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Aktuelle Ergebnisse und Zukunft der Neutrinoastronomie

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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The plan for this presentation:

- Introduction
- Present neutrino telescopes:
  ANTARES, IceCube and their recent results
- KM3NeT
- Studying low-energy neutrinos:
  The PINGU and ORCA options
- Summary

Sincere thanks to all colleagues who provided advice and material
for preparing this presentation

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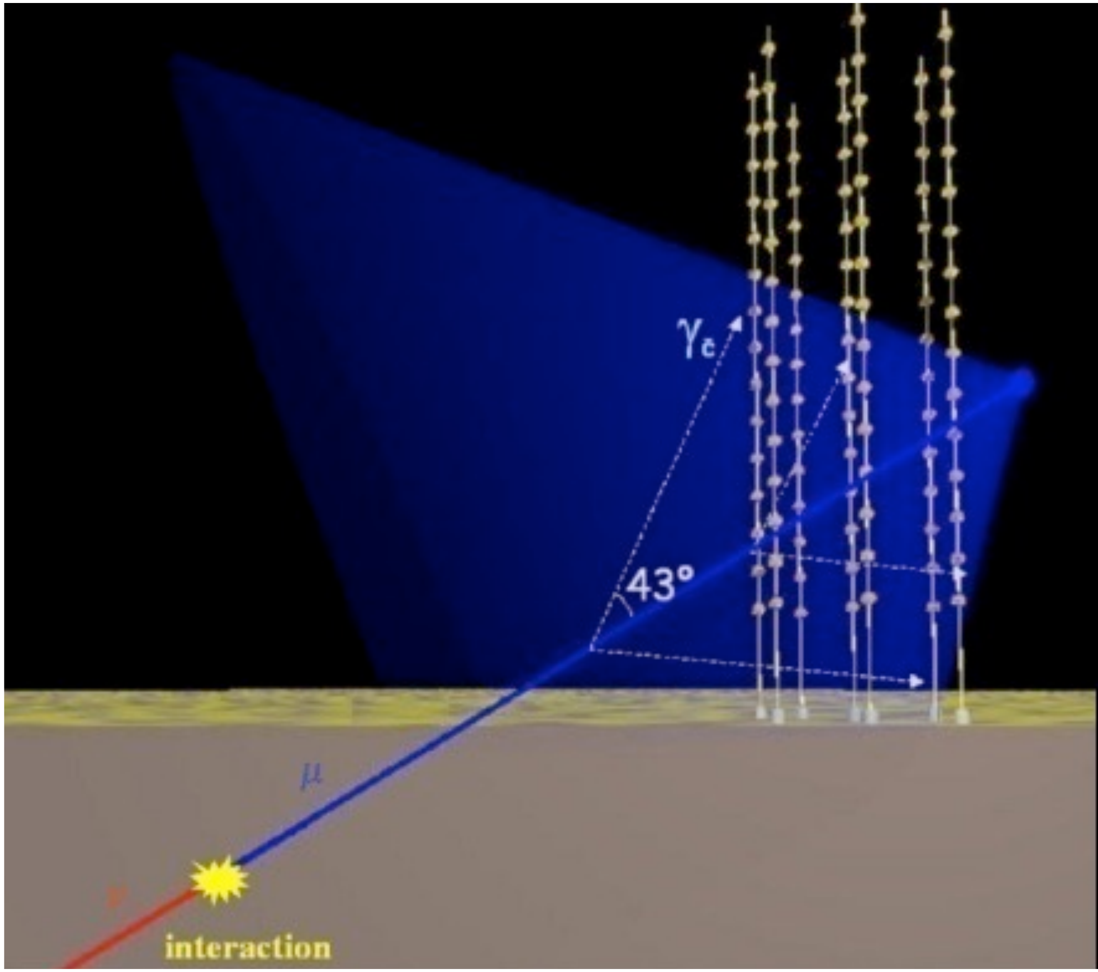
Introduction

How does a neutrino telescope work?

- Neutrino interacts in the (vicinity of the) telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission
- Recorded by a 3D-array of photo-sensors
- Most important channel:
  $\nu_\mu + N \to \mu + X$
- Energy range :
  10(0) GeV – some PeV
- Angular resolution:
  <1° for E>1 TeV
- Δ[log(E)] ~ 0.3



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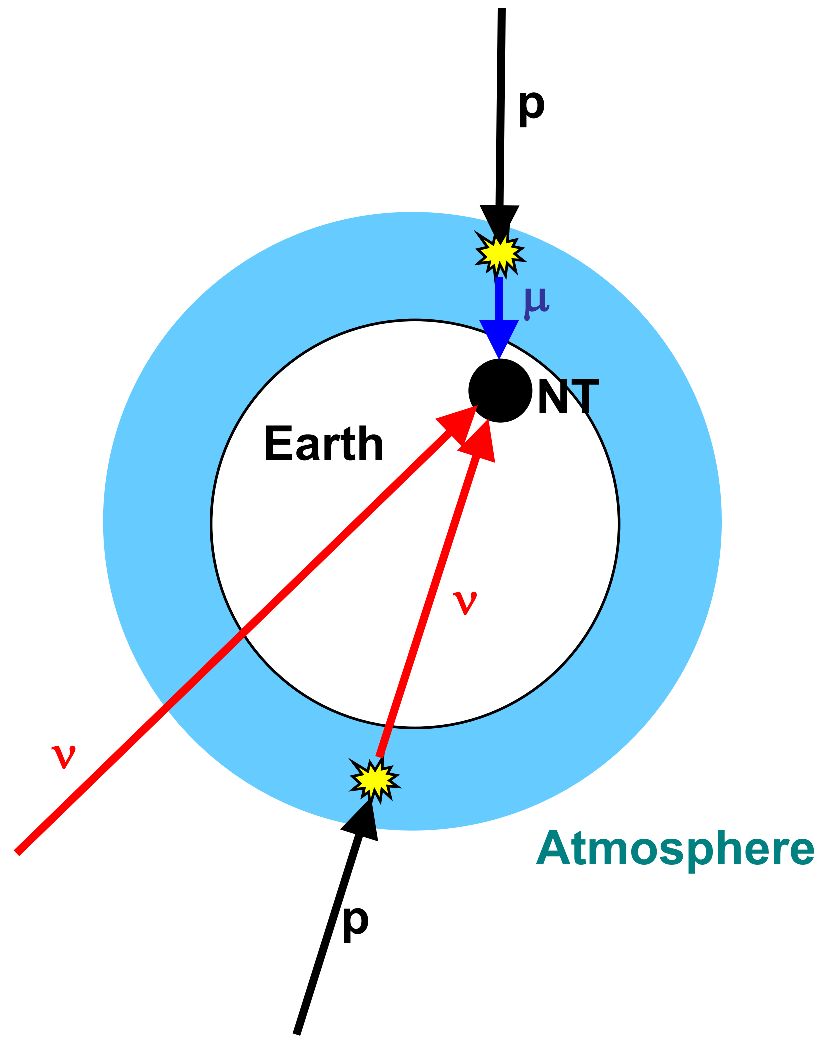
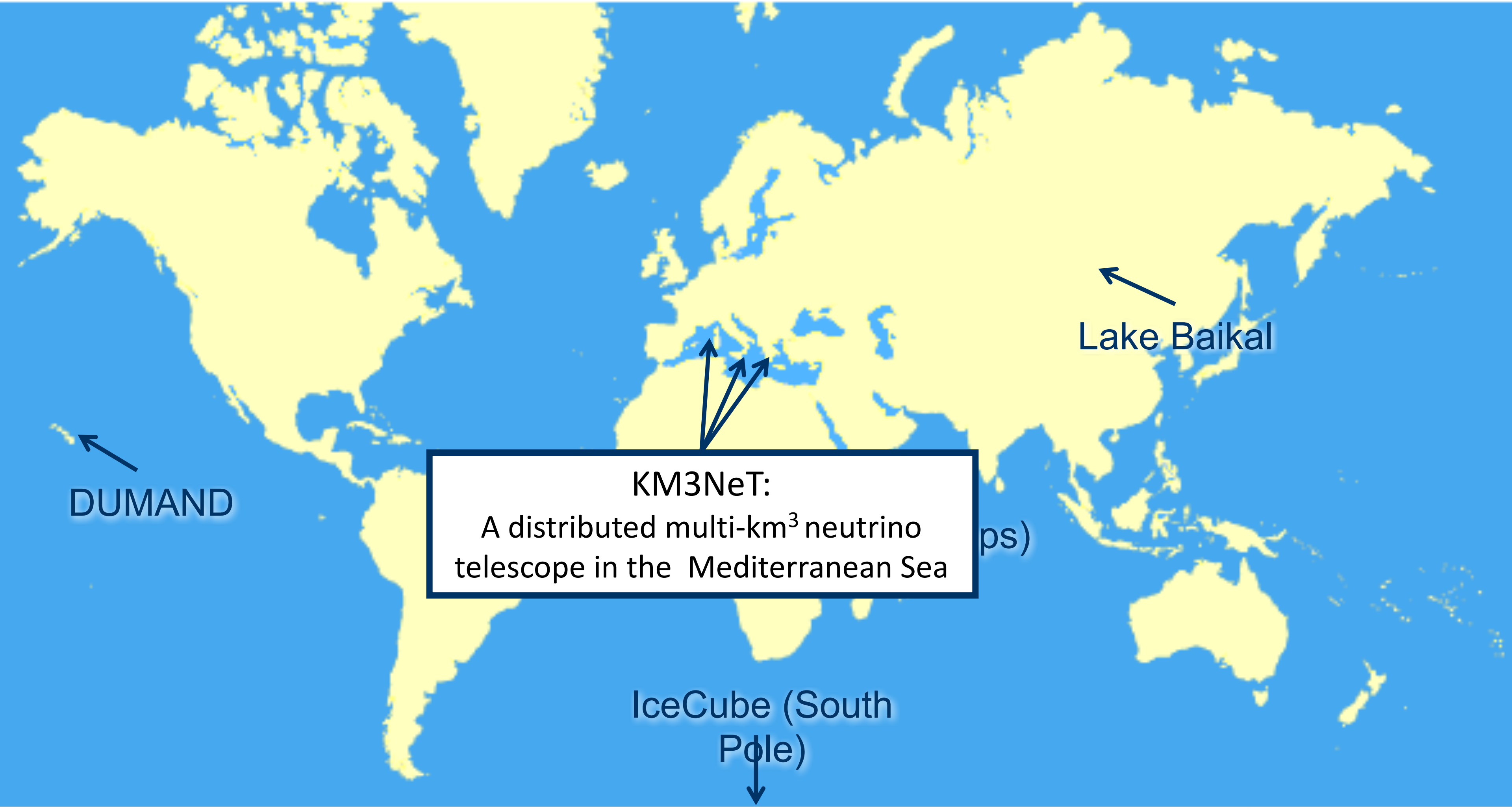
Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies
- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude
- Sea water: light from K40 decays and bioluminescence



The neutrino telescope world map



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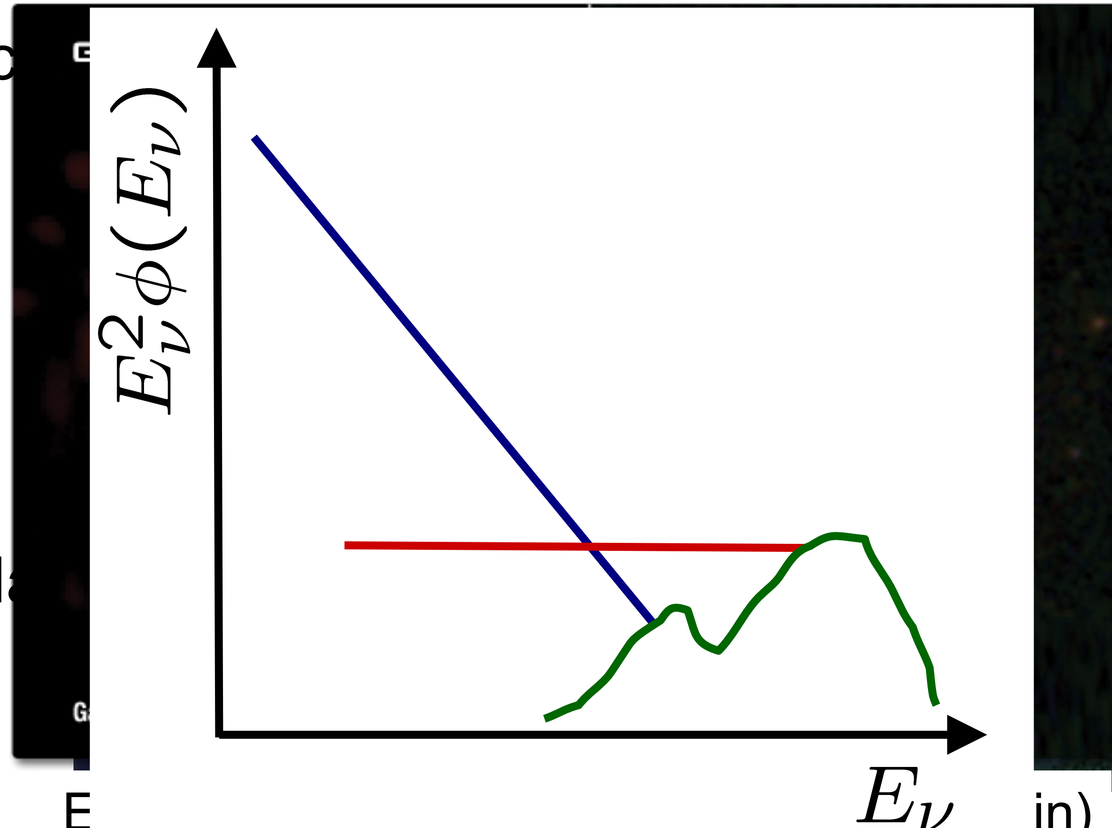
Example targets of neutrino astronomy

- Galactic neutrino sourc
- Extragalactic sources
- Transient sources
- Diffuse neutrino flux
- Neutrinos from Dark Ma annihilations
- Particle physics with atmospheric neutrinos
- Search for exotics (monopoles, nuclearites,



Isotropic high-energy neutrino flux above atmospheric neutrino background from unresolved astrophysical sources or of cosmogenic origin (GZK)

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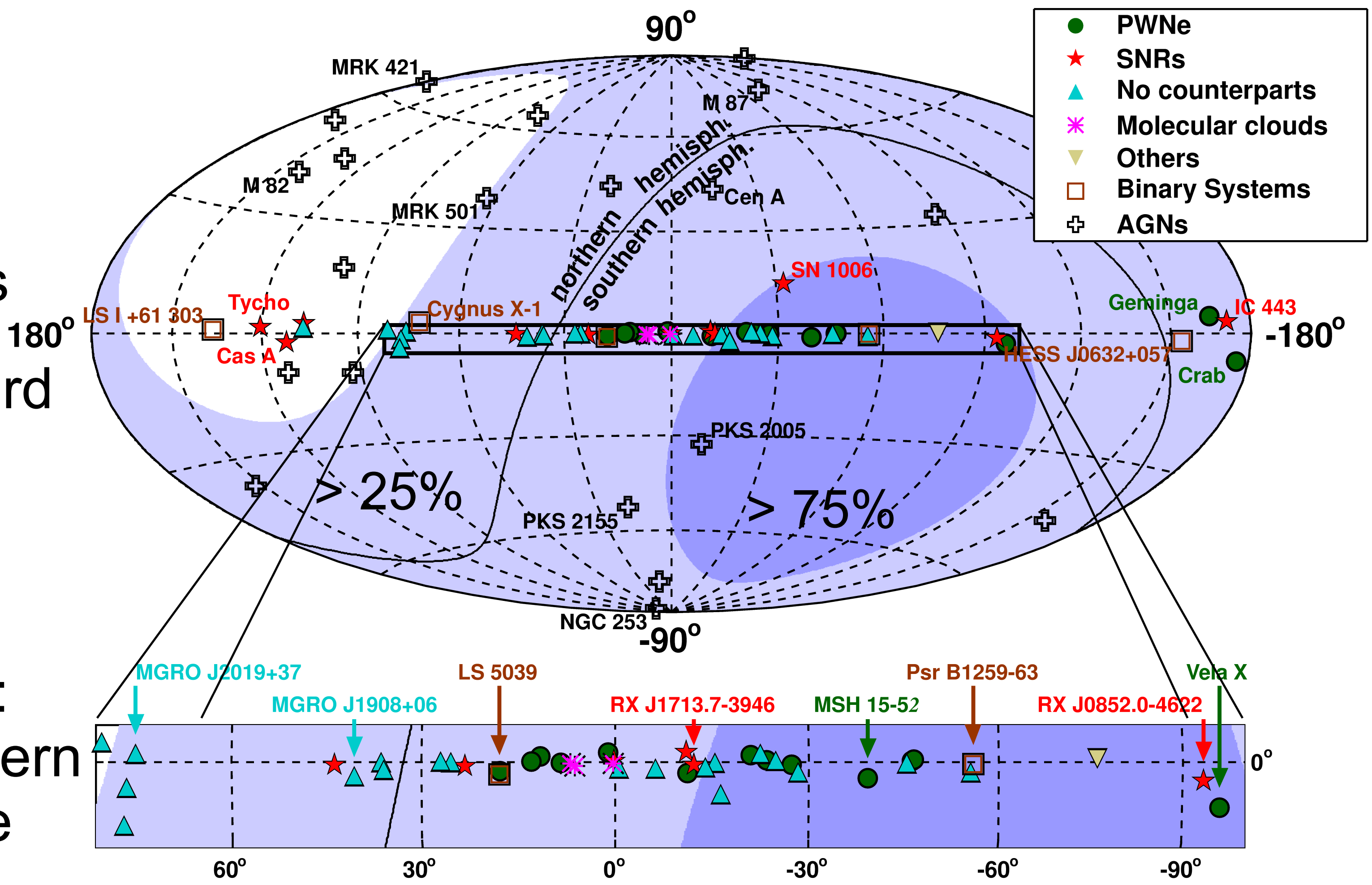
South Pole and Mediterranean fields of view

Galactic coordinates

2π downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere

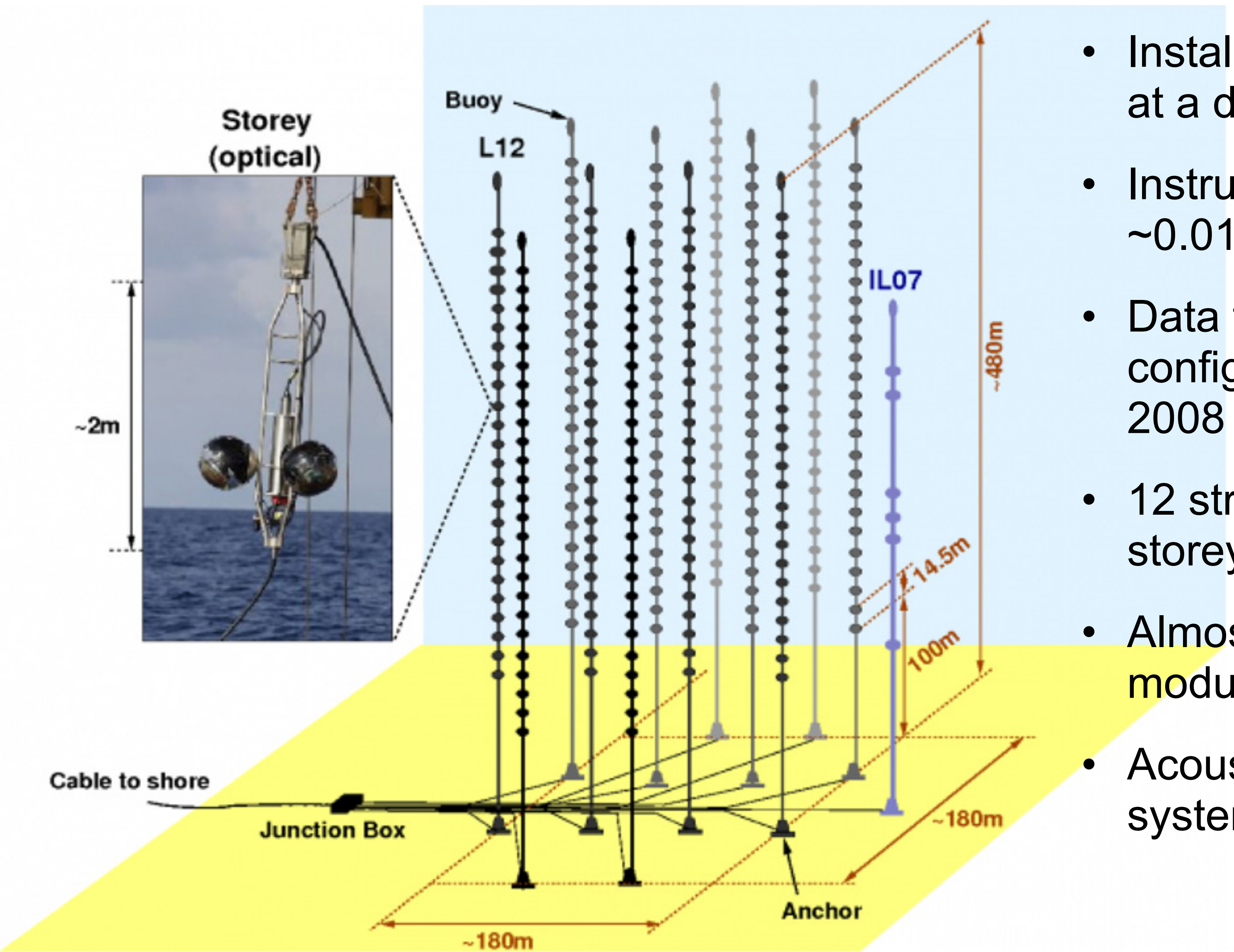


ANTARES, IceCube and (a restricted selection of) their recent results

IceCube:
Aachen, Bonn, Bochum, DESY, Dortmund, Mainz, TU München, Wuppertal
See:
T9.4, Do 15:15, Sebastian Böser, T20, T21, T55, T74, T86-T90, T92, T93, T104, T109, T111

ANTARES:
Erlangen
See:
T78, T86, T88-T90, T104, T110, T111

ANTARES: The first NT in the deep sea



- Installed near Toulon at a depth of 2475m
- Instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- 12 strings with 25 storeys each
- Almost 900 optical modules
- Acoustic sensor system

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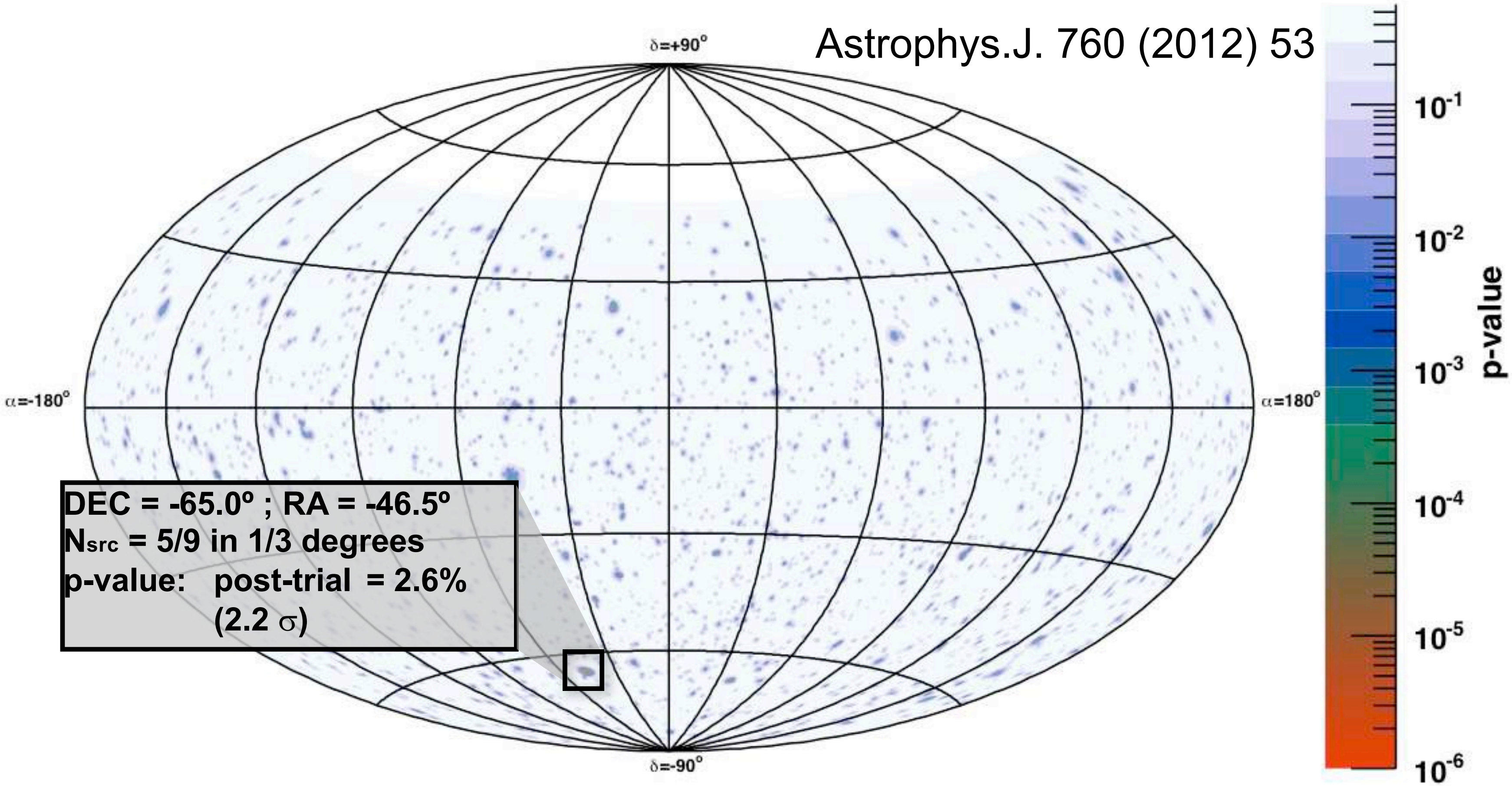
ANTARES: Point source search

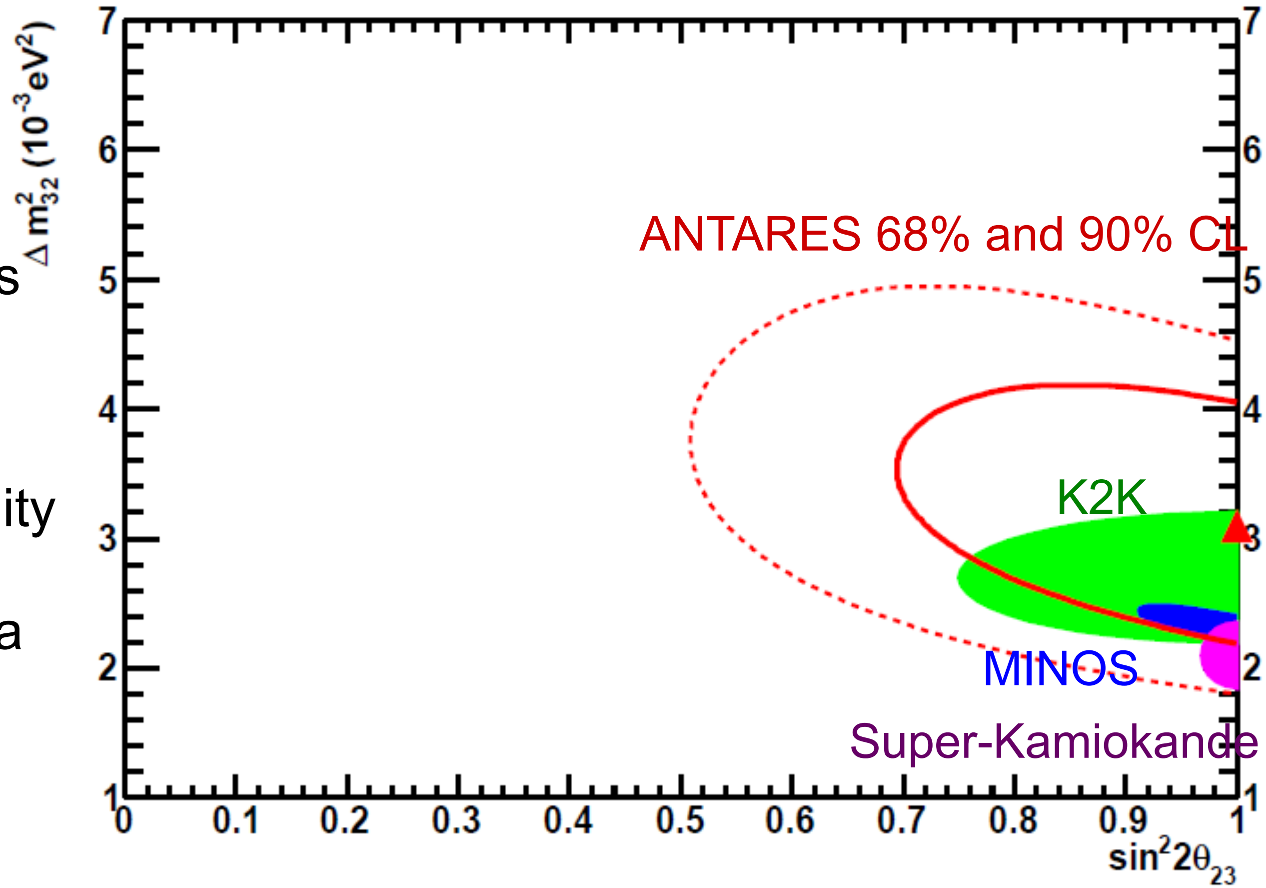


- 4 years of data, 3058 neutrino candidate events
- Search for neutrinos from selected source candidates (no significant signal)

ANTARES: Neutrino oscillations

- Measure distribution of reconstructed $E/\cos\theta \propto E/L$
- Expected oscillation signal at lowest values
- Significant signal observed
- Demonstrates capability to reconstruct events down to 20 GeV with a detector optimised for the TeV range
- Results agree nicely with other experiments

Phys.Lett.B714(2012)224



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ANTARES: Further results

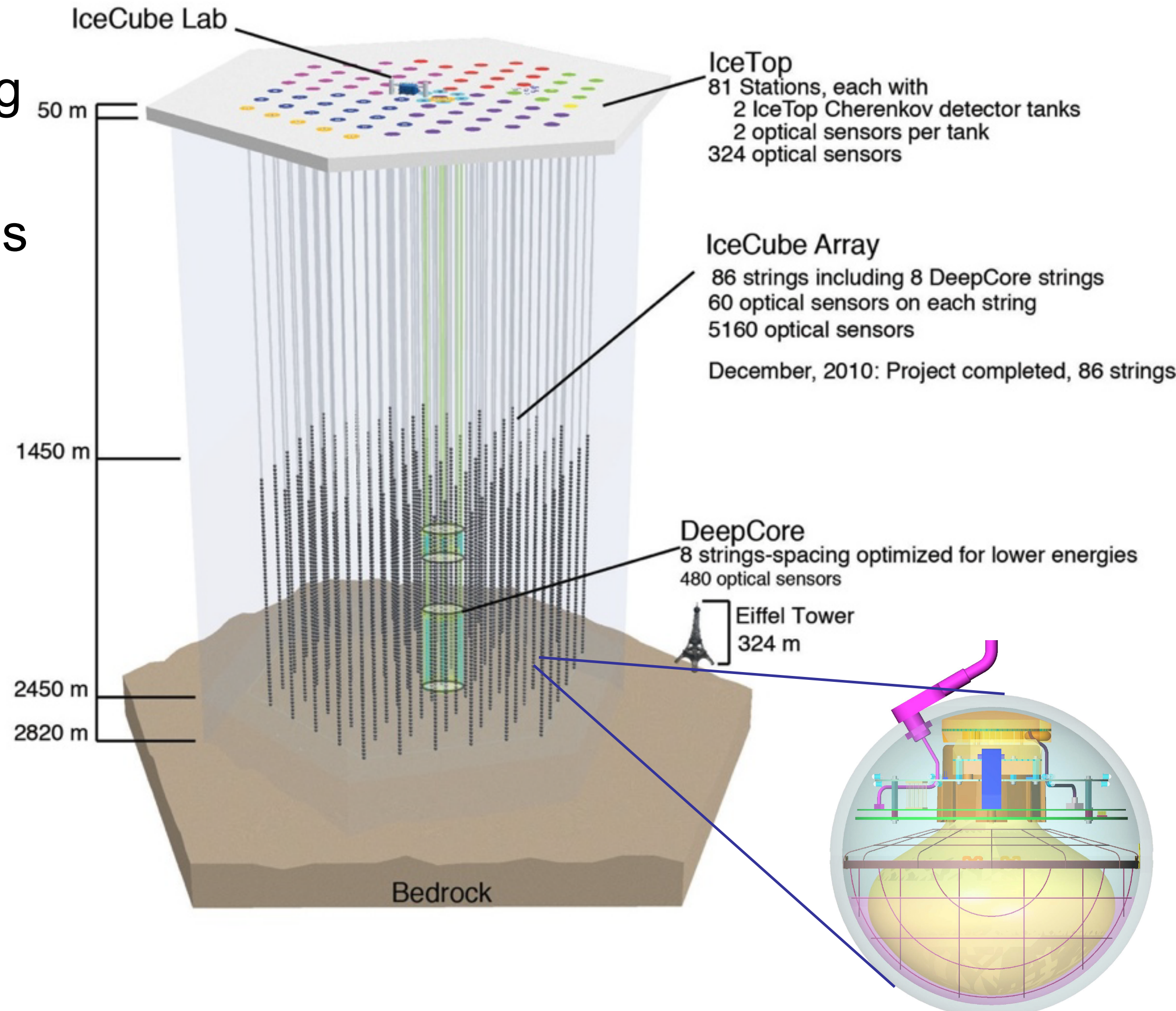
- Search for dark-matter annihilations in the Sun (arXiv:1302.6516)
- Search for ANTARES / Pierre Auger correlations (arXiv:1202.6661)
- Joint LIGO/Virgo/ANTARES analysis (J.Phys.Conf.Ser.375(2012)062002)
- Search for relativistic magnetic monopoles (Astropart.Phys.35(2012)634)
- …

ANTARES proves the feasibility and sensitivity
of a deep-sea neutrino telescope!

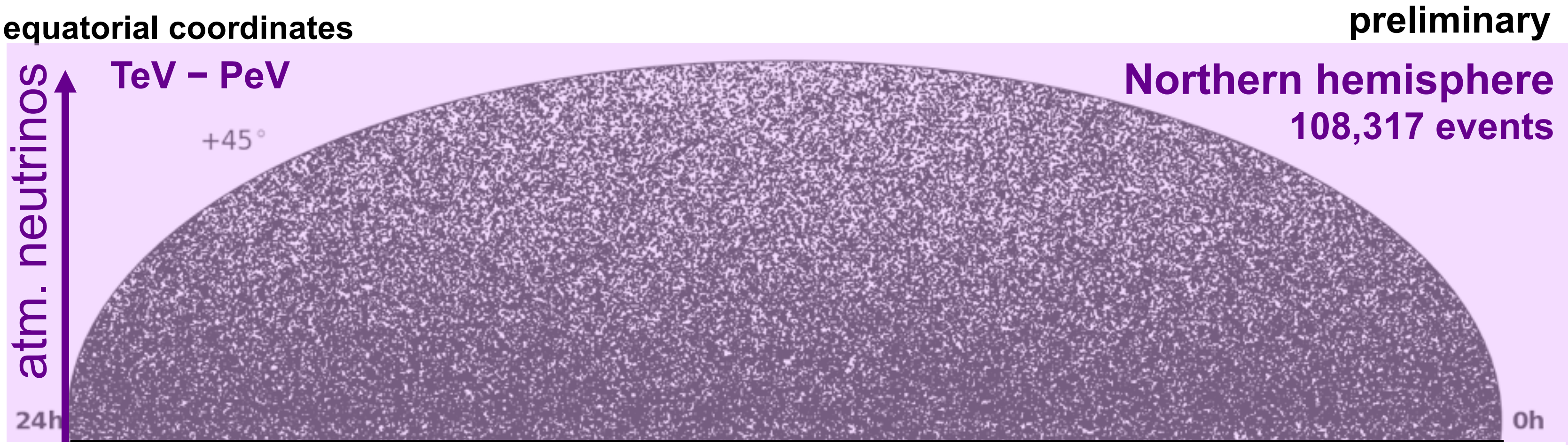
IceCube: A km^3 detector in the Antarctic ice

IceCube: Completed in December 2010

- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km^3 instrumented volume, depth 2450m
- Deep Core
  - densely instrumented region in clearest ice
  - atmospheric muon veto by IceCube
  - first Deep Core results
- Plan for future low-energy extension (PINGU)



IceCube: Event skymap (IC40+59+79)



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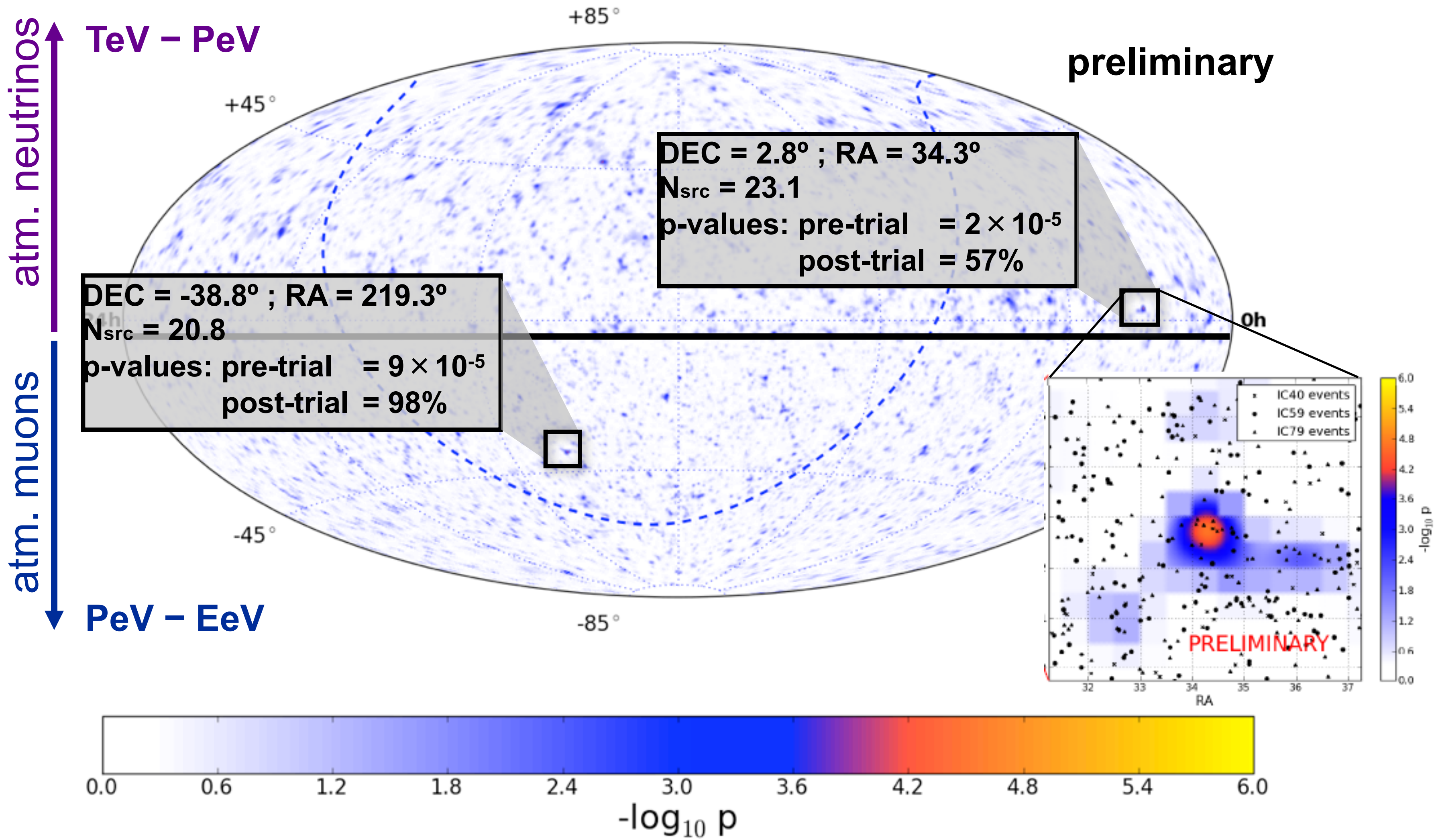
IceCube: Significance map (IC40+59+79)



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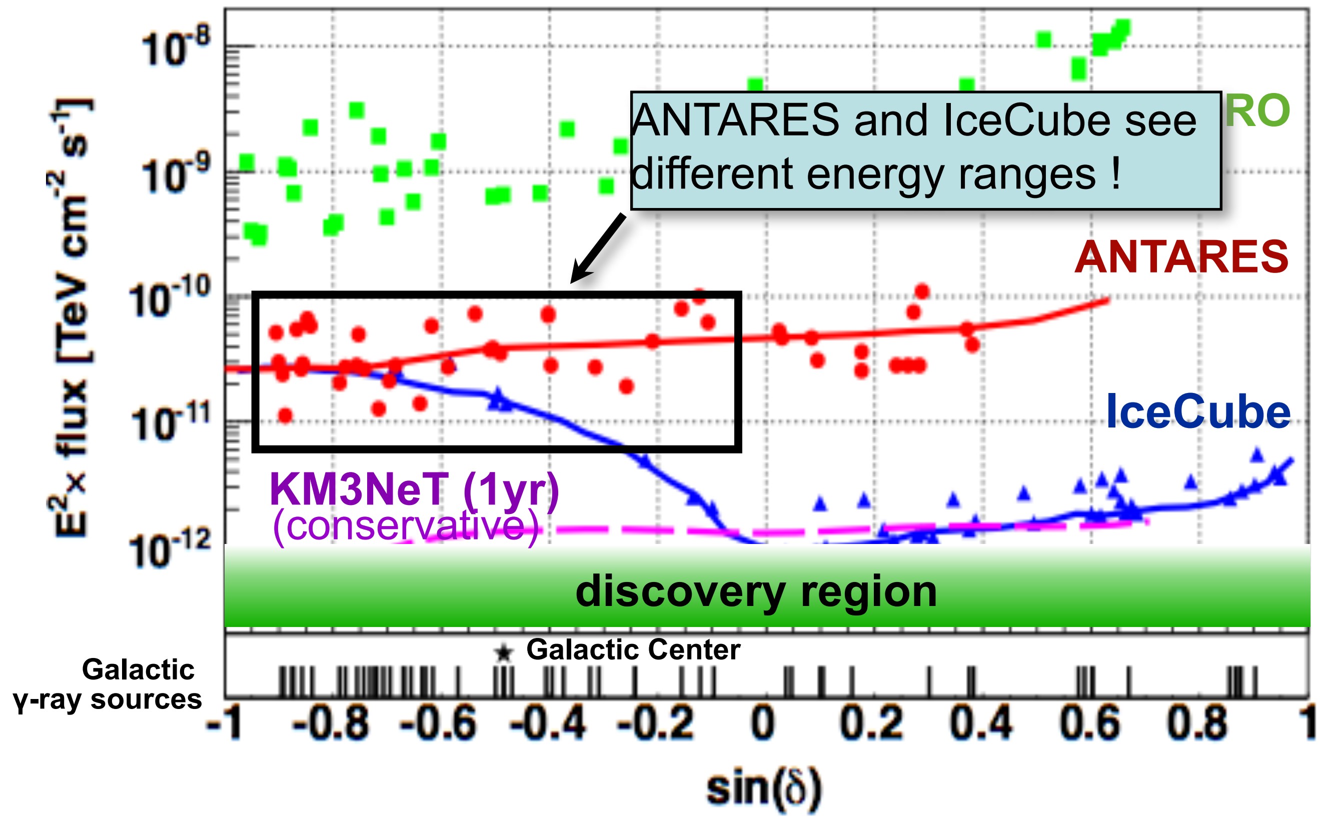
IceCube: Sensitivities & limits (IC40+59+79)

90% CL sensitivity / upper limits for E^{-2} spectrum



Predictions
Halzen, **Kappes**, O'Murchadha (2008)
Kappes, Hinton, Stegmann, Aharonian (2006)
Kistler, Beacom (2006)
. . .

- Expected improvements: Statistics, reconstruction quality
- Attention: IceCube for Southern hemisphere (sin(δ)<0) not sensitive to neutrino fluxes with cutoff at 10…100TeV (typical Galactic sources)
- Full access to Galactic sources only from Northern detector

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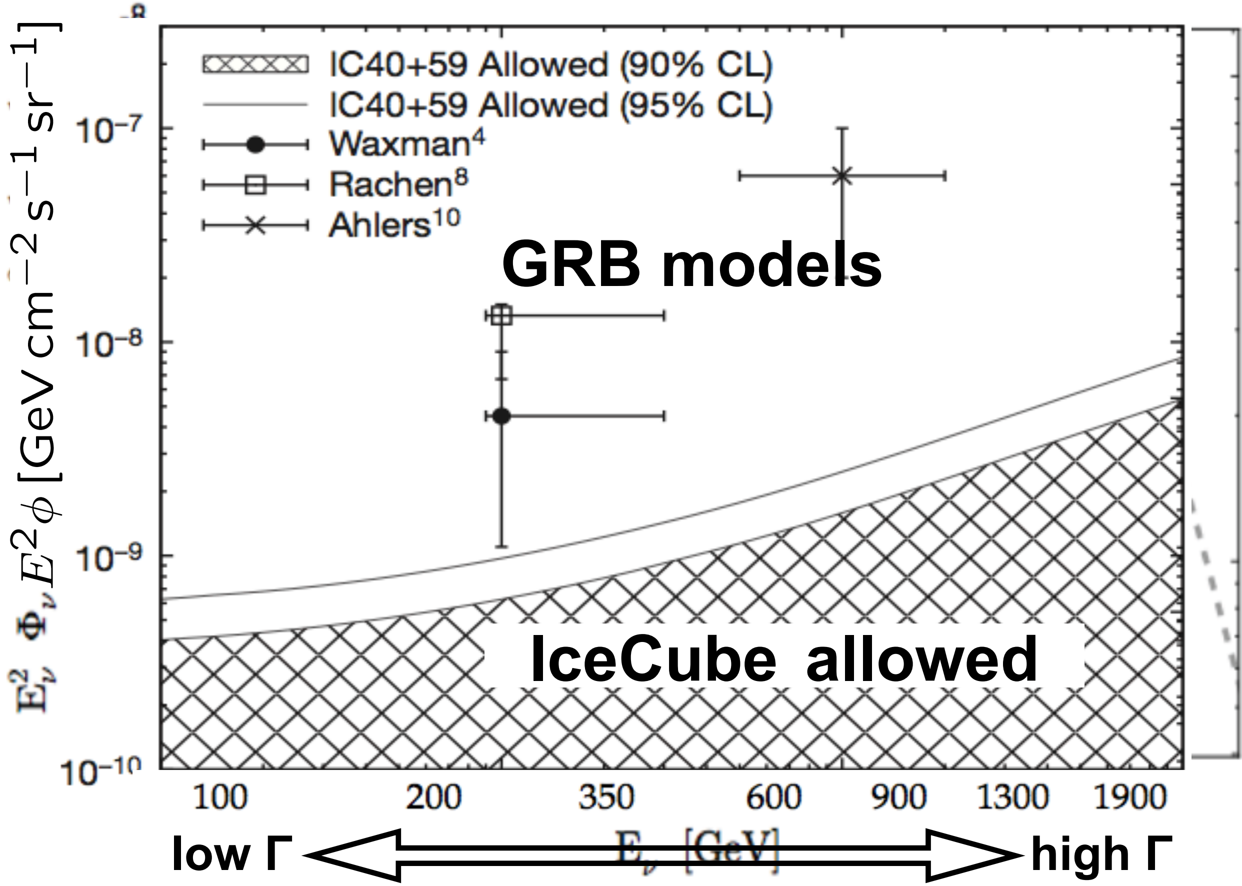
IceCube: Neutrinos from GRBs (IC40+59)

- Search for neutrinos from observed GRBs
- Increased sensitivity due to reduced time window
- 117+98 GRBs in Northern sky for IC40 and IC59 (plus 85 Southern GRBs)
- 0 neutrinos observed
- Severely constrains models

Nature 484 (2012) 351



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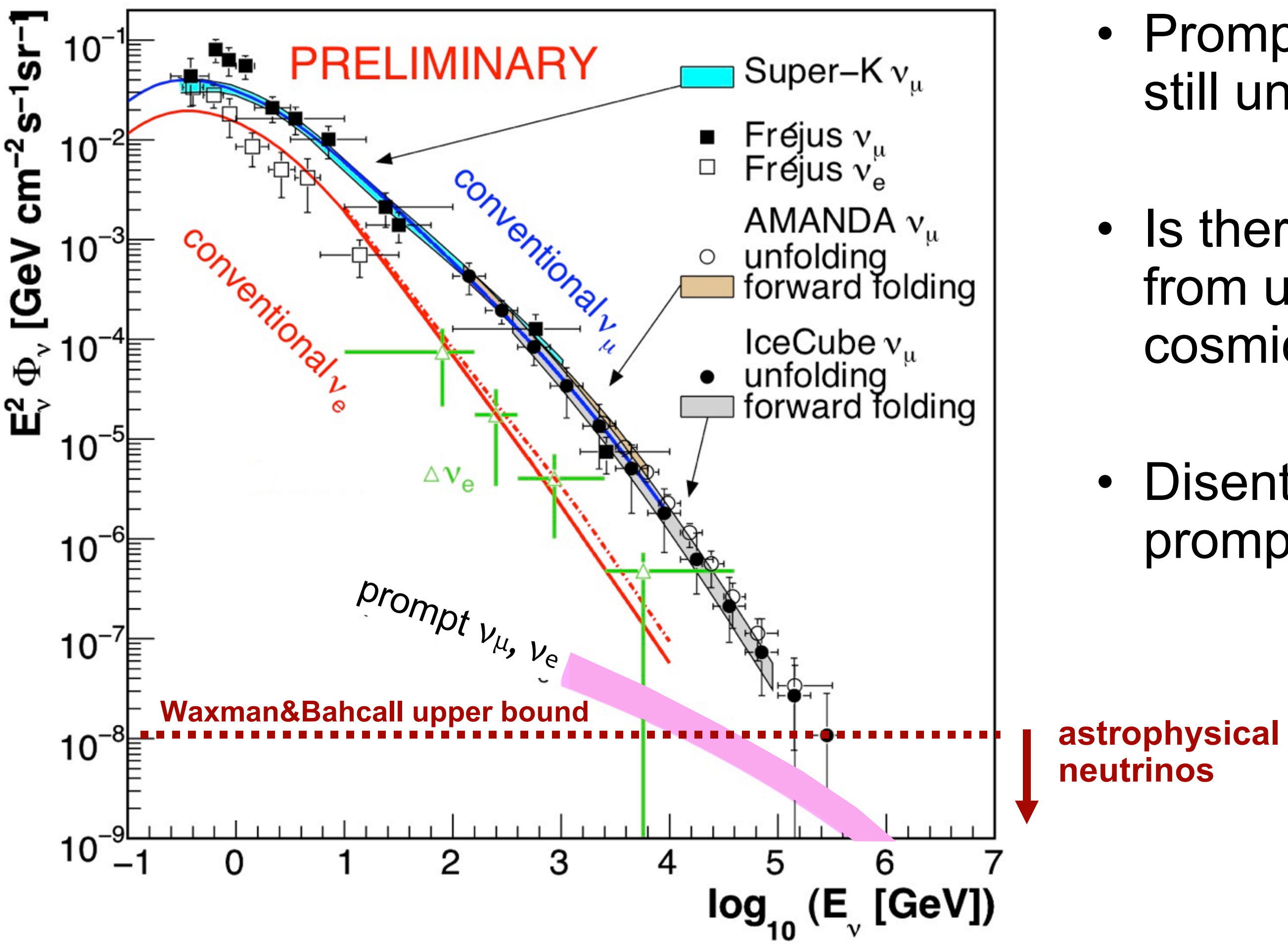
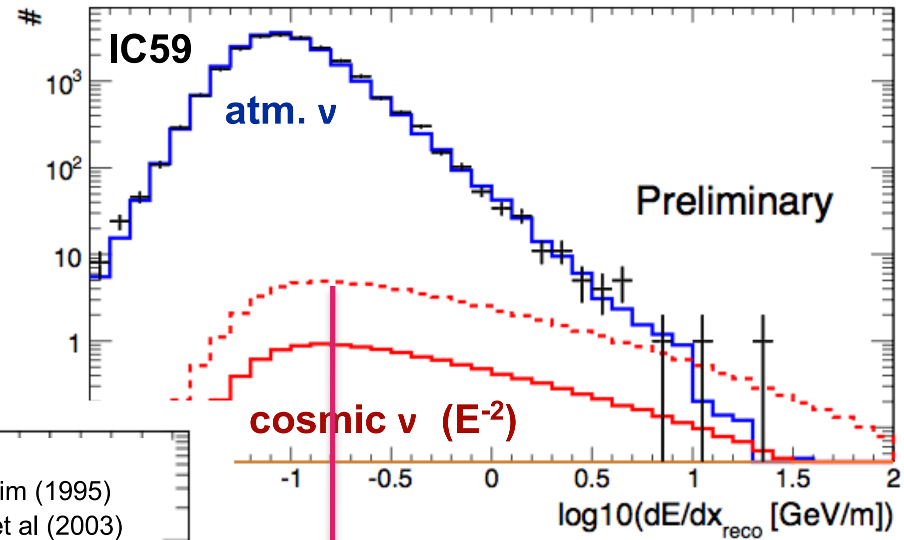
IceCube: Diffuse neutrino flux

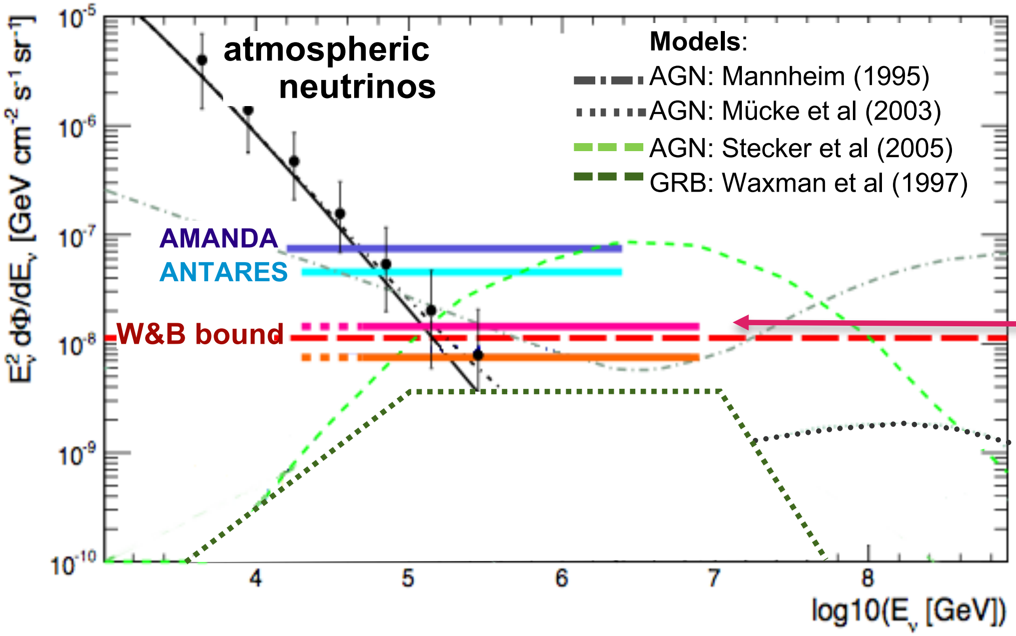


- Prompt component still unmeasured
- Is there a diffuse flux from unresolved cosmic sources?
- Disentangling cosmic and prompt fluxes challenging

Atmospheric muon neutrinos (IC59)

- Search for excess in high-energy tail
- Observed spectrum slightly harder than predicted
  → Limit > sensitivity





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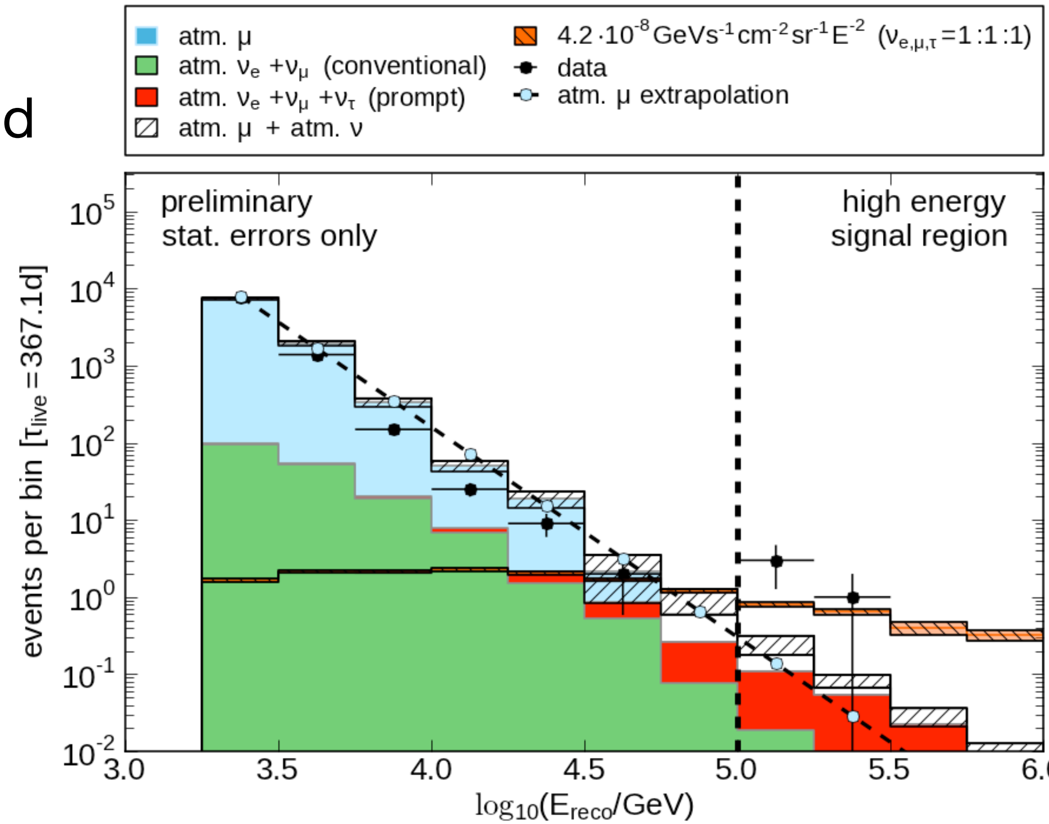
Searching for a high-energy ν_e excess

$\nu_e N \rightarrow eX$:

- all energy inside detector
- low atmospheric background
- cascade channel good for excess search

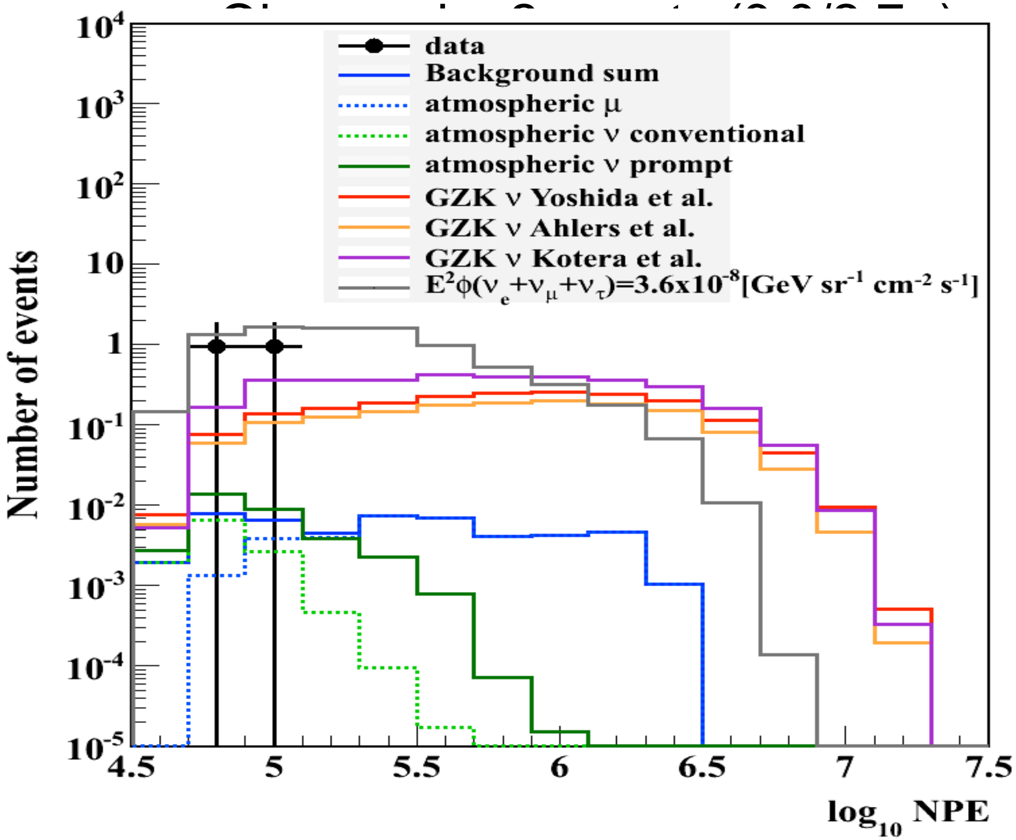


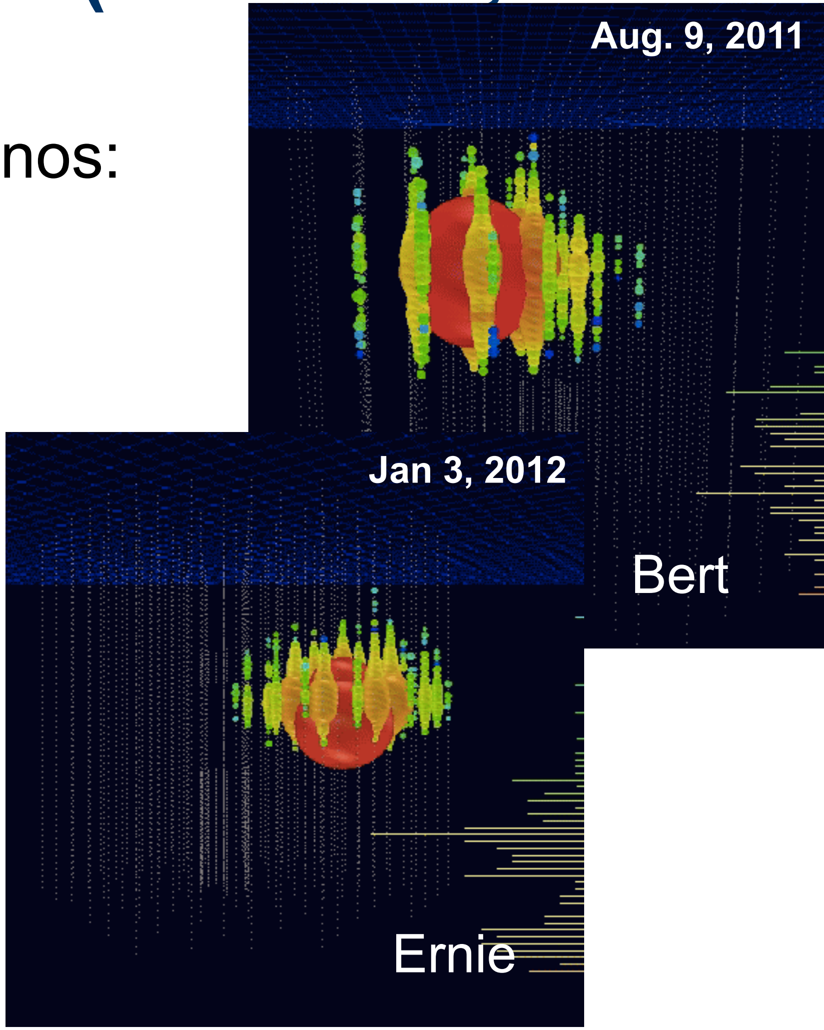
IC40 cascade analysis:

- 3 events found >100 TeV
- Estimated background: (0.4+prompt) events
- Significance 2.4σ

Cosmogenic neutrinos (IC79+86-I, 670 days)

- Optimized cuts for UHE neutrinos:
  - Expected background = 0.05/0.08 (without/with prompt)





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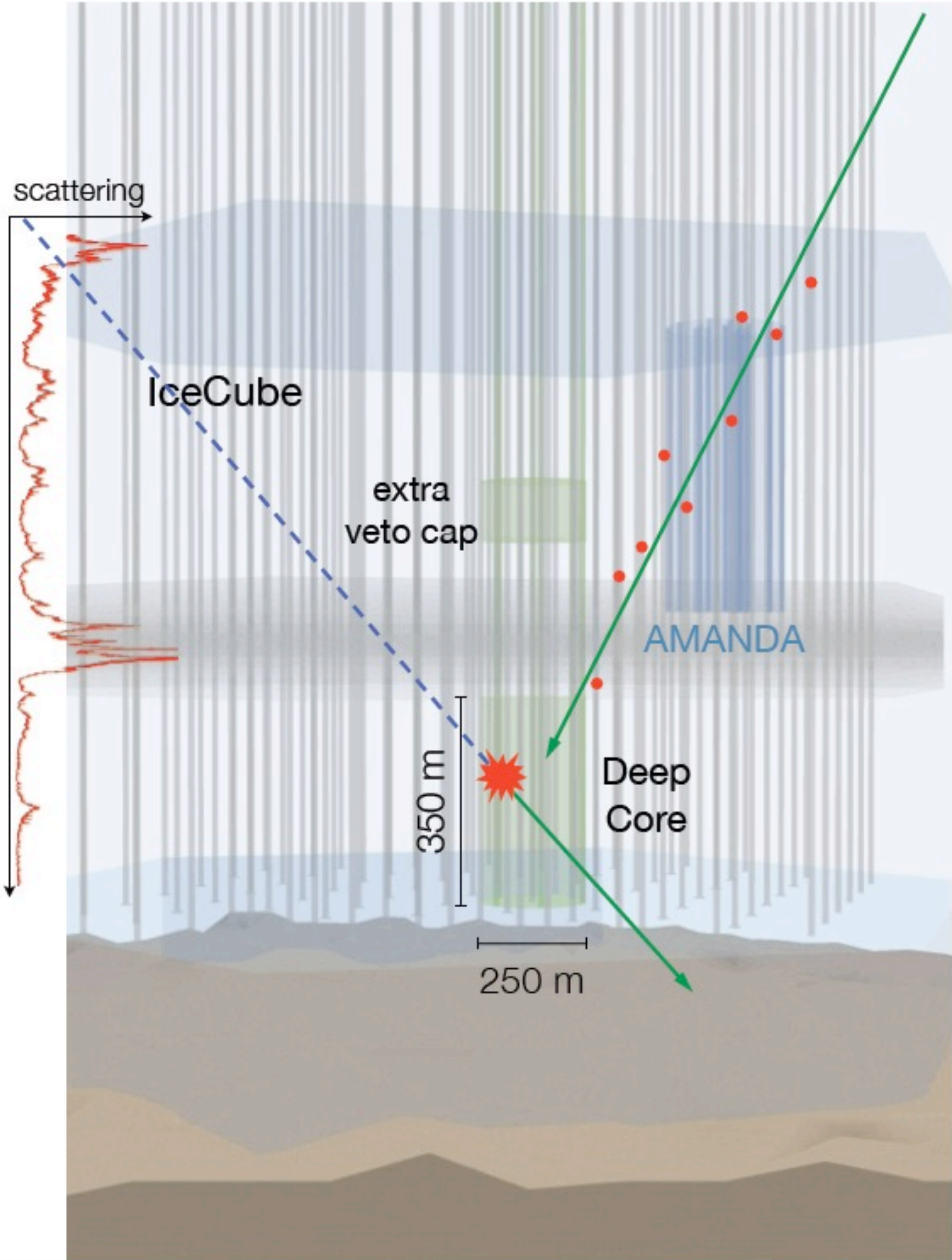
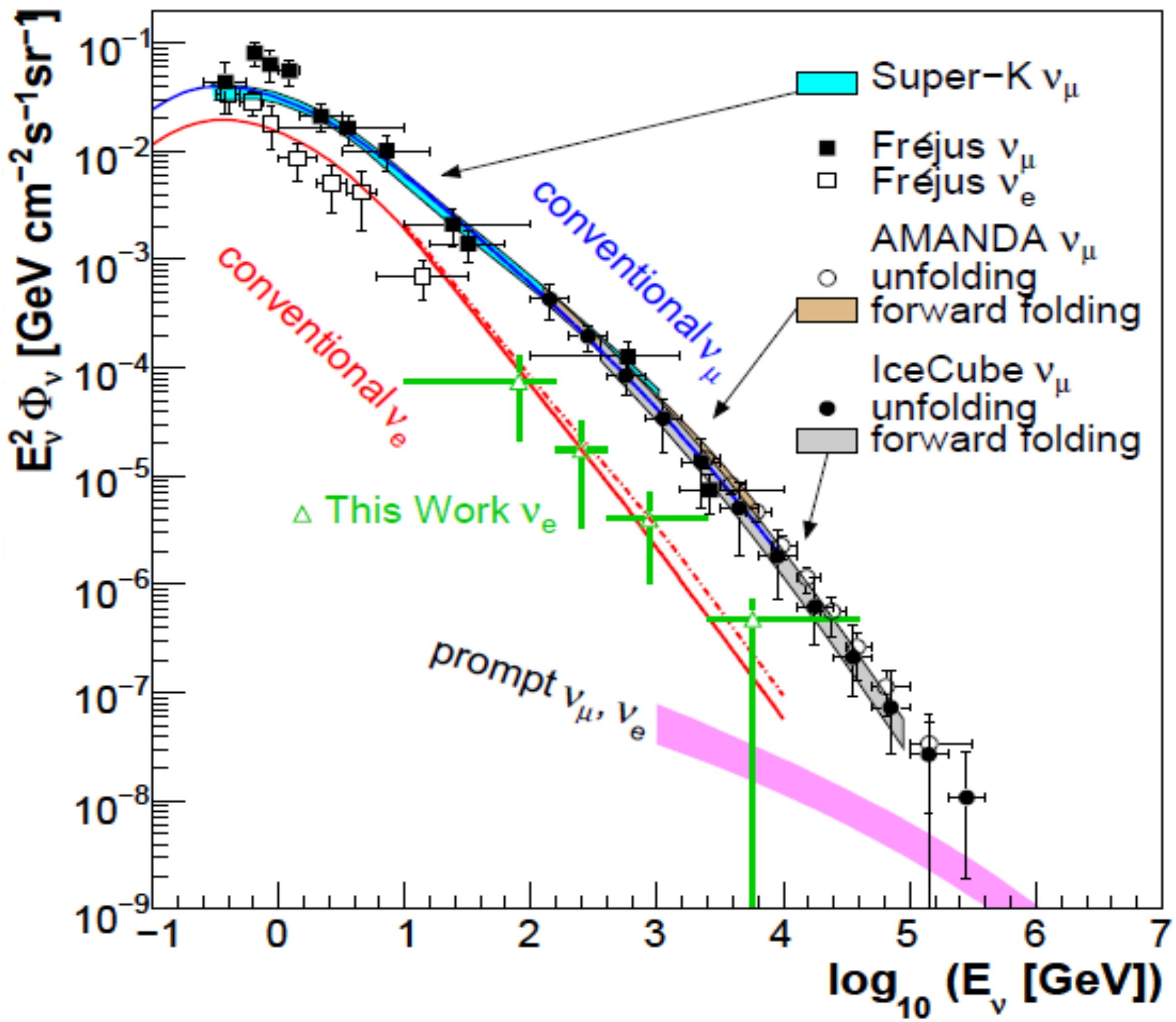
Deep Core

- 8 extra strings +
  12 standard strings
  in clearest ice
  (~5 times higher
  photocathode density)
- Photomultipliers
  with high quantum
  efficiency
- Rest of IceCube provides
  active veto against
  penetrating muons
- Extends accessible energy
  range down to 10 GeV



IceCube: A first Deep Core result …

- Identification of cascades, mainly from
  $\nu_e + N \rightarrow e + X$
  $\nu_x + N \rightarrow \nu_x + X$
- Main background:
  $\nu_\mu + N \rightarrow \mu + X$
  with short μ track
- Very difficult in IceCube
- Success in Deep Core! (see arXiv:1201.0801)



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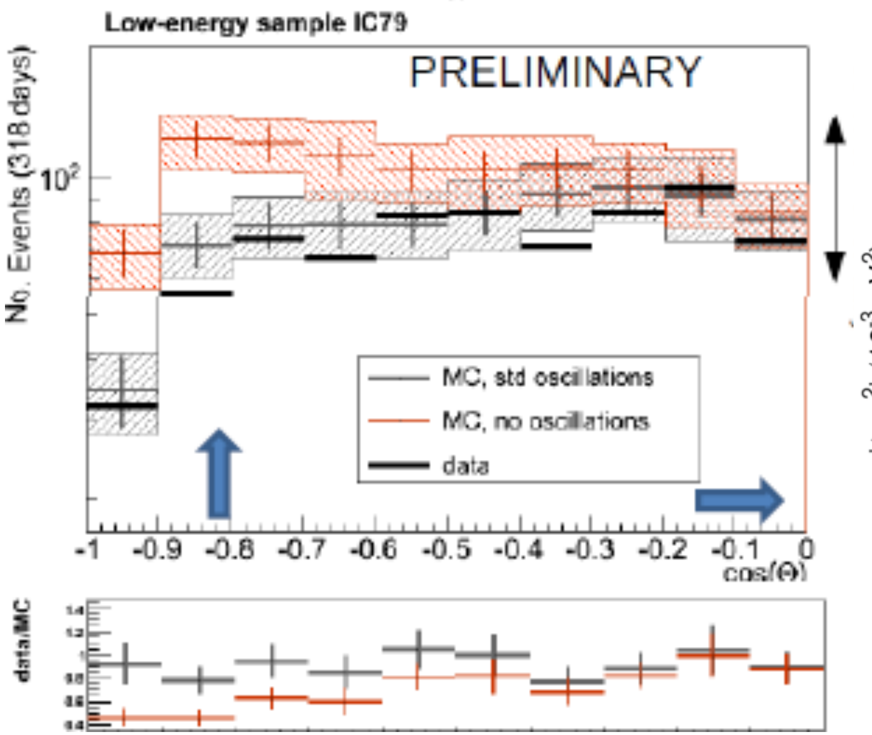
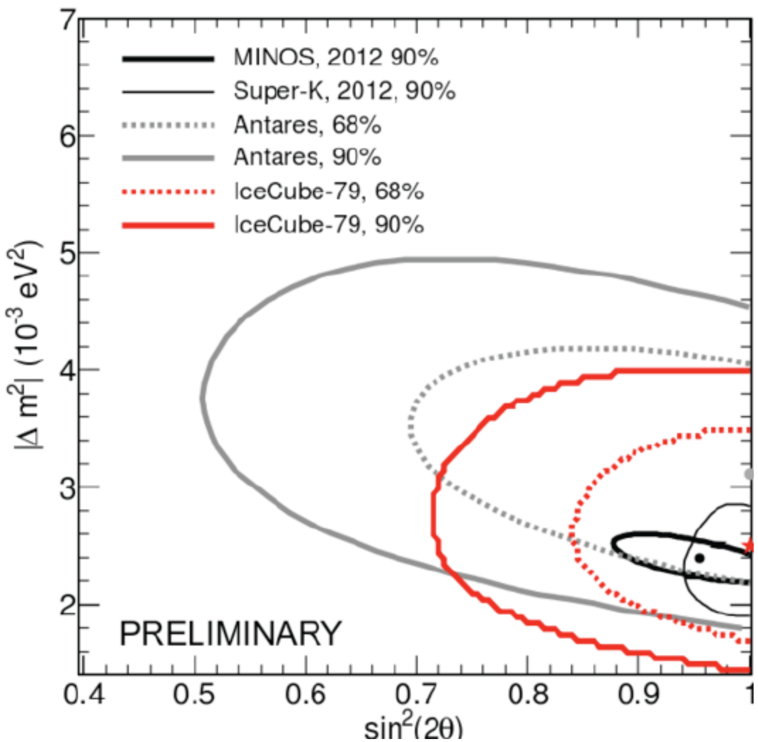
… and much more since then!

- Search for dark matter annihilation in Sun (arXiv:1212.4097)
- Atmospheric neutrino oscillations (arXiv:1301.4339)

χ^2/ndf = 41/20 (no oscillations) χ^2/ndf = 11/20 (std. oscillations)





→ no-oscillation hypothesis ruled out by 5.8σ

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IceCube: Further results

- Search for dark-matter annihilations in the Sun (arXiv:1212.4097, Phys.Rev.D85(2012)042002) and in the Galactic Centre (arXiv:1210.3557)
- Search for high-energy Galactic neutrinos (Astrophys.J.763(2013)33)
- Neutrinos from Crab nebula (Astrophys.J.745(2012)45))
- Search for UHE tau neutrinos (Phys.Rev.D86(2012)022005)
- Search for Galactic PeV gamma rays (arXiv:1210.7992)
- Cosmic ray anisotropy with IceTop (Astrophys.J.765(2013)55) and IceCube (Astrophys.J.746(2012)118)
- Lateral distribution of μ's in cosmic ray events (Phys.Rev.D87(2013)012005)
- Cosmic ray composition and energy spectrum (Astropart.Phys.42(2013)15 and arXiv:1202.3039)
- Search for relativistic magnetic monopoles (Phys.Rev.D87(2013)022001)
- …

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KM3NeT

KM3NeT:
Erlangen, Tübingen, Würzburg
See:
T78, T104, T109, T110

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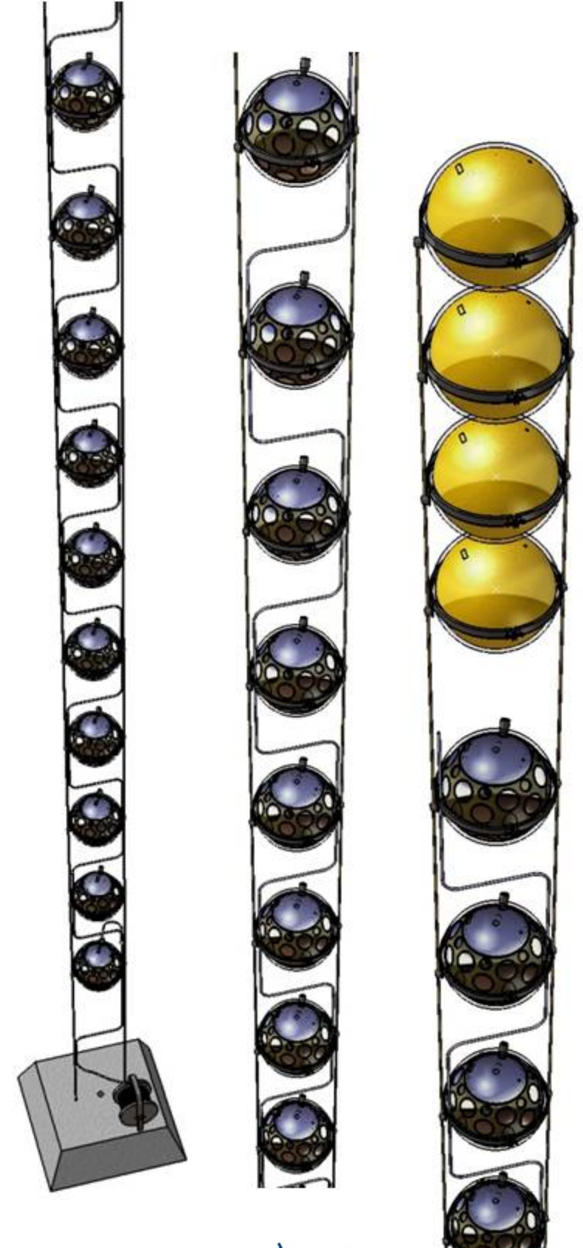
The KM3NeT project

- Multi-km^3 NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Nodes for earth/sea science instrumentation
- Central physics goals (by priority):
  - Galactic neutrino "point" sources (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- Decisions taken:
  - Technology: Strings with multi-PMT optical modules
  - Multi-site installation (France, Greece, Italy)
  - 5 building blocks of ~120 strings each
- Collaboration established
- Next steps
  - prototyping and construction (~40 M€ available for first phase)

Detection units: Strings

- Mooring line:
  - Buoy (empty glass spheres, net buoyancy 2250N)
  - 2 Dyneema ropes (4 mm diameter)
  - 18 storeys (one OM each), 30-36m distance, 100m anchor-first storey
- Electro-optical backbone:
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - fibres and copper wires
  - At each storey: 1 fibre+2 wires
  - Break out box with fuses at each storey: One single pressure transition



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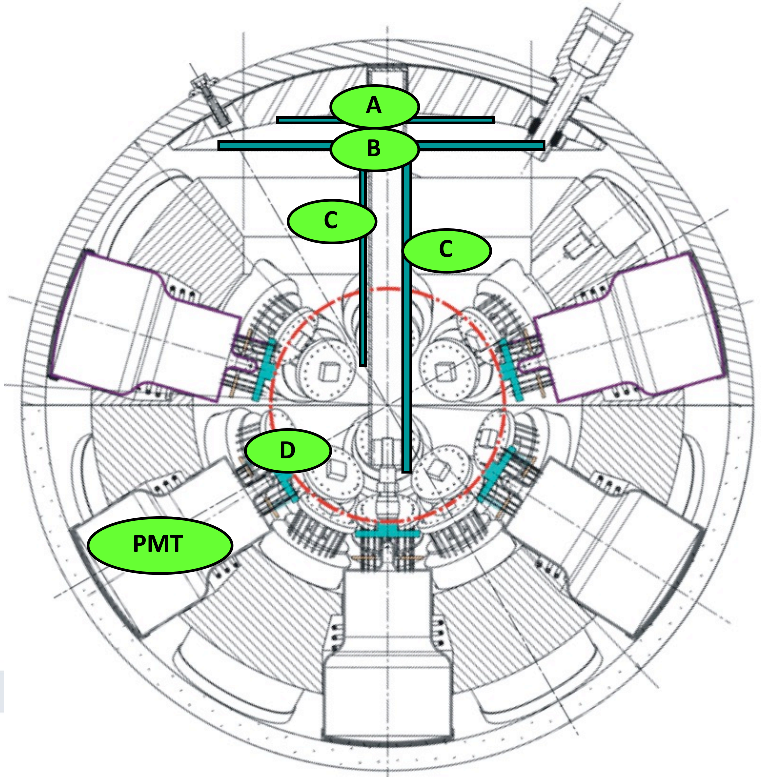
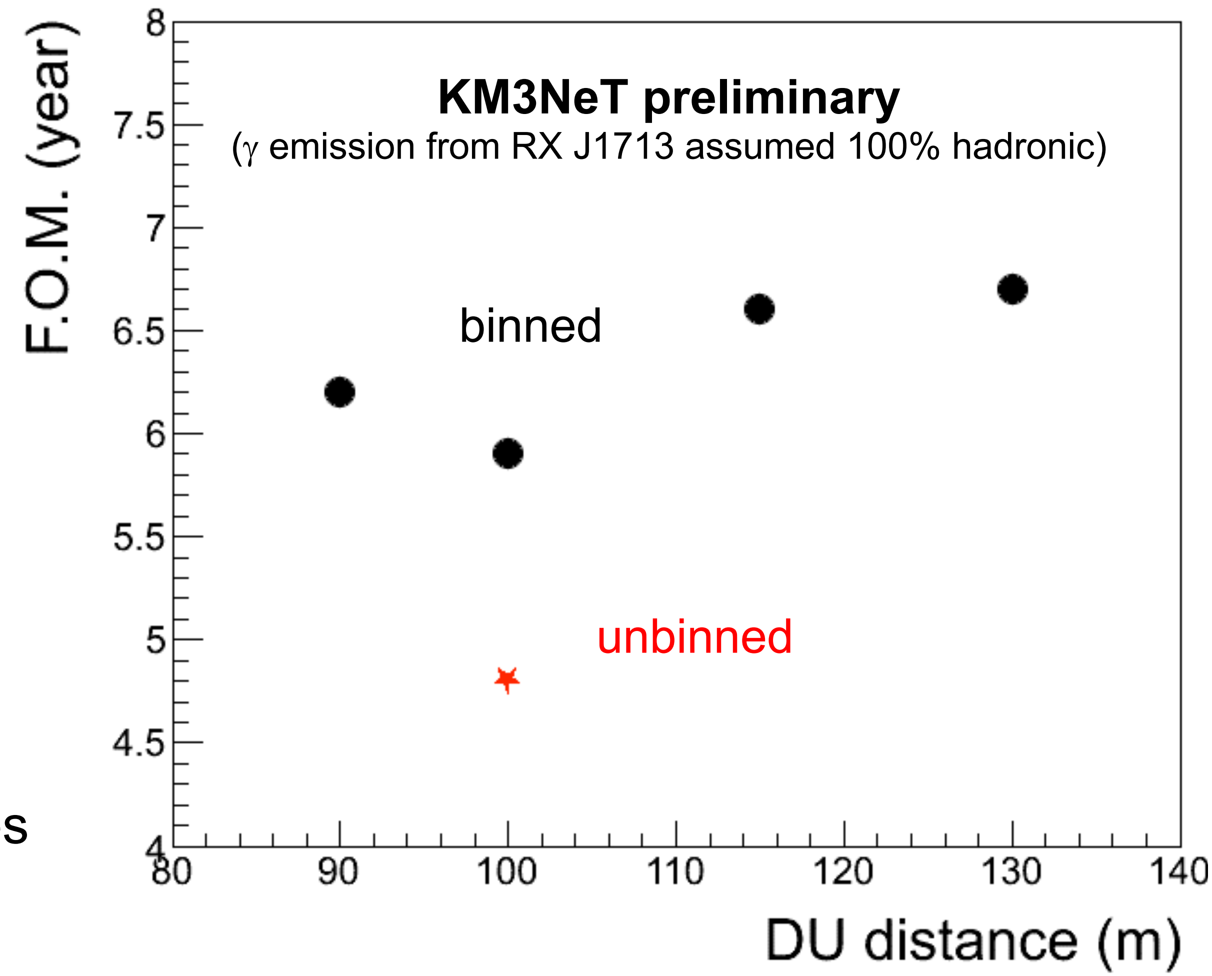
OM with many small PMTs

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10” PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by compressible foam core
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- 2mm optical gel
- Advantages:
  - increased photocathode area
  - 1-vs-2 photo-electron separation
    → better sensitivity to coincidences
  - directionality



RX J1713: A prime candidate source

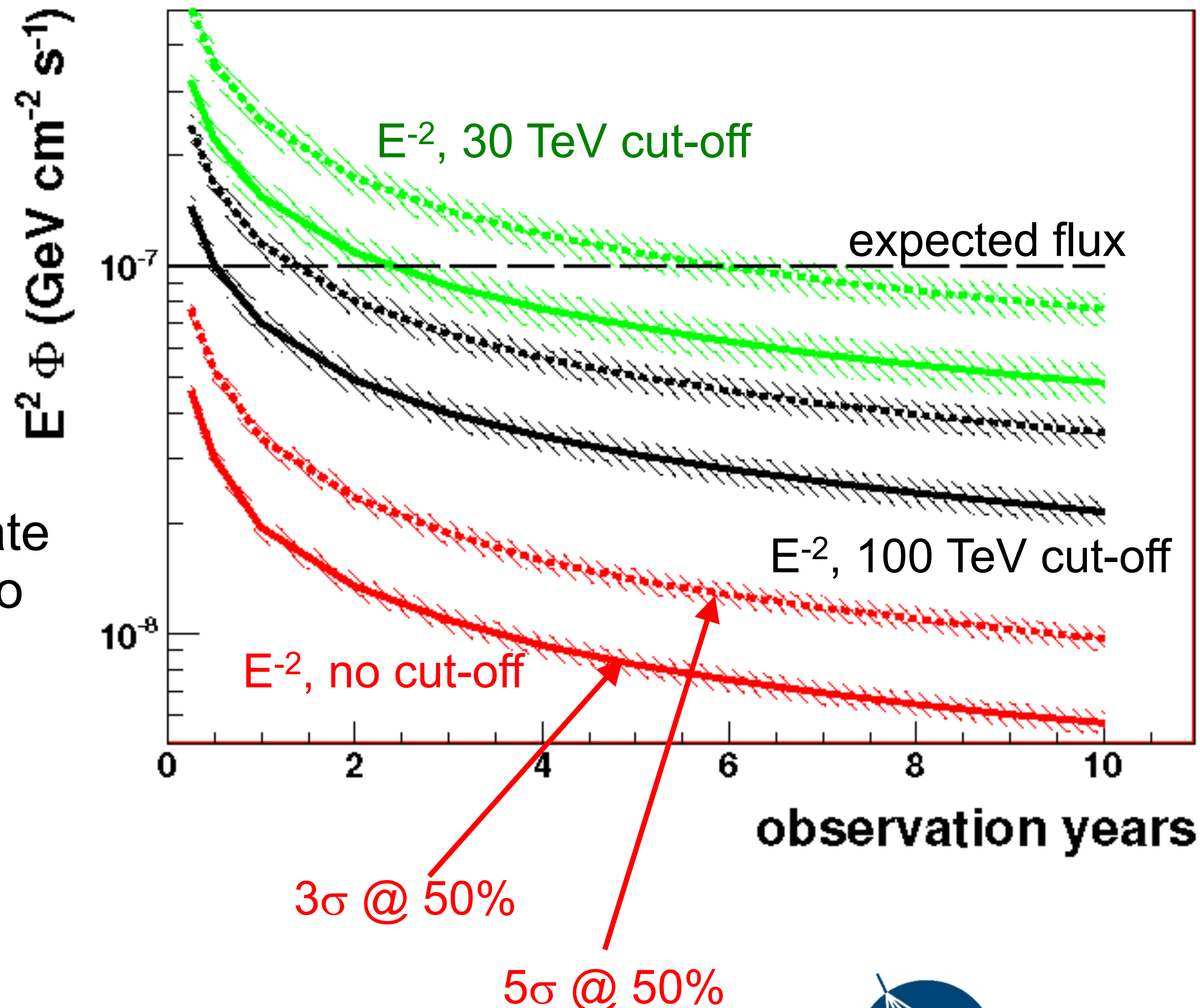
- Figure of merit (F.o.M.): time to make an observation at 5σ with 50% probability
- KM3NeT analysis very conservative; ~20% improvement by unbinned analysis
- Clear (but flat) optimum in horizontal distance between DUs
- Further candidate sources with similar or better discovery chances



The Fermi bubbles

- Two extended regions above/below centre of Galactic plane
- Fermi detected hard γ emission (E^{-2}) up to 100 GeV
- Origin and acceleration mechanisms under debate – if hadronic, hot neutrino source candidate
- Could be first source detected by KM3NeT

Astropart.Phys.42(2013)7



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Towards exploring the low-energy regime: PINGU and ORCA

PINGU:
Aachen, Bonn, Bochum, DESY,
Dortmund, Erlangen, Mainz,
TU München, Wuppertal
See:
T89, T104, T109,

ORCA:
Erlangen, Tübingen, Würzburg
See:
T104

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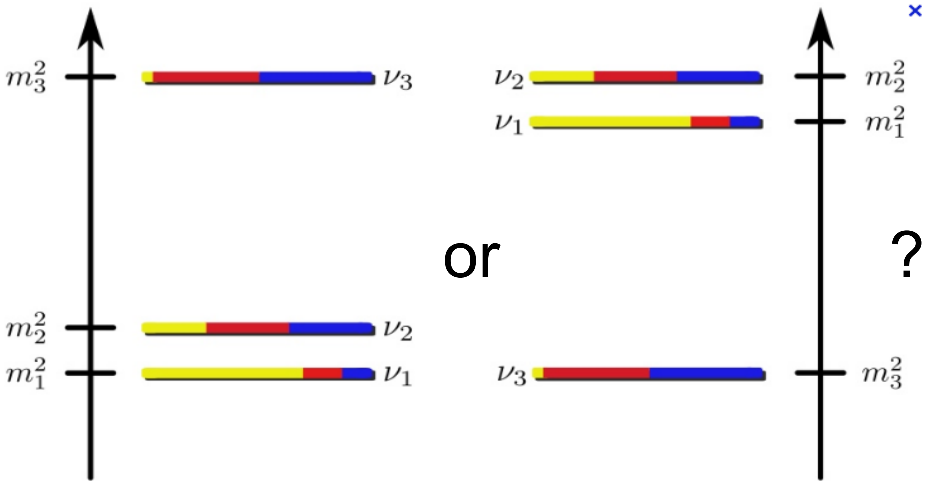
Why low energies?

- Increased sensitivity for indirect dark matter searches
- Investigate oscillations and neutrino flavour composition of atmospheric neutrinos

And in particular:

- Measure the neutrino mass hierarchy (sign of Δm^2_{23})
  - Matter effect for neutrino propagation through Earth "just right" for energies $E_\nu \sim 3 \ldots 15$ GeV
  - Discussion initiated by paper by Akhmedov, Razzaque and Smirnov (JHEP 02 (2013) 082)



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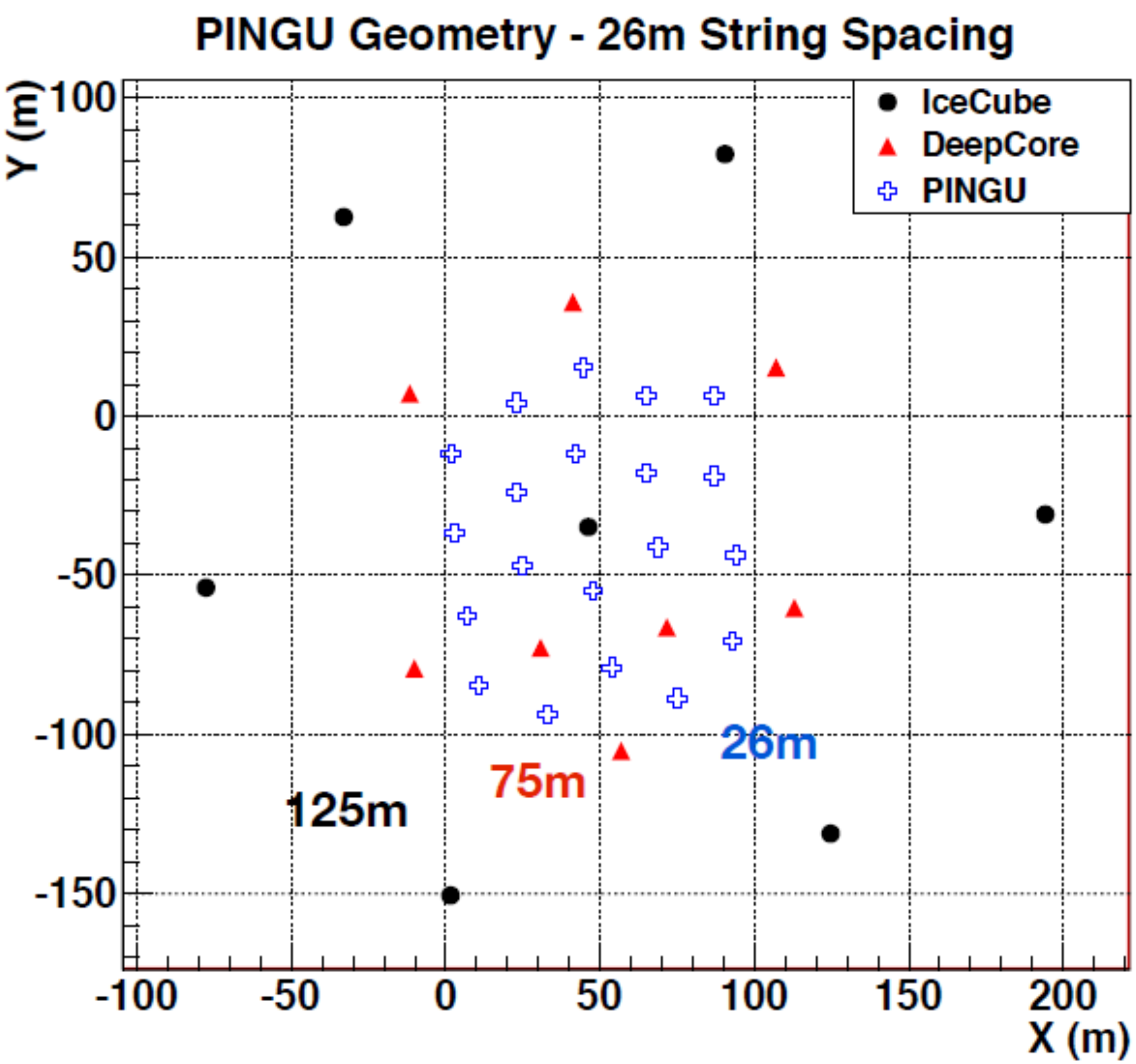
PINGU: Dense instrumentation in IceCube

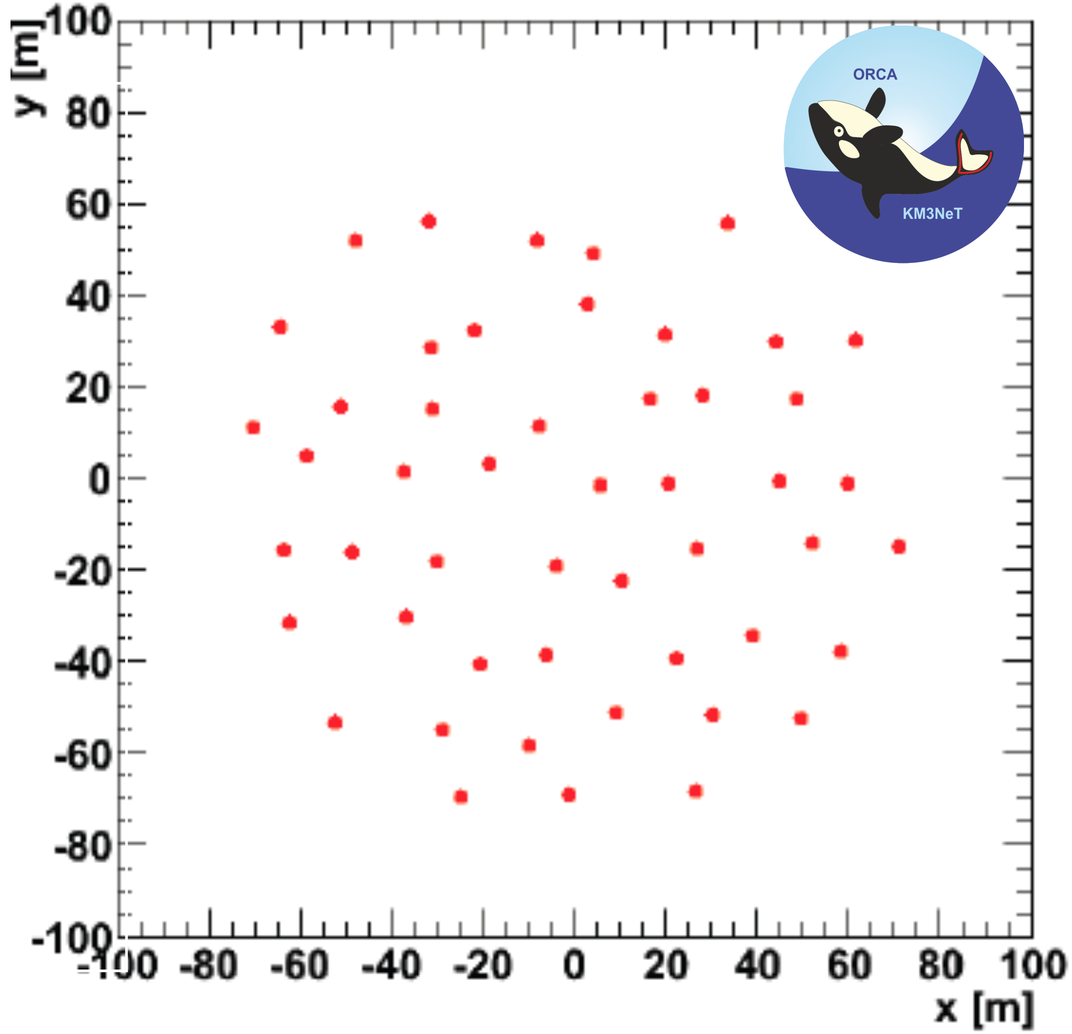
- Add ~20 (?) strings in Deep Core region, each with 60 OMs, 6m vertical distance
- Denser configurations also under investigation
- Instrumented volume ~5-6 Mton
- Expected energy threshold at ~1 GeV
- R&D opportunity for future developments
- IceCube plus further groups



ORCA: A case study for KM3NeT

- Investigated: 50 strings, 20 OMs each
- KM3NeT design: 31 3-inch PMTs / OM
- 20 m horizontal distance
- 6 m vertical distance
- Instrumented volume: 1.75 Mton water

Note; This is not a proposal but just a (scalable) example configuration



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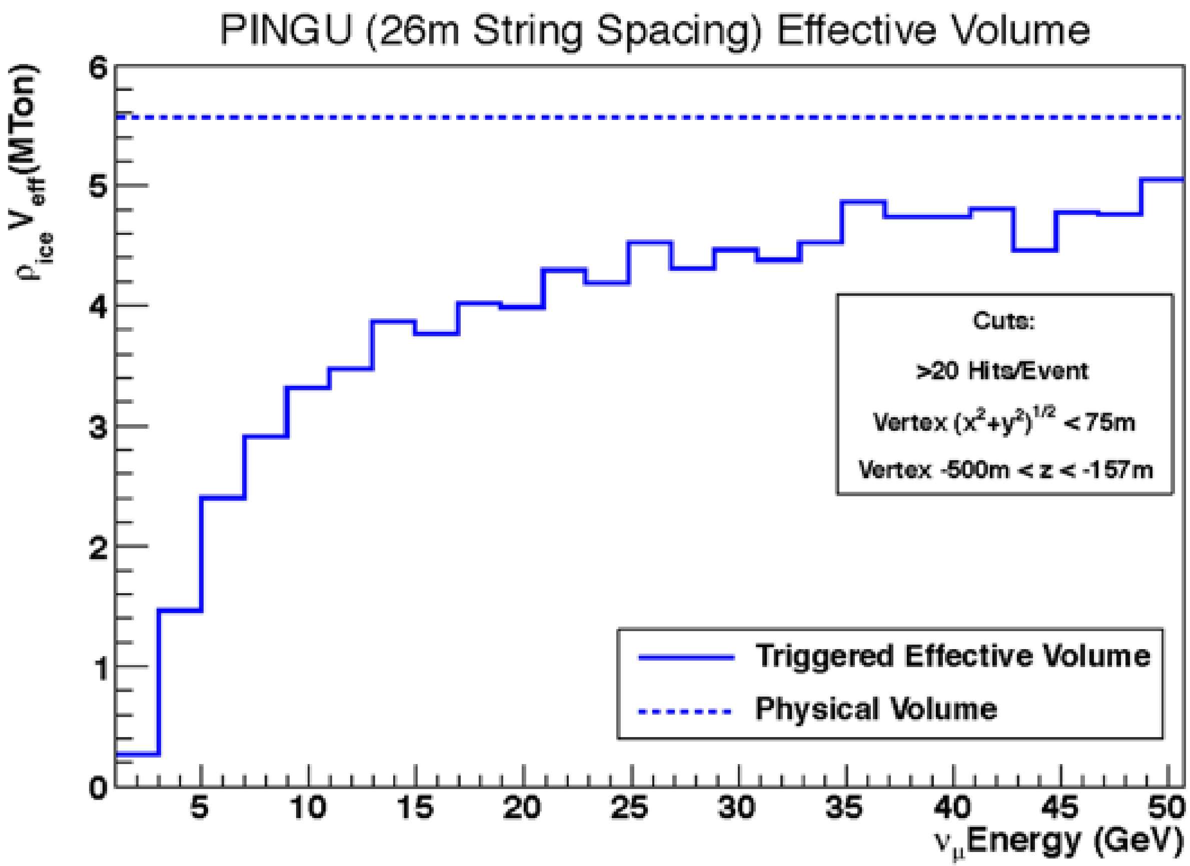
Effective volume ad efficiencies

- Require 20 hits inside PINGU volume
- Constrain generation vertex
- Gives rough estimate of reconstructable events
- Quality cuts and reconstruction efficiency not included
- Similar efficiency for ORCA



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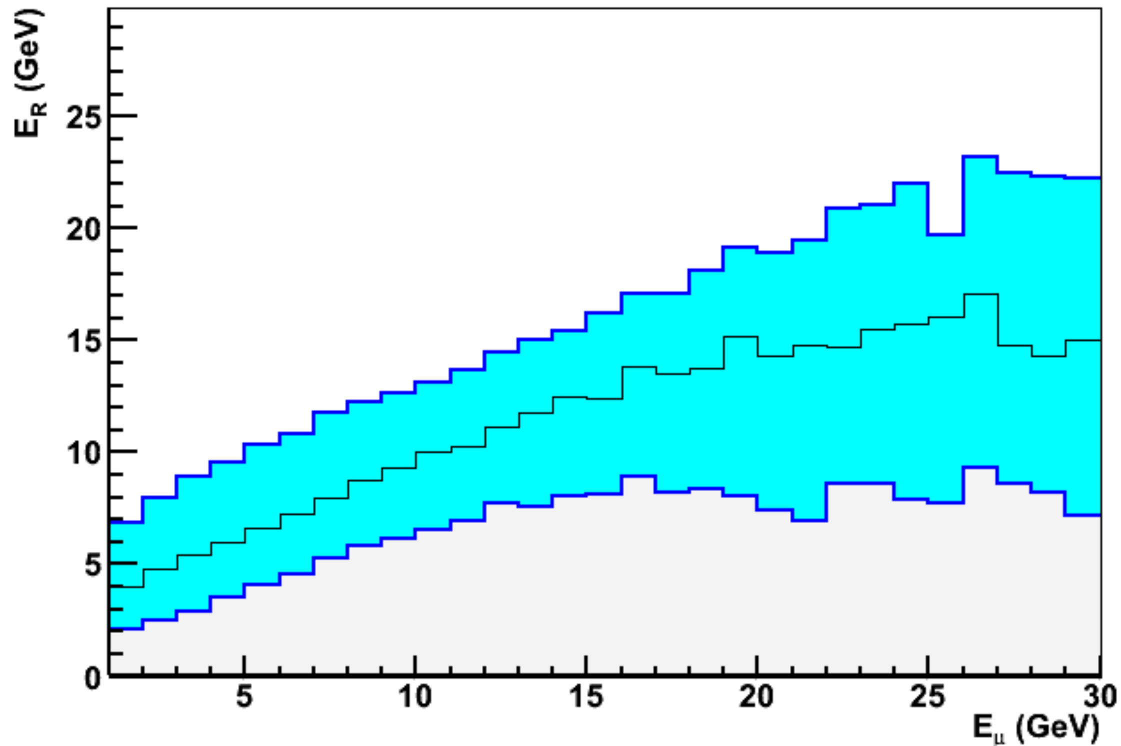
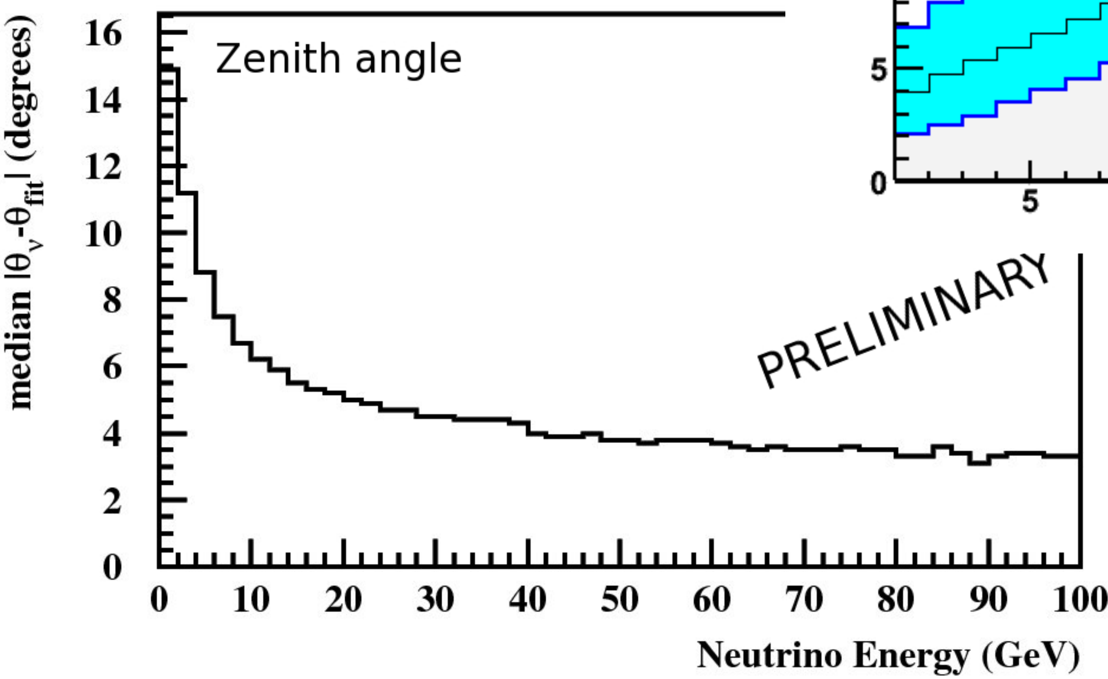
ORCA energy and zenith resolutions

- E_μ reconstructed from μ track length
- Shaded region: 16% and 84% quantiles as function of E_μ^{true}

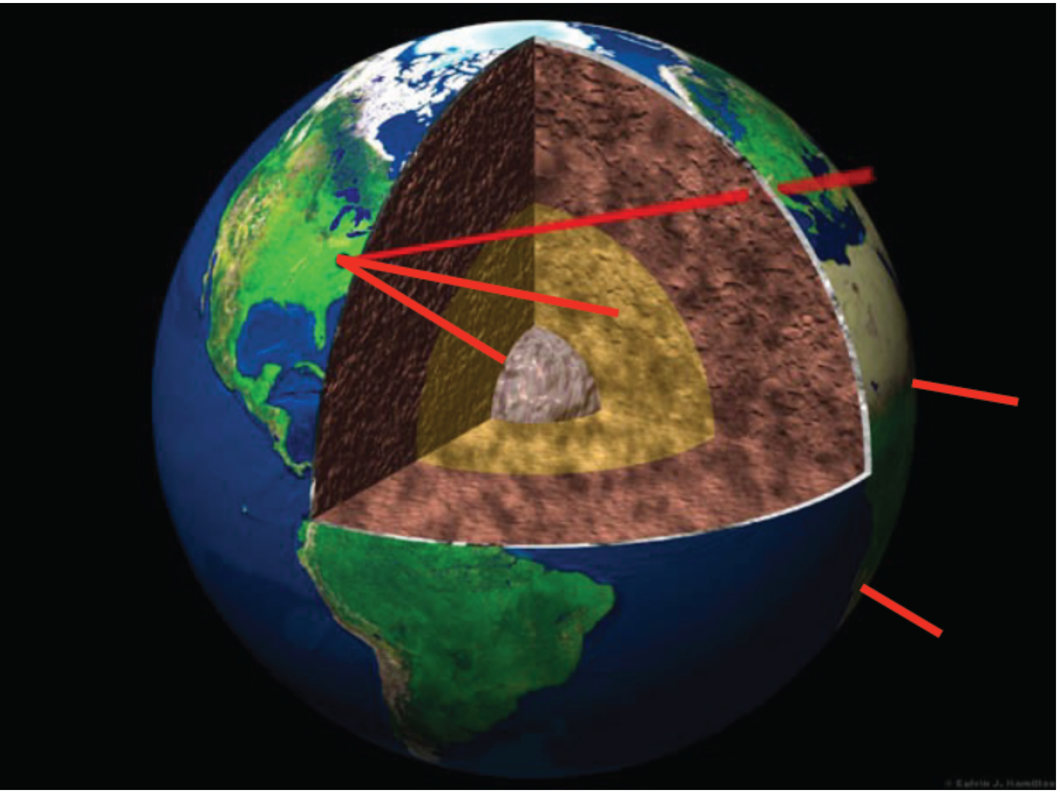


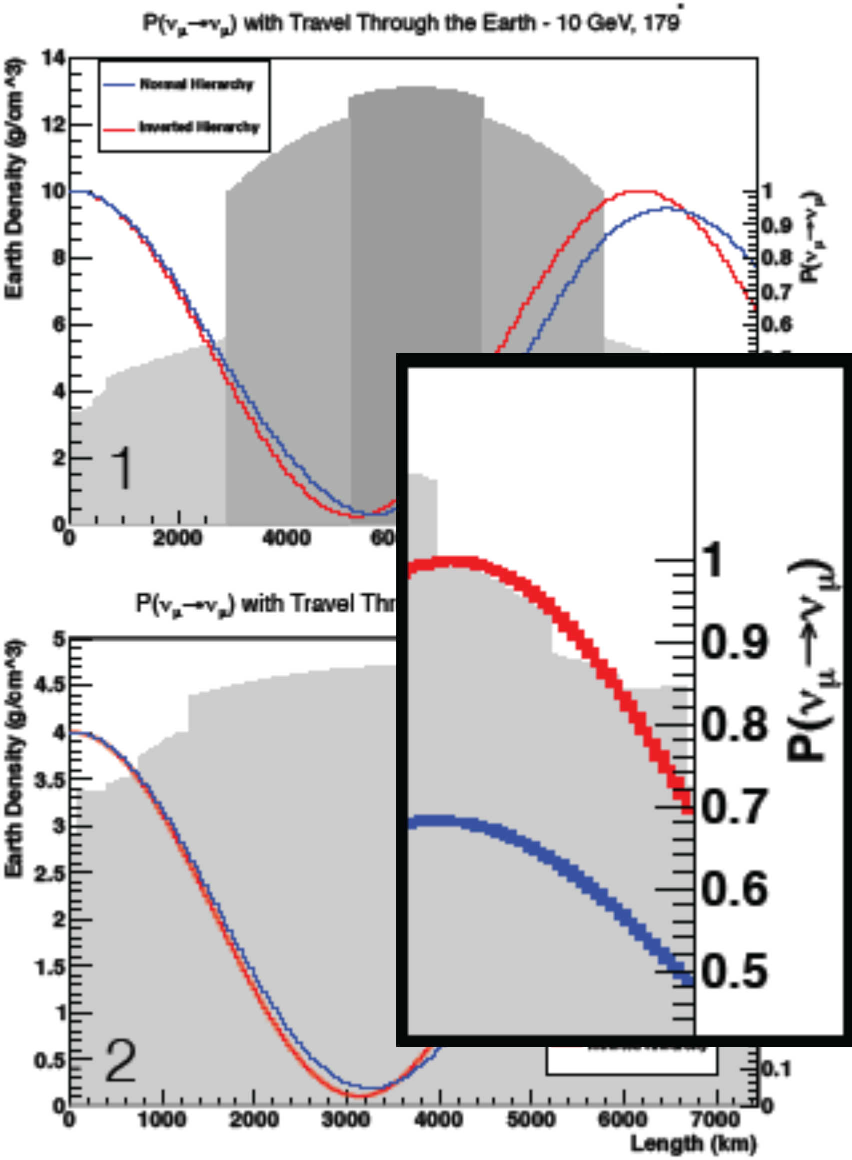


- Median of zenith angle difference $\nu - \text{rec. } \mu$

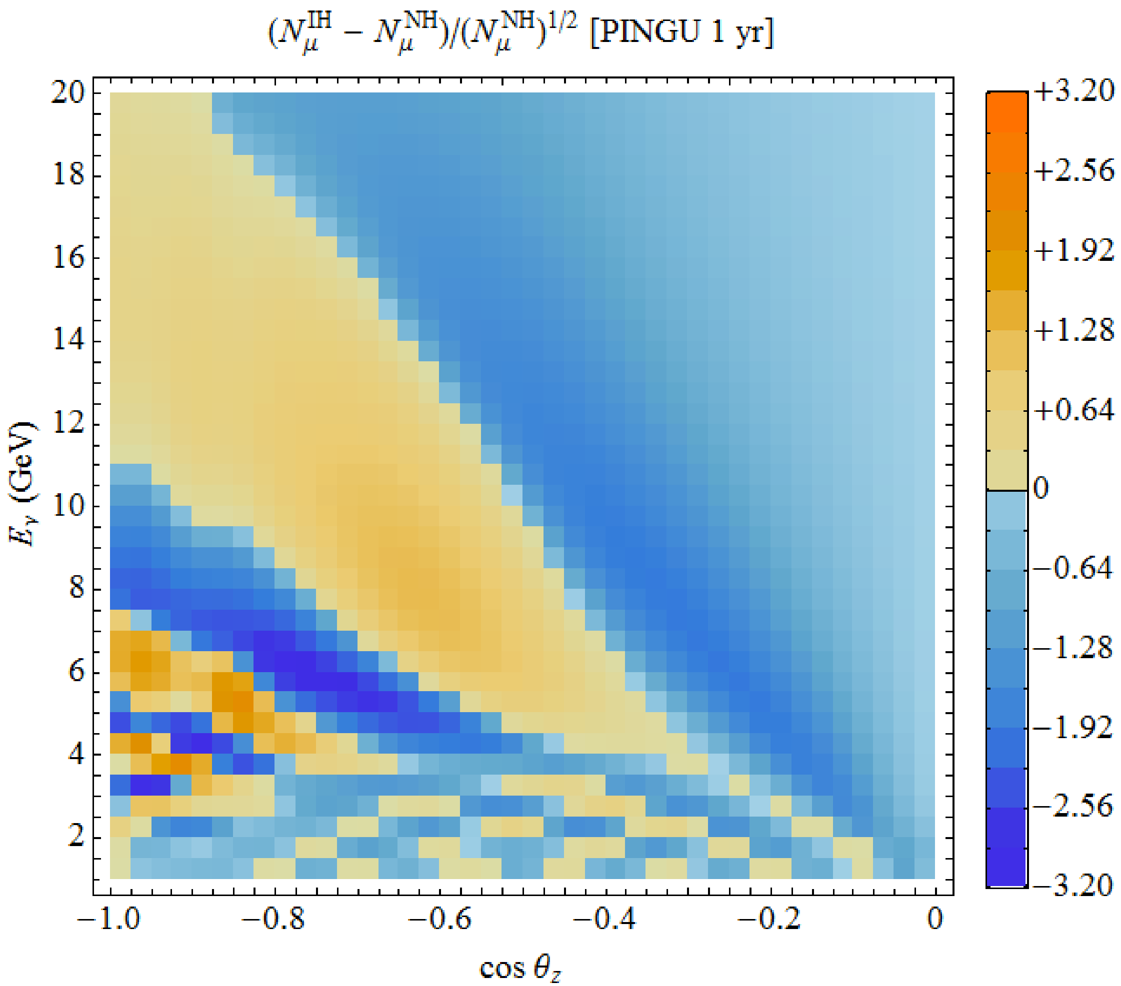
Neutrino oscillations in Earth

- Earth density 4-13 g/cm³
- Relevant: $E_\nu \sim 3\text{–}10\,\text{GeV}$





The Akhmedov/Razzaque/Smirnov paper (1)



JHEP 1302 (2013) 082; arXiv 1205.7071

- Significance for perfect resolution:

$$S_{\mathrm{tot}} = \sqrt{\sum_{\mathrm{bins}} \frac{(N_i^{\mathrm{NH}} - N_i^{\mathrm{IH}})^2}{\sigma_i}}$$

with $\sigma_i = N_i^{\mathrm{NH}} + f(N_i^{\mathrm{NH}})^2$

- Uncorrelated system. errors assumed (f)
- Result (5 years):

$f = 0.00 : \quad S_{\mathrm{tot}} = 45.5\sigma$

$f = 0.05 : \quad S_{\mathrm{tot}} = 28.9\sigma$

$f = 0.10 : \quad S_{\mathrm{tot}} = 18.8\sigma$

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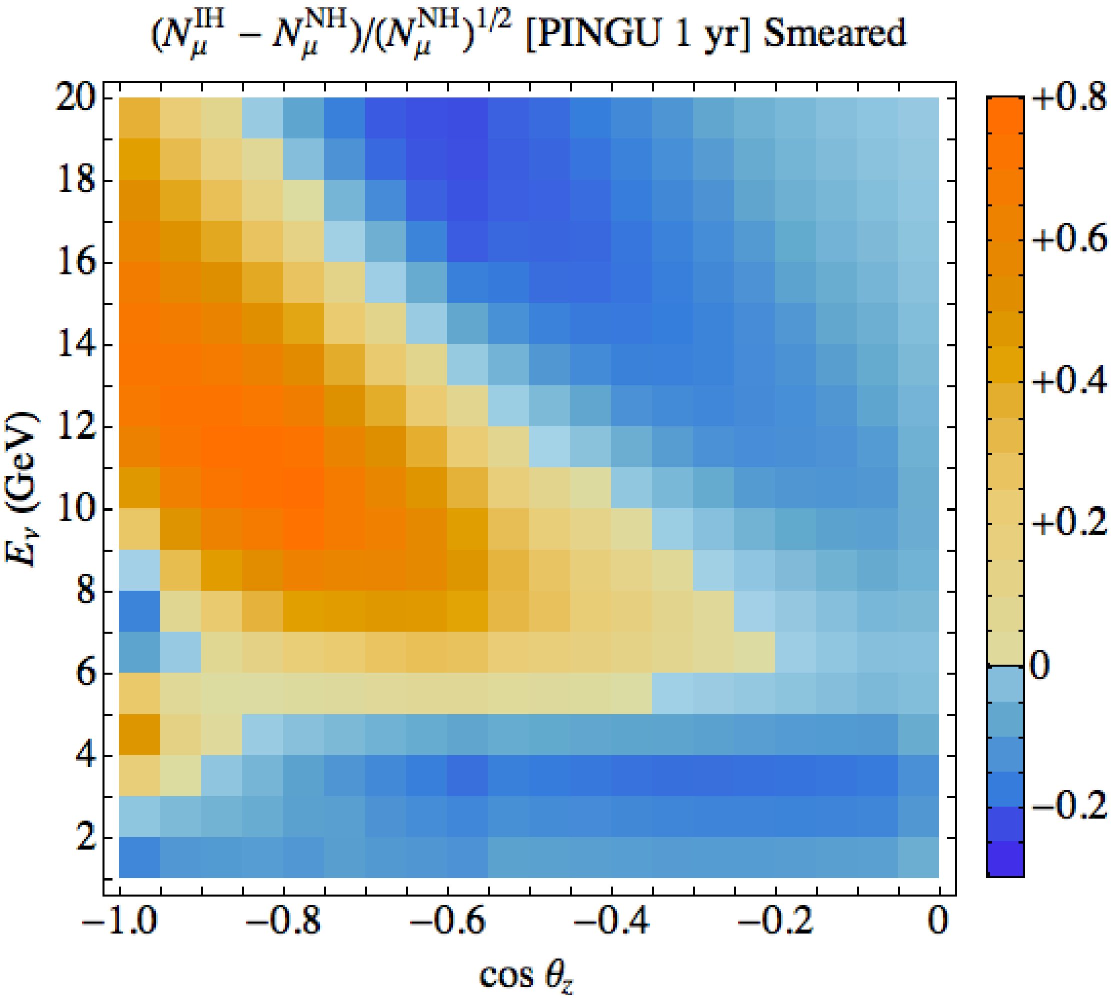
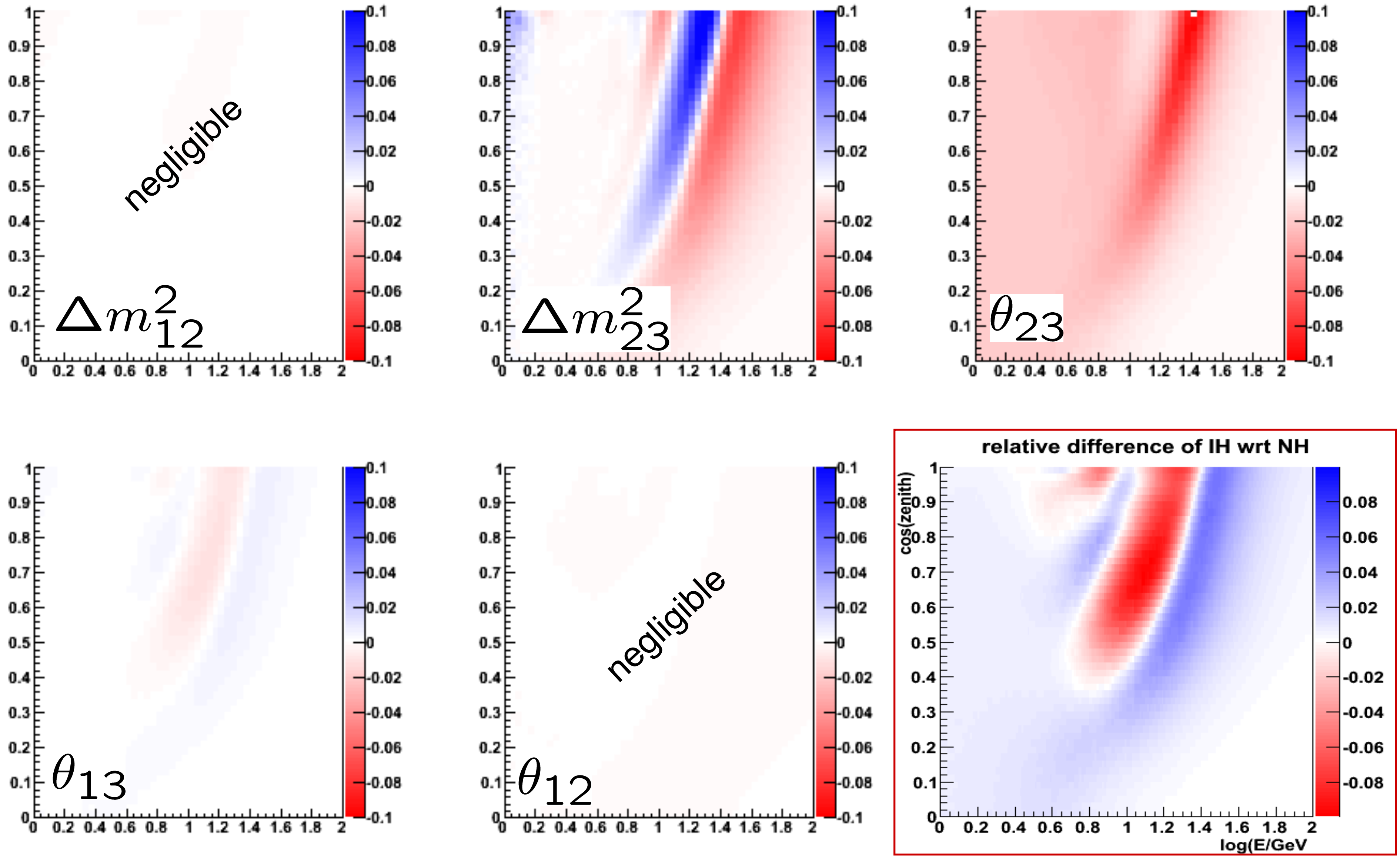
The Akhmedov/Razzaque/Smirnov paper (2)



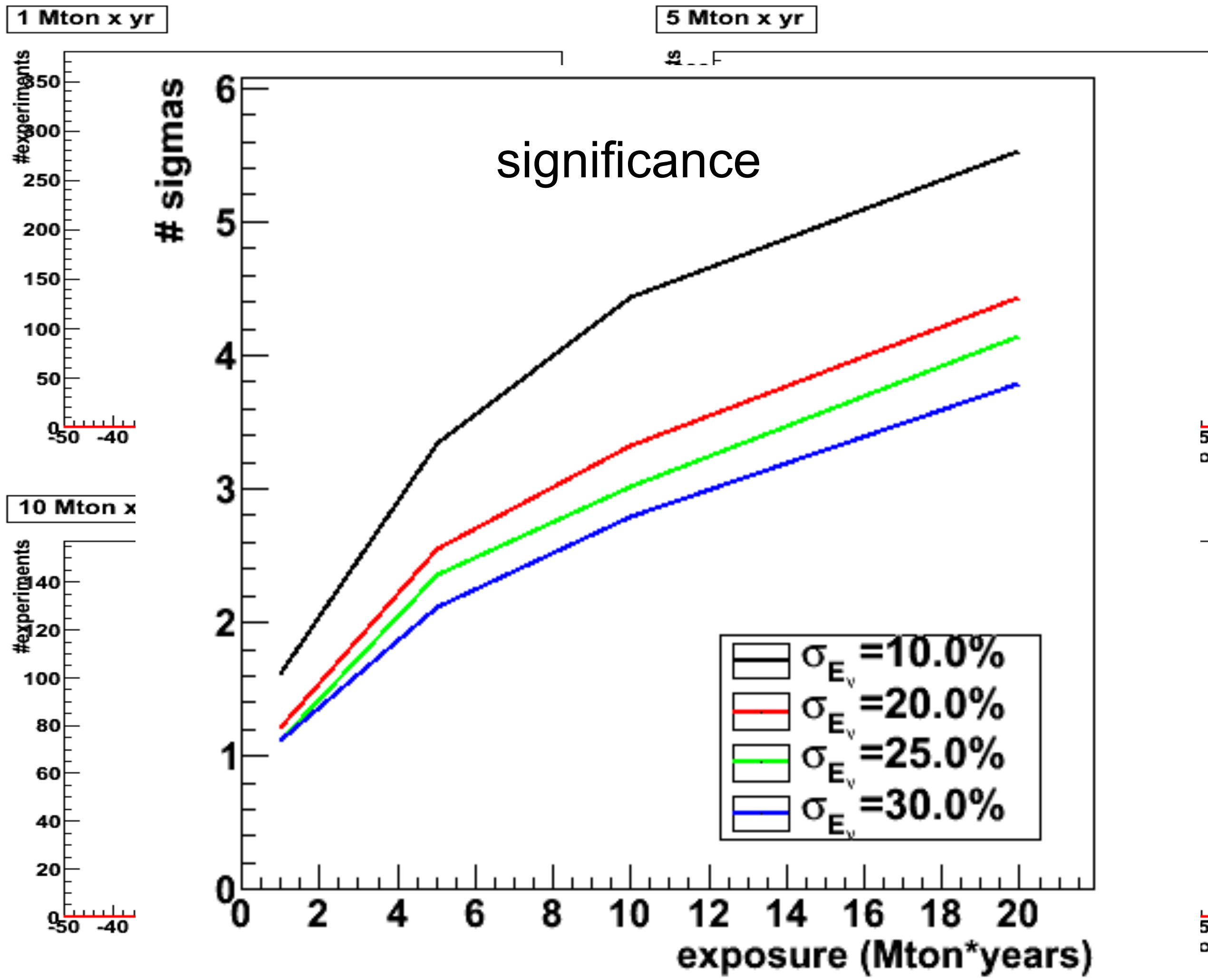
- Taking into account experimental resolutions
  $\sigma_E = 0.2E_\nu; \sigma_\theta = \sqrt{m_p/E_\nu}$
  (just an example) deteriorates result
- Remaining significances as low as 3σ
- Not yet included:
  - Non-Gaussian tails
  - Inefficiencies
  - Flavour separation
  - Backgrounds
  - …

Impact of oscillation uncertainties



Results of toy analysis (ORCA):

- Neutrino vertex in detector volume, true μ direction, $\sigma(E_\nu) = 0.2E_\nu$
- Distribution of log-likelihood ratio NH/IH for toy experiments
- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of Δm^2_{23} and θ_{23} seems possible



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PINGU and ORCA systematics

PINGU (ice):

- inhomogeneity of ice
- light scattering in ice
- missing segmentation of photocathode

ORCA (water):

- optical background from K40 and bioluminescence
- missing veto detector
- temporal variations of data taking conditions

Systematics are complementary – it may be adavantageous to make both experiments

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Summary and Outlook

- Neutrino telescopes in deep ice and water provide increasing sensitivity to cosmic neutrinos (>1TeV).
- Their results are significant and intriguing.
- The construction of the KM3NeT neutrino telescope in the Mediterranean Sea will start 2013/14.
- ANTERES and IceCube have demonstrated that studying neutrinos with energies down to 10 GeV is possible.
- Even lower energies can be studied with densely instrumented configurations, which may allow for a determination of the neutrino mass hierarchy with atmospheric neutrinos.
- If possible, this approach is expected to be significantly faster and cheaper than any alternative.
- These are exciting times for neutrino astronomers – stay tuned!