events in 3 years
- Auger: Tau neutrino decay events
  - ~1 GZK event per year?
- **SalSA sensitivity, 3 yrs live**
  - **60-230 GZK neutrino events**

ACTA: Australian Compact Telescope Array & LUNASKA Experiments.

James et al., PRD 81, 042003, 2010

LUNASKA Experiment

Contours of effective area (km^2) as fct. of arrival direction of 10^{23} eV neutrino events on the Moon



For limb-pointing configuration.

+ → Location of peak effective area.

Moon location is at 0, 0.

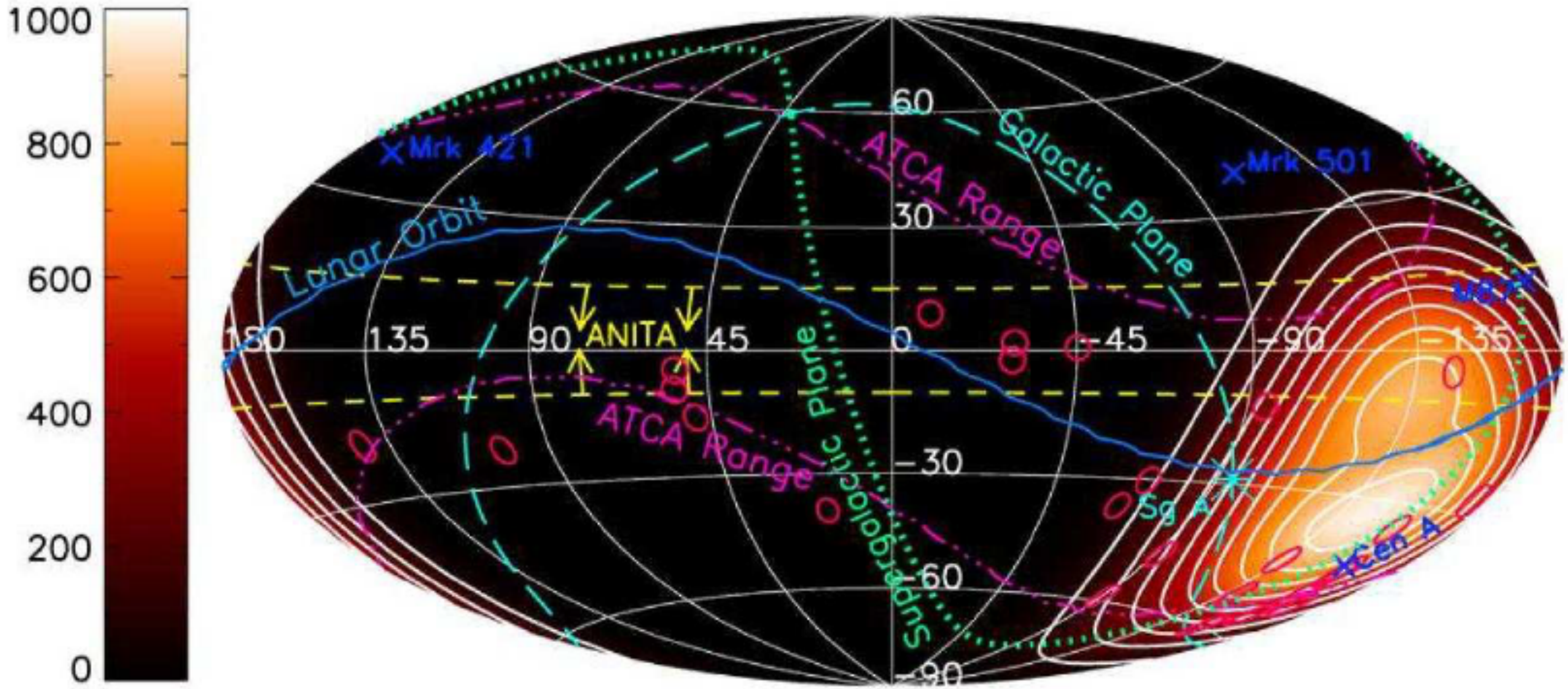
Telescope pointing at η=0.183°, ξ=0.183°

James et al., 2010

Exposure of LUNASKA 2008 Experiment

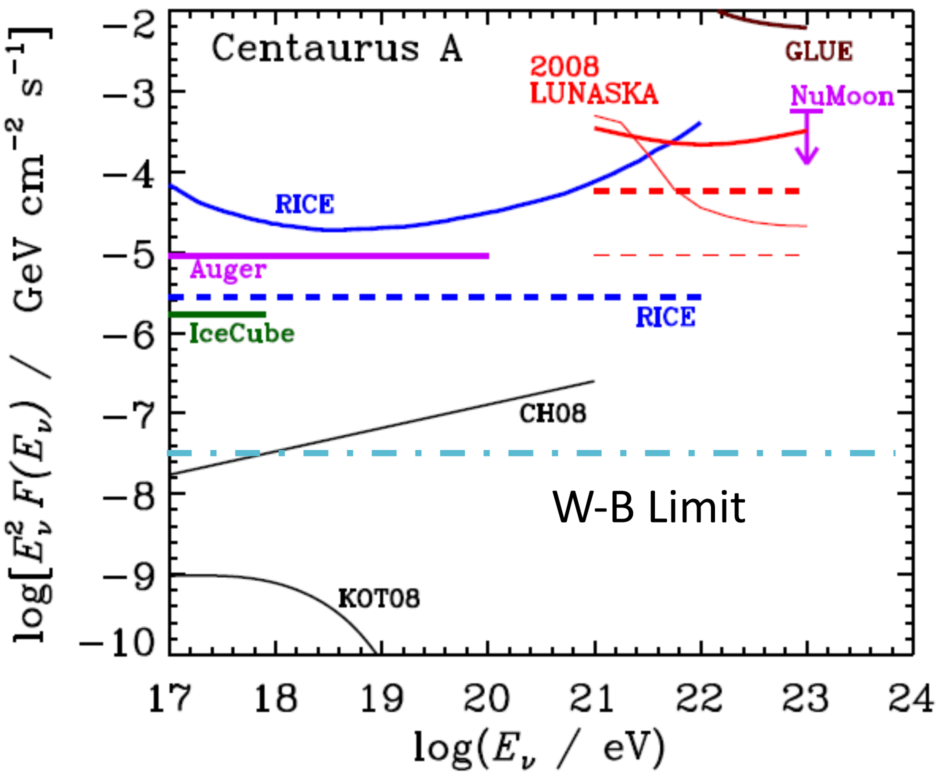
(units in km^2days) using ATCA to 10^{23} eV Neutrinos.

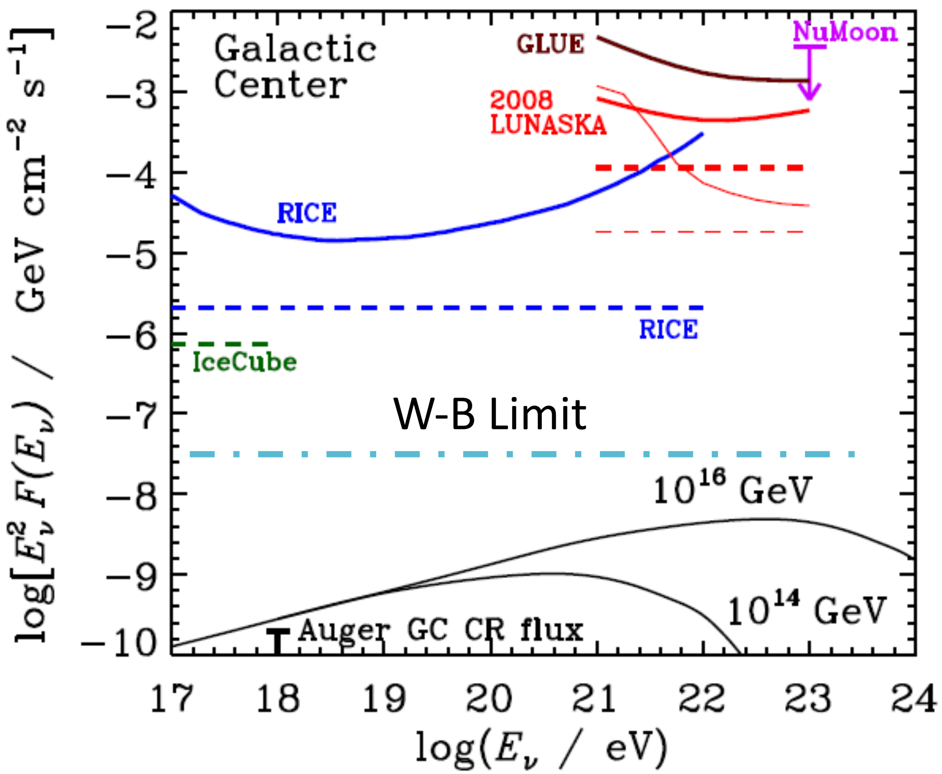
○ UHE CR Auger events E > 5.6 10^{19} eV



James et al., 2010

Neutrino Flux Limits for Cen. A and GC
from different experiments

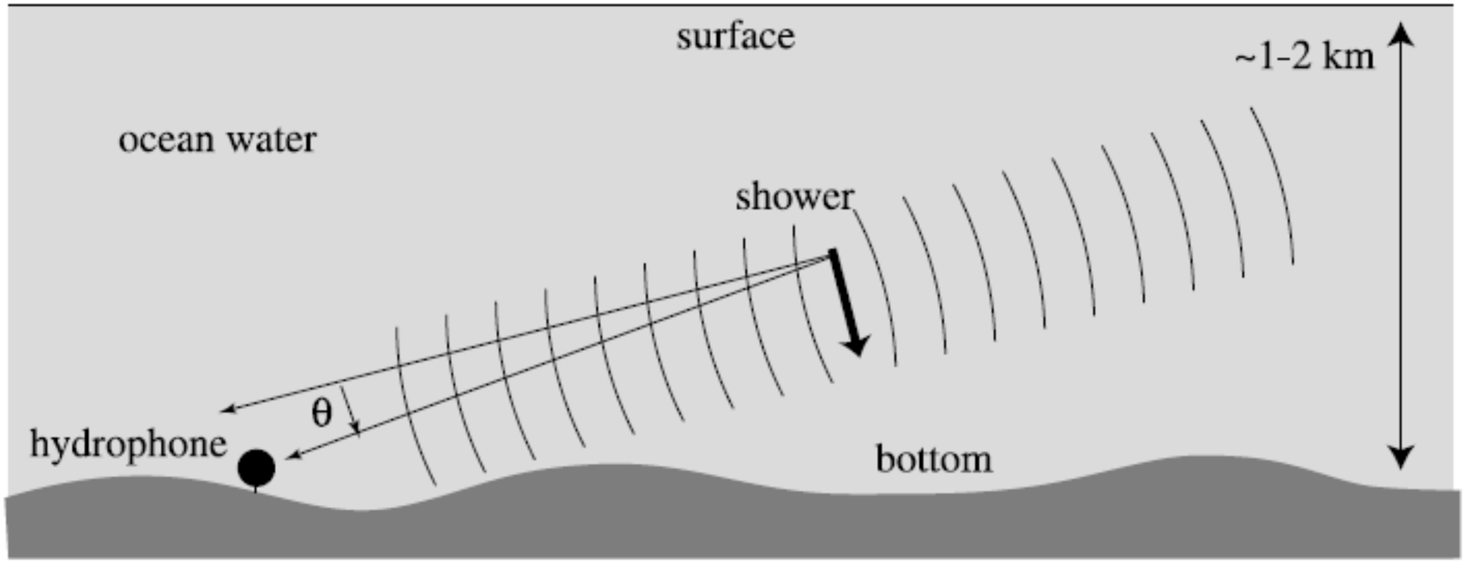




James et al., 2010

Acoustic Signature of Neutrino Events
(of neutrino induced particle cascades)

The Scenario: Neutrino Interaction in Sea Water.
(Applies to all neutrino flavors)

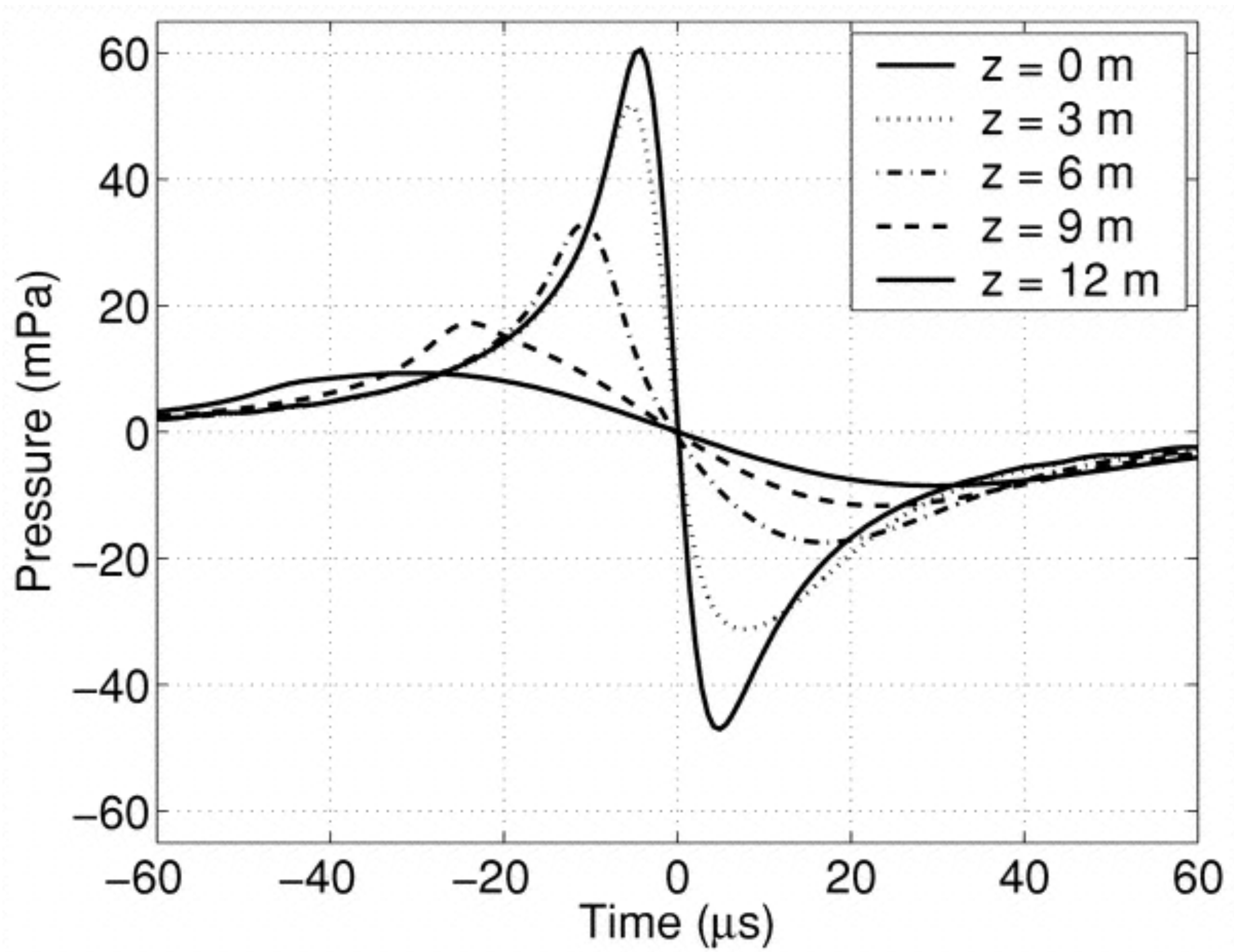


$$\nabla^2\left(p + \frac{1}{\omega_0}\dot{p}\right) - \frac{1}{c^2}\ddot{p} = -\frac{\beta}{C_p}\frac{\partial E}{\partial t}$$

Describes wave propagation in medium

Askar'yan 1957 TH
T. Bowen et al. 1977 TH
J.G.Learned, 1979 TH
L. Sulak et al. 1979 Exp.

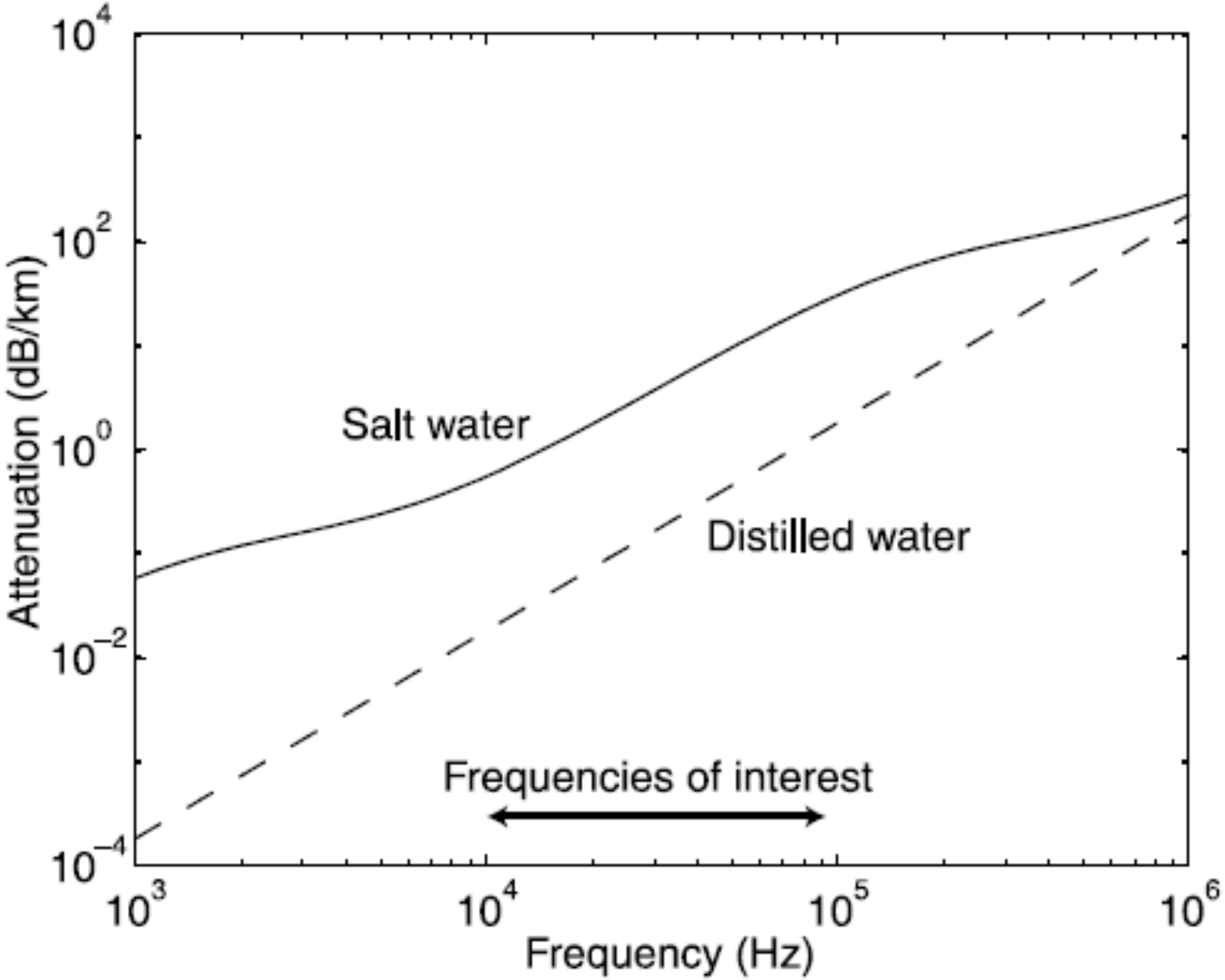
Typical Bi-polar Acoustic Pulse of UHE Interaction in Water



Simulated 10^{20} eV shower seen at 1050 m perpendicular from interaction.
Z is forward longitudinal distance from shower maximum.

Vandenbrouke et al., 2005

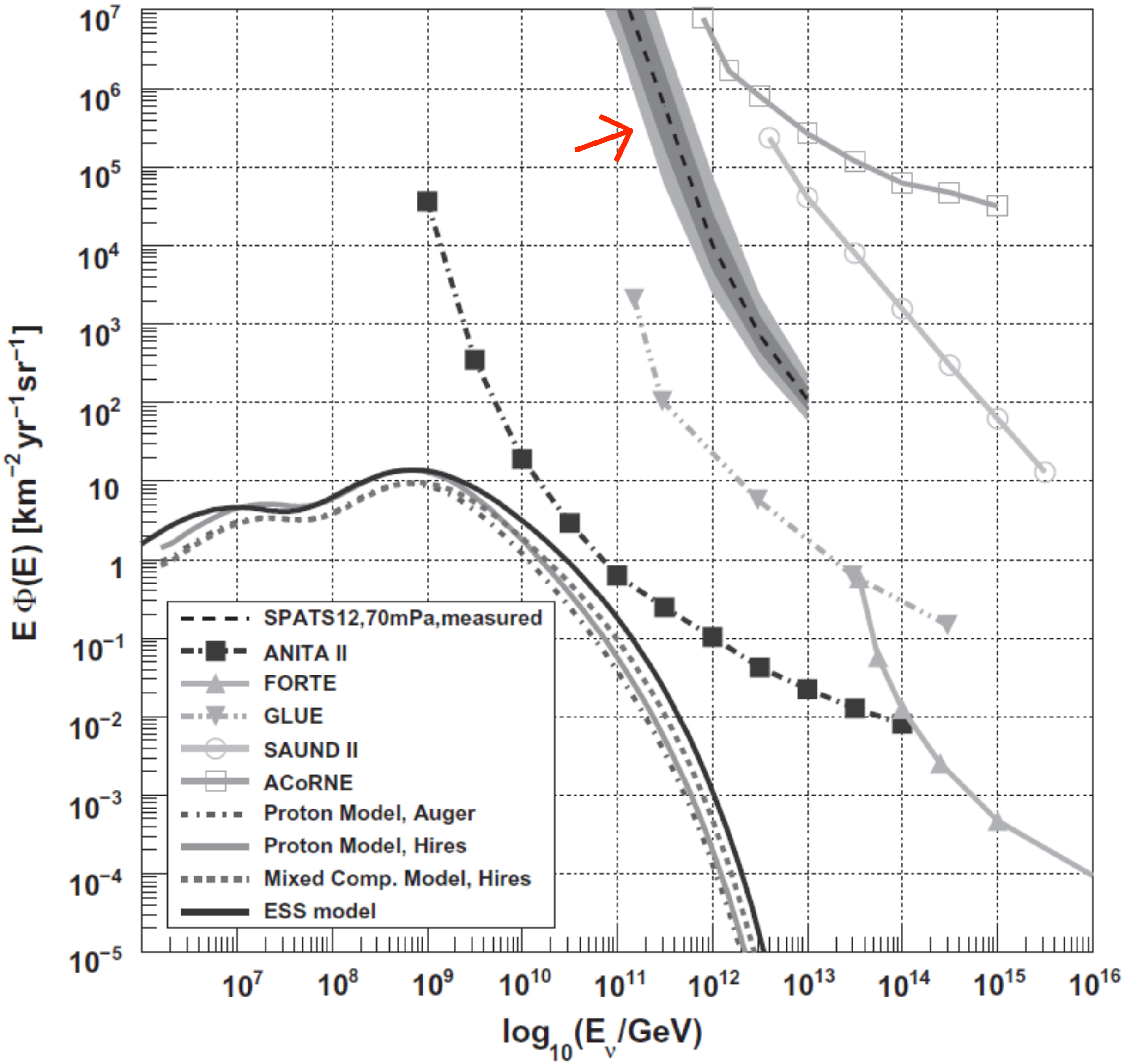
Sound Wave Attenuation in Water



Experimental Attempts at Acoustic Detection of Neutrino Events

- SAUND *Study of Acoustic Ultrahigh Neutrino Detection*
  Submarine Hydrophone array in the Bahamas.
- SalSA *Salt Dome acoustic detection Arra*y
  Detection of UHE neutrino events in salt dome.
- ANTARES In *ANTARES* integrated hydrophones.
- SPATS *South Pole Acoustic Test Setup*
  In IceCube integrated acoustic detectors.
- Baikal Exploratory setup for acoustic detection of events

Results from SPATS Experiment

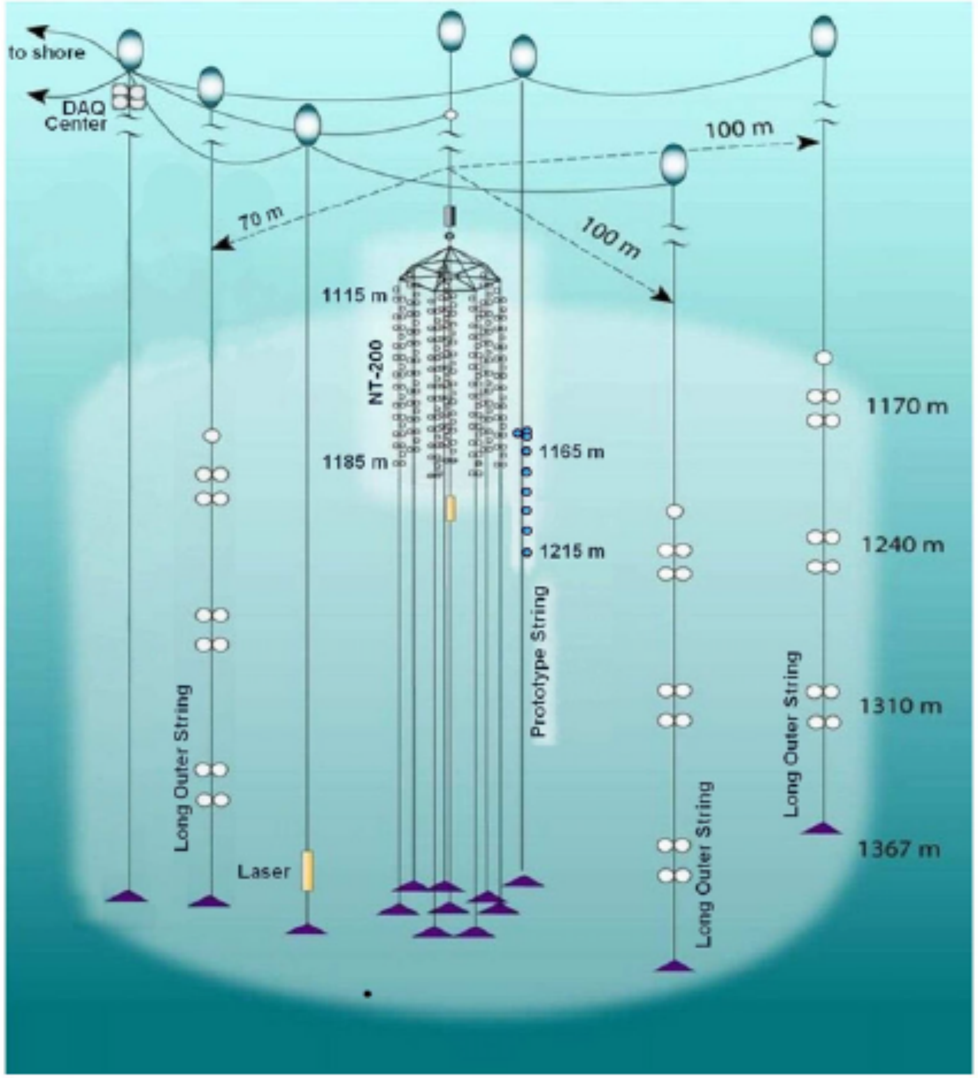


Abbasi et al. 2012

Future Giant Neutrino Detectors

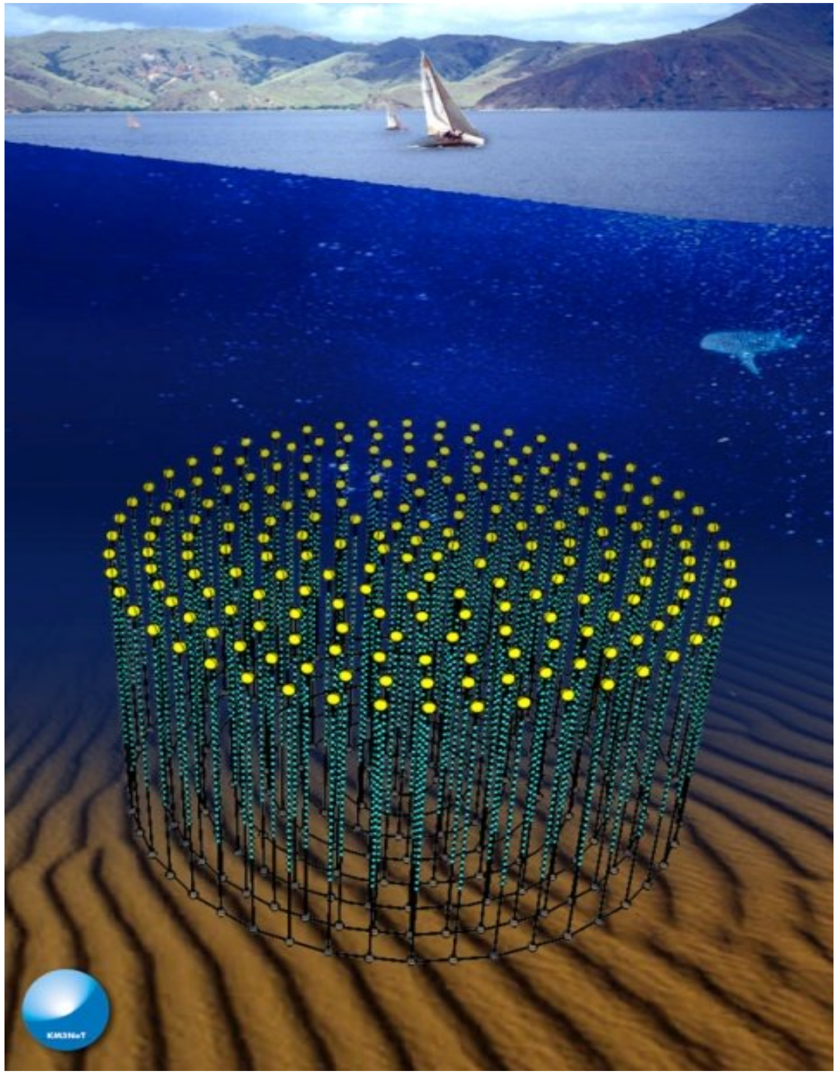
- Baikal km^3 *Optical, Acoustic in Water*
- KM3 Net *Optical, Acoustic in Water*
- LOPES *Radio from Ground Level (Moon obs.)*
- ARIANNA *Radio from Ice Shelf (30x30x0.57 km^3)*
- LORD *Radio Satellite based (Moon obs.)*
- JEM-EUSO *Optical (Air Fluorescence, Cherenkov)*
  Satellite based
- Acoustic Arrays

Baikal km^3



KM3Net Array

Concept



ARIANNA

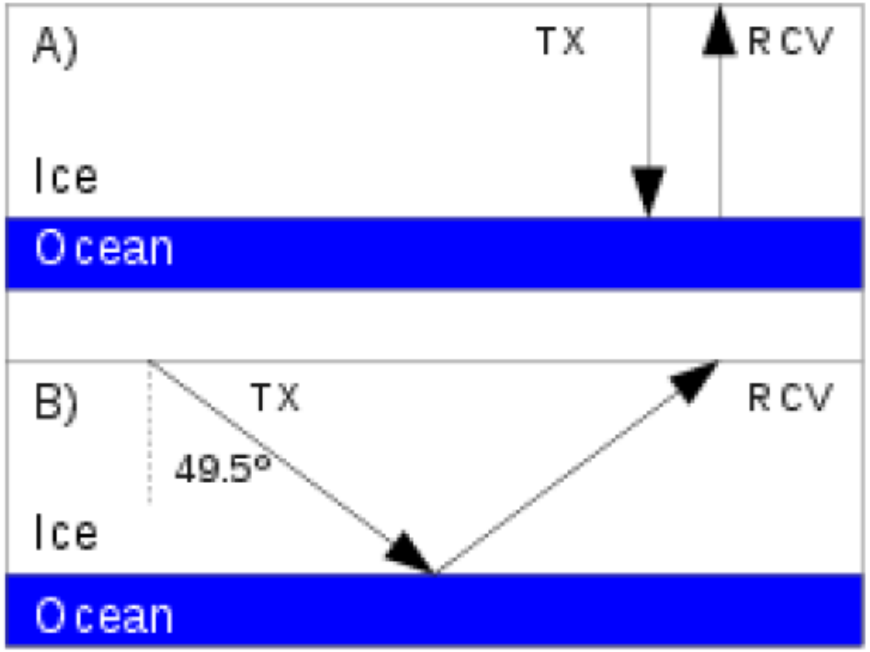
Cherenkov Radio Neutrino Detector on Ross Ice Shelf

Detector volume 513 km^3

Expect ~40 GZK events

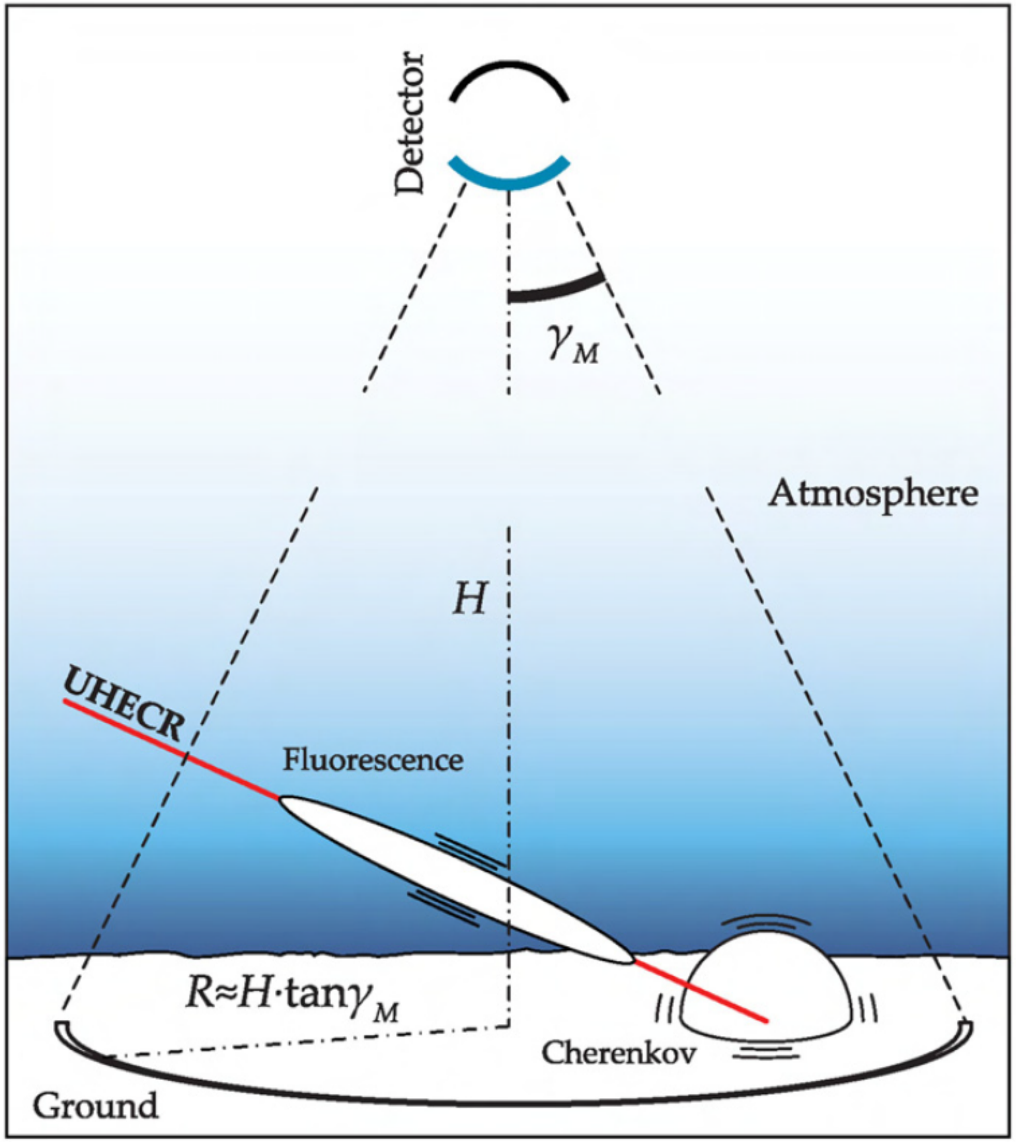
Threshold > $3x10^{17}$ eV

Principle of operation



Hanson, ICRC 2011, HE2.3, 168

JEM-EUSO Experiment on ISS



Altitude ~400 km

Geometrical acceptance

Nadir mode 5.8×10^5 $km^2 sr$

Tilt mode 52^o 2.9×10^6 $km^2 sr$

Mission duration 5 years

Event rate ~1000 $> 7 \times 10^{19}$ eV

Launch betw. 2013-2015

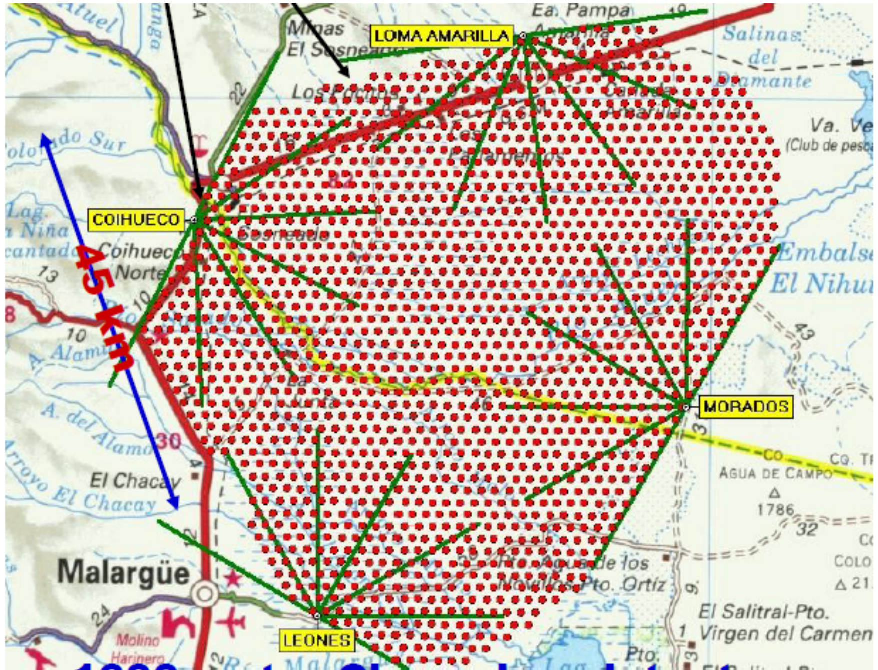
Concluding Remarks

The lack of a positive result in our search for UHE astrophysical neutrino sources with the present large optical Cherenkov detectors and the promising exploratory work with the far more economical radio or the wide-meshed acoustic arrays strongly suggest that future efforts should be directed in these directions. In addition, the sensitivities should be significantly improved. It appears that we need orders of magnitude larger detectors .

Thank you for your attention

The 2 Giant UHE EAS Hybrid Detectors

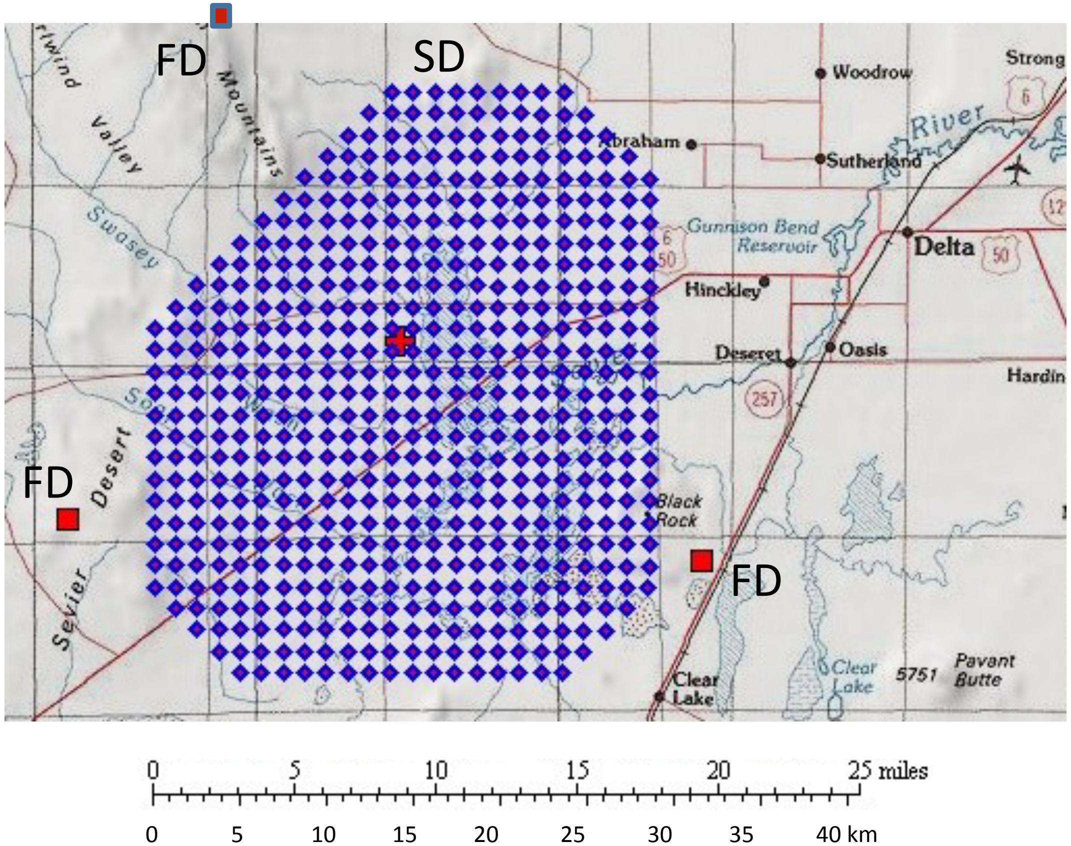
Pierre Auger Observatory (PAO), Argentina. Operational since 2005. Altitude 1300 – 1400 m



1600 water Cherenkov detectors,

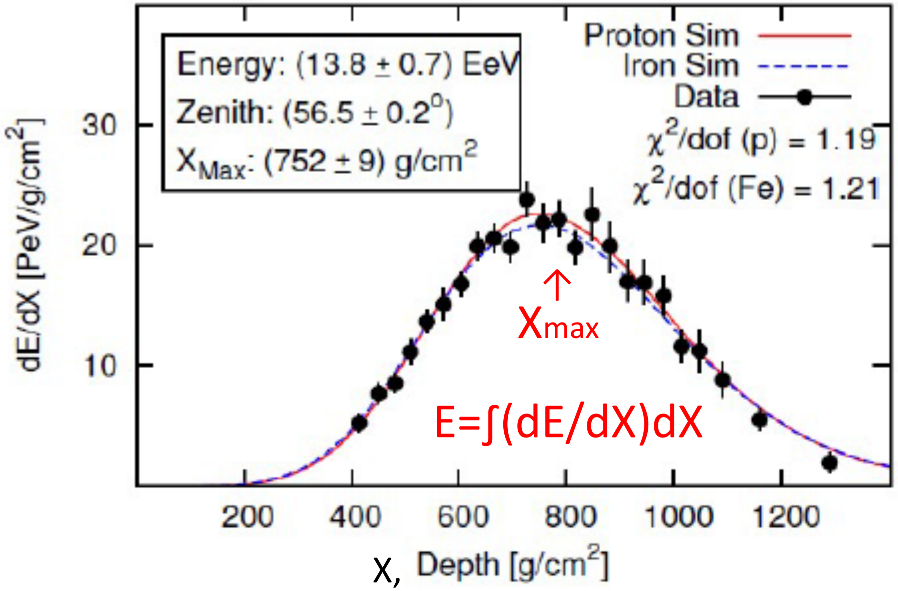
1.5 km spacing, 3000 km², 4 x 6 fluorescence telescopes

Telescope Array (TA), Western Utah Operational since 2008 Alt. 1400 m, 512 SD, 3 FD, ~750 km^2

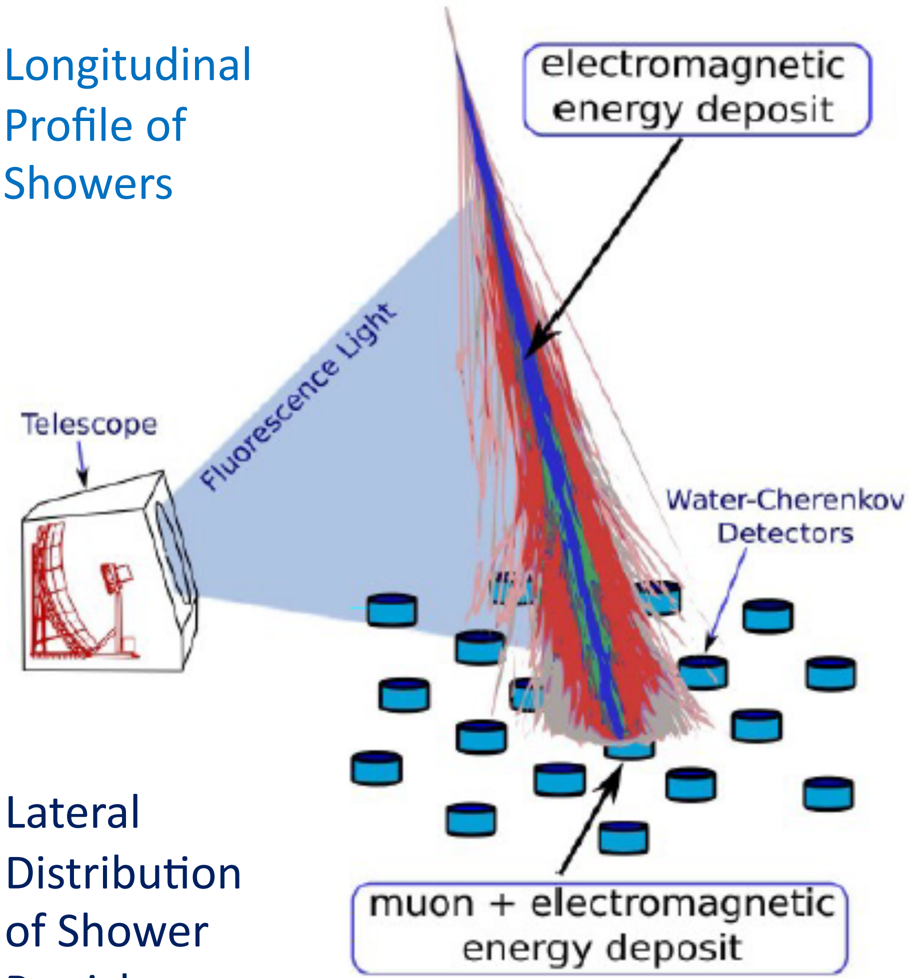


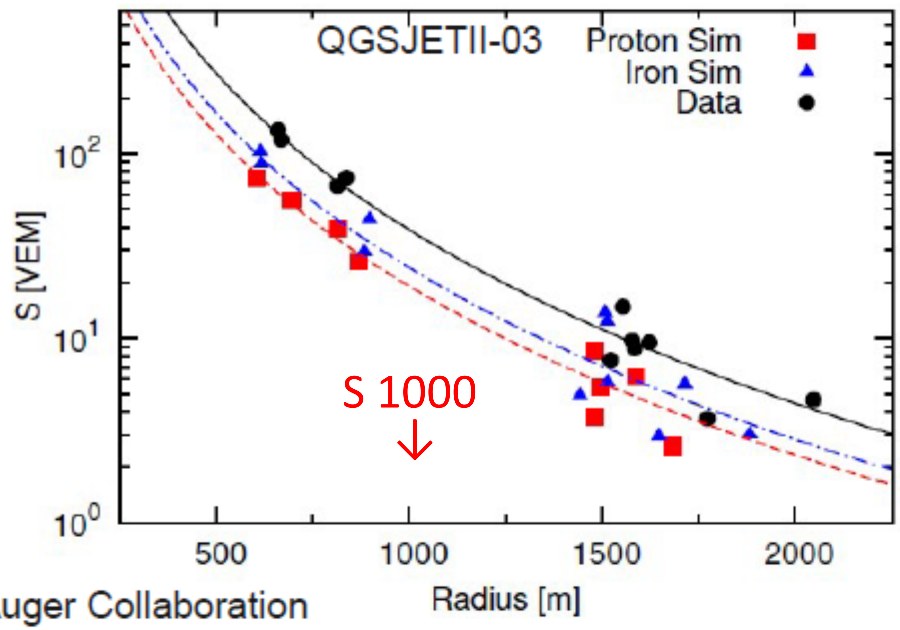
Hybrid Detector Measurements

Auger and Telescope Array



Longitudinal Profile of Showers





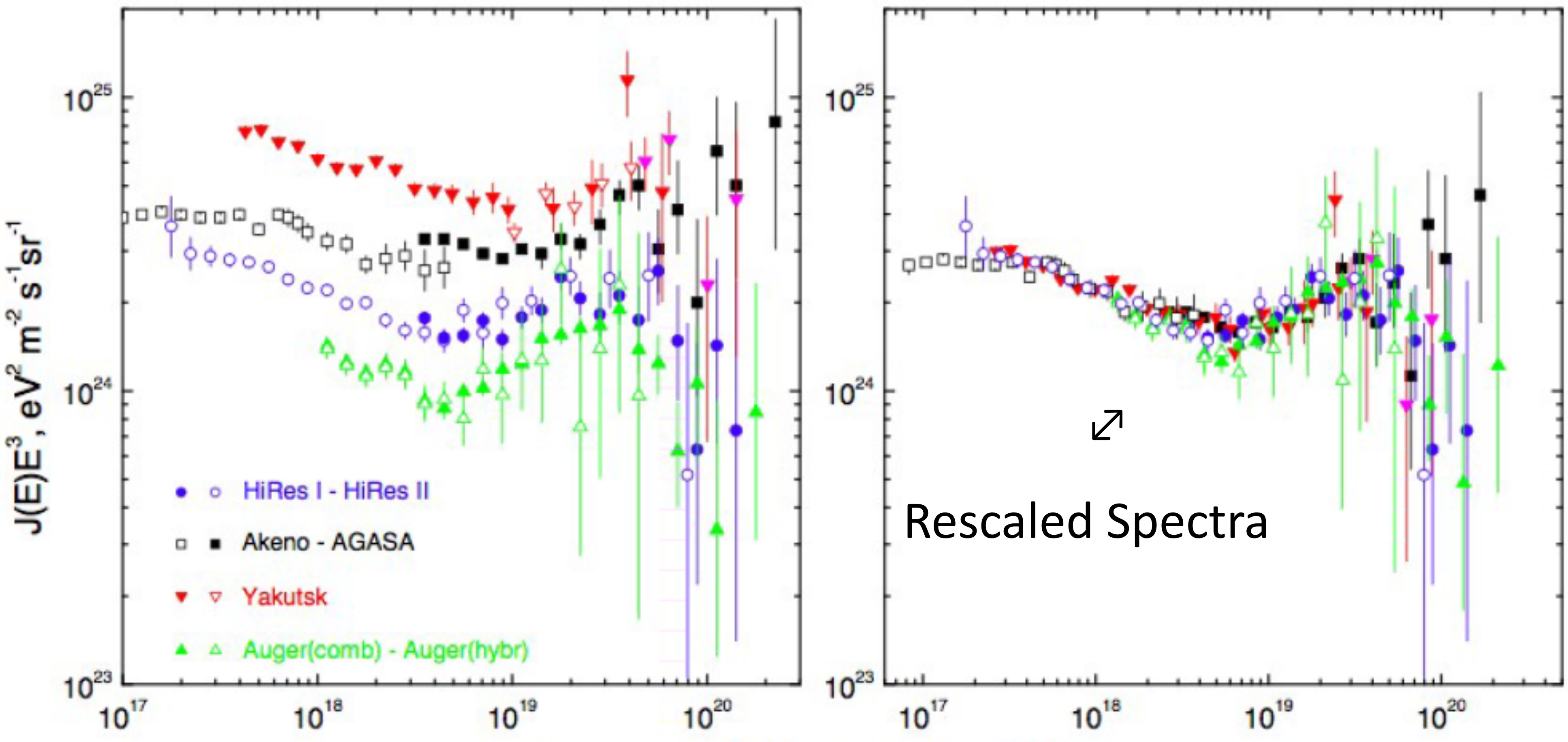
Lateral Distribution of Shower Particles

Pierre Auger Collaboration

All-Particle Primary CR Energy Spectra

Spectral Differences → **Spectra Converge**

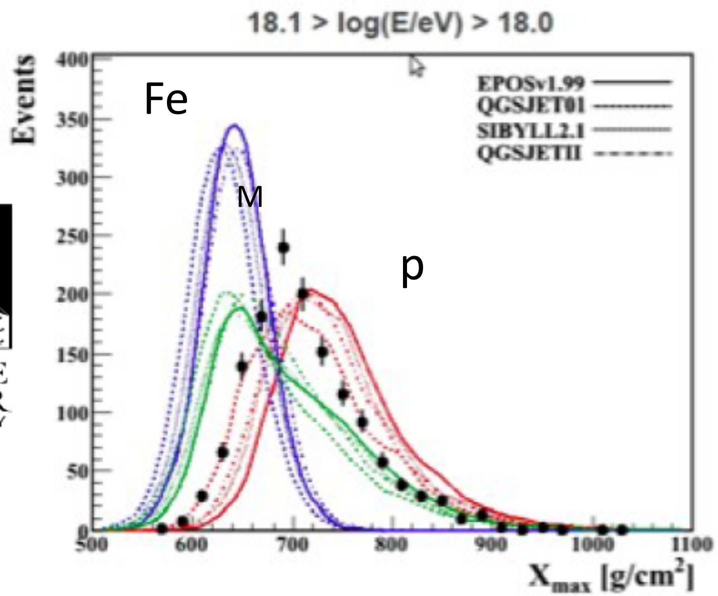
Systematic Energy Uncertainties ~20%

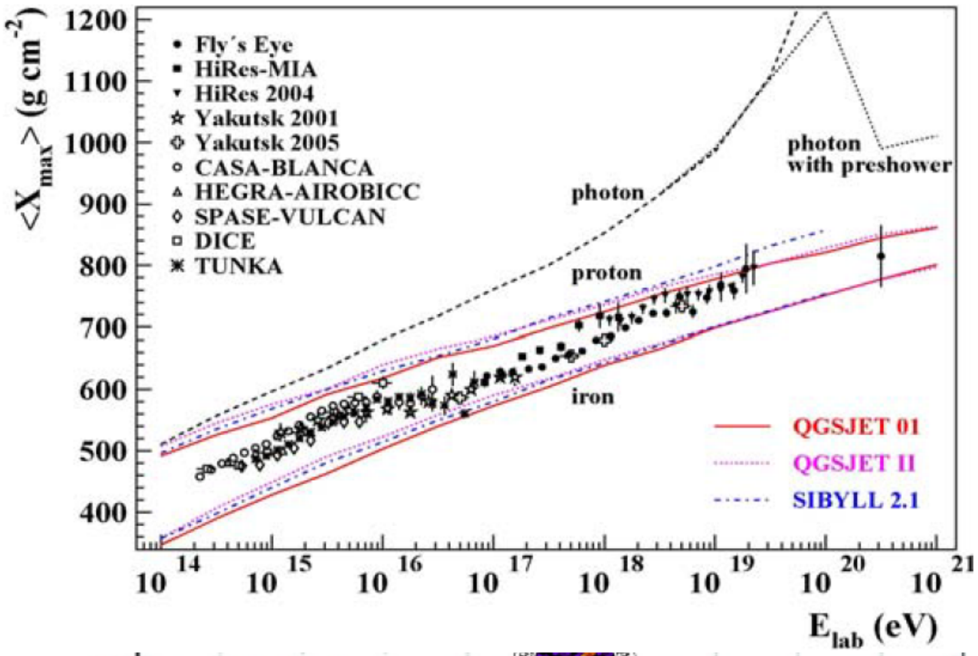


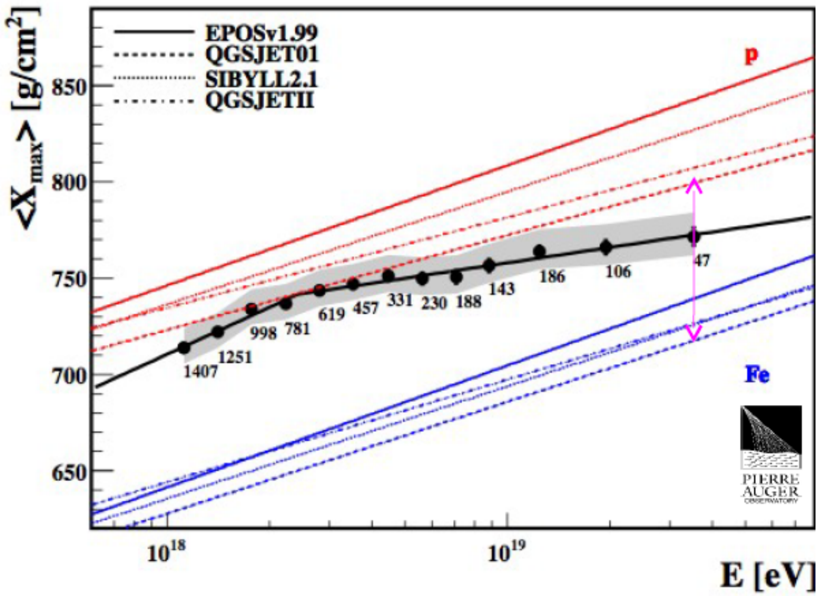
Primary Energy [eV]

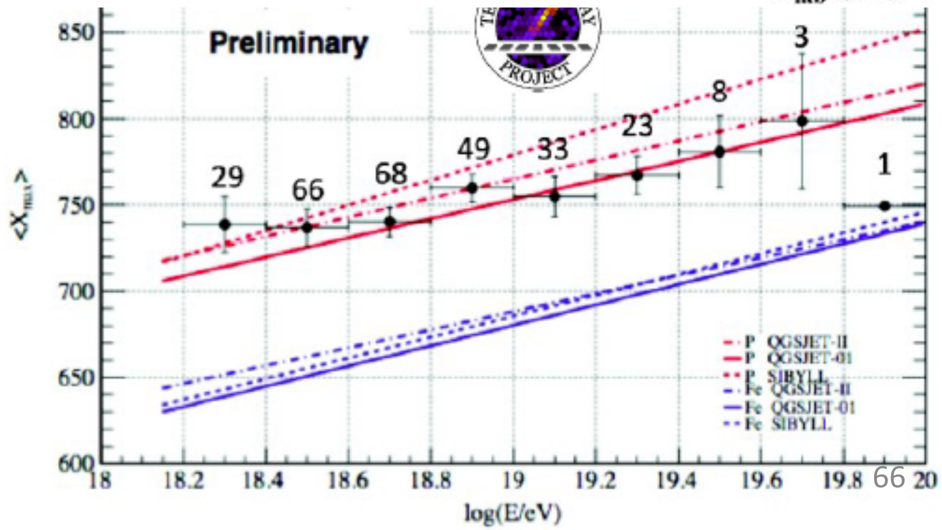
Primary Mass Composition

Determination via X_{max} Distribution ($X_{max} \rightarrow f(E_0, M_0, \sigma, \ldots)$)

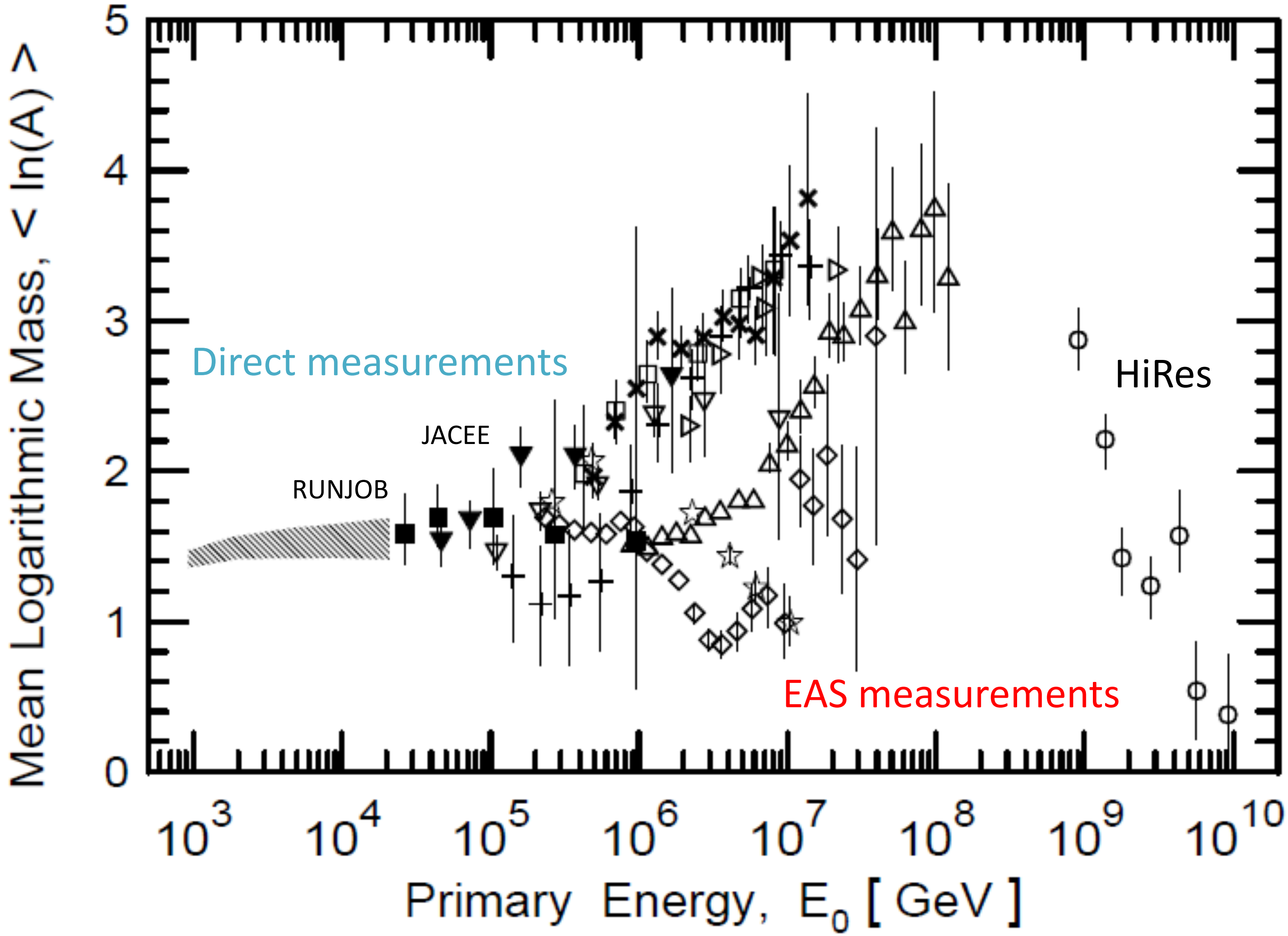








Primary Mass v/s Energy
a major problem



Ogio et al. (2004)