Nikhef Colloquium, 6 March 2009

KM3NeT – towards a km^3-Scale Neutrino Telescope in the Mediterranean Sea

Uli Katz
ECAP / Univ. Erlangen

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Friedrich-Alexander-Universität Erlangen-Nürnberg

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KM3NeT

- Scientific rationale
- Neutrino telescopes
- KM3NeT: Towards design and construction
- Summary

KM3NeT

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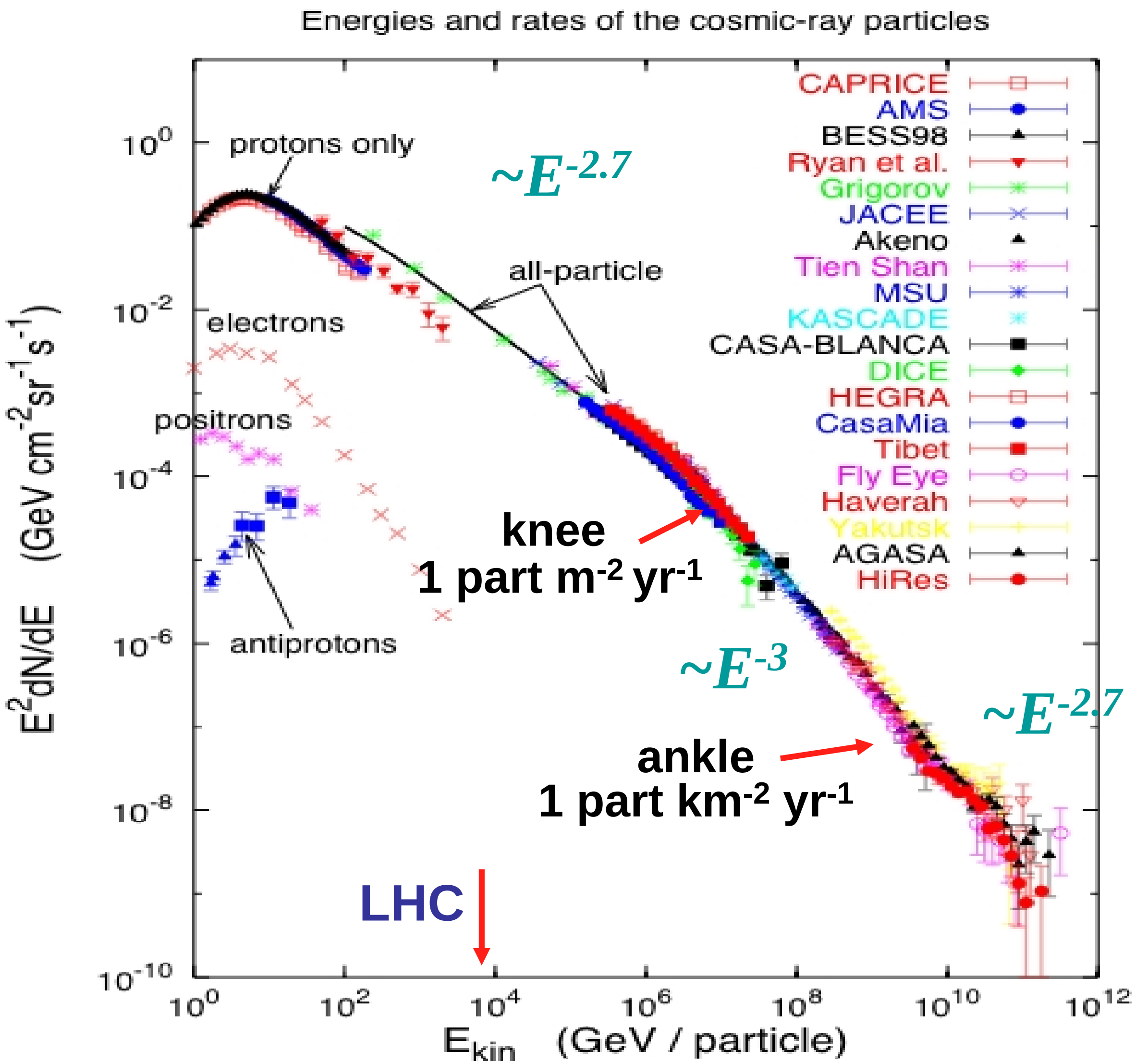
The Mysterious Cosmic Rays



- 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.

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Neutrino Production Mechanism

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

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

$$\downarrow$$

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

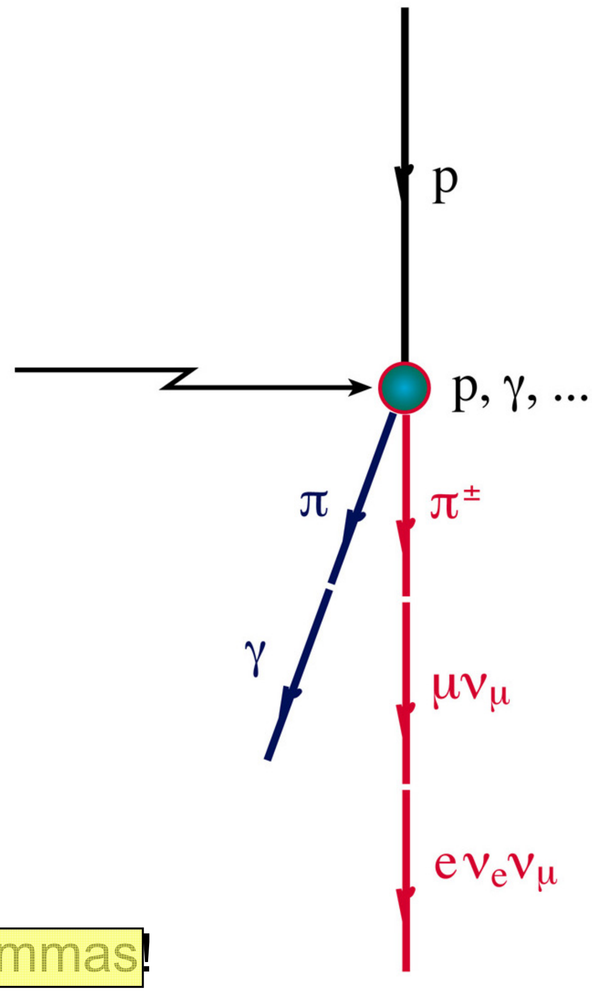
Cosmic rays

- Simultaneously, gamma production takes place:

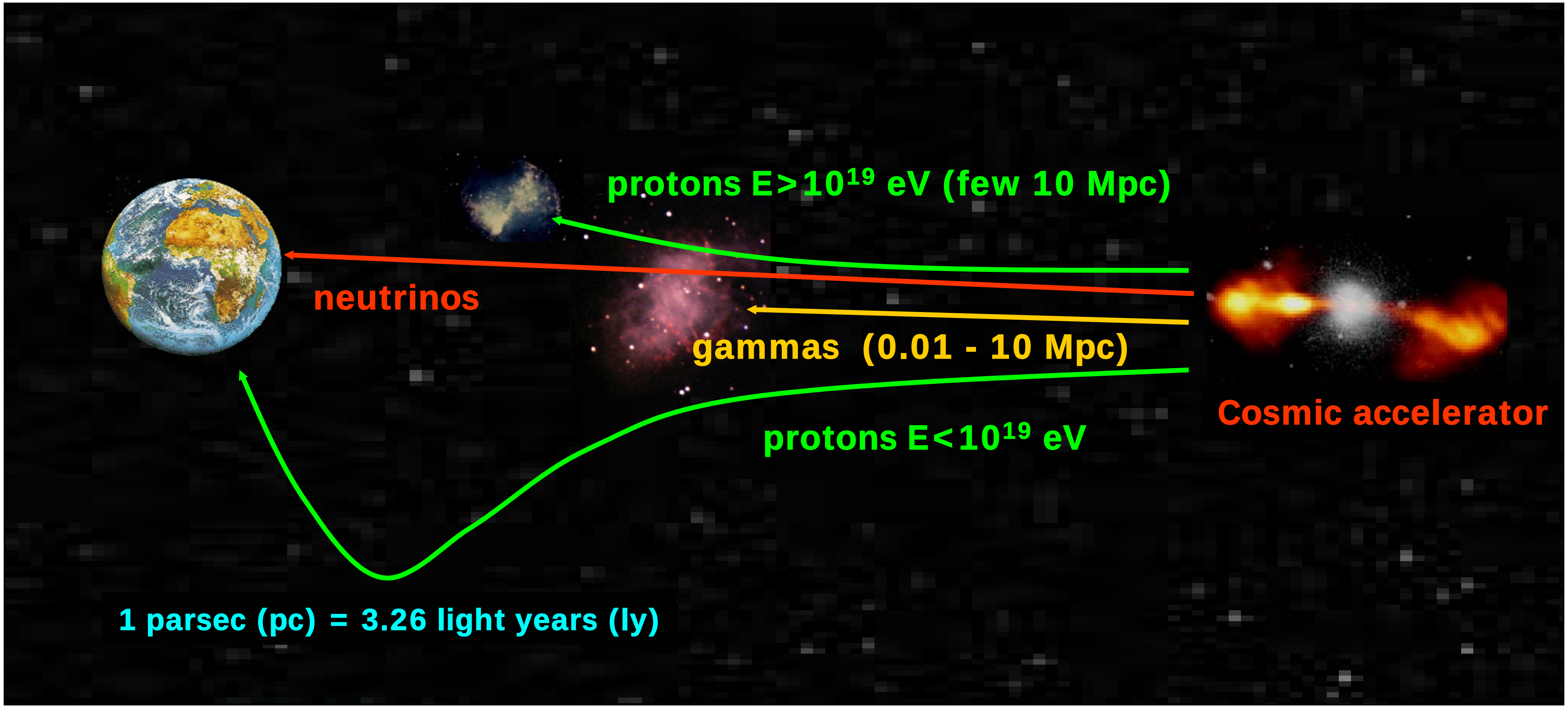
$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\,\gamma + Y$$

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)

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Potential Galactic Sources

- The candidate accelerators of cosmic rays
  - Supernova remnants
  - Pulsar wind nebulae
  - Micro-quasars
  - …
- Interaction of cosmic rays with interstellar matter
  - Possibly strong ν signal if CR spectrum harder in Galactic Centre than on Earth (supported by recent MILAGRO results)
- Unknown sources – what are the H.E.S.S. ”TeV gamma only” objects?

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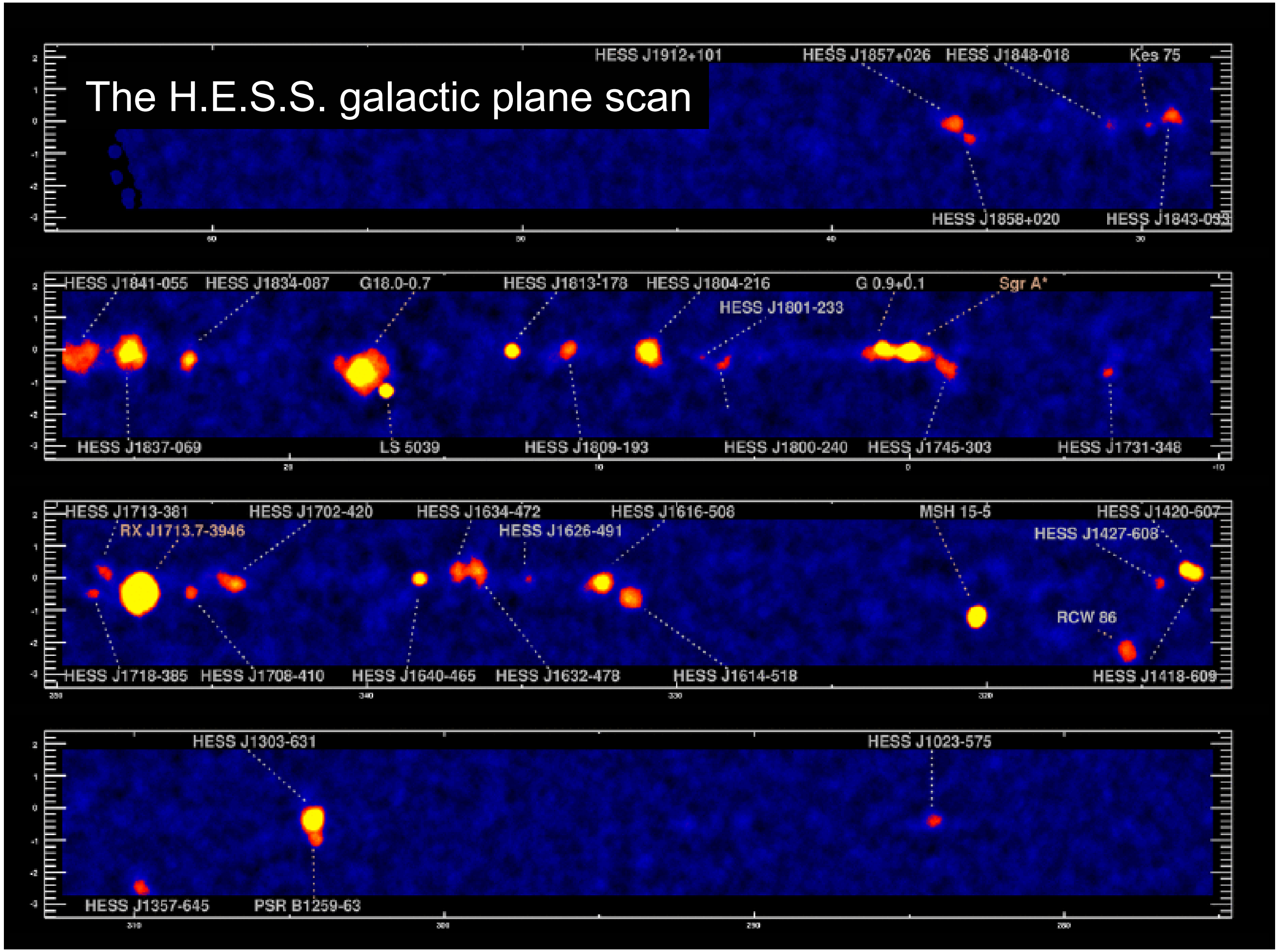
High-Energy γ Sources in the Galactic Disk



Status 2007:

- 18 Pulsar wind nubulae
- 7 Shell-type supernova remnants
- 4 Binaries
- 2 Diffuse
- 21 Unknown (no identified counterpart)

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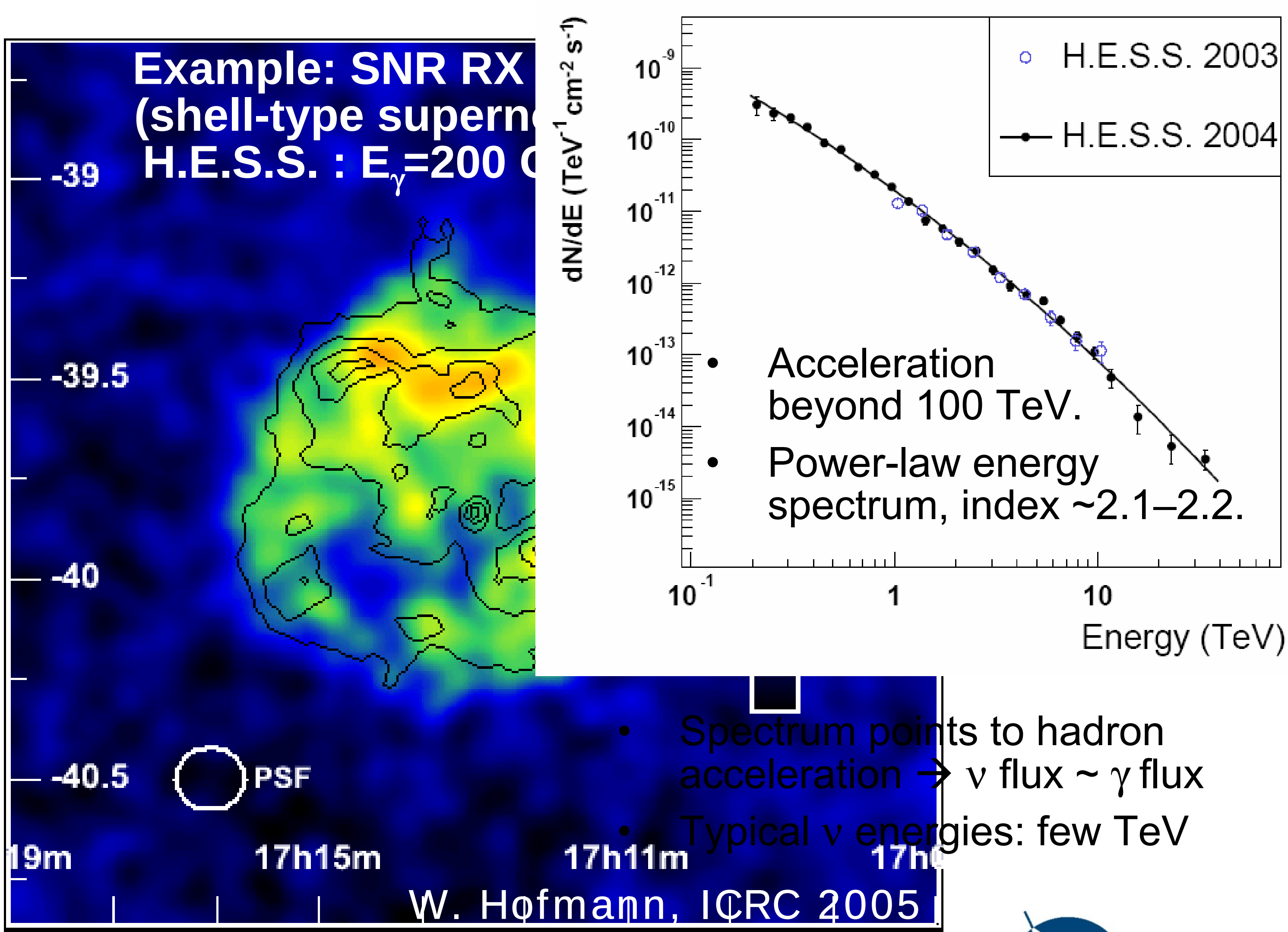
Example: ν's from Supernova Remnants



- Acceleration beyond 100 TeV.
- Power-law energy spectrum, index ~2.1–2.2.

- Spectrum points to hadron acceleration → ν flux ~ γ flux
- Typical ν energies: few TeV

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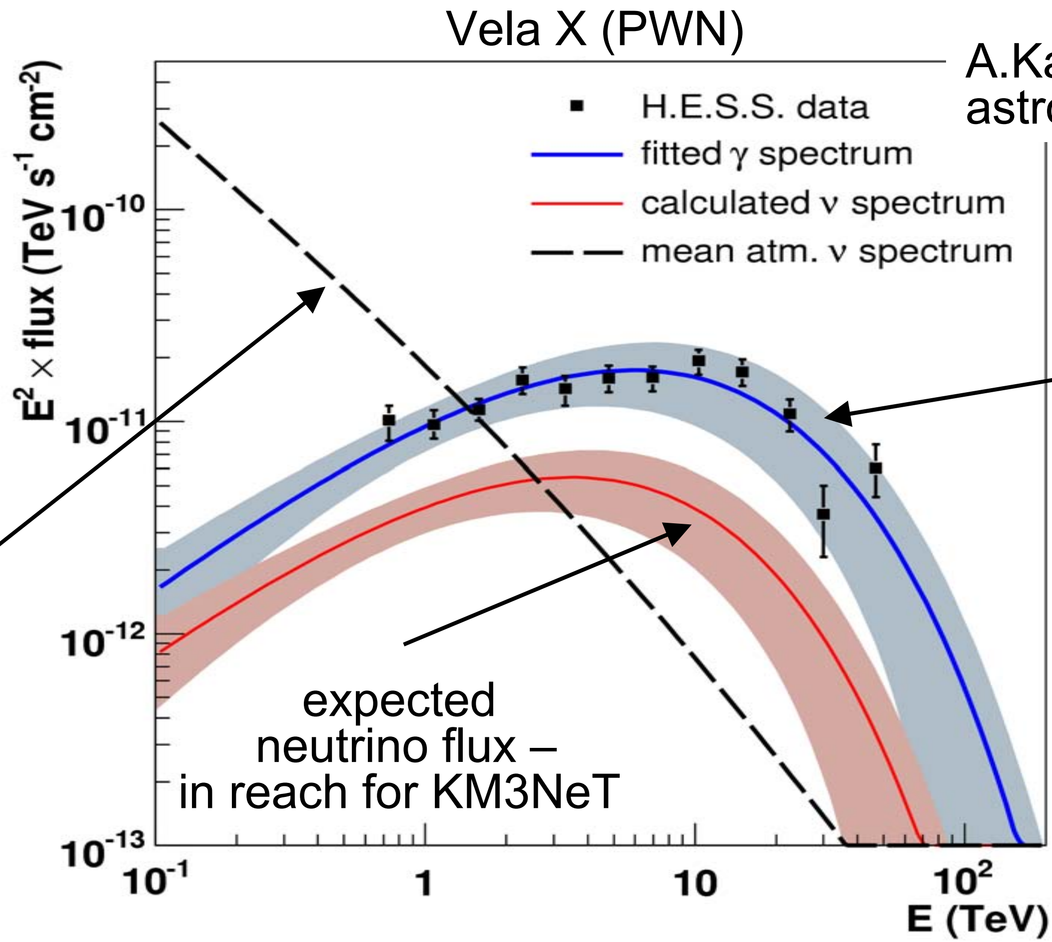
ν Flux Predictions from γ Measurements

Note:
hadronic
nature of
Vela X is
not clear!

A.Kappes et al.,
astro-ph 0607286



measured
γ-ray flux
(H.E.S.S.)

mean atmospheric
neutrino flux
(Volkova, 1980,
Sov.J.Nucl.Phys.,
31(6), 784)

1 σ error bands include systematic errors (20% norm., 10% index & cut-off)

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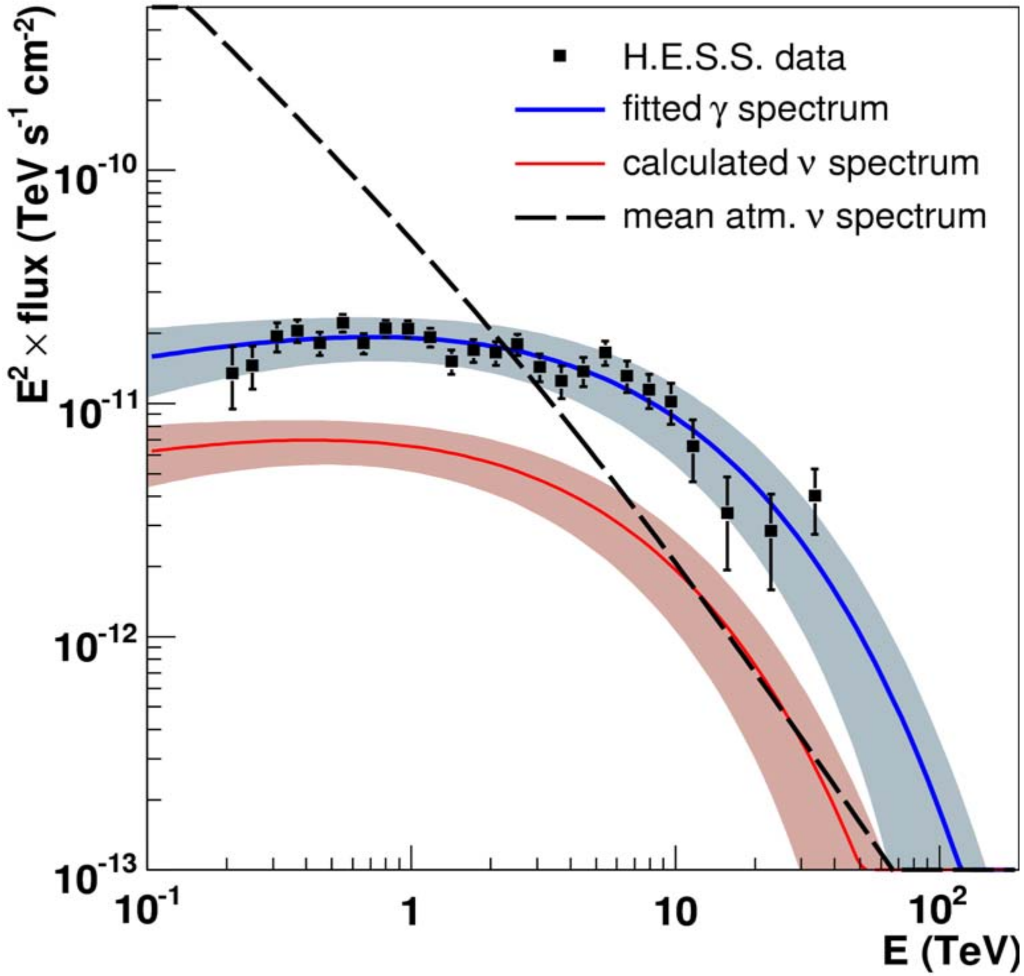
Another Case: SNR RXJ1713.7-3946

- Good candidate
  for hadronic acceleration.
- Expected signal
  well related to measured γ flux, but depends on energy cut-off.
- Few events/year
  over similar back-ground (1km^3).
- KM3NeT sensitivity
  in the right ballpark!



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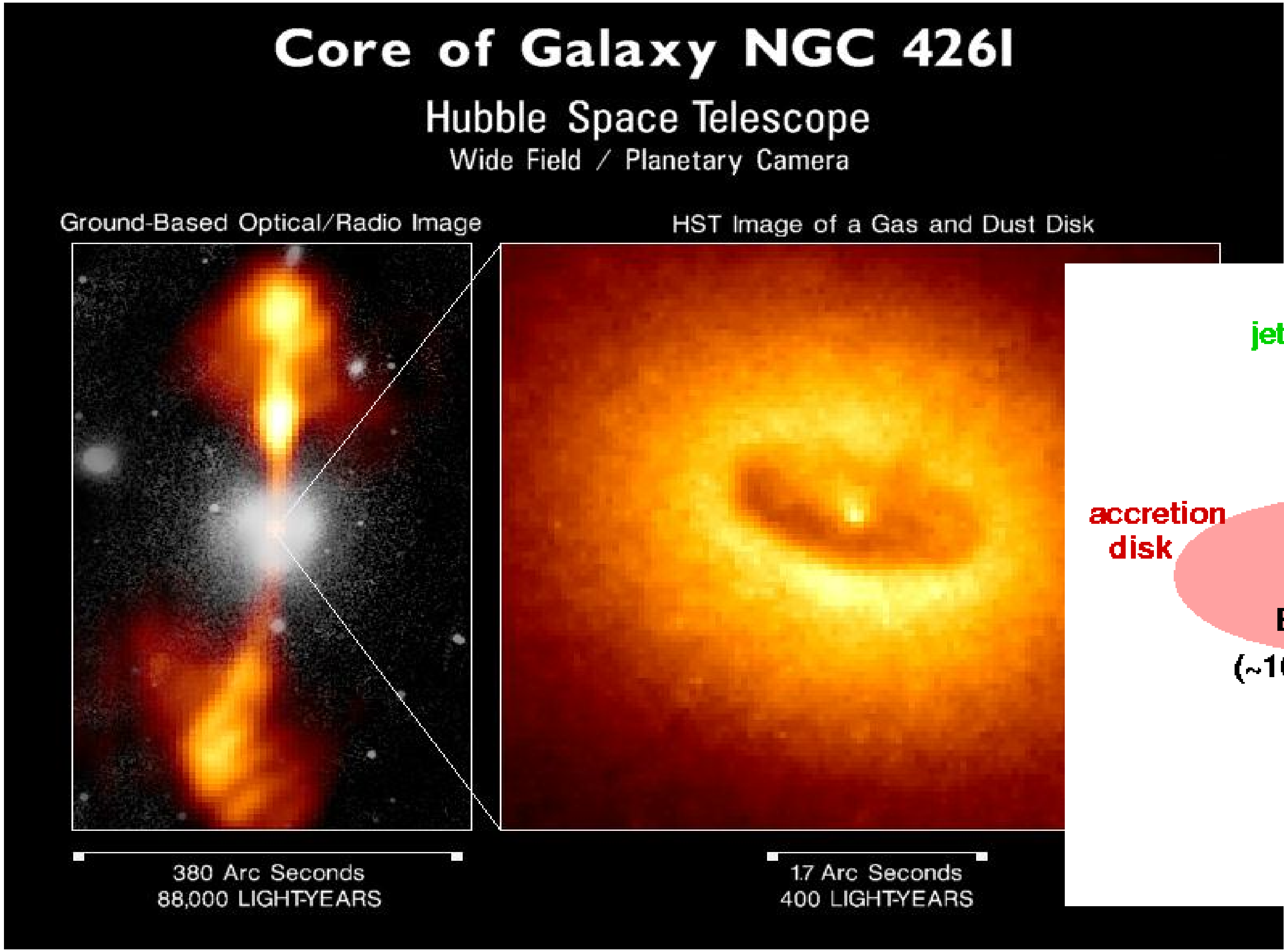
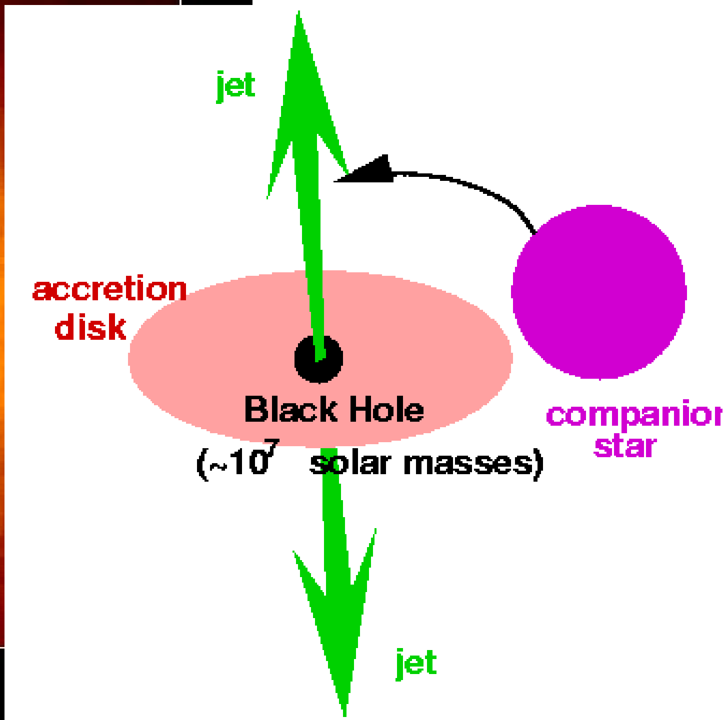
Potential Extragalactic Sources

- AGNs
  - Models are rather diverse and uncertain
  - The recent Auger results may provide an upper limit / a normalisation point at ultra-high energies
  - Note : Above some 100 TeV the neutrino telescope field of view is restricted downwards (ν absorption), but starts to be significant upwards.
- Gamma ray bursts
  - Unique signature: Coincidence with gamma observation in time and direction
  - Source stacking possible

Candidate Accelerators: Active Galactic Nuclei (AGNs)



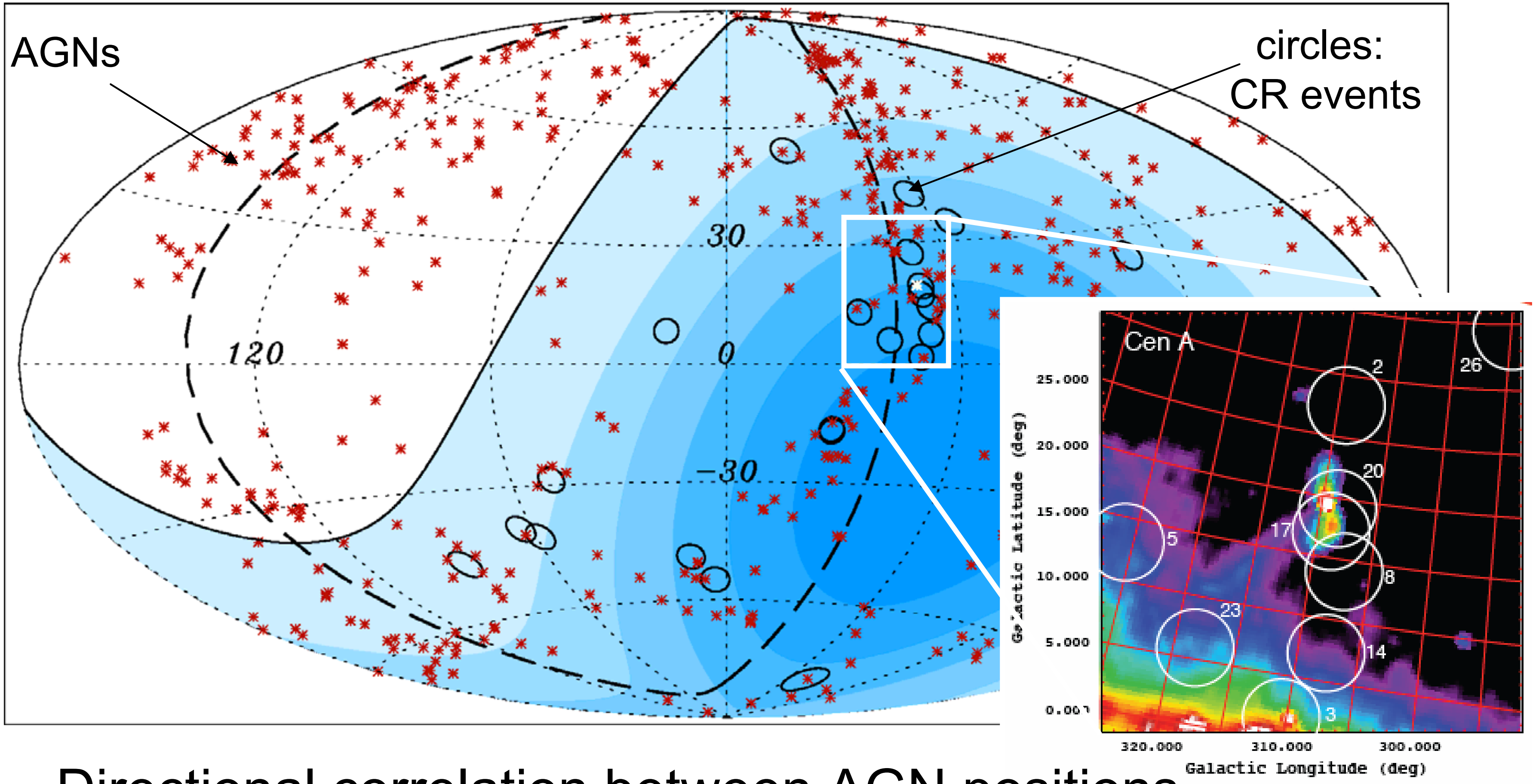
AGNs are amongst the most energetic phenomena in the universe.



Pierre Auger: First Hints at UHE Cosmic Ray Sources

red: AGNs

circles: CR events



- Directional correlation between AGN positions and cosmic rays ($E>10^{19.7}$eV, 27 events).
- Interpretation requires care and patience.

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Science Cases for Neutrino Telescopes

- Astroparticle physics with neutrinos
  - "Point sources": Galactic and extragalactic sources of high-energy neutrinos
  - The diffuse neutrino flux
  - Neutrinos from Dark Matter annihilation
- Search for exotics
  - Magnetic monopoles
  - Nuclearites, strangelets, …
- Neutrino cross sections at high(est) energies
- Earth and marine sciences
  - Long-term, continuous measurements in deep-sea
  - Marine biology, oceanography, geology/geophysics, …

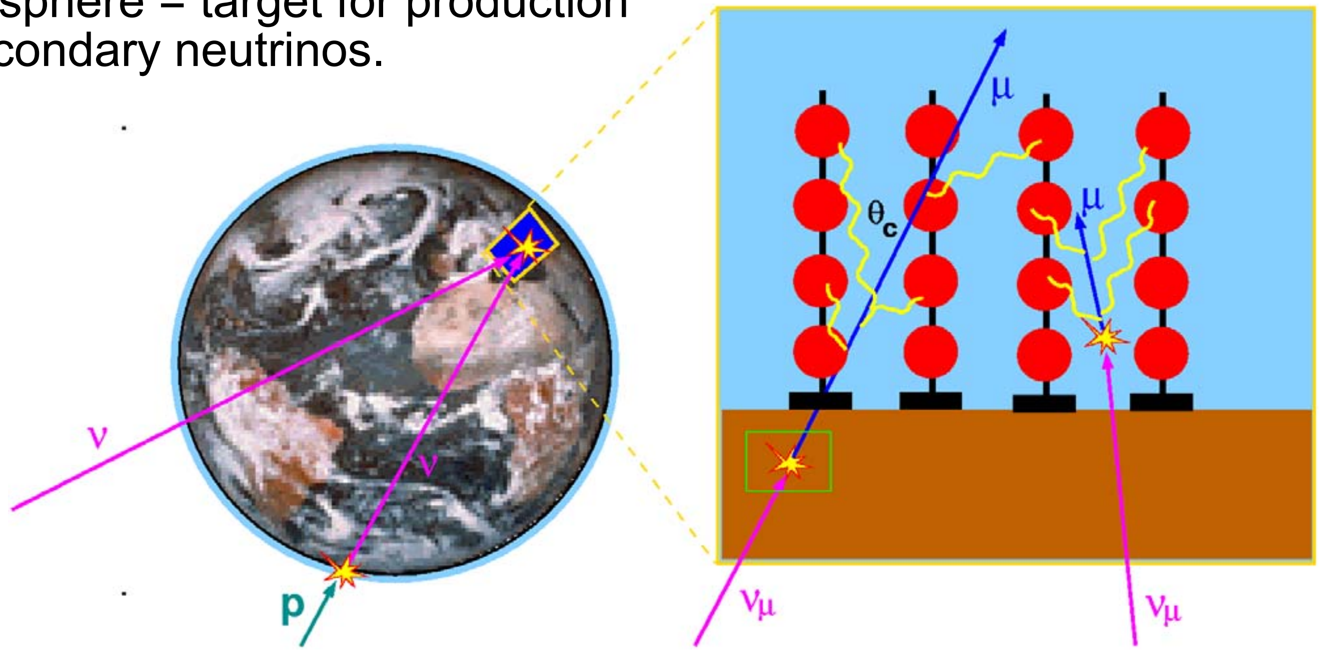
The Principle of Neutrino Telescopes

Role of the Earth:

- Screening against all particles except neutrinos.
- Atmosphere = target for production of secondary neutrinos.

Cherenkov light:

- In water: $\theta_C \approx 43°$
- Spectral range used: ~ 350-500nm.



Angular resolution in water:

- Better than ~0.3° for neutrino energy above ~10 TeV, 0.1° at 100 TeV
- Dominated by angle(ν,μ) below ~10 TeV (~0.6° at 1 TeV)

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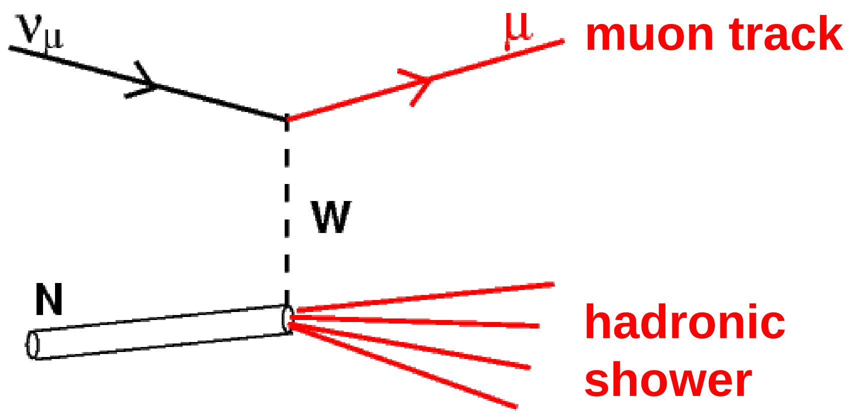
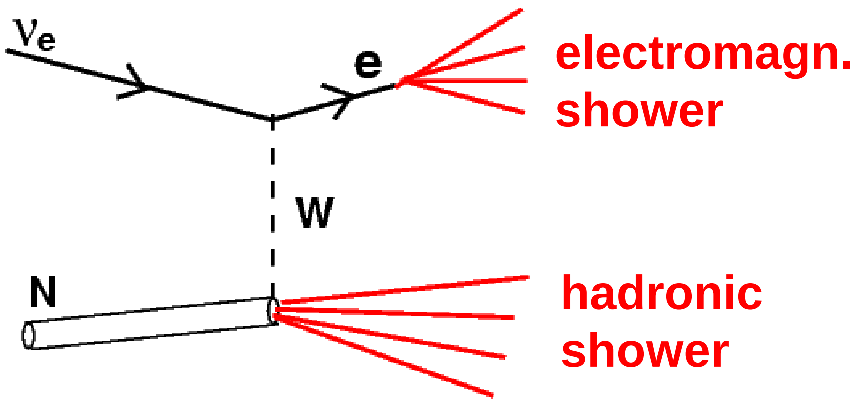
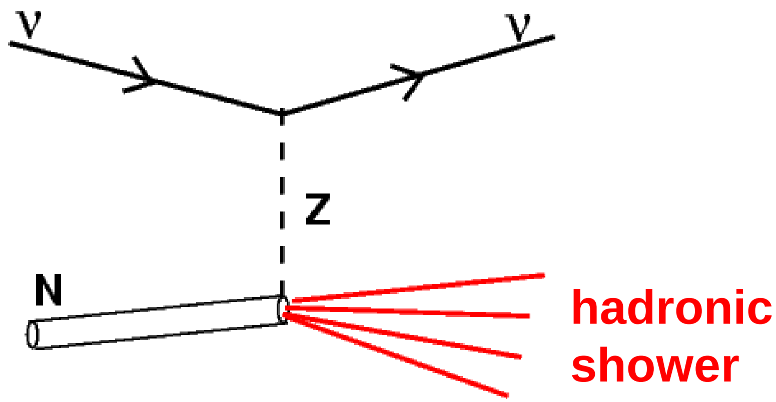
Neutrino Interaction Signatures

- Neutrinos mainly from π-μ-e decays, roughly $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$;
- Arrival at Earth after oscillations: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$;
- Key signature: muon tracks from ν_μ charged current reactions (few 100m to several km long);
- Electromagnetic/hadronic showers: "point sources" of Cherenkov light.

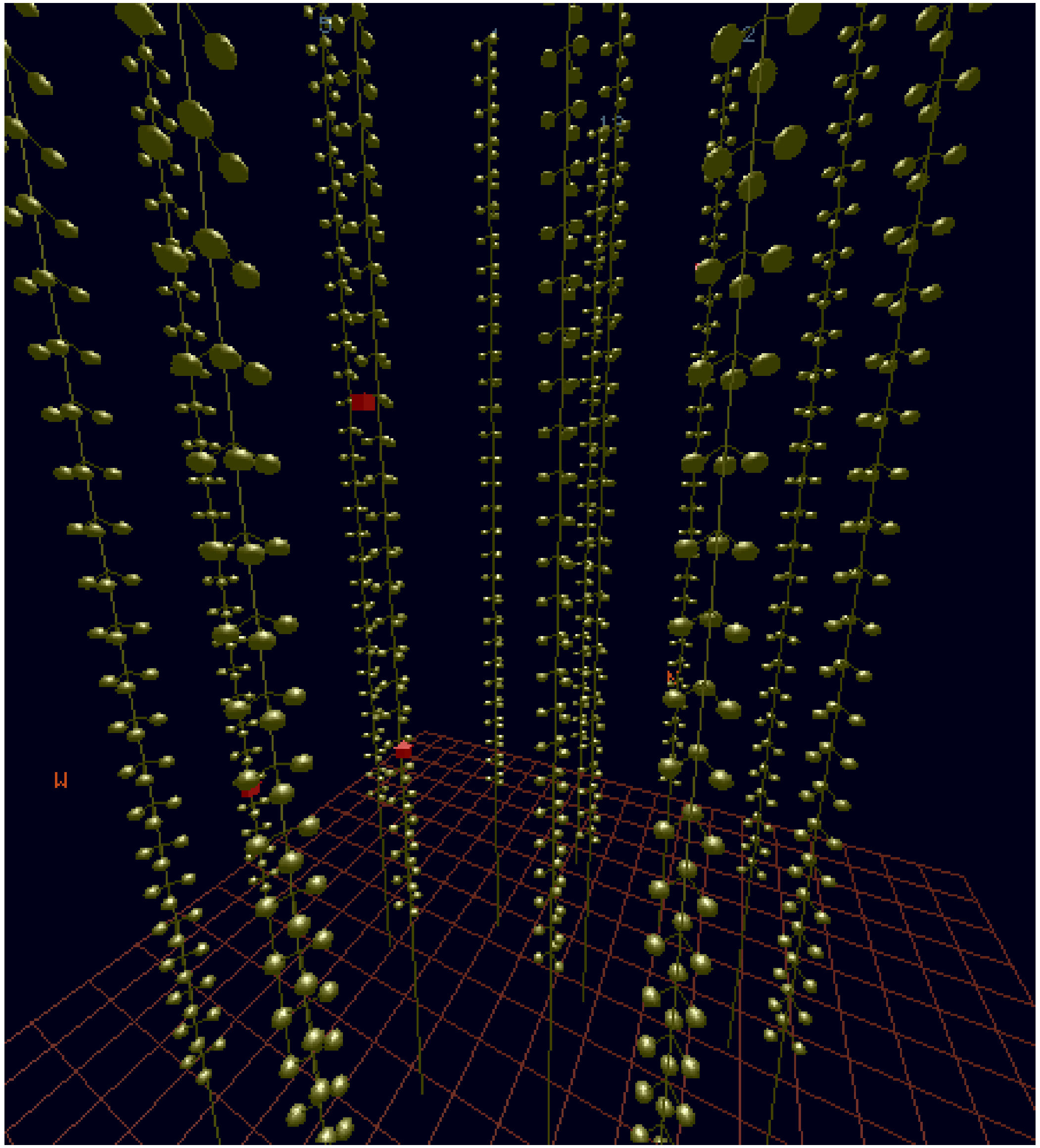






Muon Reconstruction

- The Cherenkov light is registered by the photomultipliers with nanosecond precision.
- From time and position of the hits the direction of the muon can be reconstructed to some 0.1°.
- Minimum requirement: 5 hits … in reality rather 10 hits.
- Position calibration to ~10cm required (acoustic methods).



1.2 TeV muon traversing the detector.

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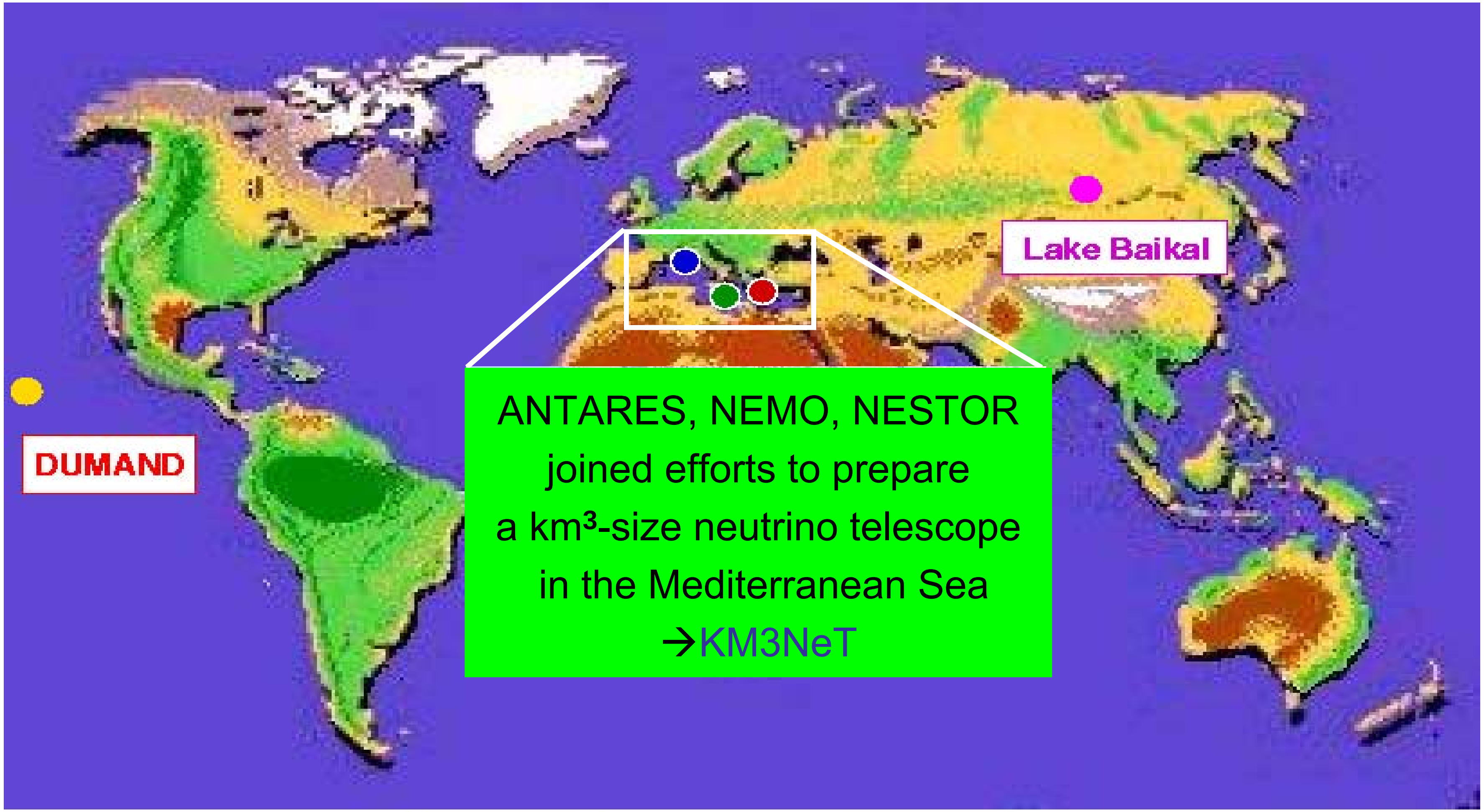
The Neutrino Telescope World Map



ANTARES, NEMO, NESTOR
joined efforts to prepare
a km³-size neutrino telescope
in the Mediterranean Sea
→KM3NeT

AMANDA South Pole IceCube

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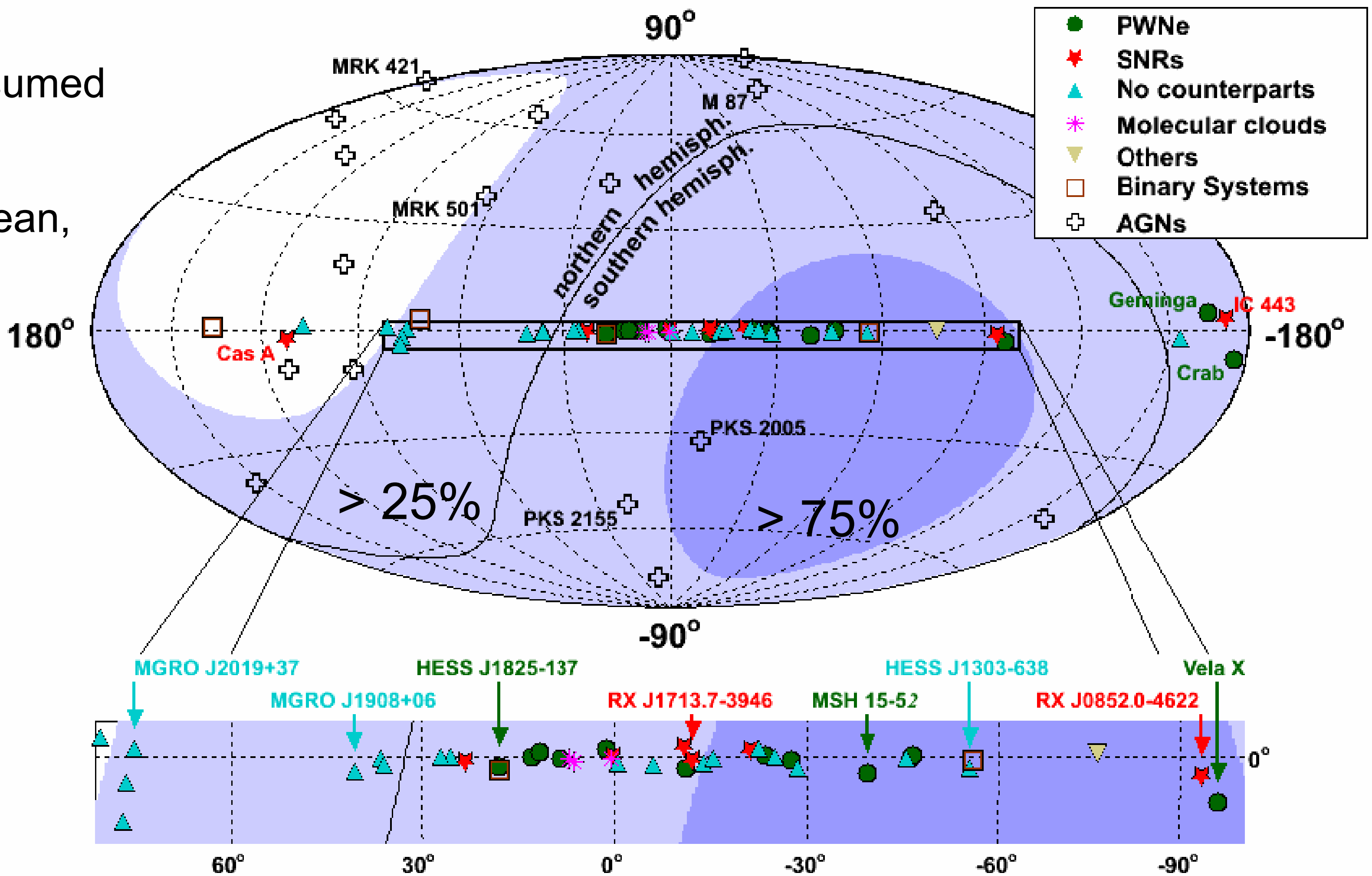
South Pole and Mediterranean Fields of View

2π downward sensitivity assumed

In Mediterranean, visibility of given source can be limited to less than 24h per day



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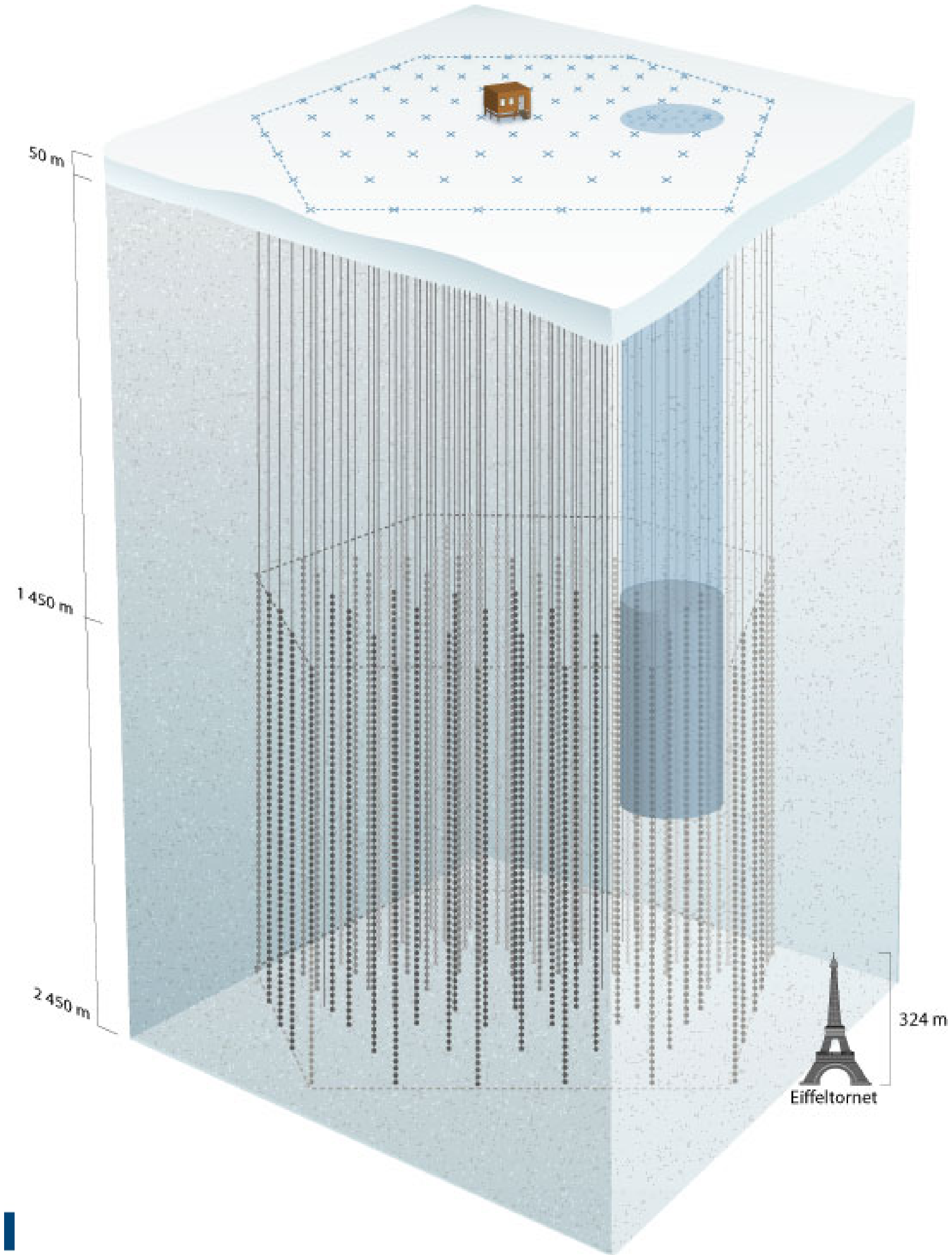
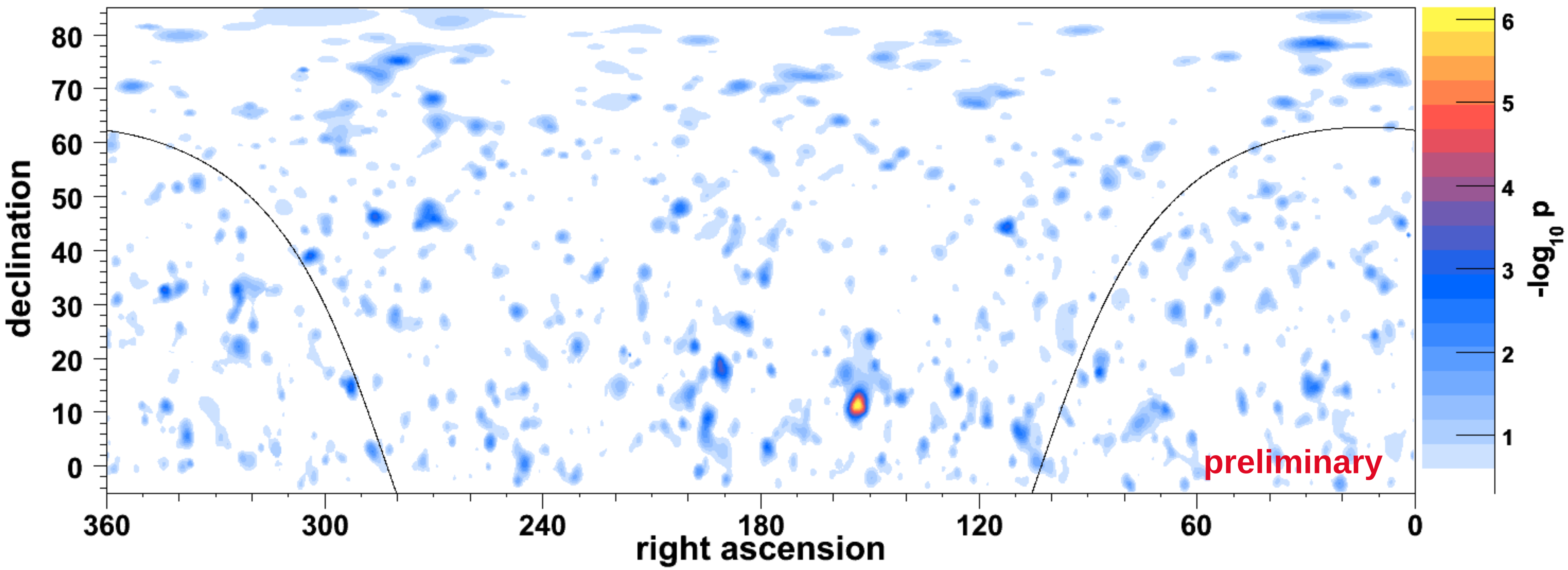


IceCube

- 4800 Digital Optical modules on 80 strings
- 160 Ice-Cherenkov tank surface array (IceTop)
- Instrumenting 1 km³ of Antarctic Ice
- Surrounding exisiting AMANDA detector

IceCube 22: Point Source Search



- Hottest spot found at right ascension 153º , declination 11º; pre-trial probability: $7{\times}10^{-7}$ (4.8 sigma).
- Accounting for trial factor, p-value is 1.34% (2.2 sigma).
- At this significance level, consistent with fluctuation of background.

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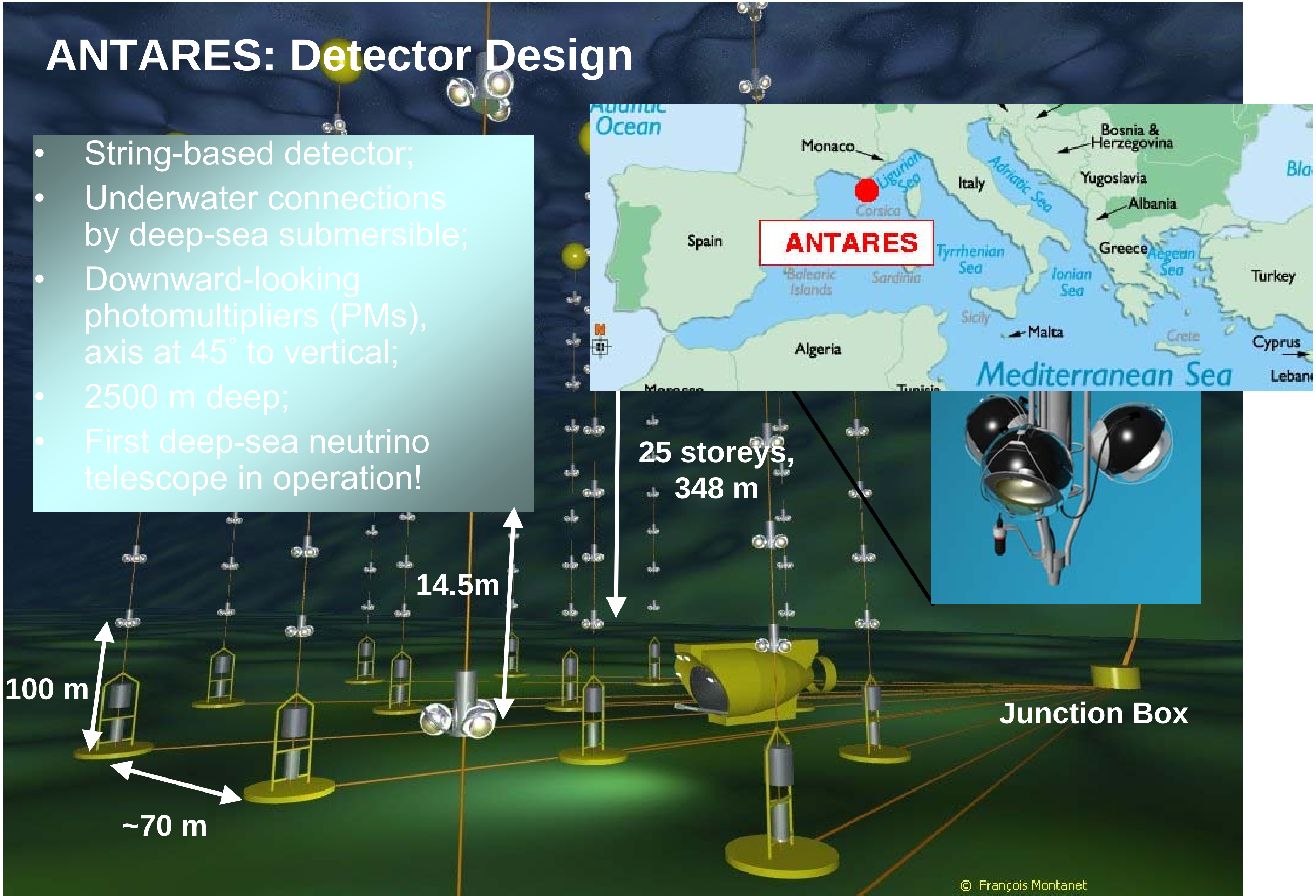
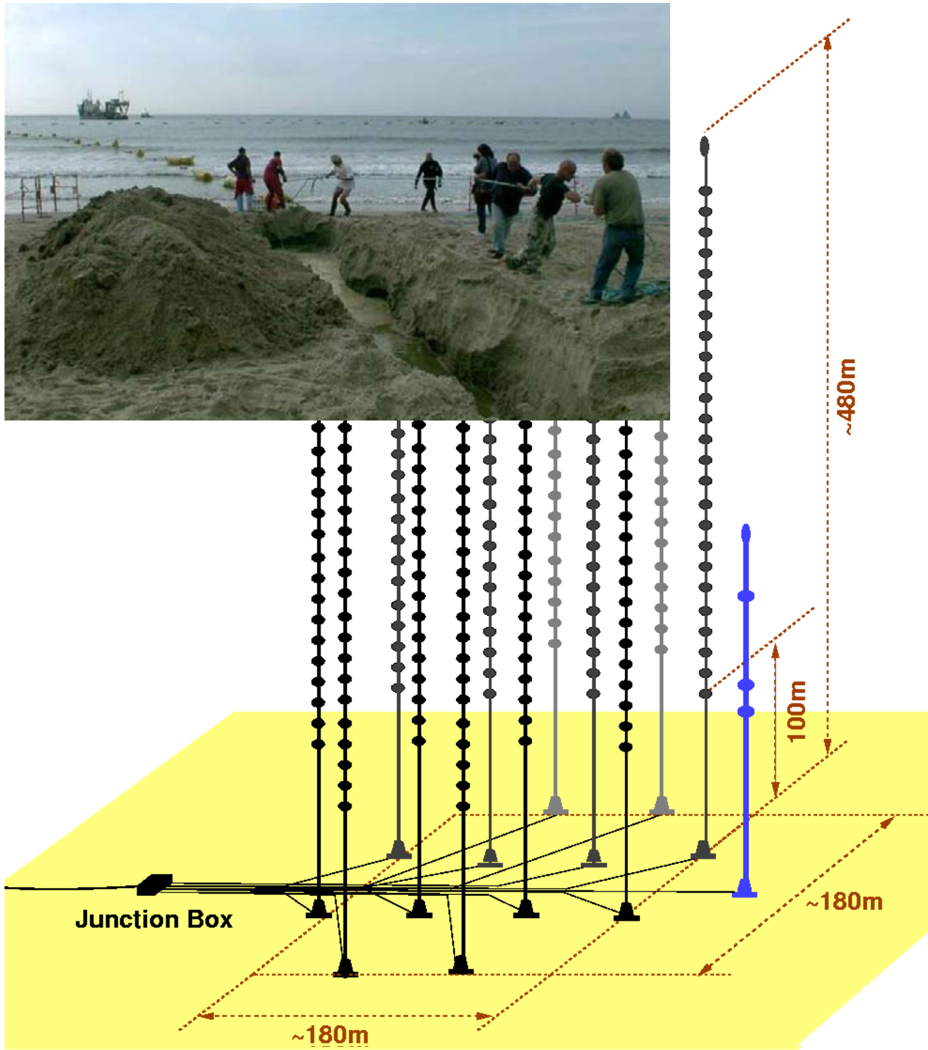
ANTARES: Detector Design

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking photomultipliers (PMs), axis at 45° to vertical;
- 2500 m deep;
- First deep-sea neutrino telescope in operation!



ANTARES Construction Milestones



2001 – 2003:

- Main Electro-optical cable in 2001
- Junction Box in 2002
- Prototype Sector Line (PSL) &
  Mini Instrumentation Line (MIL) in 2003

2005 – April 2007:

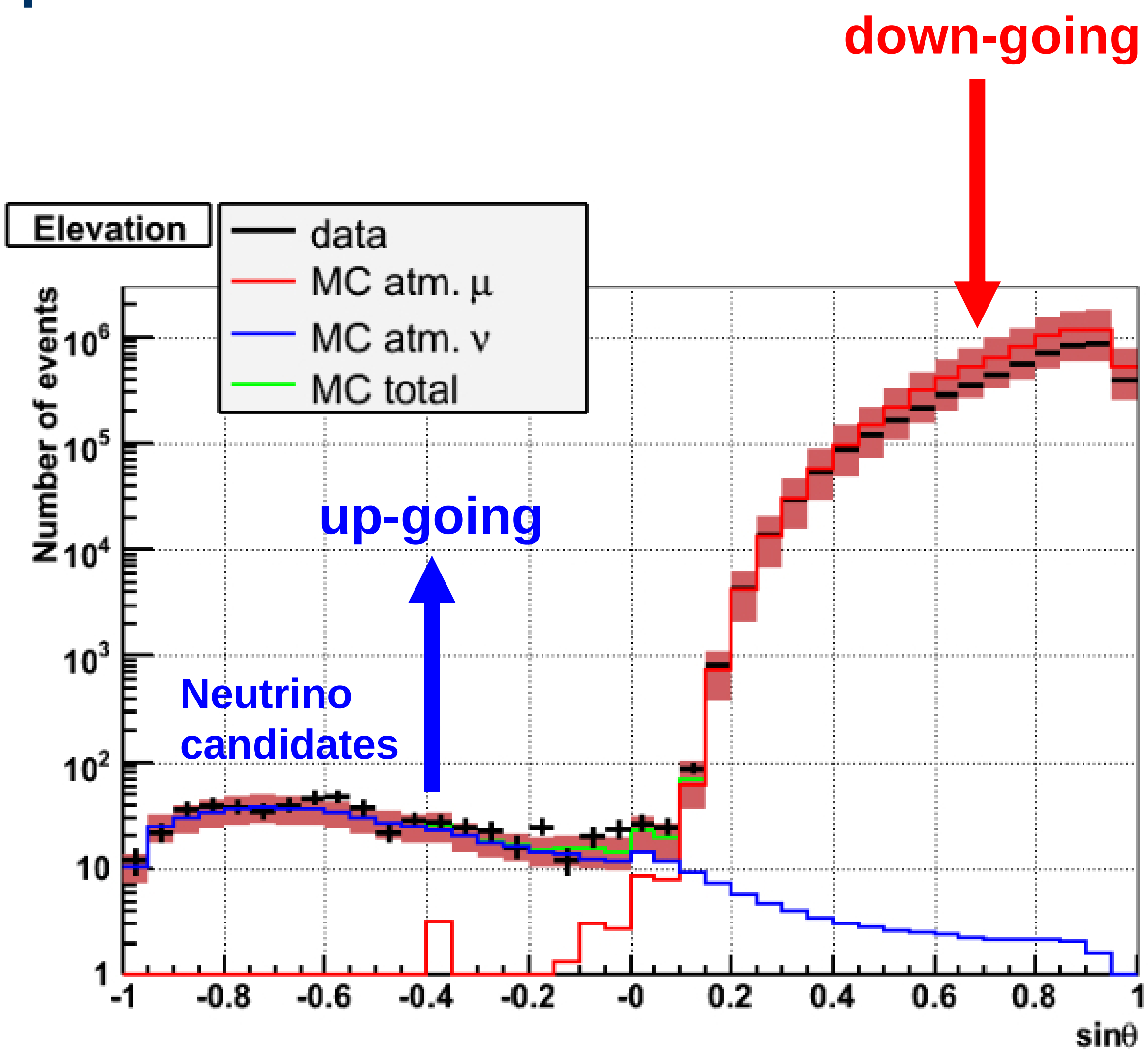
- Mini Instrumentation Line with OMs (MILOM) operated ~4 months in 2005
- Lines 1-5 running (connected between March 2006 and Jan. 2007)
- Lines 6+7 deployed March/April 2007

2007 – now:

- Deployment / connection of remaining lines completed in May 2008
- Replacement of MILOM by full instrumentation line (IL)
- **Physics with full detector !**

ANTARES: Atmospheric Neutrinos

- 174 days of data with 9-12 lines
- Reconstruction tuned for up-going tracks
- Rate of neutrino candidates: ~ 3.5 events/day

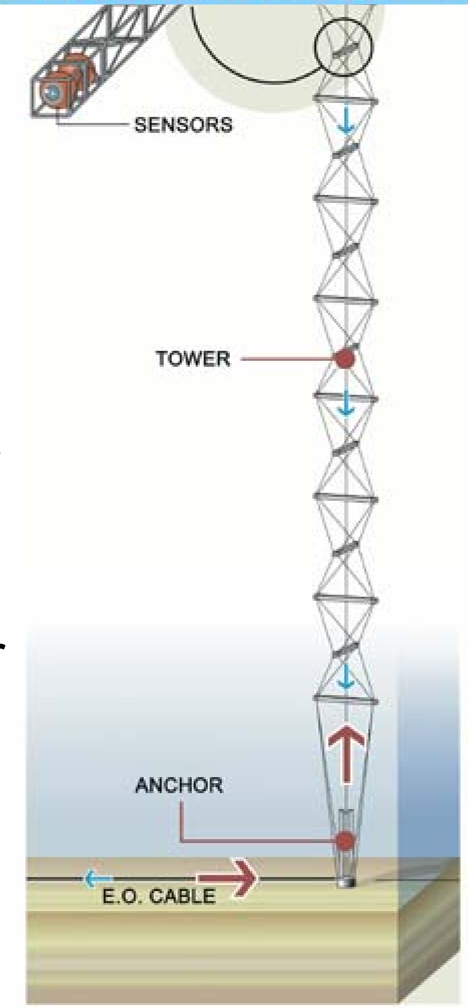


The NEMO Project

- Extensive site exploration (Capo Passero near Catania, depth 3500 m);
- R&D towards km^3: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

Example: Flexible tower

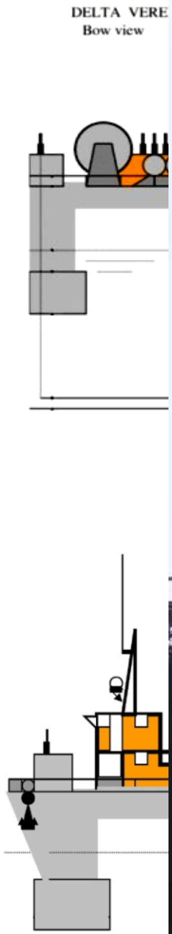
- ~10 m bar length, bars 30-40 m apart;
- 3 pairs of PMs per bar
- Unfurls after deployment as compact structure.



NESTOR

- Tower based detector (titanium structures).
- Dry connections (recover − connect − redeploy).
- Up- and downward looking PMs (15’’).
- 4000-5200 m deep.
- Test floor (reduced size) deployed & operated in 2003.
- Deployment of 4 floors planned in 2009

NESTOR: the Delta-Berenike Platform



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NeT

KM3NeT: from the Idea to a Concept

- 11/2002 — First consultations of ANTARES, NEMO and NESTOR
- 3/2004 — Design Study proposal submitted
- 9/2005 — KM3NeT on ESFRI List of Opportunities
- 2/2006 — Begin of Design Study
- 9/2006 — KM3NeT on ESFRI Roadmap
- 4/2008 — The KM3NeT Conceptual Design Report

Major Achievements to Date

- Science & technology
  - Successful prototype deployments by NEMO and NESTOR
  - Installation and operation of ANTARES

    → A large deep-sea neutrino telescope is feasible!
- Politics & funding
  - Endorsement by ESFRI, ApPEC/ASPERA and ASTRONET
  - Funding through EU: Design Study, Preparatory Phase
  - Funding through national authorities:
    pilot projects, commitments for KM3NeT
- Towards construction
  - Strong collaboration
  - Design concepts in CDR

The ESFRI Process

- ESFRI = European Strategy Forum for Research Infrastructures
- EU-initiated forum of research ministries and funding agencies.
- Objective: Identify and support the priority research infrastructures in all fields of science.
- Roadmap: Two editions with 35 (2006) and 43 (2008) RIs.
- KM3NeT included in both editions.

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The KM3NeT Conceptual Design Report

- Presented to public at VLVnT0 workshop in Toulon, April 2008
- Summarises (a.o.)
  - Physics case
  - Generic requirements
  - Pilot projects
  - Site studies
  - Technical implementation
  - Development plan
  - Project implementation

available on www.km3net.org

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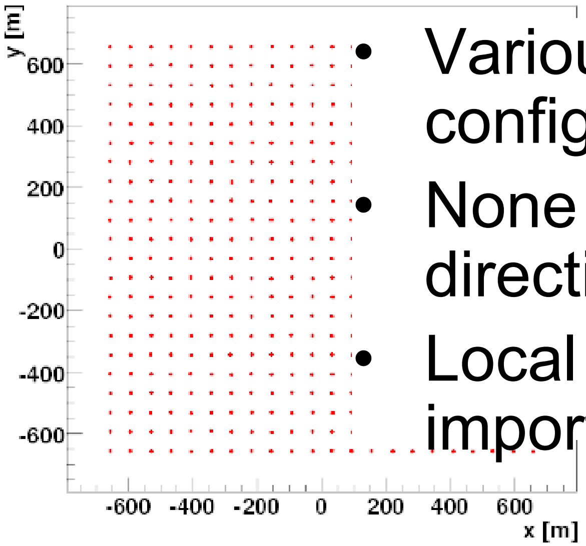
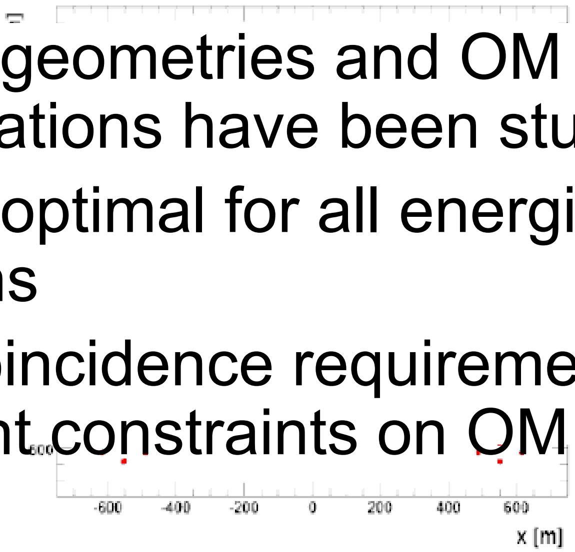
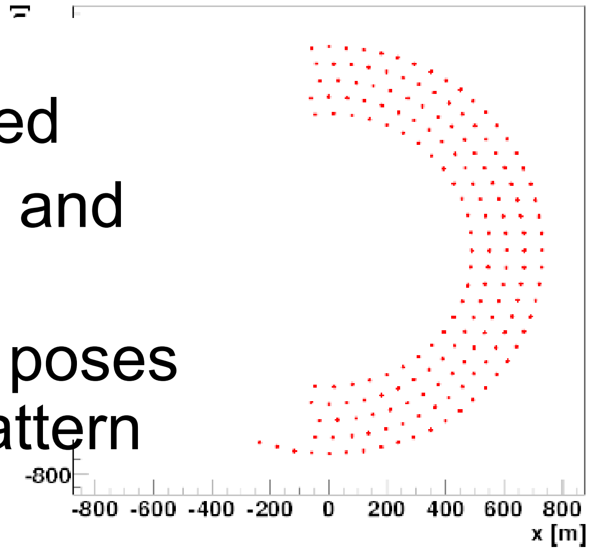
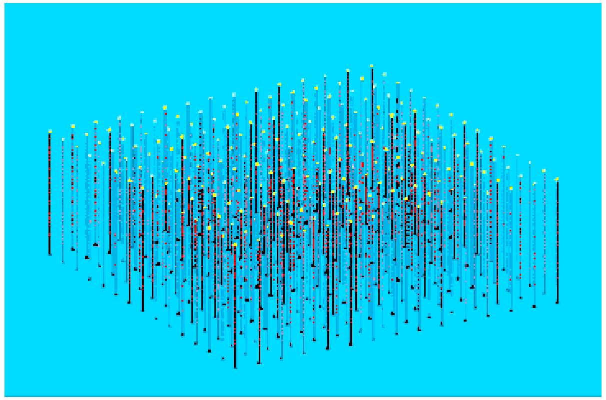
Configuration Studies

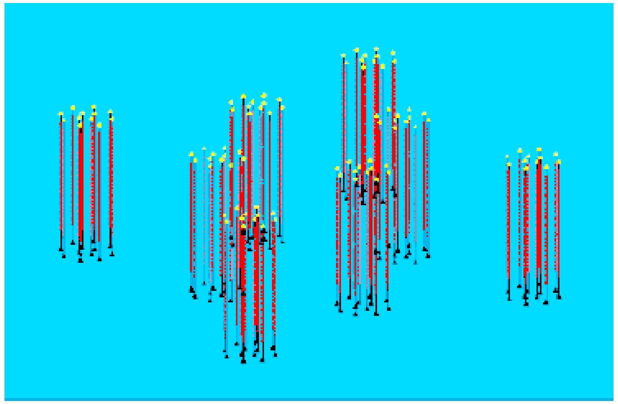
- Various geometries and OM configurations have been studied
- None is optimal for all energies and directions
- Local coincidence requirement poses important constraints on OM pattern

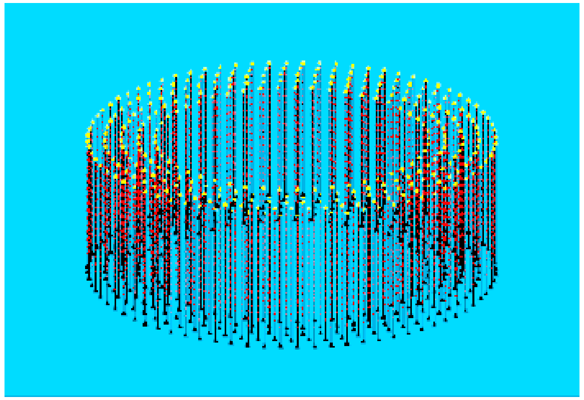






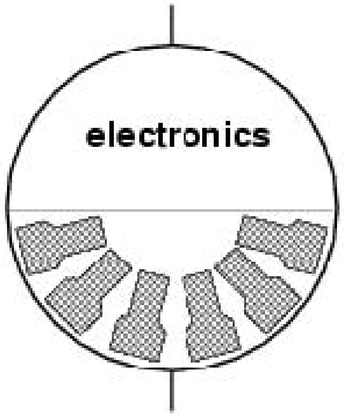


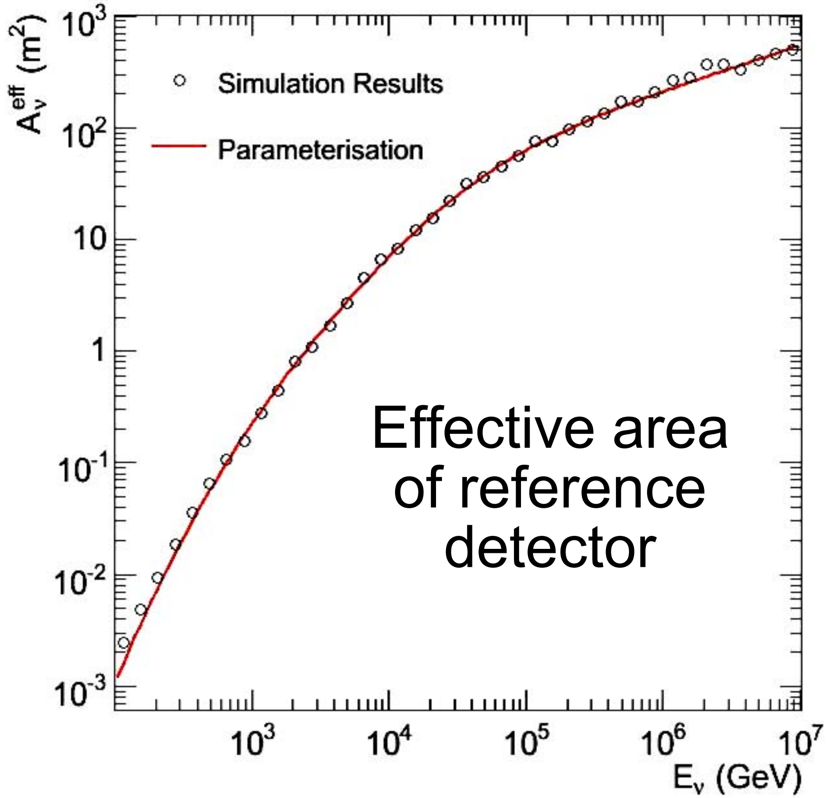




The Reference Detector

- Sensitivity studies with a common detector layout
- Geometry:
  - 15 x 15 vertical detection units on rectangular grid, horizontal distances 95 m
  - each carries 37 OMs, vertical distances 15.5 m
  - each OM with 21 3'' PMTs



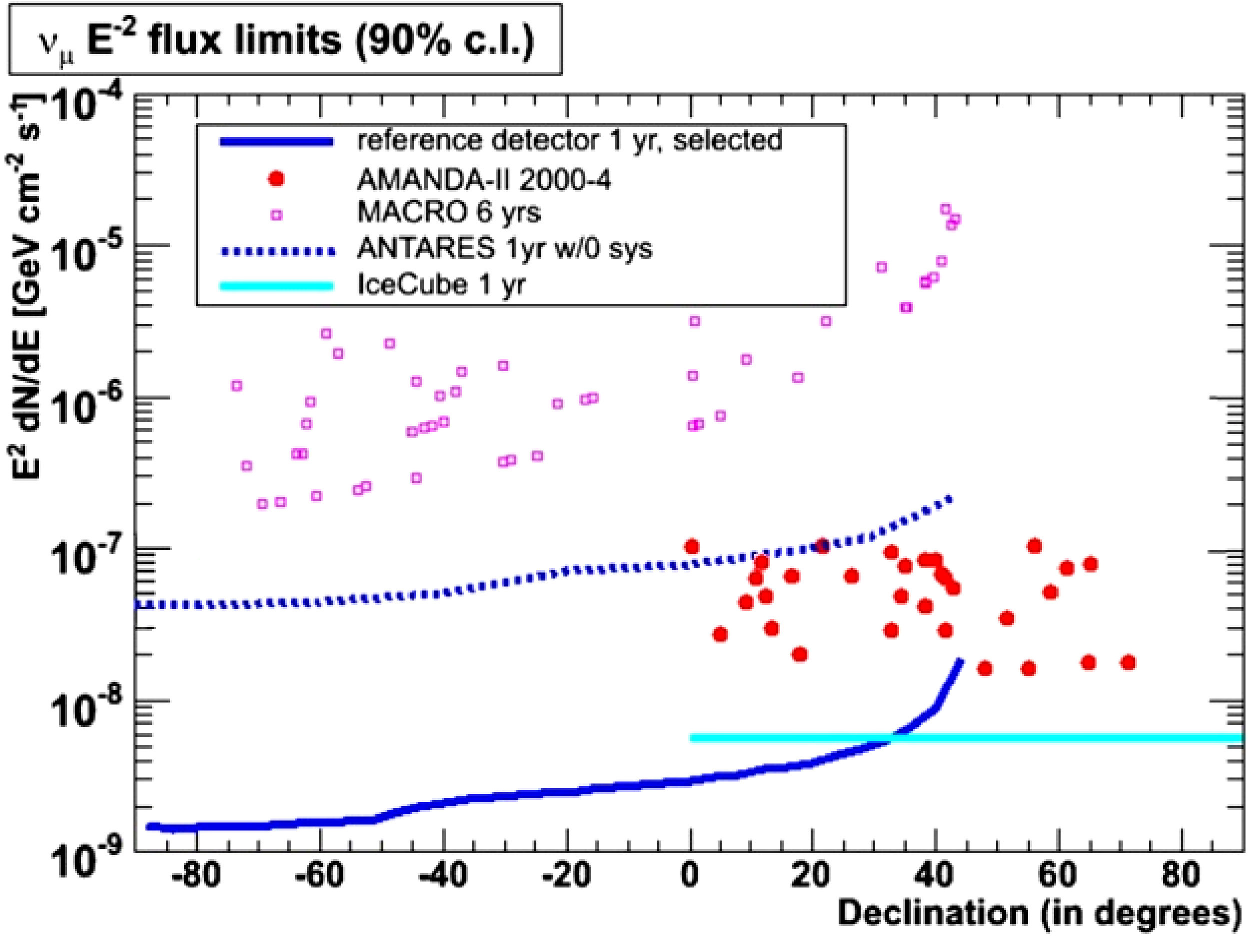


Effective area of reference detector

This is NOT the final KM3NeT design!

Point Source Sensitivity

- Based on muon detection
- Why factor ~3 more sensitive than IceCube?
  - larger photo-cathode area
  - better direction resolution
- Study still needs refinements



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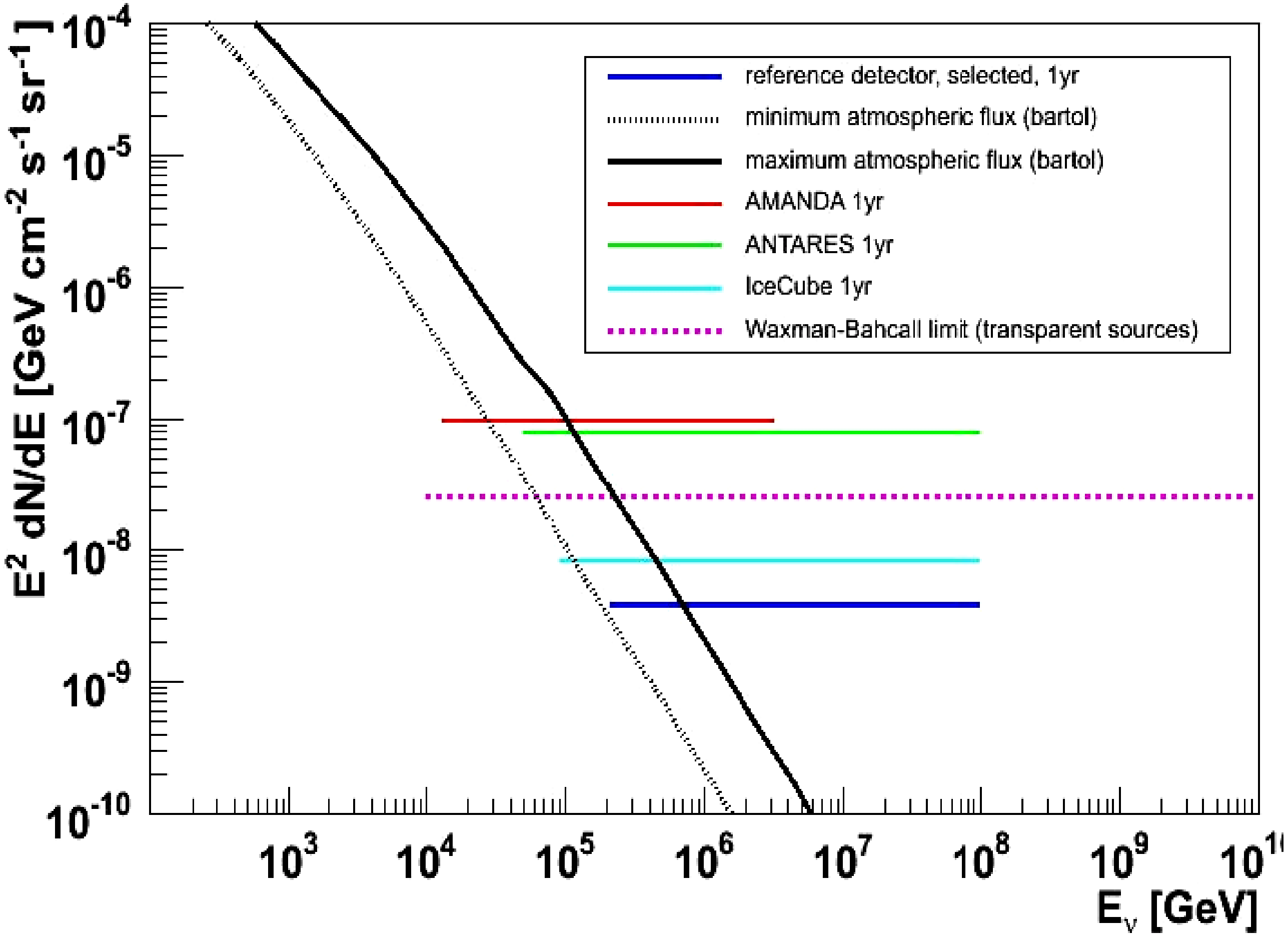
Diffuse Fluxes

- Assuming E^{-2} neutrino energy spectrum
- Only muons studied
- Energy reconstruction not yet included



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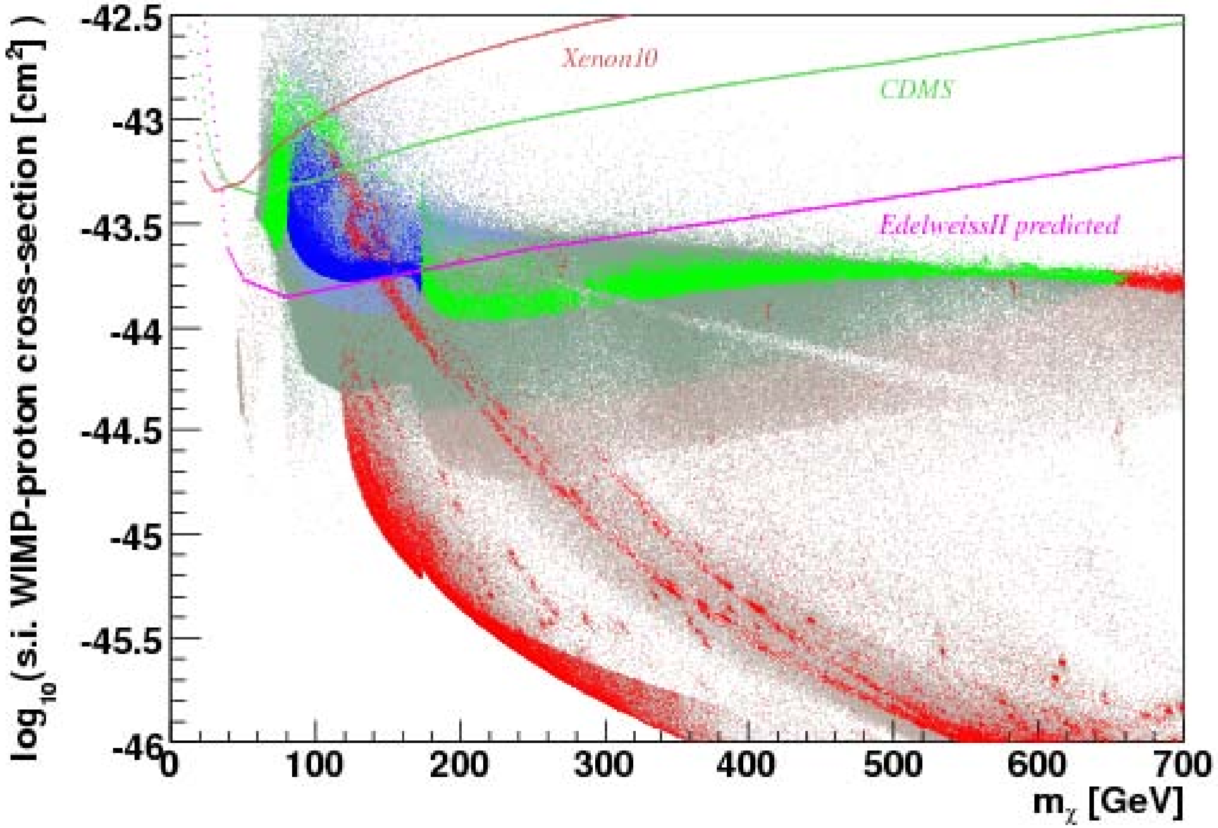
Dark Matter Sensitivity

- Scan mSUGRA parameter space and calculate neutrino flux for each point
- Focus on points compatible with WMAP data
- Detectability:
  - Blue: ANTARES
  - Green: KM3NeT
  - Red: None of them



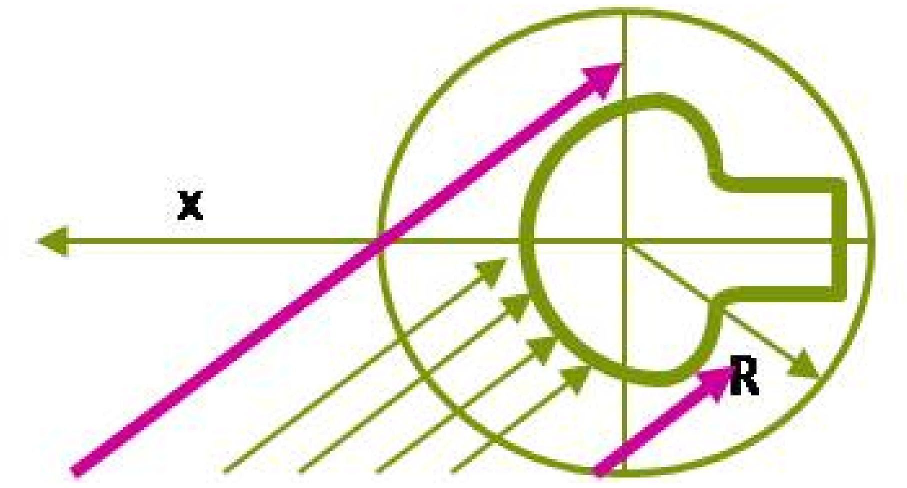
KM3NeT Design Goals

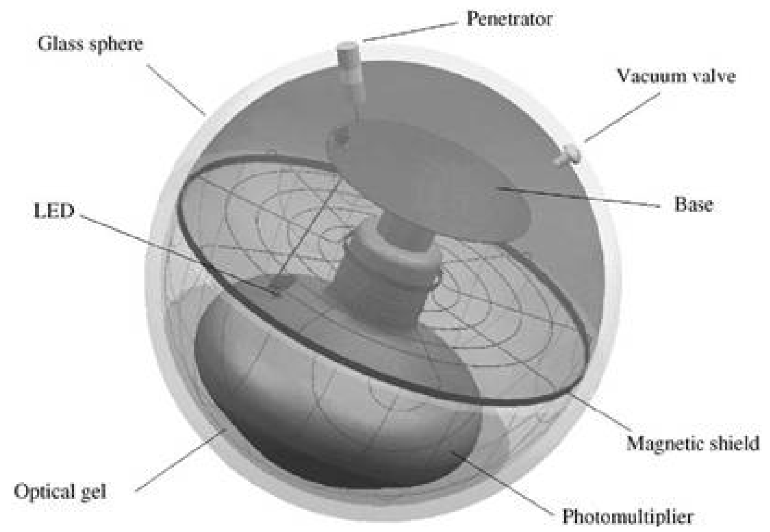
- Sensitivity to exceed IceCube by “substantial factor”
- Core process:
  $\nu_\mu + N \rightarrow \mu + X$ at neutrino energies beyond 100 GeV
- Lifetime > 10 years without major maintenance, construction and deployment < 4 years
- Some technical specifications:
  - time resolution 2 ns
  - position of OMs to better than 40 cm accuracy
  - two-hit separation < 25 ns
  - false coincidences dominated by marine background
  - coincidence acceptance > 50%
  - PM dark rate < 20% of ^{40}K rate

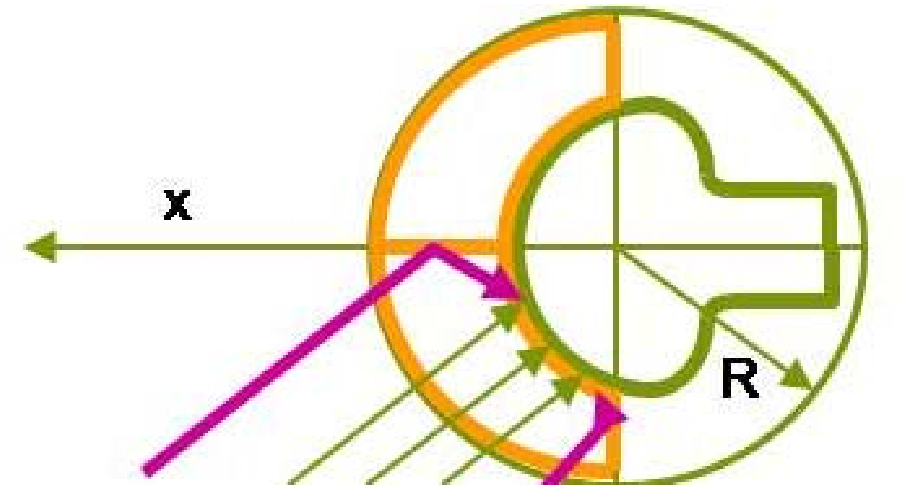
Technical implementation

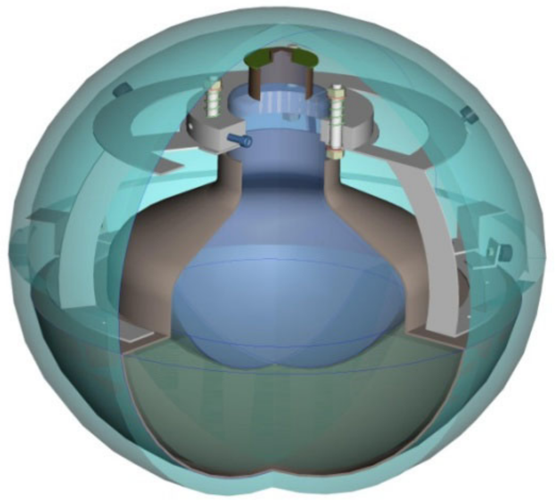
- Photo-sensors and optical modules
- Data acquisition, information technology and electronics
- Mechanical structures
- Deep-sea infrastructure
- Deployment
- Calibration
- Associated science infrastructure

Optical Modules: Standard or Directional









… or Many Small Photomultipliers …

- Basic idea: Use ca. 30 small (3'' or 3.5'') PMTs in standard sphere
- Advantages:
  - increased photocathode area
  - improved 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality
- Prototype arrangements under study

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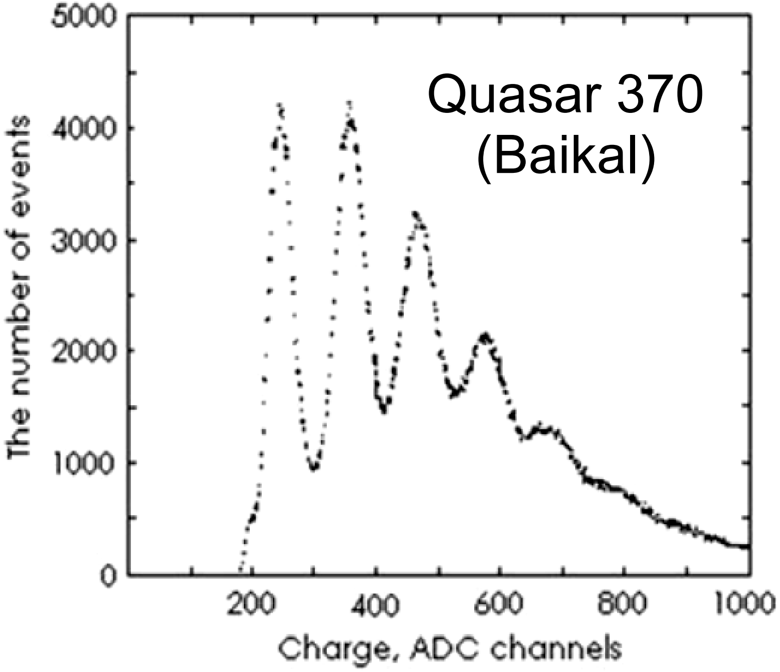
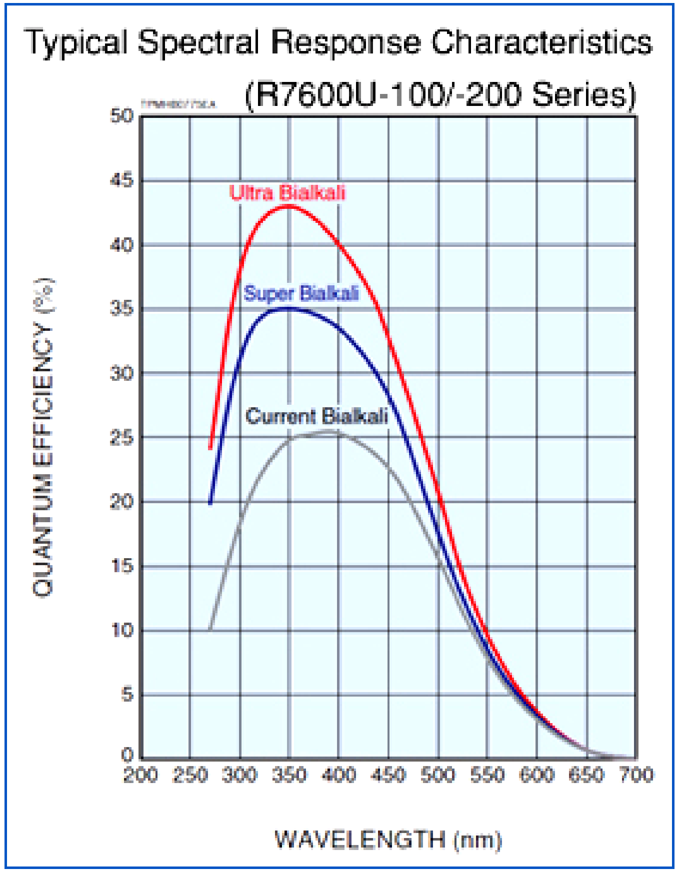
… or Hybrid Solutions

- Idea: Use high voltage (~20kV) and send photo electrons on scintillator; detect scintillator light with small standard PMT.
- Advantages:
  - Very good photo-electron counting, high quantum eff.
  - large angular sensitivity possible
- Prototype development in CERN/Photonis/CPPM collaboration

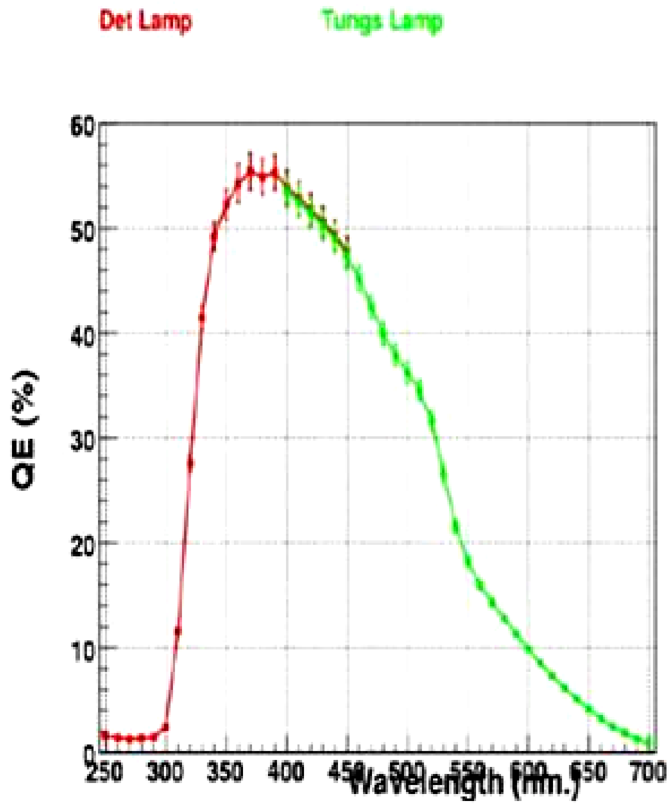


Photocathode News

Hamamatsu



- New photocathode developments by two companies (Hamamatsu, Photonis)
- Factor 2 in quantum efficiency → factor 2 in effective photocathode area!
- Major gain in neutrino telescope sensitivity expected



Photonis

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Data Acquisition and Information Technology

Optical Module:

- Conversion of PM signal for transmission
- “Standard” electronic components or passive electro-optical solutions
- Local thresholds/requirements

Vertical signal transmission:

- Fibres or copper?
- Critical: time calibration and synchronisation, reliability

On shore:

- Computer farm for online data filter
- High-bandwidth connection to mass storage and data analysis facilities

Transmission to shore:

- All data to shore (GB/s)
- No alternative to fibres

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Deep-Sea Infrastructure

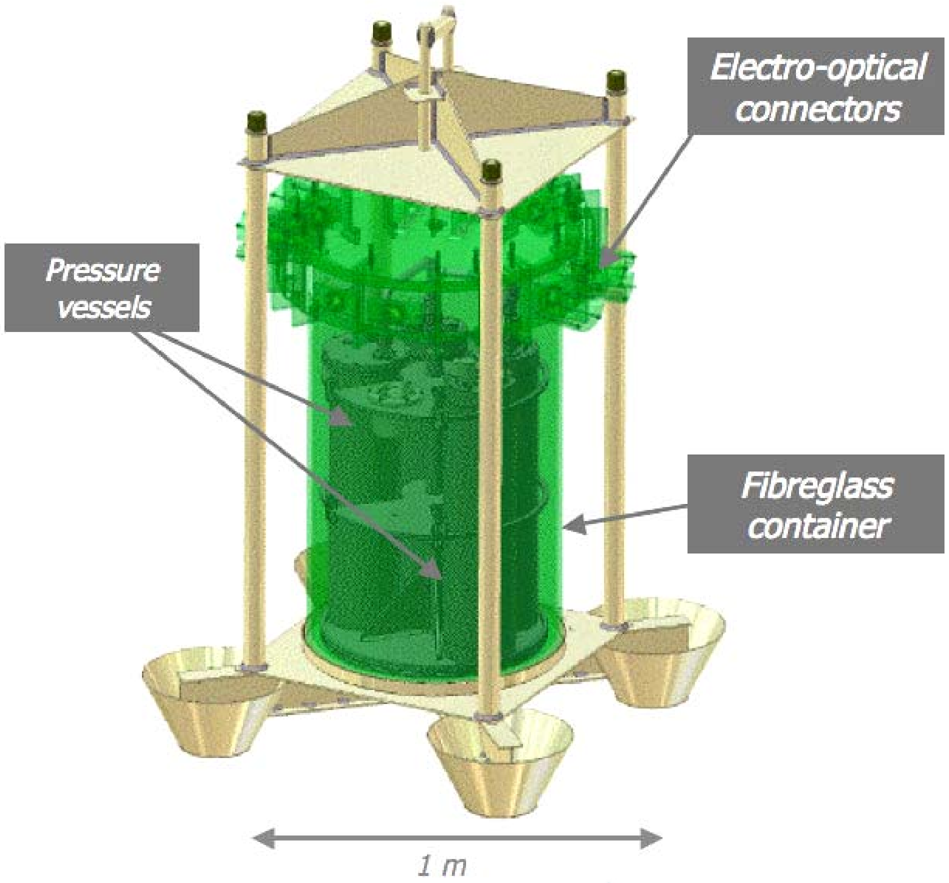
Major components:

- main cable & power transmission
- network of secondary cables with junction boxes
- connectors

Design considerations:

- cable selection likely to be driven by commercial availability
- junction boxes: may be custom-designed, work ongoing in NEMO
- connectors: expensive, reduce number and/or complexity
- risk considerations (single-point failures etc.)

NEMO junction box design:



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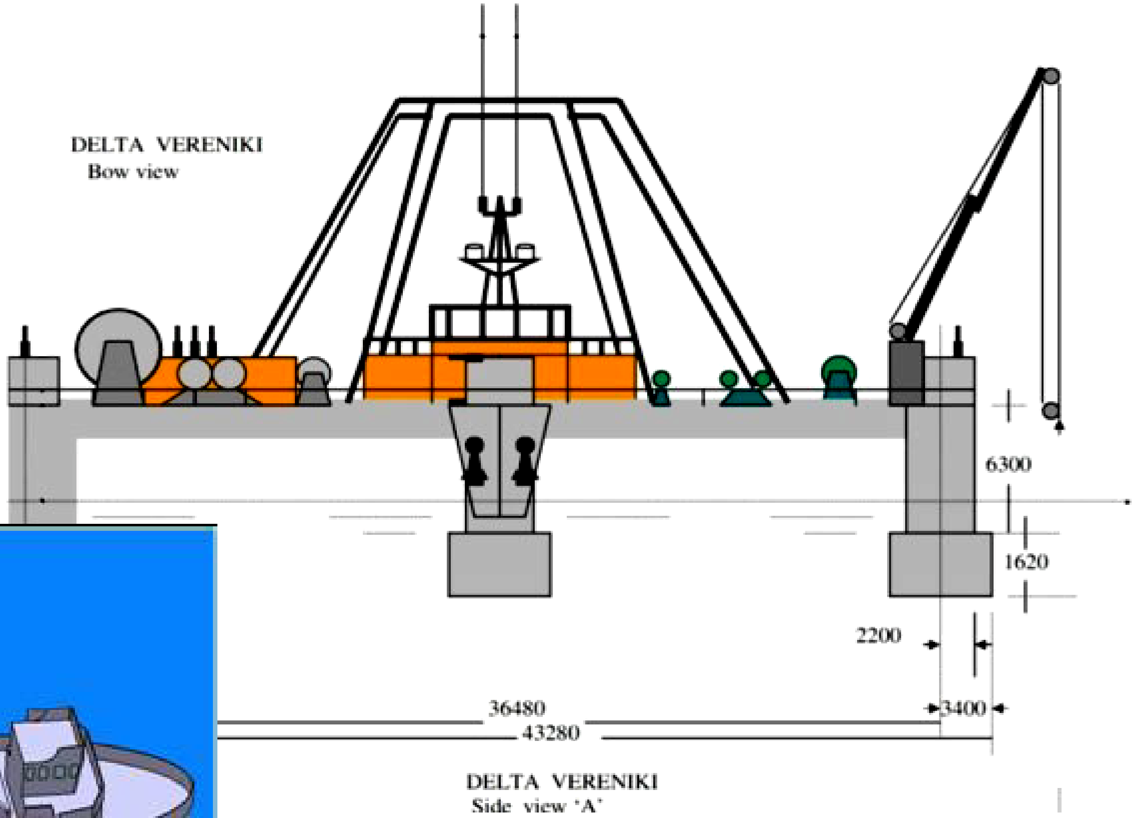
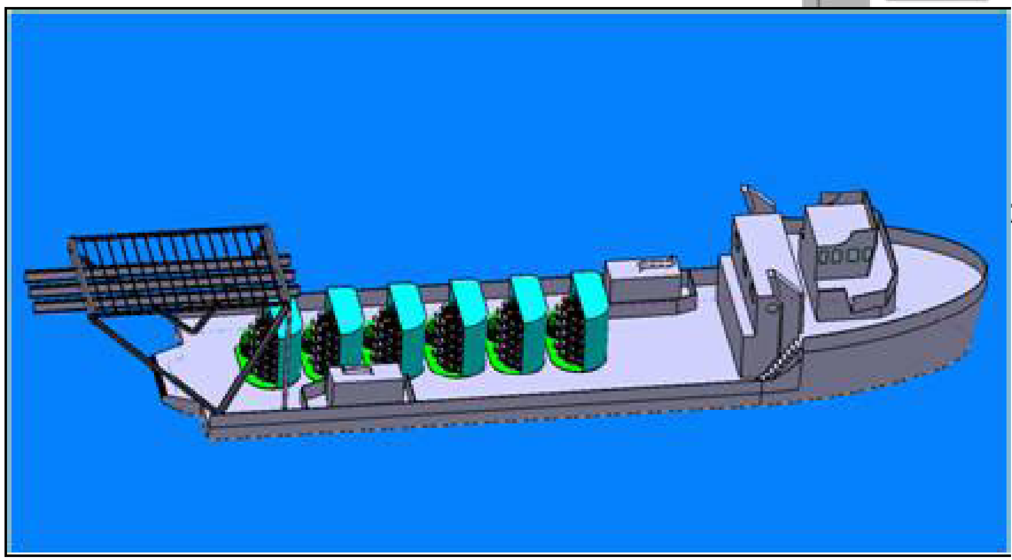
Deployment: on the Surface …

- Deployment operations require ships or dedicated platforms.
- Ships: Buy, charter or use ships of opportunity.
- Platform: Delta-Berenike.





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… and in the Deep Sea

- Deep-sea submersibles are likely needed for
  - laying out the deep-sea cable network
  - making connections to detection units
  - possibly maintenance and surveillance
- Remotely operated vehicles (ROVs) available for a wide range of activities at various depths
- Use of autonomous undersea vehicles (AUVs) under study

Commercially available ROVs:

	Number of Models	Maximum Depth (m)	Maximum Load (kg)
Micro	7	300	5
Mini	20	1500	20
	1	6000	
General	1	4000	500
	41	2000	
	2	5000	
Work Class	1	4000	4500
	1	3500	
	11	3000	
	1	3500	
Trenching ROV	2	3000	38000
	8	2500	

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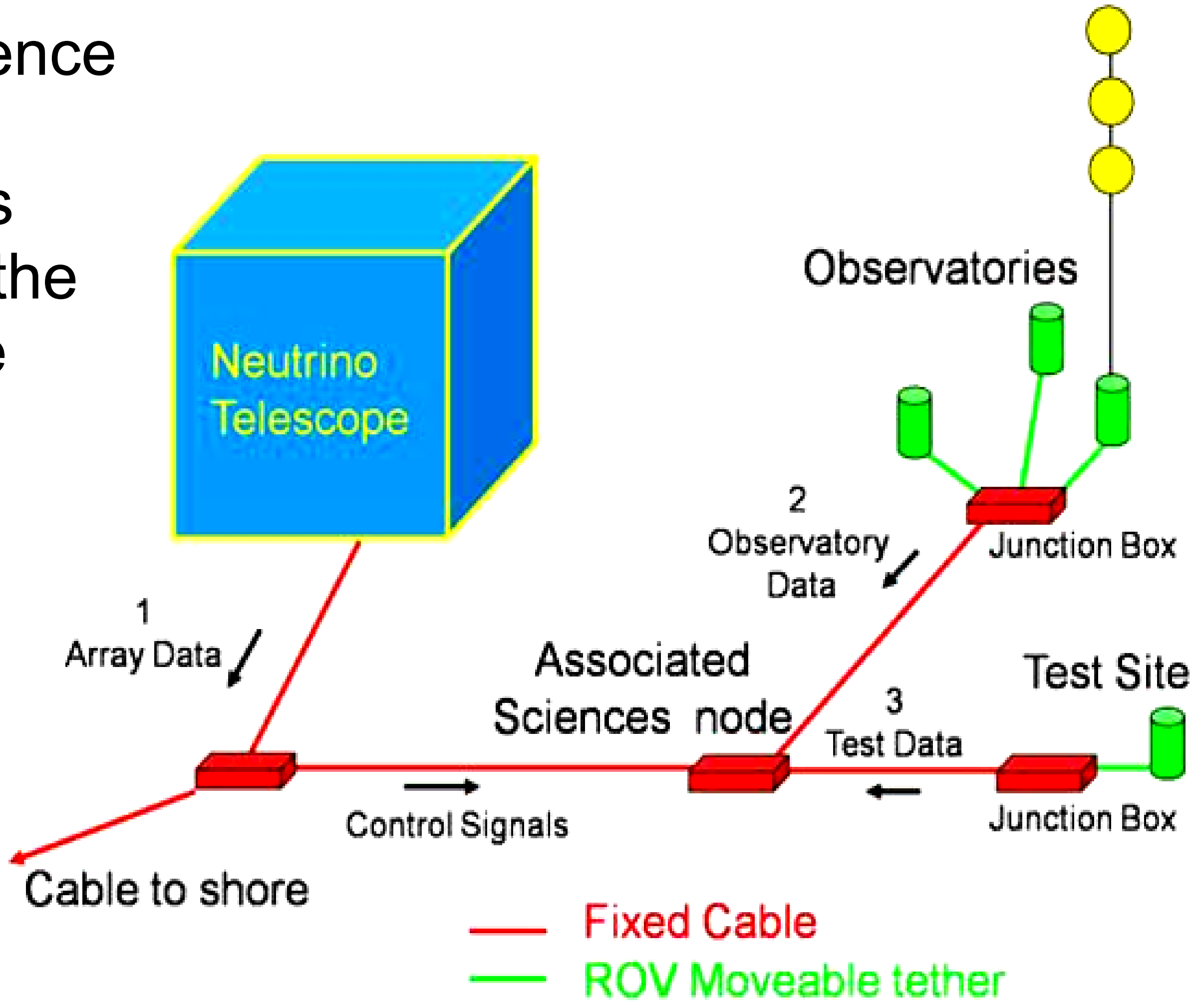
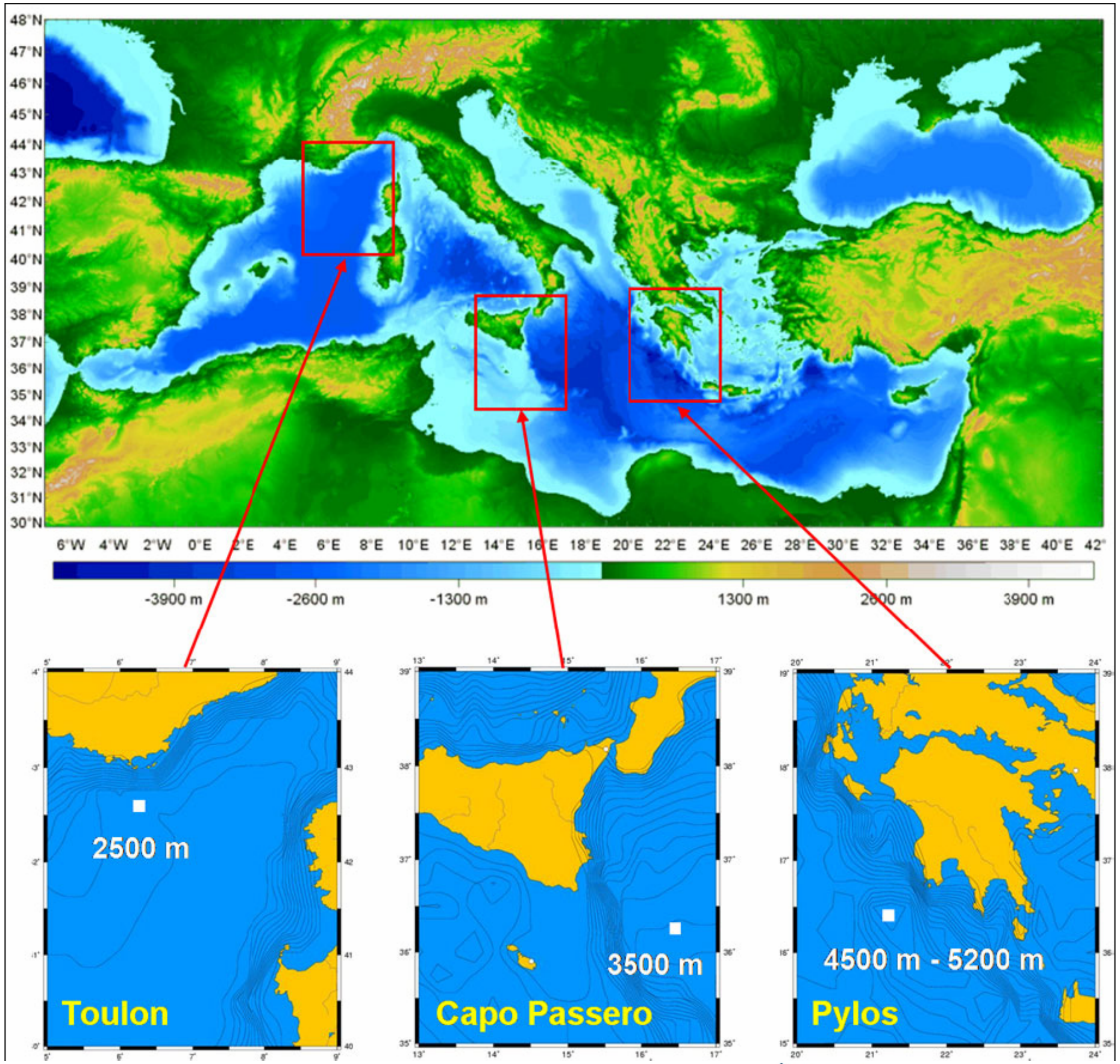
Installations for Earth and Sea Sciences

- Earth and sea science devices will be installed at various distances around the neutrino telescope
- Issues:
  - interfaces
  - operation without mutual interference
  - stability of operation and data sharing
- Synergy effects



The Candidate Sites

- Locations of the three pilot projects:
  - ANTARES: Toulon
  - NEMO: Capo Passero
  - NESTOR: Pylos
- Long-term site characterisation measurements performed and ongoing
- Site decision requires scientific, technological and political input



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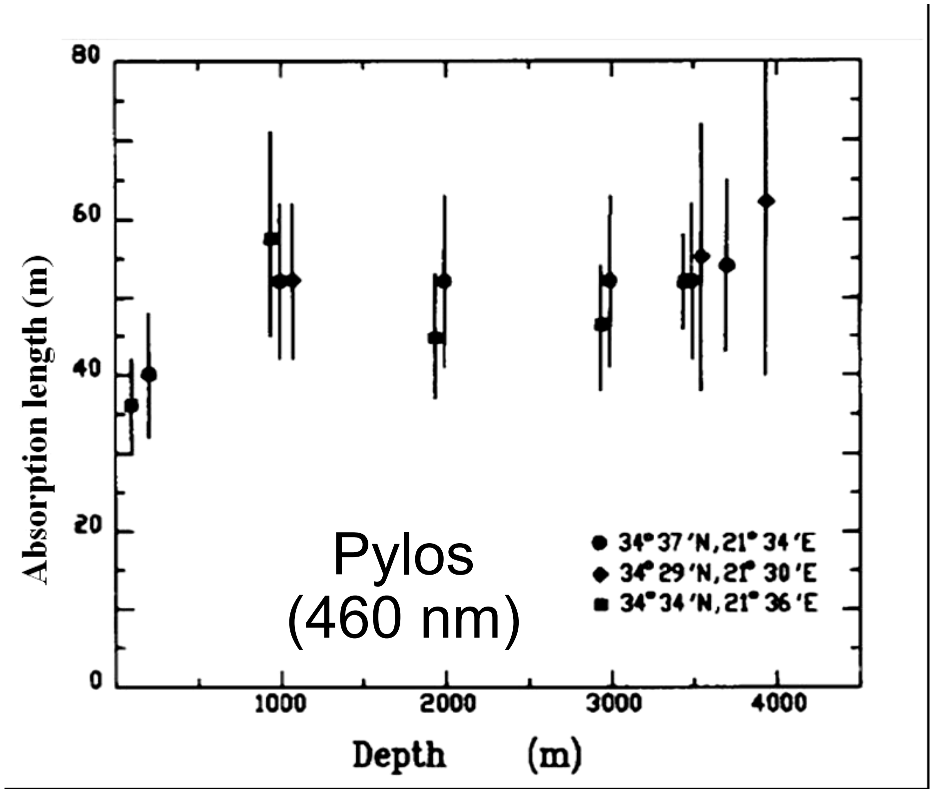
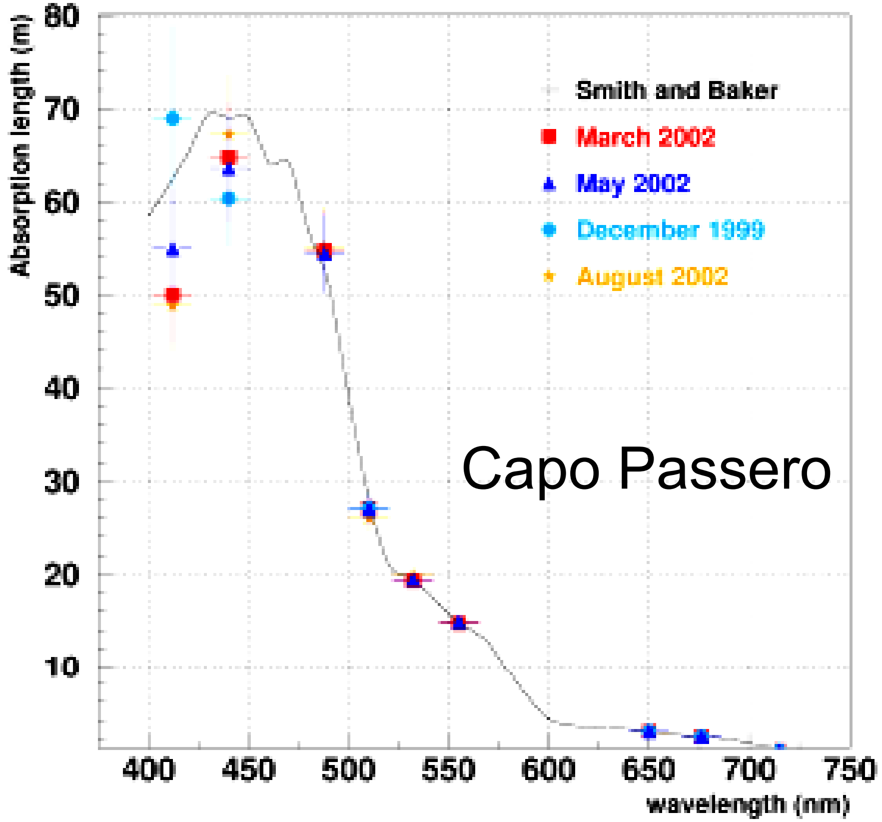
Site Characterisation: an Example

Important parameter:
water transparency
(absorption and scattering)





Also: optical background,
sea currents, sedimentation,
biofouling, radioactivity, …

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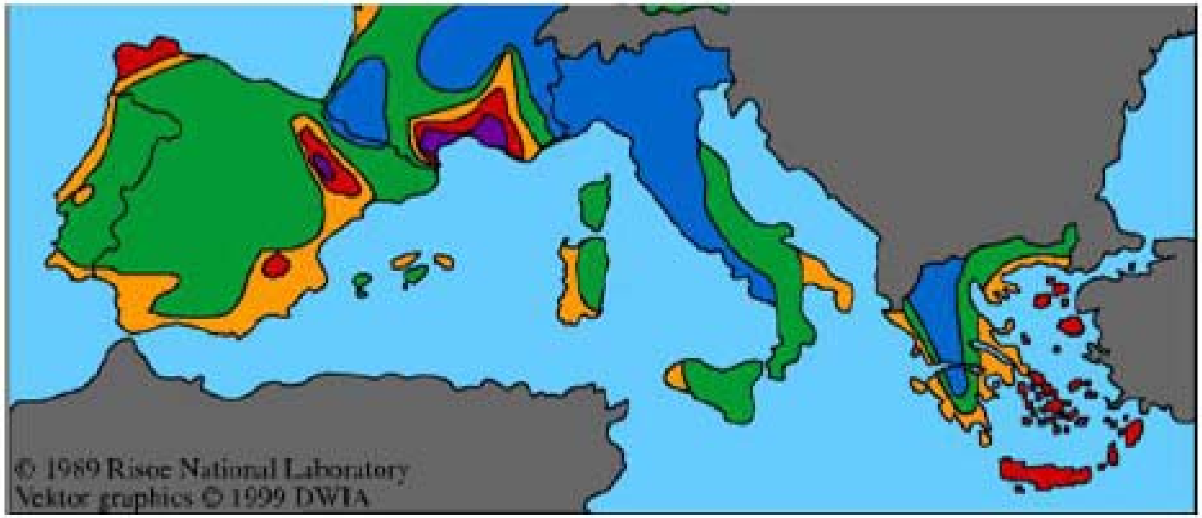
A Green Power Concept for KM3NeT

- Idea: Use wind and/or solar power at KM3NeT shore installations to produce the required electrical power.
- Requires investment of 4-5 M€.
- Can only work if coupled to a larger (public) power network.



	Open sea		Hills and ridges	
	m/s	W/m²	m/s	W/m²
(purple)	>9.0	>800	>11.5	>1800
(red)	8.0-9.0	700	10.0-11.5	1500
(yellow)	7.0-8.0	500	8.5-10.0	1000
(green)	5.5-7.0	300	7.0-8.5	500
(blue)	<5.5	<200	<7.0	<400

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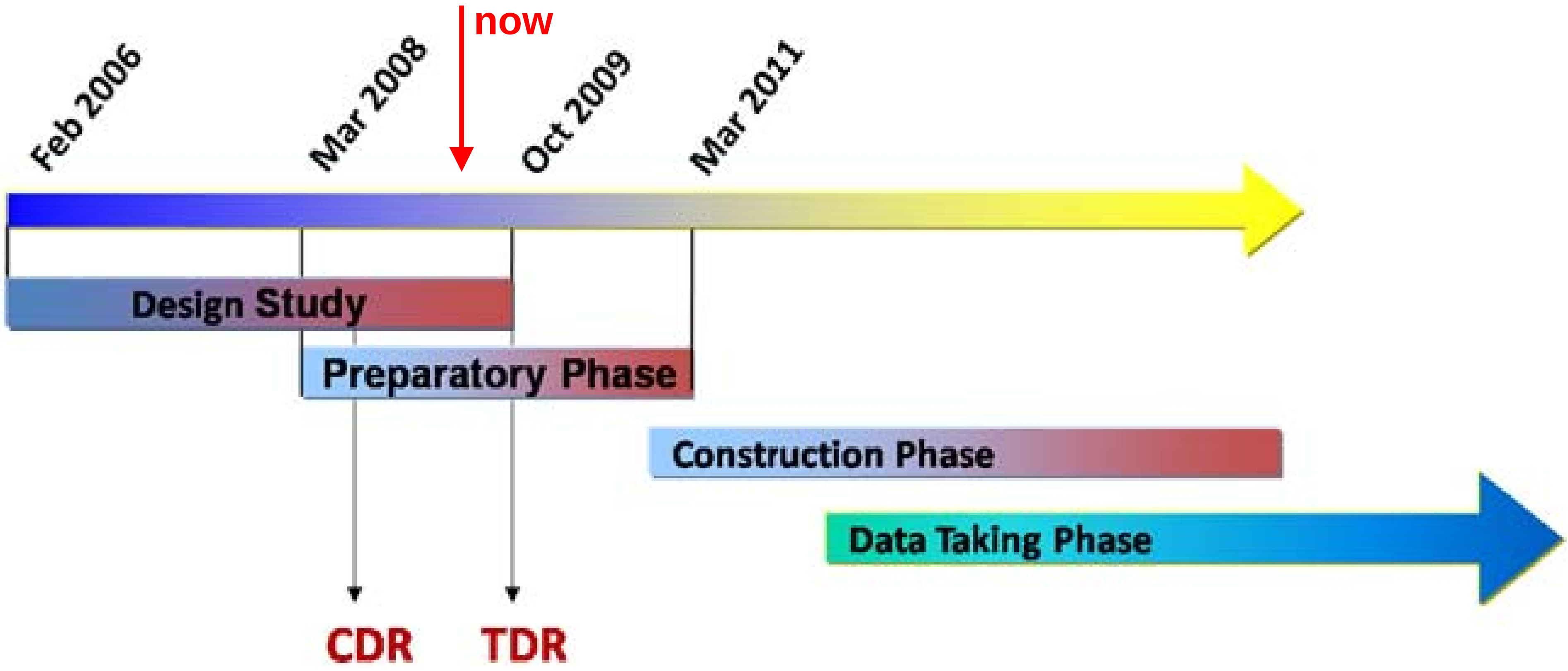
The KM3NeT Preparatory Phase

- “Preparatory Phase”: A new EU/FP7 funding instrument restricted to ESFRI projects.
- KM3NeT proposal funded with 5 M€
- 3-year project, 3/2008 – 2/2011
- Major objectives:
  - Initiate political process towards convergence (includes funding and site selection/decision)
  - Set up legal structure and governance
  - Strategic issues: New partners, distributed sites, extendibility
  - Prepare operation organisation & user communities
  - Organise pre-procurement with commercial partners
  - Next-step prototyping

Timeline Towards Construction



Note: “Construction” includes the final prototyping stage

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Summary

- Neutrinos would (and will) provide very valuable astrophysical information, complementary to photons and charged cosmic rays.
- Exploiting the potential of neutrino astronomy requires cubic-kilometre scale neutrino telescopes providing full sky coverage.
- The KM3NeT detector in the Mediterranean Sea will complement IceCube in its field of view and exceed its sensitivity by a substantial factor.
- We are working towards a start of construction by 2011.