Neutrino astronomy: Observations around the globe

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Physics Colloquium, University of Wuppertal
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KM3NeT

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

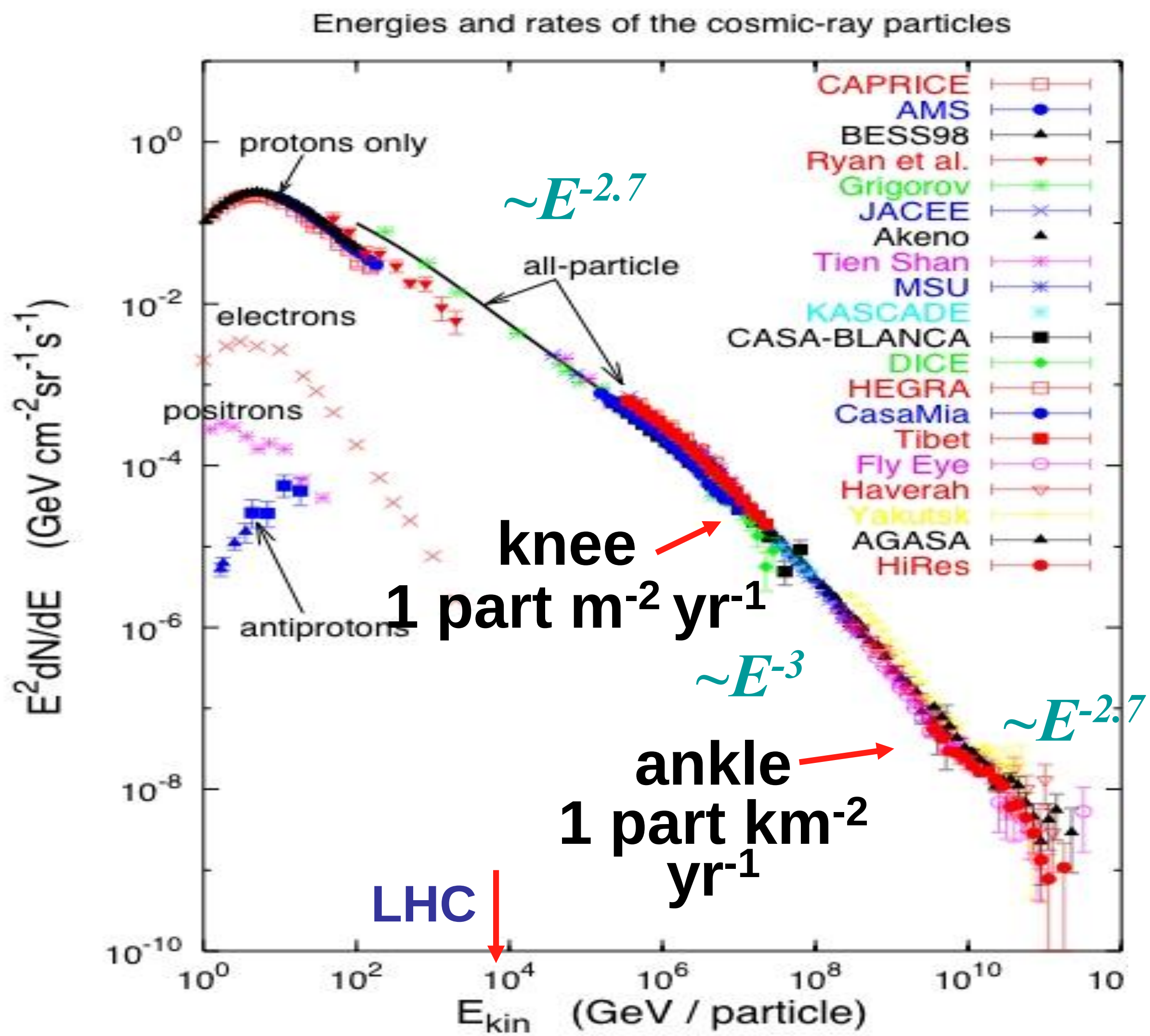
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

The plan for the next 45+ minutes

- Introduction to neutrino astronomy
- First detection of cosmic neutrinos with IceCube
- KM3NeT: Design, status, prospects
- Measuring the neutrino mass hierarchy
- Summary and outlook

Neutrino astronomy

The mysterious cosmic rays



- Particles impinging on Earth from outer space carry energies up to
  10^{21} eV
  (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.

Neutrino production mechanism

- Neutrinos are produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}...) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\downarrow$$

$$e^{\pm} + \bar{\nu}_{e}(\nu_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

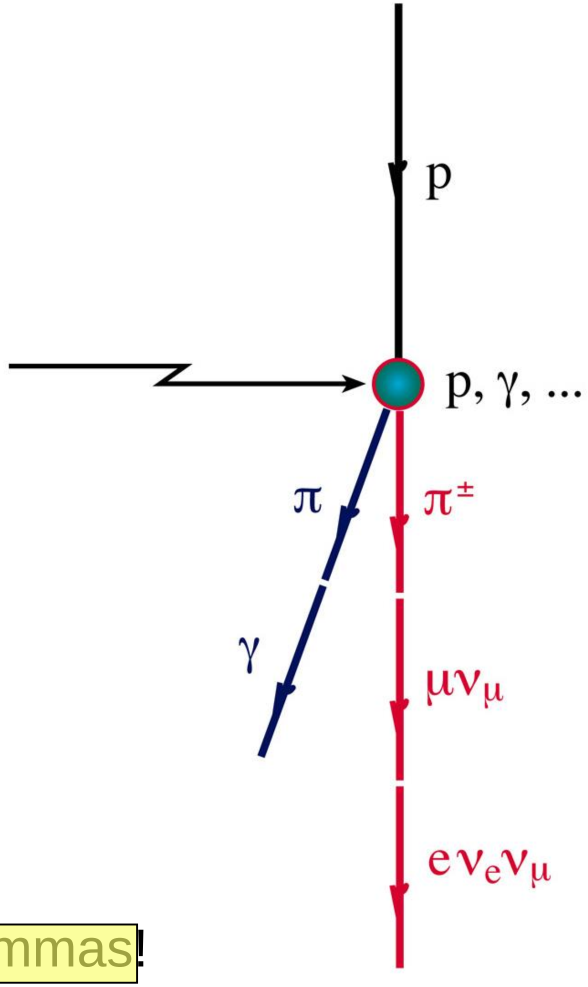
Cosmic rays

- Simultaneously, gamma production takes place:

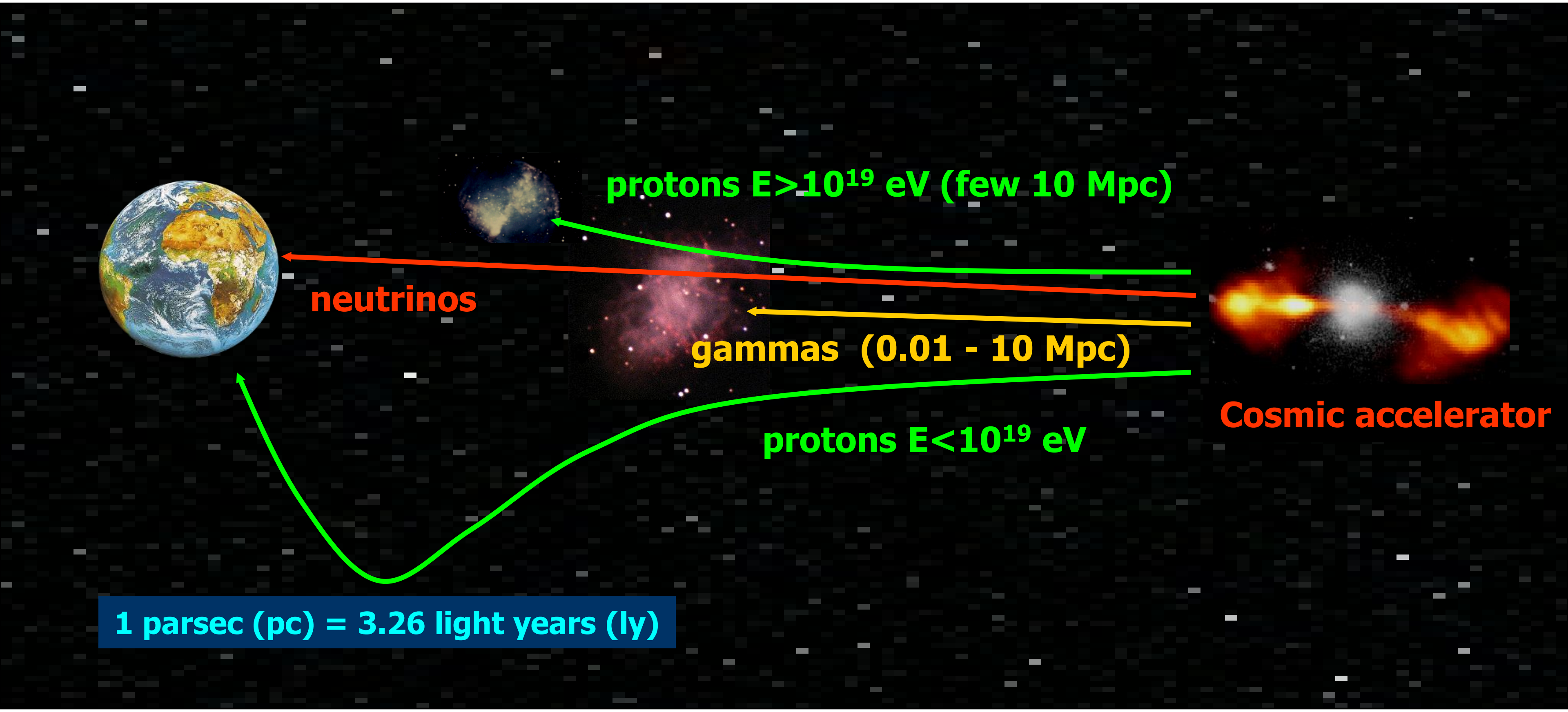
$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\ \gamma + Y$$

Cosmic rays

- Cosmic ray acceleration yields neutrinos and gammas!
- … but gammas also from purely leptonic processes



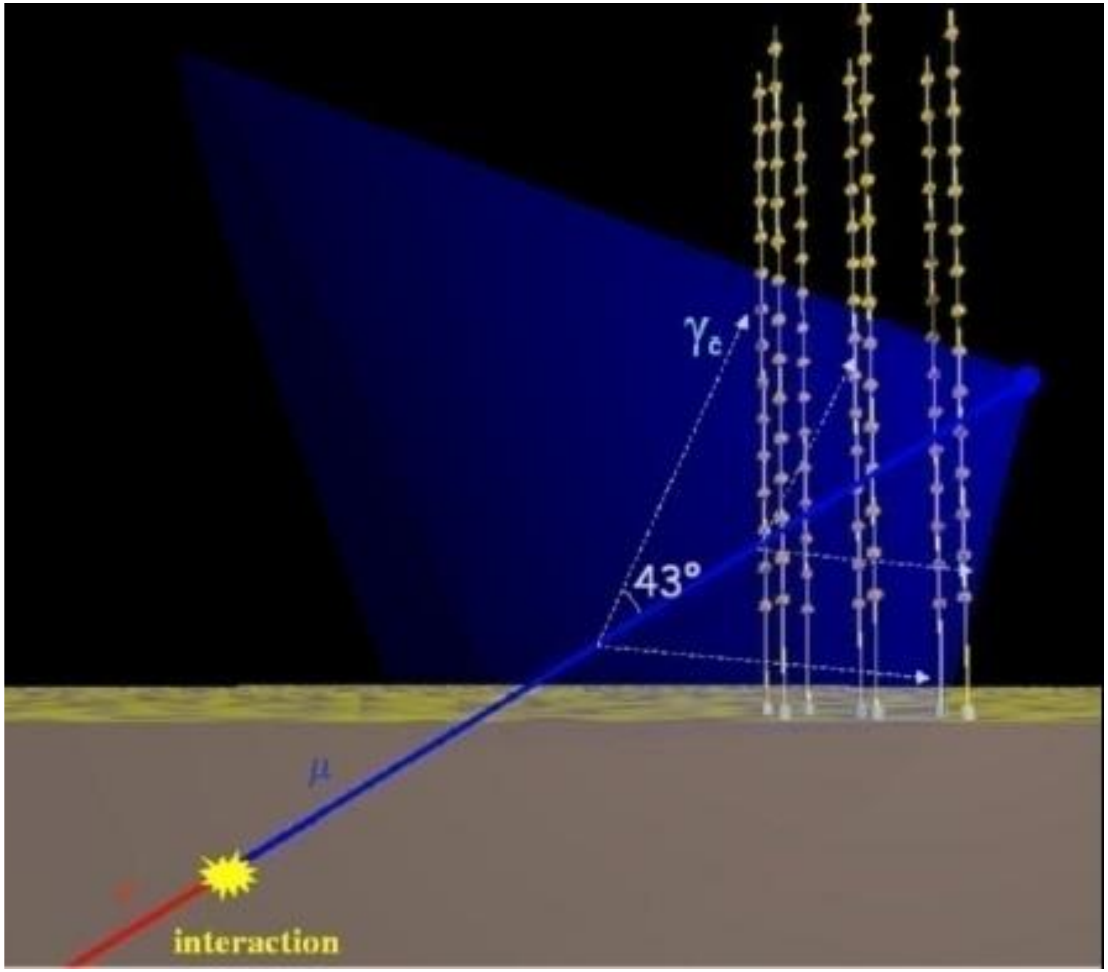
Particle propagation in the Universe



Photons: absorbed on dust and radiation;
Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

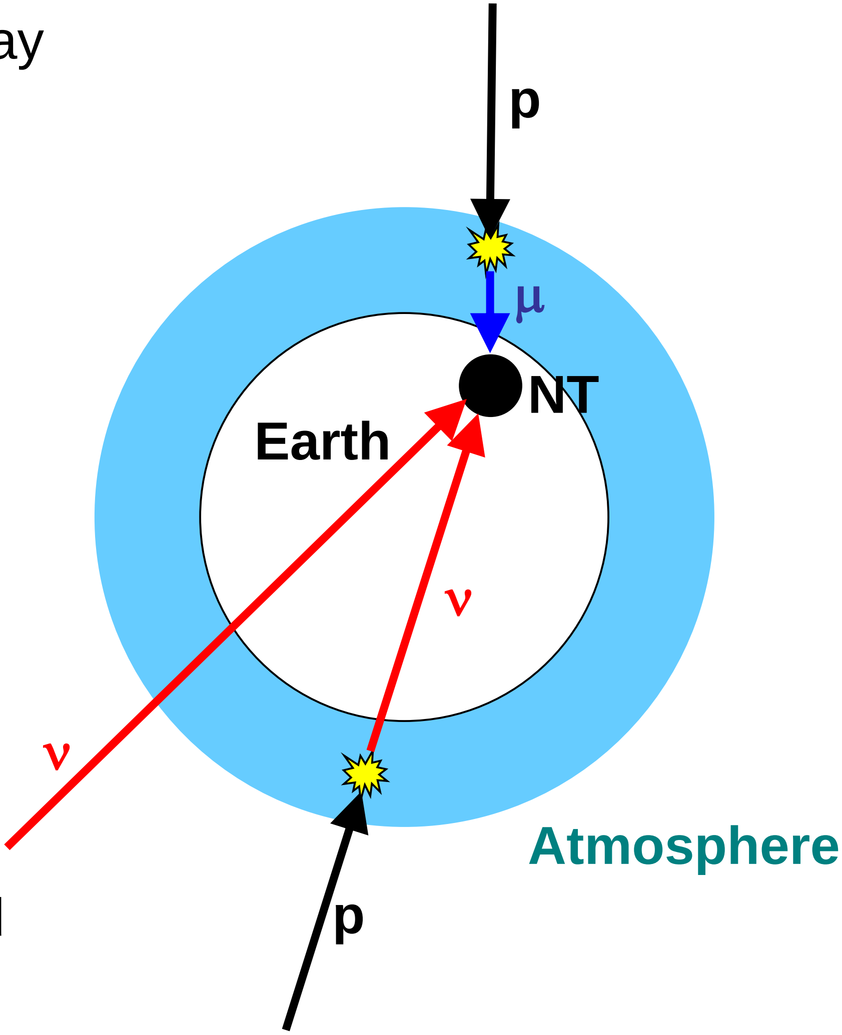
How does a neutrino telescope work?

- 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

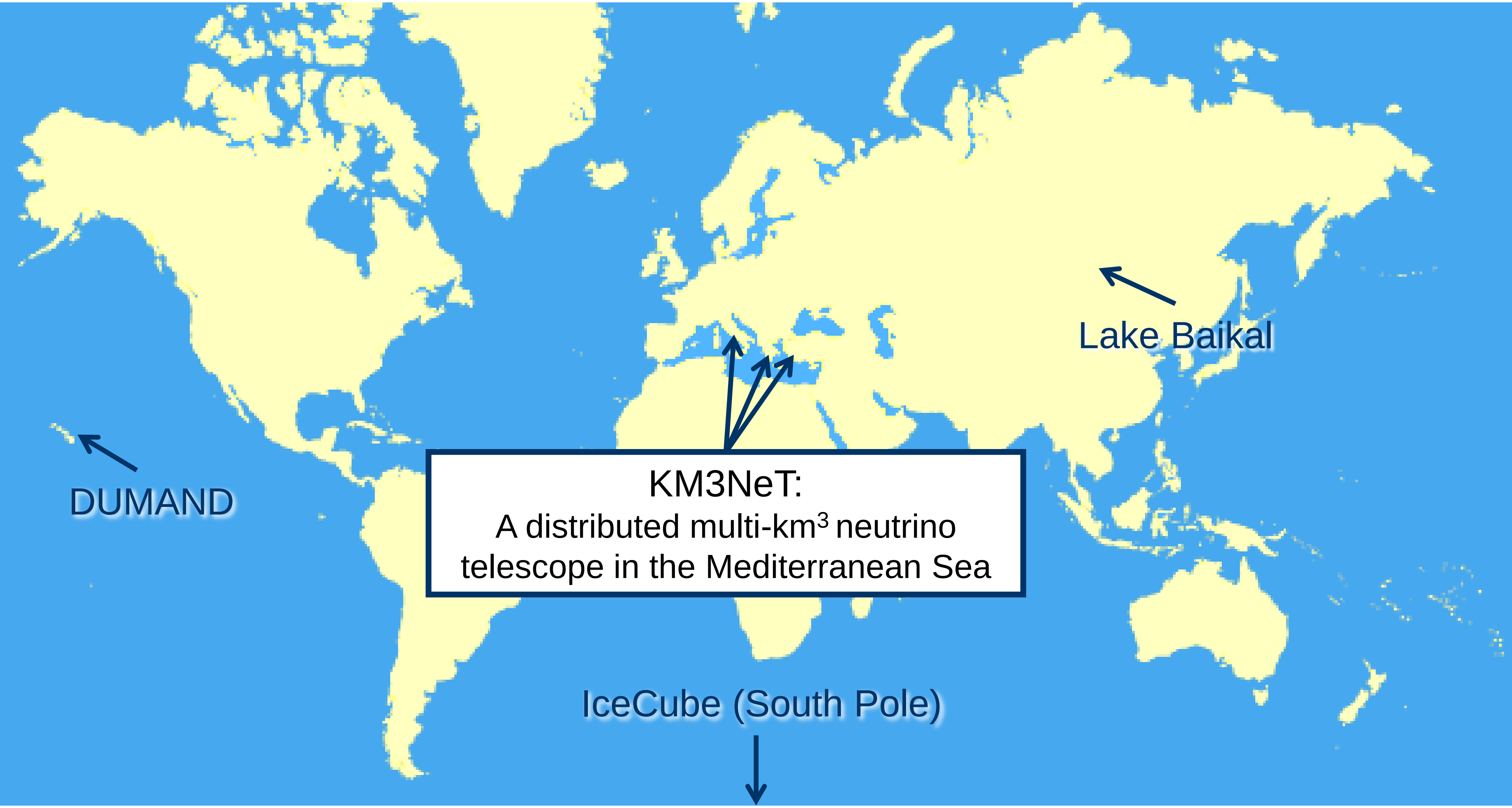


Backgrounds, or maybe not

- 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

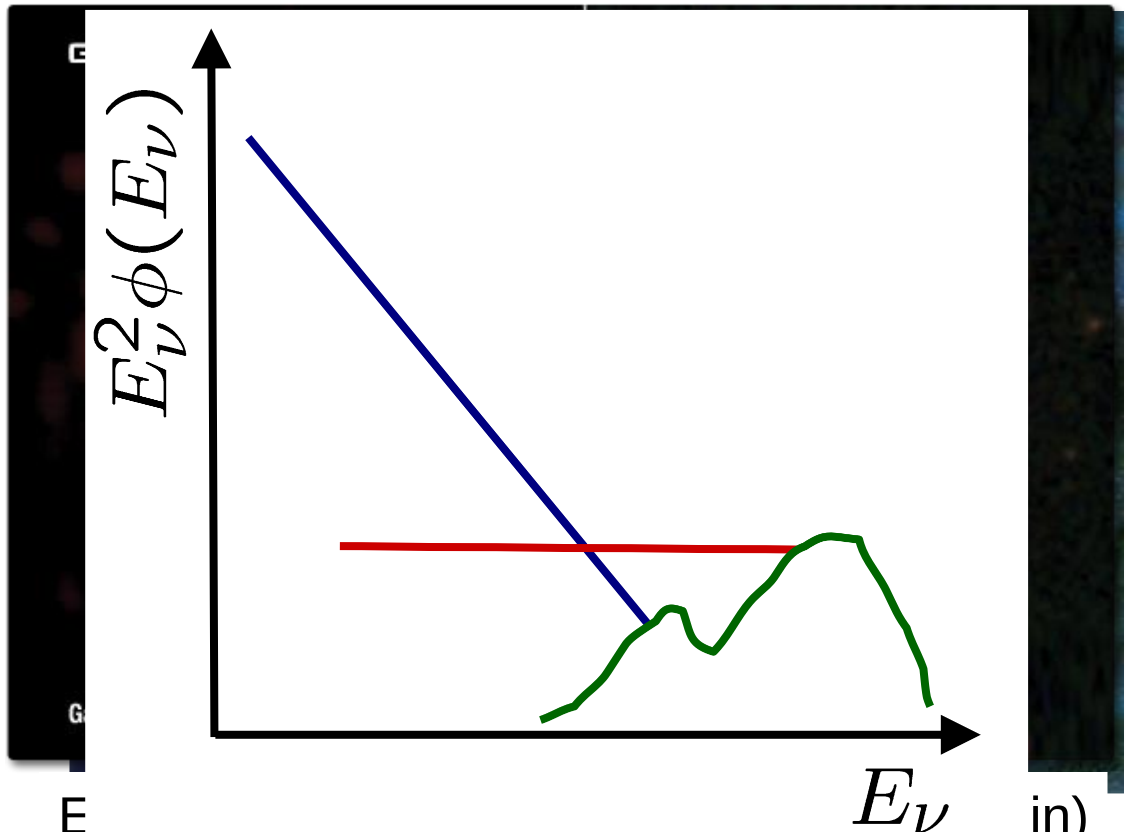


The ν telescope world map



Example targets of ν 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

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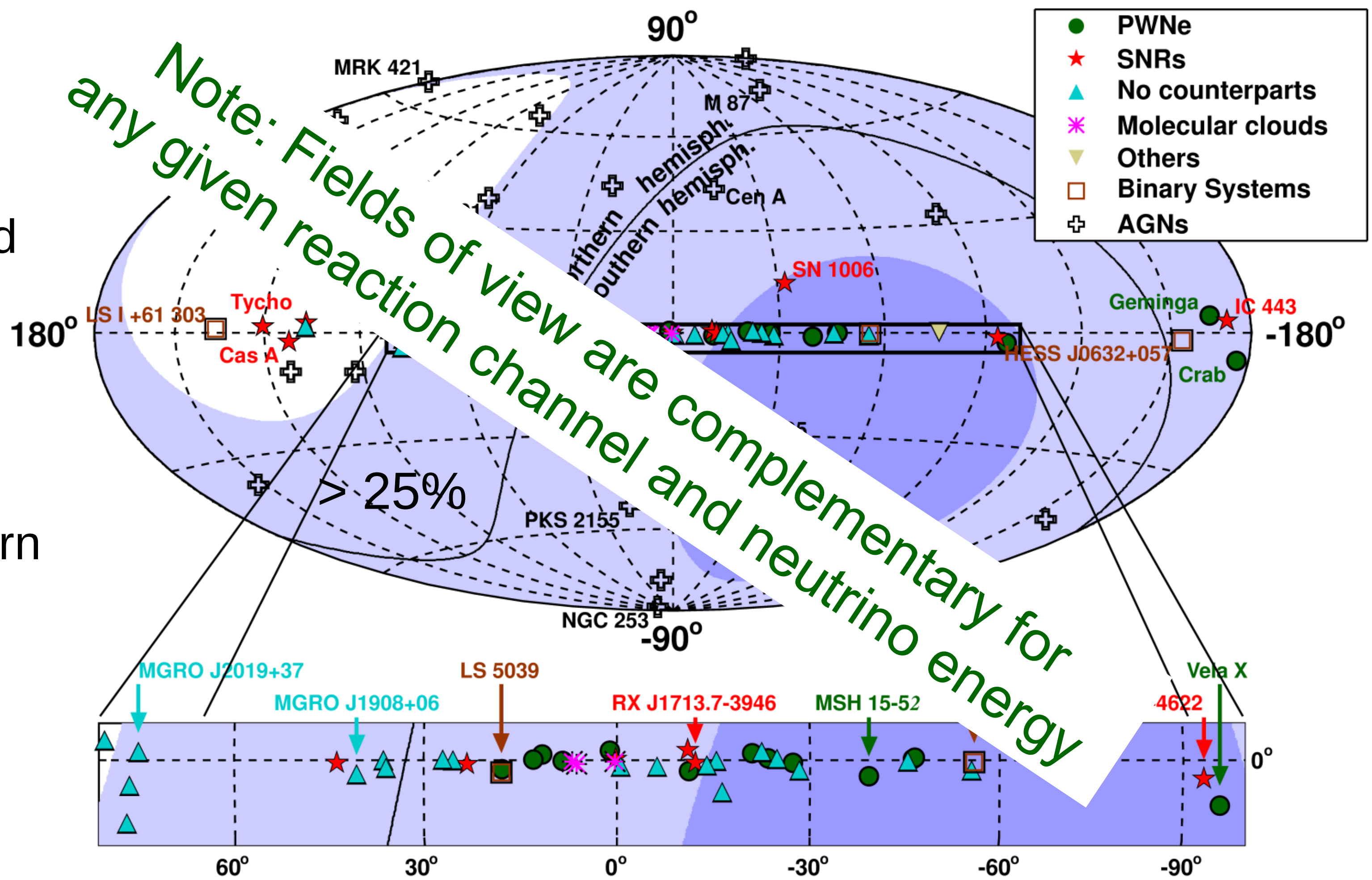
Galactic coordinates

2π downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere



Note: Fields of view are complementary for any given reaction channel and neutrino energy

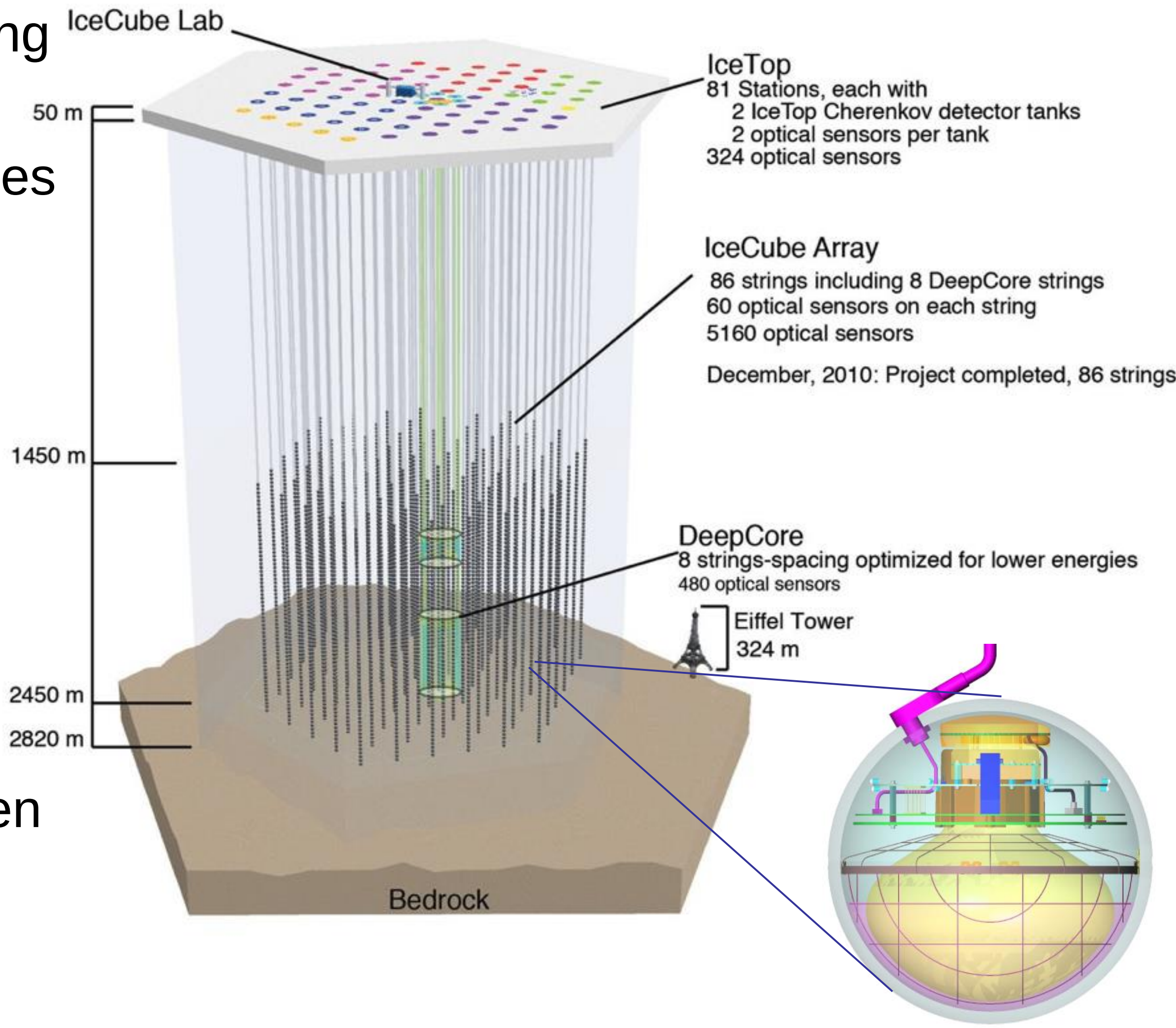
IceCube and the first detection of cosmic neutrinos

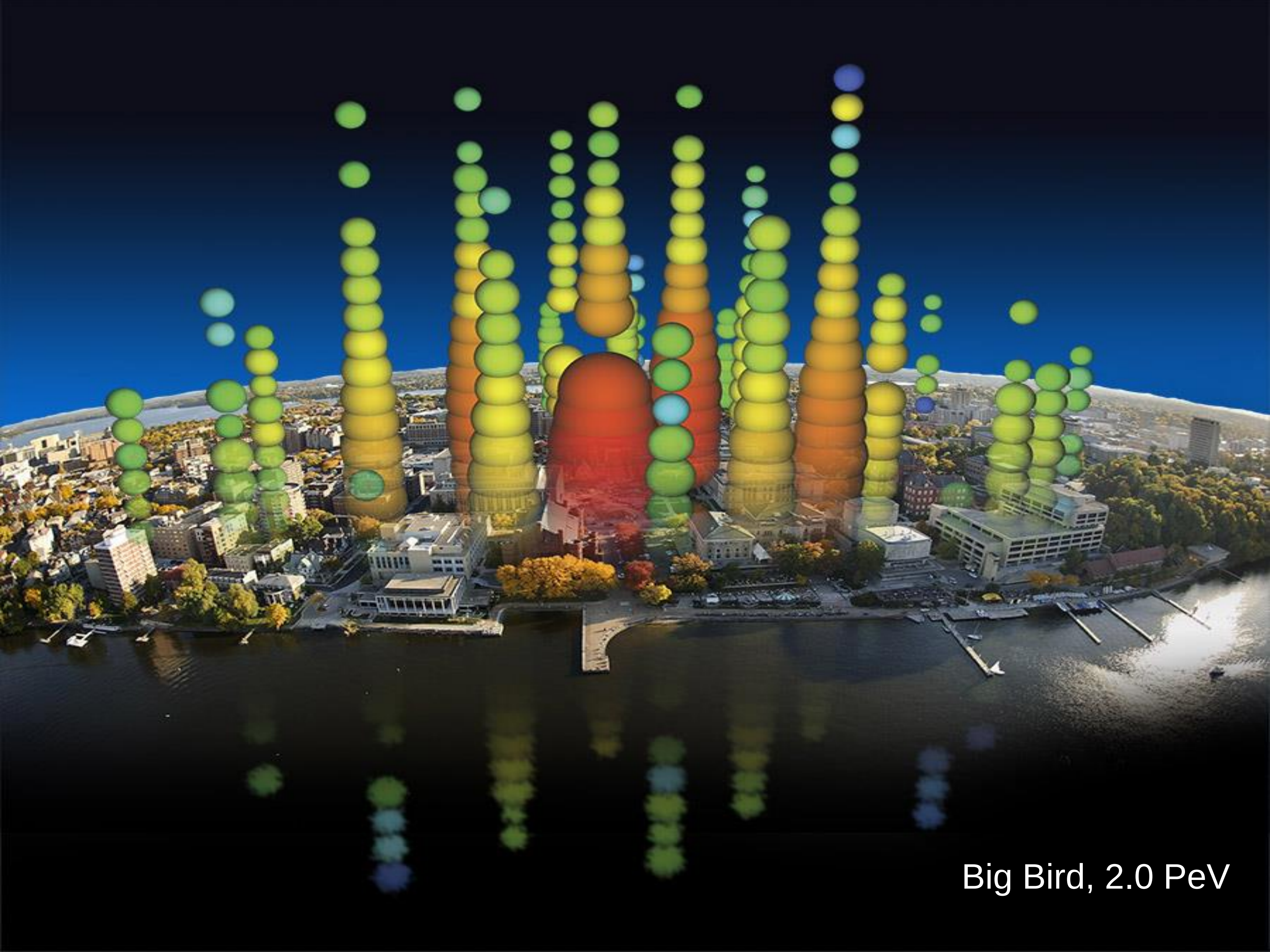
Several slides adapted from:
F. Halzen: “IceCube: the discovery of cosmic neutrinos”, VHEPA 2016
K. Hanson: “IceCube Gen2”, VHEPA 2016

IceCube: A km^3 detector in the Antarctic ice

The IceCube detector

- 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
- Completed in Dec. 2010
- Extremely stable and efficient operation since then

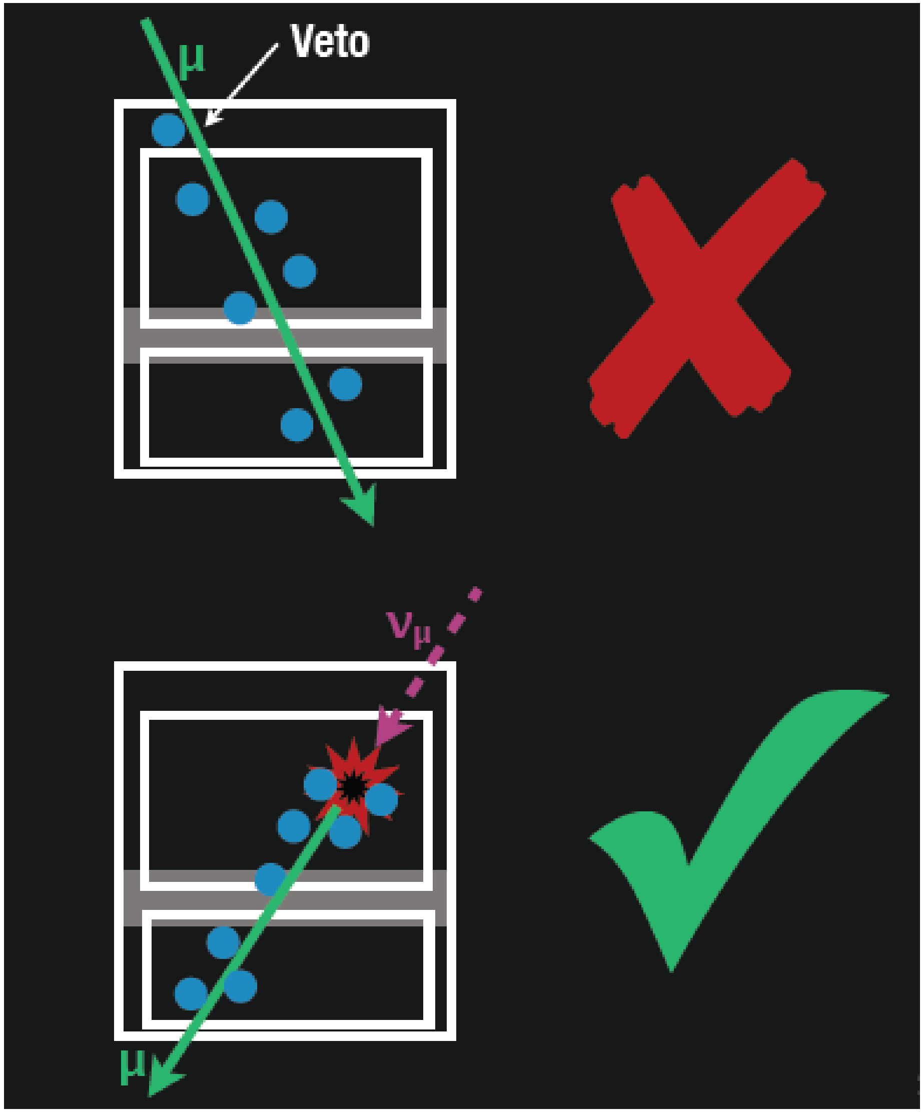




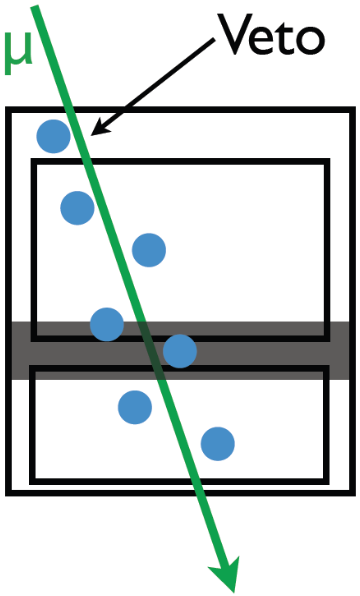
Big Bird, 2.0 PeV

Systematic search for such events …

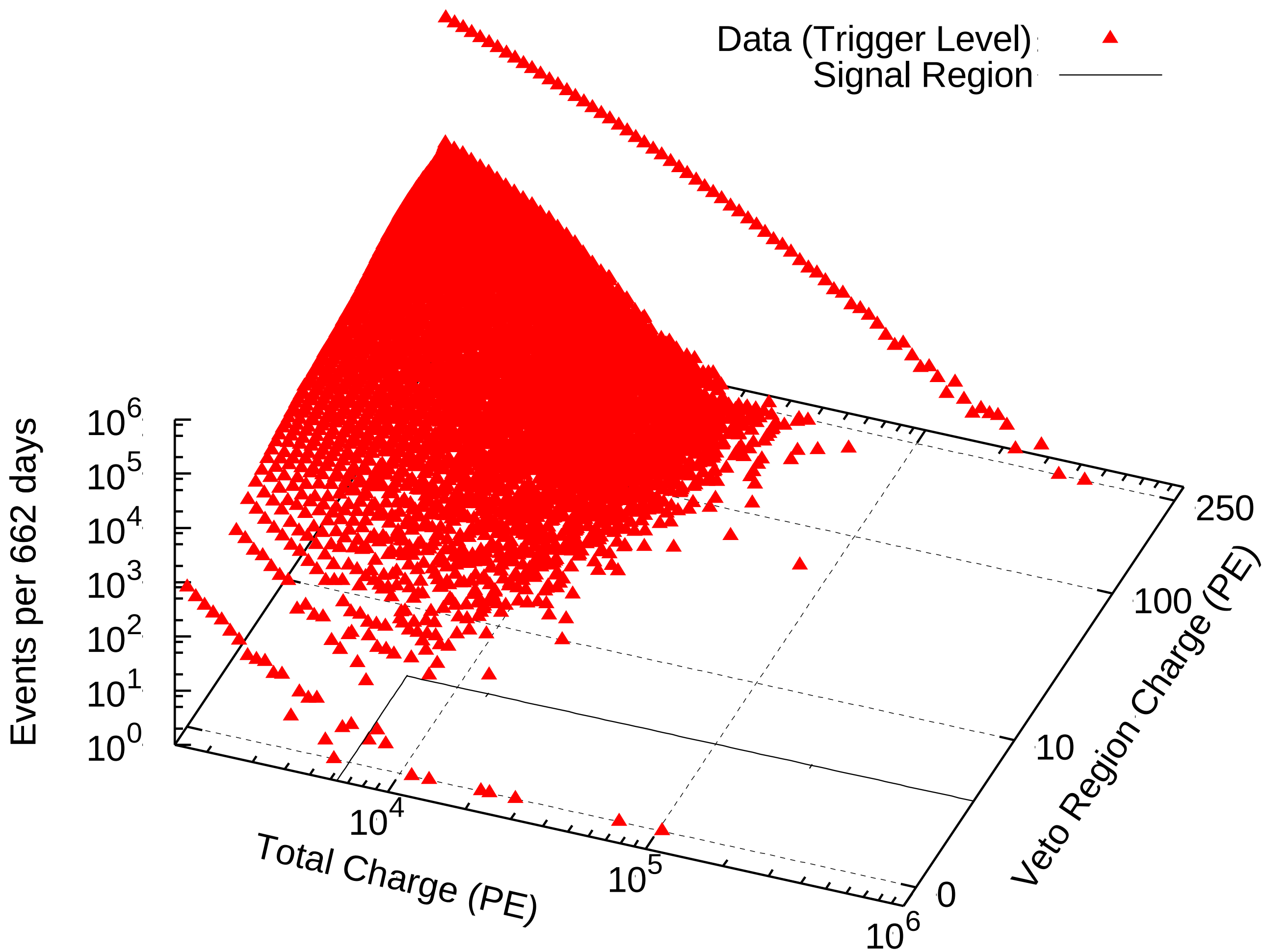
- Select events interacting inside the detector only
- No light in the veto region
- Veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- Energy measurement: total absorption calorimetry
- → “High-energy starting events” (HESE)
- Meanwhile further analyses



… success!

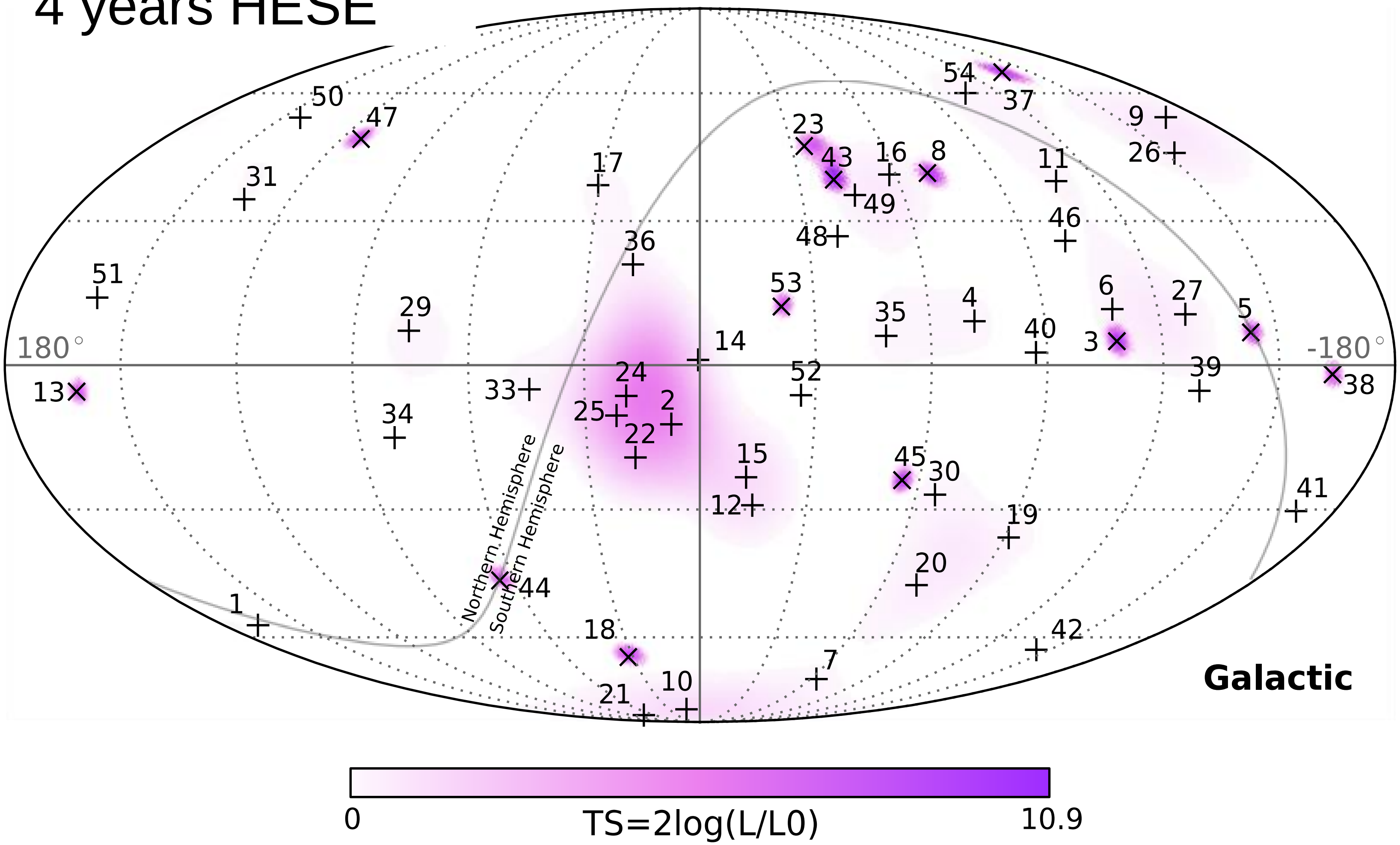


26 events in one year of data!

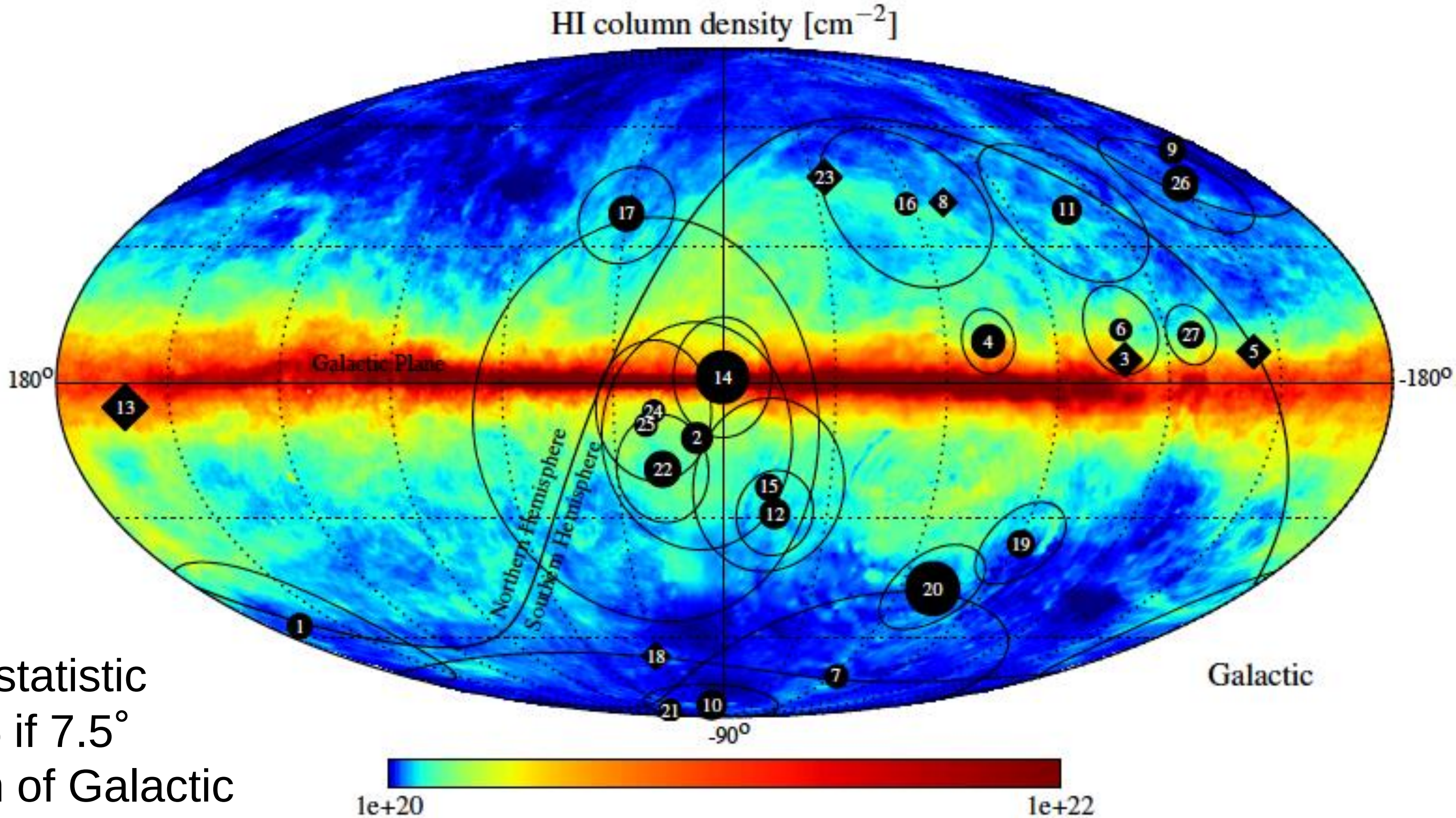


Where do they come from?

4 years HESE



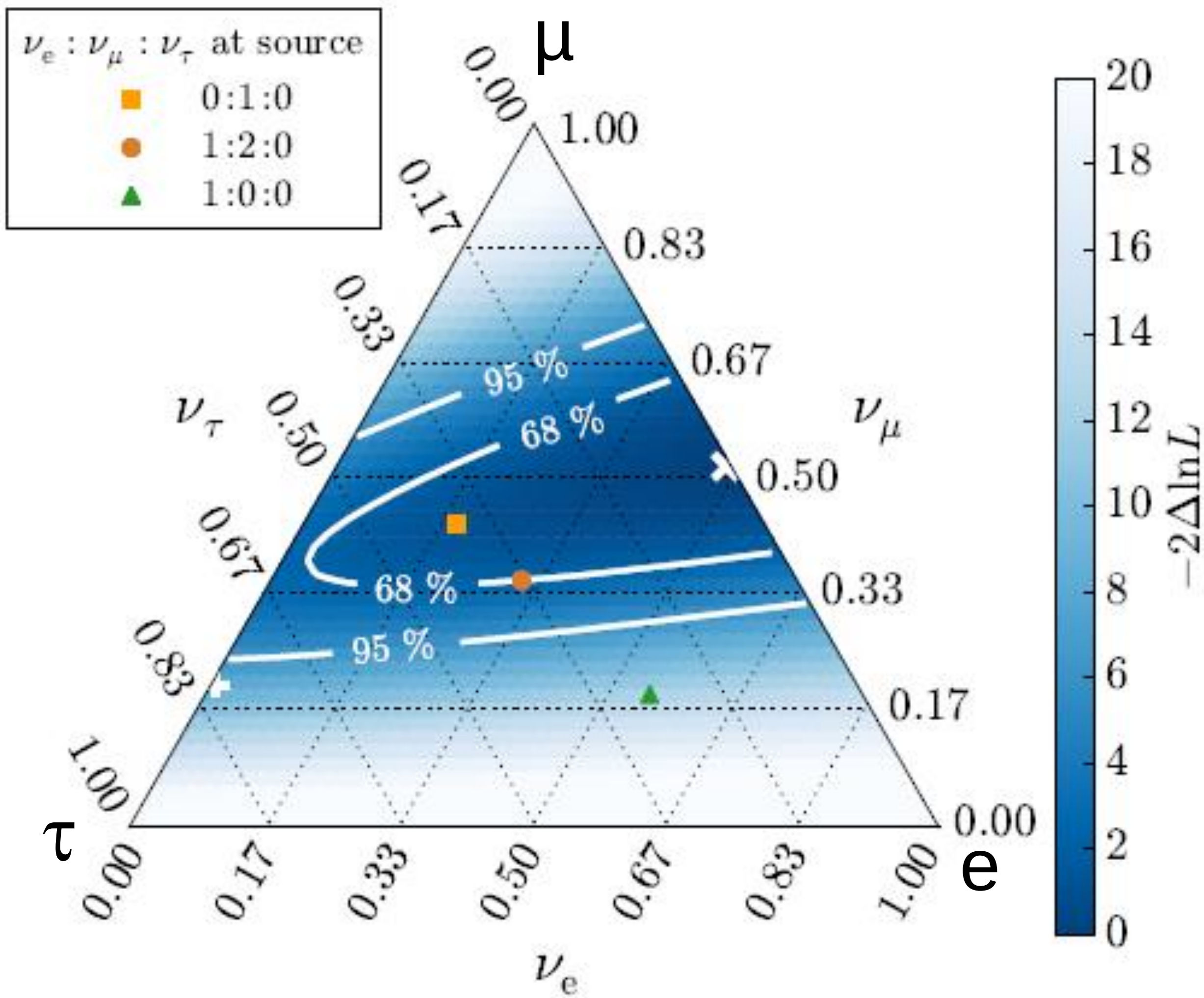
Correlation with Galactic plane?



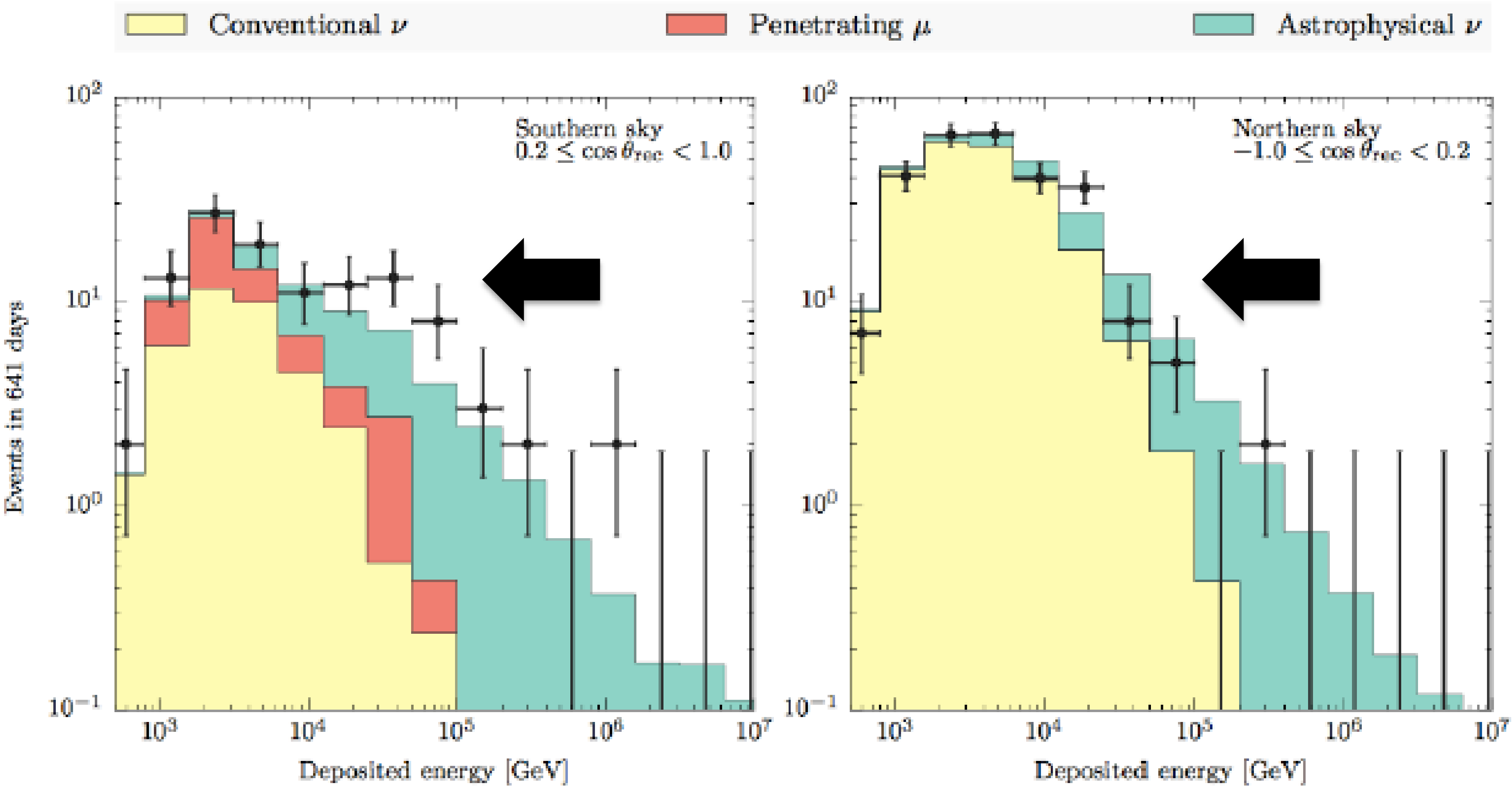
Test statistic 2.5% if 7.5° width of Galactic plane assumed

Neutrino flavor composition?

- Neutrinos from p/K decays oscillate to e:μ:τ = 1:1:1 over cosmic distances
- IceCube measures mostly μ:(e+τ)
- Result consistent with expectation



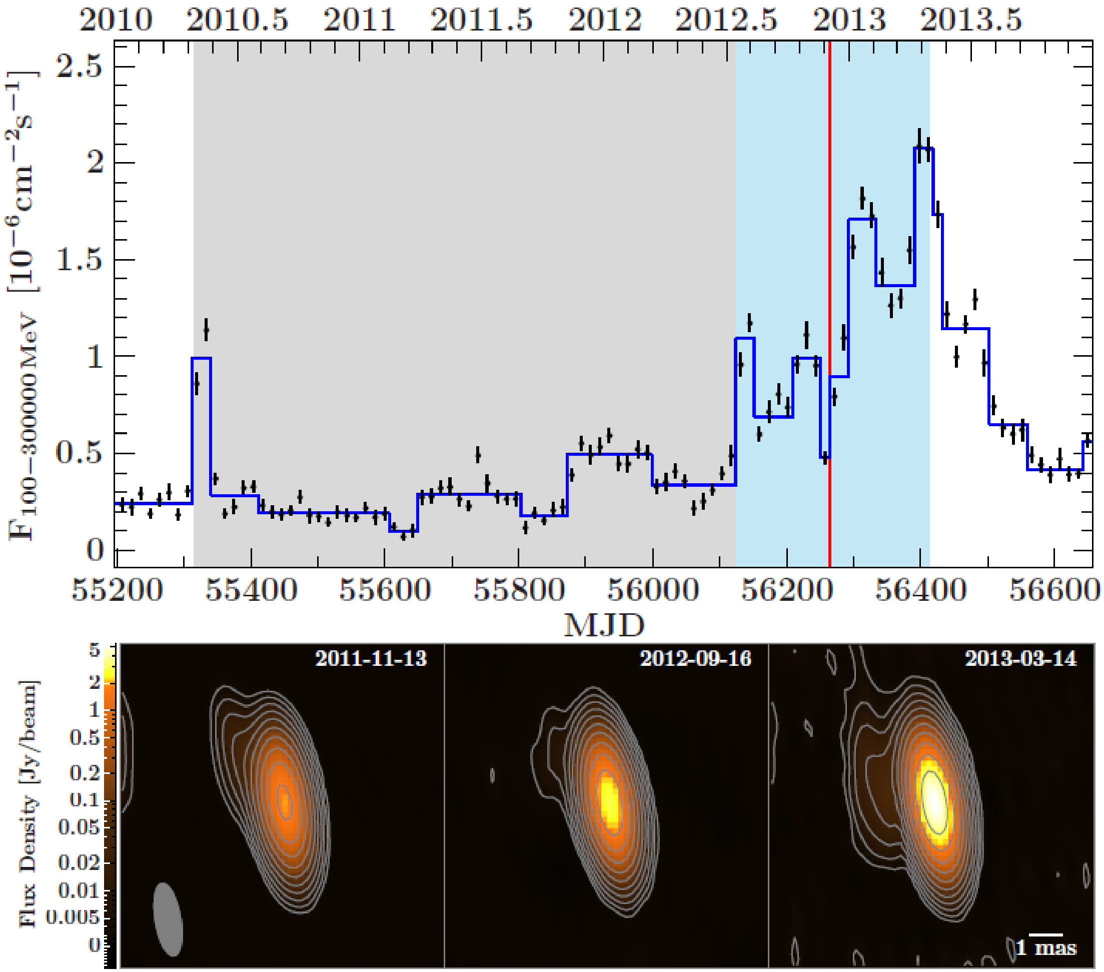
Questions, no answers (yet)



- A non-power-law component? Different source classes?
- Attention: Neutrinos are absorbed in Earth above ~100 TeV

IceCube events from blazars?

- Multi-messenger analysis using Fermi-LAT and radio data
- Candidate source for Big Bird: “Flat-spectrum radio quasar (FSRQ)” B1424-418
  – temporally and spatially coincident
- Consistent with astrophysical modelling
- Probability for random association 5%



M. Kadler et al., arXiv:1602.02012
to appear in Nature Physics

And now?

- More data needed to draw firm conclusions!
- Future projects: KM3NeT and IceCube-Gen2

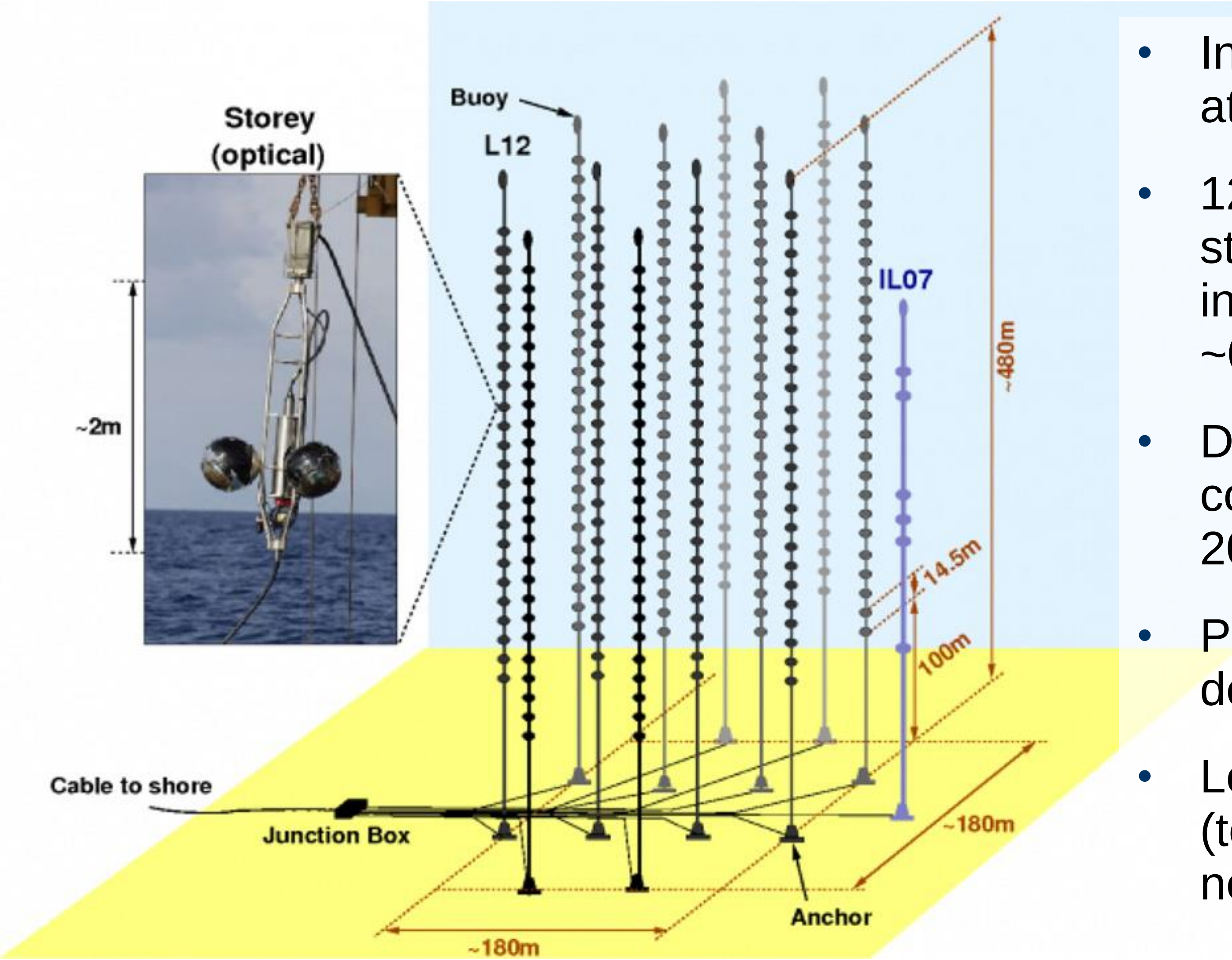
- KM3NeT-ORCA:
  Dense array, ν physics
  Construction 2017-
- KM3NeT-ARCA:
  High-energy ν telescope
  Construction 2018-

- PINGU:
  Dense array, ν physics
  Construction 2021-
- Gen2-HEX:
  High-energy ν telescope
  Surface array
  Radio array ?
  Construction 2025-

- And also: GVD in Lake Baikal

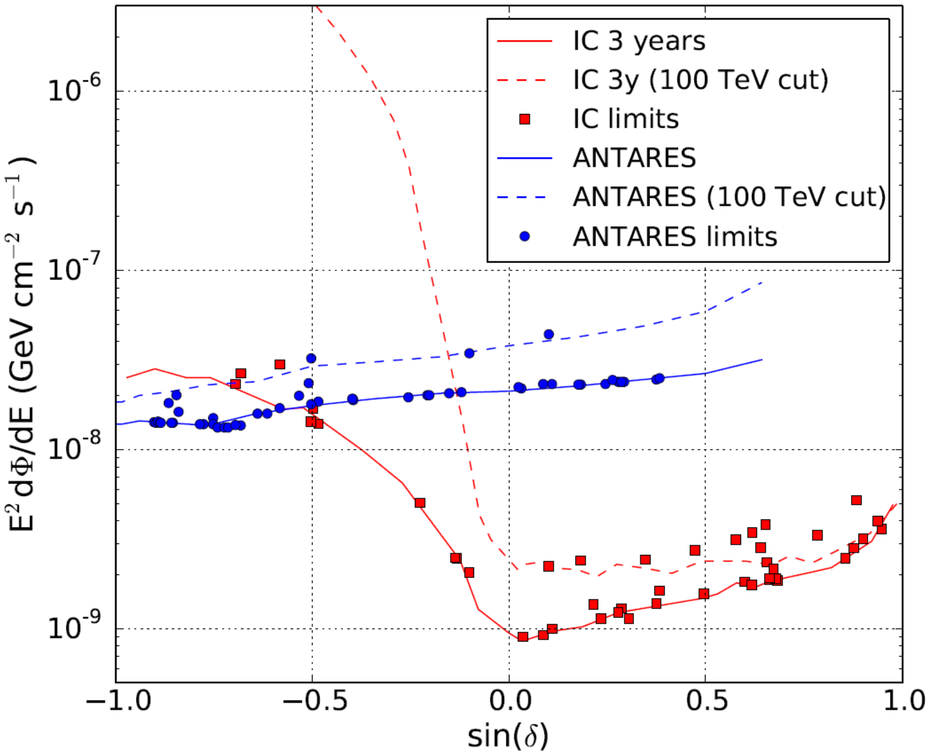
Neutrino astronomy in the Mediterranean Sea: ANTARES and KM3NeT

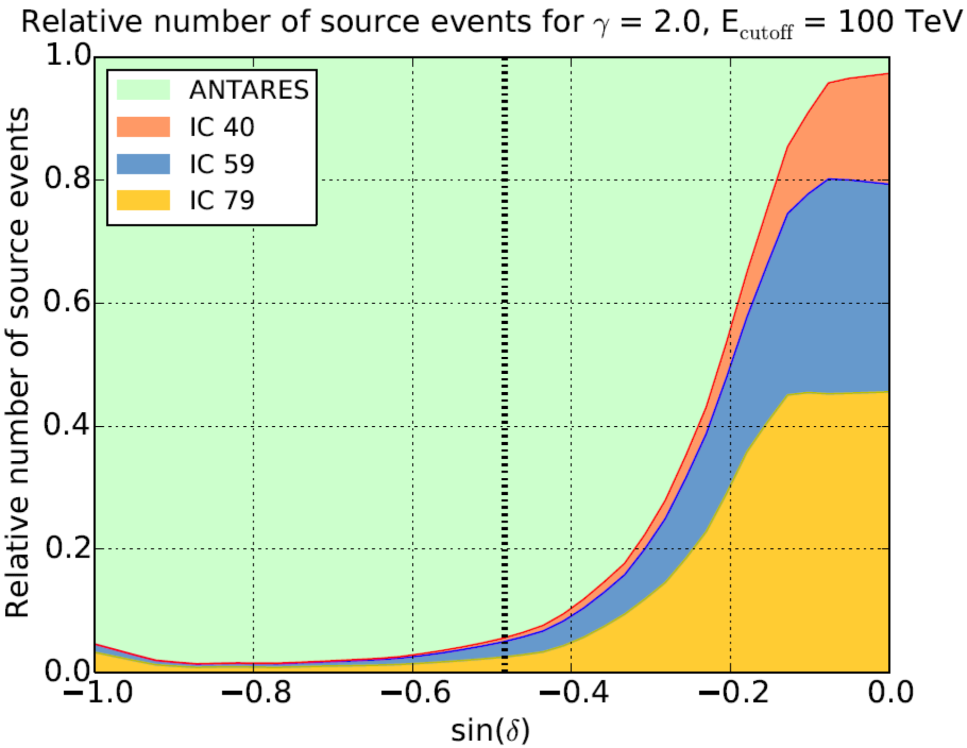
ANTARES: The first deep-sea ν telescope



- Installed near Toulon at a depth of 2475m
- 12 strings with 25 storeys each, instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- Proof of principle of deep-sea ν telescope
- Lots of results – but (too) small for cosmic neutrinos

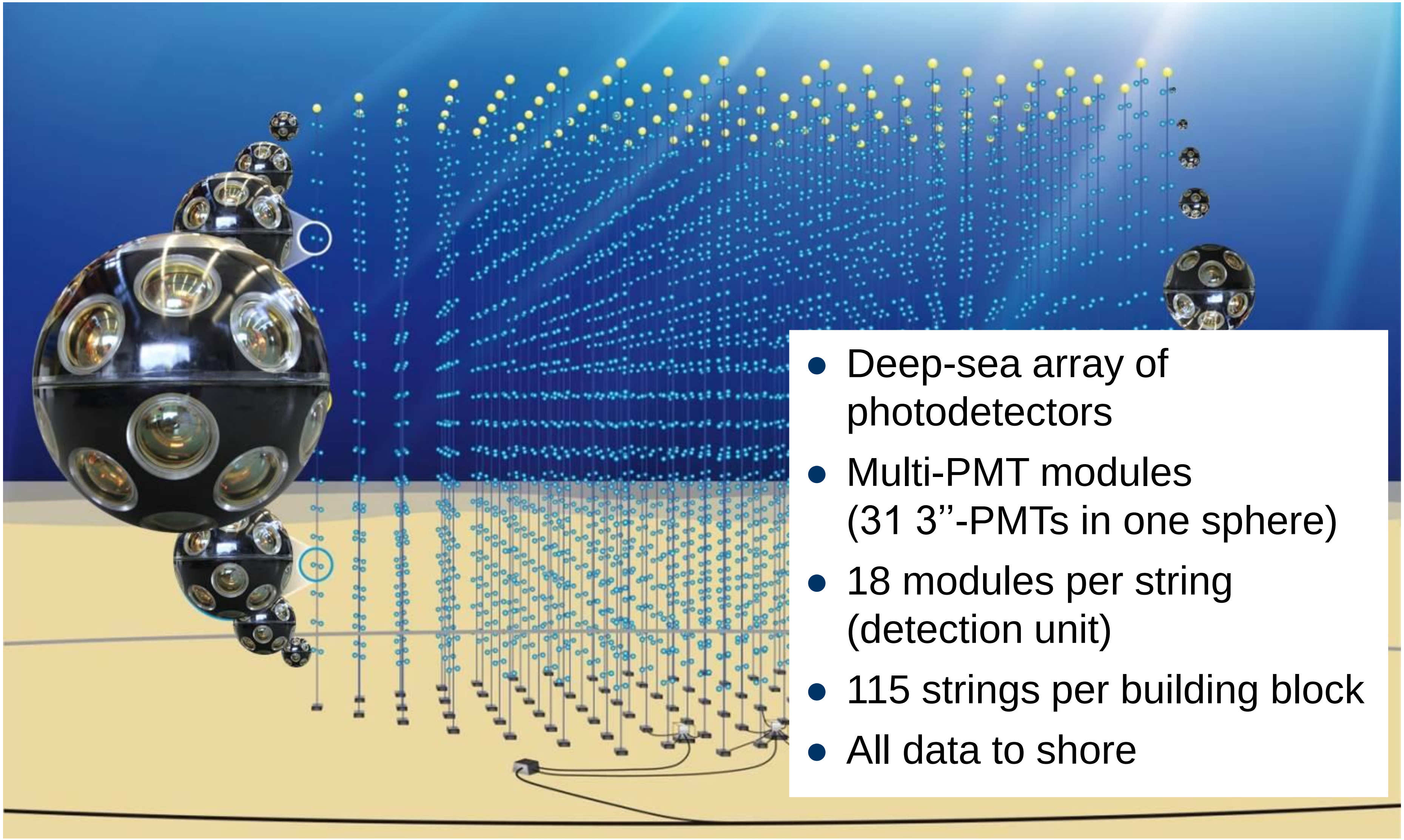
ANTARES and IceCube: Combined analysis





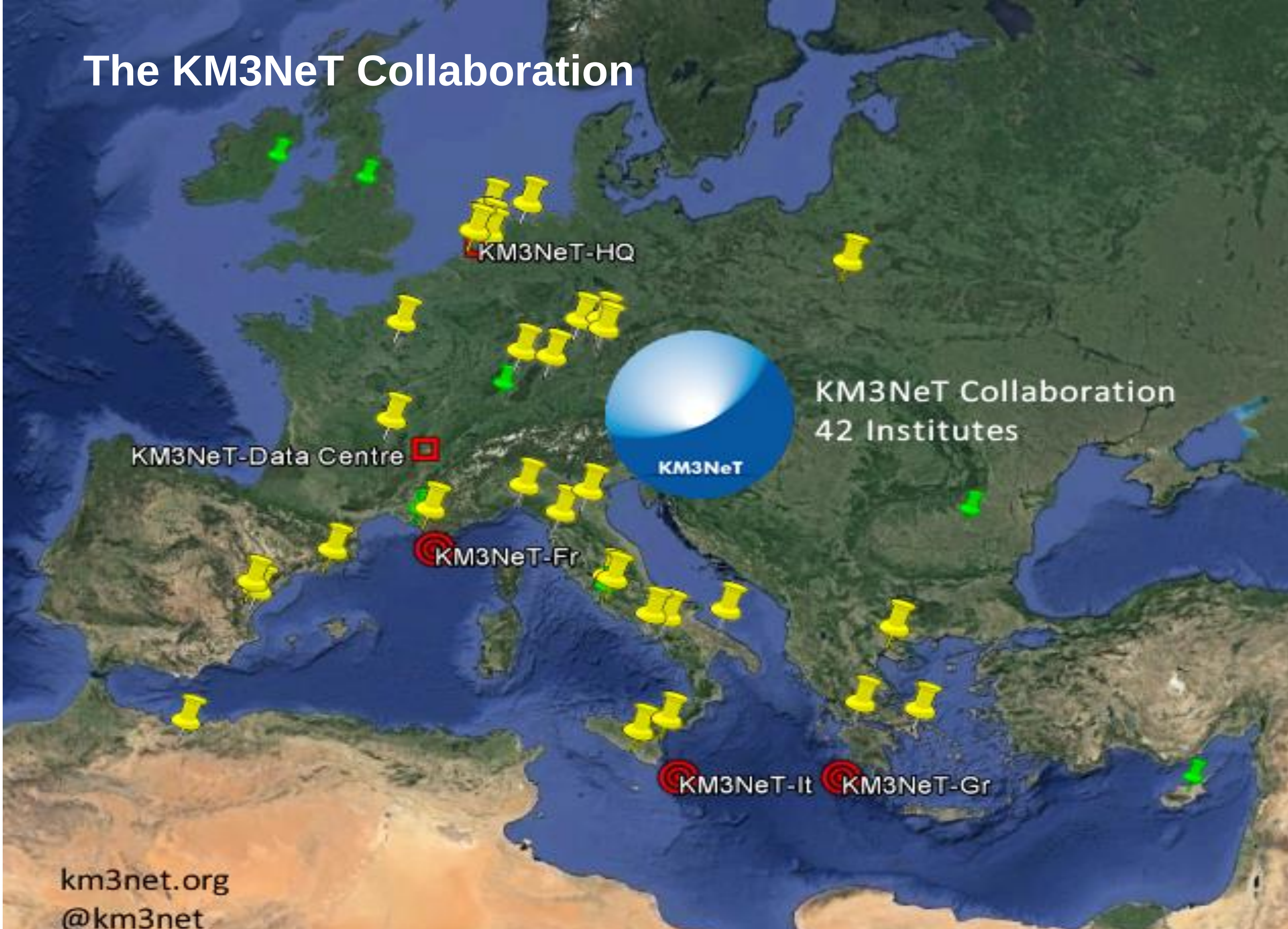
- Common analysis of ANTARES and IceCube data
- Search for point-like neutrino sources, spectrum ~ $E^{-\gamma}$ * cutoff(E_{cutoff})
- Substantial contribution from ANTARES for spectra with E_{cutoff} ~ 100 TeV

The KM3NeT concept



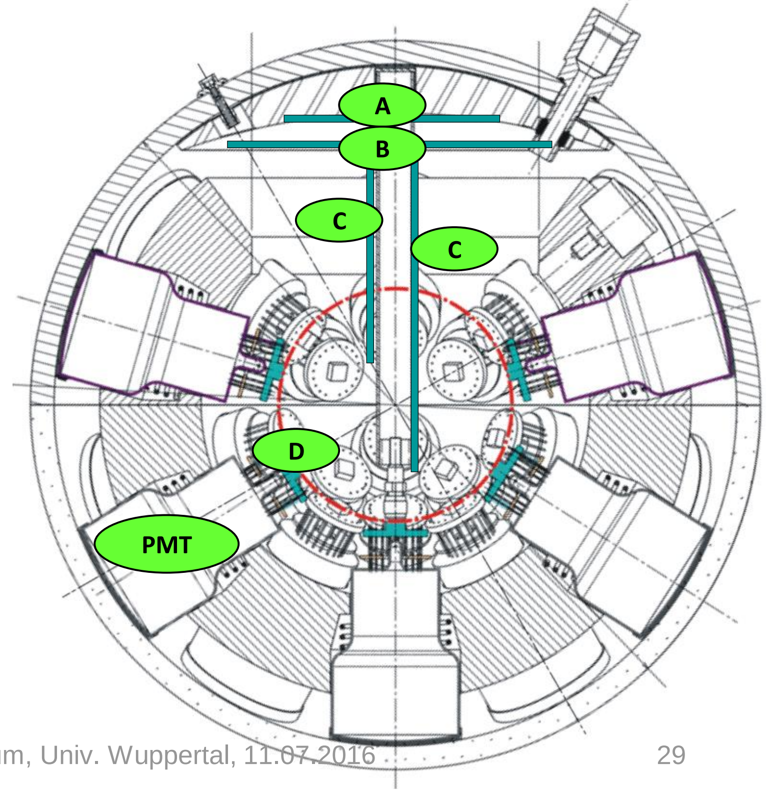
- Deep-sea array of photodetectors
- Multi-PMT modules (31 3''-PMTs in one sphere)
- 18 modules per string (detection unit)
- 115 strings per building block
- All data to shore

The KM3NeT Collaboration



The KM3NeT Digital Optical Module

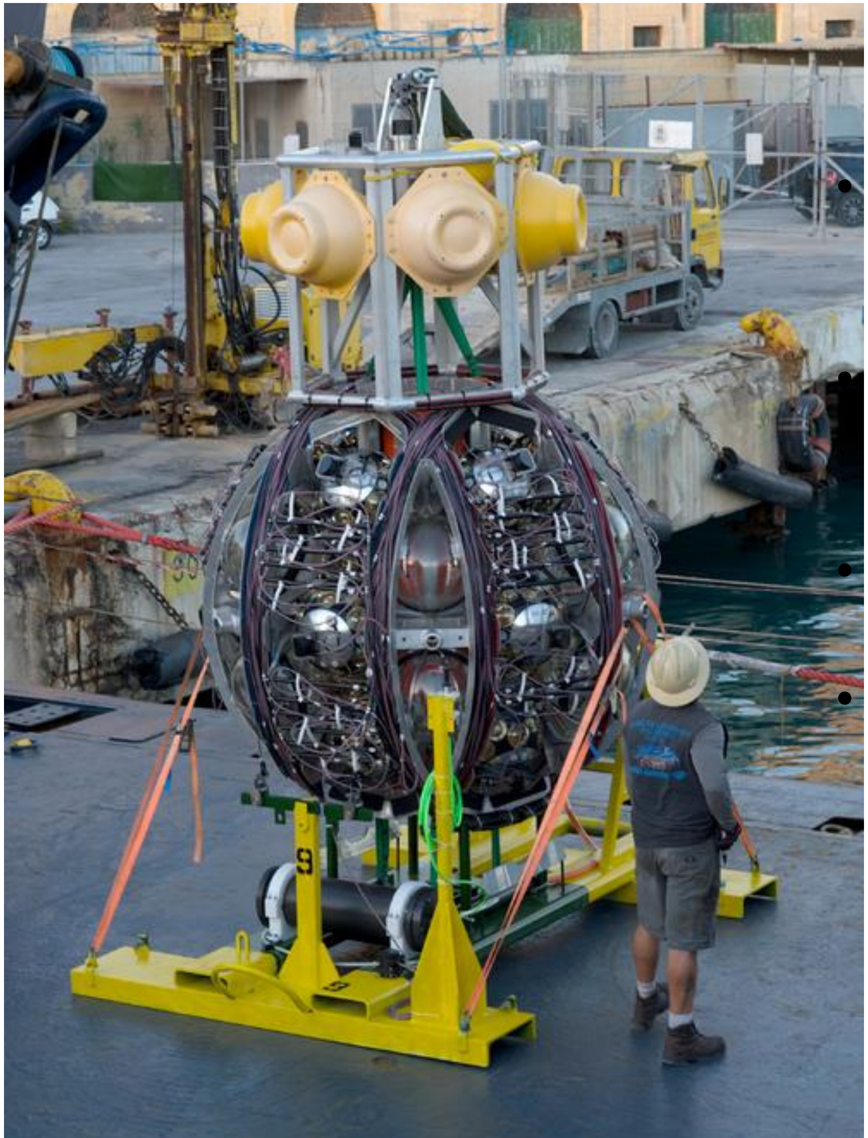
- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10-inch PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk



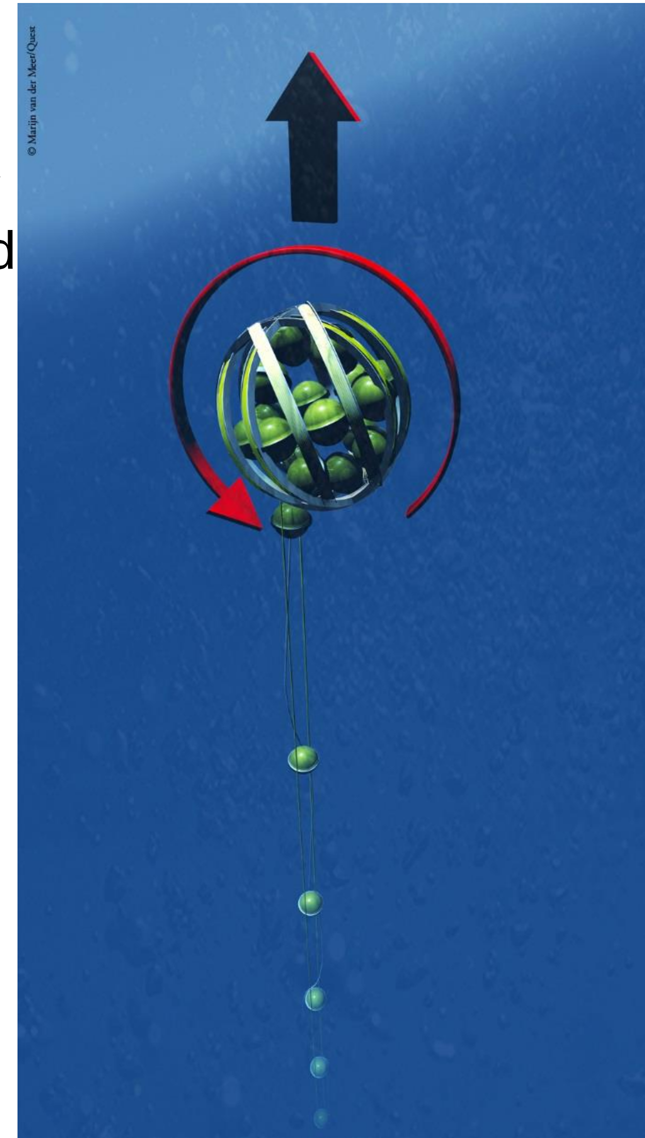
The KM3NeT detection unit (DU)

- Mooring line:
  - Buoy (empty spheres)
  - 2 pre-stretched Dyneema© ropes (4 mm diameter)
  - 18 storeys (one DOM each)
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 7mm diameter
  - Oil-filled
  - Optical fibres and copper wires
  - At each storey: Break-out box for connection to 1 fibre + 2 wires (one single pressure transition)

Deployment



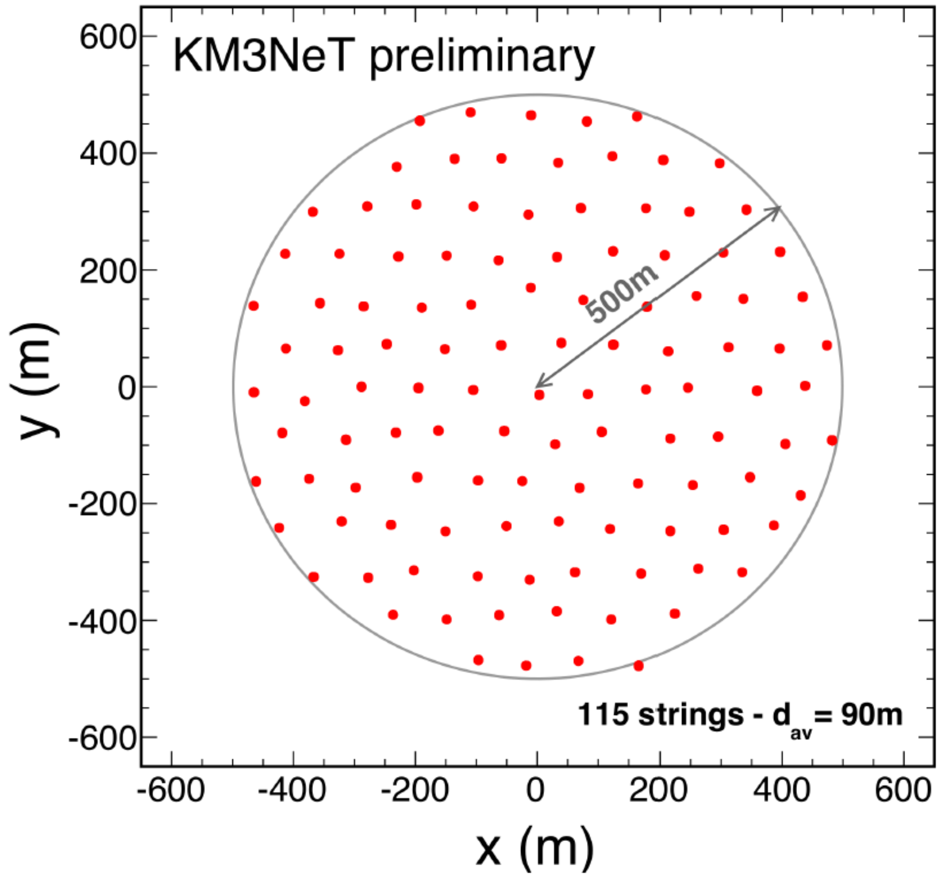
- ← Deploy to sea bed
- Release by ROV
- Unfurl →
- Collect frame



The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
- Large block (neutrino astronomy)
  - Sensitivity per string for muons independent of block size above ~75 strings
  - One block ~ half IceCube
- Small block (neutrino oscillations)
  - Precision measurement of atmospheric neutrinos
  - One block ~ 6 Mtons
- Allows for staged, block-wise, multi-site installation

DU distance adjusted to scientific objective:
90-120 m for neutrino astronomy /
20 m for oscillation research



KM3NeT 2.0 = ARCA and ORCA

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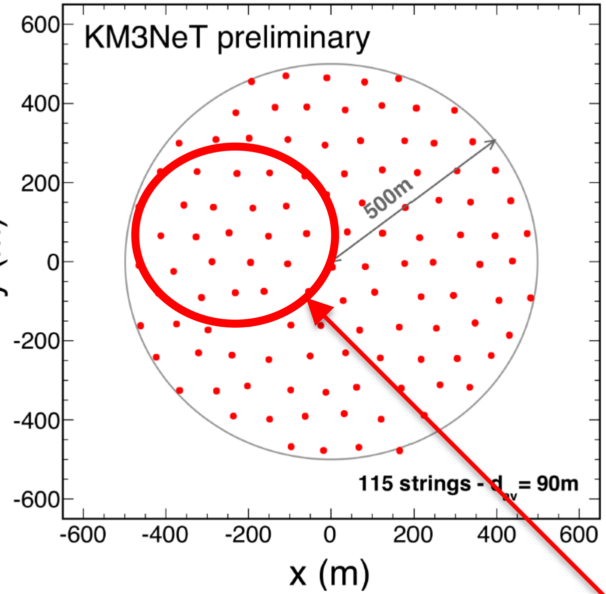
ARCA =

Astroparticle Research with Cosmics in the Abyss

Vertical DOM distance = 36 m



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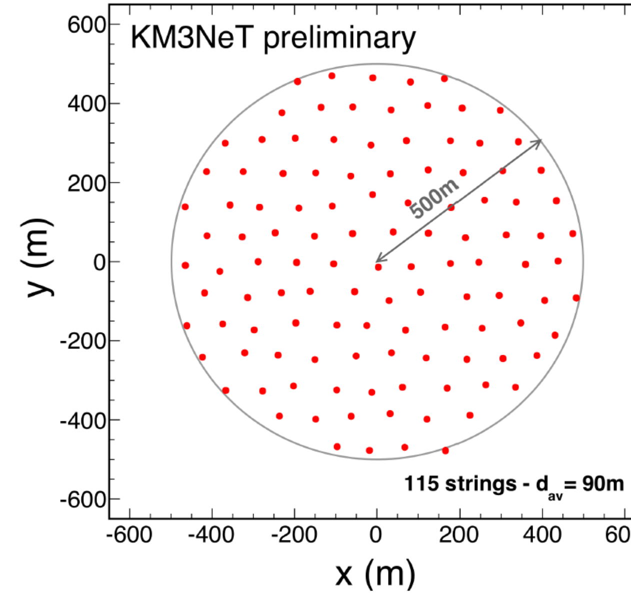
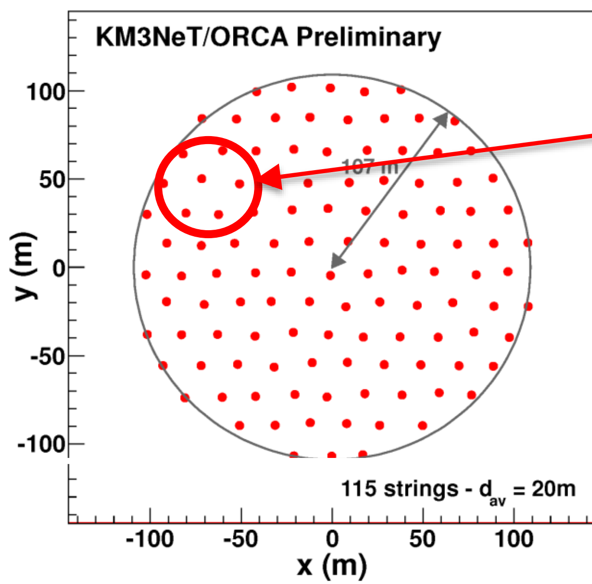


ORCA =
Oscillation Research with Cosmics in the Abyss

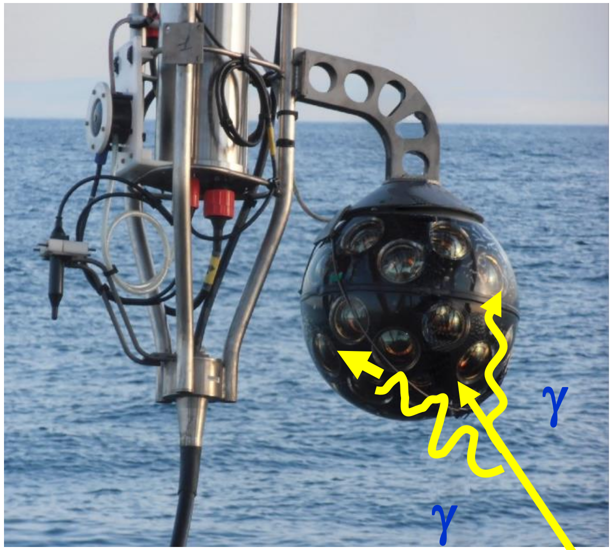
Vertical DOM distance = 9 m



Phase1 (fully funded)

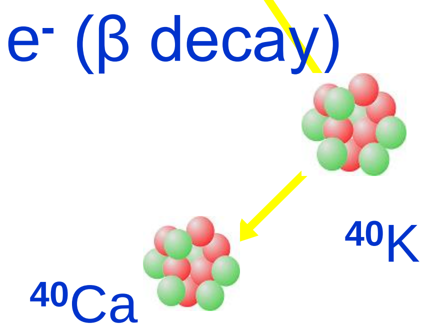
KM3NeT 2.0 Letter of Intent:
arXiv:1601.07459
to appear in J.Phys.G

DOM prototype (PPM-DOM)

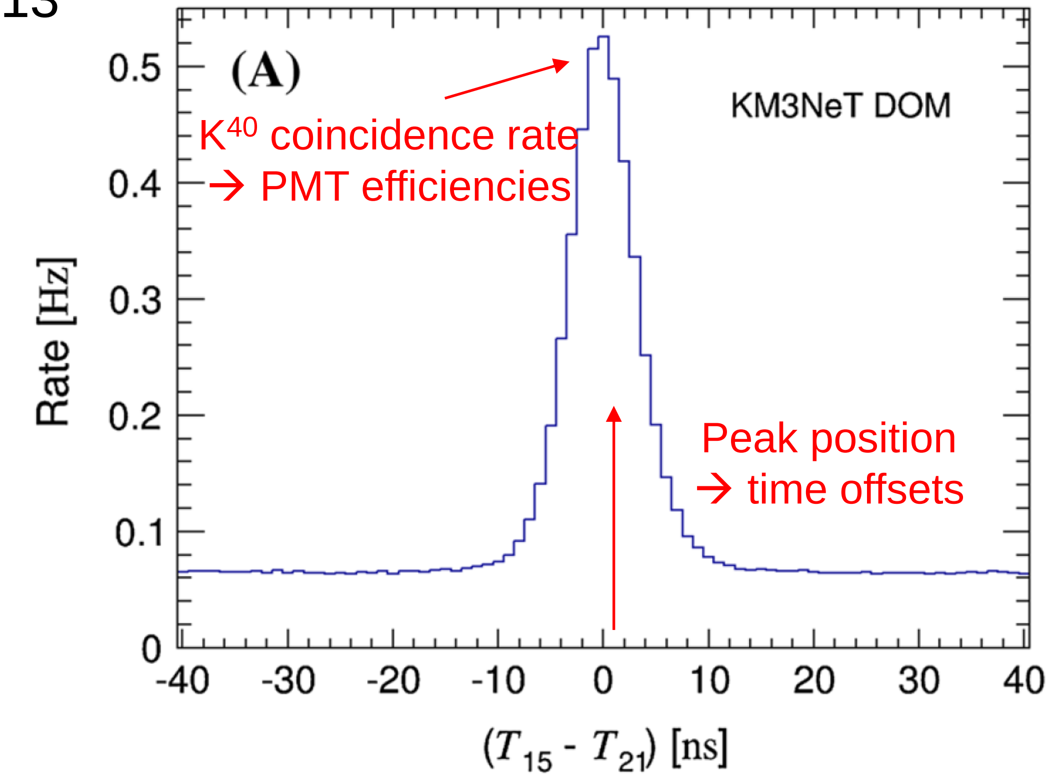


Deployed at ANTARES in April 2013

Up to 150 Cherenkov photons per decay



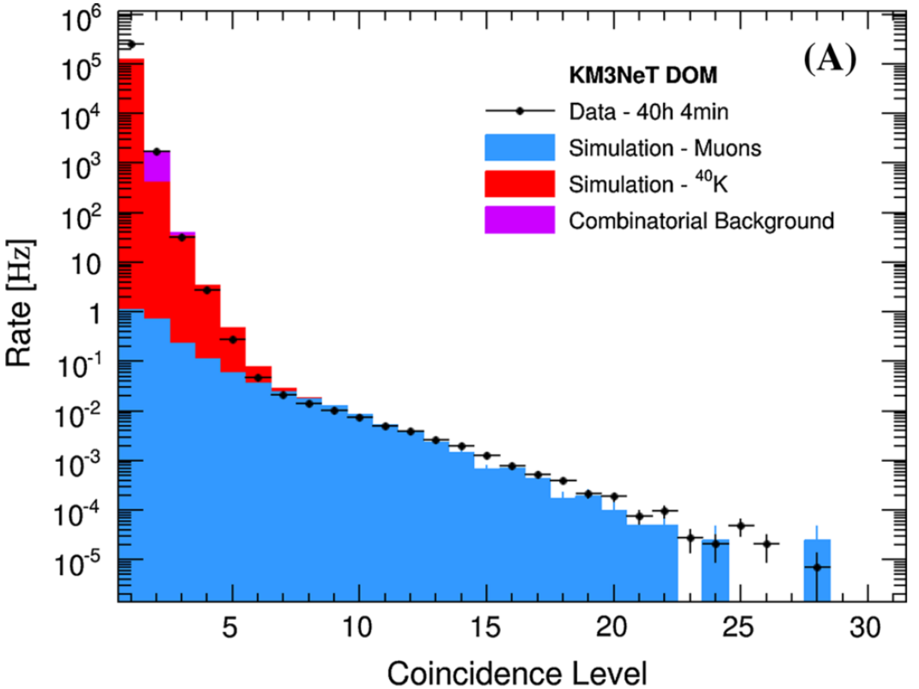
Coincidence rate on 2 adjacent PMTs (33° angular separation)



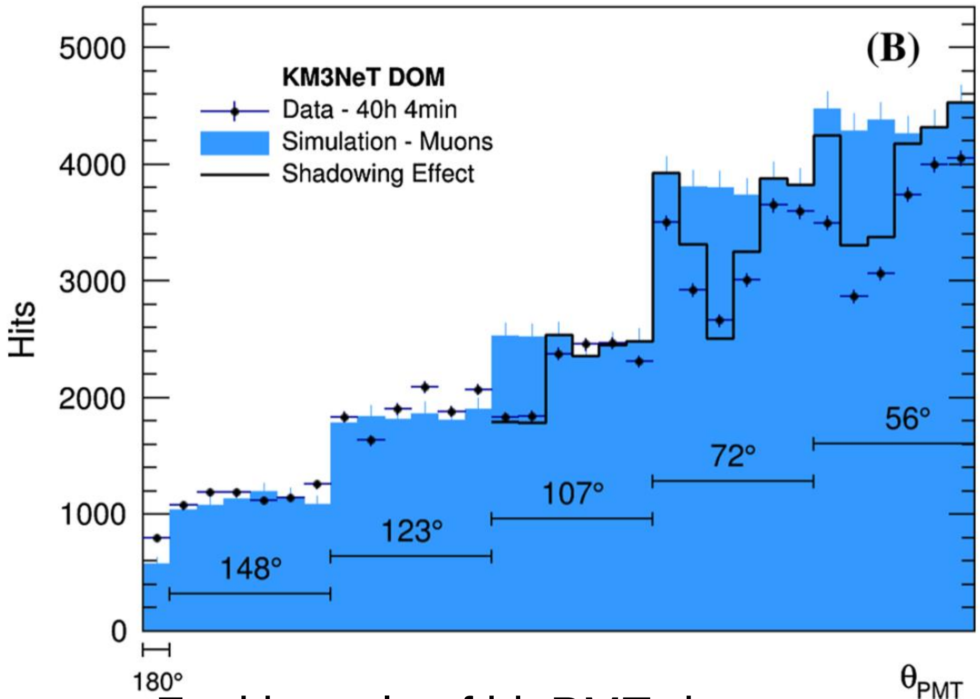
Concentration of ^{40}K is stable (coincidence rate ~5 Hz on adjacent PMTs)

Eur.Phys.J. C74 (2014) 3056

PPM-DOM: Atmospheric muons



Number of coincident hits in a DOM

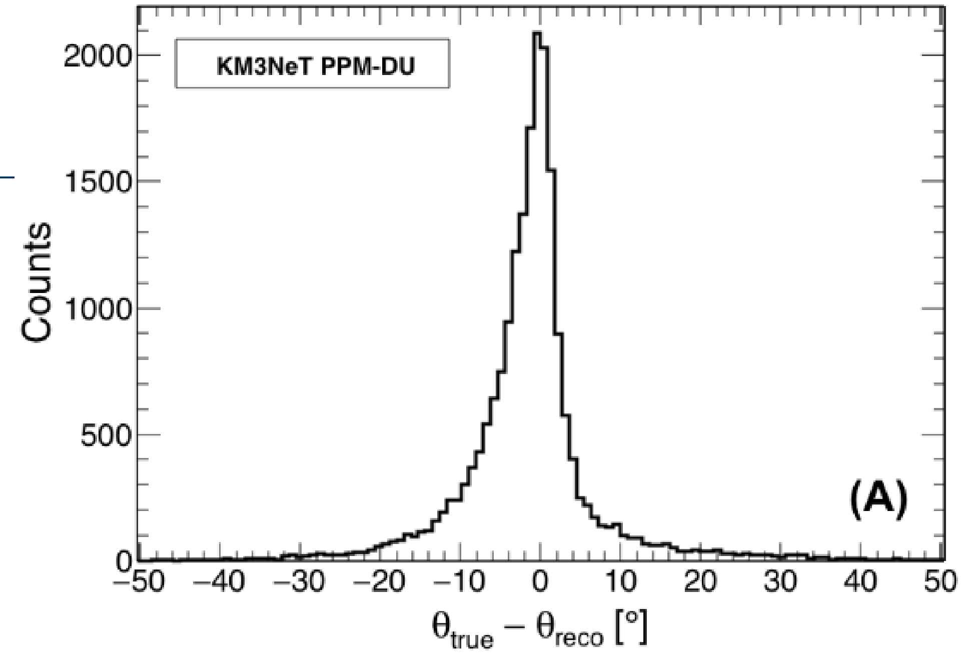


Zenith angle of hit PMTs in events with more than 7 coincident hits

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

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

PPM-DU: Muon reconstruction

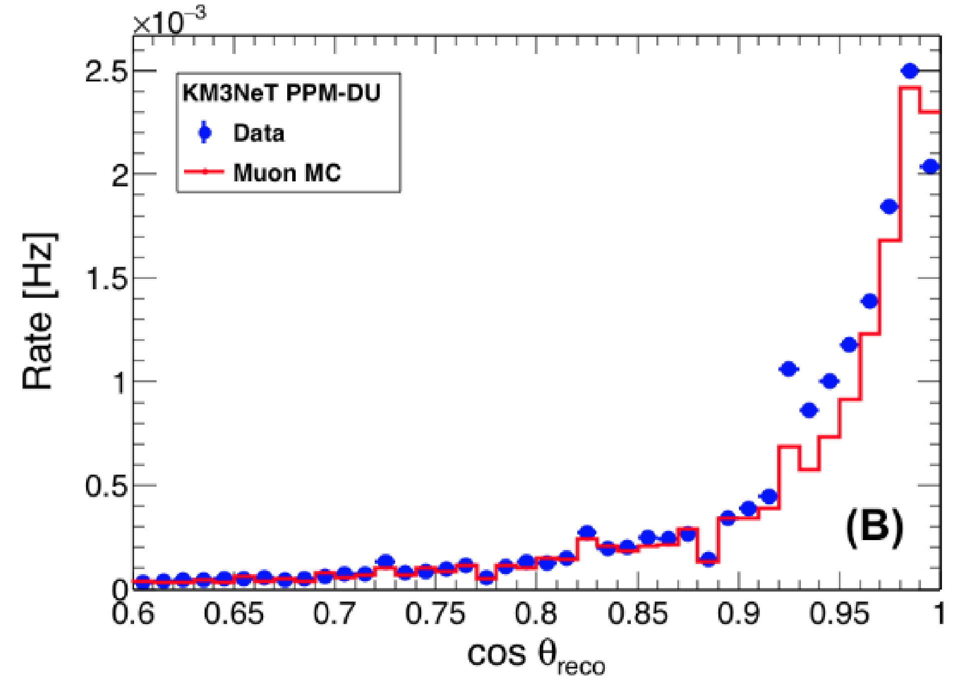


- Reconstruct muon trajectory from hits on 3 DOMs

- Ambiguities can be reduced by cuts on time differences

- 7° FWHM resolution achieved

Eur.Phys.J. C76 (2016) 54



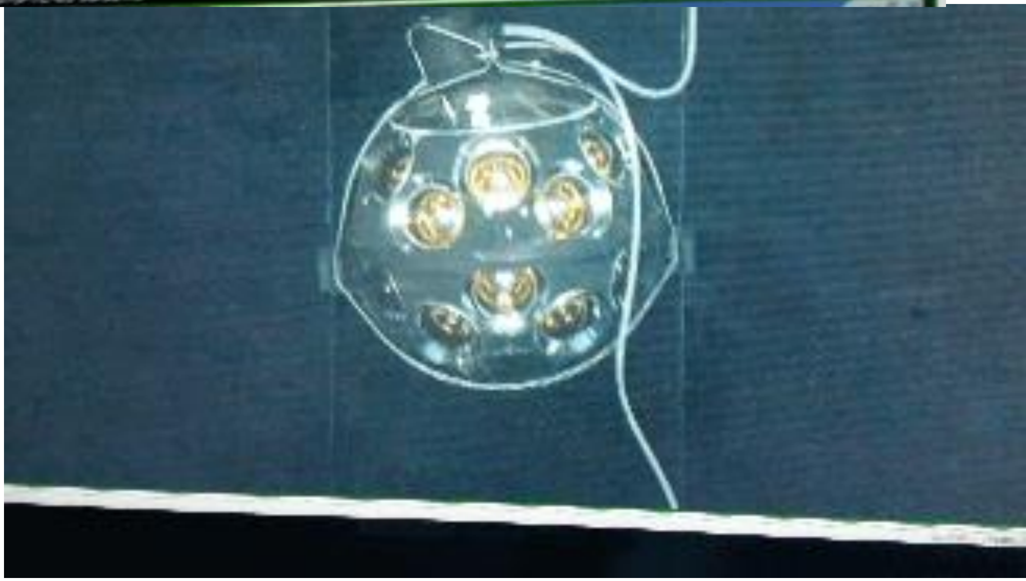
First KM3NeT-ARCA strings deployed

First string (Dec 2015)

- Smooth operation
- All 18 DOMs alive and functional
- First muons reconstructed within hours after switch-on
- Data taking in progress

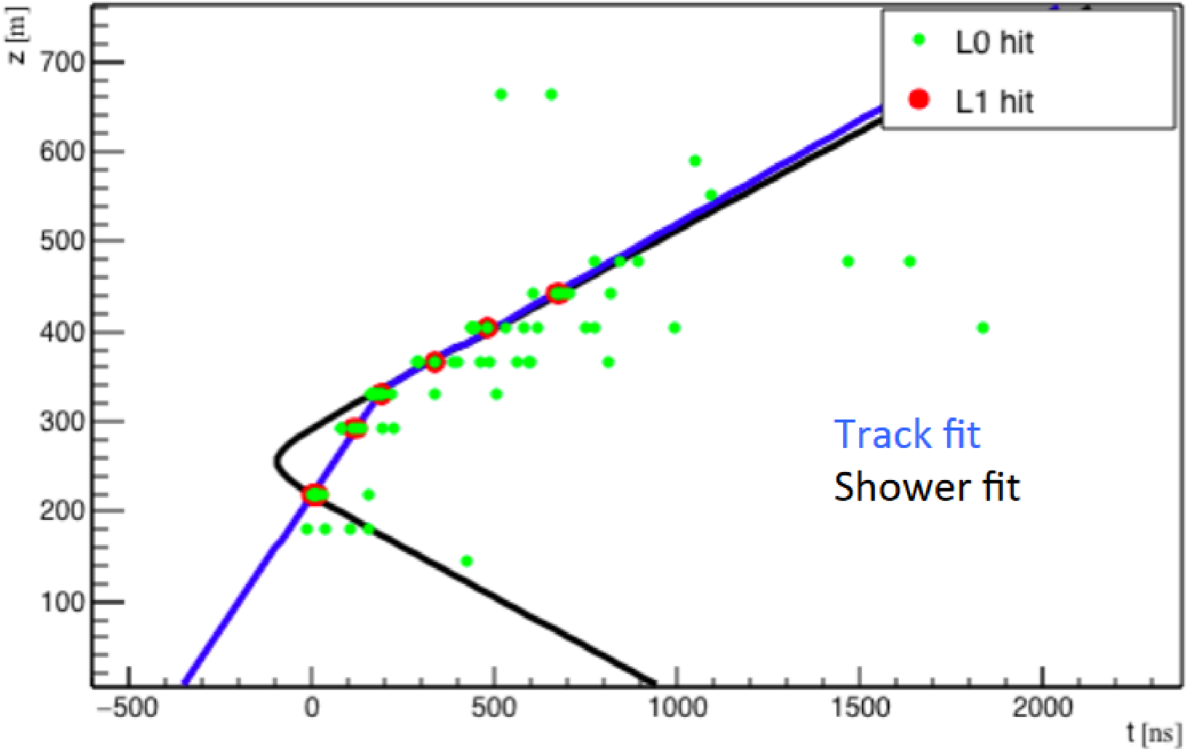
Strings #2 and #3 (May 2016)

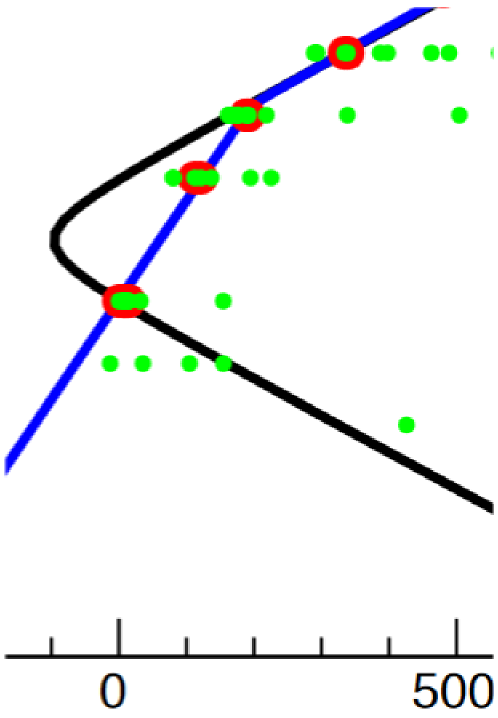
- String #2: 16/18 DOMs work, data taking in progress
- String #3: Short in power system, not operational
- Problems under investigation



First neutrinos …

A good candidate:

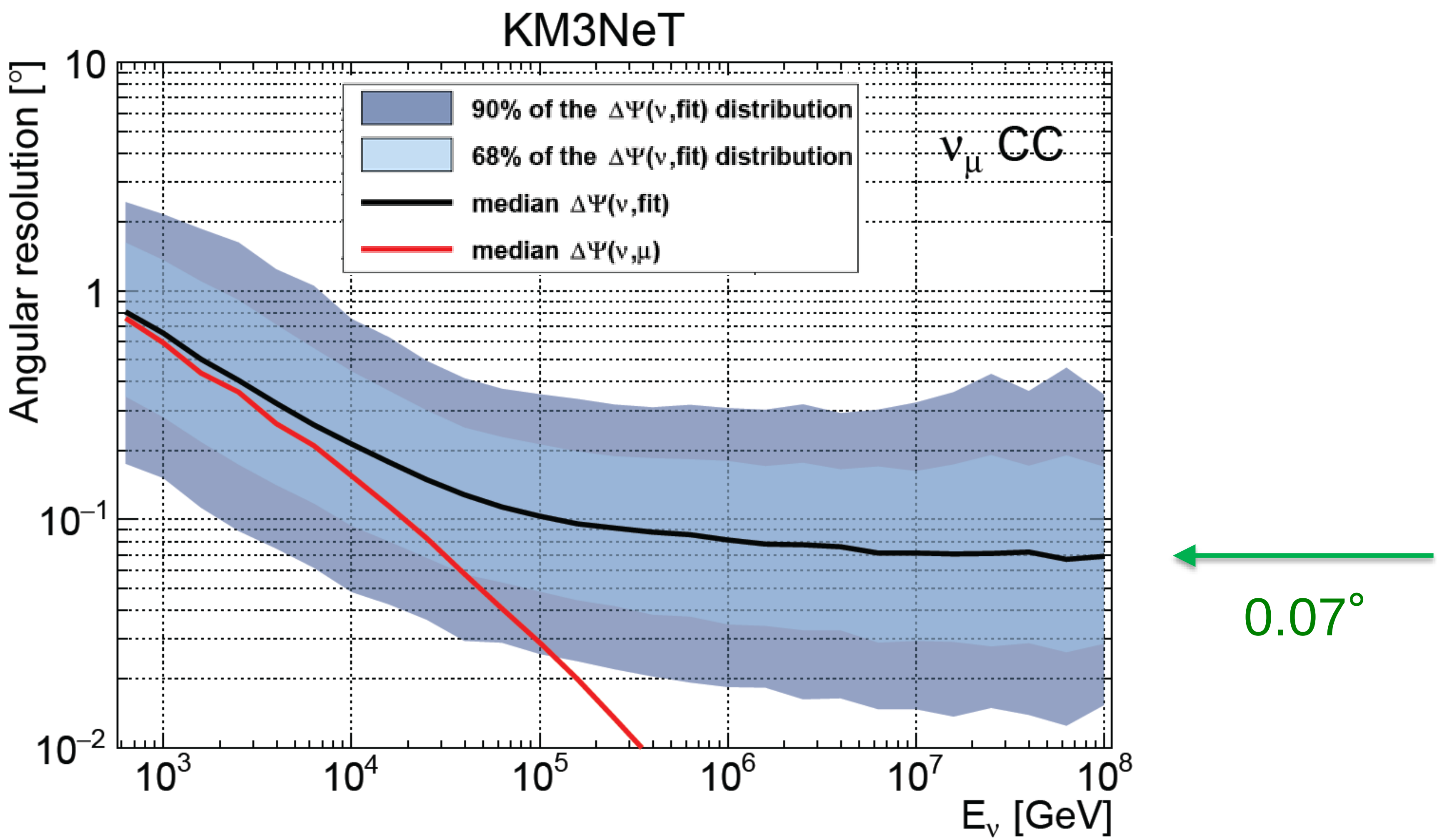




Note: Track direction from slope, rising z(t) not sufficient

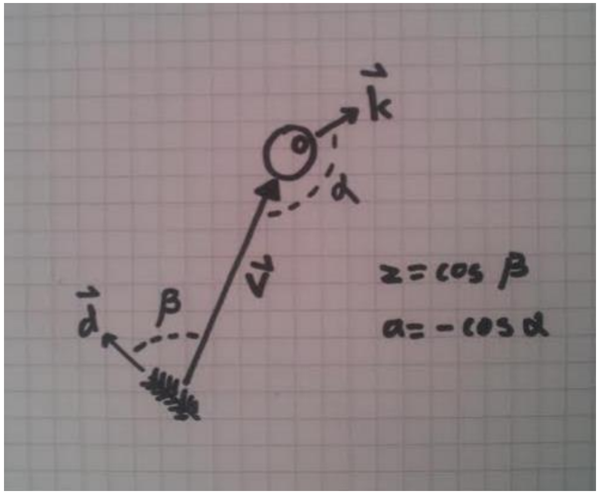
Muon angular reconstruction

Reconstruction using new PMT response simulation:
Median of angle ΔΩ between reconstructed μ and true ν direction

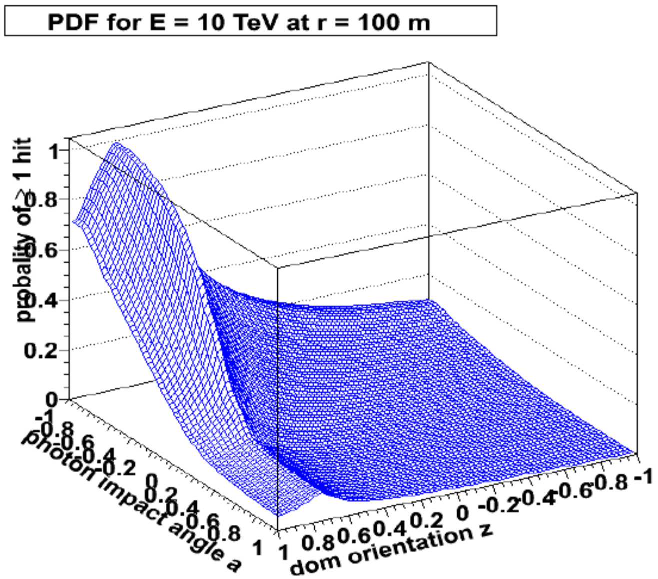


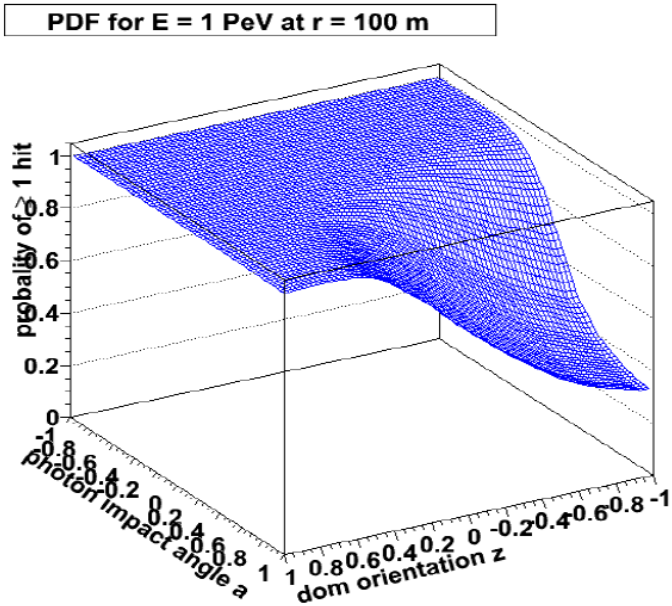
Shower reconstruction: Method

- Vertex fit: Suitable hit selection, fit uses timing; result used for containment requirement
- Direction and energy: Uses PDF depending on
  - Distance vertex – DOM
  - Angle between shower direction and DOM
  - Orientation of PMTs
  - Hit information used: yes/no



- Resolution (contained ν_e CC events): ~10% in E, <2° in direction

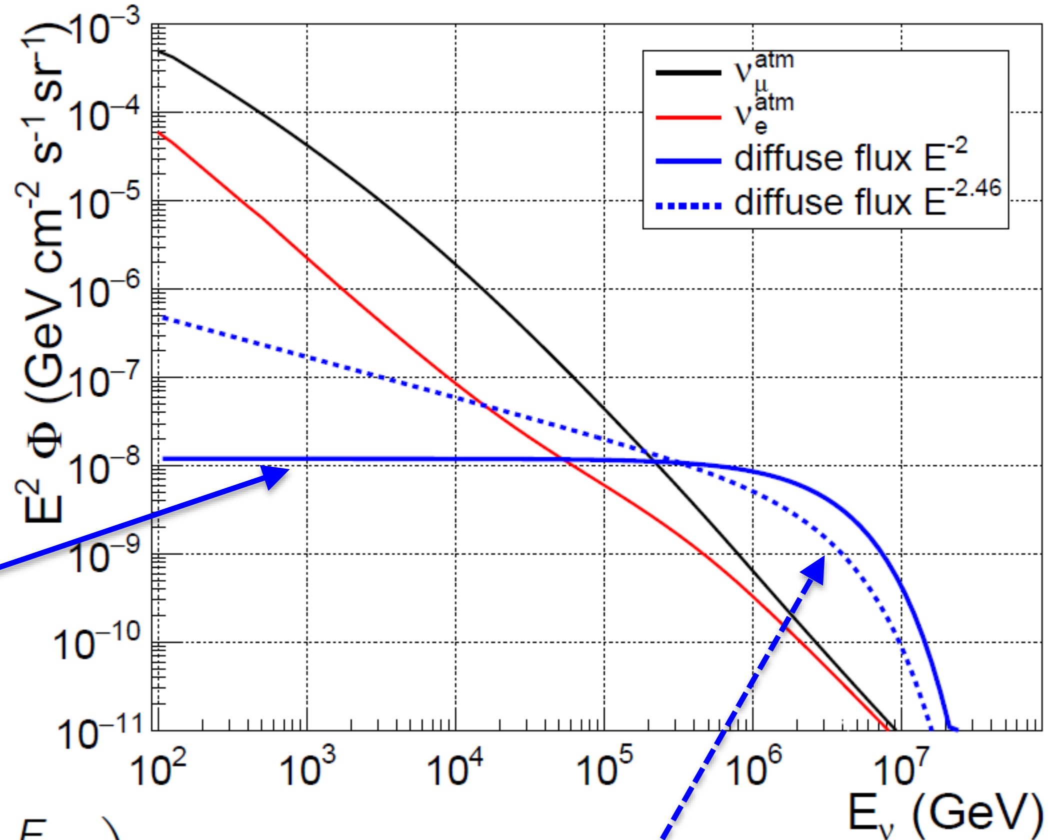




Diffuse extragalactic neutrino flux

Assumptions:

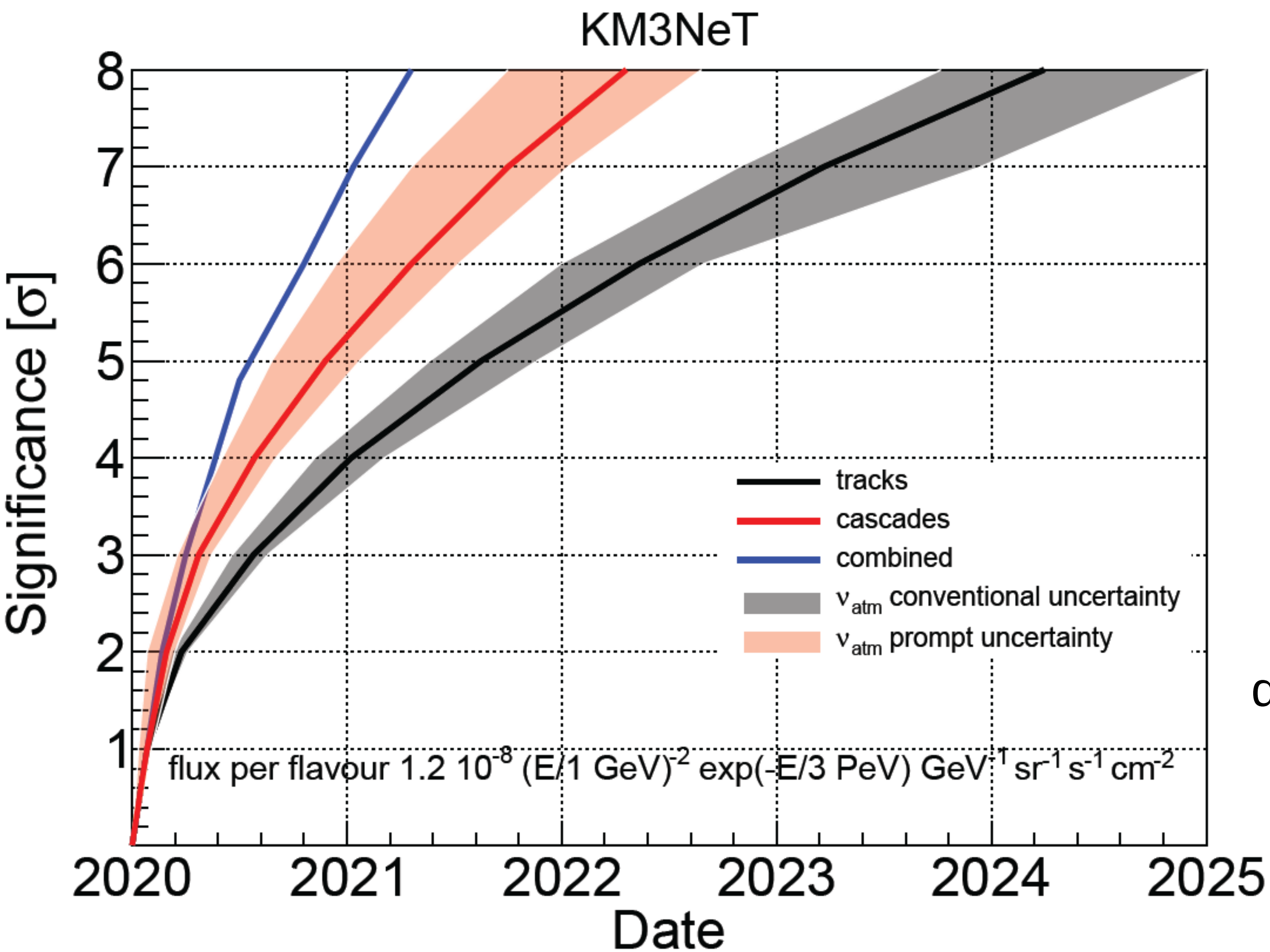
1. Flavour-symmetric
2. Isotropic
3. Energy spectrum consistent with IceCube findings



$$\Phi(E_\nu) = 1.2 \times 10^{-8} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$\Phi(E_\nu) = 4.11 \times 10^{-6} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2.46} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

Diffuse flux results (max. liklihood)



Event numbers (cut&count):

16/9 cascades

7.5/5 track-like

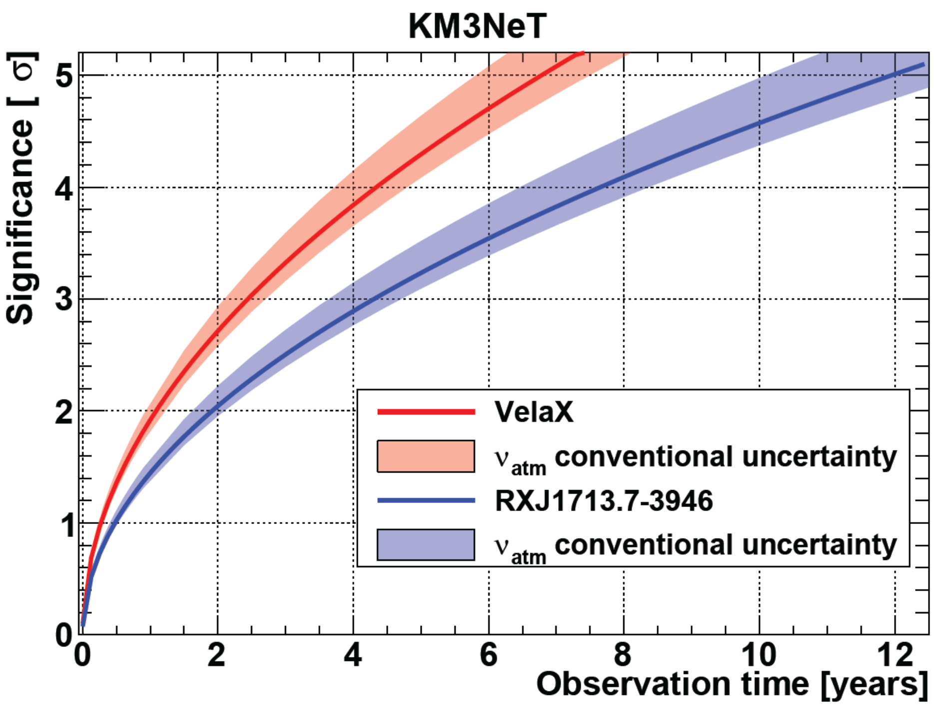
(signal/background per ARCA year)

Note:

For each energy, direction and flavour, KM3NeT is complementary to IceCube

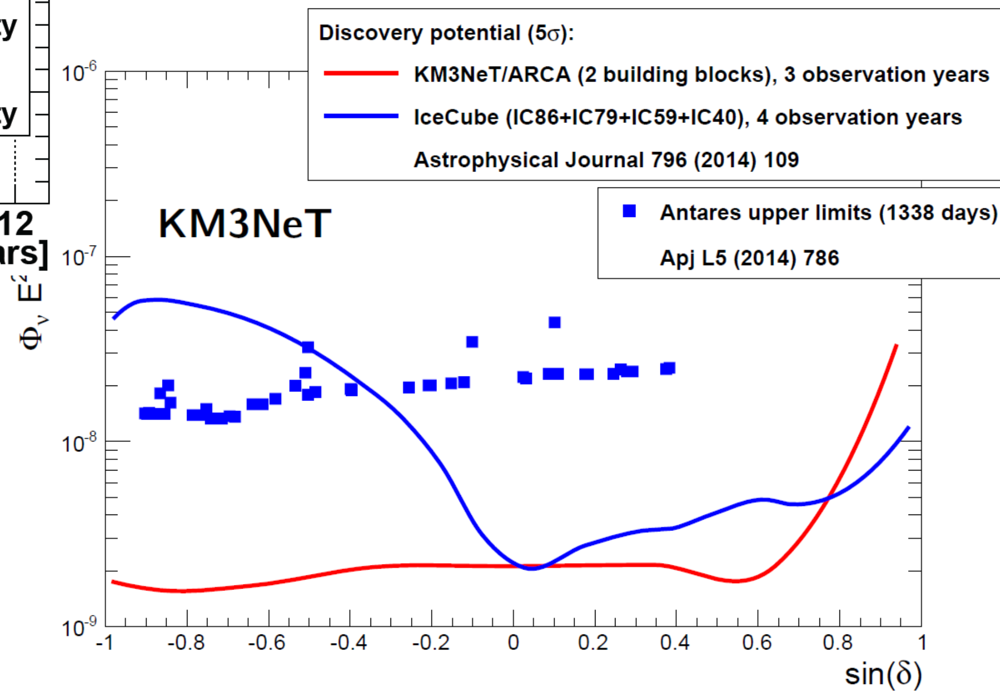
Other flux assumptions yield 10-30% improvement in discovery time.

Point-source results



- Galactic sources in reach

- Significant discovery potential for extragalactic sources



Measuring the neutrino mass hierarchy

Neutrino oscillations in vacuum

- Neutrino flavour and mass eigenstates are not the same:

$$[\text{mass}] \rightarrow \quad |\nu_i\rangle = \sum_{\alpha=1}^{3} U_{i\alpha}|\nu_\alpha\rangle \quad \leftarrow [\text{flavour}]$$

(propagation) (production)

- Consequence: Neutrino oscillations
  Very simplified case: 2 flavours, vacuum

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2/\text{eV}^2 \cdot L/\text{km}}{E_\nu/\text{GeV}}\right)$$

- No information on sign of Δm^2

- In the above units:

$L/E \ll 1/\Delta m^2 \quad \rightarrow$ no effect
$L/E \sim 1/\Delta m^2 \quad \rightarrow$ observe oscillations
$L/E \gg 1/\Delta m^2 \quad \rightarrow$ observe averaged oscillations

The 3-flavour case

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- Parameterisation of mixing matrix
(up to Majorana phases that are not discussed here):

$$U_{\mathrm{PNMS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

- Neutrino oscillation parameters (only central values given):

$\sin^2(2\theta_{23}) = 0.97; \quad |\Delta m^2_{23}| = 2.35 \times 10^{-3}\,\mathrm{eV}^2$ atmos. + acc.

$\sin^2(2\theta_{12}) = 0.86; \quad \Delta m^2_{12} = 7.58 \times 10^{-5}\,\mathrm{eV}^2$ solar + reactor

$\sin^2(2\theta_{13}) = 0.096;$ reactor (2012)

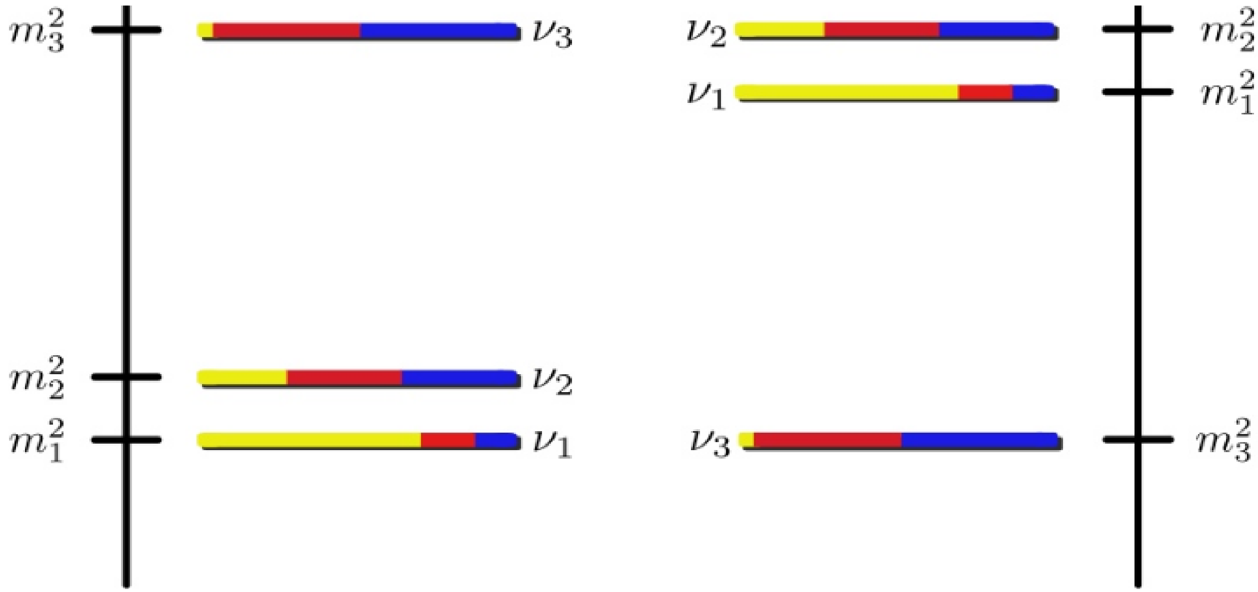
- Unknown: sign of Δm^2_{23}
CP-violating phase δ

The neutrino mass hierarchy

- Depending on sign of Δm^2_{23} :

"normal hierarchy" or "inverted hierarchy"

(NH) (IH)



- A fundamental parameter of particle physics!
  → Knowledge required to investigate neutrino CP violation
  → Important also for cosmology

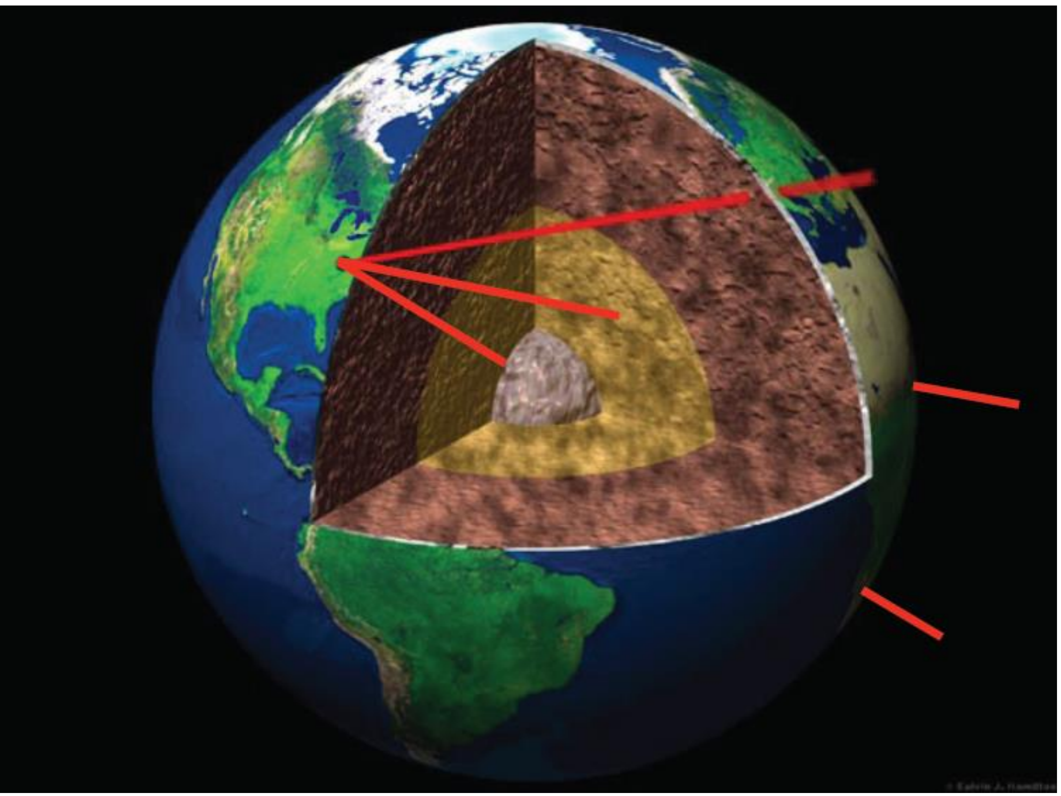
Neutrino oscillations in matter

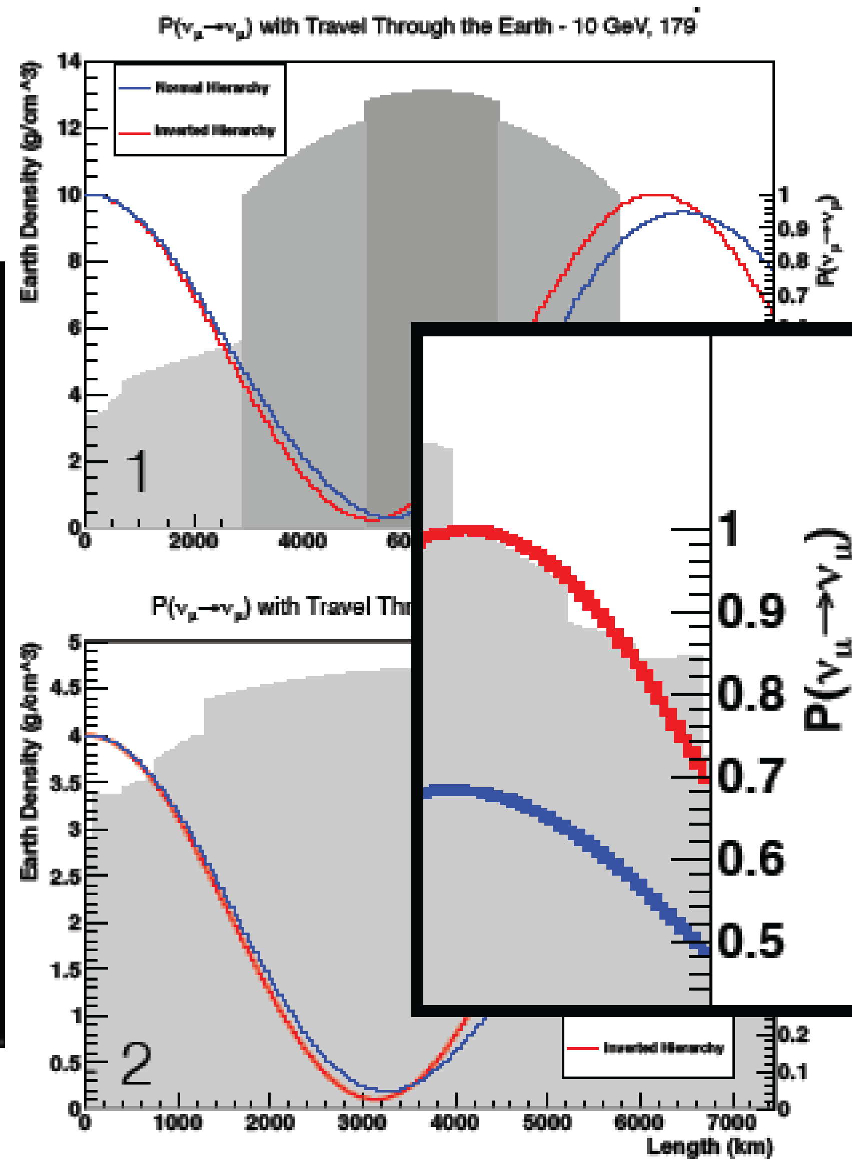
- Electron density induces dependence of oscillation pattern on sign of Δm^2_{23}
- Effect equal for neutrinos/NH and antineutrinos/IH
- Oscillation in Earth “just perfect” if E_ν = few GeV
- Measurable using atmospheric neutrinos because
  - Less antineutrinos than neutrinos in atmospheric flux
  - σ(antineutrino+N) < σ(neutrino+N)

Neutrino oscillations in the Earth

Earth density 4-13 g/cm³ →

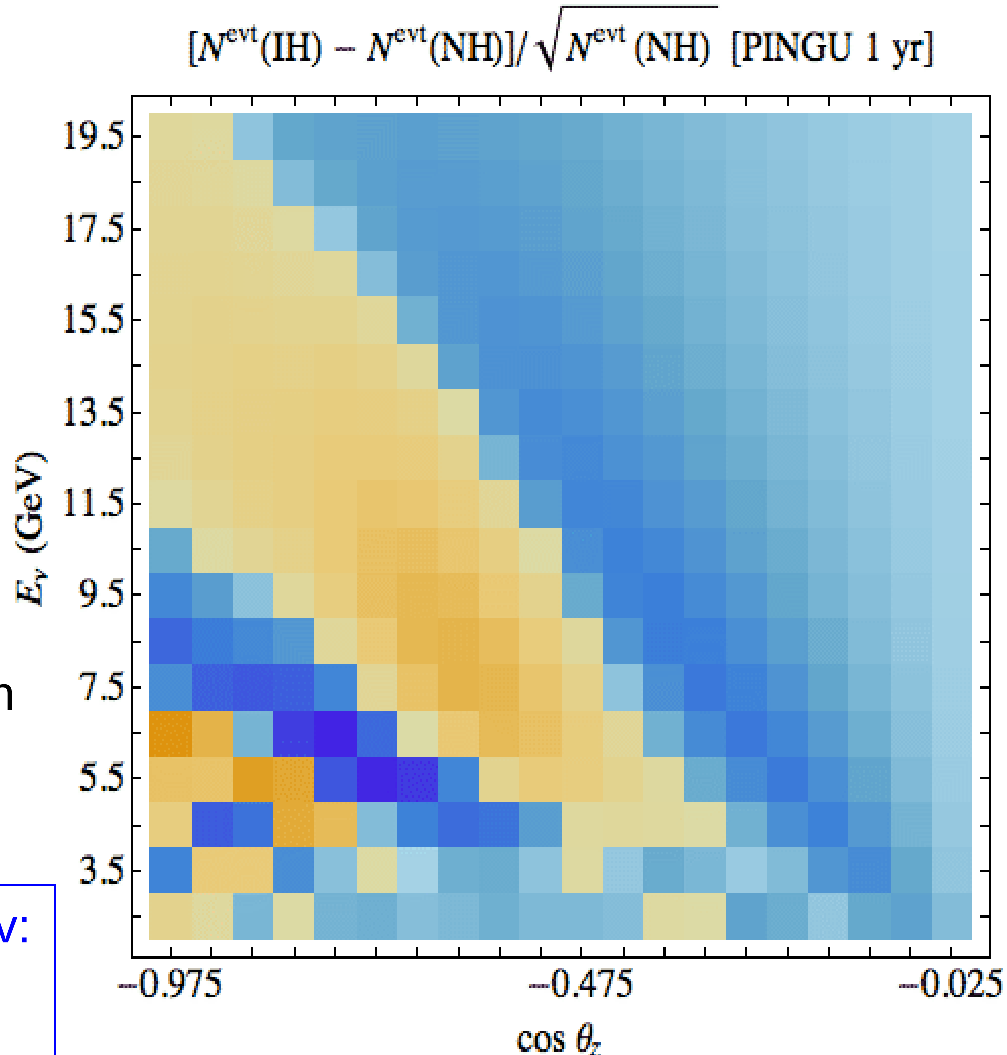
Relevant: $E_\nu \sim 3\text{–}10\,\text{GeV}$





Mass hierarchy "oscillogram"

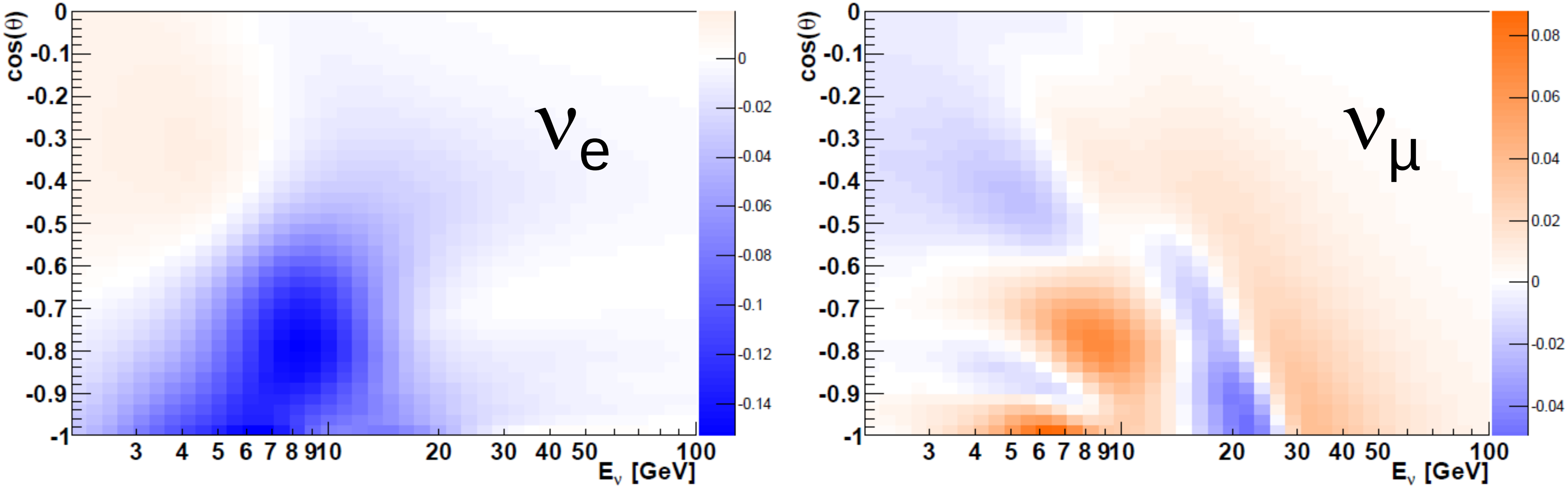
- Expected signal significance in energy vs. zenith w/o experimental effects
- Need to assess neutrino reactions at 3–20 GeV
- Required:
  - Good angular and energy resolution
  - Flavour separation



Akhmedov, Razzaque, Smirnov:
JHEP 1302 (2013) 082,
JHEP 1307 (2013) 026

… and in the real world

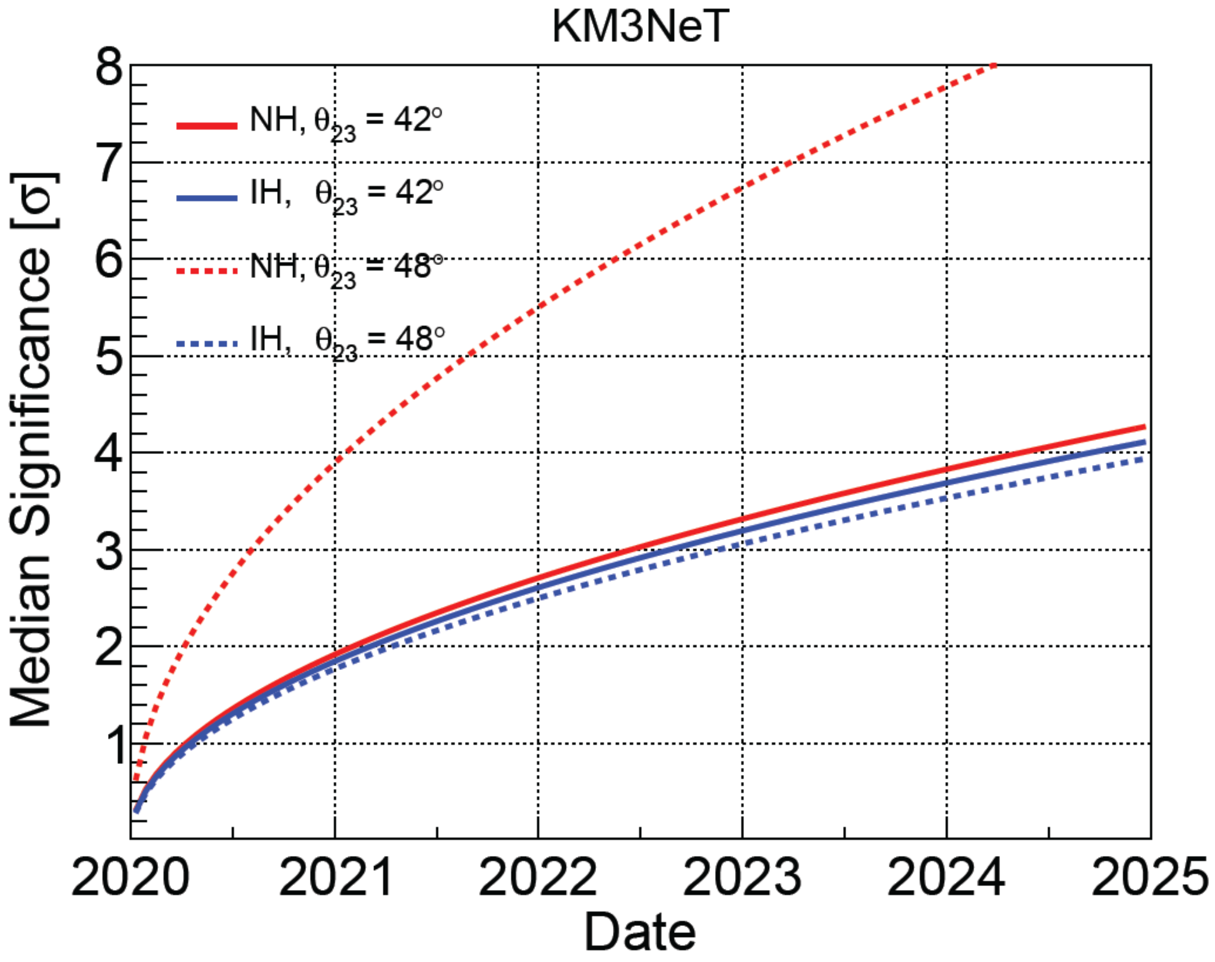
$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$



- Both muon (ν_μ survival) and electron channel ($\nu_\mu \rightarrow \nu_e$ conversion) contribute
- Removal of atmospheric muon background essential
- Major effort to control systematics
- But: Measurement in reach

Measuring the mass hierarchy

- Sensitivity depends on true value of θ_{23} ("the octant")
- CP phase δ=0 assumed
- 3σ in 3 years for most unfavourable situation
- Similar result for PINGU, but later starting date



Summary and outlook

- Neutrino astronomy has become mature – transition from searches to observation
- Addressing fundamental questions of particle and astrophysics, and of cosmology
- Cubic-kilometre detectors required for astrophysical observations
- Full sky coverage by IceCube and KM3NeT, complementary environments and sensitivities
- Neutrino mass hierarchy in reach within 10 years

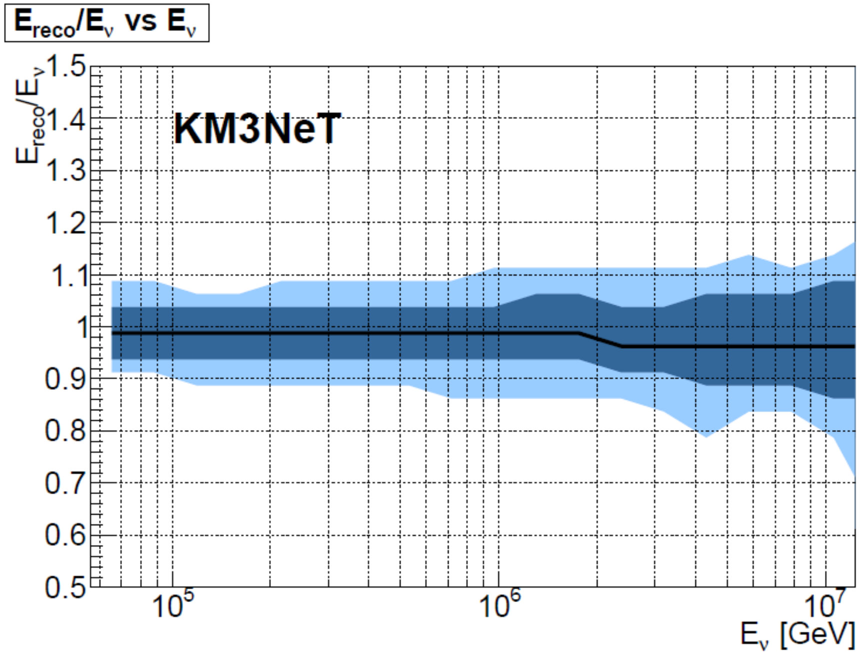
Stay tuned!

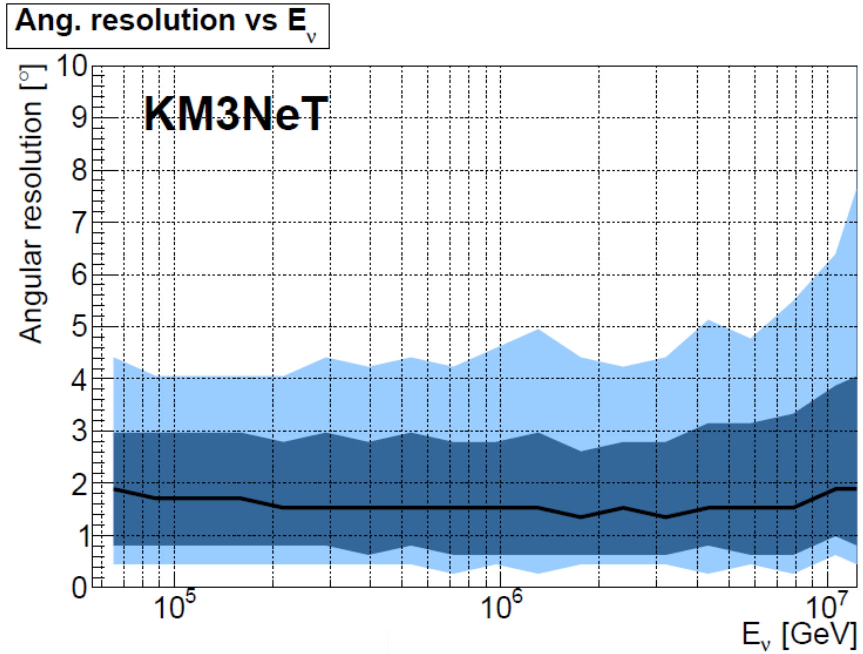
Backup

KM3NeT development

Phase	Blocks/ strings	Primary deliverables / site(s)	Funding Construction
1	0.2/31	Proof of feasibility and first science results; KM3NeT-Fr + KM3NeT-It sites	Fully funded 2015-17
2.0	2/230	Measurement of neutrino signal reported by IceCube; All-flavor neutrino astronomy; KM3NeT-It site	Applications pending 2017-2020
	1/115	Neutrino mass hierarchy; KM3NeT-Fr site	
3	6+1/805	Neutrino astronomy including Galactic sources; Multiple sites	t.b.d. ?

Shower reconstruction: θ, E





- For contained ν_e CC events
- Event sample after selection cuts
- ~10% in E, better than 2° in direction

Implementation in DOM

- Reflective rings around PMTs (+27% light detection, see JINST 8 (2013) T03006)
- PMTs supported by plastic structure produced by 3D-printing
- Calibration: Acoustic sensor and compass + tiltmeter
- Electronics components attached to cooling structure
- One single penetrator for connection to vertical cable

PMT specifications

Parameter	Requirement
Photocathode diameter	> 72 mm
Nominal Voltage for Gain $3x10^6$	900 – 1300 V
Gain slope = $\log_{10}(gain)/\log_{10}(HV)$	6.5 – 8.0
QE at 404 nm	> 23 %
QE at 470 nm	> 18 %
TTS (FWHM)	< 5 ns
Dark count rate (0.3 p.e. threshold)	< 2 kHz
Pre-pulses	< 1 %
Delayed pulses	< 3.5 %
Early afterpulses	< 2 %
Late afterpulses	< 10 %

PMTs available

+MELZ …

ETEL D792

Hamamatsu R12199

HZC XP53B20

Fulfil specifications; orders placed / expected

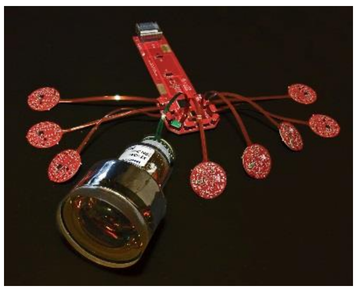
First prototype not yet compliant with specifications (gain, dark rate, afterpulses, …), further development under way

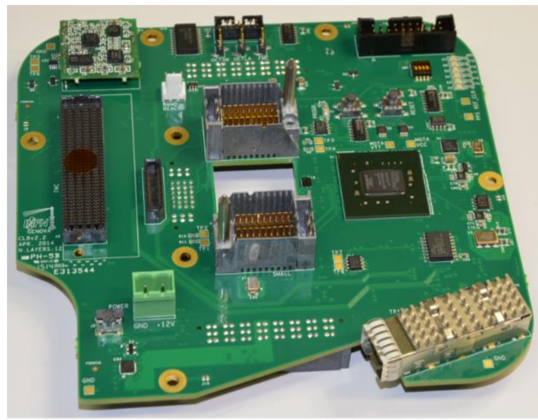
Note: In all cases price/photocathode area < 10-inch tubes (MELZ?)

KM3NeT readout

Power board

31 PMTs + bases
2 octopus boards





Central Logic Board (CLB)

All data to shore (optical fibres)

Online filter on shore

HV for PMTs

Discrimination w.r.t. predefined threshold

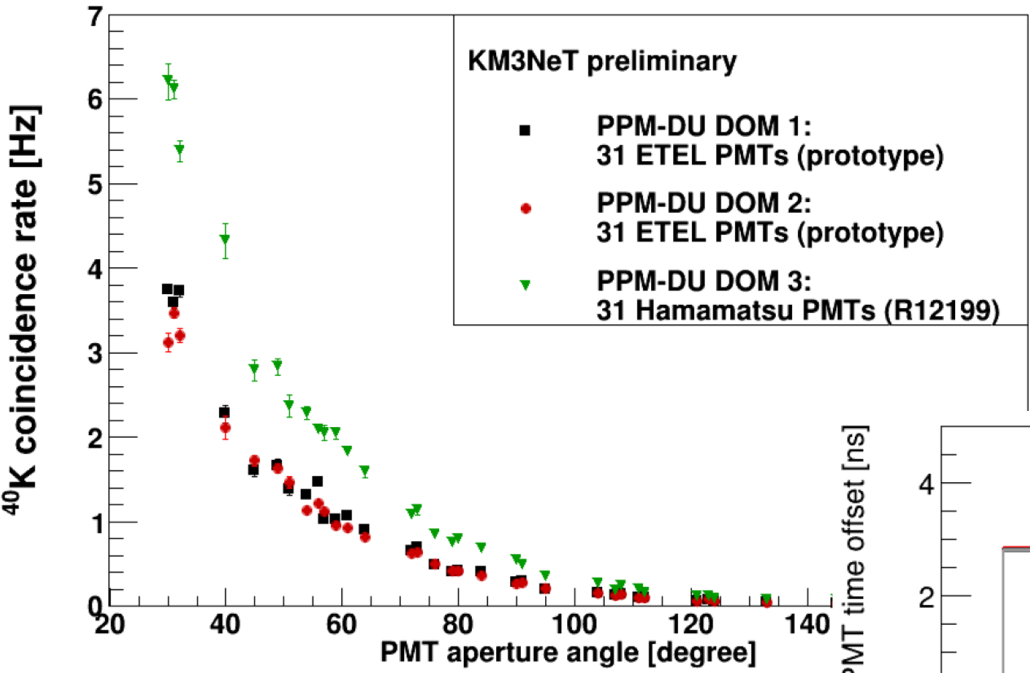
Signal collection

FPGA for TDC (time & time over threshold), time stamping (1 ns precision);

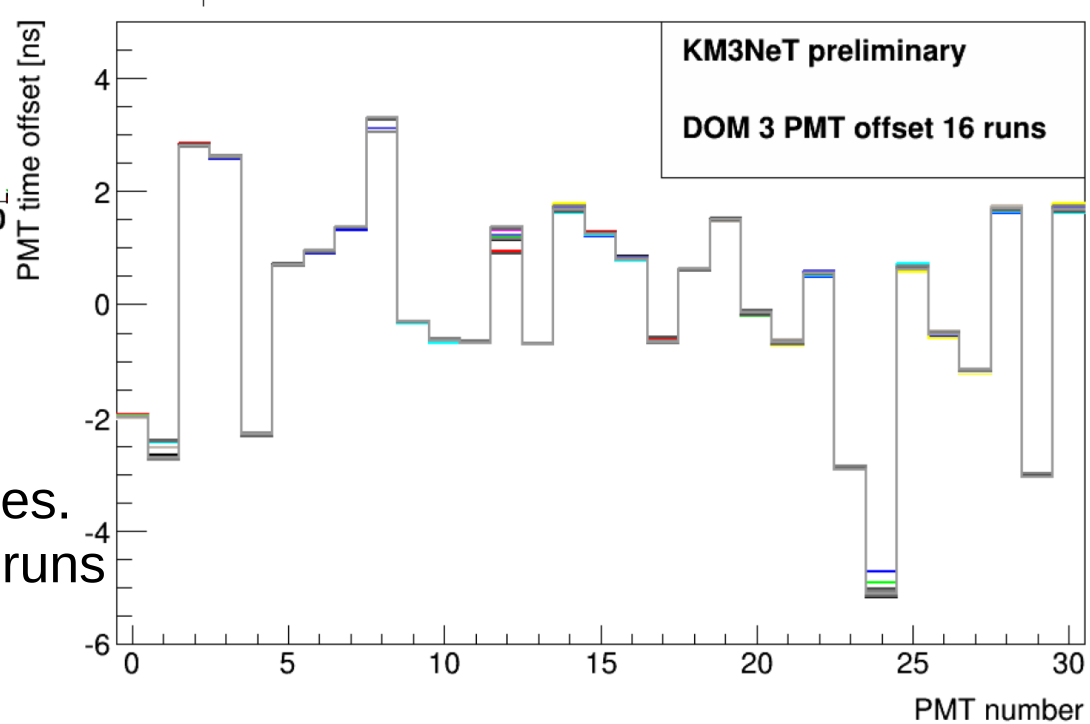
Interface for time synchronisation:

Control of calibration devices;
Communication;

PPM-DU: Inter-DOM timing



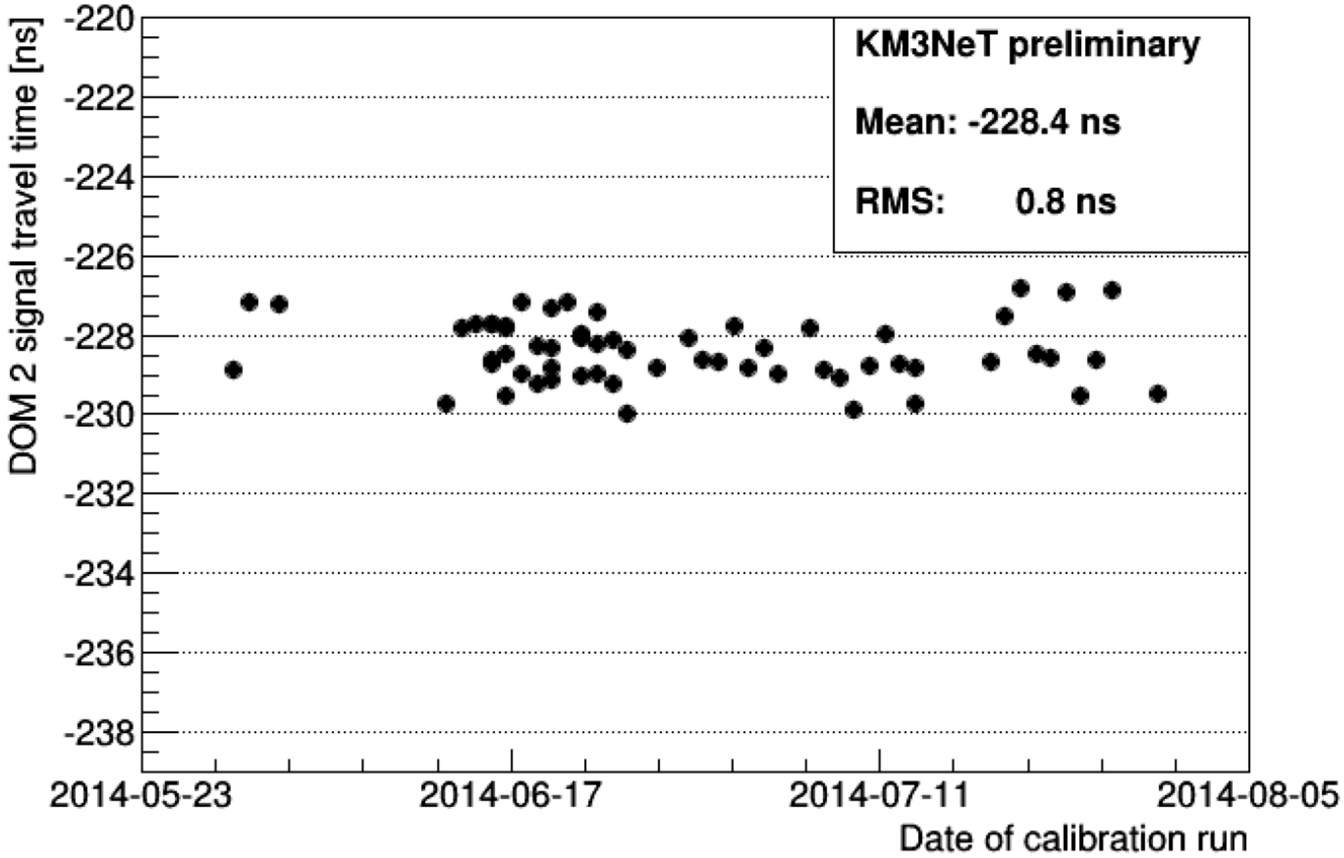
K40 coincidence rate as a function of the angle between PMTs.
Note: Different PMT types!



Relative timing calibration of
31 PMTs in DOM using coincidences.
Note: Extremely stable over many runs

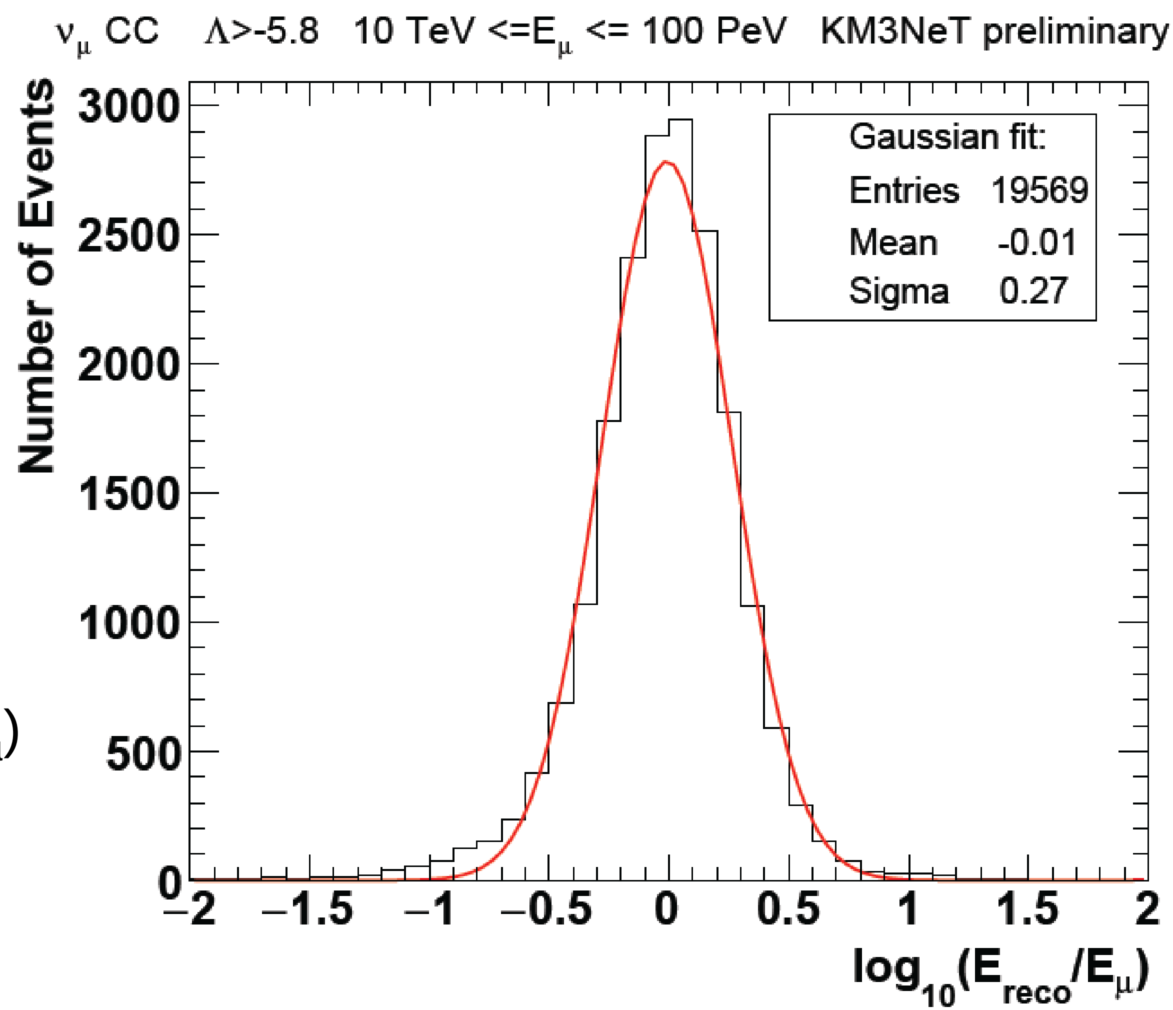
PPM-DU: Intra-DOM timing

- Calibration with pulsed LED
- Time difference – light travel time = Signal travel time
- Result very stable over several months, RMS of jitter < 1 ns



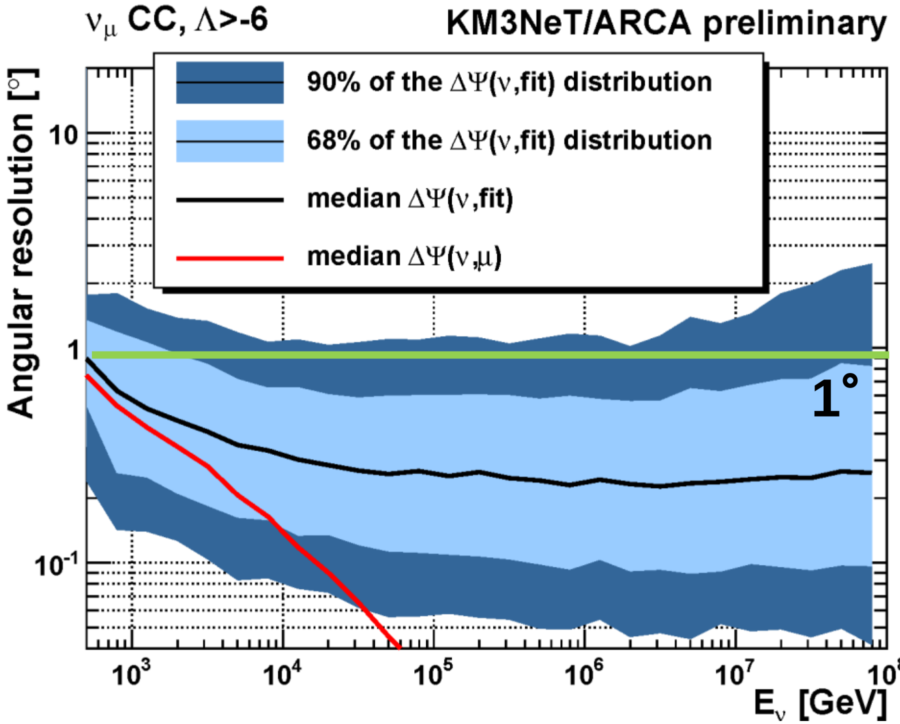
Muon energy reconstruction

- E_μ > 10 TeV
- Containment required (minimum reconstructed muon path length in detector)
- “Very Gaussian” in $\log(E_\mu)$

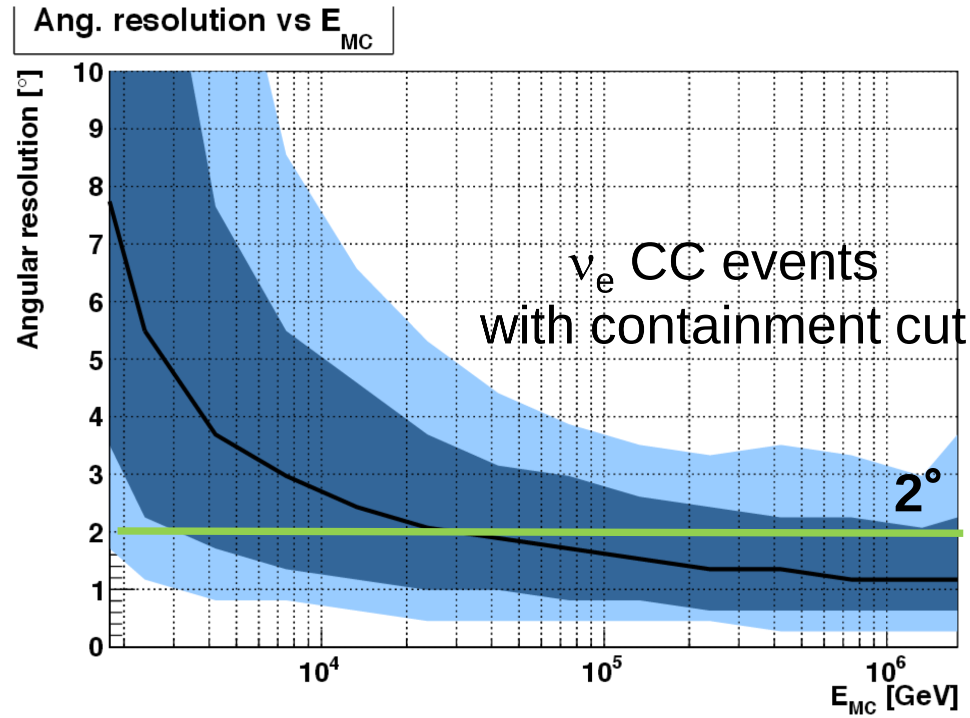


KM3NeT resolutions

Track-like events:

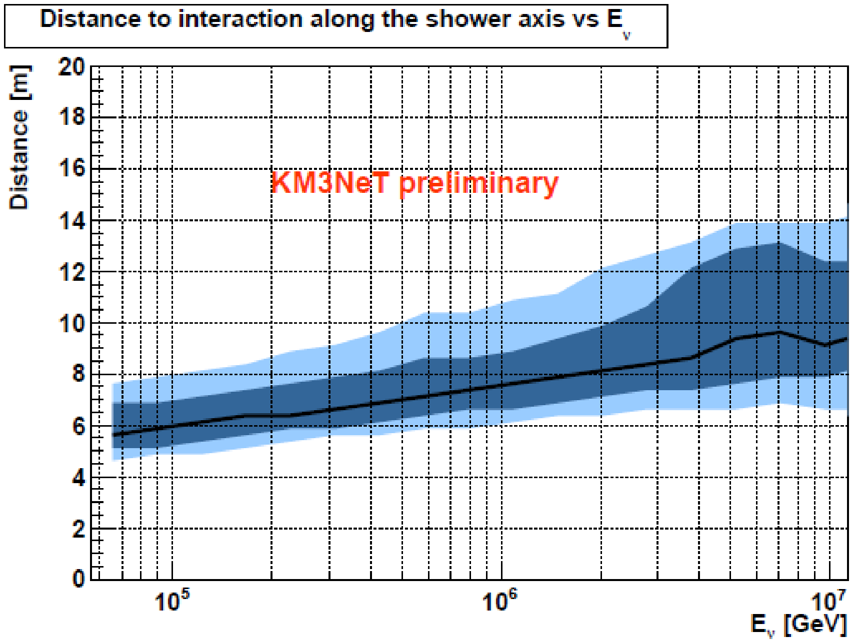


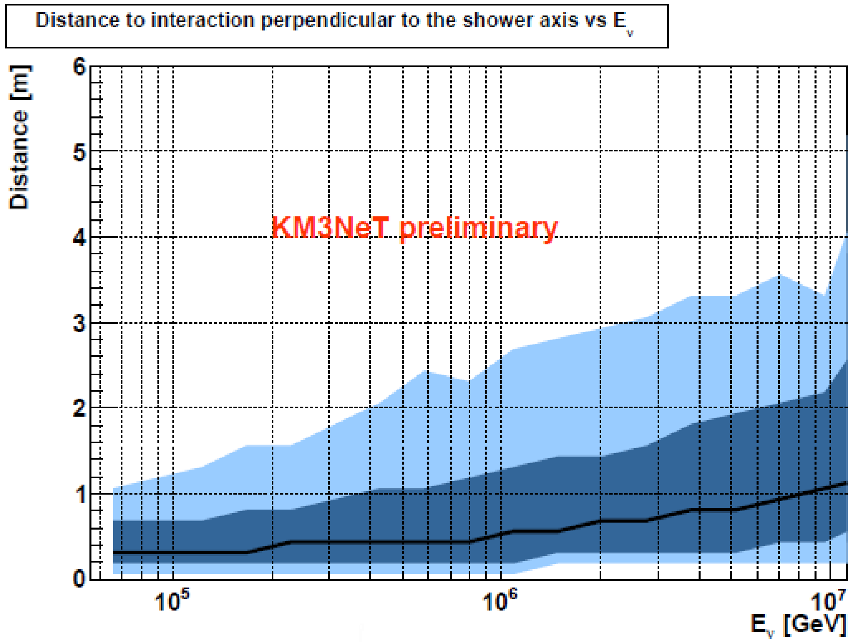
Cascades:



- Muon energy: d(log10 E)=0.25-0.3 at E > 10 TeV
- Cascade energy: 5-10% at E > some 10 TeV
- All-flavour neutrino astronomy in reach

Shower reconstruction: vertex





<u>Along shower axis</u>:
Offset = distance vertex – shower-max ~ log(E)

<u>Perpendicular to shower axis</u>

Analysis scheme

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- All analyses proceed through 4 consecutive steps:
  1. Preselection (e.g. quality cuts or cuts on reconstructed zenith or N_{hit})
  2. Further background rejection by Boosted Decision Tree
  3. 'Cut-and-count' significance analysis
  4. Maximum-likelihood analysis using likelihood ratio

$$LR = \sum_{k=1}^{n} \log \frac{\frac{n_{sig}}{n} \cdot P_{sig}(X_k) + \left(1 - \frac{n_{sig}}{n}\right) \cdot P_{back}(X_k)}{P_{back}(X_k)}$$

Significance determined by generating pseudo-experiments

Note: All detector information is in the probability density functions P(X), where the event variables X depend on the type of analysis.

- Main results:
  - → Event samples with high signal content from step (3)
  - → Optimised sensitivities from step (4)

Signal/background separation

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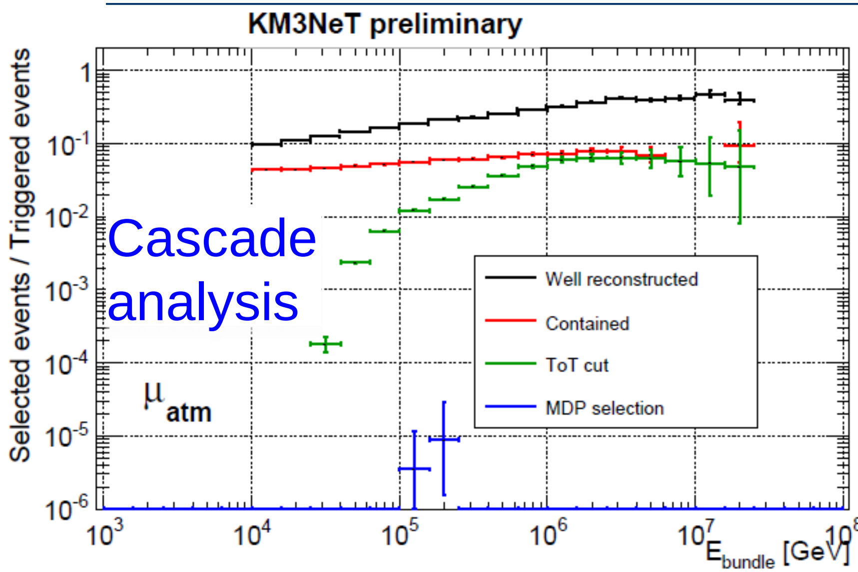
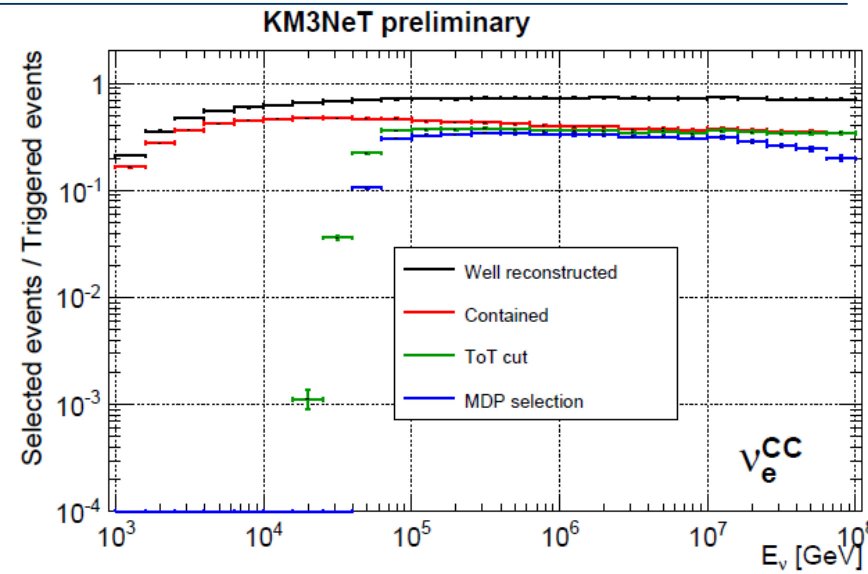
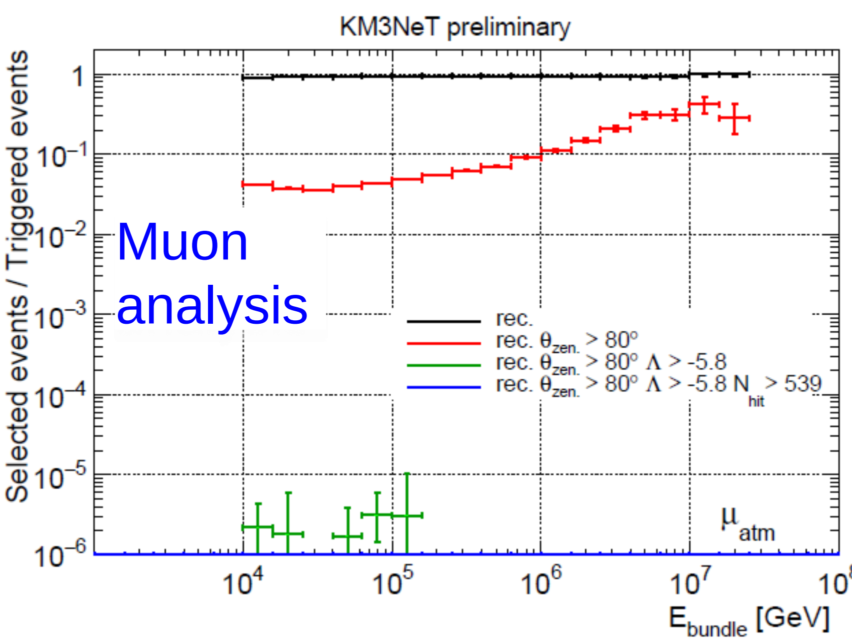
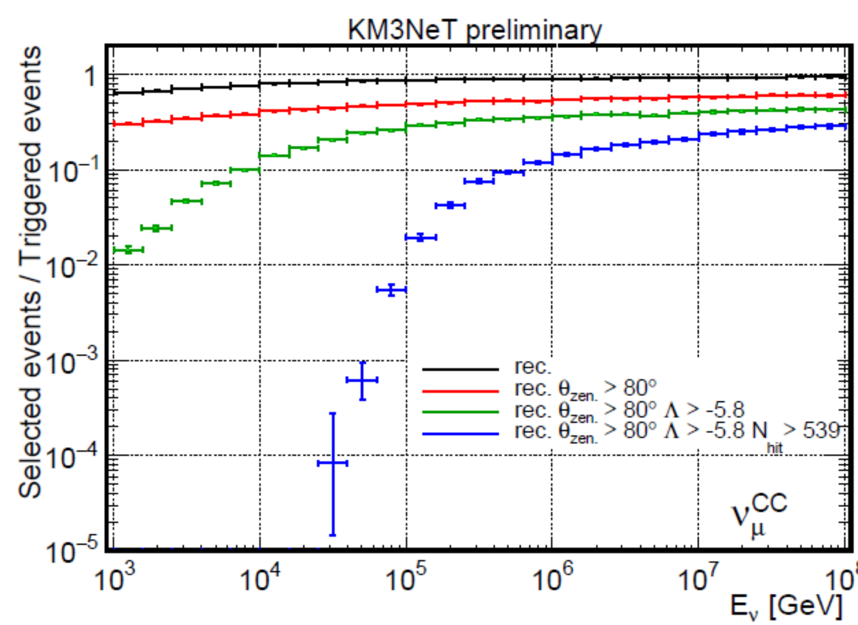








Results (cut-and-count)

Event numbers per year for ARCA

Cascade analysis

	reconstruction level	after preselection cuts	after final cuts
μ_{atm}	4.8×10^6	1.1×10^4	1.2
ν^{μ}_{atm}	2.0×10^4	9.8	4.0
ν^{e}_{atm}	1.41×10^3	4.66	3.8
ν^{μ}_{cosm}	70.4	6.8	2.2
ν^{e}_{cosm}	60.8	9.8	8.2
ν^{τ}_{cosm}	50.0	6.8	5.2

Muon analysis

	reconstruction level	after preselection cuts	after final cuts
μ_{atm}	5.5×10^7	2.2×10^6	0
ν^{μ}_{atm}	3.2×10^5	1.6×10^5	5.32
ν^{e}_{atm}	1.2×10^4	9.9×10^3	0.04
ν^{μ}_{cosm}	384	195.4	6.52
ν^{e}_{cosm}	120	76.2	0.44
ν^{τ}_{cosm}	131	80.0	0.62

Diffuse flux from galactic plane

- New model by D. Gaggero at al.

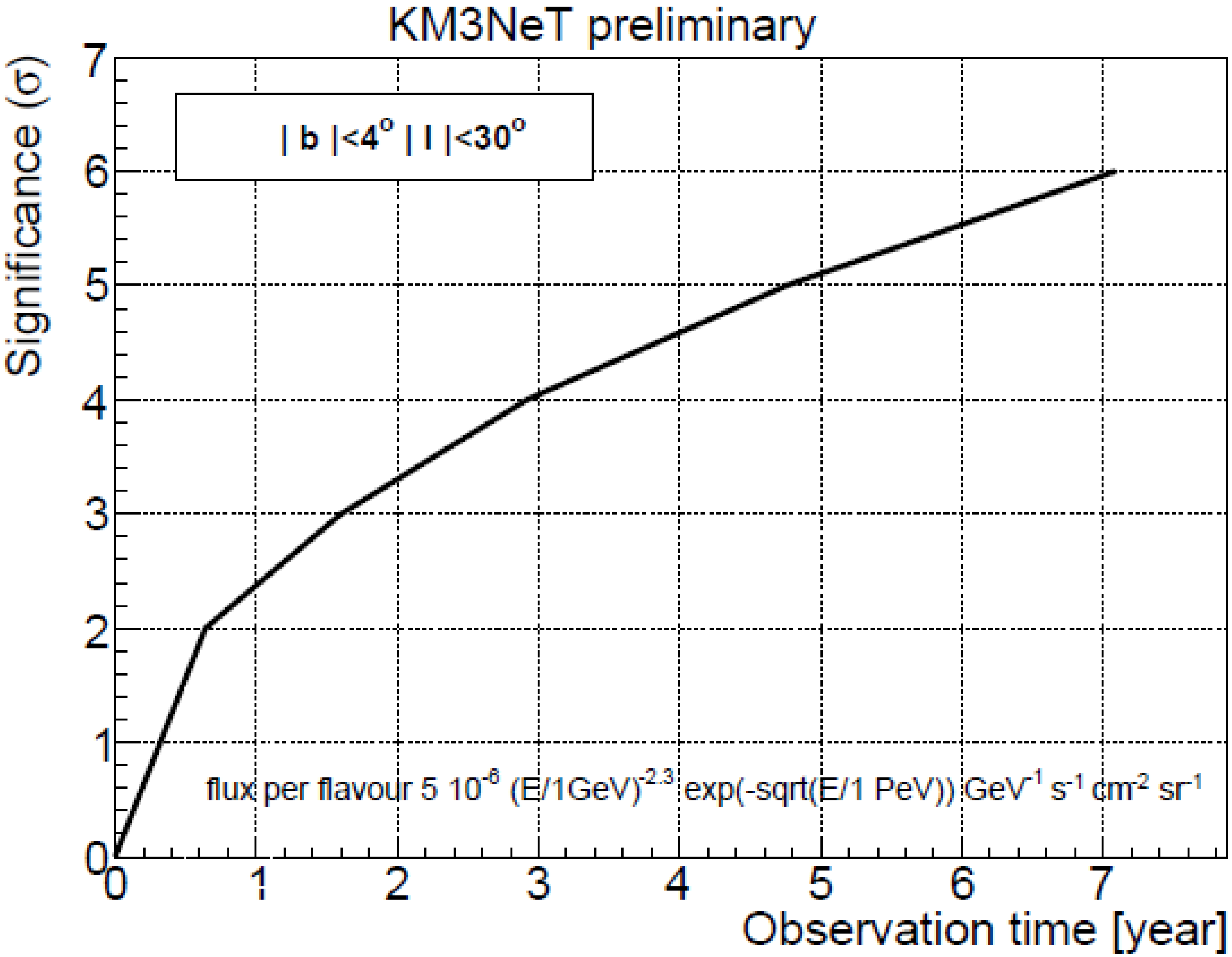
- Neutrino flux prediction for central part of Galaxy
(longitude |l| < 30° and latitude |b| > 4°):

$$\frac{\mathrm{d}\phi}{\mathrm{d}E_\nu} = 5 \times 10^{-6} \left(\frac{E_\nu}{1\,\mathrm{GeV}}\right)^{-2.3} \cdot \exp\left(-\sqrt{\frac{E_\nu}{1\,\mathrm{PeV}}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

per flavour (small region but much higher flux than extragalactic)

- Region very well visible for KM3NeT for up-going events
→ First analysis in muon channel

Galactic plane: First results



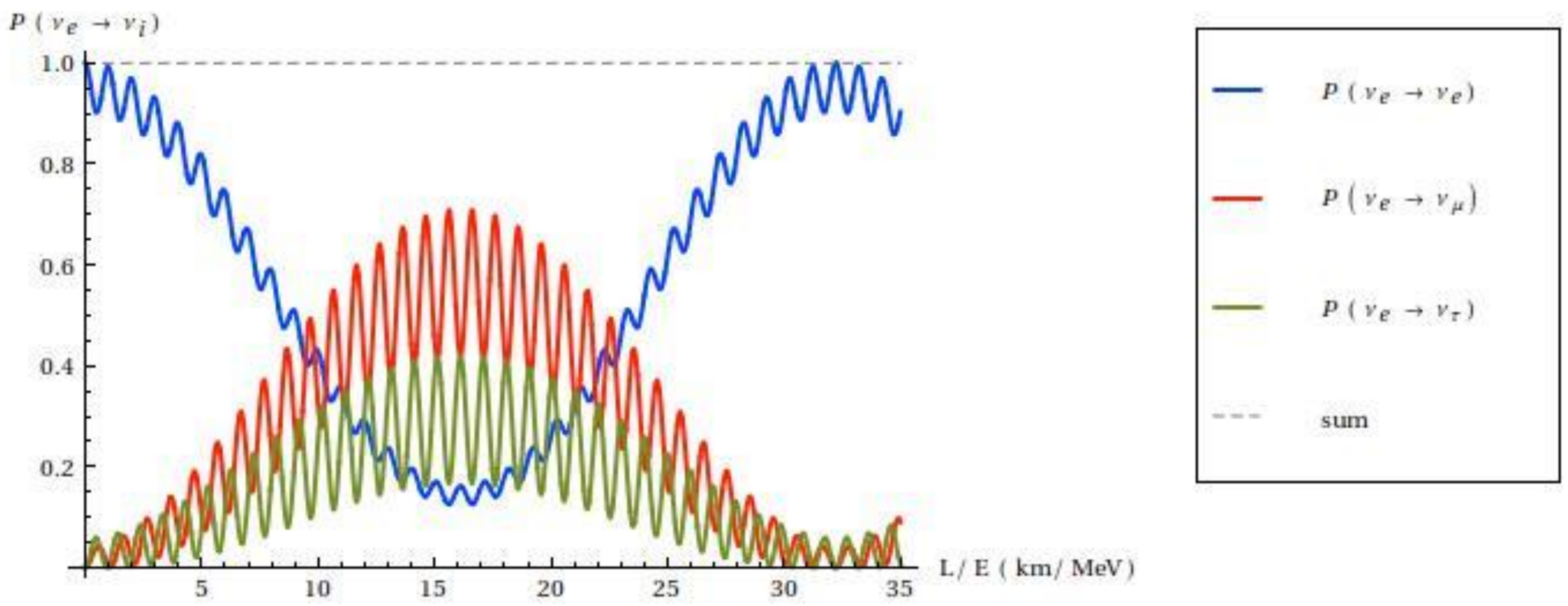
- Discovery in 4-5 years
- Inclusion of cascade channel will improve this result
- Confirmation of this flux: major breakthrough in astrophysics

Point-source searches

- Studied:
  - Two example Galactic sources with γ-ray flux beyond 100 TeV:
    → RXJ 1713: Supernova remnant, 0.6°
    → Vela-X: Pulsar wind nebula, 0.8°
    100% hadronic emission assumed
  - Generic (extragalactic) point sources with E^{-2} spectrum
- Analyses:
  - Muon channel
  - Cascade channel

Oscillations of atmospheric neutrinos

- Neutrino telescopes observe large numbers of atmospheric neutrinos
- Path length through Earth depends on zenith angle (0–12.000 km)
- Can we use them to study neutrino physics? … Yes!



Neutrino oscillations in matter

- Neutrino propagation in matter different for ν_e and $\nu_{\mu,\tau}$

  $\nu_e e^- \rightarrow \nu_e e^-$ and $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ W and Z exchange

  $\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-$ and $\overline{\nu}_{\mu,\tau} e^- \rightarrow \overline{\nu}_{\mu,\tau} e^-$ Z exchange only

  Result: Modification of oscillation pattern
- Dominant cause of solar neutrino oscillations (MSW effect)
- For atmospheric ν_μ and $\overline{\nu}_\mu$:
  Matter effect depends on sign of Δm^2_{13}
  Same effect for $\Delta m^2_{13} < 0, \overline{\nu}_\mu$ and $\Delta m^2_{13} > 0, \nu_\mu$
- Atmospheric neutrinos offer just the right $L \lesssim 2R_E$ and $E = \mathcal{O}(\text{a few GeV})$ to measure the effect.
- In neutrino telescope: ν_μ and $\overline{\nu}_\mu$ cannot be distinguished, but net effect since $\sigma(\nu_\mu N) \approx 2\sigma(\overline{\nu}_\mu N)$

Oscillations of atmospheric neutrinos

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- 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:

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

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

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

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

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