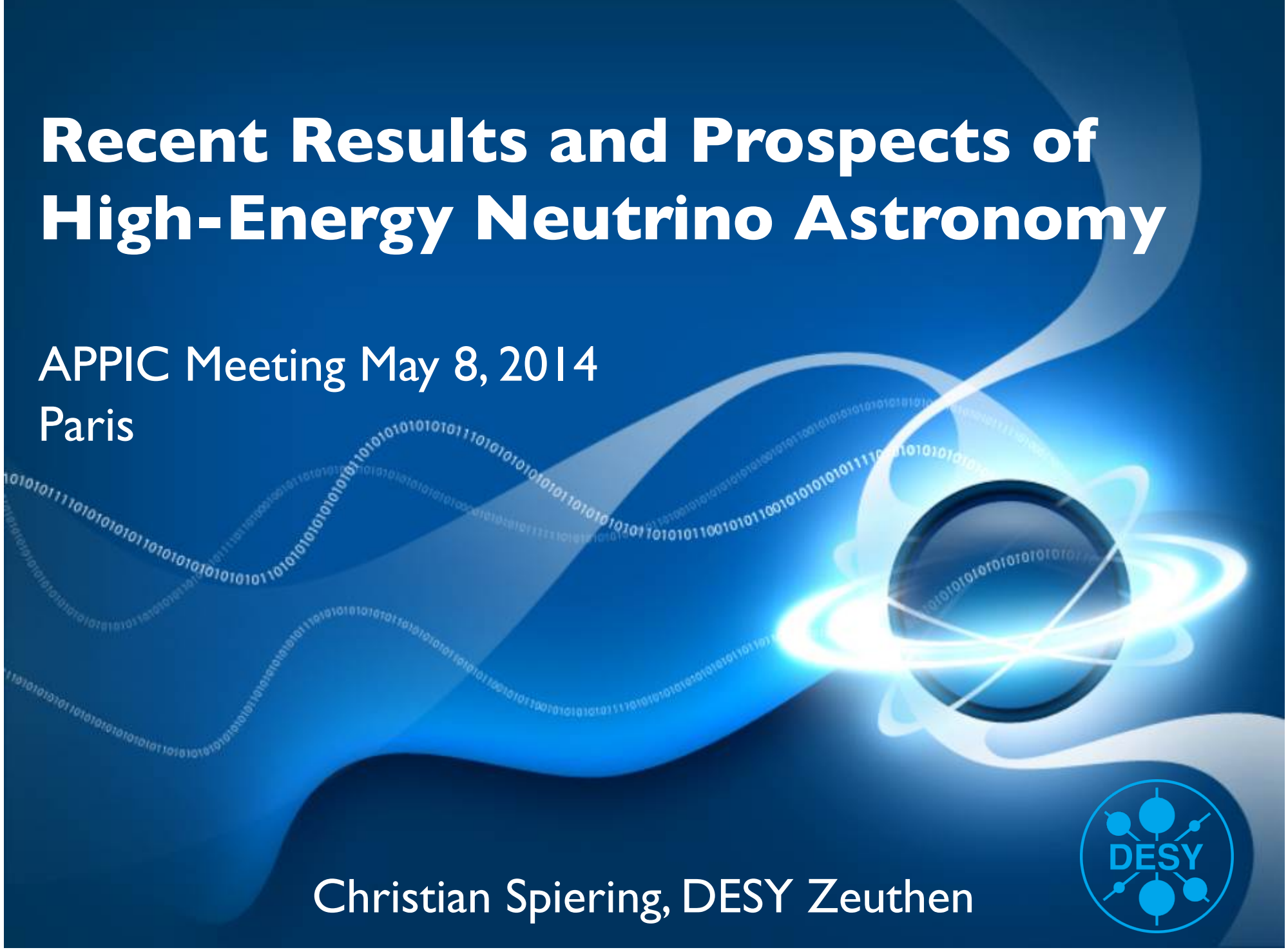
Recent Results and Prospects of High-Energy Neutrino Astronomy

APPIC Meeting May 8, 2014
Paris



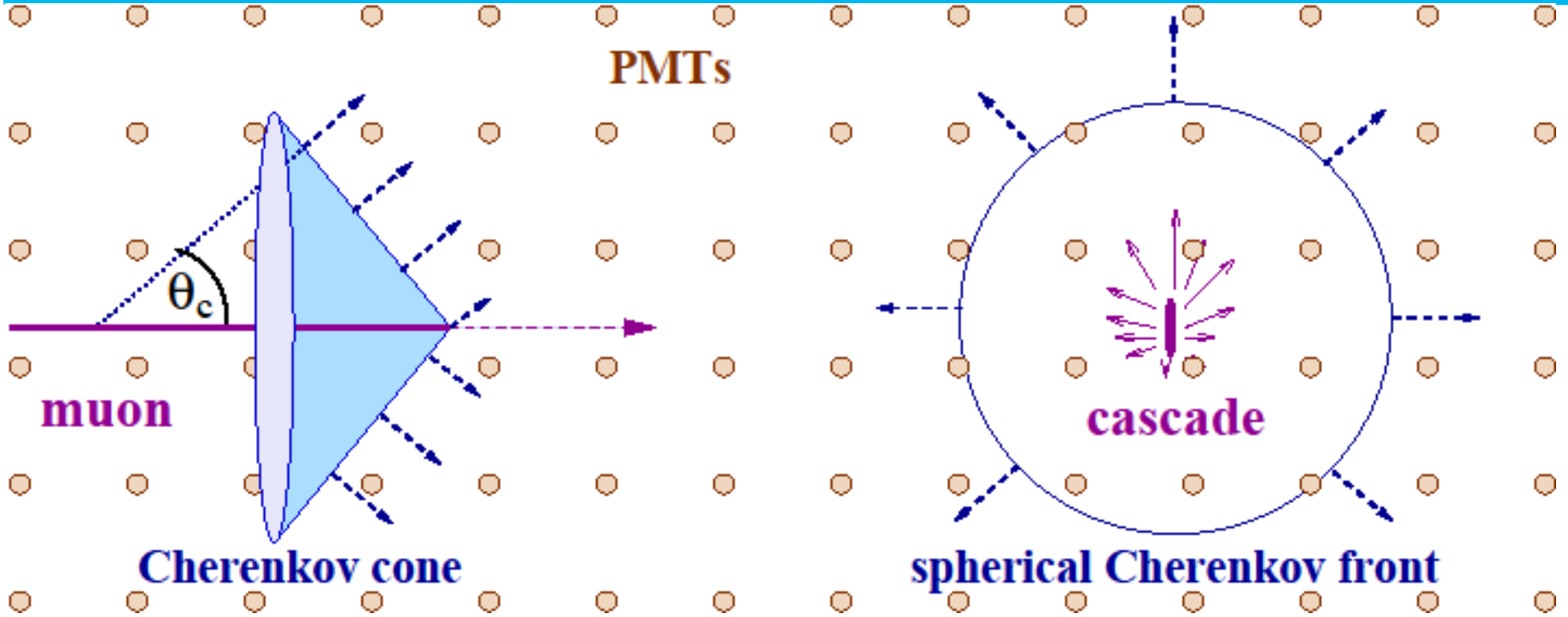
Christian Spiering, DESY Zeuthen

DETECTION PRINCIPLE

AND

PHYSICS GOALS

Detection Modes



- Muon track from CC muon neutrino interactions
  - Angular resolution 0.5°/0.1° for ice/water 1km³
  - dE/dx resolution factor 2-3
- Cascade from CC electron/tau and NC all flavor interactions
  - Angular resolution 10°/3° at 100 TeV for ice/water
  - Energy resolution ~ 15%

Physics with neutrino telescopes

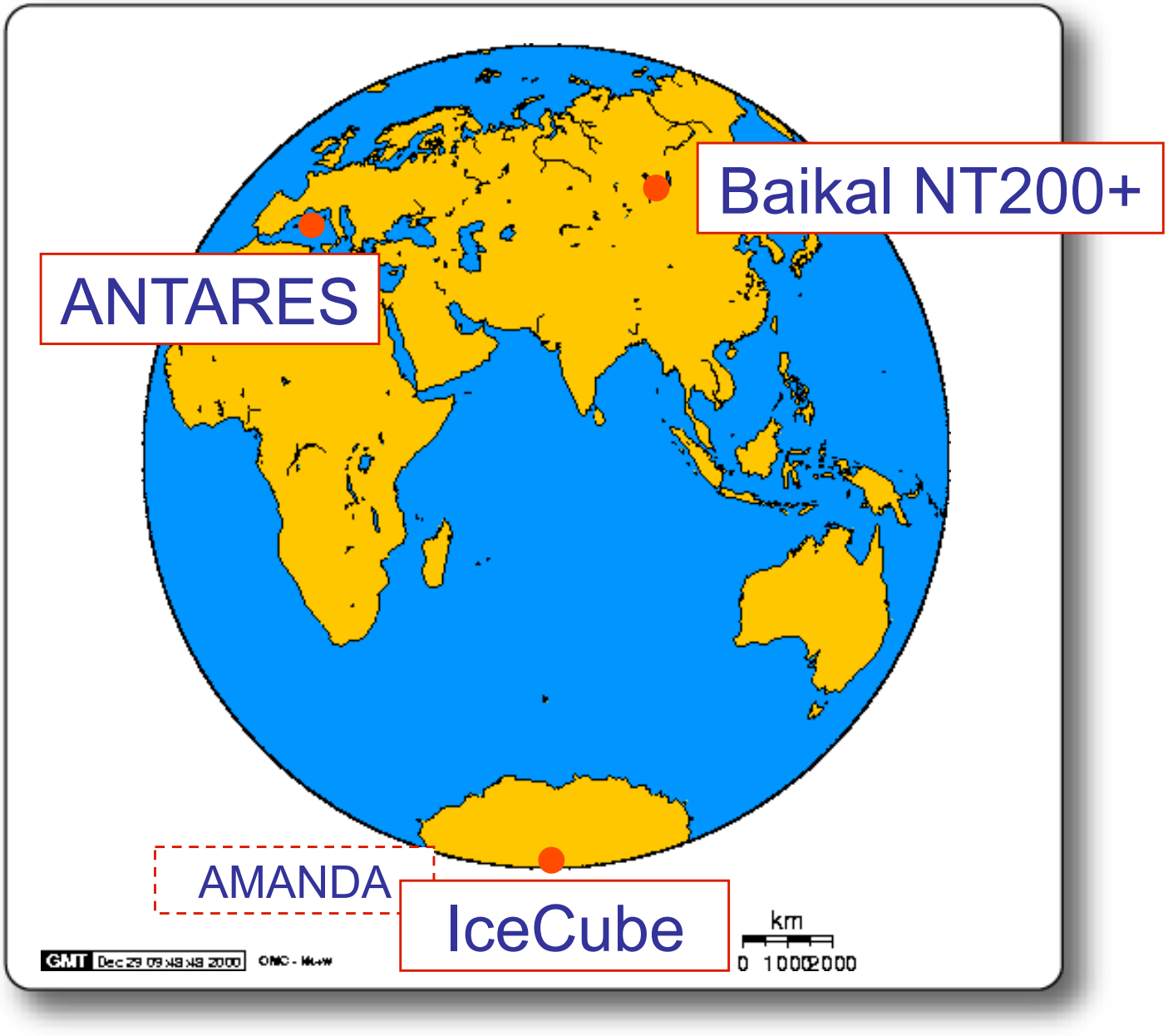
- Search for the sources of high-energy cosmic rays
- Dark Matter and Exotic Physics
  - WIMPs
  - Magnetic Monopoles and other superheavies
  - Violation of Lorentz invariance
- Neutrino and Particle Physics
  - Neutrino oscillations (incl. mass hierachy)
  - Charm physics
  - Cross sections at highest energies
- Supernova Collapse Physics
  - MeV neutrinos in bursts → early SN phase, neutrino hierarchy, ...
- Cosmic Ray Physics
  - Spectrum, composition and anisotropies
- Earth and marine science, glaciology

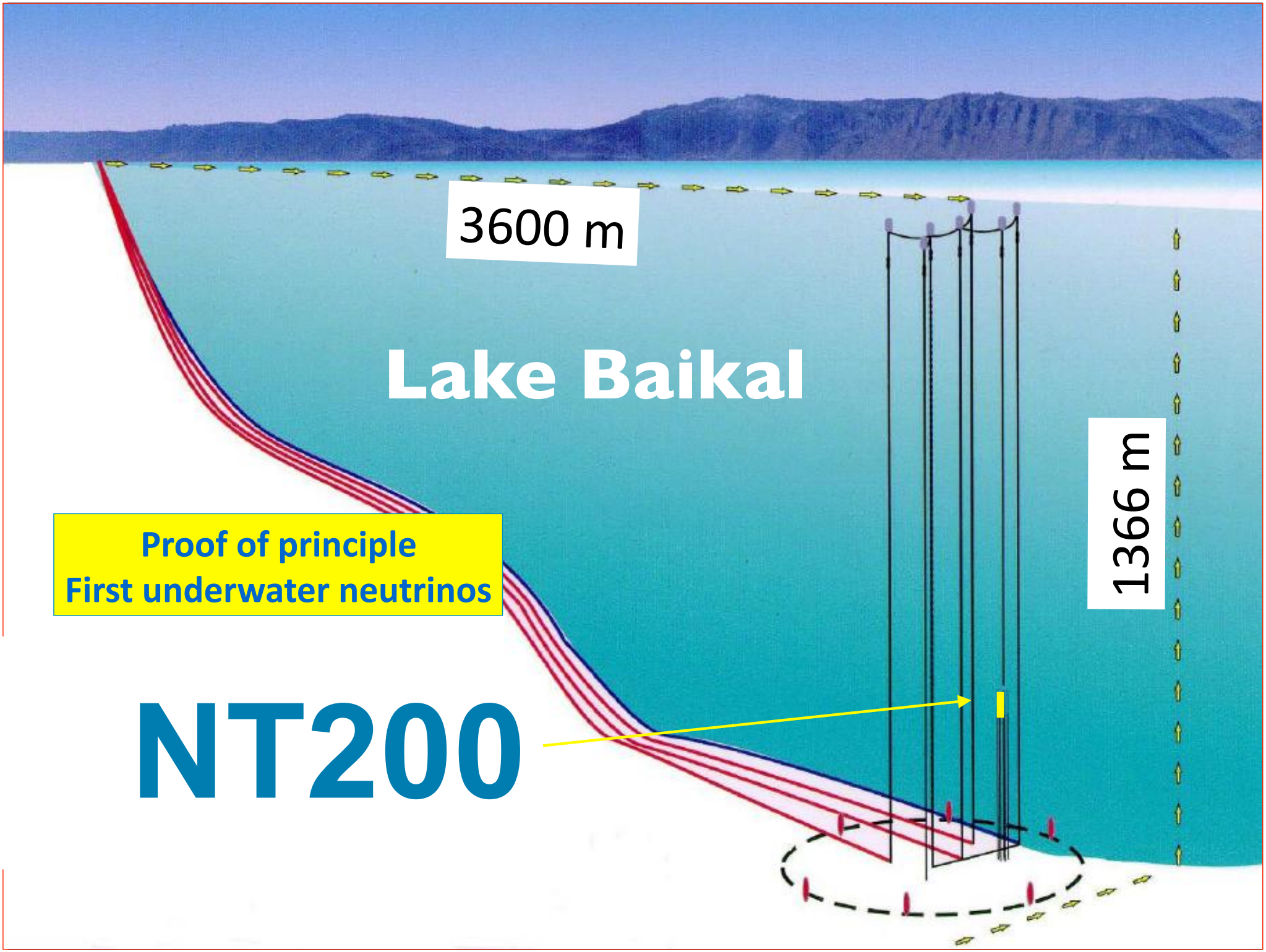
Main physics drivers for new projects

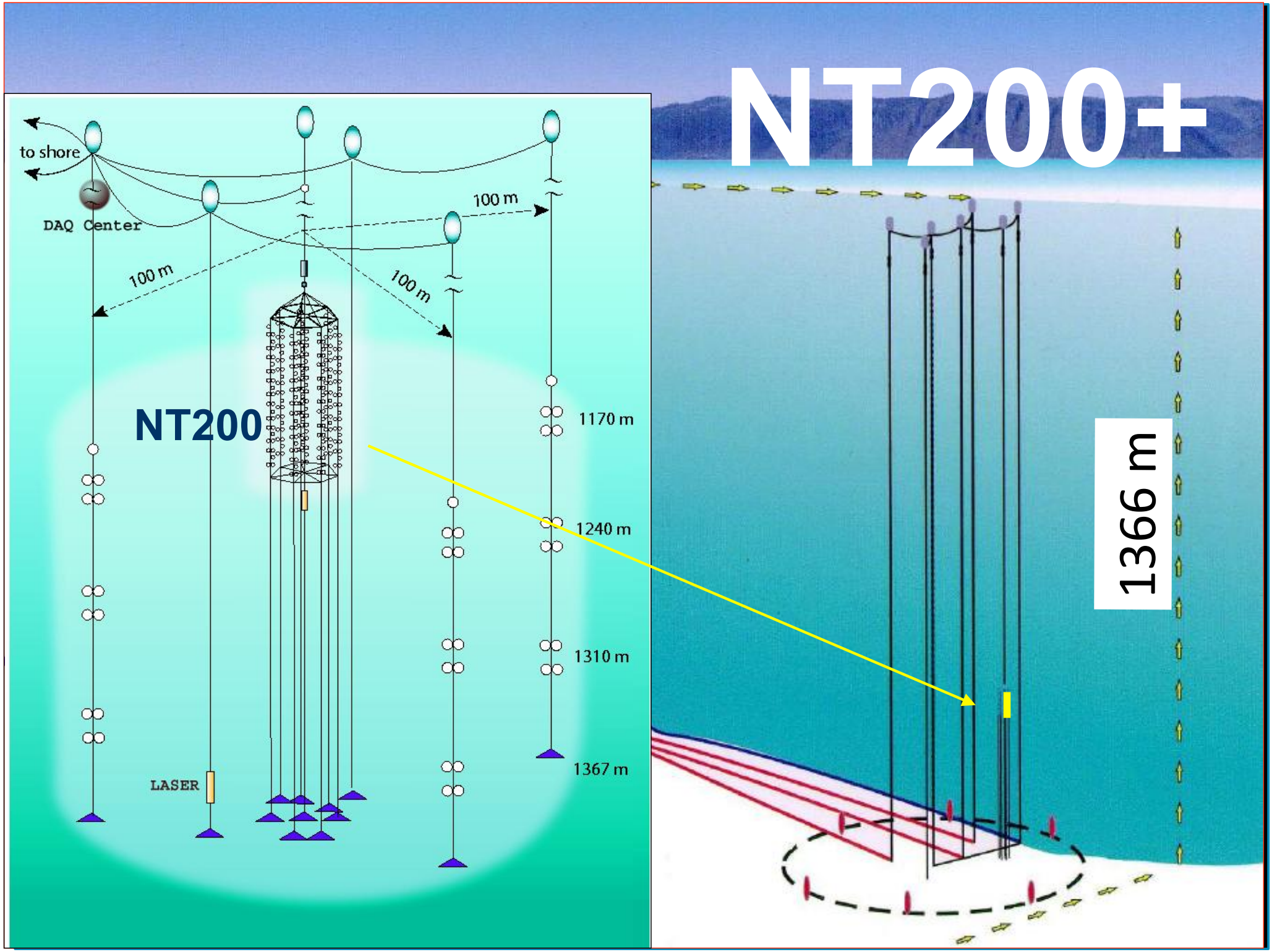
- **Search for the sources of high-energy cosmic rays** ***Gton scale***
- Dark Matter and Exotic Physics
  - WIMPs
  - Magnetic Monopoles and other superheavies
  - Violation of Lorentz invariance
- Neutrino and Particle Physics
  - **Neutrino oscillations (incl. mass hierachy)** ***Mton scale***
  - Charm physics
  - Cross sections at highest energies
- Supernova Collapse Physics
  - MeV neutrinos in bursts → early SN phase, neutrino hierarchy, ...
- Cosmic Ray Physics
  - Spectrum, composition and anisotropies

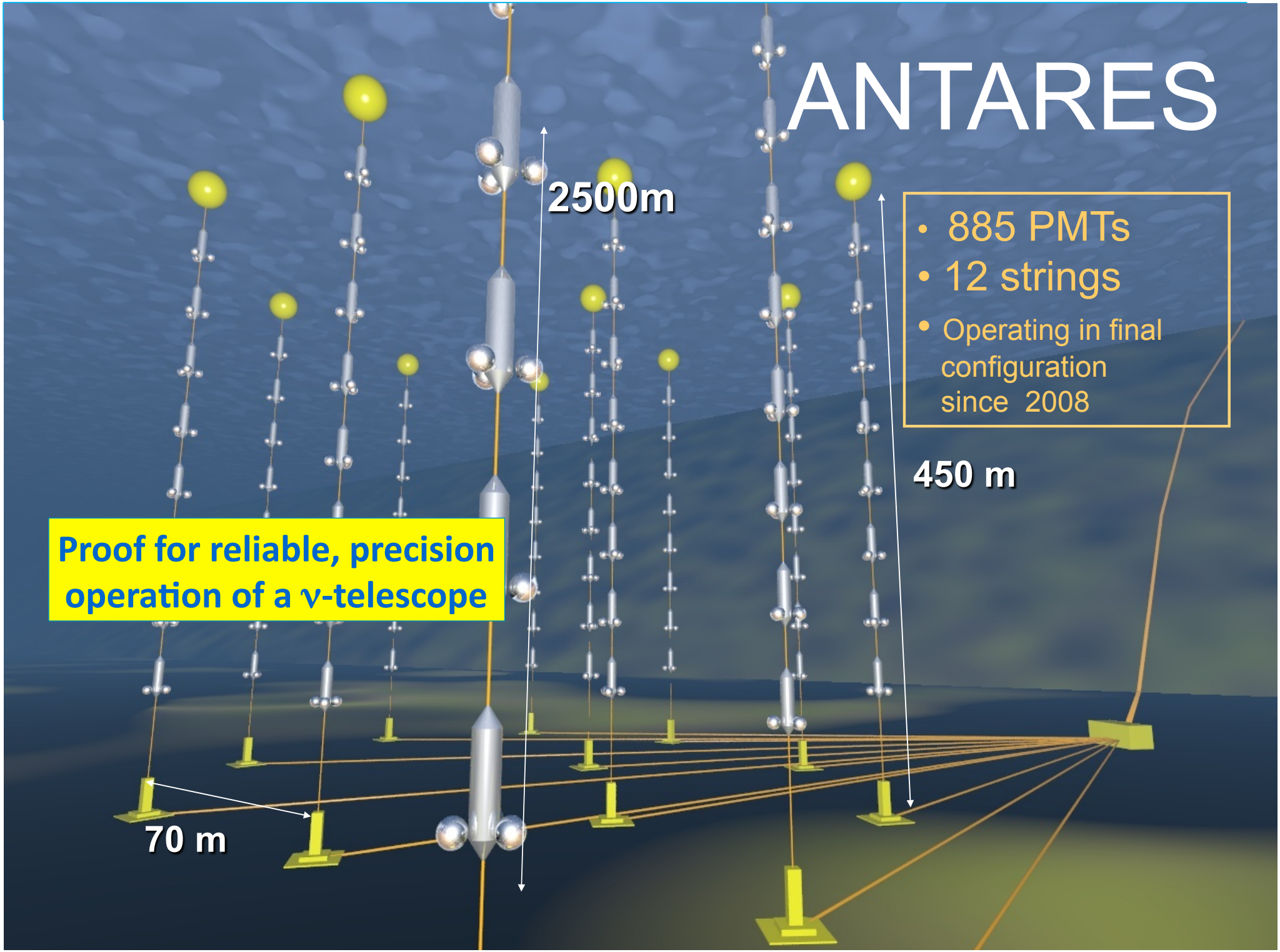
PRESENT DEVICES

Existing detectors

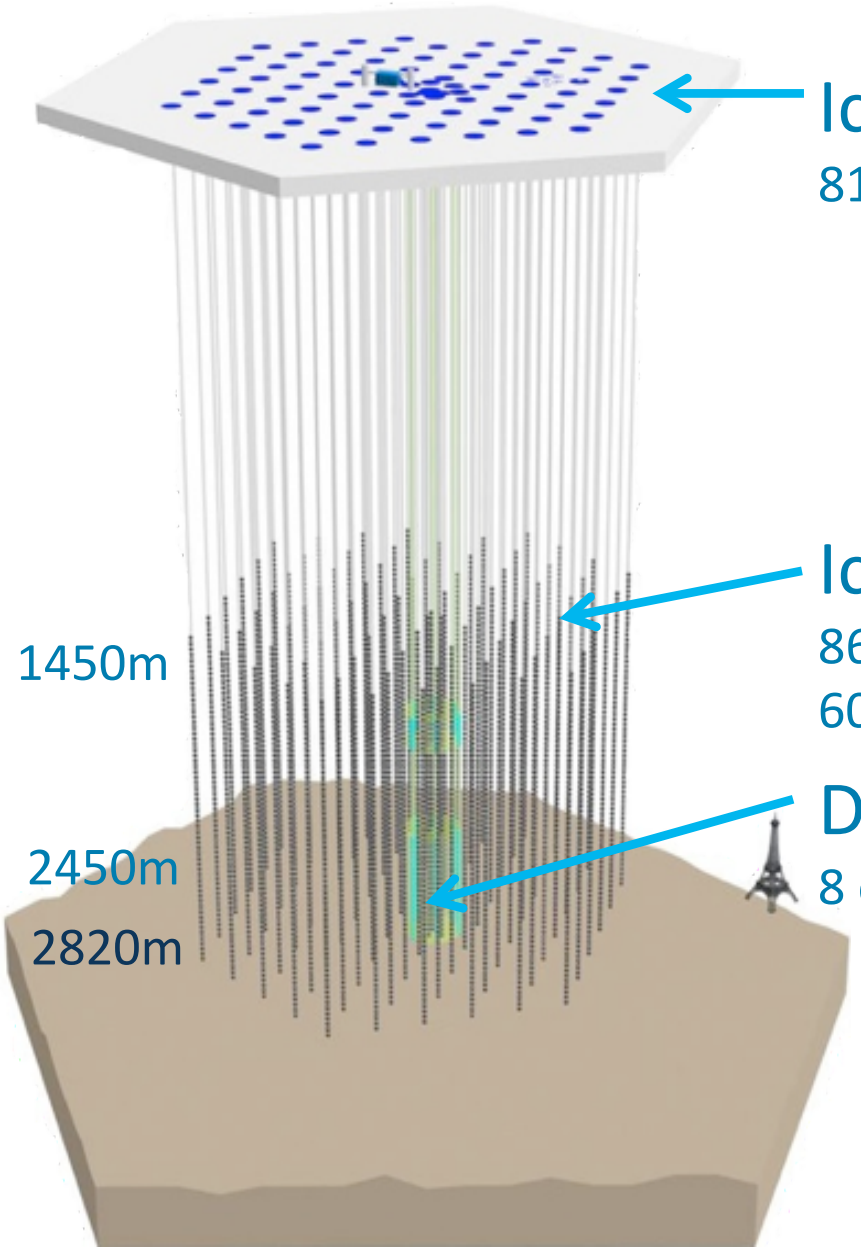



3600 m
Lake Baikal
1366 m
Proof of principle
First underwater neutrinos
NT200


NT200+
to shore
DAQ Center
100 m
100 m
100 m
NT200
1170 m
1240 m
1310 m
1367 m
LASER
1366 m


ANTARES
2500m
• 885 PMTs
• 12 strings
• Operating in final configuration since 2008
450 m
Proof for reliable, precision operation of a ν-telescope
70 m

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

86 strings including 8 Deep Core strings
60 PMT per string

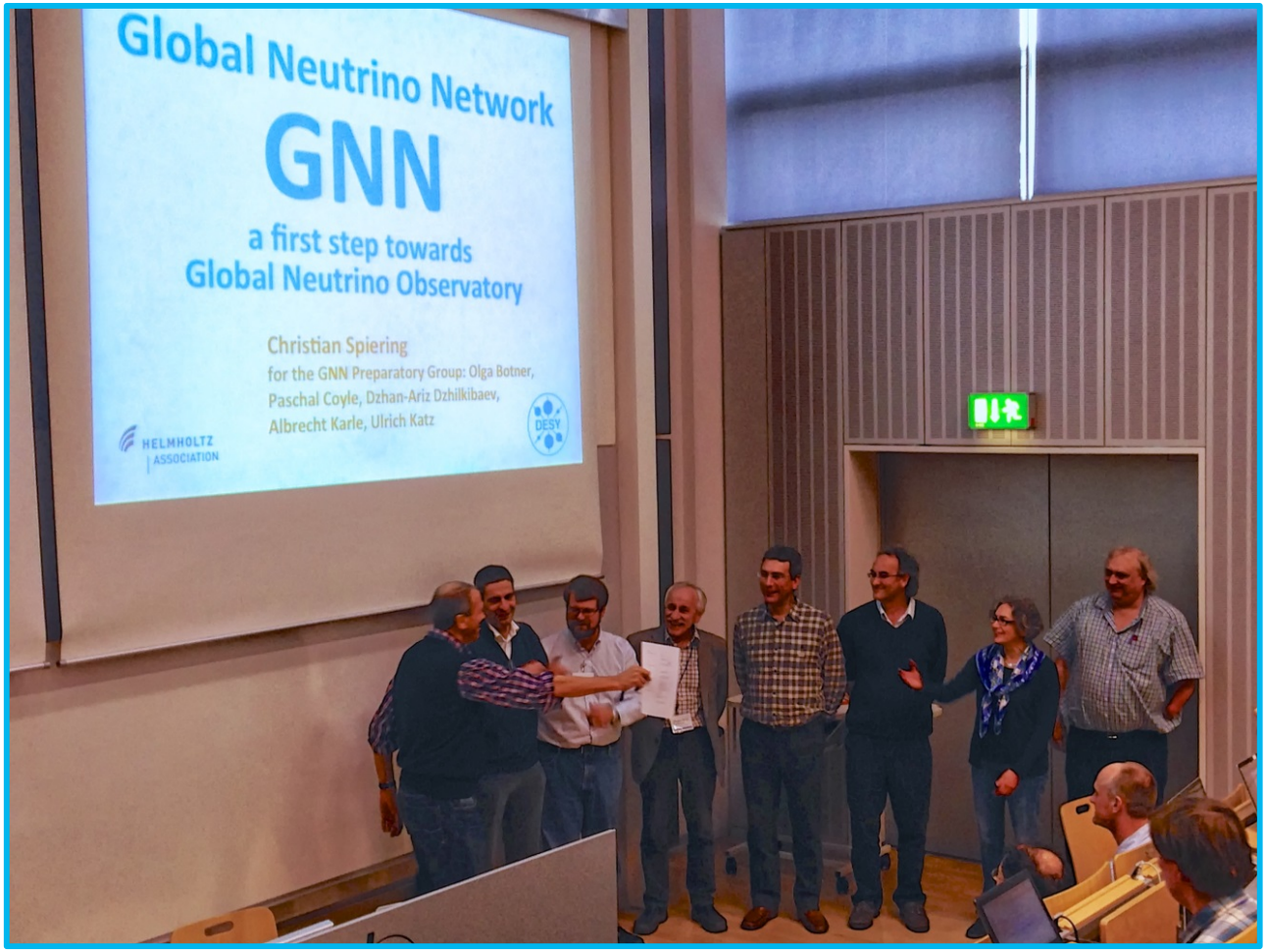
DeepCore

8 closely spaced strings

Threshold: IceCube ~ 100 GeV
DeepCore ~10 GeV

GNN

The Global Neutrino Network



- Oct. 2013, Munich

- Antares
- Baikal
- IceCube
- KM3NeT

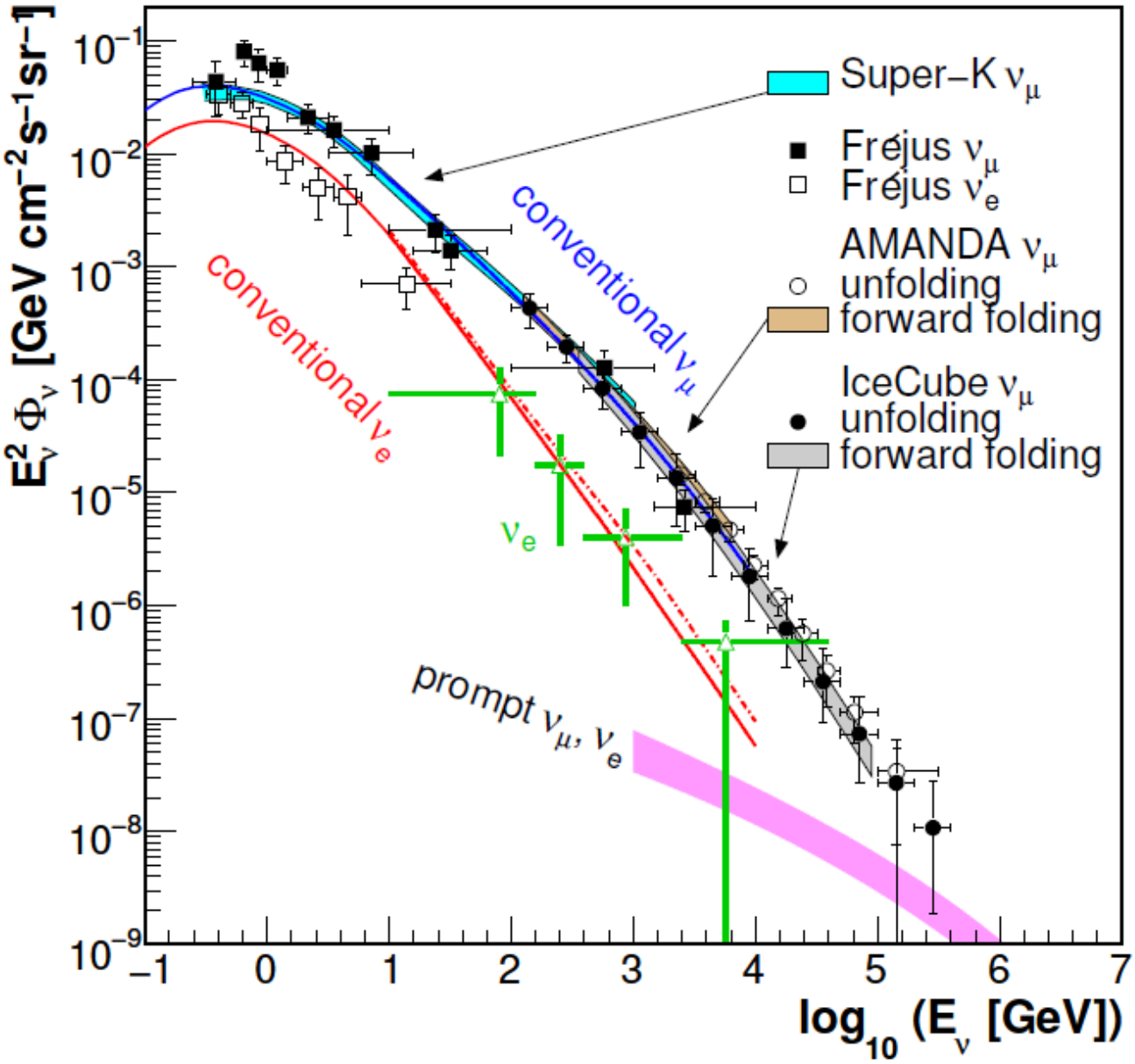
- **http://www.globalneutrinonetwork.org/**

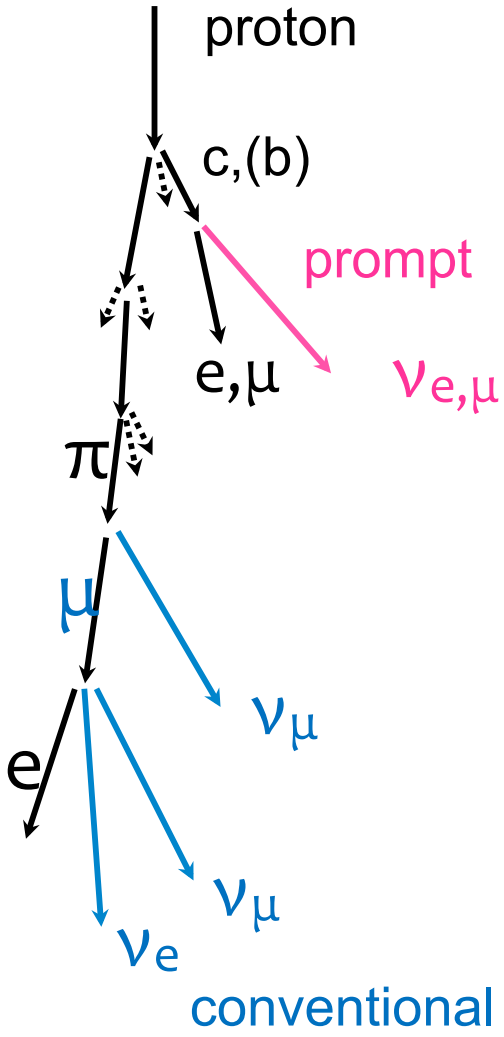
SELECTED RECENT RESULTS

WITH FRESH MOTIVATION FOR

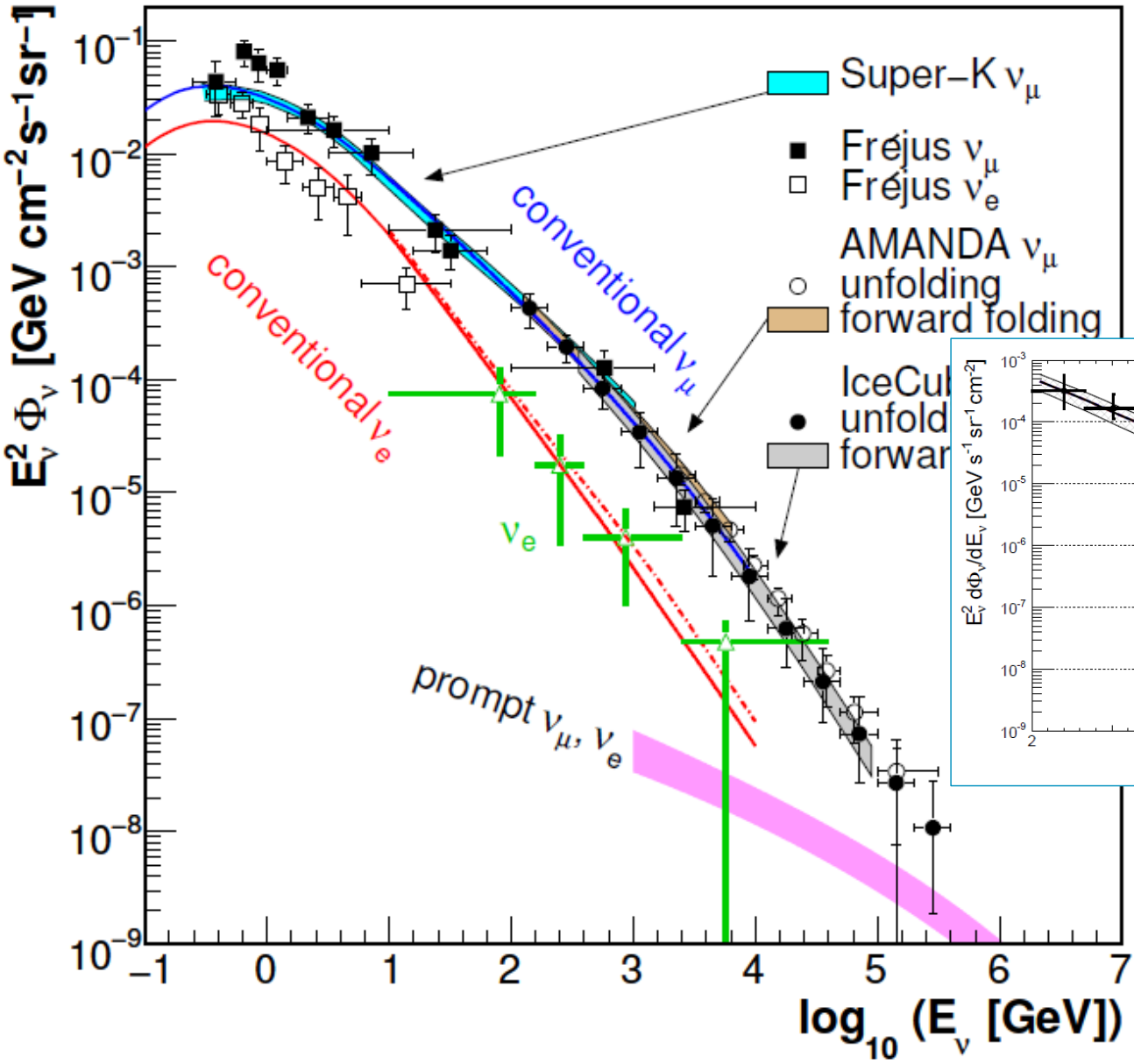
NEW GENERATION DEVICES

Atmospheric neutrino spectrum

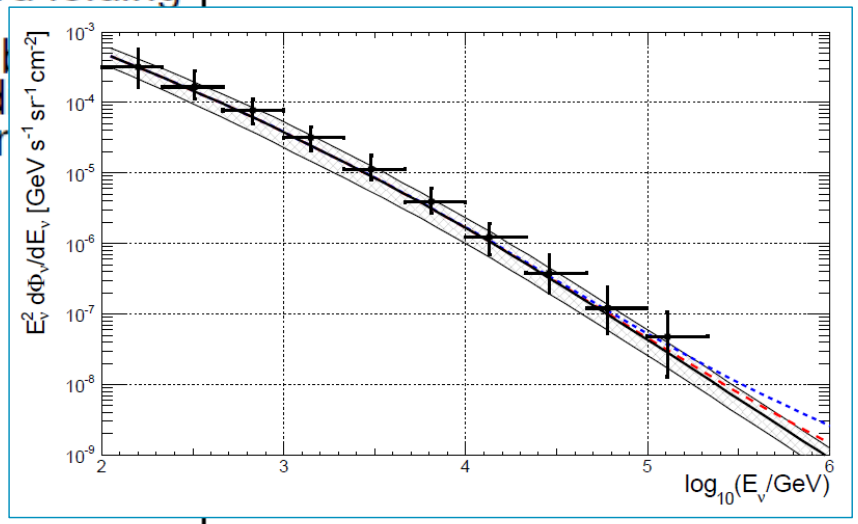




Atmospheric neutrinos in IceCube



.. and ANTARES

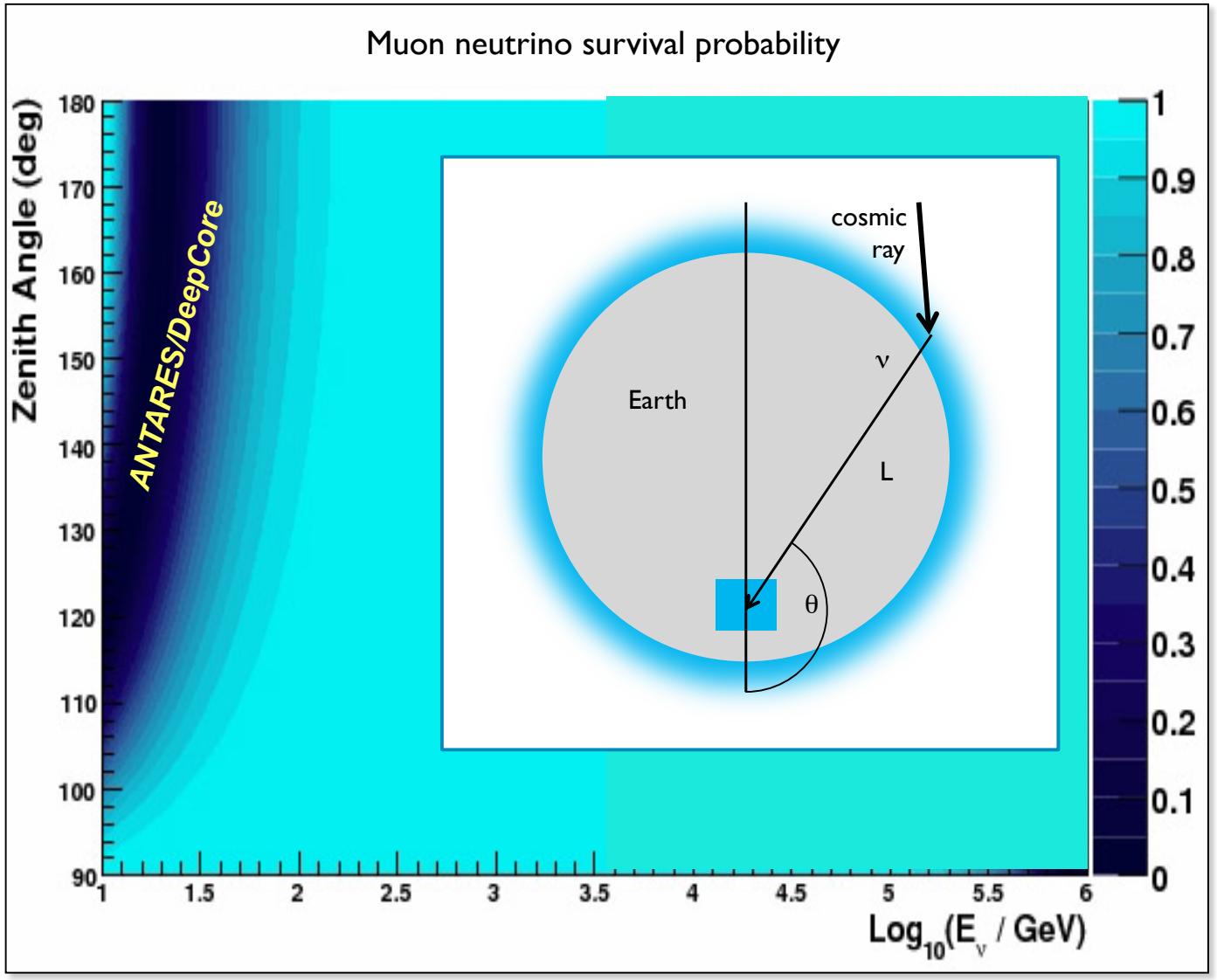


arXiv:1308.1599

Oscillations of atmospheric neutrinos

Vertically upward

Horizontal



Oscillations of atmospheric neutrinos

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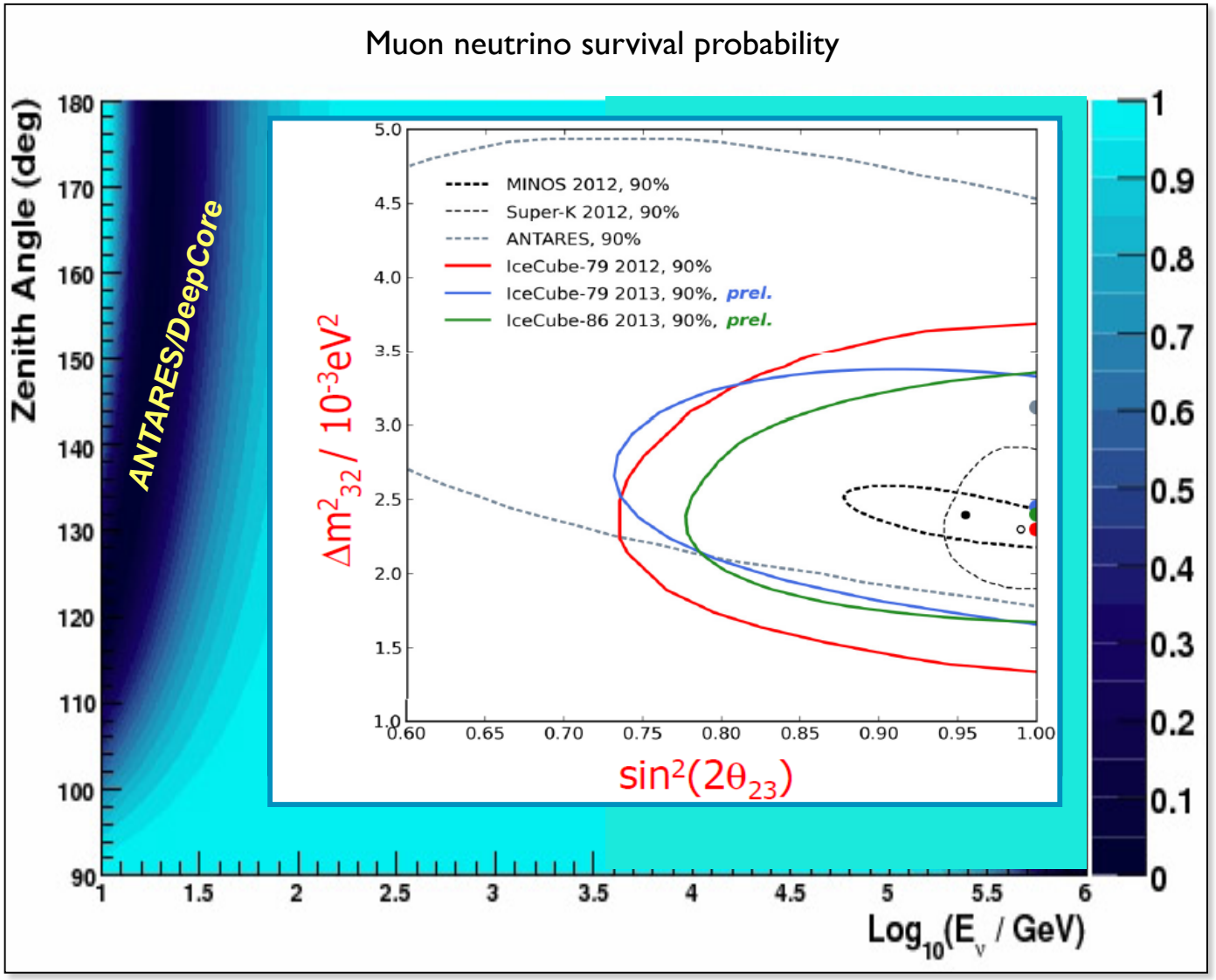
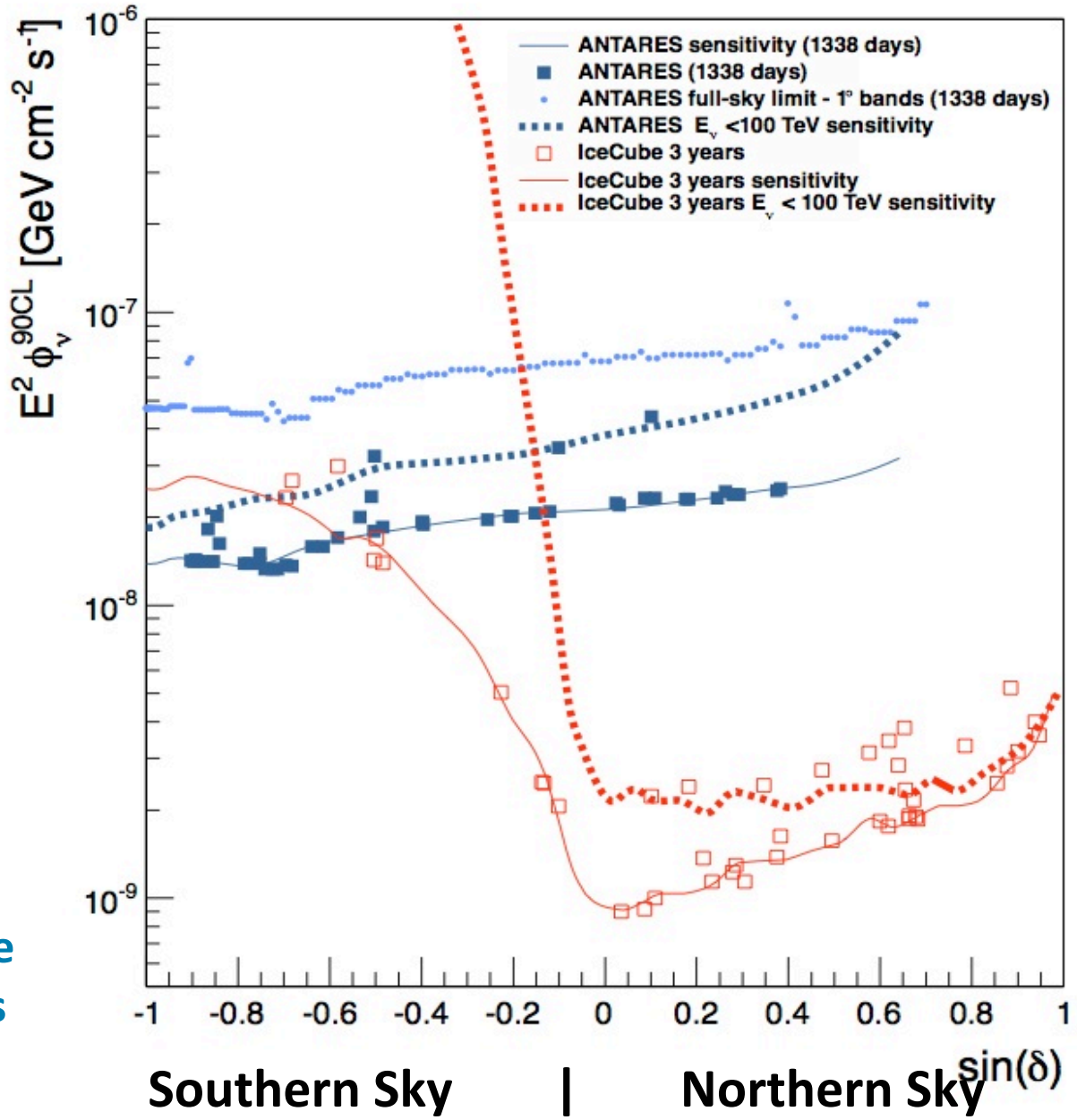


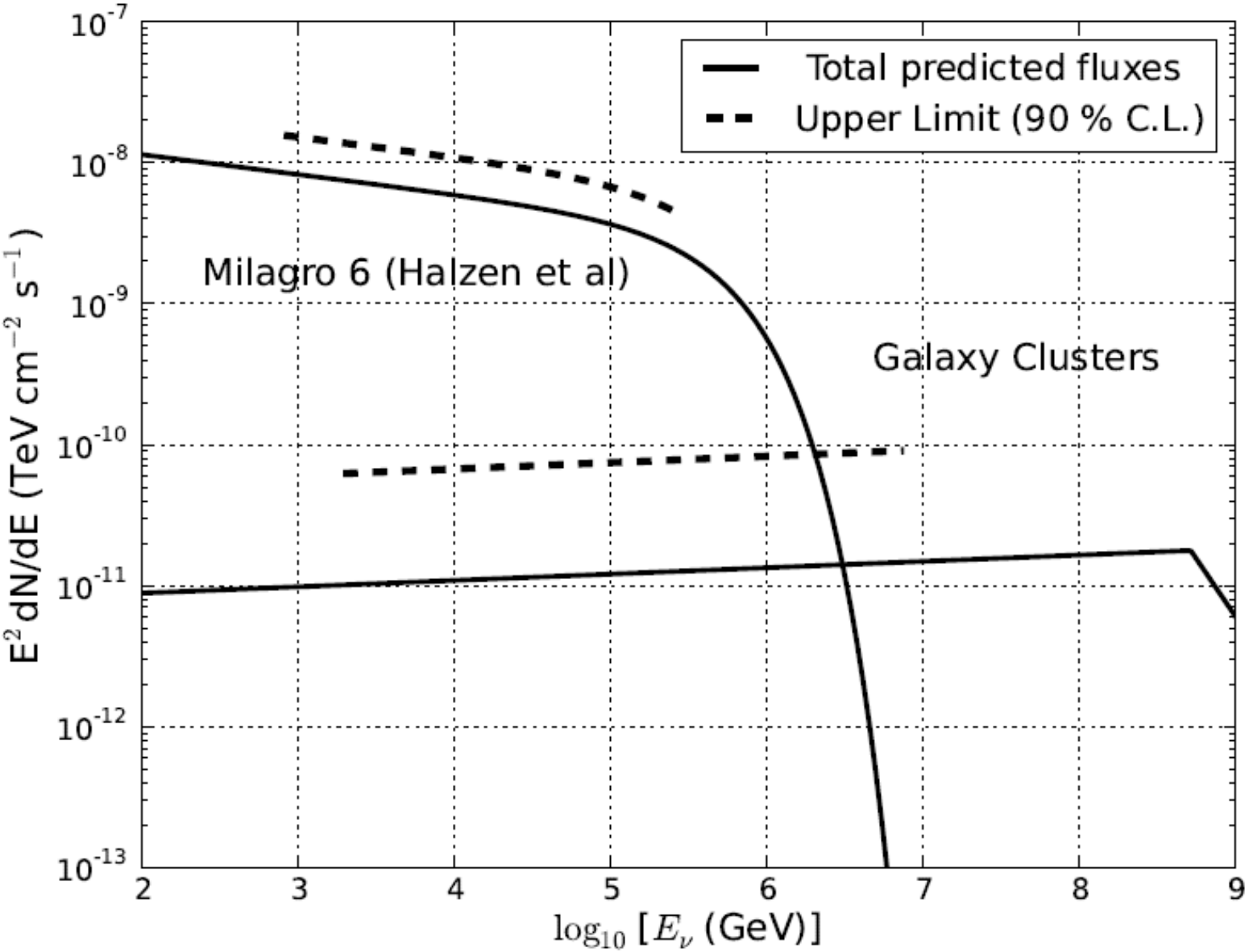
SEARCH FOR POINT SOURCES OF EXTRA-TERRESTRIAL NEUTRINOS

Limits for steady point sources (assuming E^{-2} spectra)

- Factor 1000 in 12 years
- No detections yet
- ANTARES is best at Southern Sky
  IceCube sensitivity at Southern sky only for cut-off at >> 100 TeV
- Expect another factor 5 for IceCube in 2016
- KM3Net+GVD would give ~ factor 50 w.r.t. Antares



IceCube 3 years: upper limits and predictions

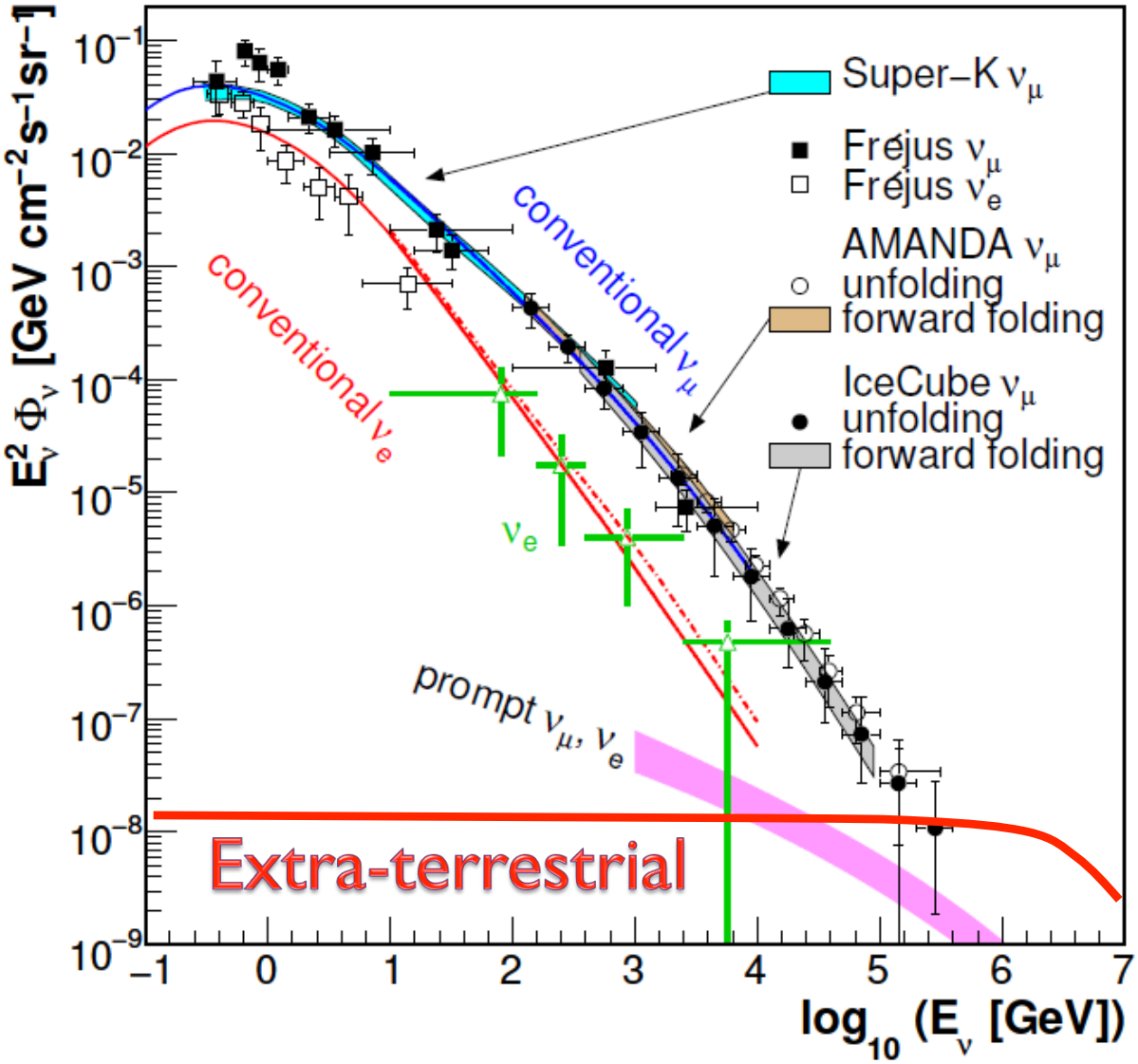


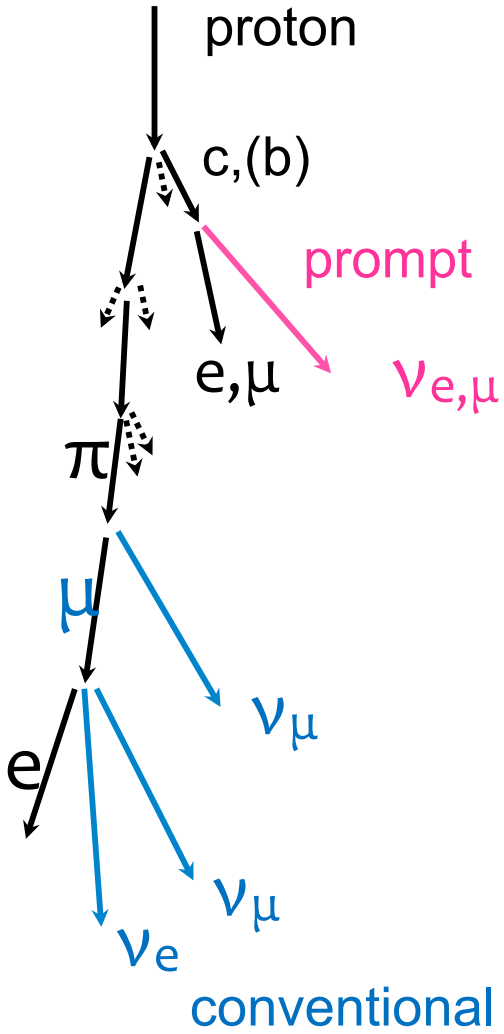
DIFFUSE FLUX

SEARCH FOR AN EXCESS

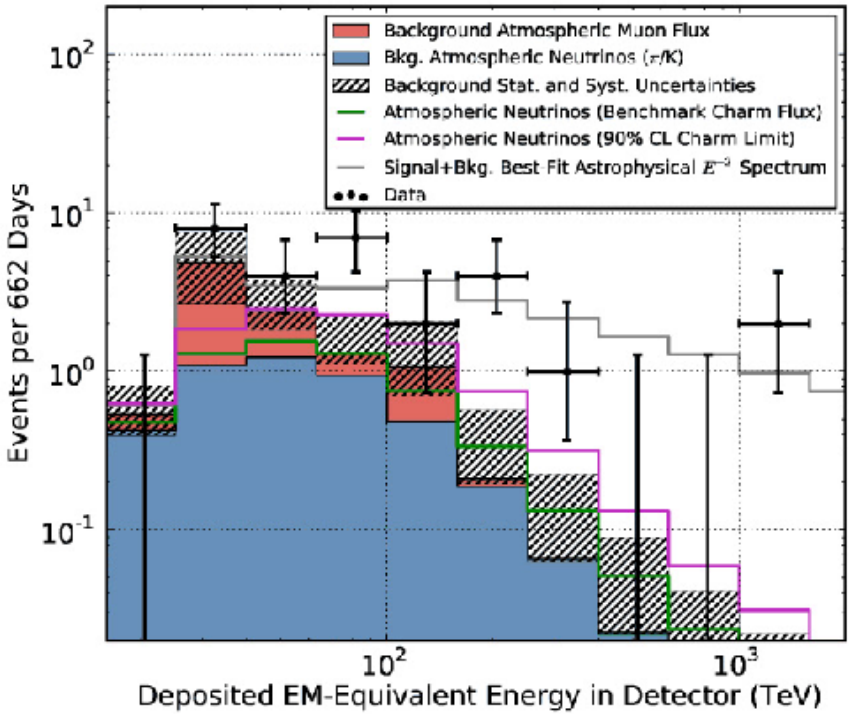
AT HIGHEST ENERGIES

Search for an extraterrestrial diffuse ν flux

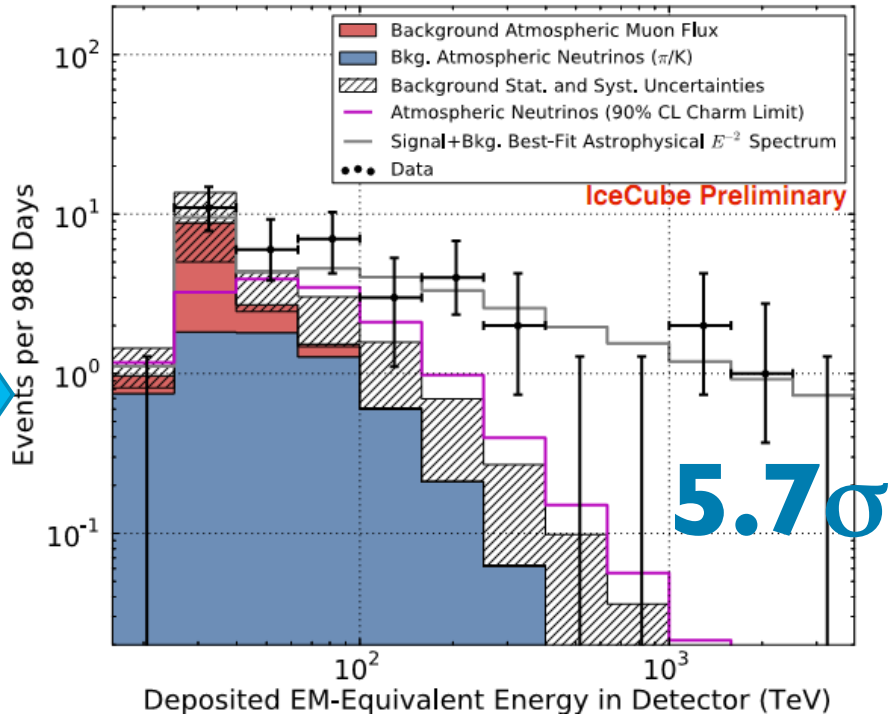




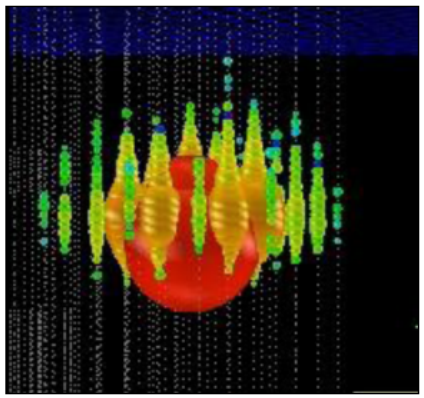
HESE results IceCube

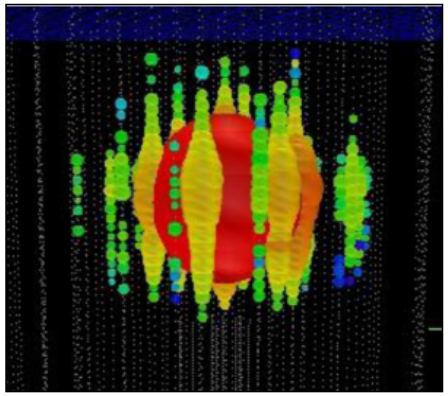


3rd year

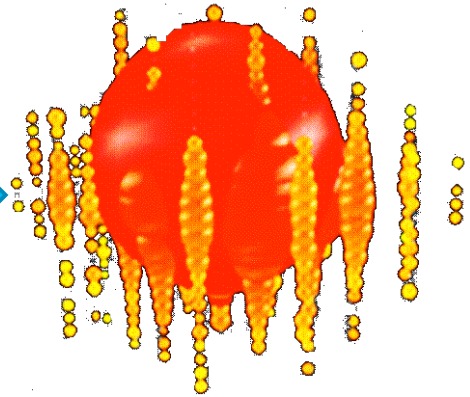


5.7σ



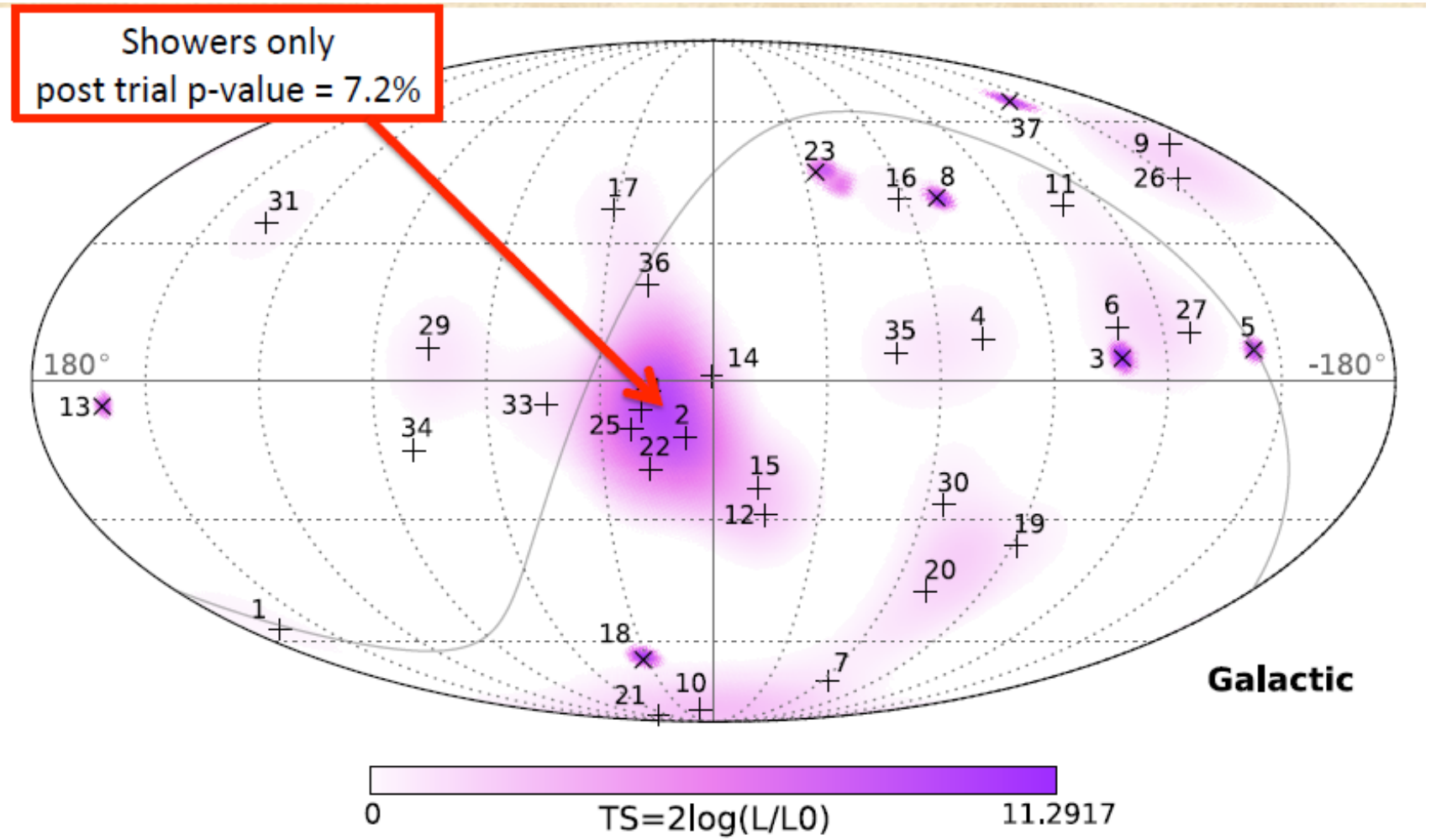


3rd PeV event.



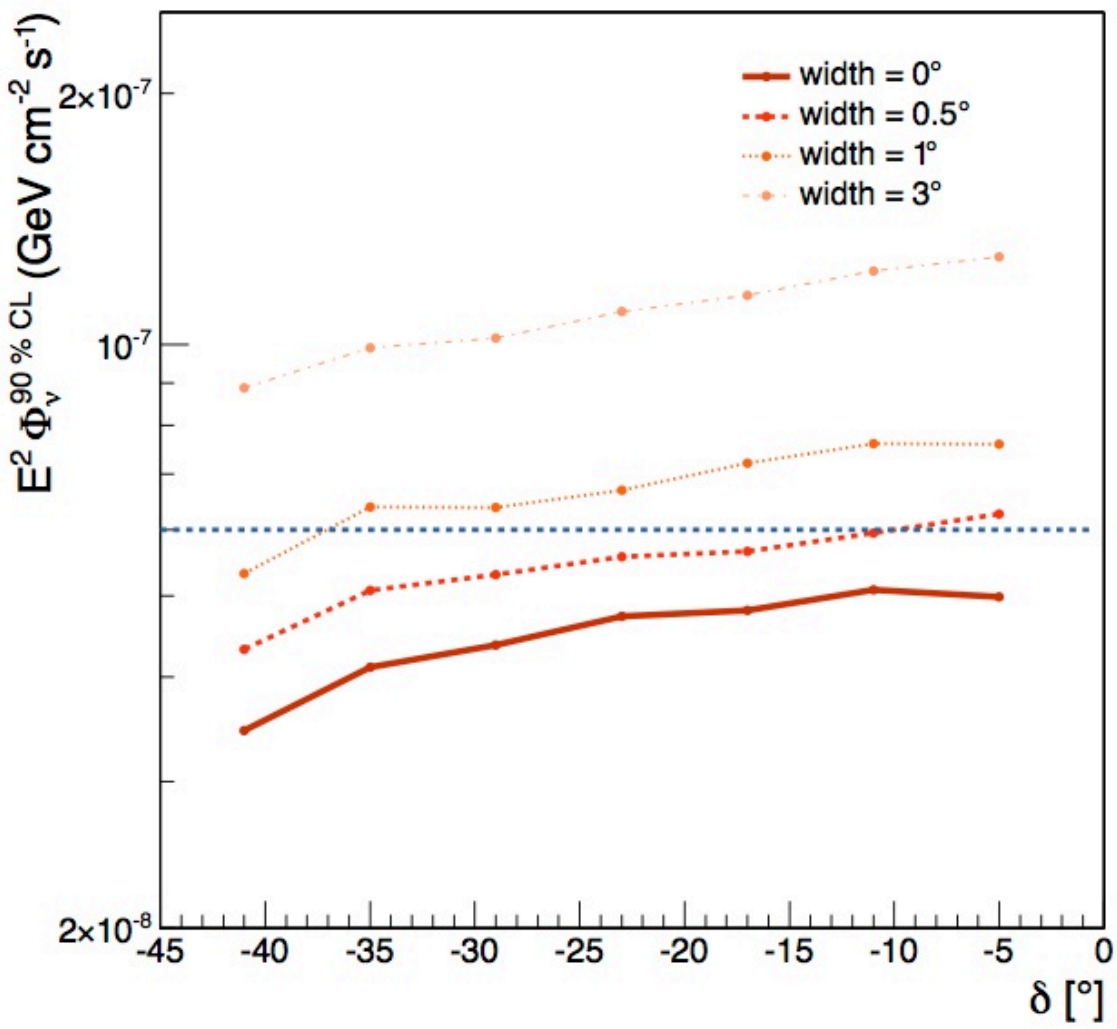

physicsworld
BREAKTHROUGH
OF THE YEAR
2013
IceCube
NSF

HESE skyplot, 3 years



Could that be a point source?

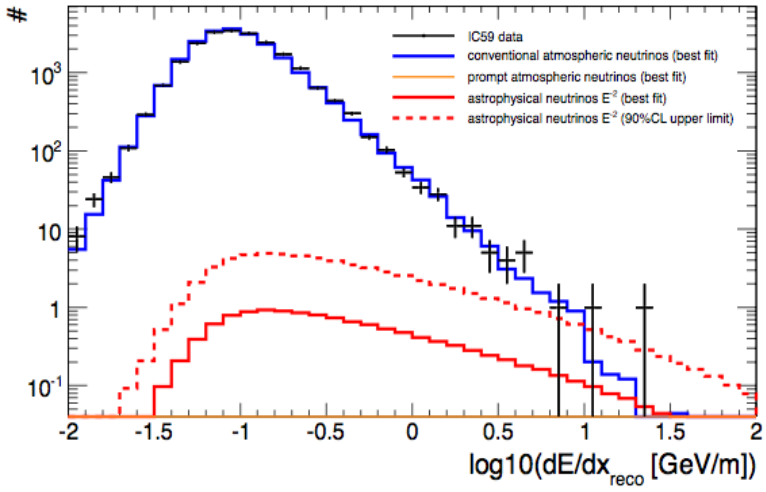
Importance of Northern detector



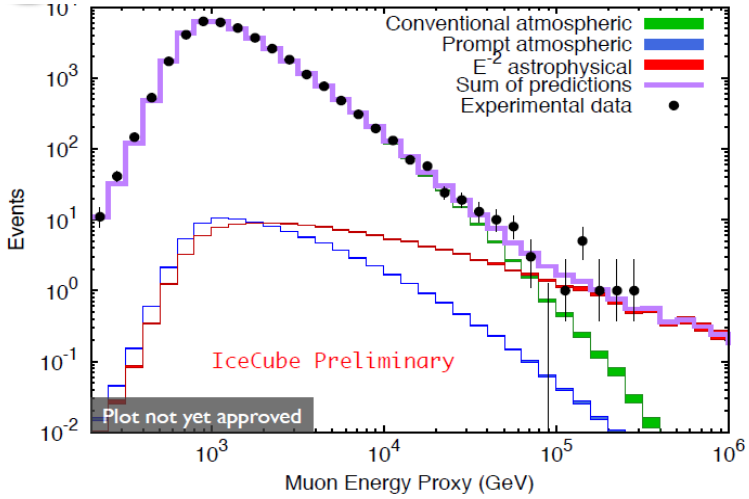
ANTARES, arXiv 1402.6182:
ceCube accumulation in tension with point-source interpretation

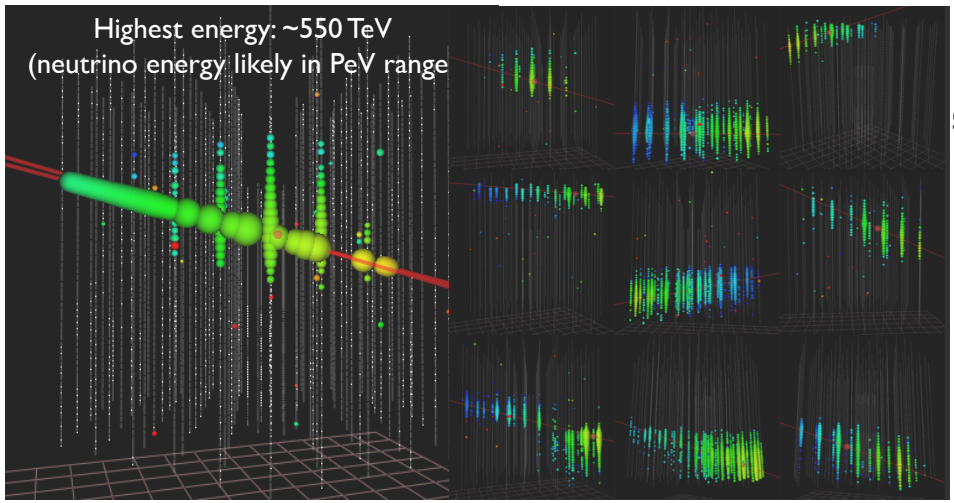
Through-going muons in IceCube

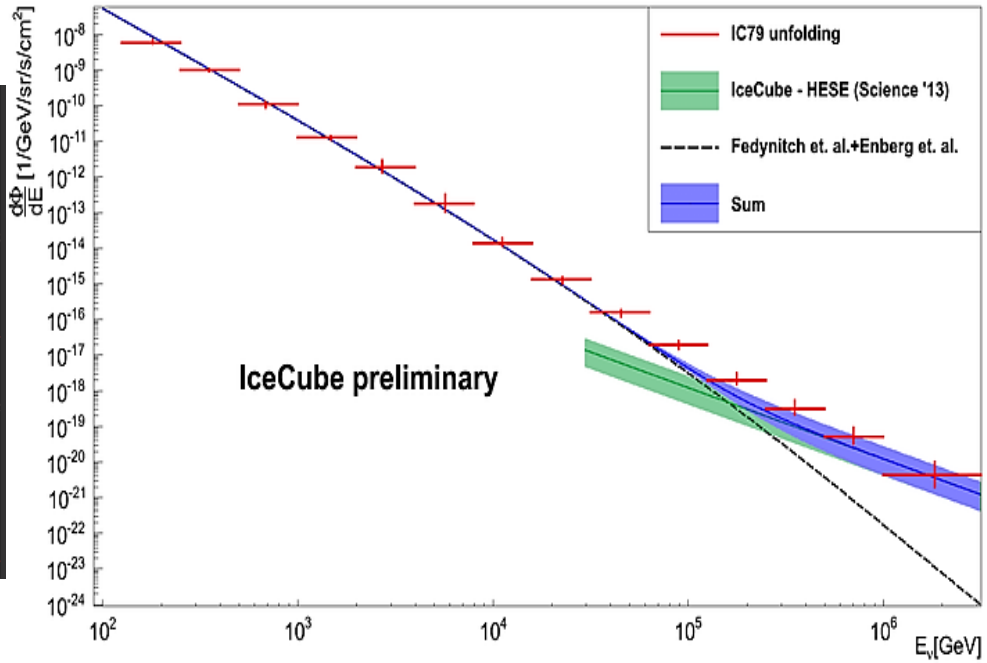
IC-59: 1.8σ



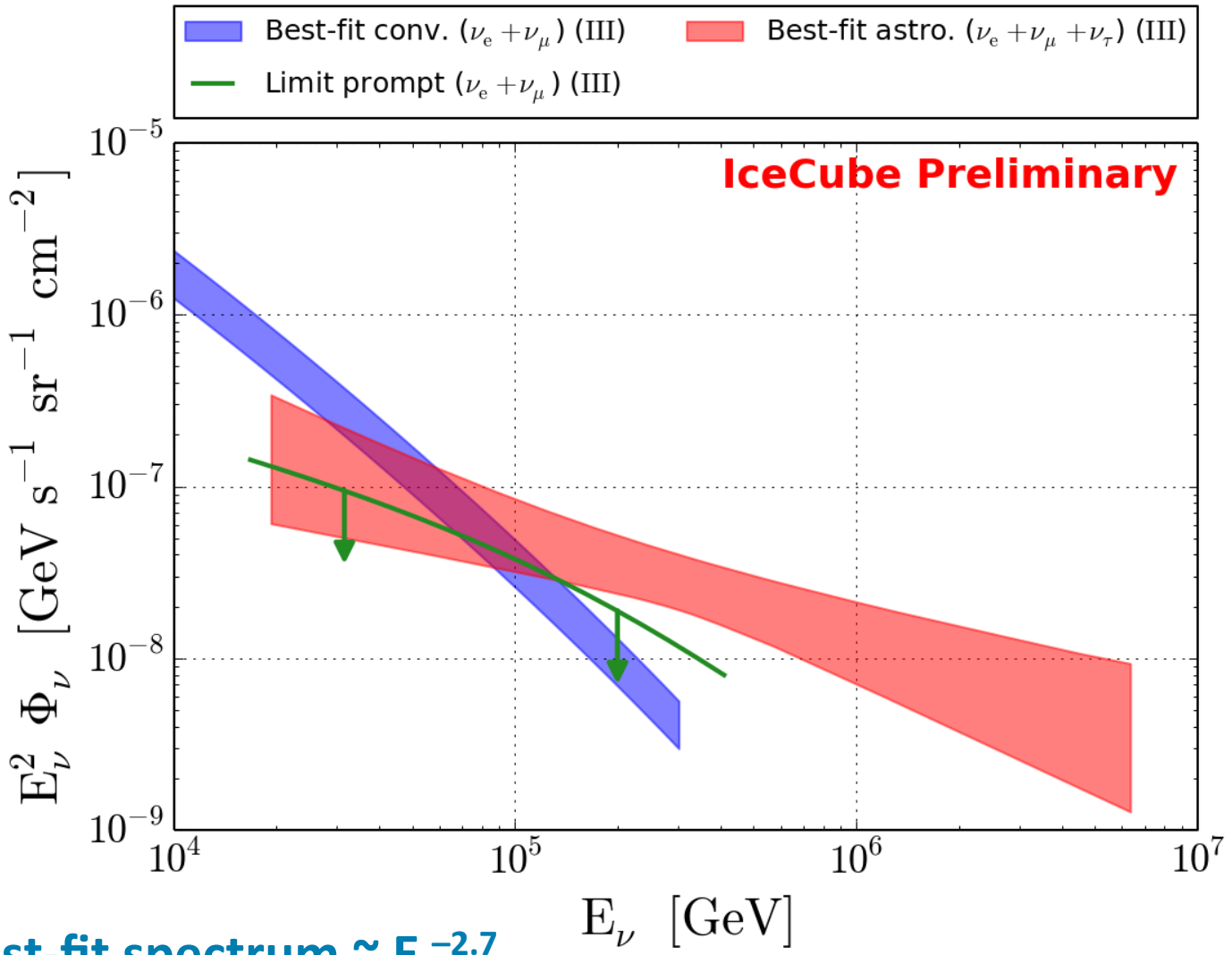
IC-79: 3.7σ







A global fit to the IceCube results



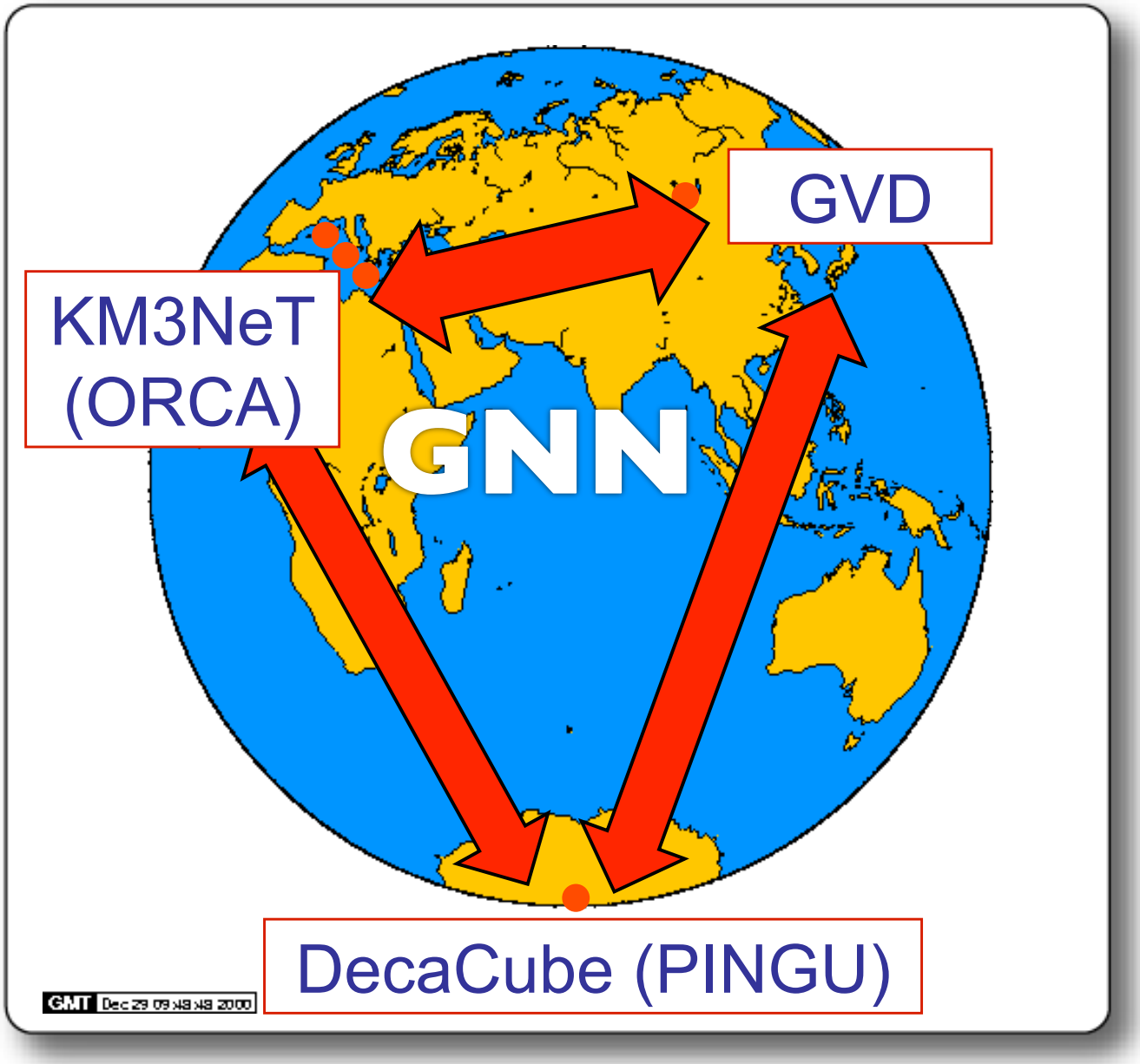
- **Best-fit spectrum ~ $E^{-2.7}$**
- **E^{-2} requires cut-off at some PeV**

Interpretations

- Theoretical interpretations
  - Galactic Sources
  - Extragalactic Sources
  - Exotics
  - …
- Present conclusions still based on poor data. Soon:
  - 4 years HESE
  - More upwgardgoing muon data
  - More cascades
  - Stacking of point sources
- We are entering a period where theoretical speculations can rely on better data, and some useful conclusions could be drawn for the configuration of future detectors

THE FUTURE PROJECTS

Baikal, Mediterranean Sea, South Pole



Rationale for the multi-km^{3}scale, South & North

- Identify point sources !
- Measure their spectrum !

} This is „astronomy“

- IceCube is scratching the point source discovery region at best
- Need larger detectors! (How much larger?)

- Detectors on the North and South look to different parts of the sky (but with some overlap!)
- Can cover different parts of the spectra of the same sources.
- Ice and water have different sytematics. Important for flavor ratios and spectral form, in particular for diffuse fluxes.

Overview on high-energy projects

- **KM3NeT:** **6 x 0.6 km³**
  - Phase 1 (scale ~3 x ANTARES): complete 2016, funded
  - Phase 1.5 (2 x 0.6 km³): complete 2020 positive signals for funding
  - Phase 2 (6 x 0.6 km³): complete mid 2020s

- **DecaCube („IceCube High-Energy extension“, HEX)** **5-10 km³**
  - Start 2018/19 ?
  - Complete 2027 ? Including PINGU with the 3 first of the 8 seasons
  - Positive first responses from NSF …

- **GVD (Baikal):** **0.4 km³**
  - First of 10 clusters in early 2015
  - Full array in 2020

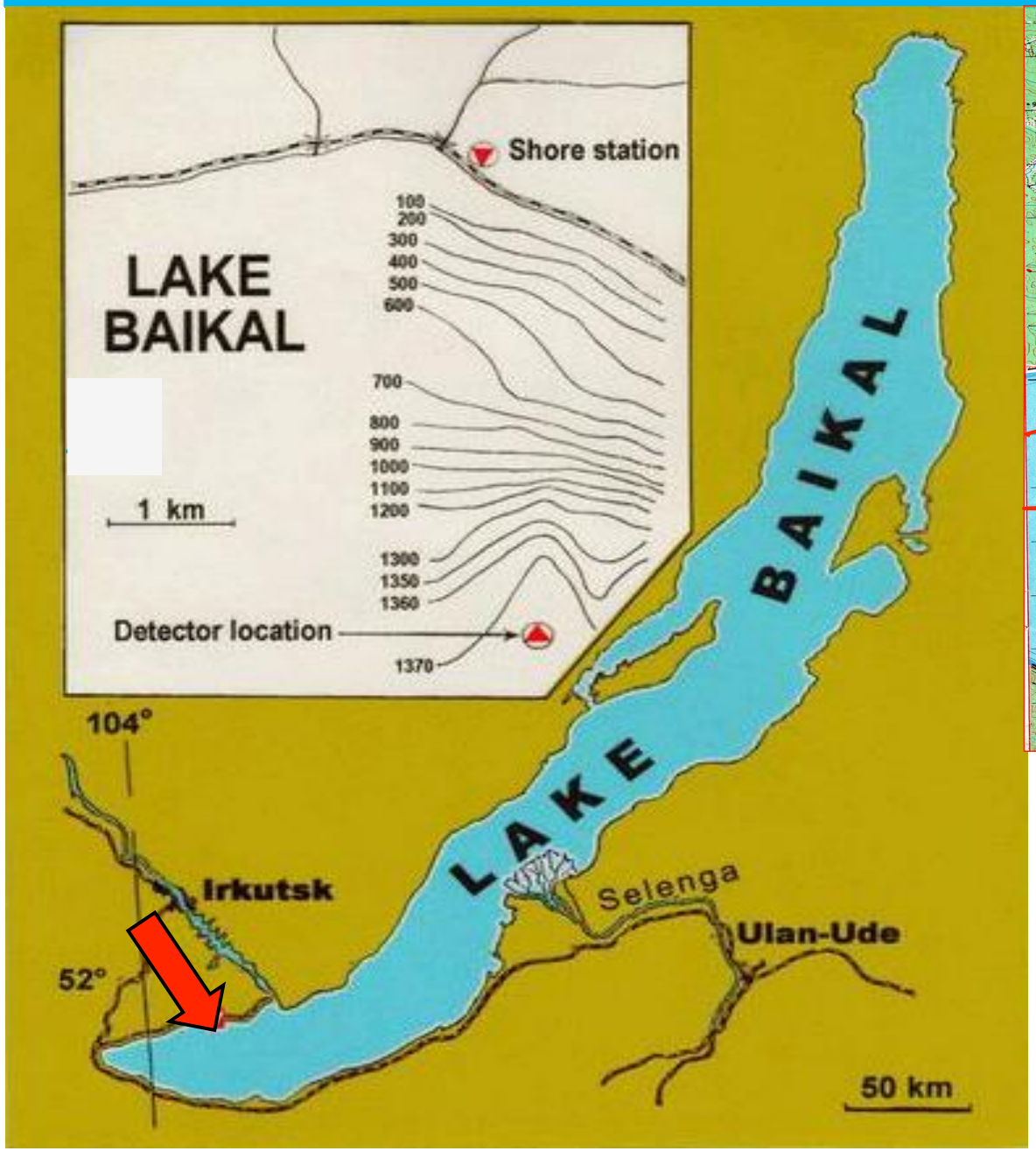
GIGATON VOLUME DETECTOR

BAIKAL GVD

~ 50 authors, role of Dubna increasing

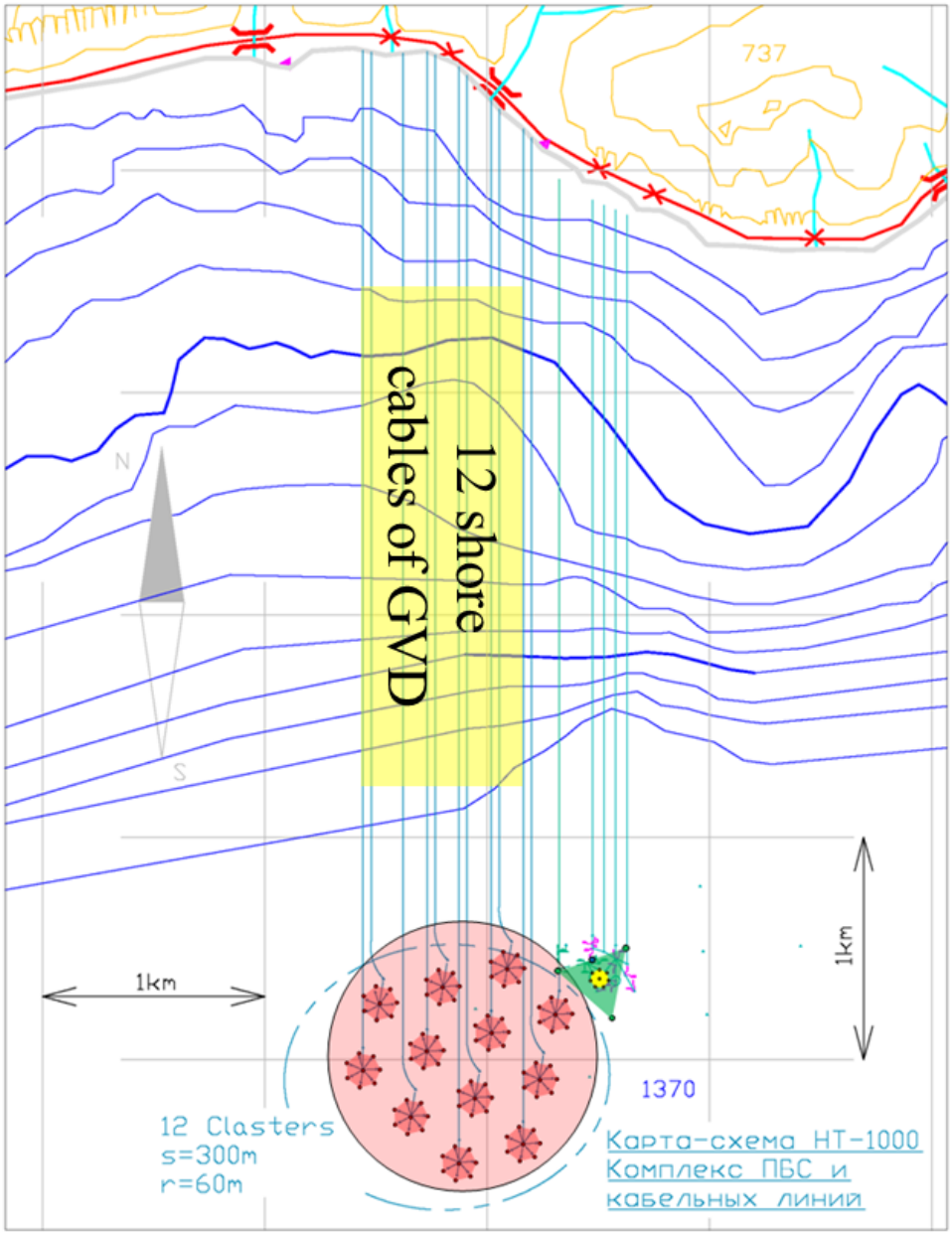
SAC installed (Berezinsky, de Wolf, Gerhstein, **Rubakov**, Spiering, Spiro)

Gigaton Volume Detector GVD



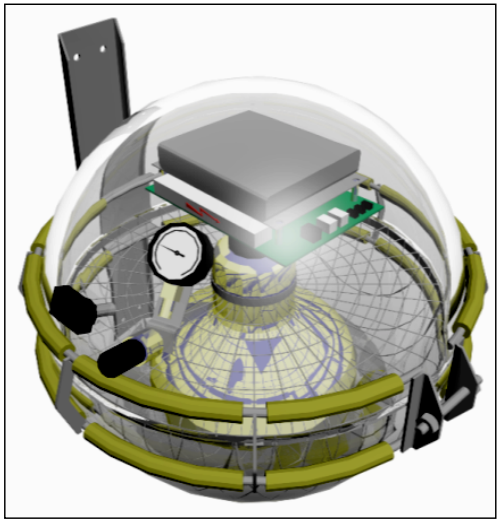
0.4 to 1.5 km³ Detector in Lake Baikal

Gigaton Volume Detector GVD



Stage 1

- 10-12 clusters with 8 strings each
- Cluster diameter 120 m
- Height 375 m
- Volume ~ 0.4 km^3
- 24 OMs per string



PMT

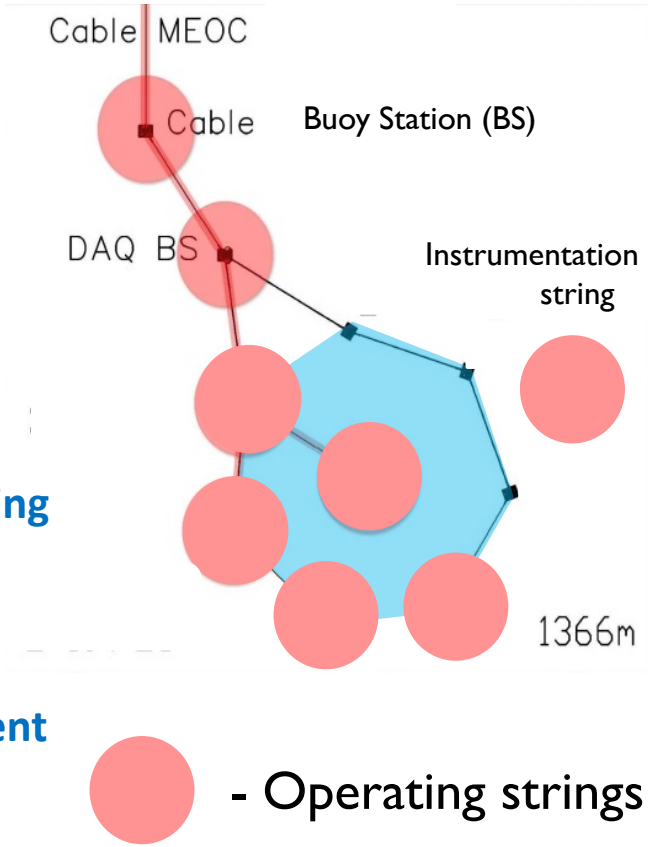
Hamamatsu
R7081-HQE
∅ = 10”
QE ~ 0.35%

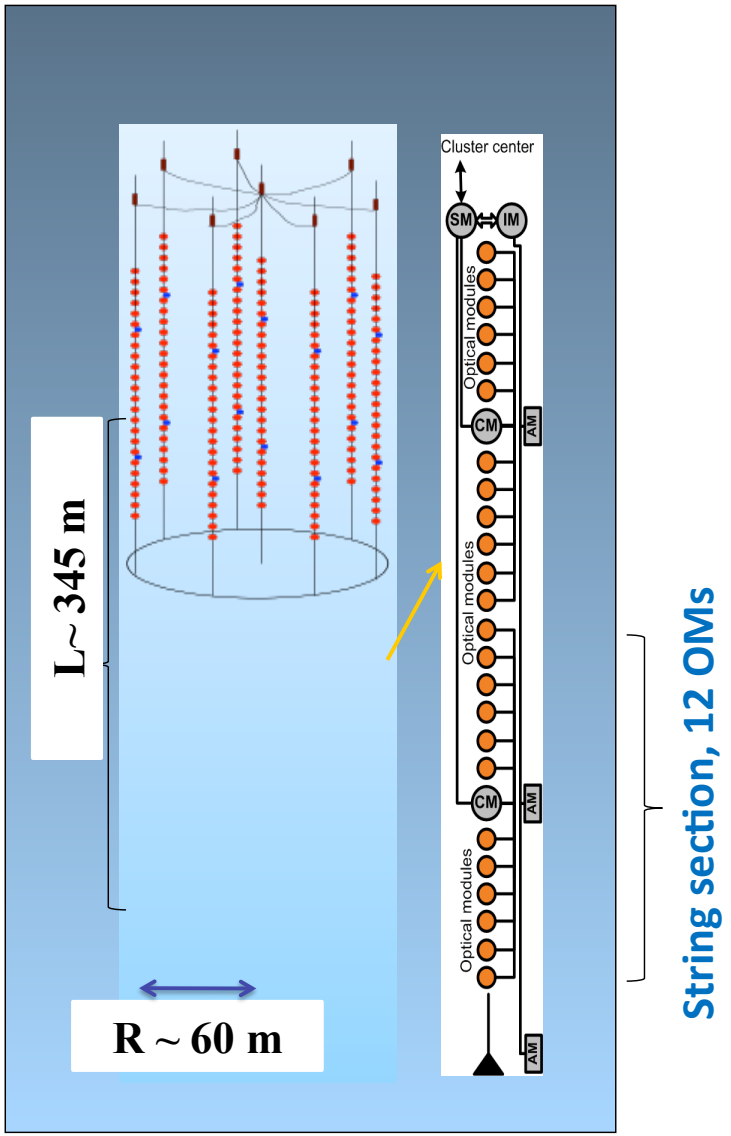
Prototype phase 2011-2015:

demonstration cluster „DUBNA“

- 192 OMs at 8 Strings
  - 2 Sections per String
  - 12 OMs per Section
- DAQ-Center
- Cable to Shore
- Acoustic Positioning System
- Instrumentation String with detector calibration and environment monitoring equipment
- Active depth 950 – 1300 m

Layout - 2014





GVD timeline

cumulative number of clusters vs. year

Year	2015	2016	2017	2018	2019	2020
baseline	*1*	*1*	*3*	*5*	*7*	*10*
Compressed baseline	*1*	*2*	*4*	*7*	*10*	

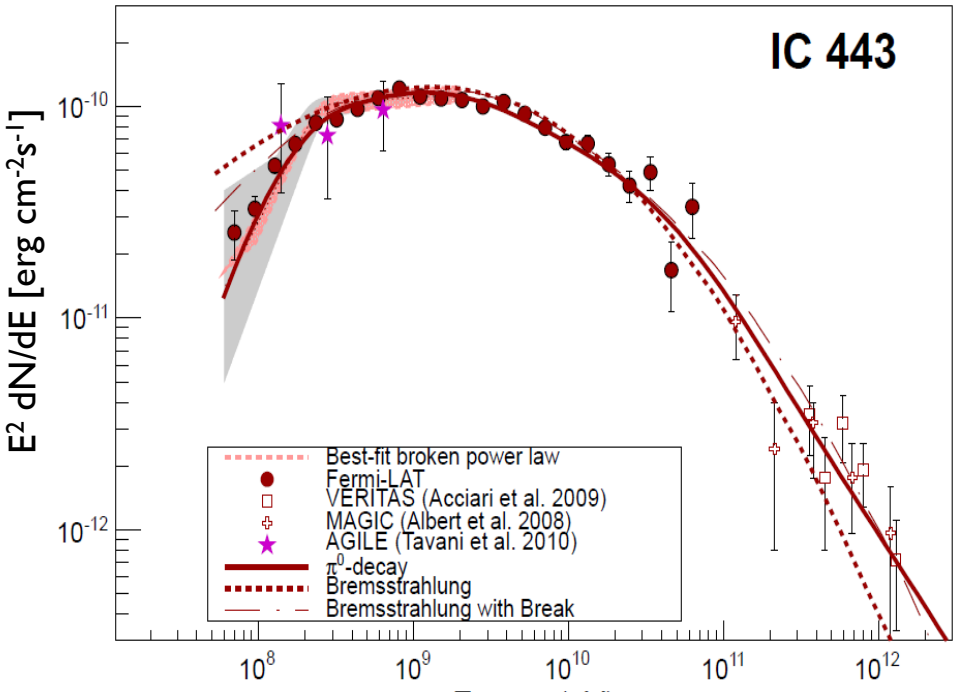
1 cluster = 8 strings = 192 PMT = 1 event (> 100TeV, cascade)/year

Cost of the first cluster (“Dubna”): ~ 2.2 M€

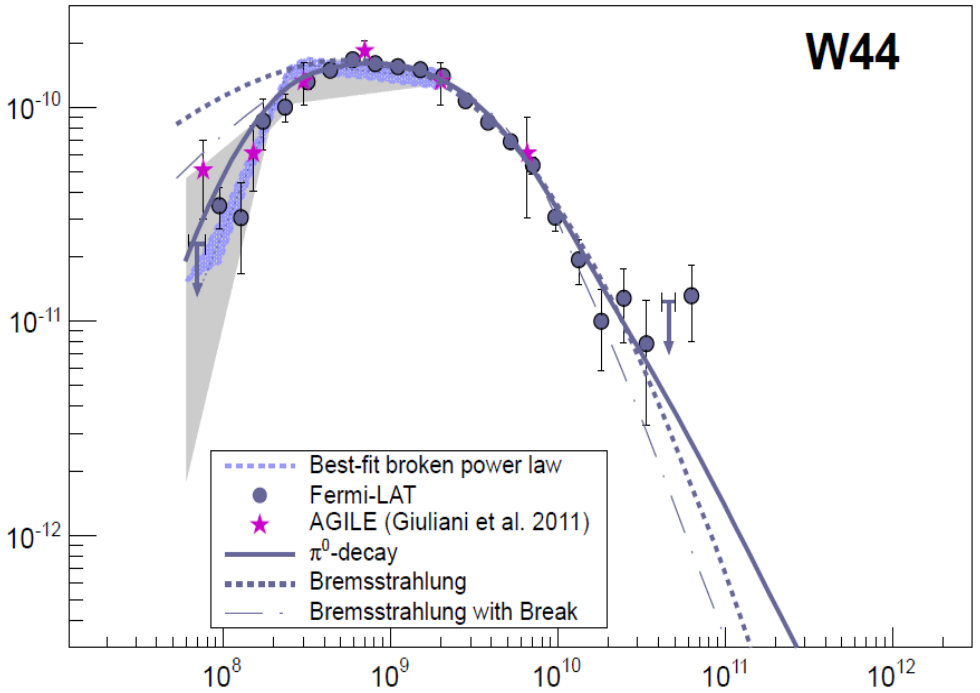
KM3NET

Fermi: encourages Northern detctors w.r.t galactic sources

Science 339 (15-02-2013) 807–811

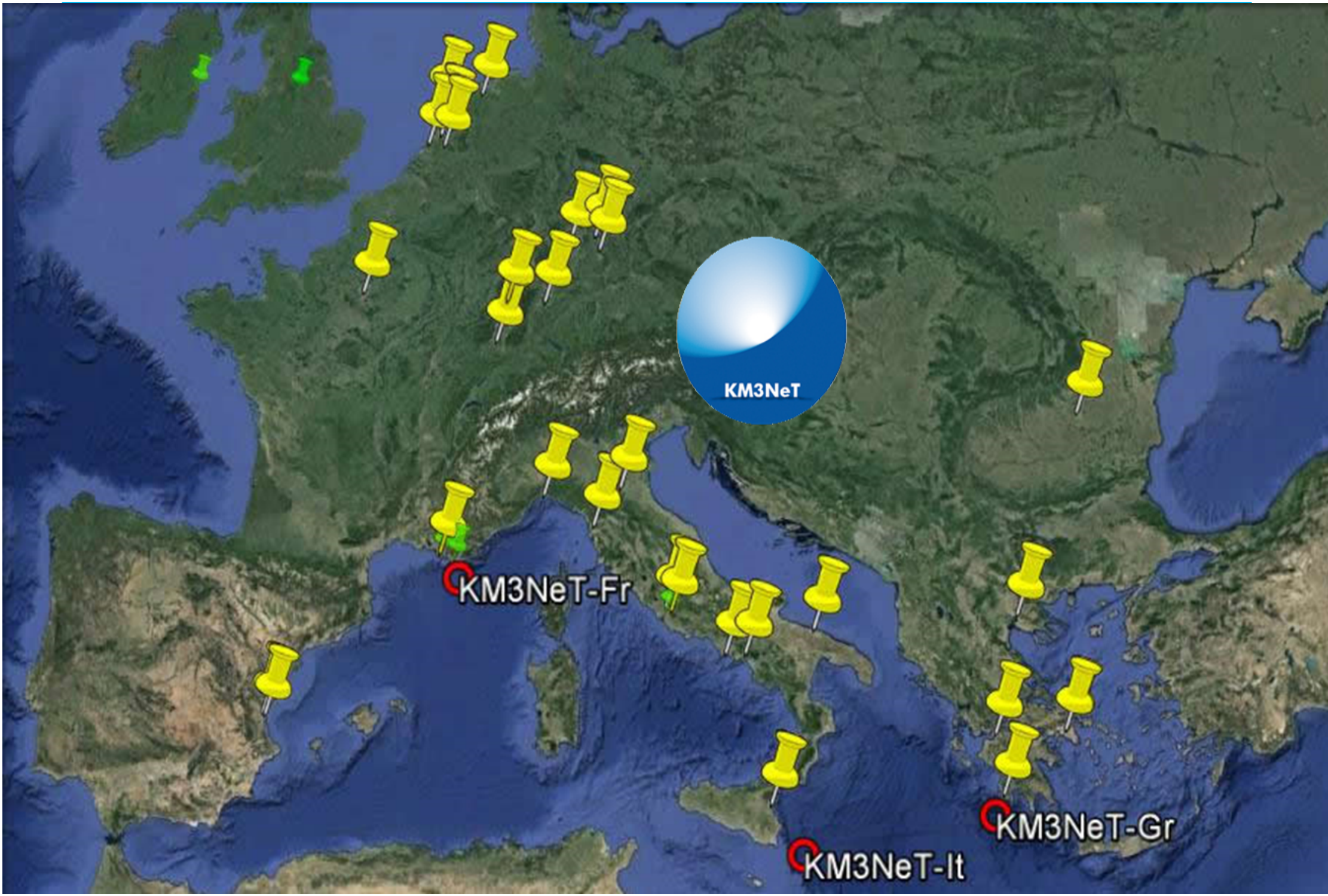


E_γ [eV]



E_γ [eV]

- Fermi LAT: *"This detection provides direct evidence that cosmic-ray protons are accelerated in SNRs."*


KM3NeT
KM3NeT-Fr
KM3NeT-It
KM3NeT-Gr

KM3NeT

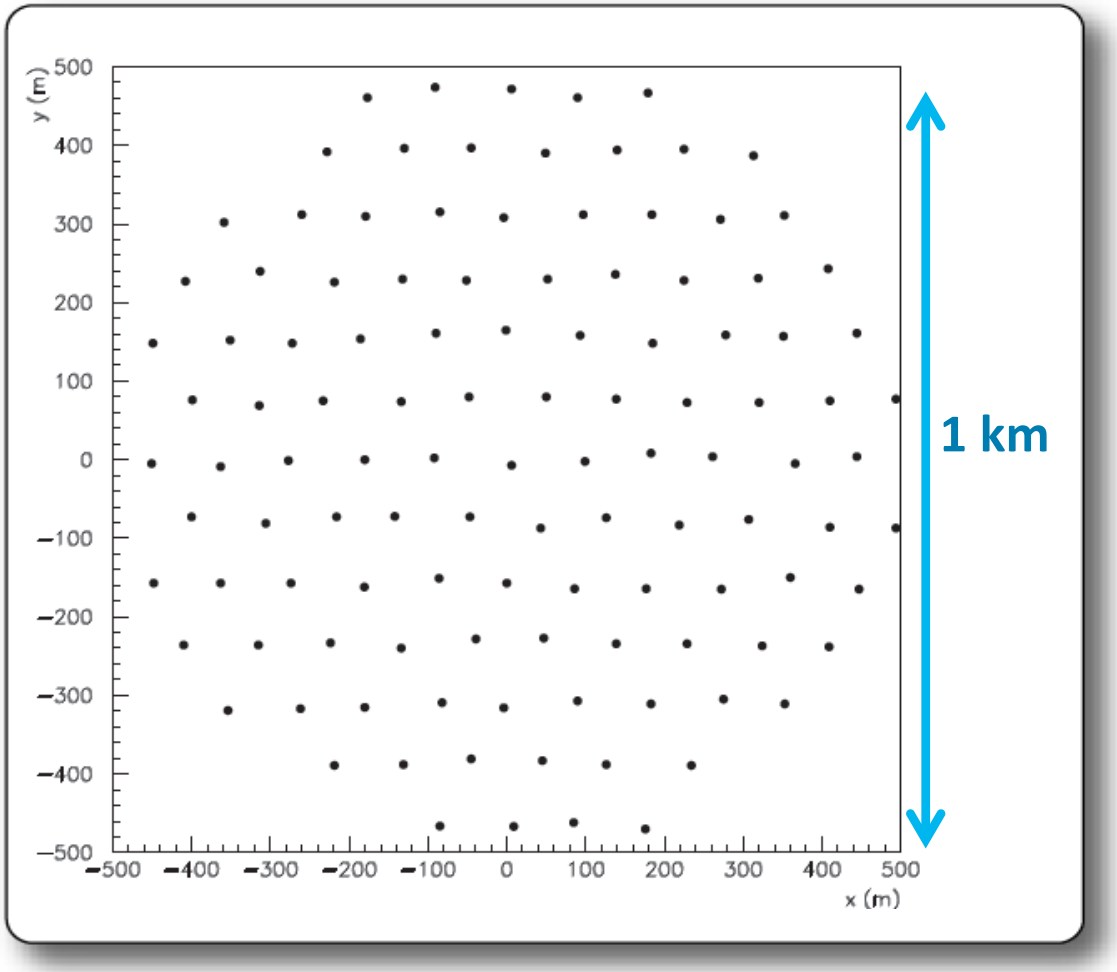
Distributed infrastructure

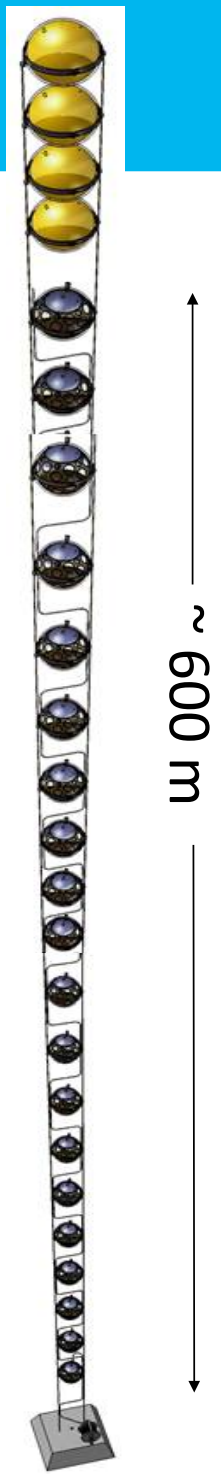
- KM3NeT-France (Toulon) ~2500m
- KM3NeT-Italy (Capo Passero) ~3400m
- KM3NeT-Greece (Pylos) ~4500m

Until 2016: construction of KM3NeT phase I detectors in France and Italy (~30 M€)

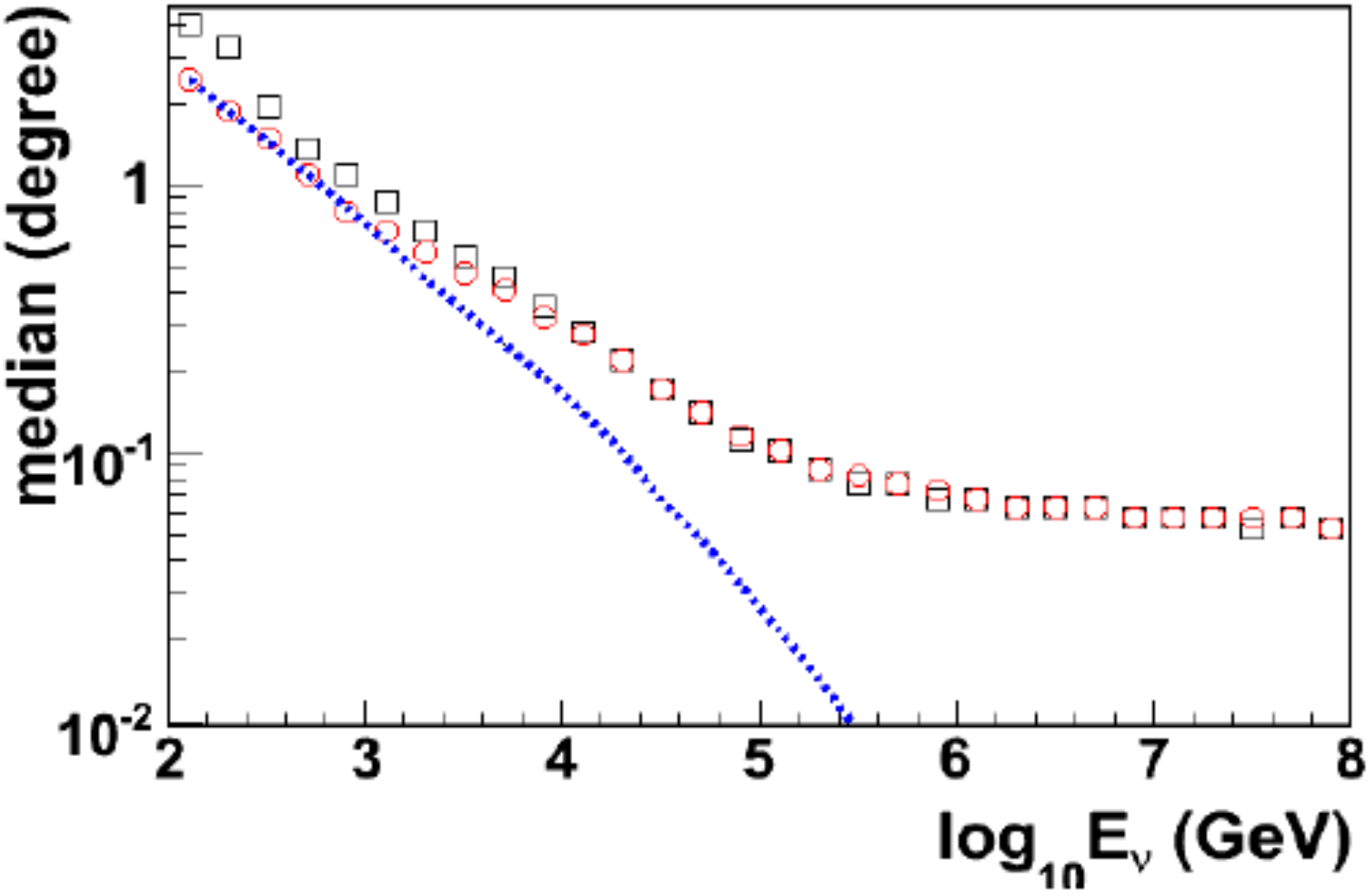
KM3NeT

- 6 building blocks, 2 per site. Overall volume ~ 4 km³
- 115 strings at 90 m distance
- 18 OMs per string, 36 m vertical distance



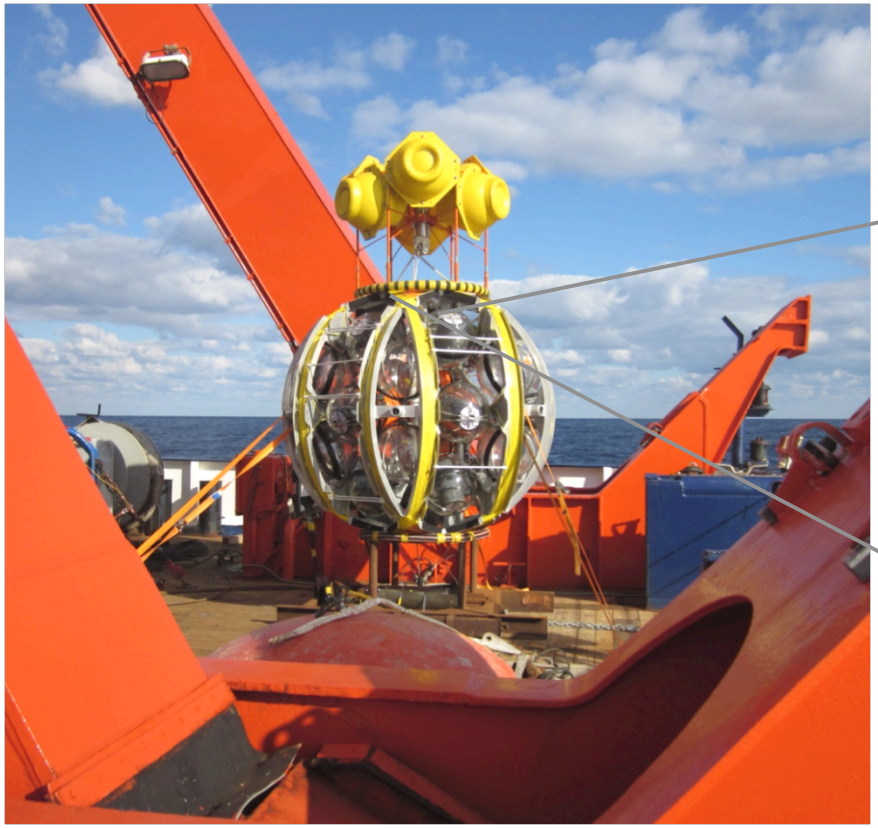


Muon angular resolution KM3NeT



Key elements

Launcher vehicle



- *rapid deployment*
- *autonomous unfurling*
- *recoverable*

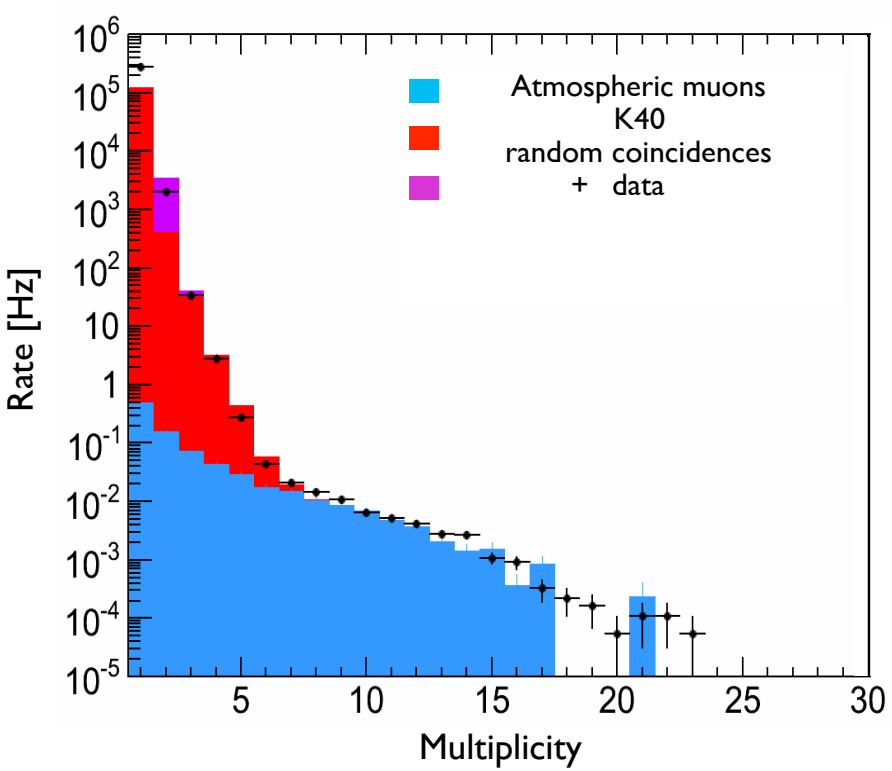
Optical module

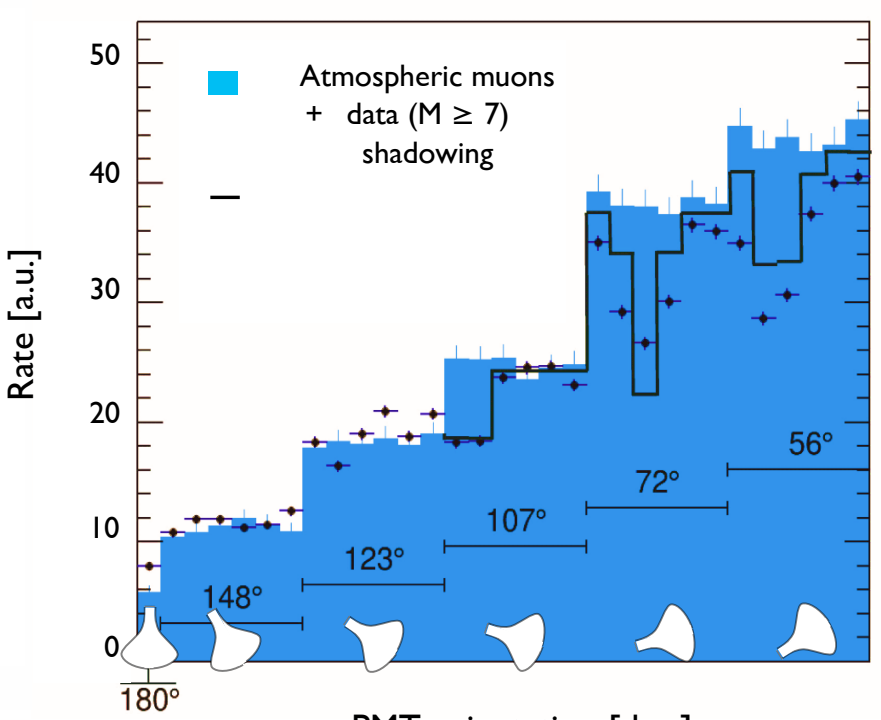
- *31 x 3” PMTs*
- *low-power HV, LED*
- *White Rabbi time synch.*

In-situ test with prototype DOM

Photon counting

Directionality





Management

- **EU funded Design Study** *2006–2009*
- **EU funded Preparatory Phase** *2008–2012*

- **KM3NeT phase-1** *2013–20XX*
  - ✓ **established collaboration**
    - 40 institutes, more than 240 persons
  - ✓ **elected central management**
  - ✓ **set up project organisation**
    - prototyping, cost review, planning, QA/QC
  - ✓ **drafted Memorandum of Understanding**
    - investments, facilities, human resources, access policy
  - ✓ **set up Resources Review Board**
  - ✓ **set up Scientific & Technical Advisory Committee**
  - ✓ **Technical design**

    agreed technology is part of existing CDR and TDR
    - updates ongoing following PRRs

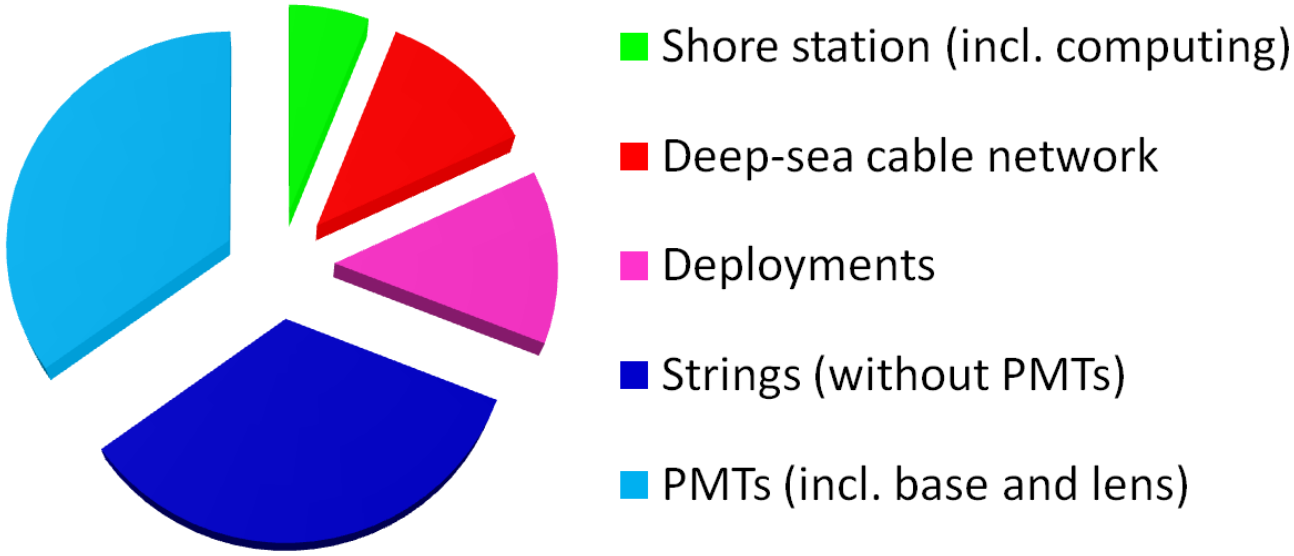
Cost

- **Total** investment costs **220–250 M€**
  - conform with ESFRI roadmap (2006) and **TDR** (2010)
  - **includes contingency of 10%, provided no VAT**

- **Operational costs 3% of investment per year**

- **Operation > 15 years**

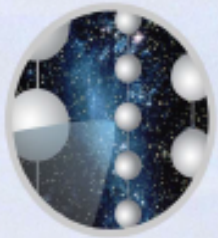
- **Cost of 1 string**
  incl. PMT ~ 230 k€
  + Interlink cables, deployment and connections ~ 90k€



Summary on the phases of KM3NeT

Phase	Total cost [M€]	Primary deliverable Size	Status
1	31	Proof of feasibility of network of distributed neutrino telescope ~ 3 x ANTARES	Funded
1.5	80–90	Measurement of neutrino signal reported by IceCube ~ 1 x IceCube	Letter of Intent¶
2	220–250	Neutrino astronomy 4-5 x IceCube	ESFRI road map

SOUTH POLE



The IceCube Collaboration

43 Institutions
~220 collaborators

USA
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

Canada
University of Alberta–Edmonton
University of Toronto

Niels Bohr Institutet, **Denmark**

Chiba University, **Japan**

Sungkyunkwan University, **Korea**

University of Oxford, **UK**

Belgium
Université Libre de Bruxelles
Université de Mons
Universiteit Gent
Vrije Universiteit Brussel

Sweden
Stockholms universitet
Uppsala universitet

Germany
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität München
Universität Bonn
Technische Universität Dortmund
Universität Mainz
Universität Wuppertal

Université de Genève, **Switzerland**

University of Adelaide, **Australia**

University of Canterbury, **New Zealand**

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

South Pole infrastructure for neutrino (astro-)physics

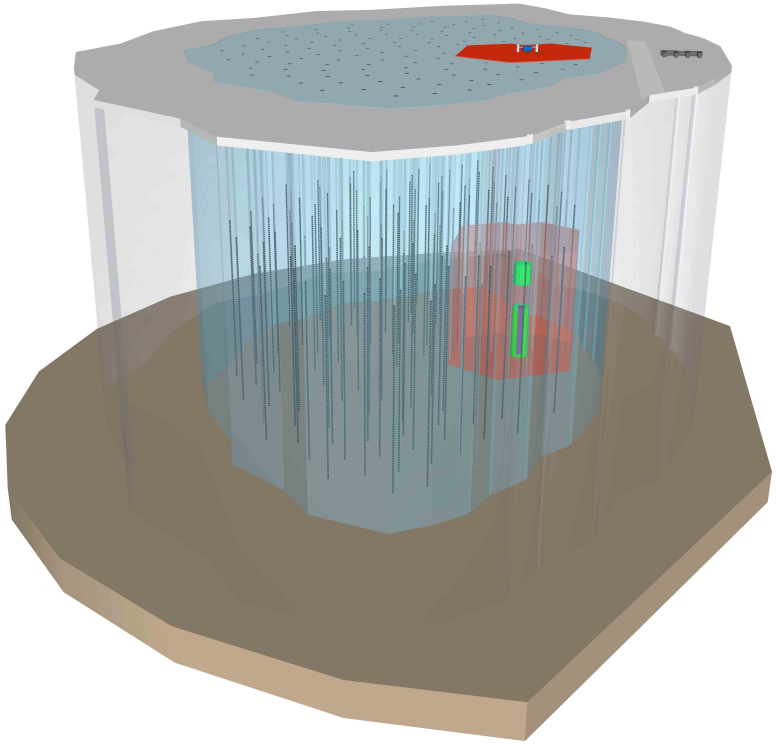
Device	Volume	Threshold	Primary Goal
PINGU	few Mton	2-3 GeV	ν mass hierarchy
DecaCube*	5-10 km^3	~10 TeV	ν astronomy
			cosmogenic neutrinos
Surface veto	~120 km^2		veto for IceCube
			CR physics
ARA	~120 km^2	~50 PeV	cosmogenic neutrinos

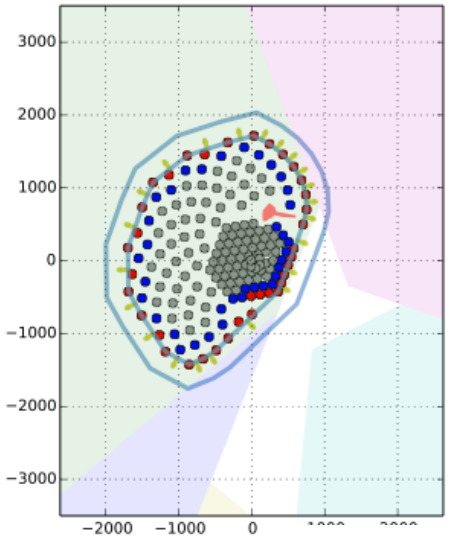
* including IceCube (1 km^3 with 100 GeV threshold)

DECACUBE

(ICECUBE – HEX)

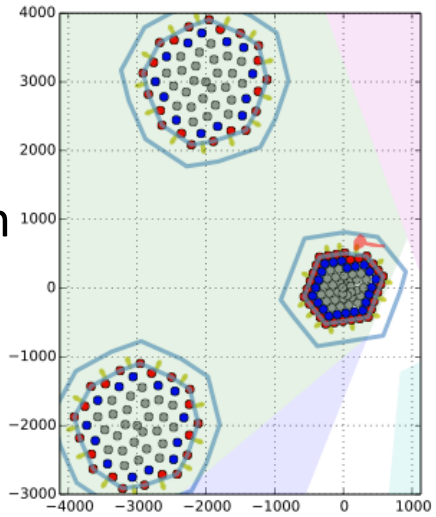
DecaCube





IceCube + 96 strings
Spacing 240 m

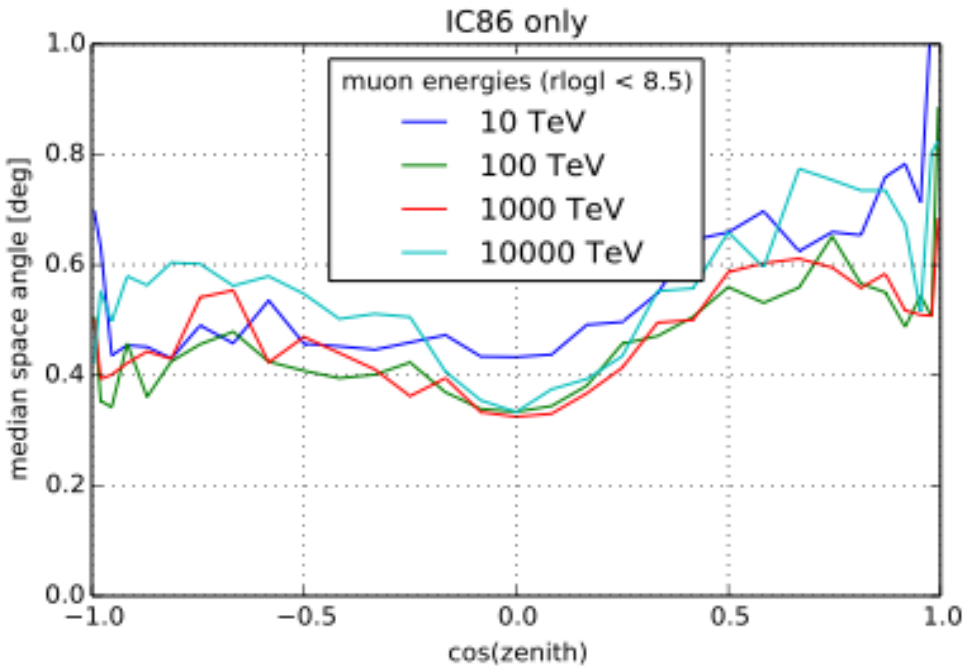
IceCube +
2 x 60 strings
spacing 240 m

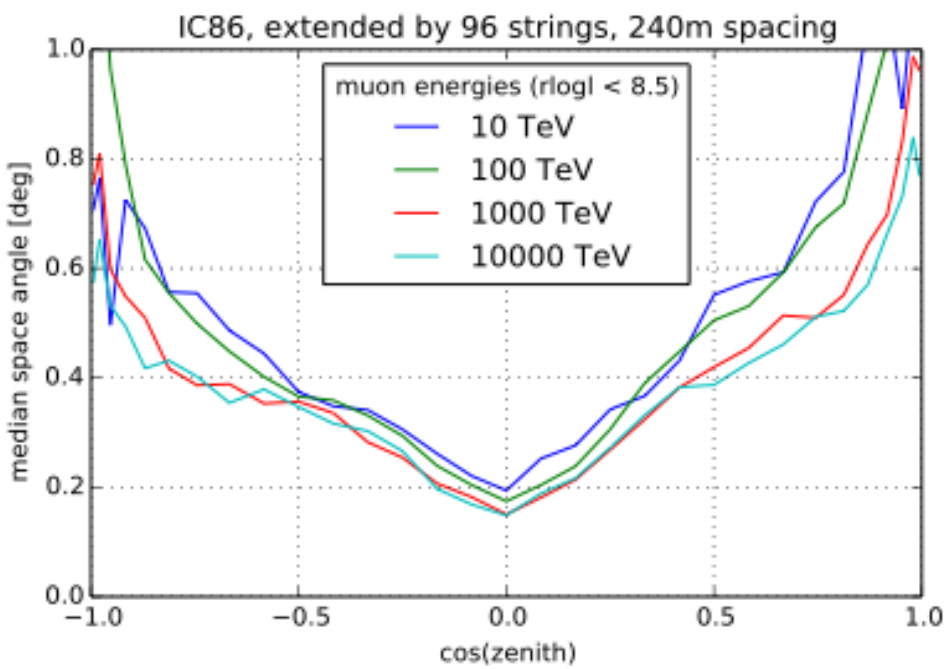


- **~ 100 strings**
- **+ surface veto detector**
- **+ PINGU for oscillations (40 strings)**
- **Start 2018/19?**

Albrecht Karle, Arlington Meeting April 24, 2014

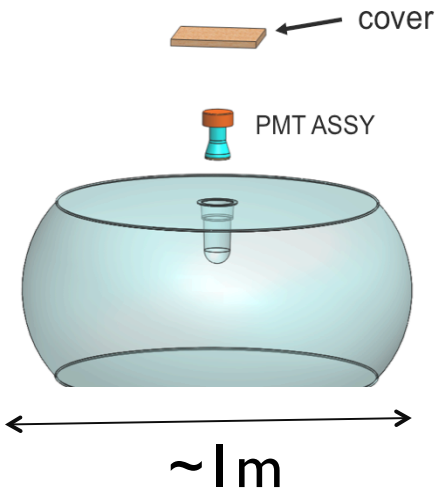
Angular resolution



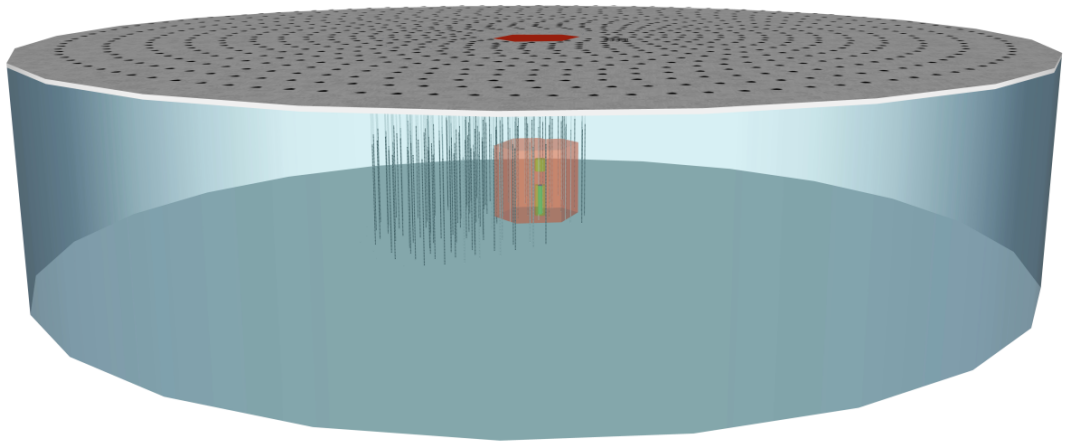


A surface veto

R&D under way



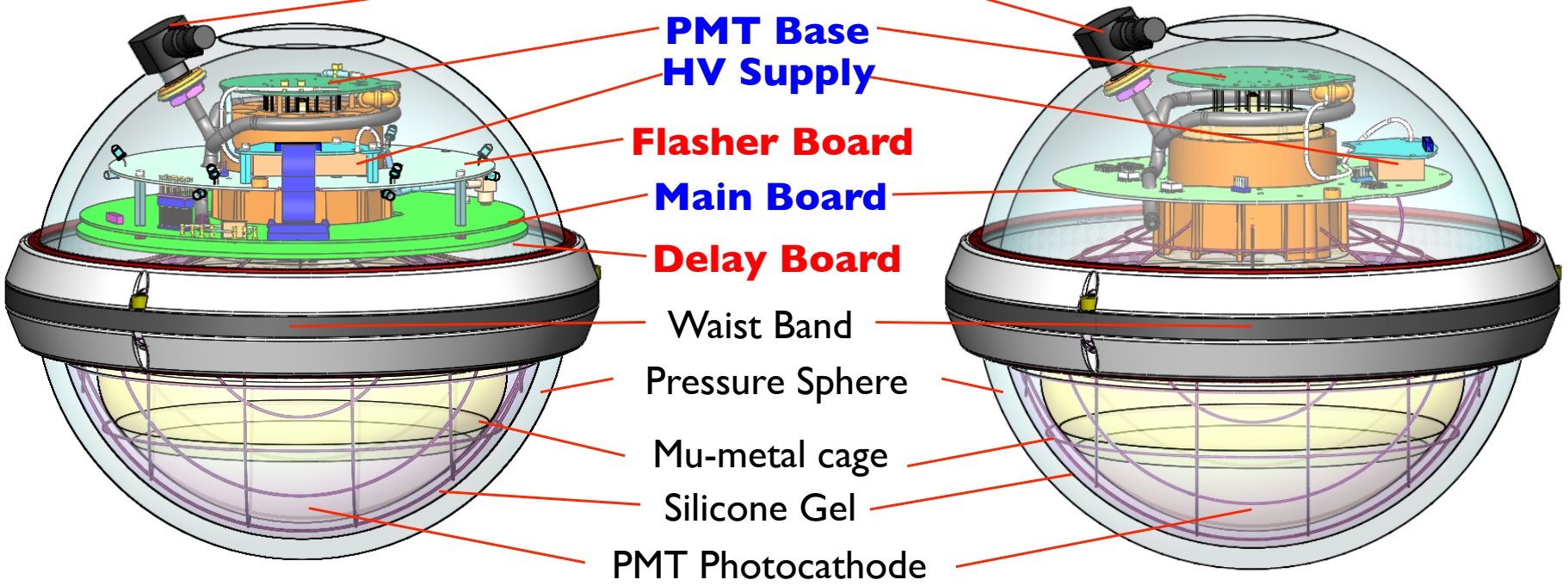
up to ~120 km² and 1000 modules



- >100 TeV: Earth opaque
- Expect most of the signal from above
- Veto could give 50-75% more events above 100 TeV (averaged over 4 π)
- Galactic center !
- CR physics somewhere between 1 km² and 3000 km³

Next Generation DOM

Assumption for baseline



IceCube DOM

Next-Generation DOM

KEY:

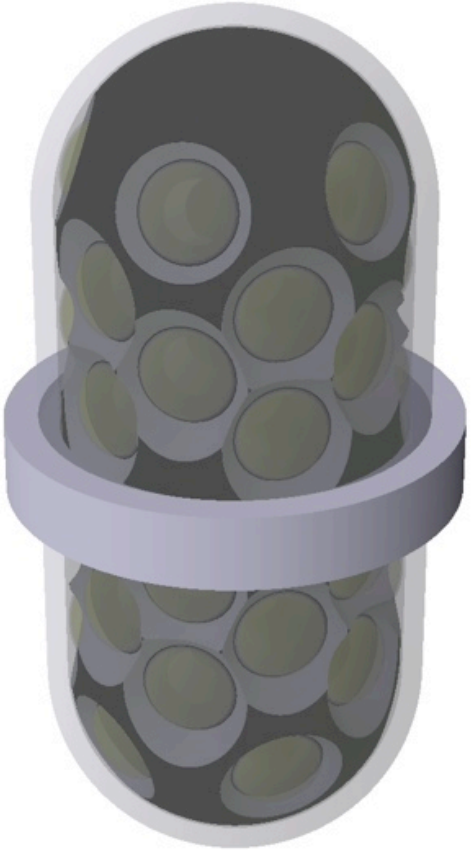
Component identical

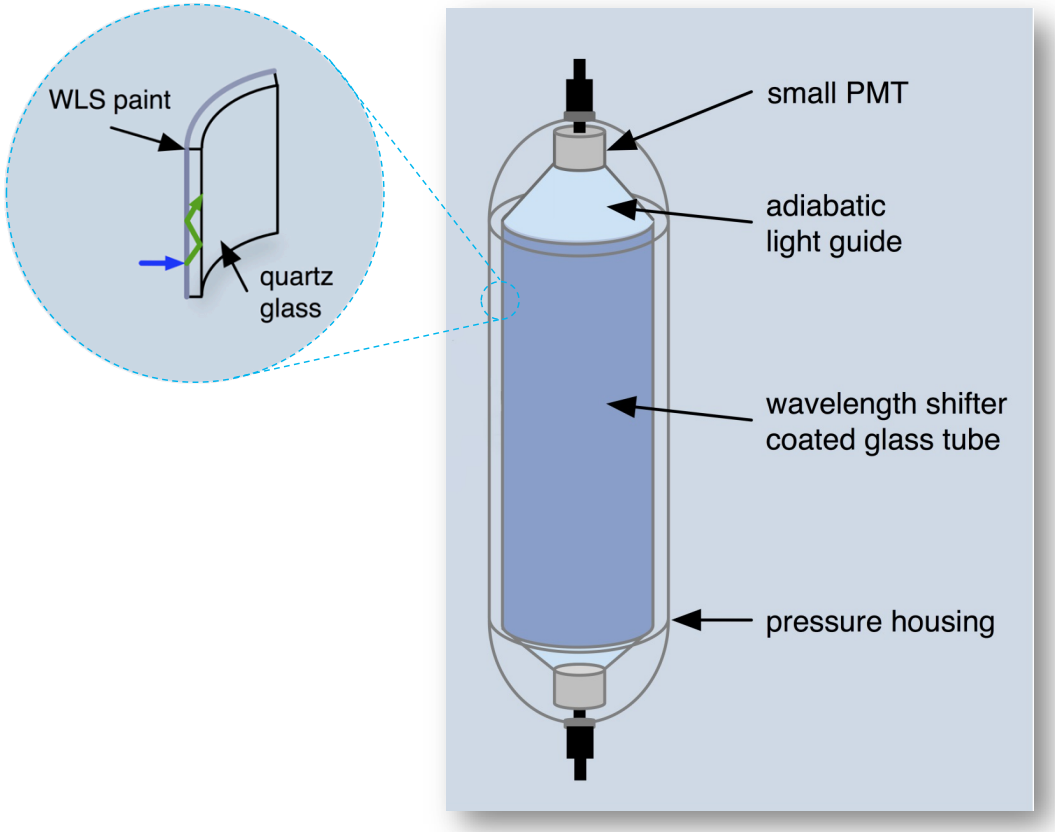
Component eliminated

Component redesigned

*P. Sandstrom *et al.*, VLVnT13 (Stockholm)

R&D on alternative DOMs





- 41× 3” PMTs
- fits into standard IceCube bore holes
- based on proven KM3NeT design
- prototype to be tested in PINGU

- Light collection via WLS guides
- fits into standard IceCube bore holes
- Low noise rate
- Better UV sensitivity

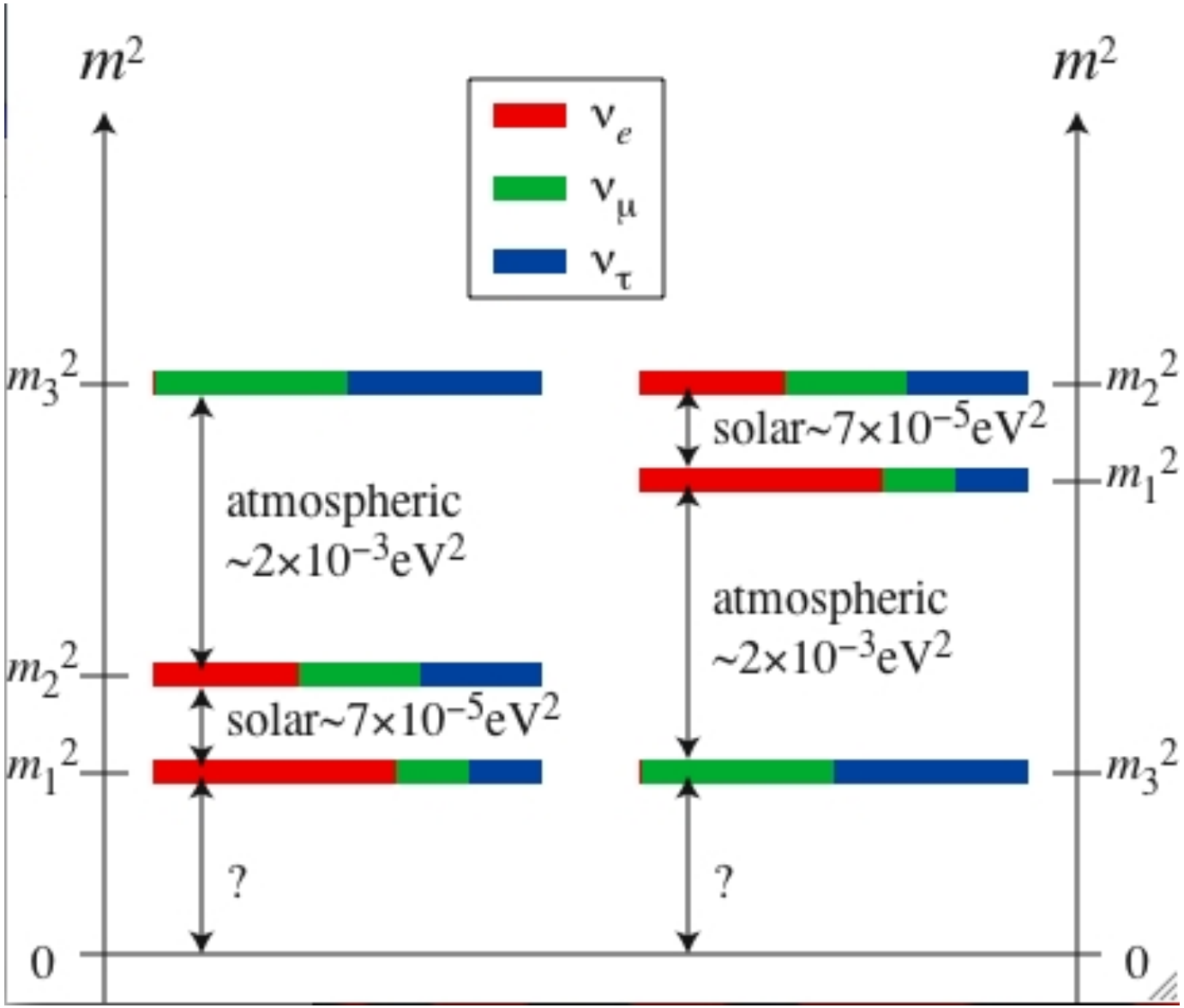
Schedule (optimistically) assuming start in season 2018/19

Description	Strings Installed	Cumulative strings installed	Austral Summer
PINGU(+HEX)	8	8	18/19
PINGU	16	24	19/20
PINGU + HEX	18	42	20/21
HEX	20	62	21/22
HEX	20	82	22/23
HEX	20	102	24/25
HEX	20	122	25/26
HEX	14	136	26/27

Albrecht Karle, Arlington Meeting April 24, 2014

PINGU AND ORCA

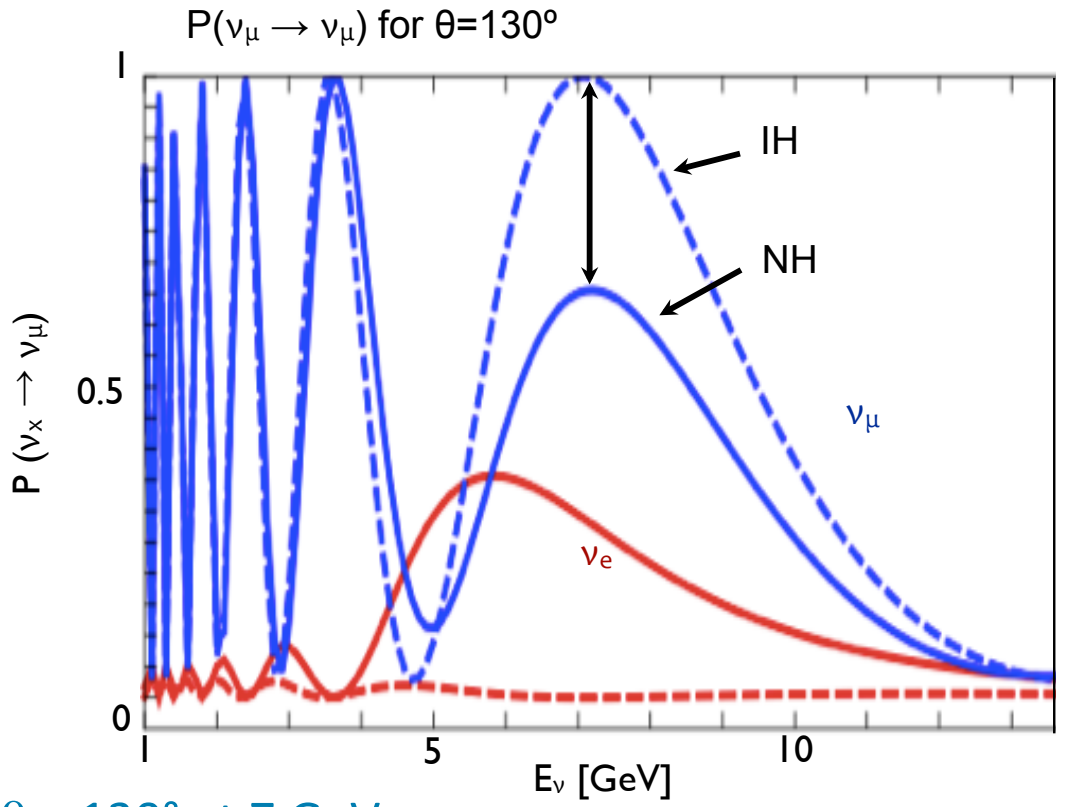
The neutrino mass hierarchy



Normal **Inverted**

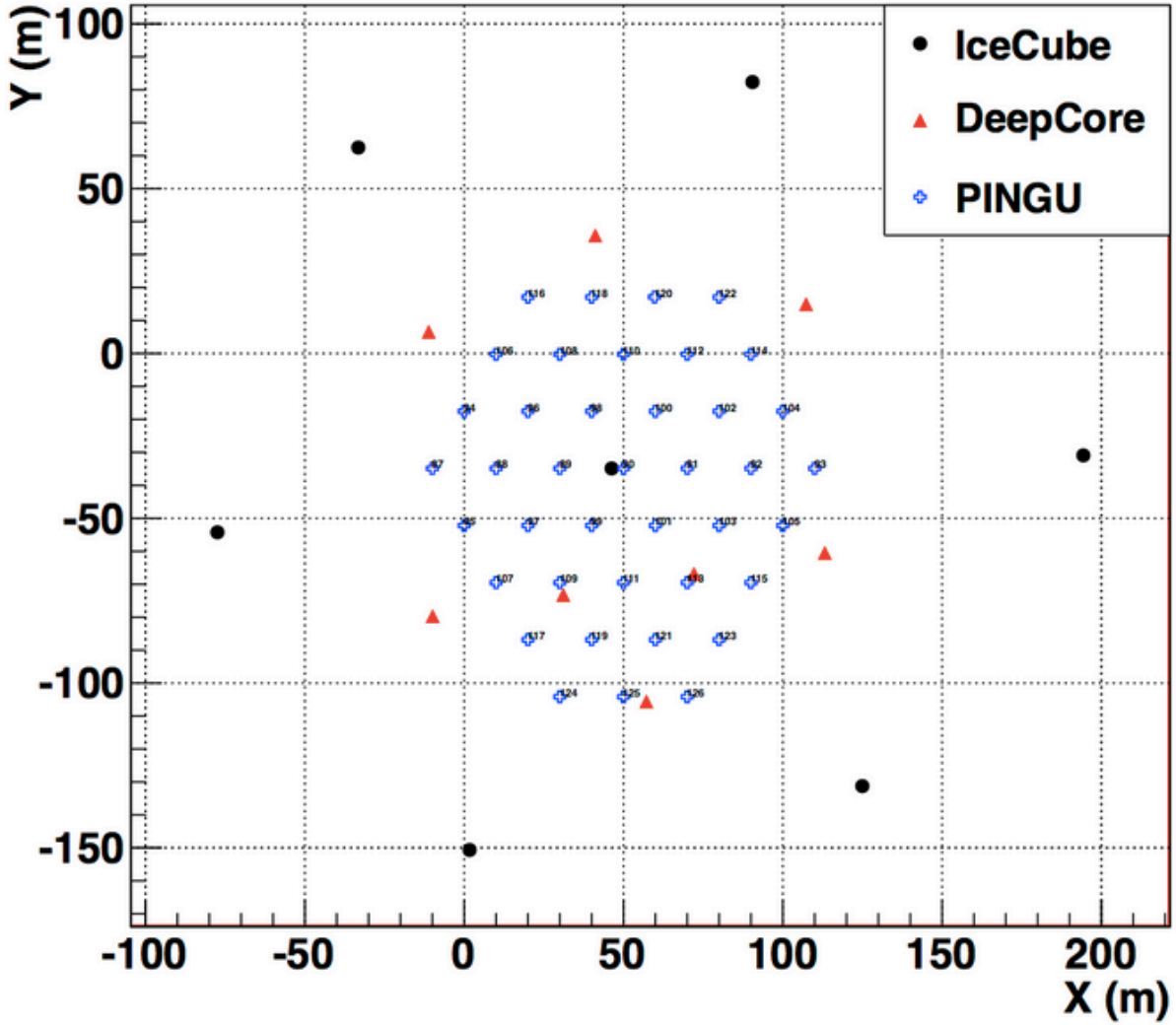
PINGU & ORCA

How it works …



- Maximum difference NH ↔ IH for θ = 130° at 7 GeV
- For anti-ν, NH and IH are approximately swapped → effect cancels if detector cannot distinguish μ^+ and μ^-
- However: flux of atm.ν ~ 1.3 × flux of atm. anti -ν and σ(ν) ~ 2 × σ(anti-ν) at low energies
- **→ Count $N_\mu(\theta, E)$ from $\nu_\mu + N \rightarrow \mu + X$ and compare with NH/IH predictions**

PINGU: determine the neutrino mass hierarchy

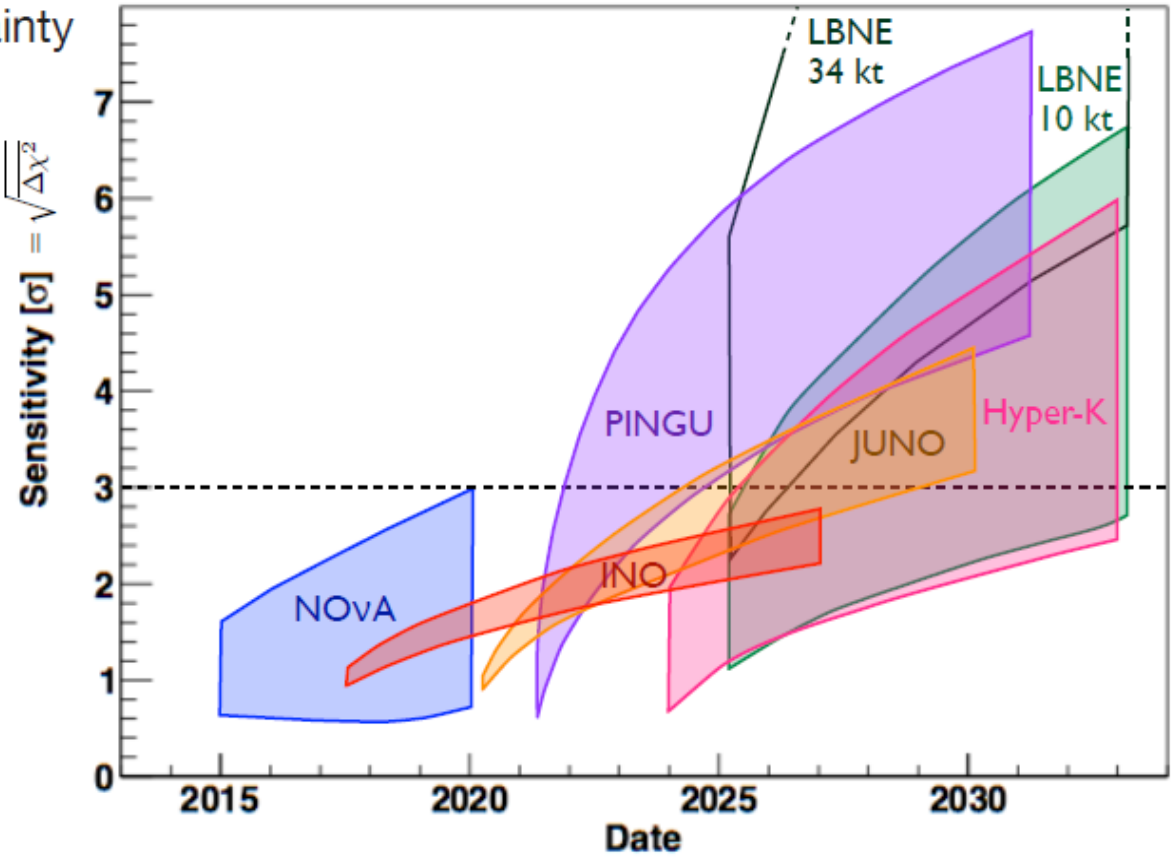


- ~40 additional strings
- Proposal submitted to US roadmap process in December 2013
- Cost 40-50 M$ (strings, DOMs, 3 South Pole seasons)

Sensitivity to mass hierarchy

- Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years
  - NB: *median* outcomes shown – large fluctuations possible
- Widths indicate main uncertainty
  - LBNE/NOvA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°–51.3°, 40°–50°)
  - Other projections presented here assume worst-case parameters (1st octant)
- PINGU timeline based on aggressive but feasible schedule; LBNE from LBNE-doc-8087-v10, all others from Blennow

after Blennow et al., arXiv:1311.1822



Slide taken from Ty DeYoung, Arlington Meeting April 24, 2014

Summary

- **Extraterrestrial HE neutrinos discovered !**
- **Need detectors on both hemispheres**
  - **complementarity w.r.t. field of view**
  - **many common sources, but in different energy regimes**
- **Detection of point sources: importance of directional resolution**
- **Ongoing: more and better data from IceCube (and ANTARES)**
- **Next steps:**
  - **First GVD cluster (2015) → GVD (2020)**
  - **KM3NeT phase 1 (2016) → KM3NeT phase 1.5 (2020) ← secure funding!**
  - **Prepare South Pole extensions**
- **Towards multi-km^3 detectors**
  - **KM3NeT phase 2**
  - **IceCube extensions**

END