Festkolloquium zum 80. Geburtstag von Professor Dr. Norbert Schmitz
3. Dezember 2013, Max-Planck-Institut für Physik, München

Enlightening Neutrinos

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FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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The plan for the next 45 minutes:

- Nobert Schmitz: A few memories

  ____

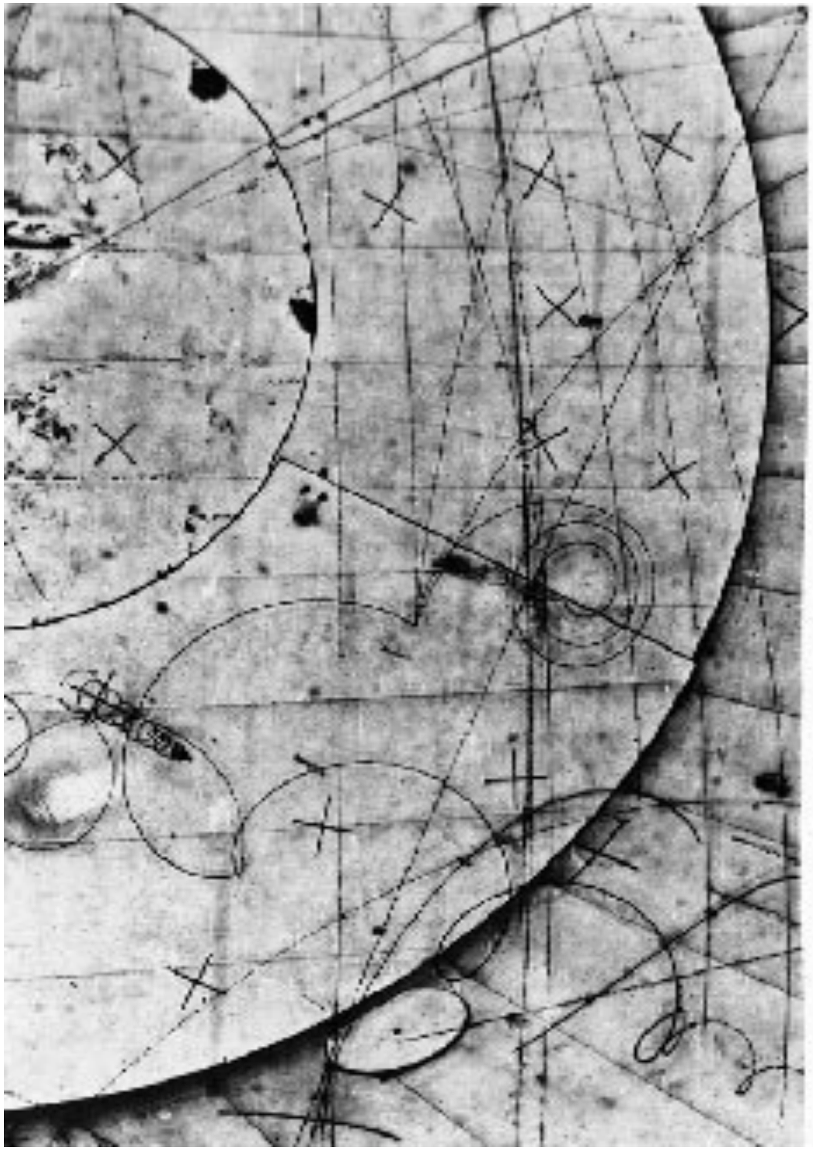
- Neutrino astronomy
- ANTARES and KM3NeT:
  Neutrino telescopes in the Mediterranean Sea
- IceCube and its recent findings
- Studying lower-energy neutrinos
- Summary

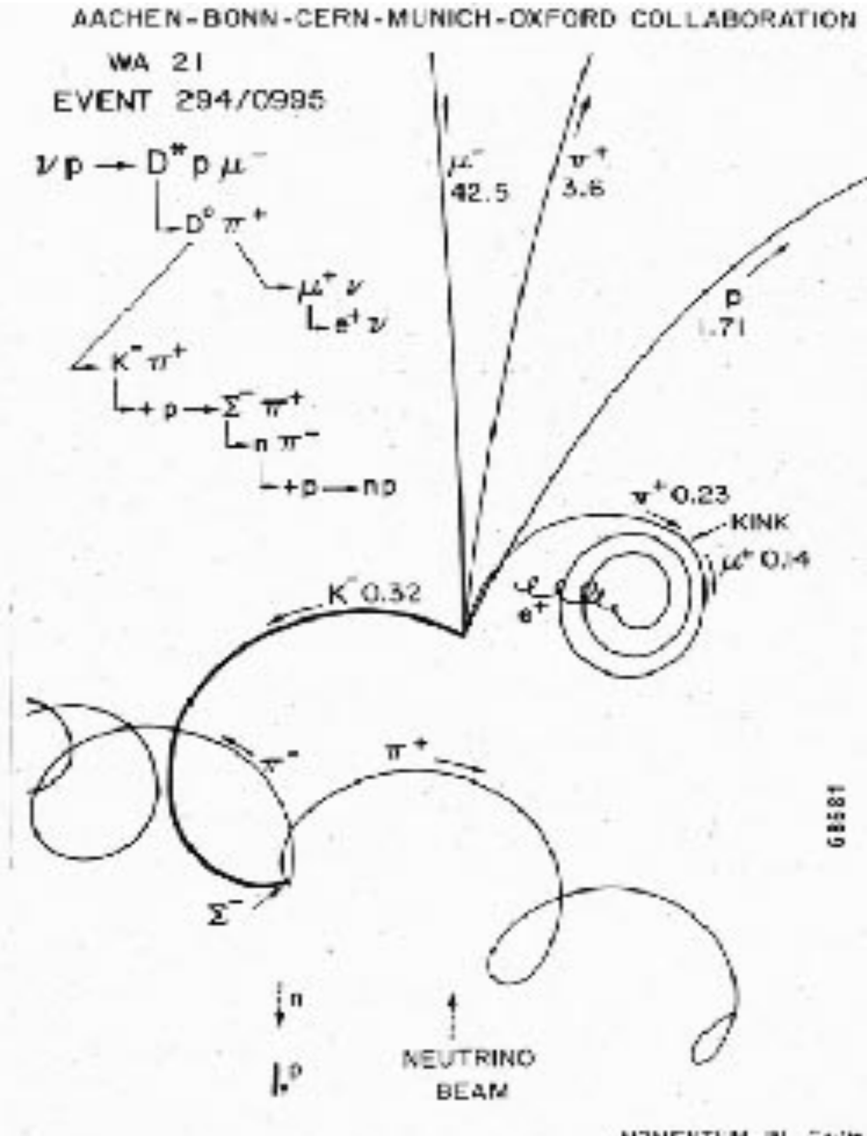
Nobert Schmitz, neutrinos and all that

When we first met (early 1980s)

- Lectures at the Technical University Munich on particle physics
- An exciting decade of particle physics had just passed:
  - Discovery of weak neutral currents (Gargamelle bubble chamber, 1973)
  - Discovery of W and Z bosons (CERN UA1 and UA2, 1983)
- For the first time an encompassing and powerful theoretical model emerged: The Standard Model of particle physics

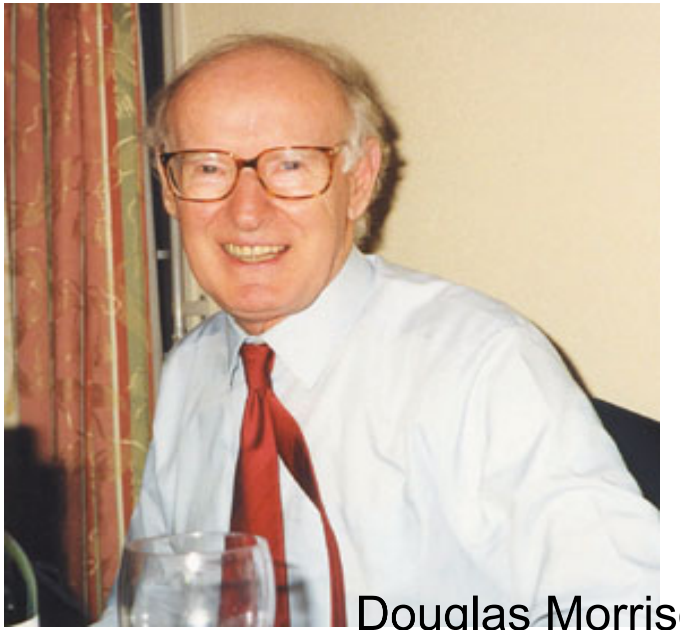
Neutrinos in the MPI for Physics (1984-93)





Neutrino oscillations (around 1990)

- There was the “solar neutrino deficit” … and nothing else
- Most people were highly sceptical
  - Discussed at the level of “pathological science”, like cold fusion
- Note: Neutrinos are always good for surprises!



Douglas Morrison

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The book (1997)

- Haven’t read it?
- You should!

The Neutrino Conference in Munich (2002)

A few pictures and memories

Thank you for the time at MPI Munich
and for teaching me the ultimate question:
"Have you checked this?"

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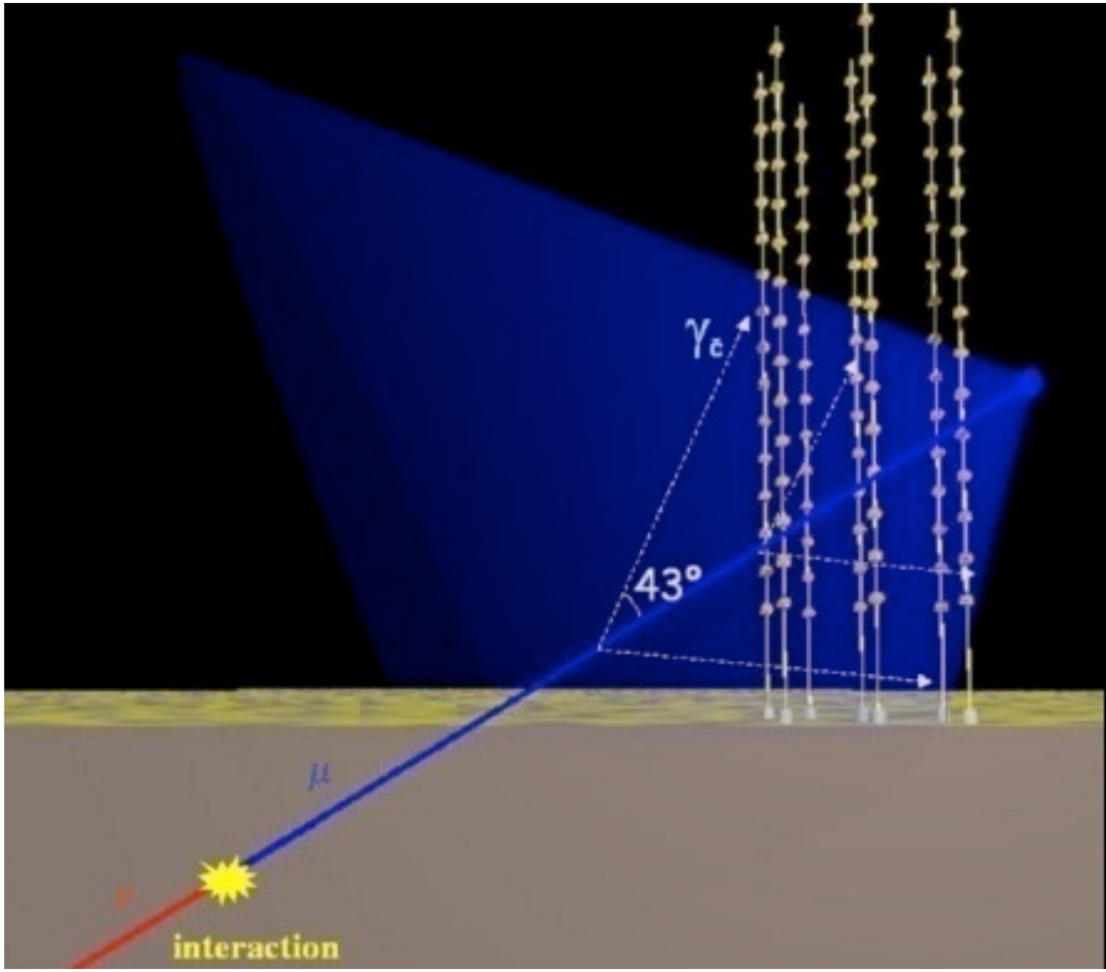
Neutrino astronomy

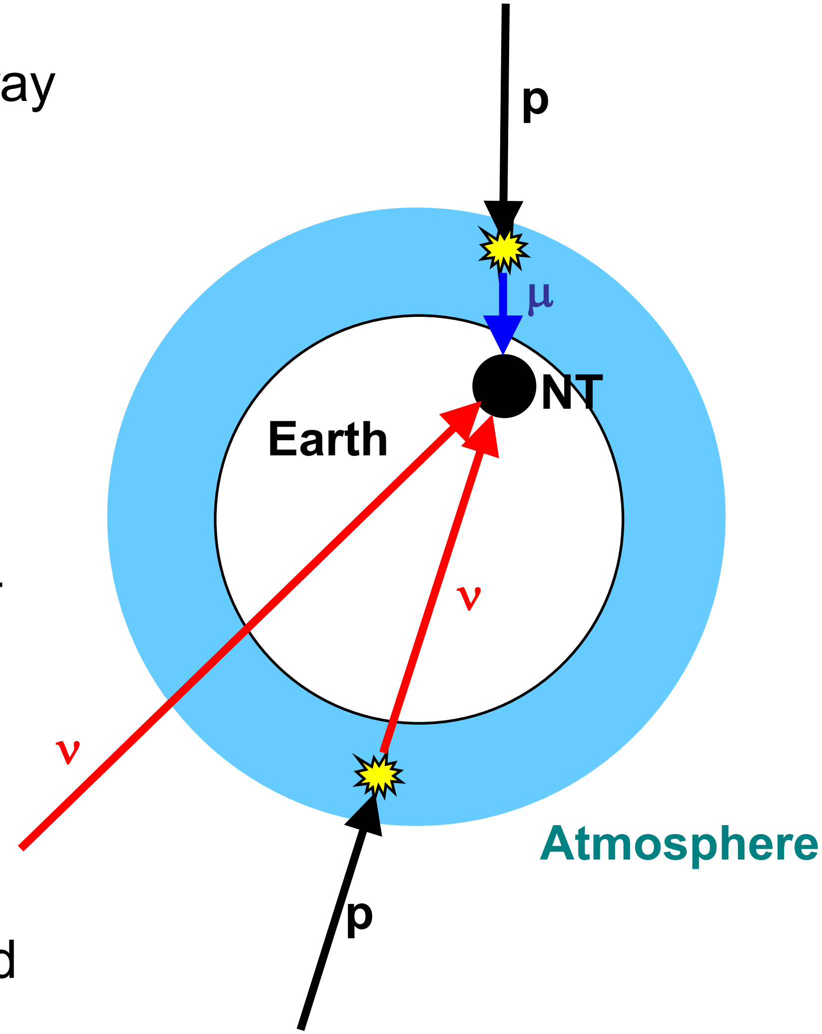
How does a neutrino telescope work?

- 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
- "Traditional" channel: $\nu_\mu + N \rightarrow \mu + X$
- Energy range : 10(0) GeV – some PeV

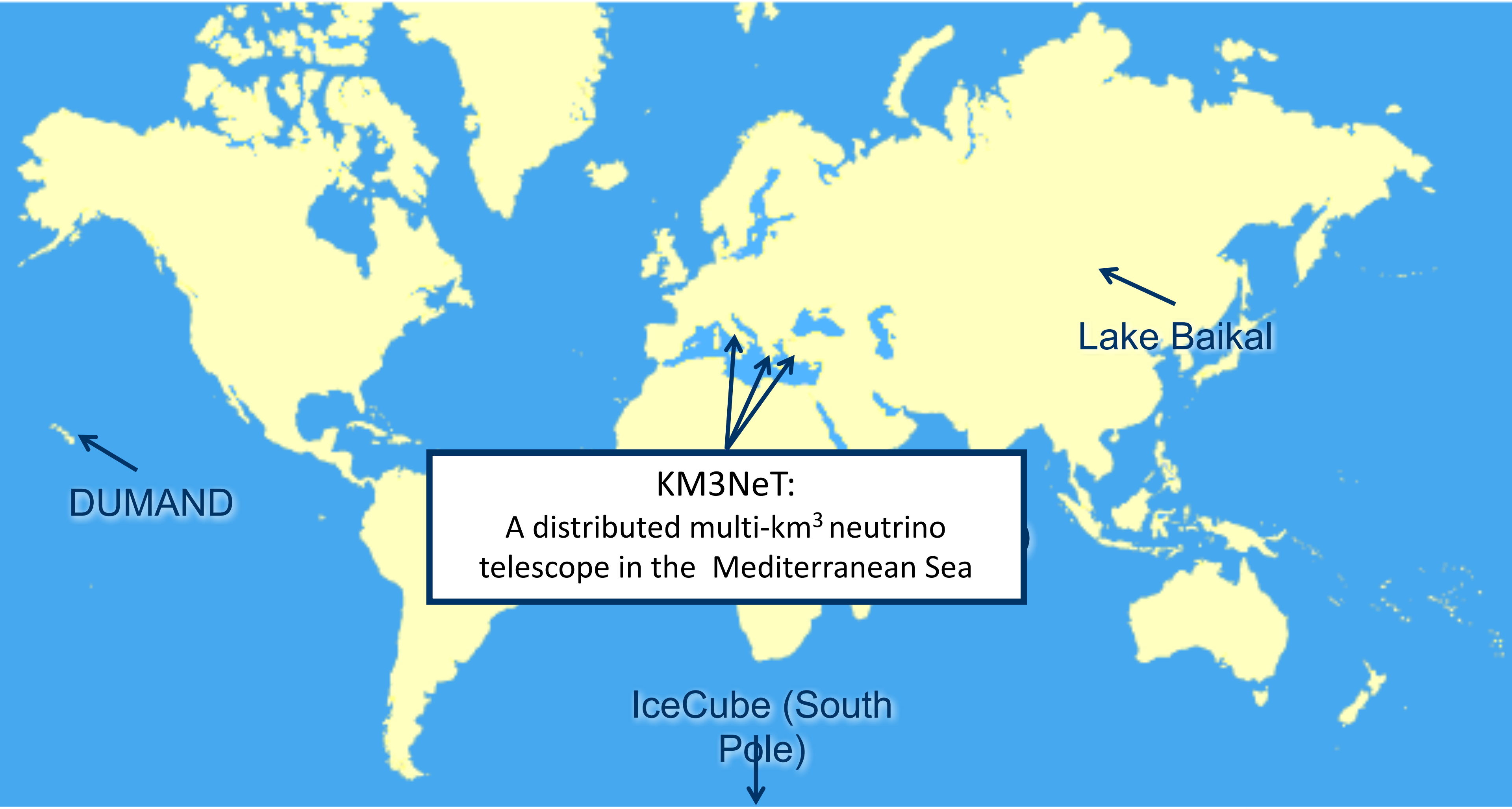


Backgrounds, or maybe not

- 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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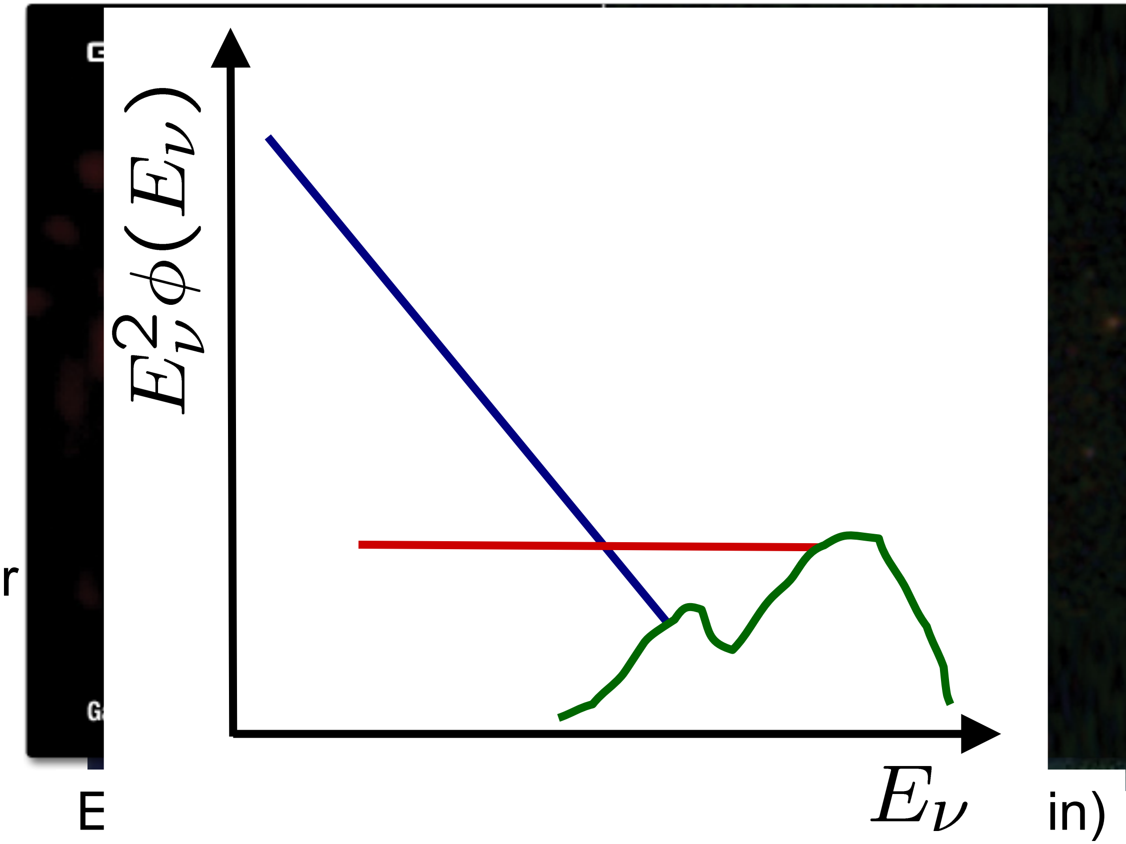
Example targets of neutrino astronomy

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



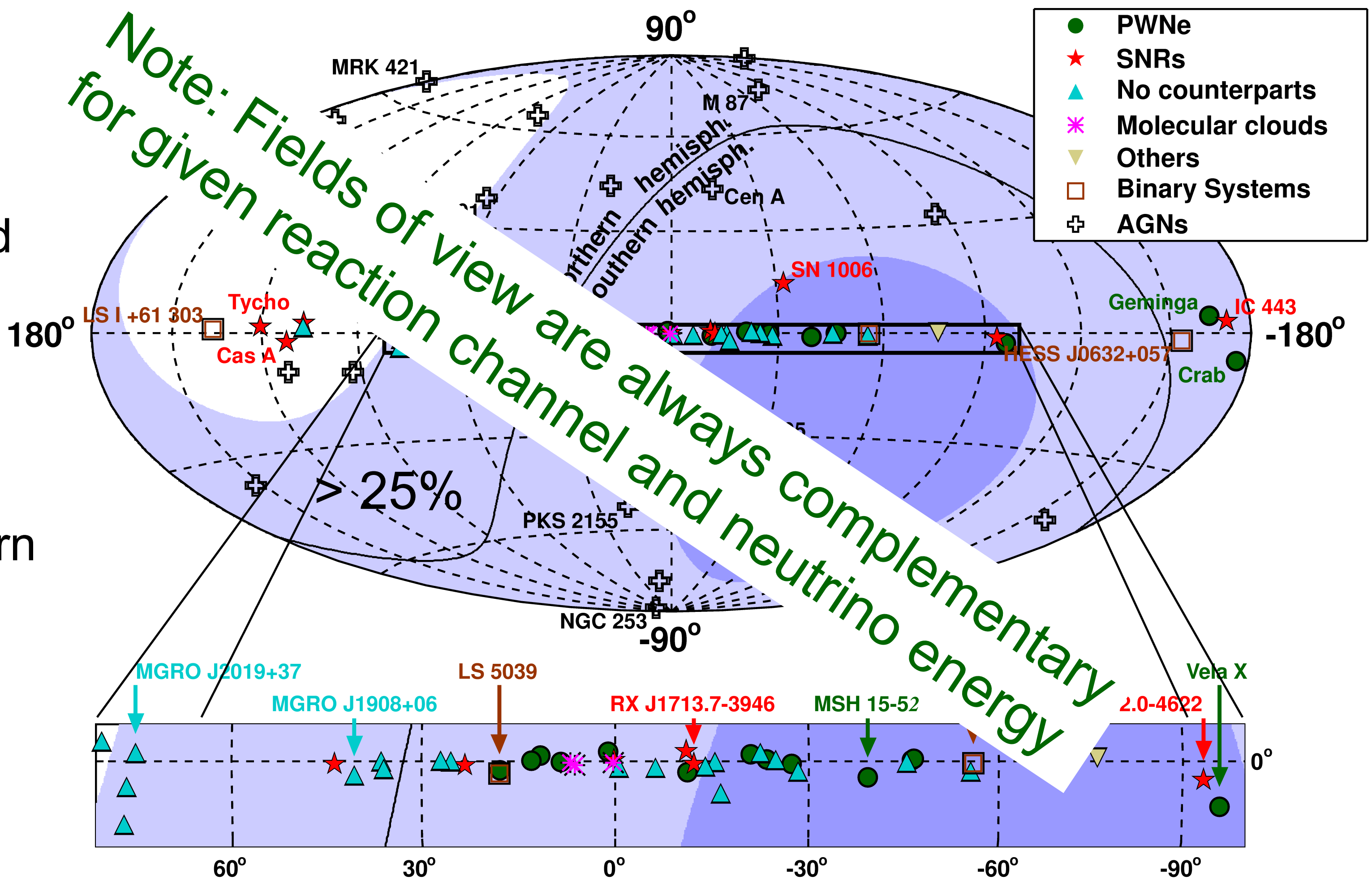
Isotropic high-energy neutrino flux
above atmospheric neutrino background
from unresolved astrophysical sources
or of cosmogenic origin (GZK)

South Pole and Mediterranean fields of view

Galactic coordinates

2π downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere



ANTARES and KM3NeT: Neutrino telescopes in the Mediterranean Sea

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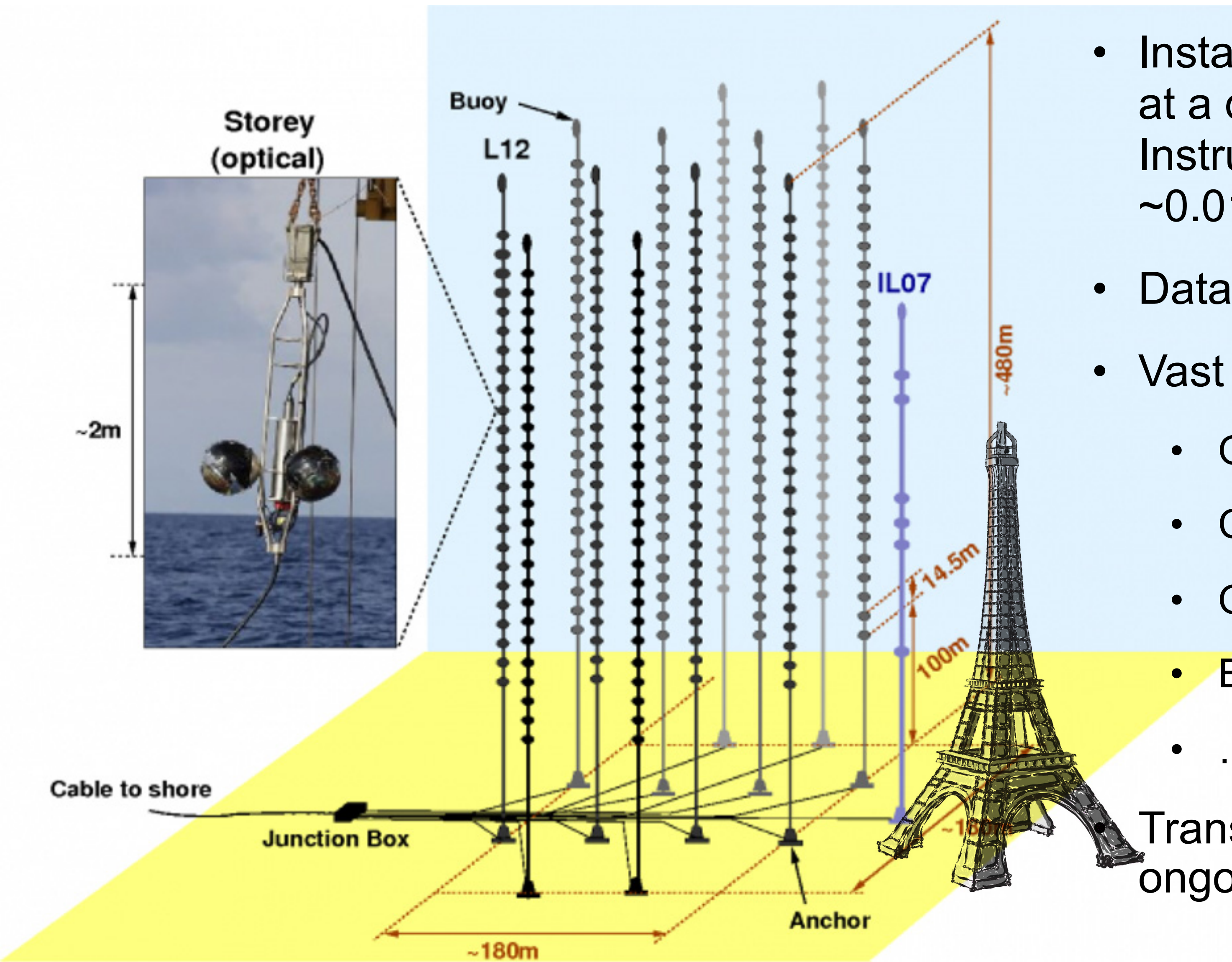
ANTARES: The first NT in the deep sea



- Installed near Toulon at a depth of 2475m, Instrumented volume ~0.01km^3
- Data taking since 2008
- Vast experience in
    - Operation
    - Calibration
    - Online filter
    - Even reconstruction
    - …
- Transfer of knowledge ongoing

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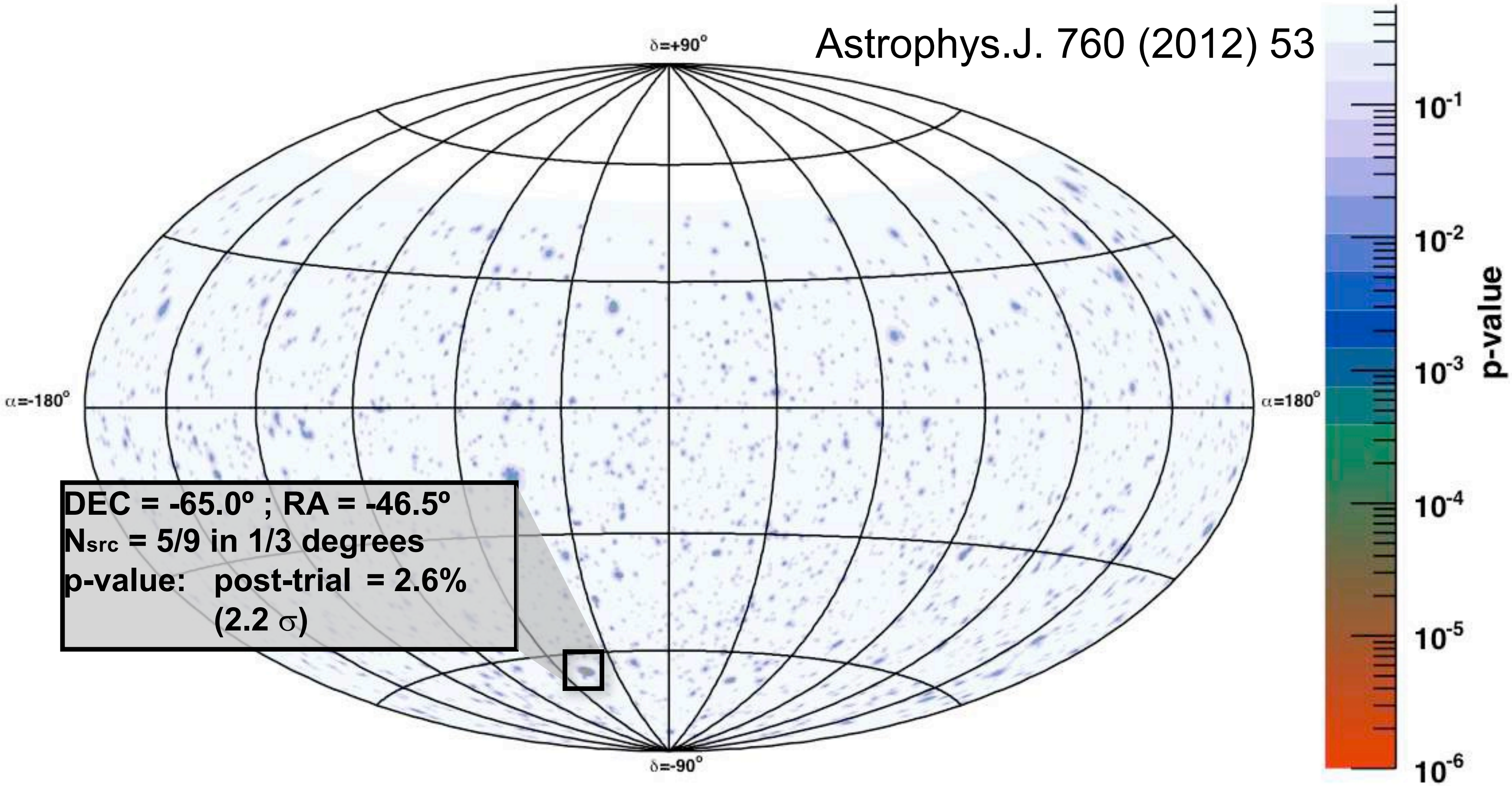
ANTARES: Point source search



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

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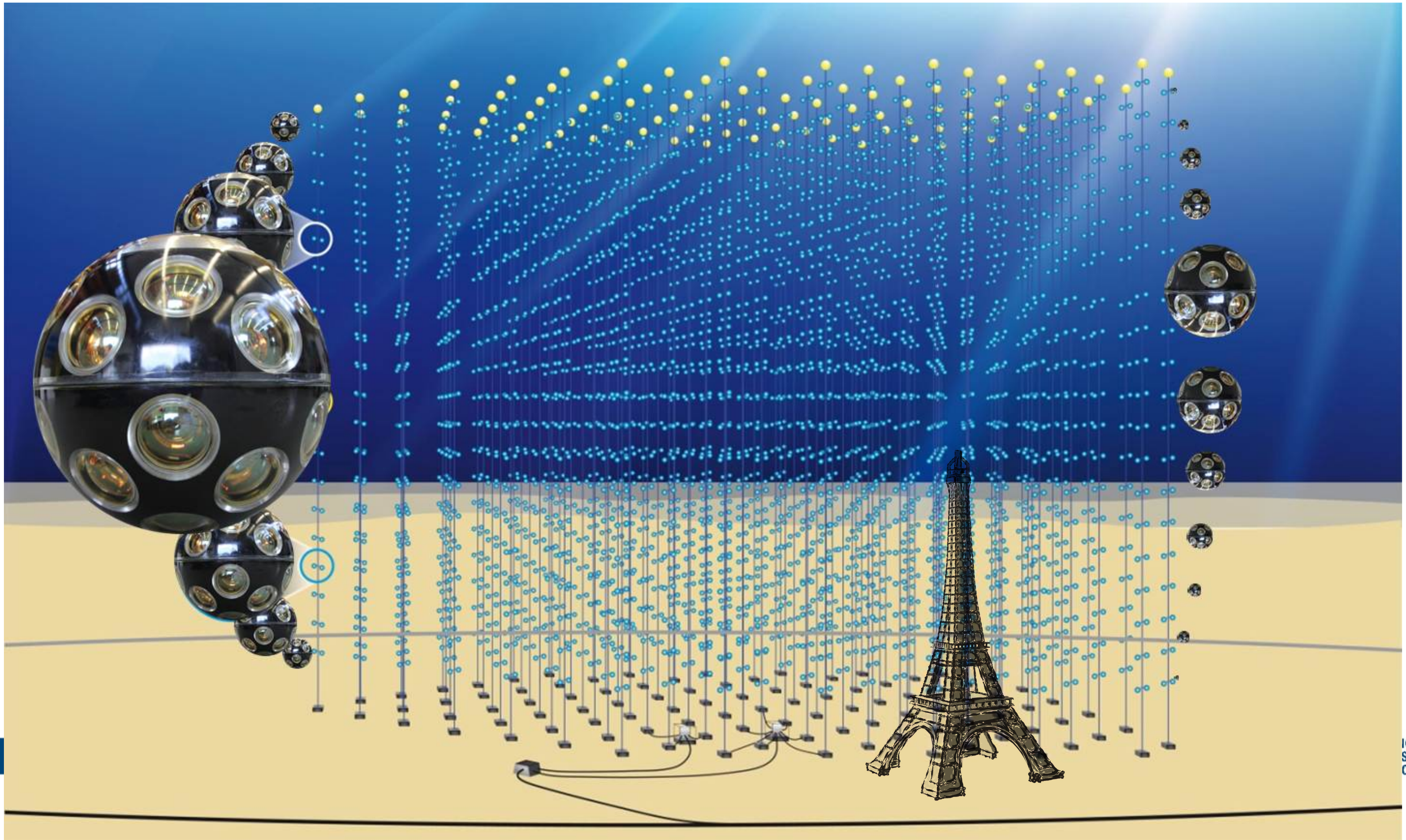
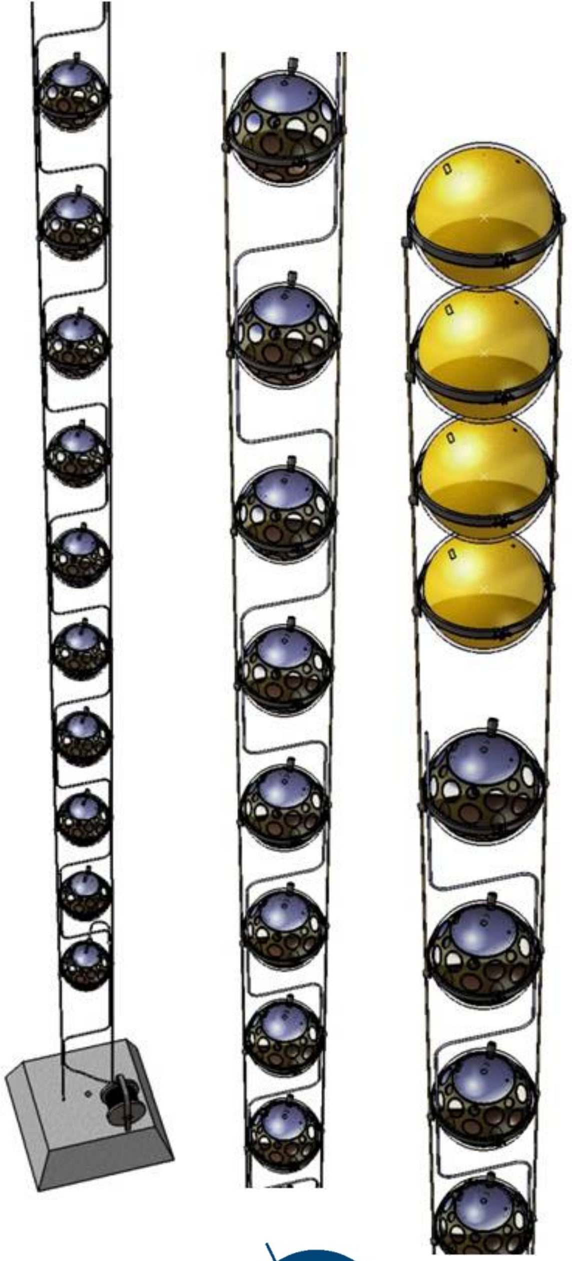
What is KM3NeT ?

- Future cubic-kilometre scale neutrino telescope in the Mediterranean Sea
- Exceeds Northern-hemisphere telescopes by factor ~50 in sensitivity
- Exceeds IceCube sensitivity by substantial factor
- Provides node for earth and marine sciences



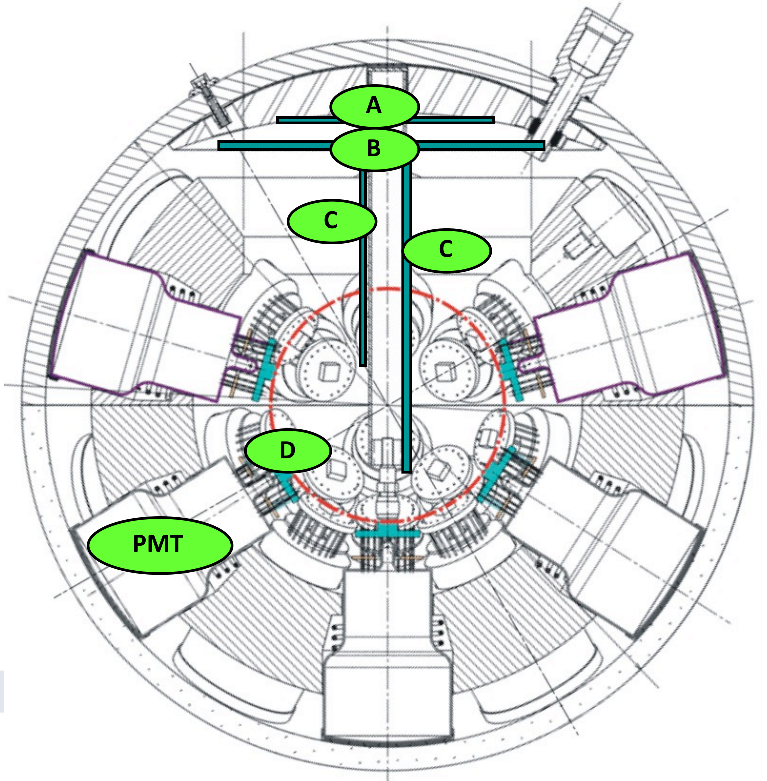
Detection units: Strings

- Mooring line:
  - Buoy (probably syntactic foam)
  - 2 Dyneema© ropes (4 mm diameter)
  - 18 storeys (one OM each),
    30-36m distance, 100m anchor-first storey
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - fibres and copper wires
  - At each storey:
    connection to 1 fibre+2 wires
  - Break out box with fuses at each storey: One single pressure transition



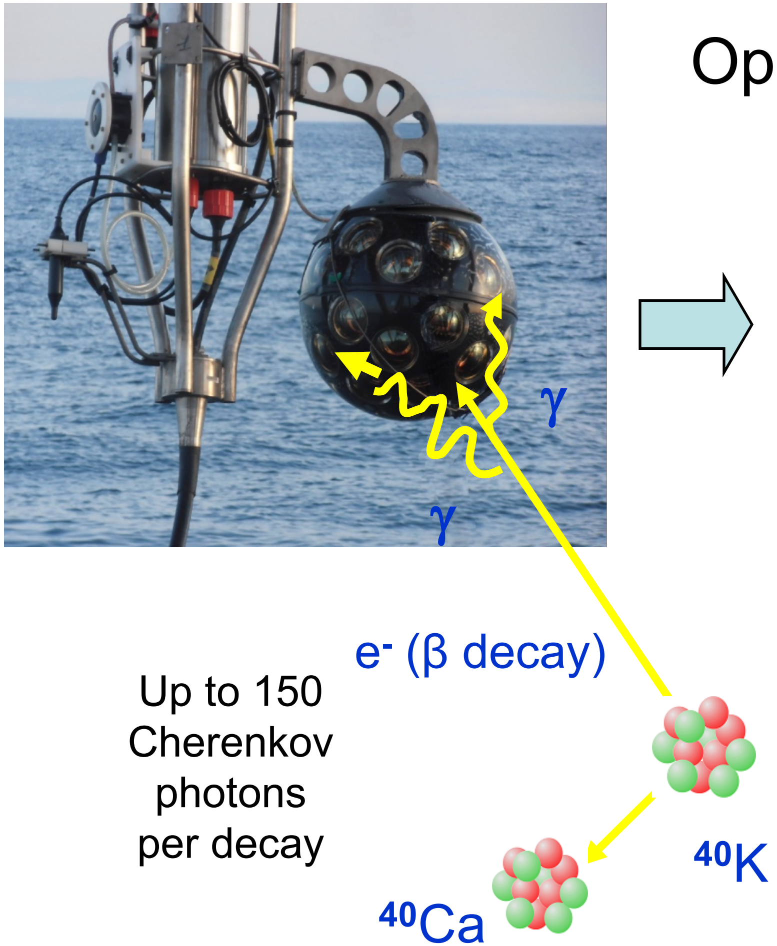
OM with many small PMTs

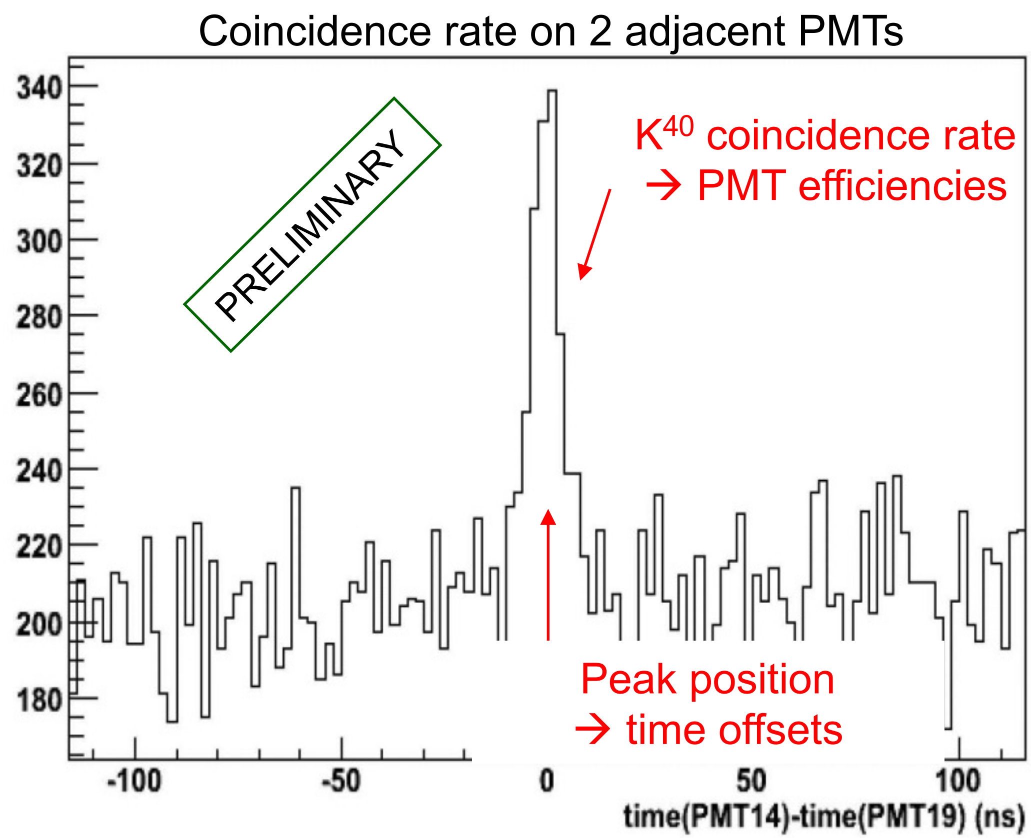
- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10" PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- 2mm optical gel
- Advantages:
  - increased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



Prototype Optical Module

Operated since April 2013 in ANTARES





Concentration of ^{40}K is stable
(coincidence rate ~5 Hz on adjacent PMTs)

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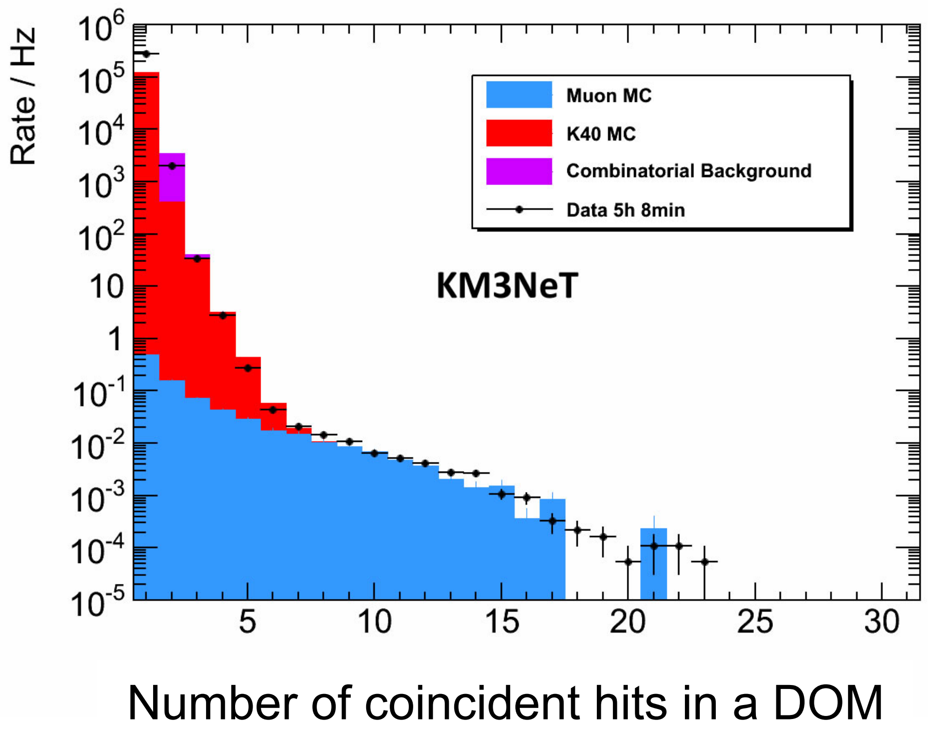
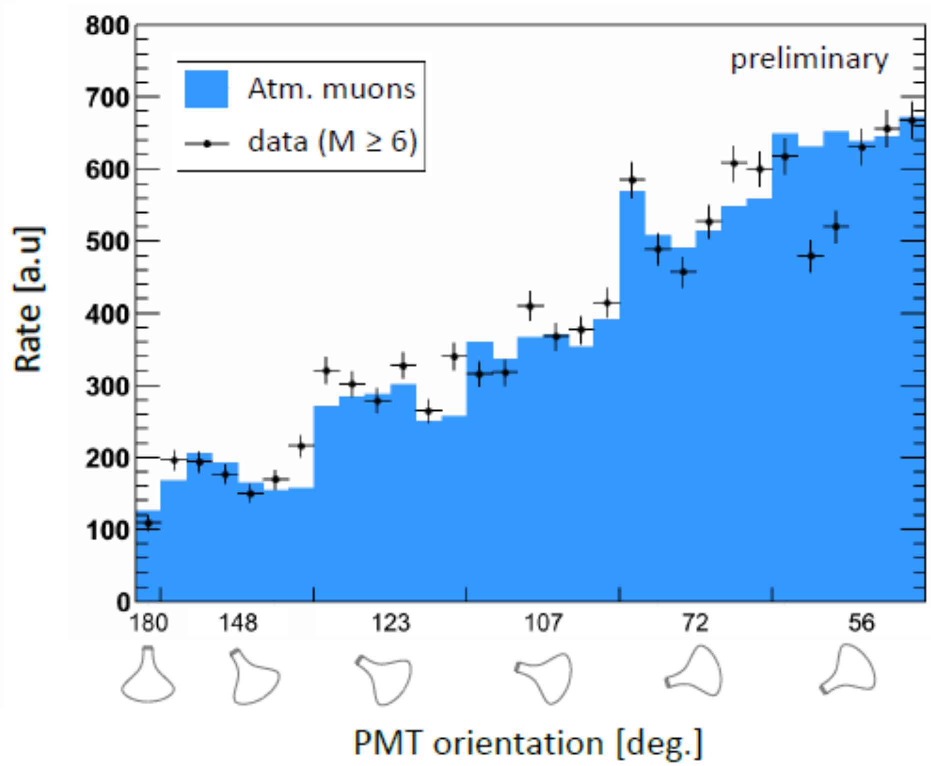
PPM-DOM: Atmospheric Muons





>5 coincidences within 20ns ⇒
reduced K40 contribution,
dominated by atmospheric muons

More upper PMTs in multi-hit events ⇒
directional information
from single storey

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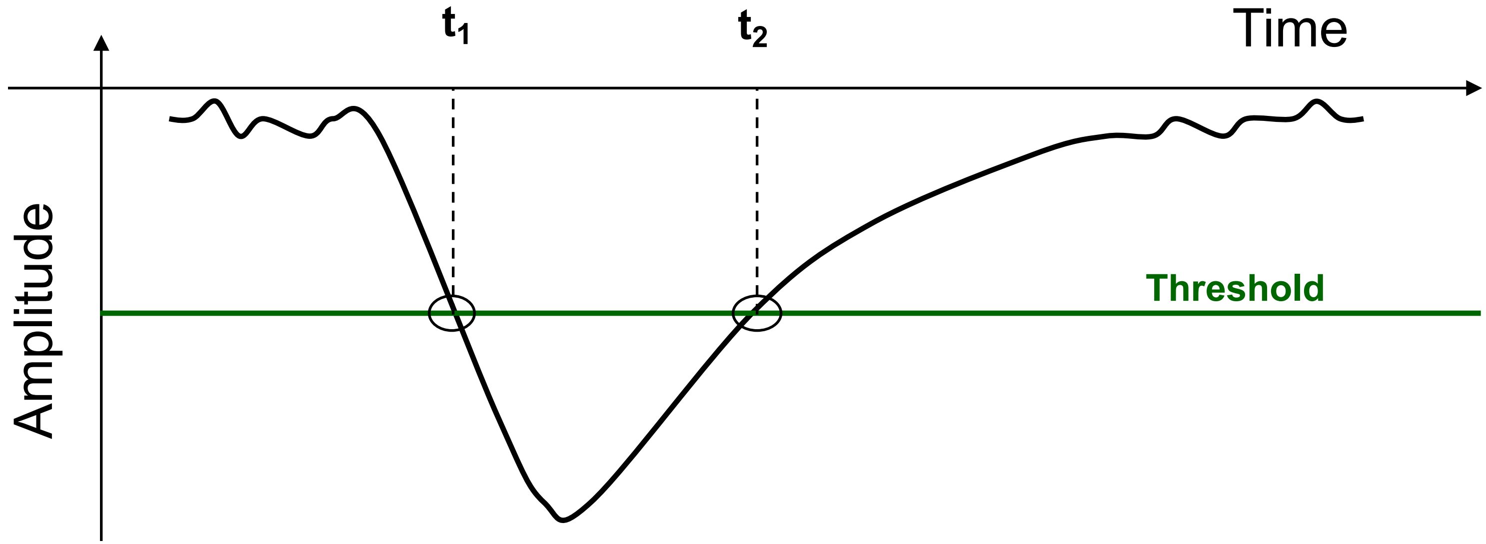
Readout: time-over-threshold

From the analogue signal to time stamped digital data:

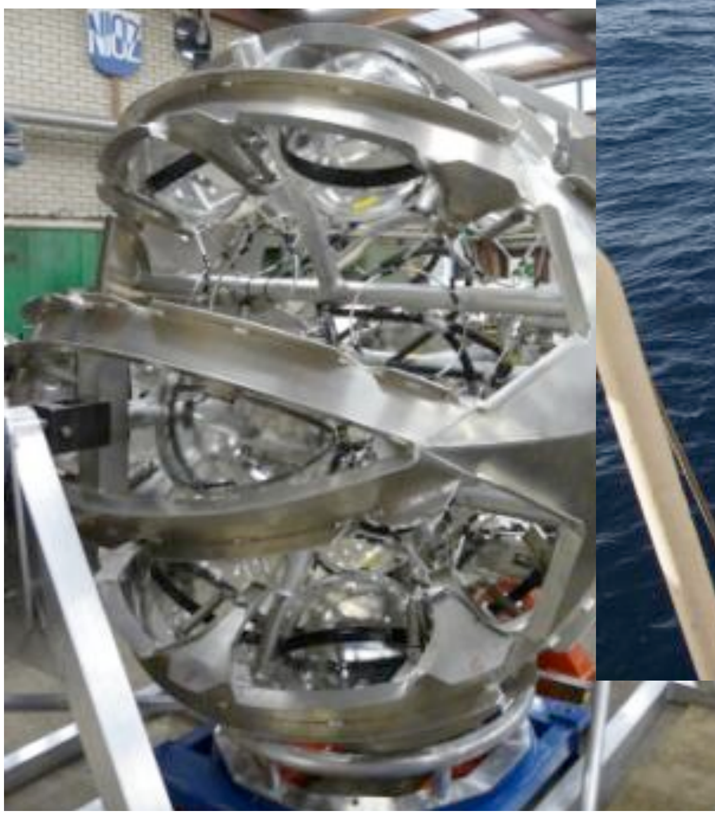


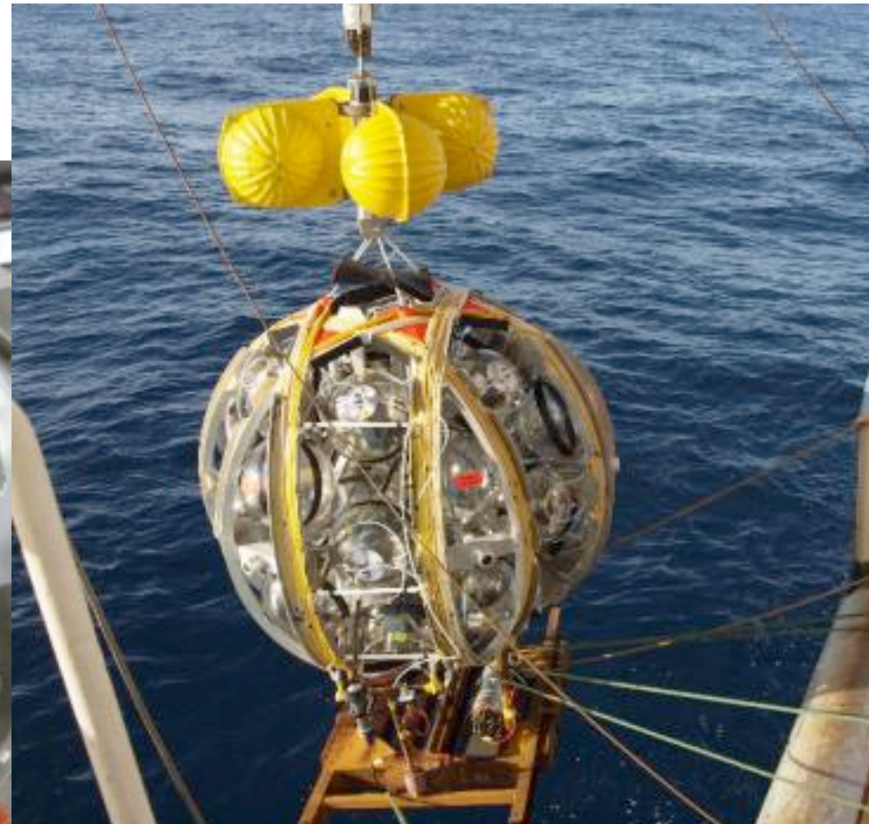
…

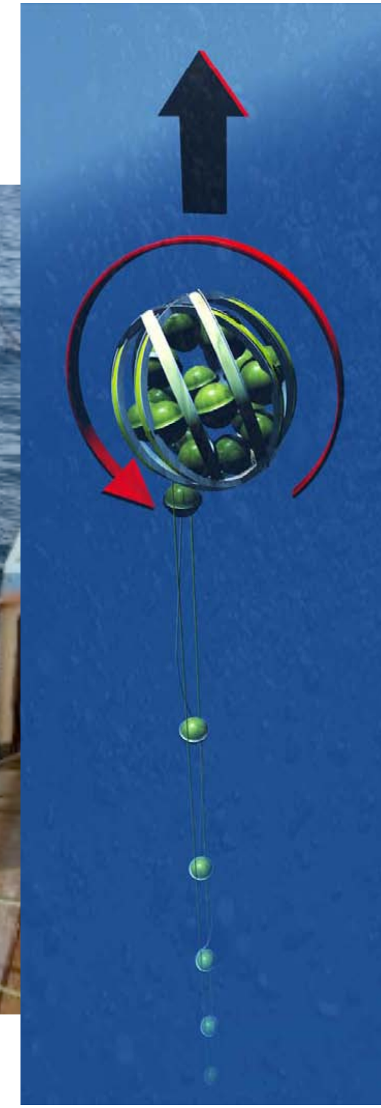
- Implemented through FPGA on central logic board contained in optical module
- All data to shore via optical fibres
- Time synchronisation and slow control

Deploying strings

string rolled
up for self-unfurling:



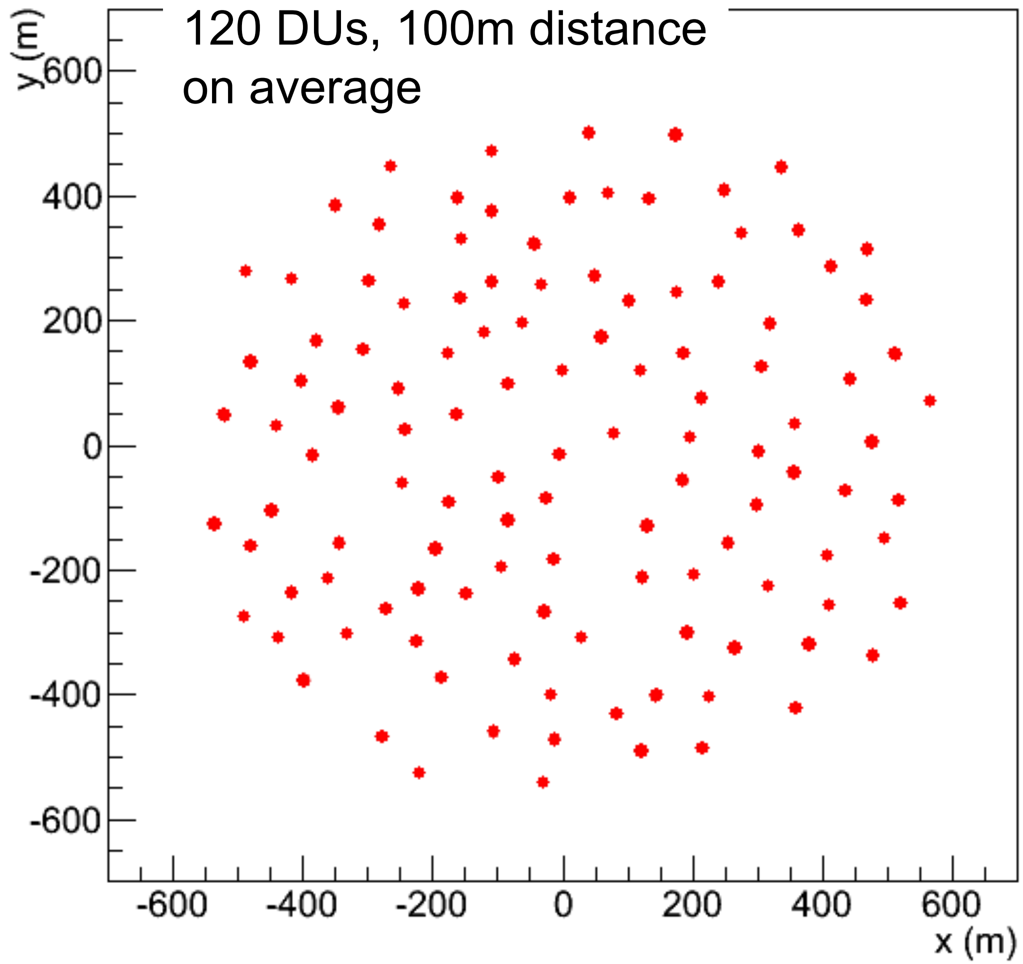




The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
  - Sensitivity for muons independent of block size above ~75 strings
  - One block ~ 1/2 IceCube
- Geometry parameters optimised for galactic sources (E cut-off)
- Final optimisation in progress

Example configuration:
120 DUs, 100m distance on average



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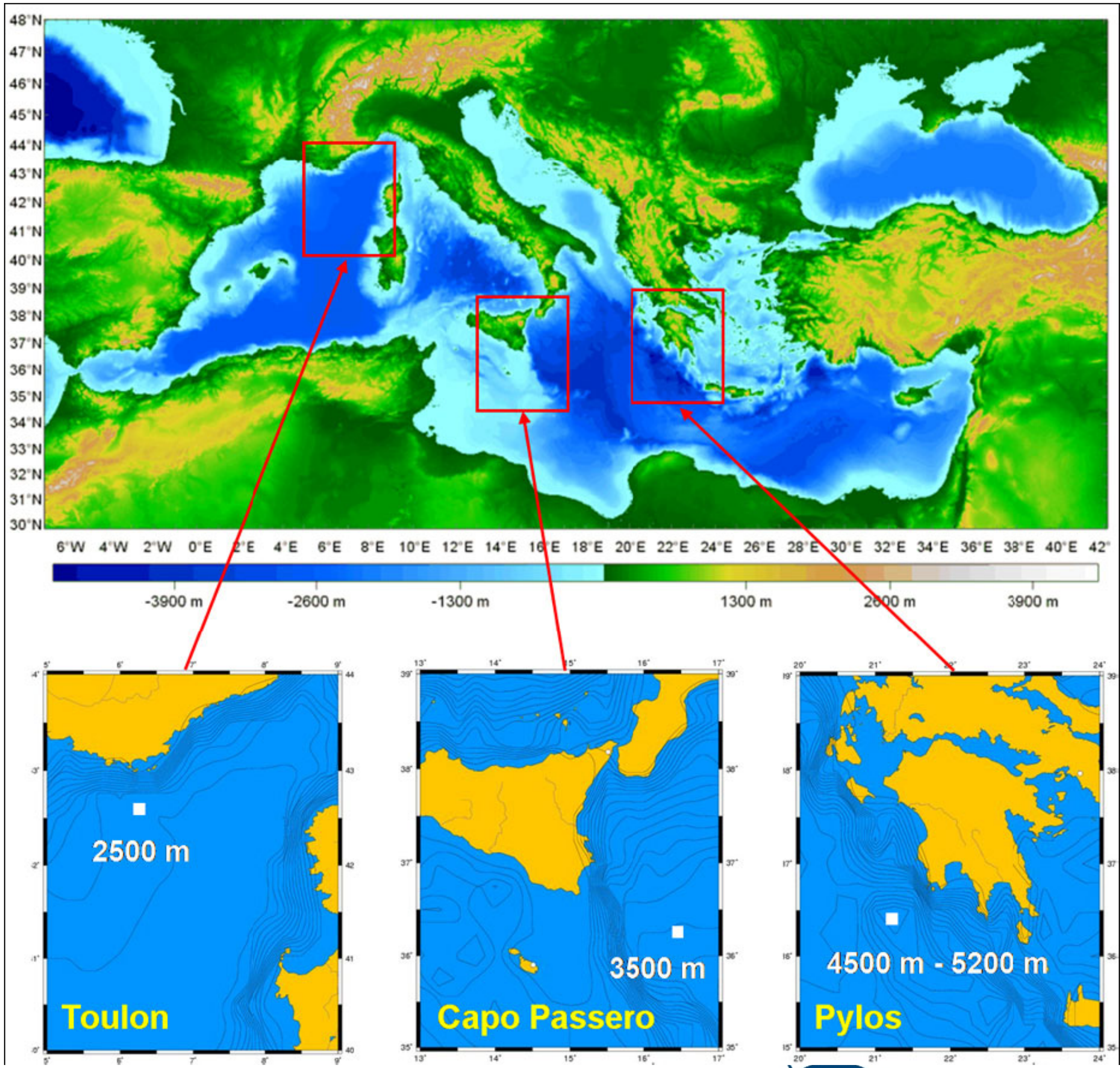
Installation Sites

- Locations of the three pilot projects:
  - ANTARES: Toulon
  - NEMO: Capo Passero
  - NESTOR: Pylos
- Long-term site characterisation measurements performed
- Political and funding constraints
- Solution: networked, distributed implementation



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KM3NeT plans

- Phase 1:
  Prepare infrastructure at 2 sites and construct ~30 strings
  - Funding available
  - Construction 2015-16
- Phase 1.5:
  Construct a detector of 1 km^3 size (“IceCube class”)
  - Letter of Intent in preparation
  - Expected cost: Additional 50 M€
- Phase 2:
  Full KM3NeT (600 strings)
  - Expected overall cost (including phases 1 and 1.5): 220-250 M€

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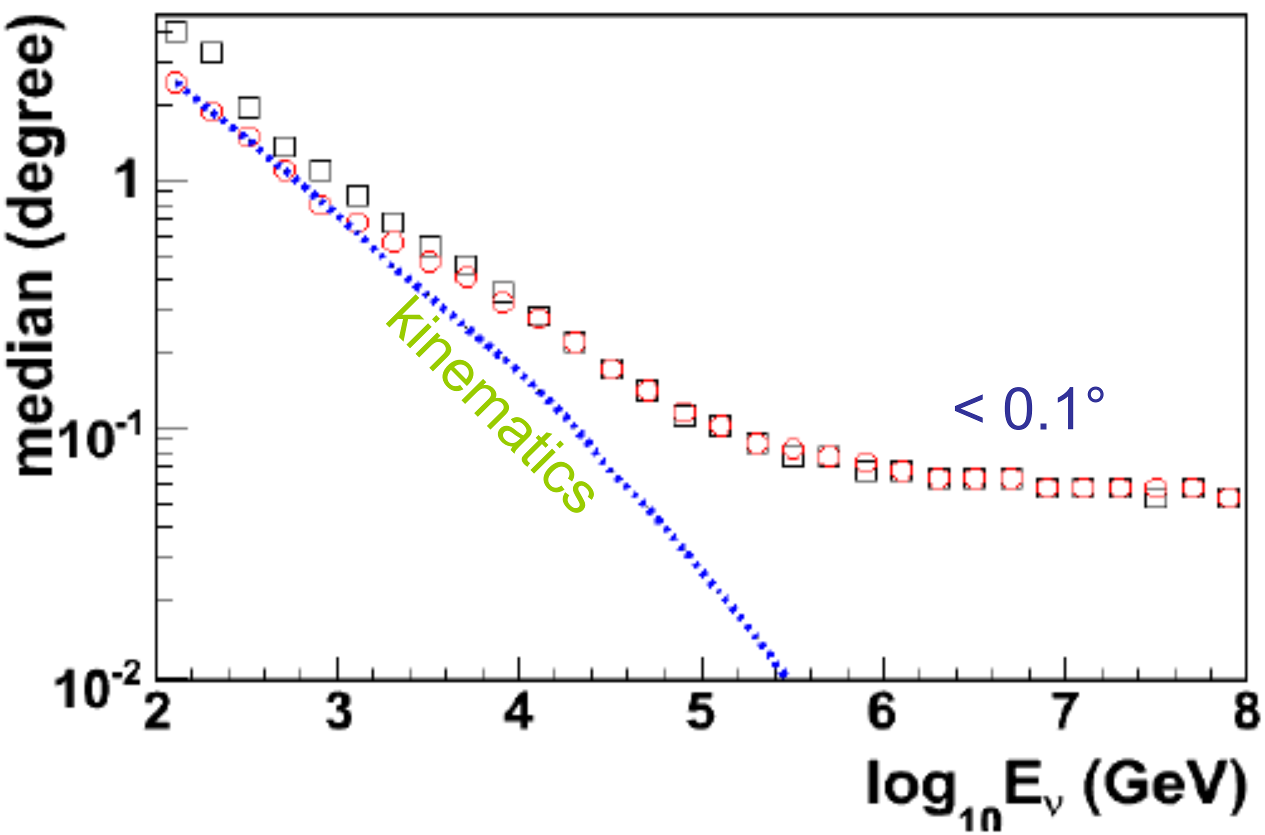
Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to ~1TeV
- Energy resolution ~0.3 in $\log_{10}(E_\nu)$ if E_μ>1 TeV



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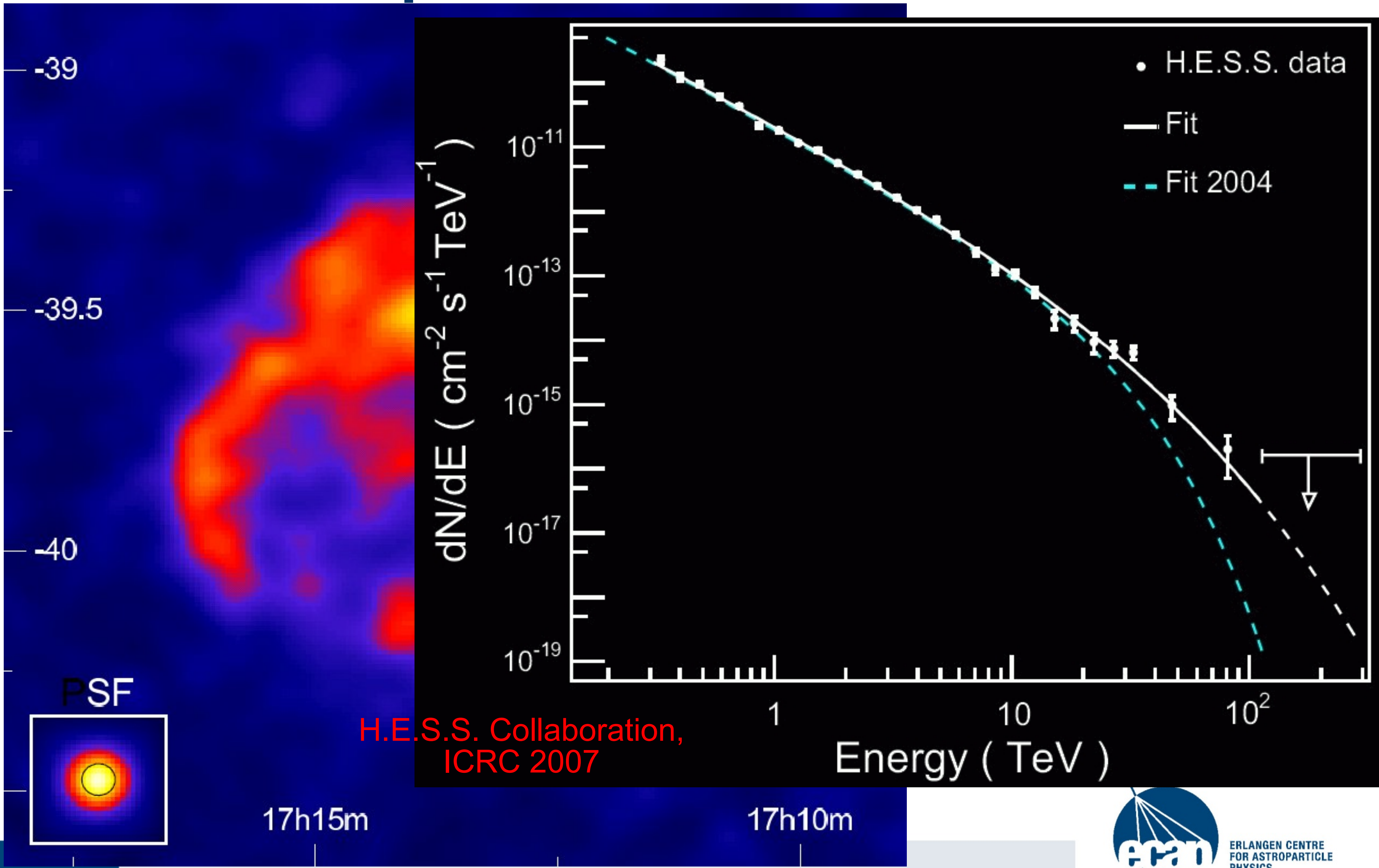
RX J1713: A prime candidate source



H.E.S.S. Collaboration, ICRC 2007

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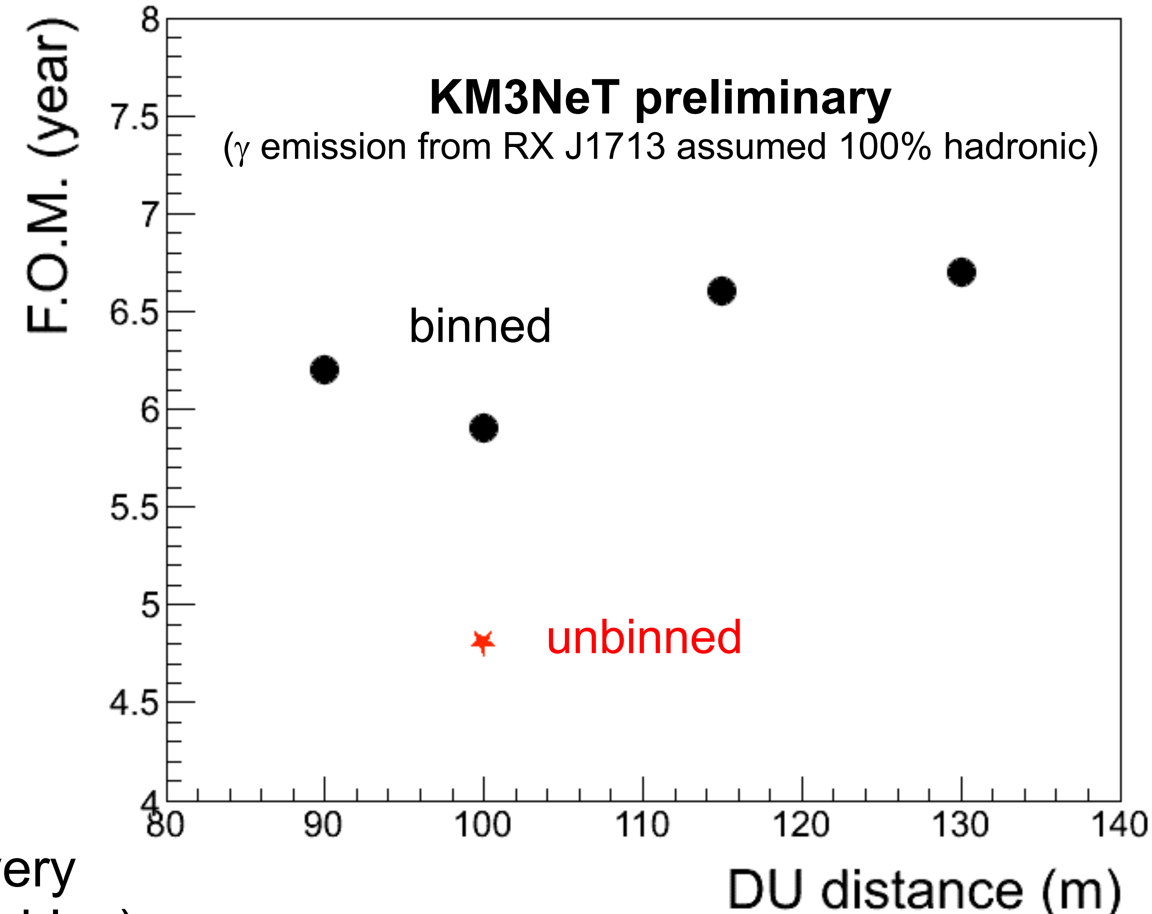
RX J1713: A prime candidate source

- Figure of merit (FOM): 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 (Vela X, Fermi Bubbles)



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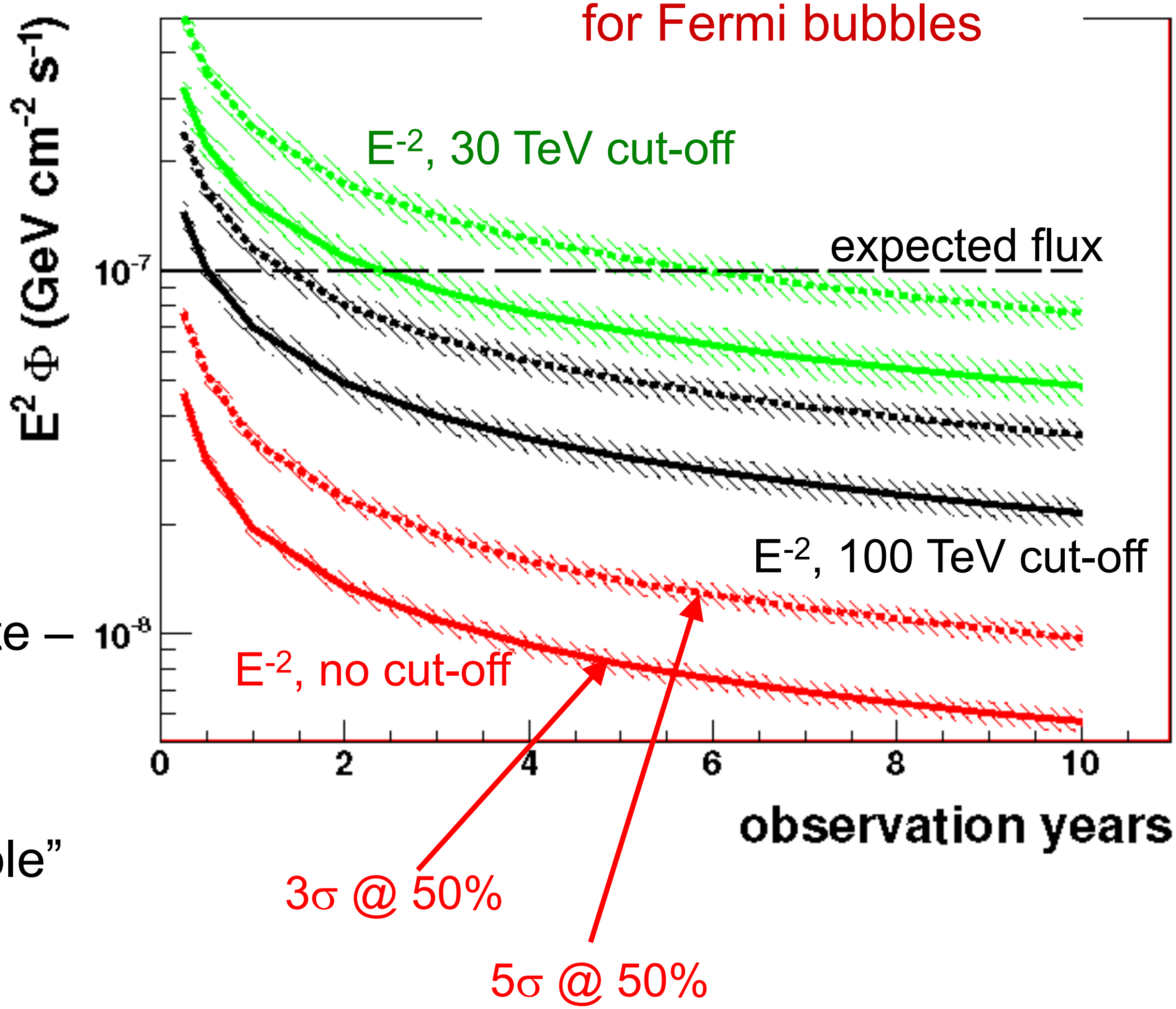
The Fermi bubbles

Note: ANTARES has limits (and small excess) for 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 "easily detectable" by KM3NeT



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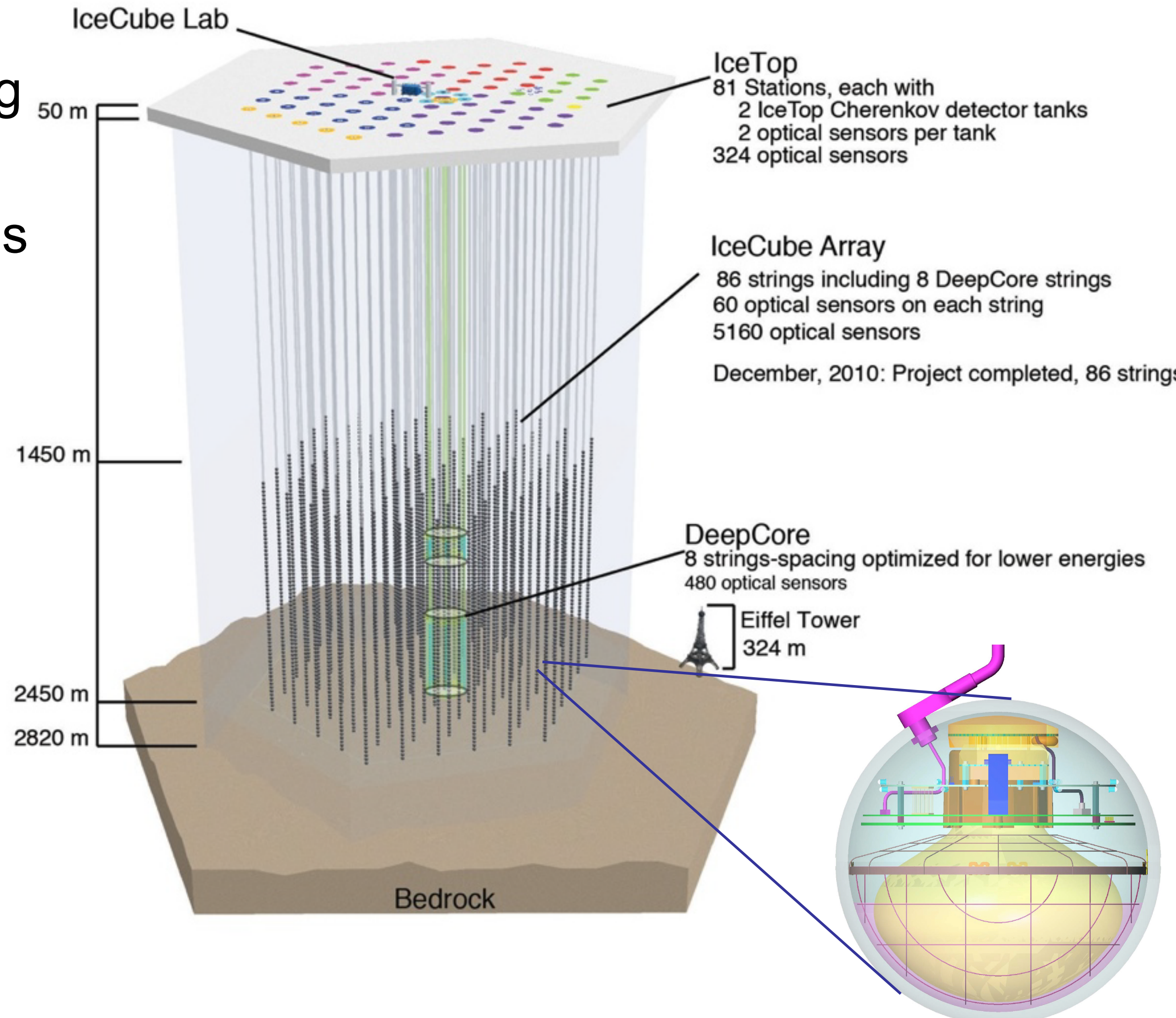
Recent IceCube findings

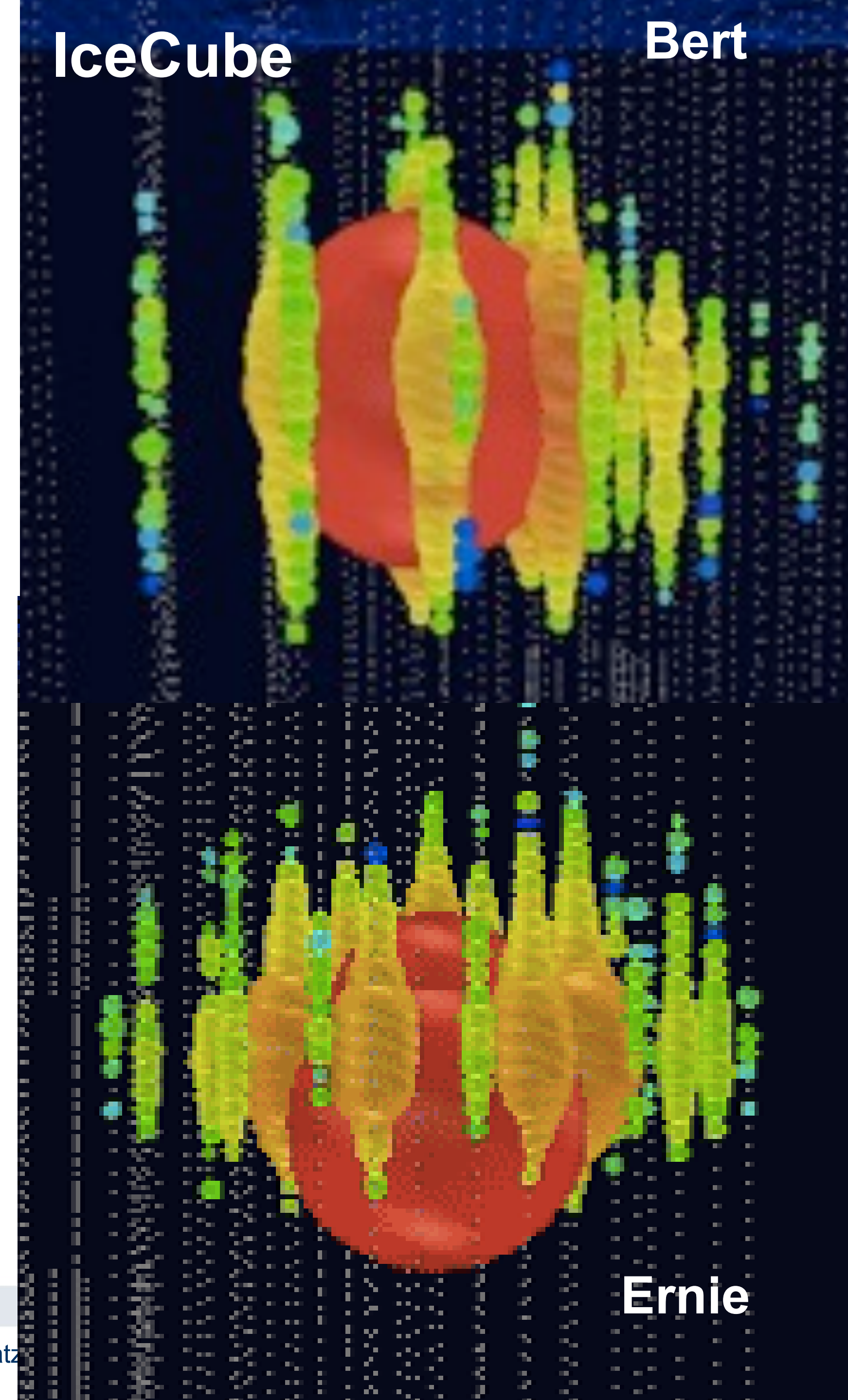
IceCube: Completed in December 2010

- 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)



The first glimpse

- Two cascade events found, energies about 1 PeV.
- Triggered an extensive analysis effort and development of new analysis methods:
    - Cascade reconstruction
    - Contained events: Use outer detector layers to veto incoming (atmospheric) muons
    - Muon veto against atmospheric neutrinos
- Clear excess of events between some 10TeV and PeV emerged.
- First observation of high-energy cosmic neutrinos!



IceCube analysis characteristics

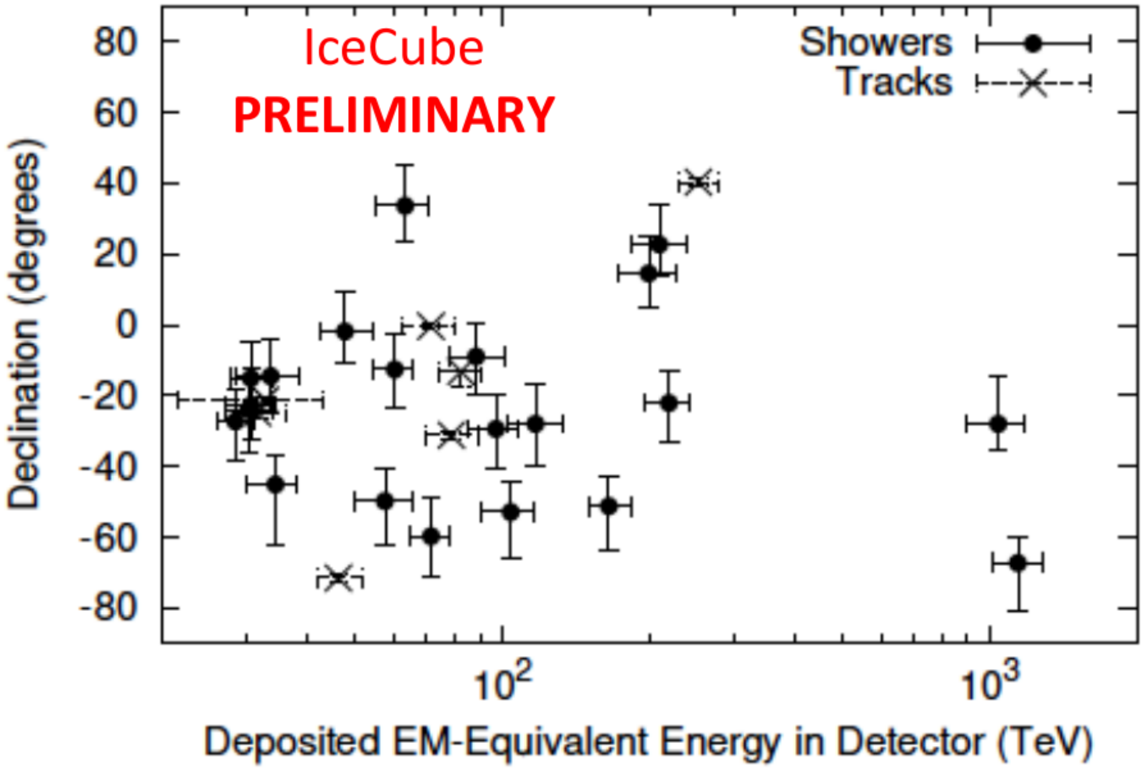
- Cascade resolutions (above some 10 TeV):
  ~10-15% in energy, ~10-15° in angle
- Roughly ½ detector used for veto purposes
- Expected backgrounds:

Atmospheric muons	6.0
Atmospheric neutrinos (conv.)	4.6
Prompt neutrinos (charm)	1.5
Overall	12.1 ± 3.4

- 2 years of data analysed

IceCube results (1: E vs. declination)

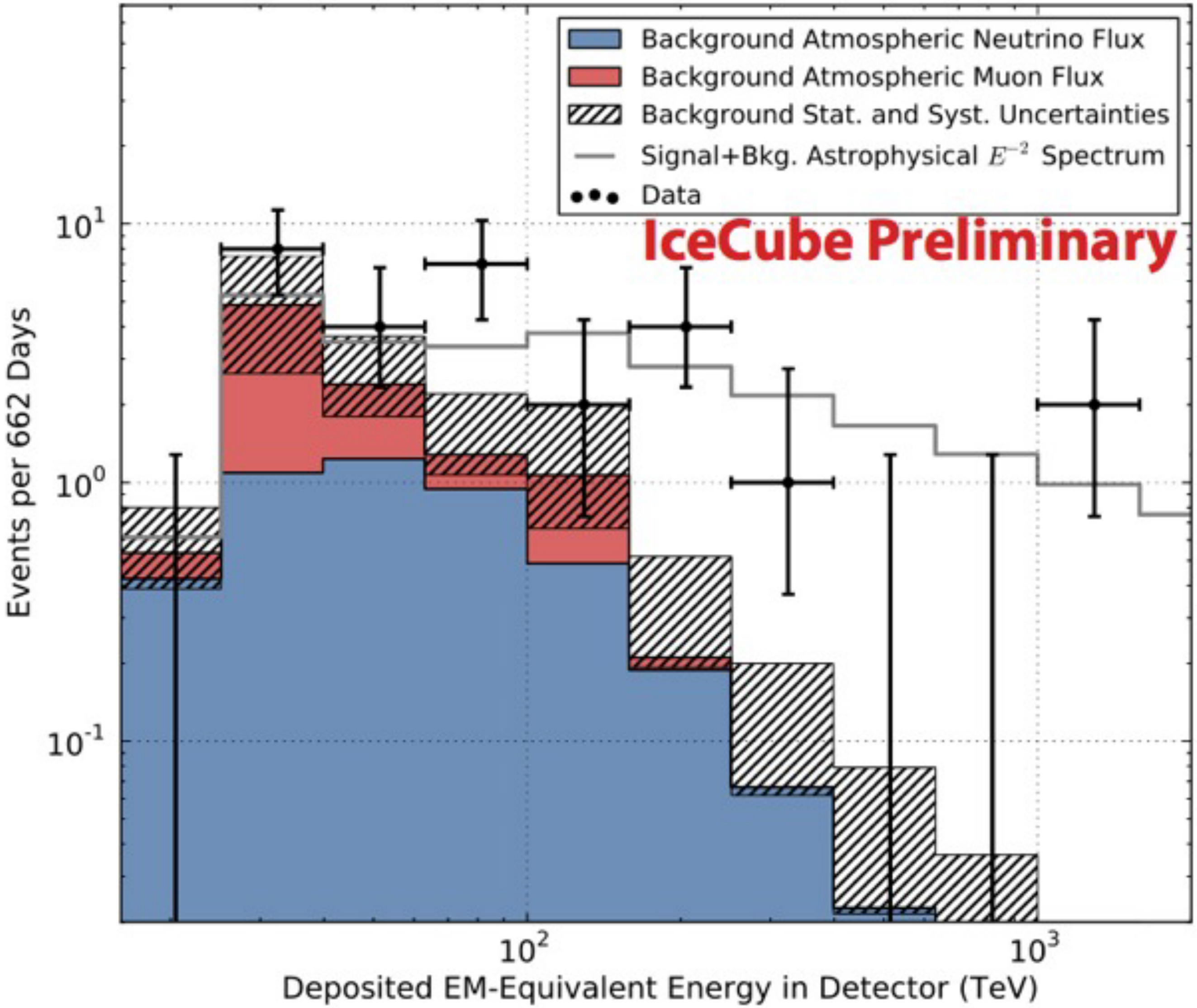
- 28 events observed, 12.1 expected
- Not compatible with background
- Significance 4.1 σ
- Meanwhile: Big Bird ….



7 track-like events	21 cascade-like events
1^o ang resolution	10^o – 45^o ang resolution
Muon takes some energy away	15% visible energy resolution

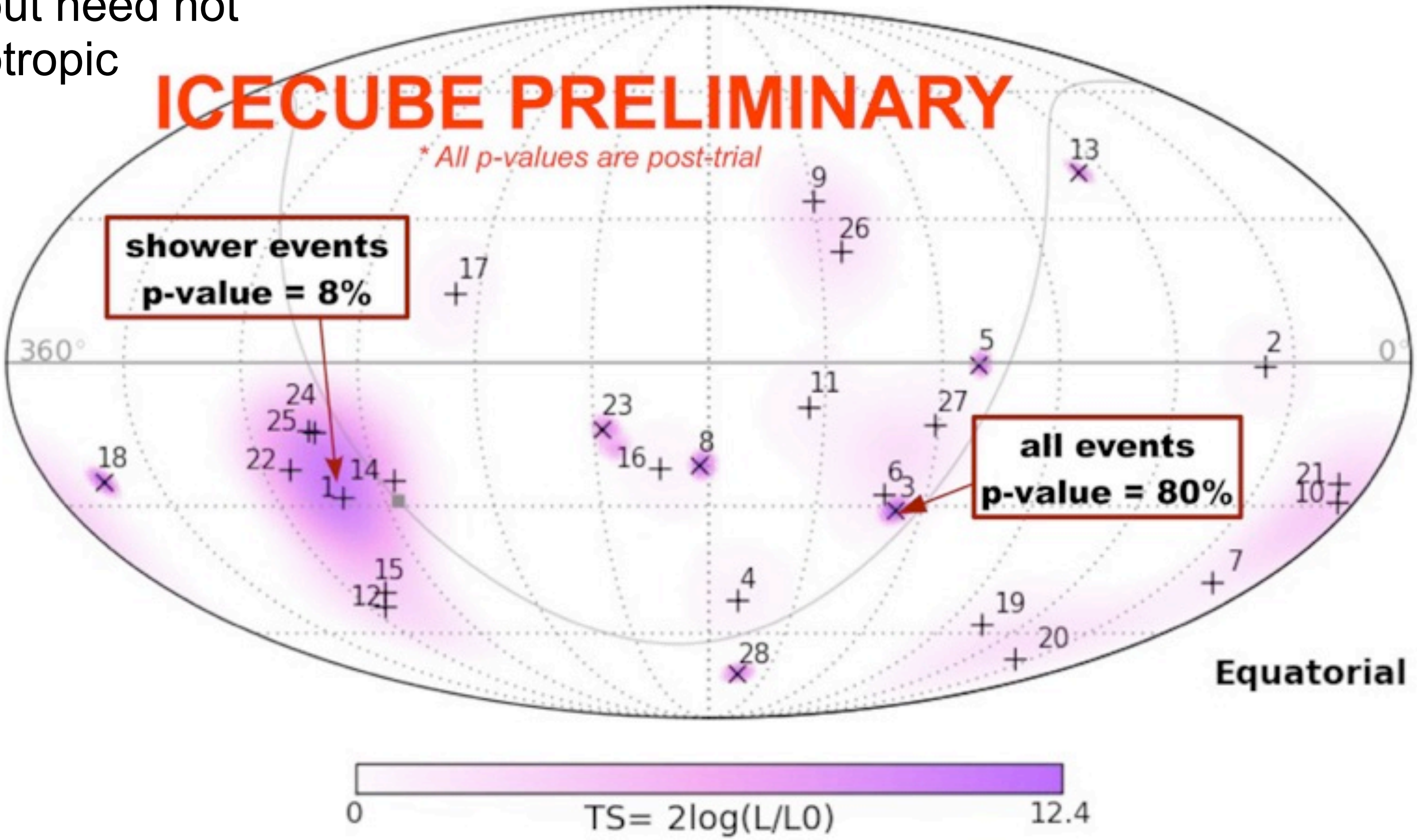
IceCube results (2: E distribution)

- Could be a E^{-2} spectrum
- Cutoff between 1 and 6 PeV likely



IceCube results (3: sky-map)

- Can but need not be isotropic



Studying lower-energy neutrinos

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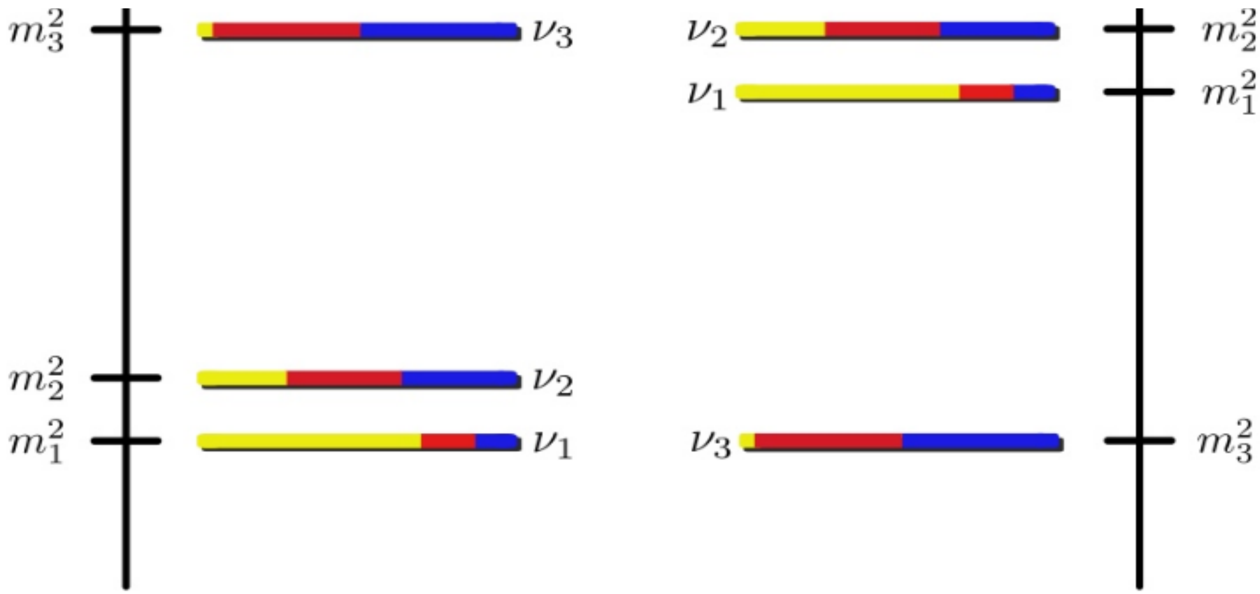
Neutrino mass hierarchy

- Depending on sign of Δm^2_{23} :
  "normal hierarchy" or "inverted hierarchy"
  (NH) (IH)



- A fundamental parameter of particle physics!

Mass hierarchy and atmospheric neutrinos

- Determining the sign of Δm^2_{23} requires matter effect. Oscillation of ν_e and/or $\overline{\nu}_e$ must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta_{13}^{\rm eff})\sin^2\left(\frac{\Delta_{13}^{\rm eff}L}{2}\right)$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \qquad \sin^2(2\theta_{13}^{\rm eff}) = \frac{\Delta_{13}^2\sin^2(2\theta_{13})}{\left(\Delta_{13}^{\rm eff}\right)^2}$$

$$\Delta_{13}^{\rm eff} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta_{13}^2\sin^2(2\theta_{13})}$$

$$A = \sqrt{2}G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2}G_F N_e \text{ for } \overline{\nu}$$

- "Matter resonance" for $A = \Delta_{13}\cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30\,\mathrm{GeV}/\rho[\mathrm{g\,cm^{-3}}]$

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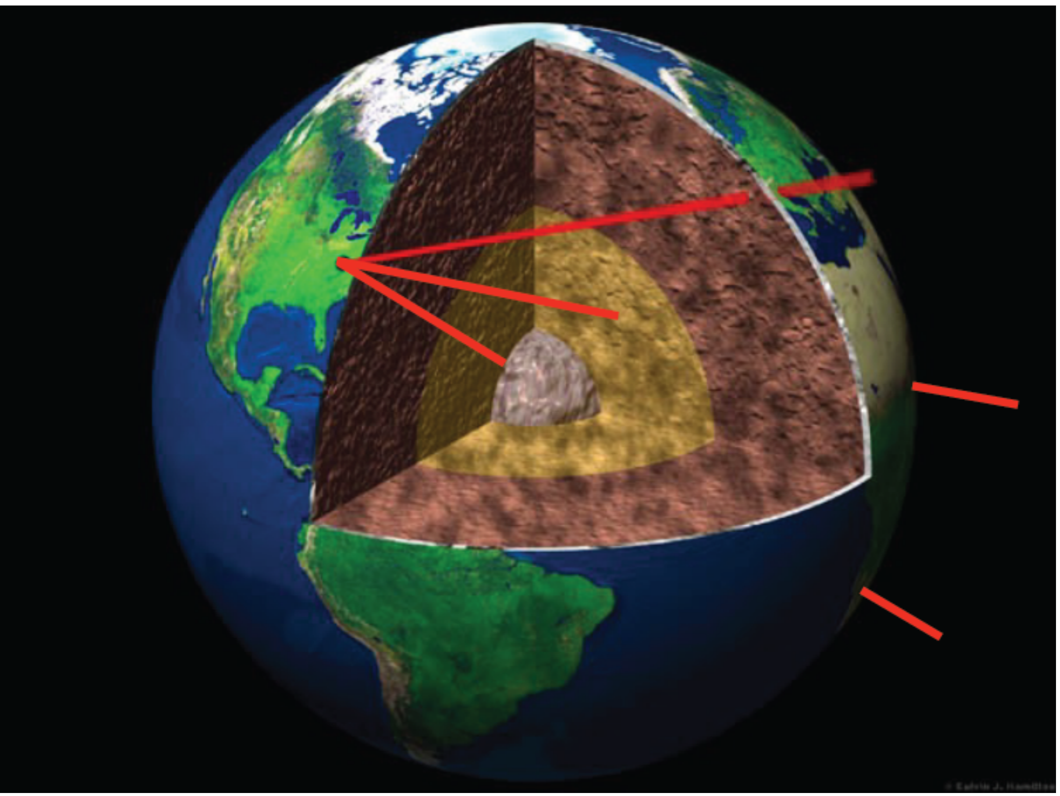
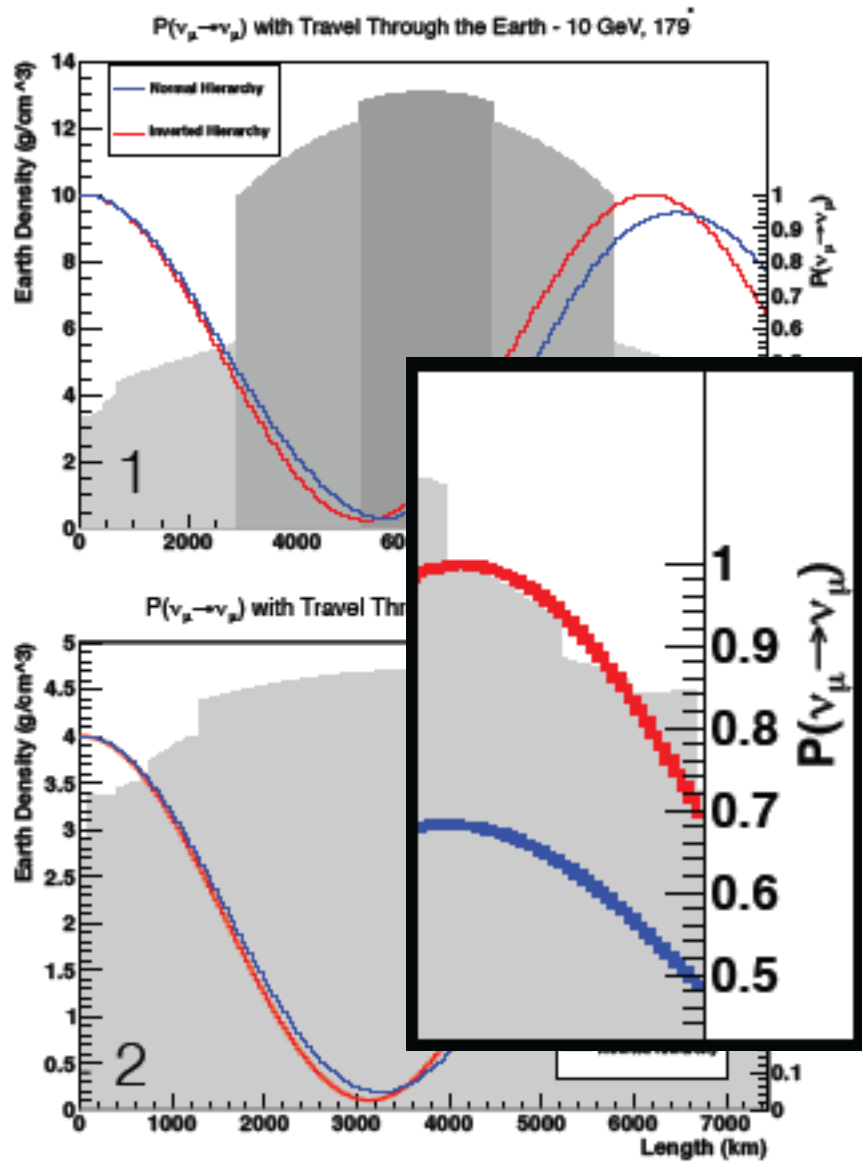
Neutrino oscillations in Earth

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





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The major experimental questions

- What are the trigger/event selection efficiencies?
- How and how efficiently can we separate different event classes?
- How can we reconstruct these events and what resolutions can we reach on E_ν and θ ?
- How can we control the backgrounds?
- What are the dominant systematic effects and how can we control them?
- What precision of calibration is needed and how can it be achieved?

A proposal requires knowing the answers!

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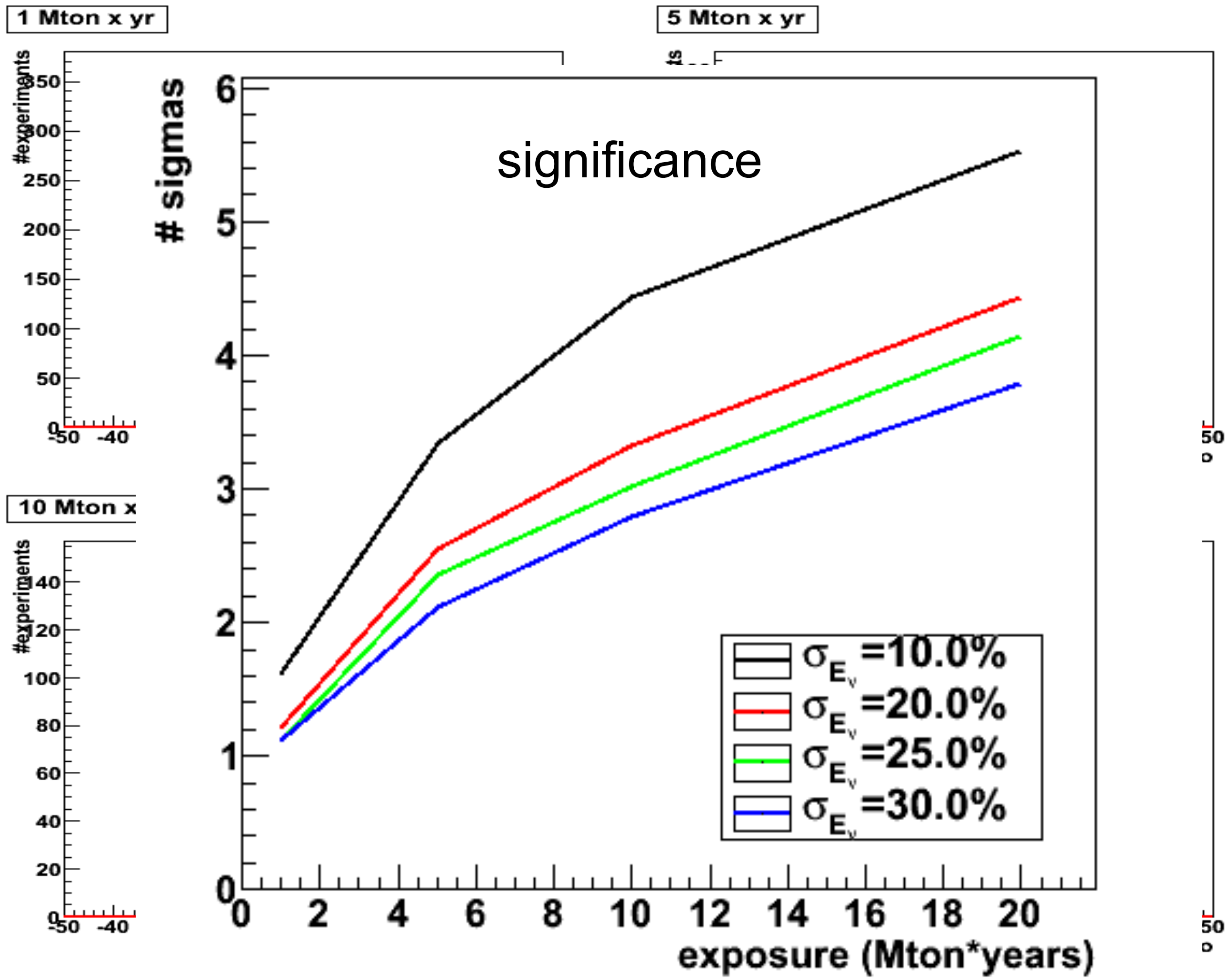
PINGU and ORCA

- PINGU (Precision IceCube Next-Generation Upgrade): Planned installation of additional strings in DeepCore region
  - Expected energy threshold few GeV
  - Letter of Intent for 40 strings in preparation
  - Claim: 3σ measurement in about 3 years
- ORCA (Oscillation Research with Cosmics in the Abyss): Option to employ KM3NeT technology for dense detector
  - Feasibility study in progress in KM3NeT
  - Final report expected early 2014
  - No immediate plans for funding applications or construction

ORCA: Results of toy analysis

- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of Δm^2_{23} and θ_{23} seems possible
- Note: ORCA is not an option for first KM3NeT phase



Summary and outlook

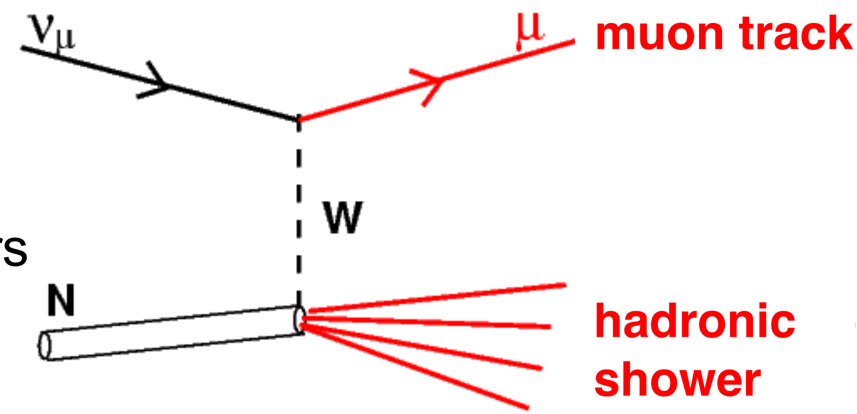
- Neutrinos taught us the Standard Model and have shown us the first physics beyond the Standard Model
- We want them to also reveal the mysteries of high-energy astrophysics
- Neutrino telescopes are reaching the required senstivity
- IceCube has seen a first signal of cosmic Neutrinos
- KM3NeT is on its way … stay tuned!

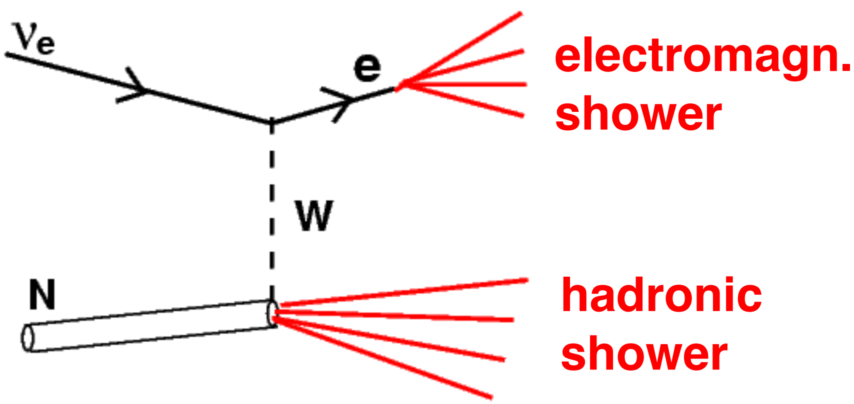
Alles Gute zum Geburtstag,
lieber Norbert Schmitz,
und auf viele weitere gesunde Jahre!

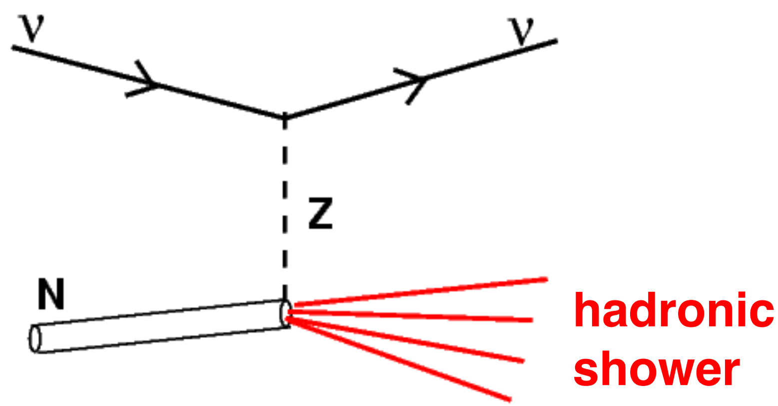
Backup

Neutrino Interaction Signatures

- Neutrinos mainly from π-μ-e decays, roughly $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$.
- Arrival at Earth after oscillations: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$.
- Experimental signatures: long tracks vs. short cascades/showers







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Deployment Strategy

- Compact package – deployment – self-unfurling
  - Eases logistics
    (in particular in case of several assembly lines)
  - Speeds up and eases deployment;
    several units can be deployed in one operation
  - Self-unfurling concepts is being thoroughly tested and verified
- Connection to seabed network by ROV

RX J1713: Caveats

- Analysis based on TDR detector configuration
- New version (see talk by Maarten):
  - 6 building blocks, 115 strings each (was 2 times 310)
  - 36m vertical distance (was 40m)
  - 18 modules per string (was 20)
  - string distance 90 m (was 100m)
- Systematic studies of PMT parameters (QE, acceptance, TTS) in simulation
- Still under investigation: μ energy reconstruction
  (currently used: number of hits)
- Discovery time depends strongly on flux sensitivity
  → variations of FoM in range 5 … 9 years in binned analysis
  → currently under scrutiny

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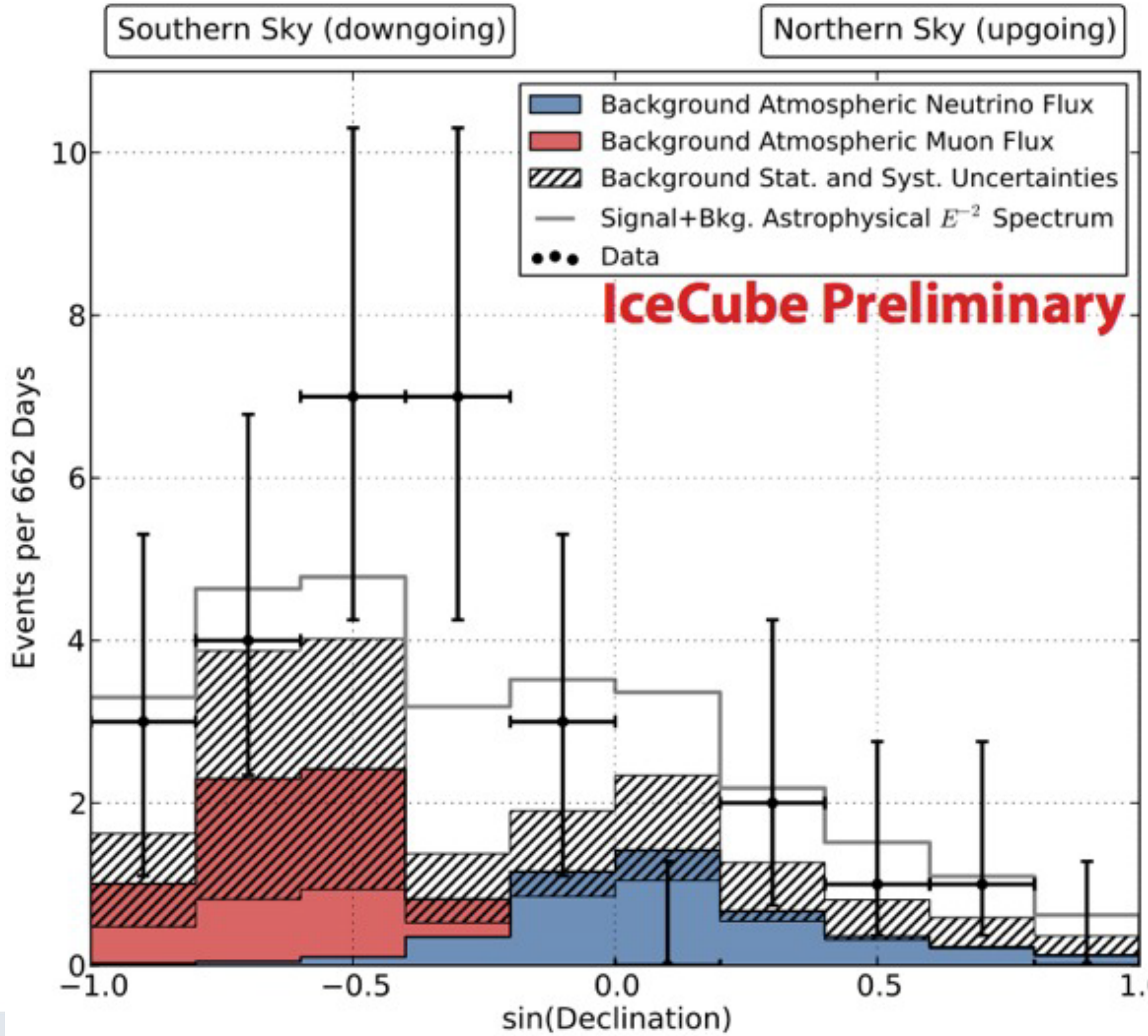
IceCube results (4: declination distribution)

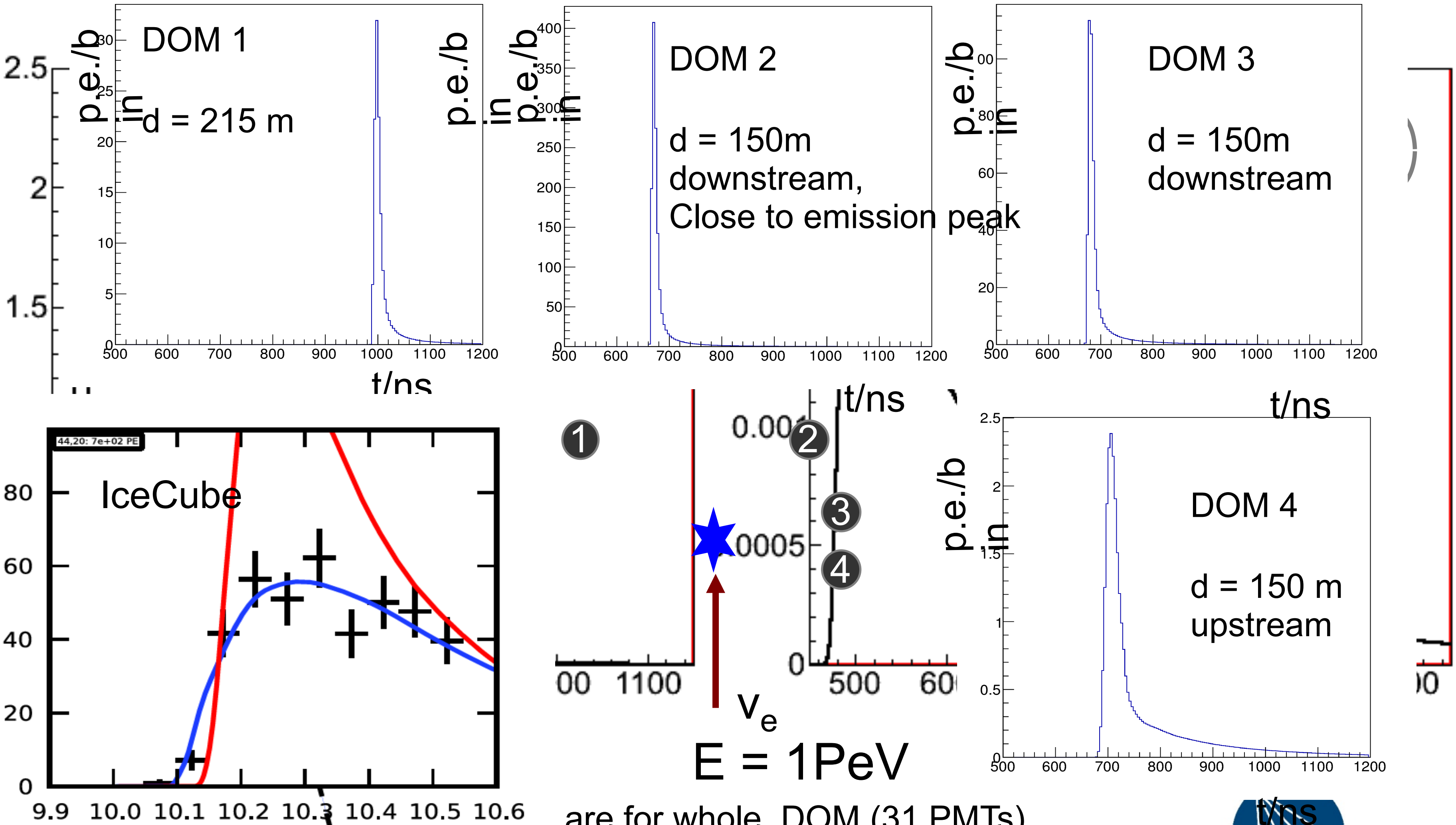
- No significant deviation from expectation for isotropic flux



Some KM3NeT specifics

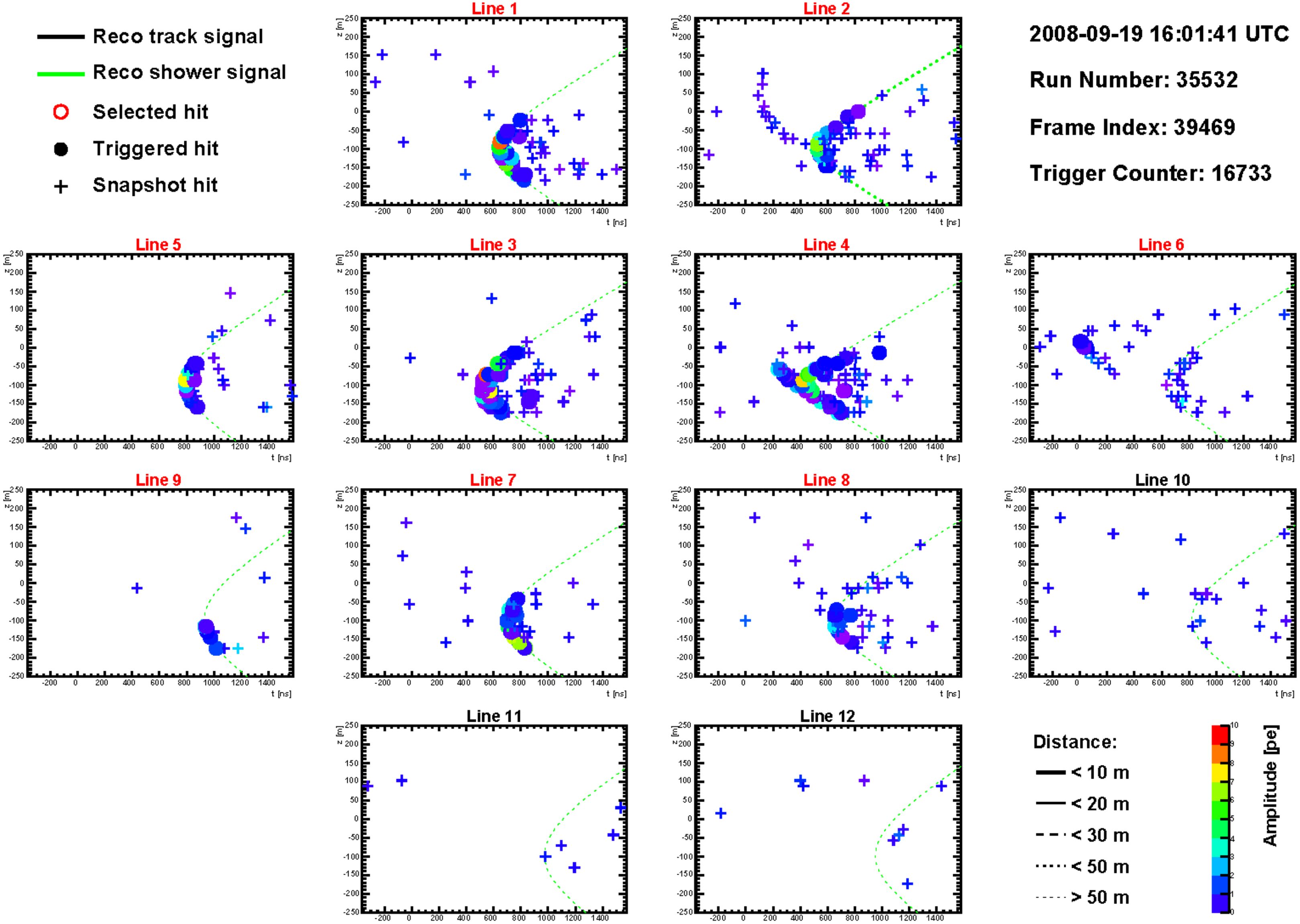
- Multi-PMT DOMs:
  - Very good 1-vs-2 photoelectron separation
  - Directional sensitivity
    → PMTs without signal carry information
    → Sampling a Cherenkov front with different PMT viewing angles can resolve saturation effects
  - 12 of 31 PMTs pointed to upper hemisphere
    → Advantage in atmospheric muon recognition and suppression
- Water is highly homogeneous and its optical properties are well understood
  - Very good timing
    → Options for "veto techniques" without sacrificing part of the detector
    → Angular resolution of a few degrees for cascades in reach

Example: Light arrival PDFs



are for whole DOM (31 PMTs)

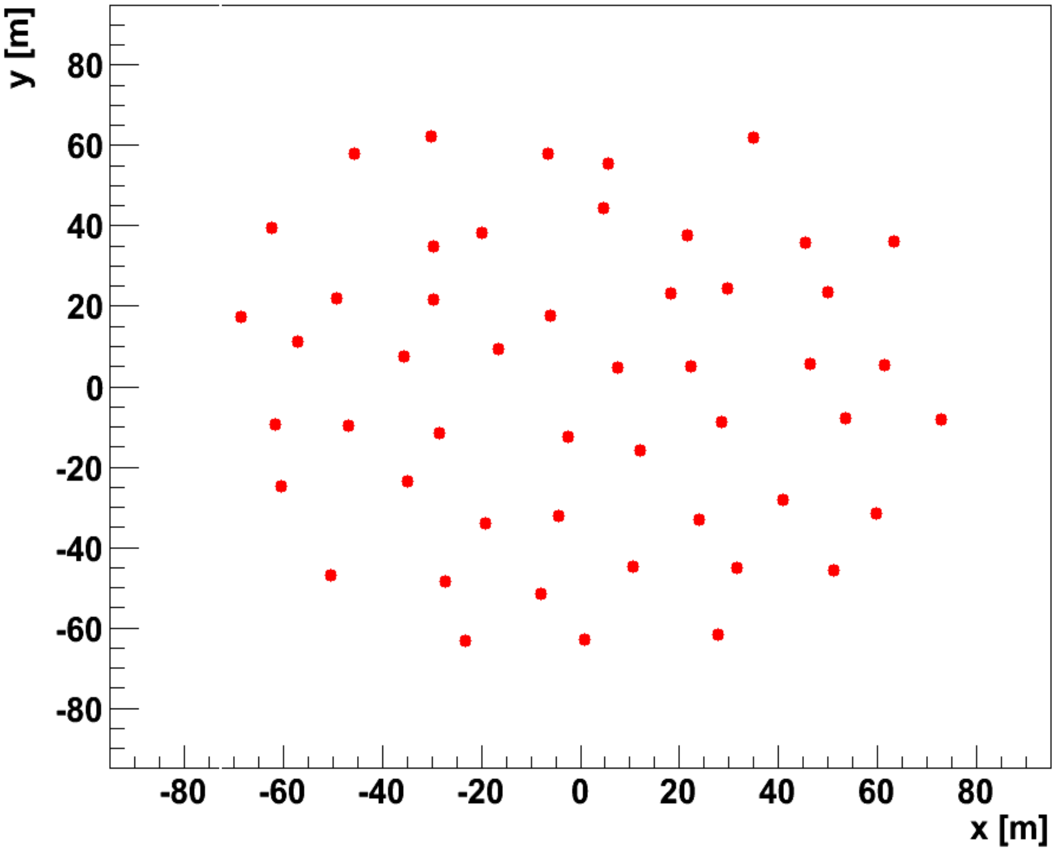
ANTARES: A shower event with muon



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

This is just a (scalable) example configuration



Note: ORCA construction in Phase-1 is not an option
Also under study: Beam option (e.g. from Protvino)

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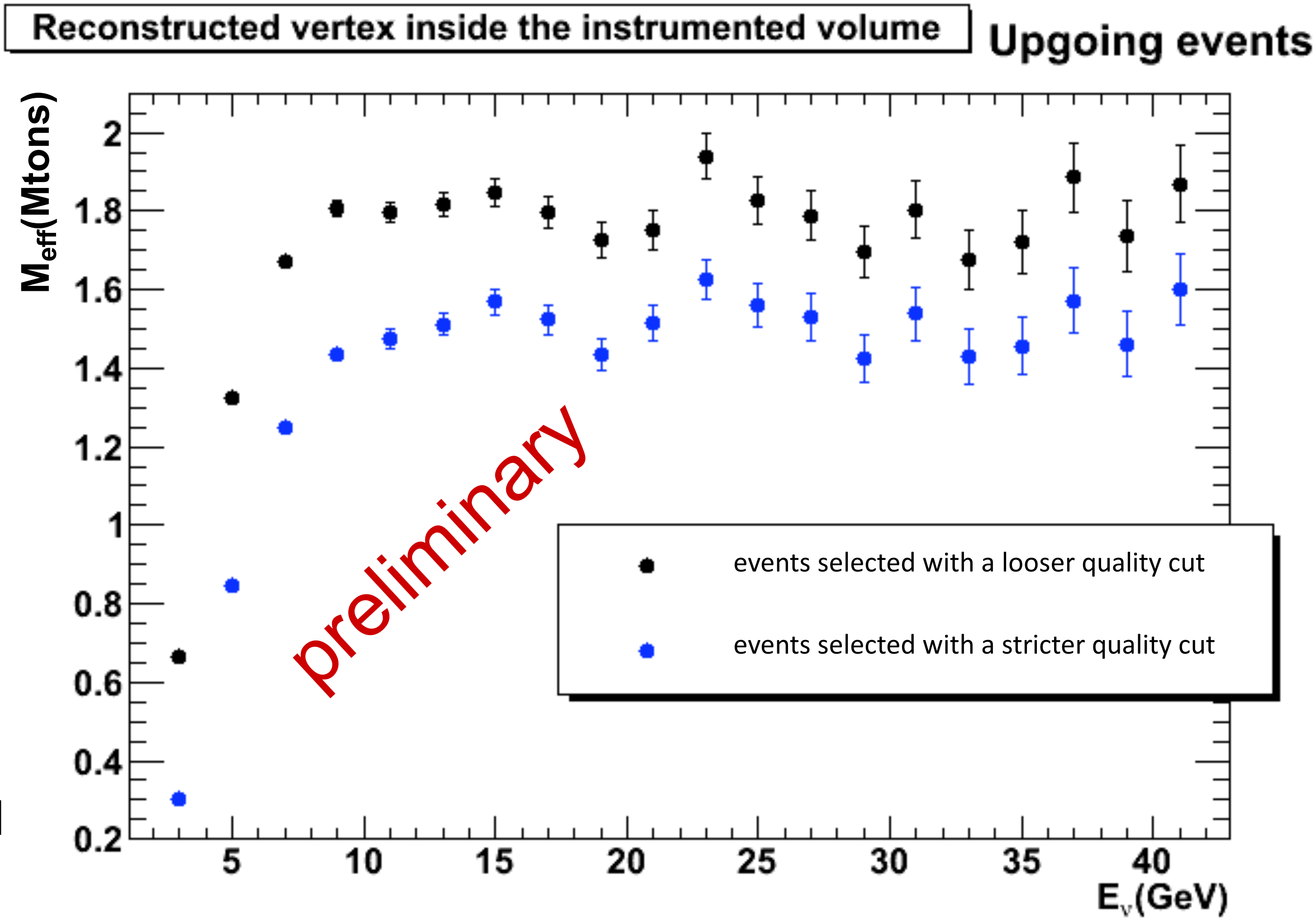
ORCA reconstruction efficiency

- Isotropic ν_μ CC events generated
- Event must be reconstructed as up-going with vertex in instrumented volume
- Efficiencies determined for two levels of quality cuts
- No background rejection



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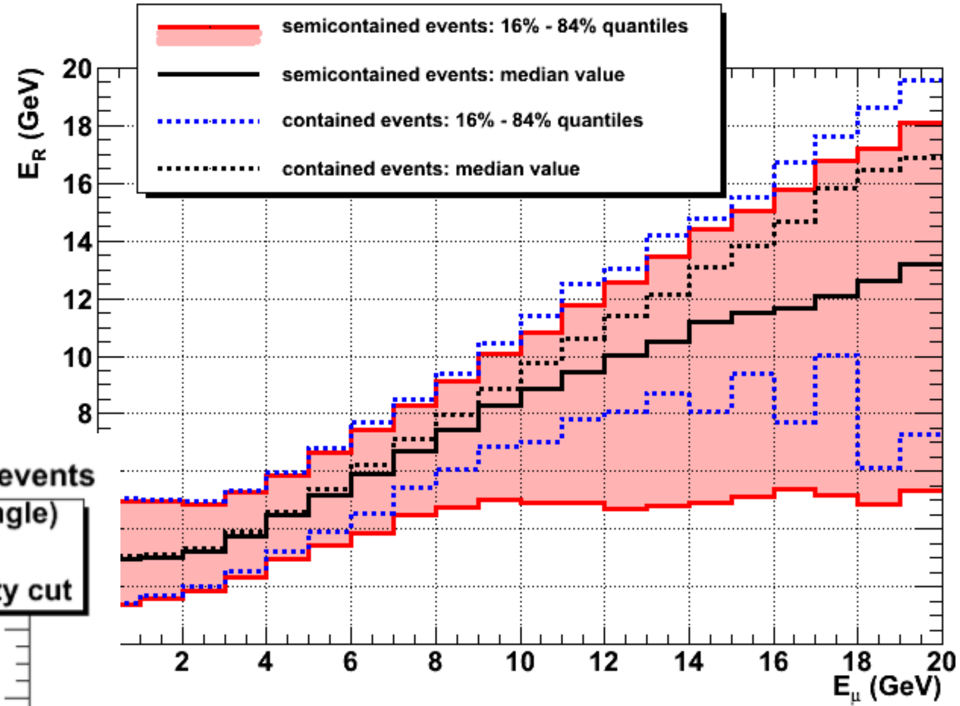
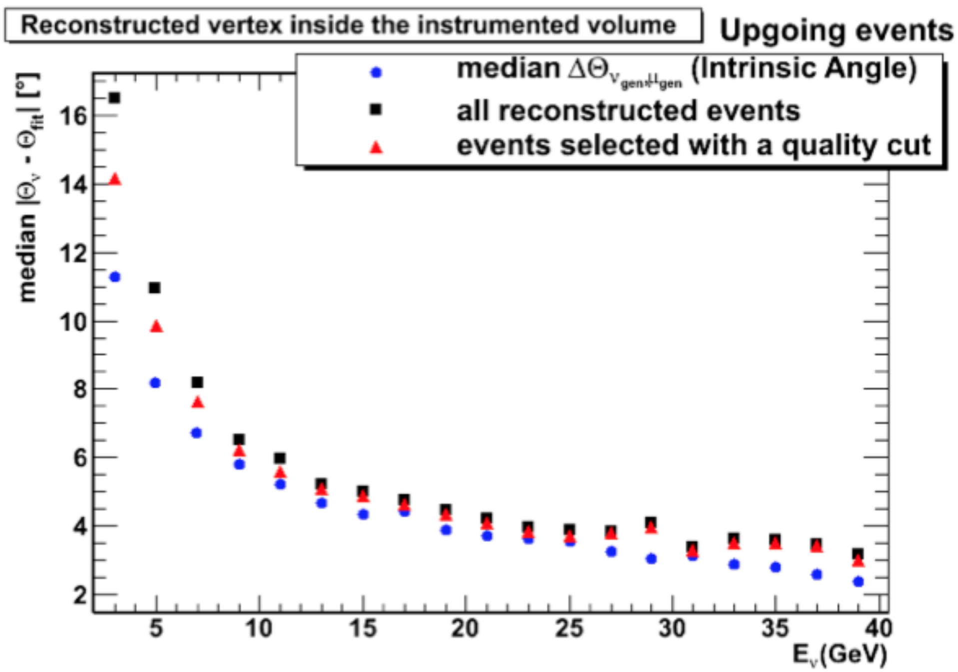
ORCA energy and zenith resolutions

- E_μ reconstructed from μ track length
- Shaded region: 16% and 84% quantiles as function of E_μ^{true}
- $\Delta E_\nu \overset{?}{\approx} 1\,\text{GeV}|_\mu + 0.2 E_{\text{shower}}$





- Median of zenith angle difference ν – rec. μ

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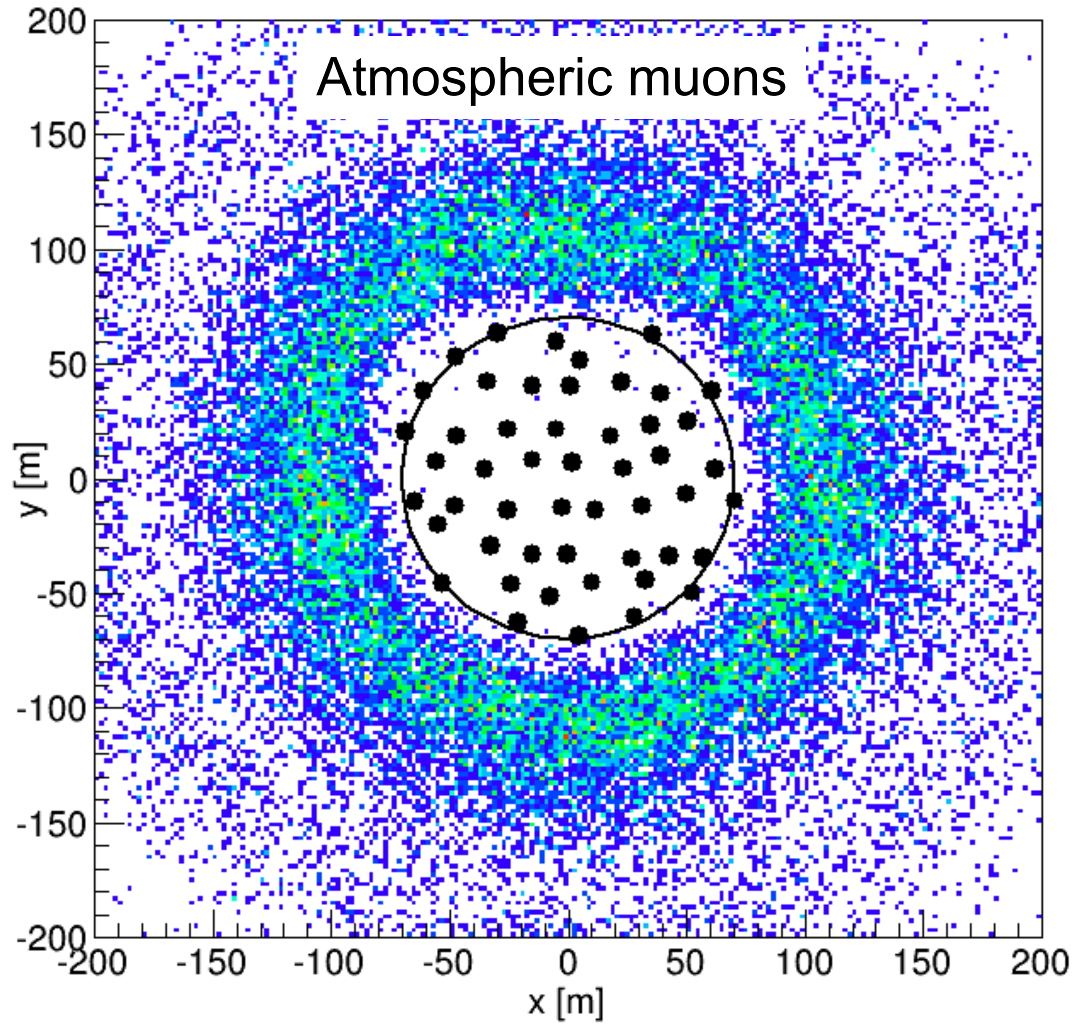
ORCA: A recent analysis progress

- Use quality cuts on muon (angular uncertainty, reconstruction quality)
- Investigate reconstructed vertex position



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