Vulcano Workshop 2012
Frontier Objects in Astrophysics and Particle Physics
28 May – 2 June 2012

Neutrinos as Cosmic Messengers in the Era of IceCube, ANTARES and KM3NeT

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The plan for the next 20 minutes:

- Introduction
- Current neutrino telescopes:
  ANTARES and IceCube
- Results so far
- The future of neutrino astronomy: KM3NeT
- Summary

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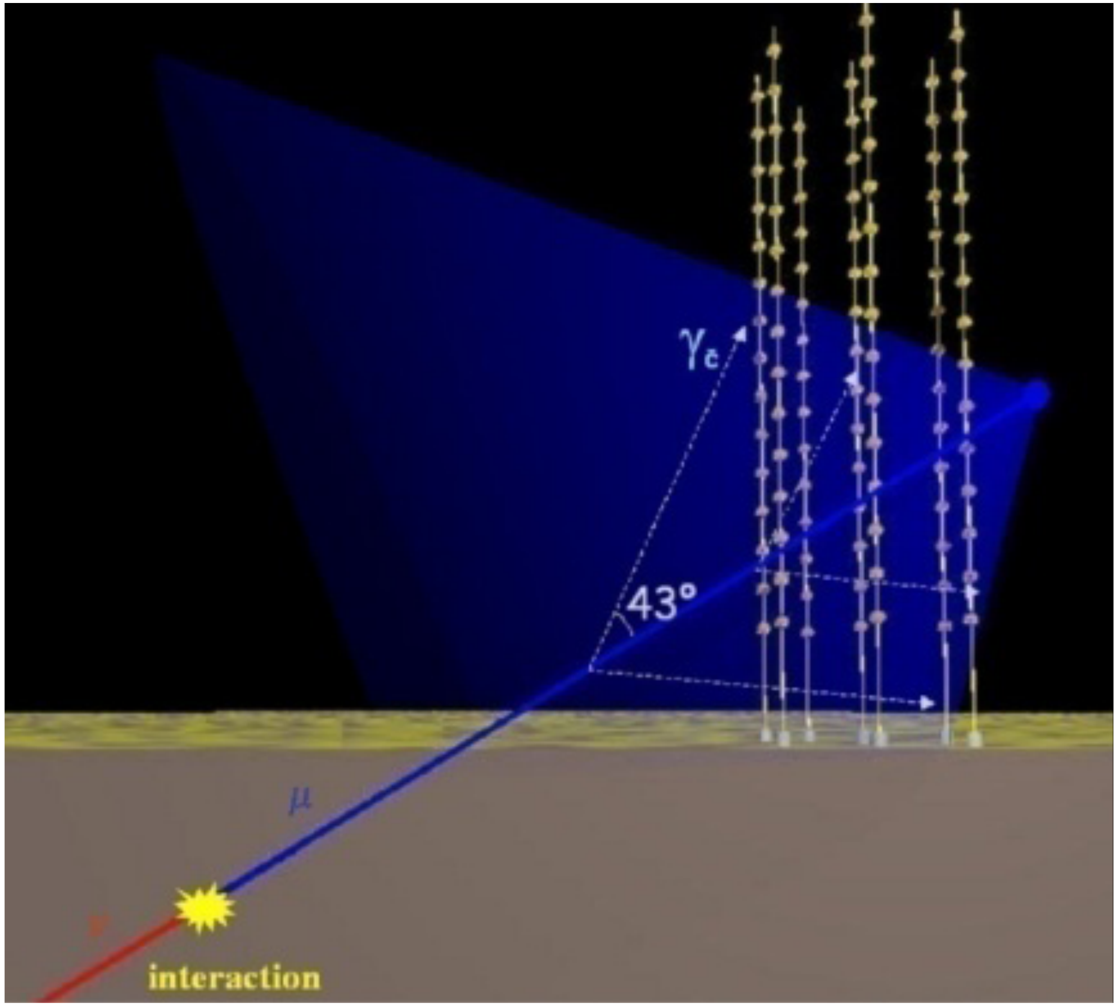
Introduction

How does a neutrino telescope work?

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



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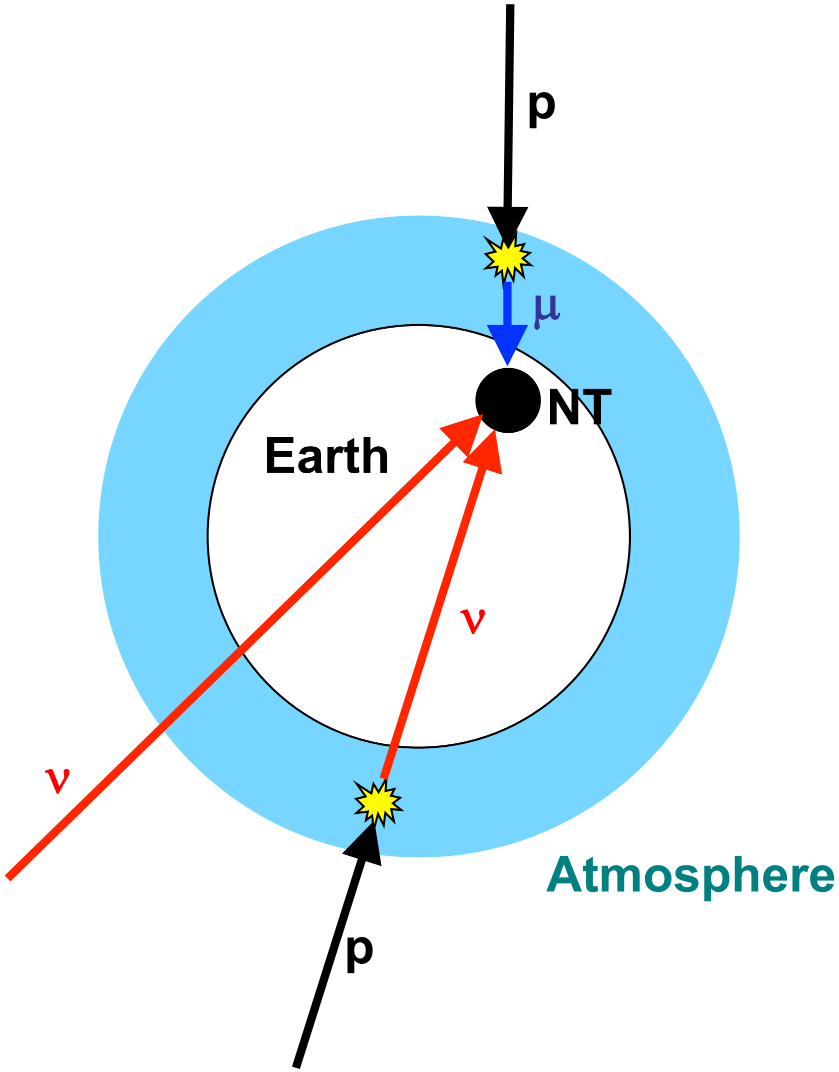
Backgrounds

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



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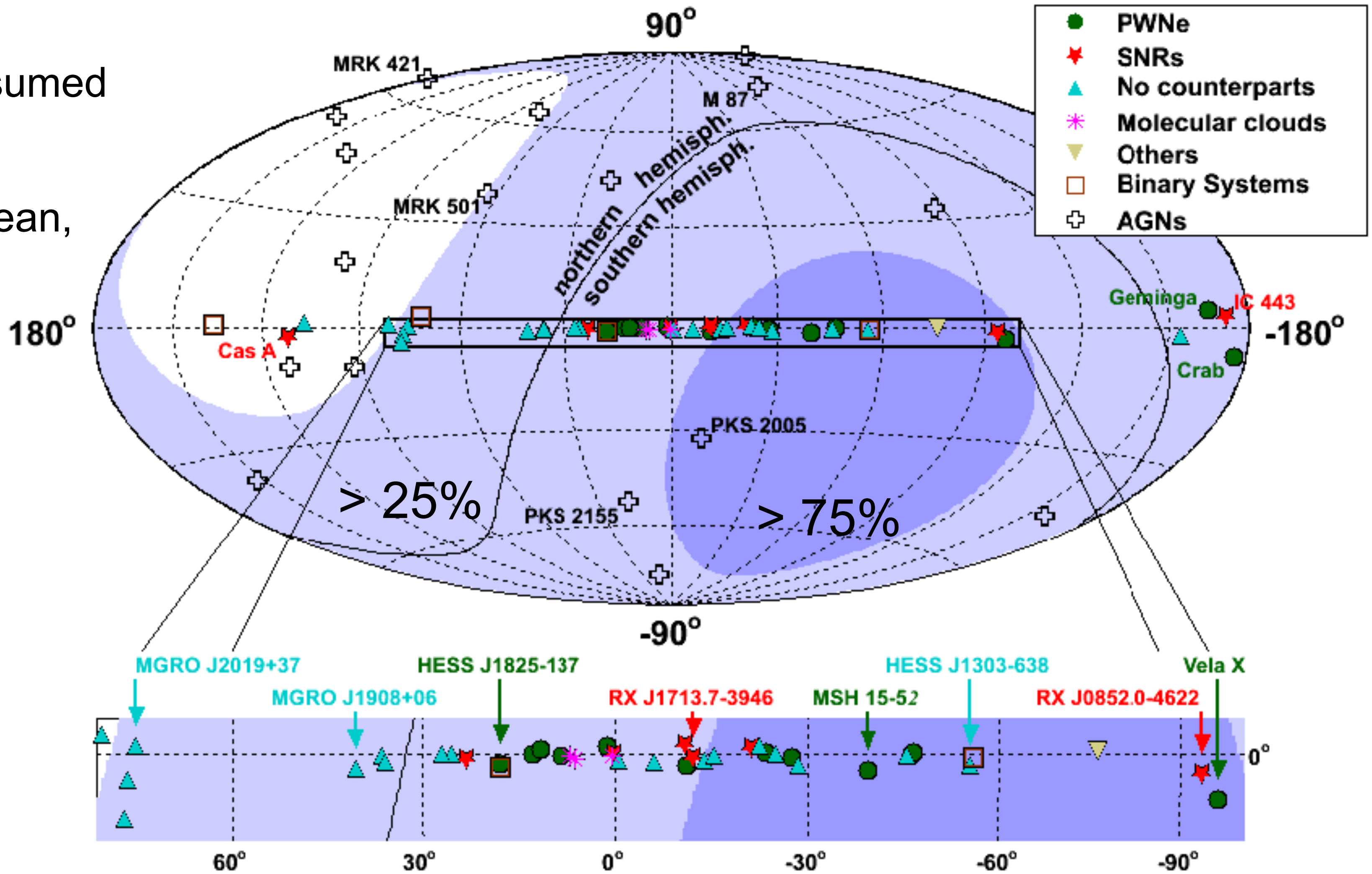
The neutrino telescope world map

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

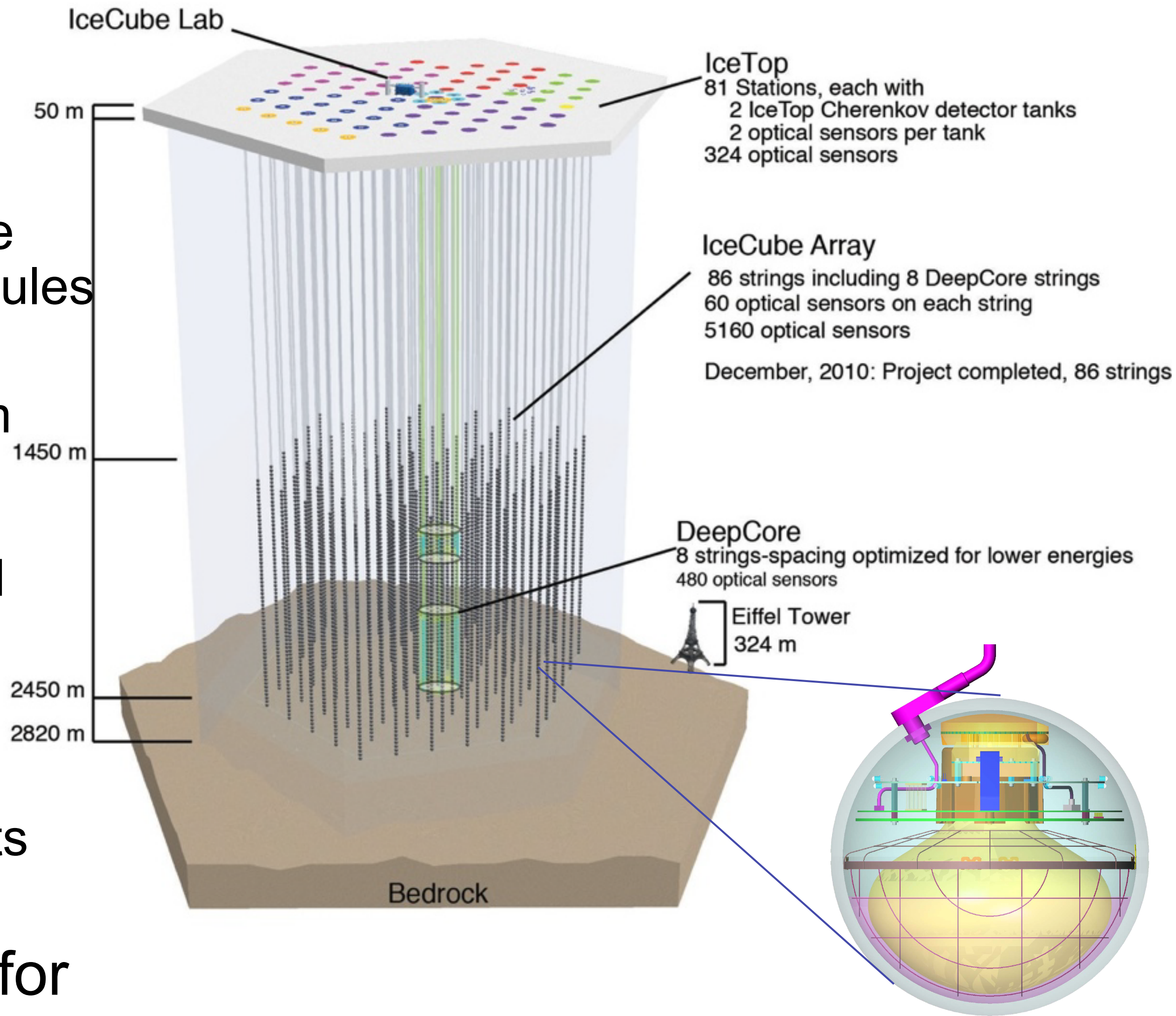


Current Neutrino Telescopes:
IceCube and ANTARES

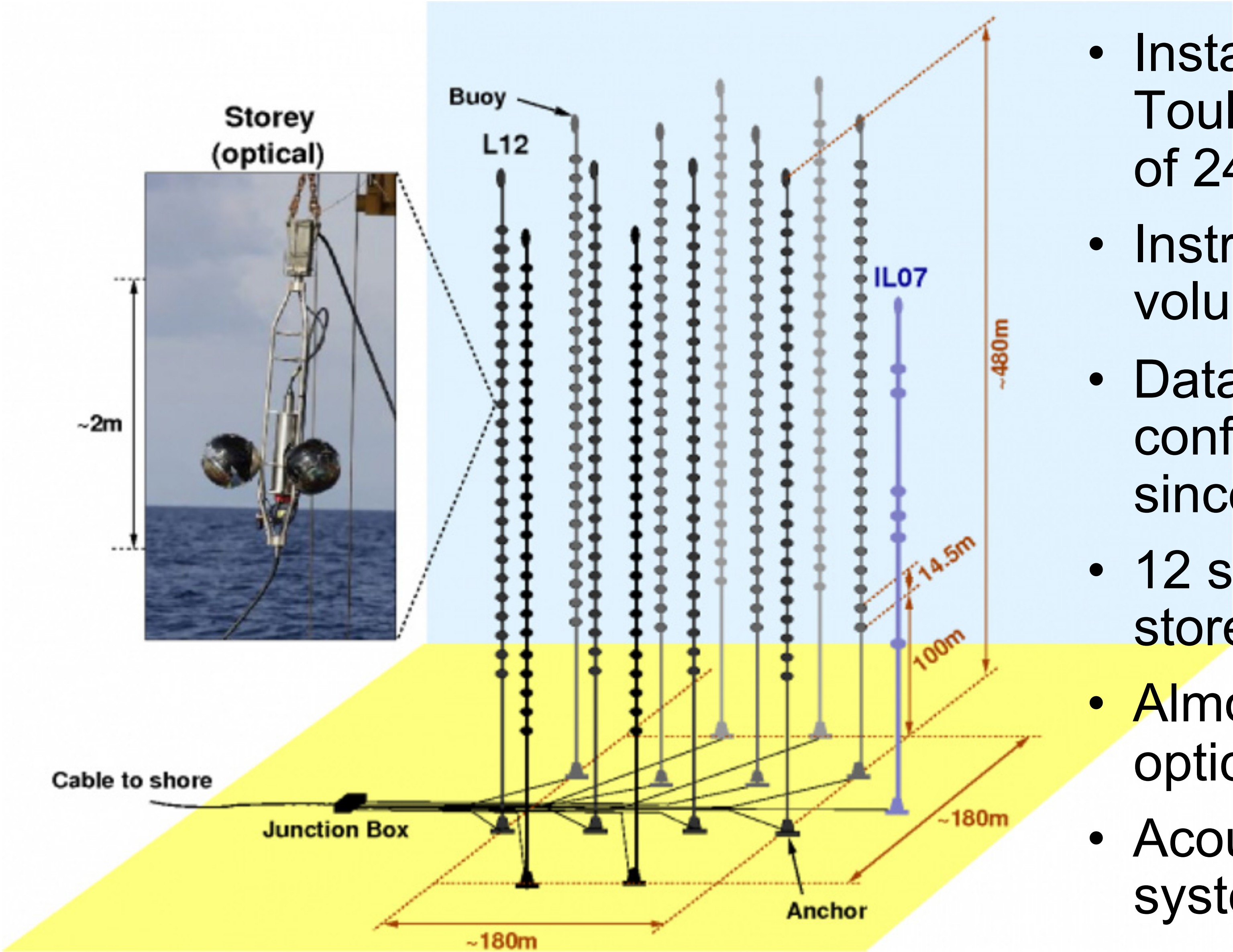
IceCube: a km^3 detector in the Antarctic ice

IceCube as of June 2012

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



ANTARES: The first NT in the deep sea



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

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ANTARES achievements

- Proof of feasibility and long-term operation of a deep-sea neutrino telescope
- Position and orientation calibration of optical modules with required accuracy
  - acoustic positioning by triangulation
  - compasses and tilt-meters
- Time synchronisation at nanosecond level
- Use of optical technologies for readout
- All data to shore: Every PMT hit above threshold (typically 0.3 pe) is digitised and transmitted to shore
- Trigger/filter logic by computer farm on-shore

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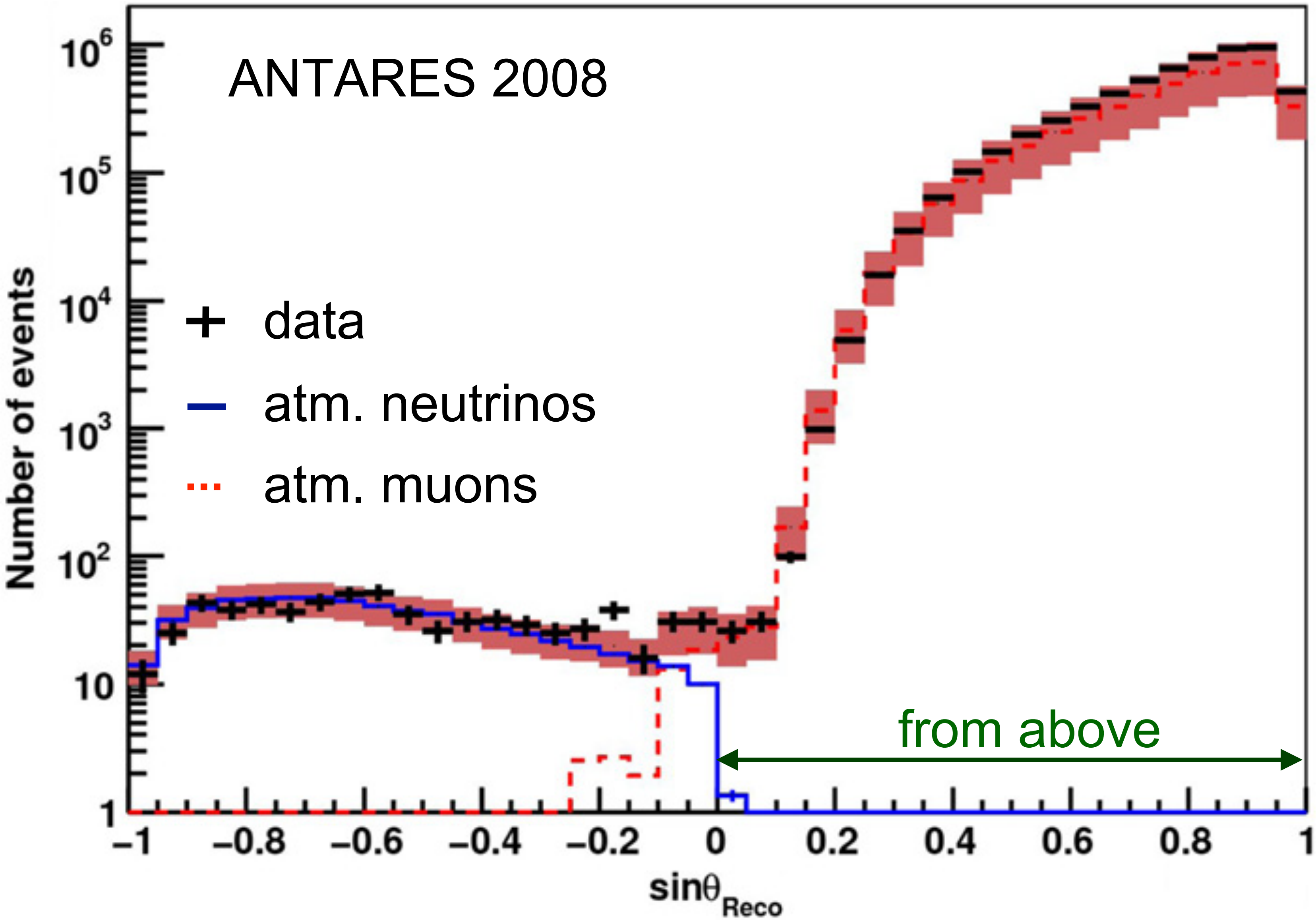
IceCube and ANTARES Results

Understanding detector and signals



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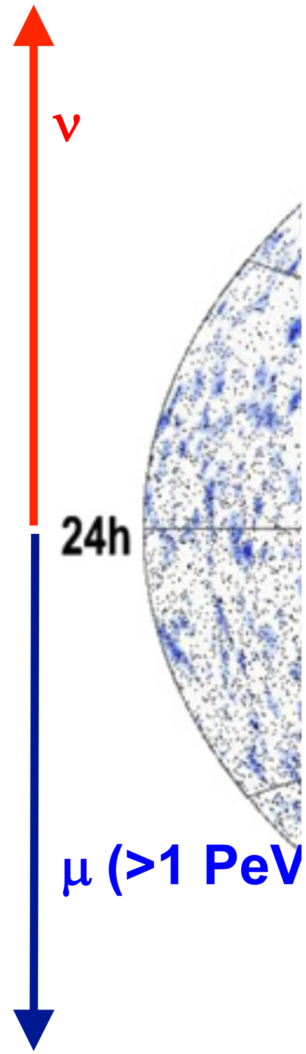
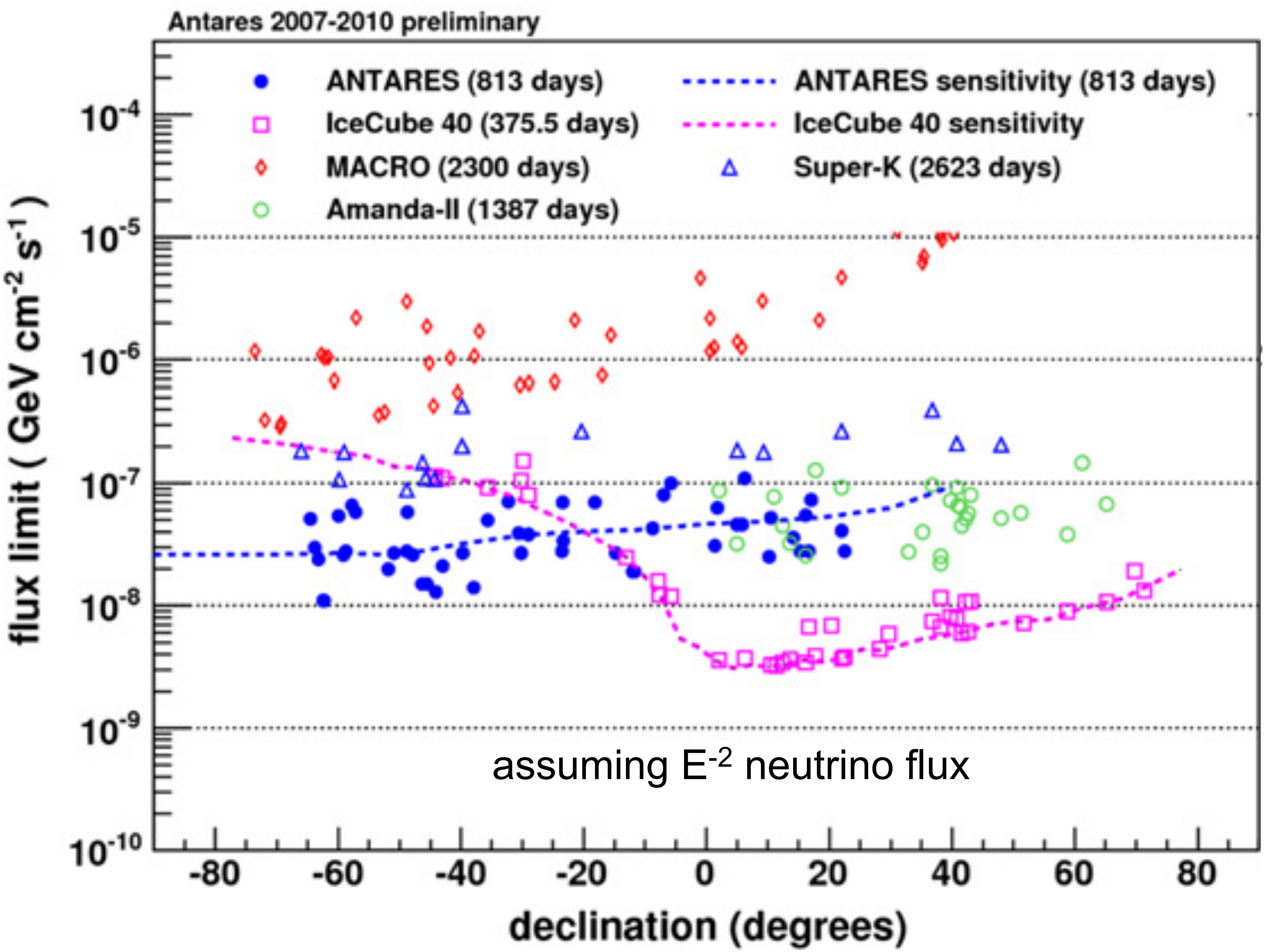
Search for steady point sources

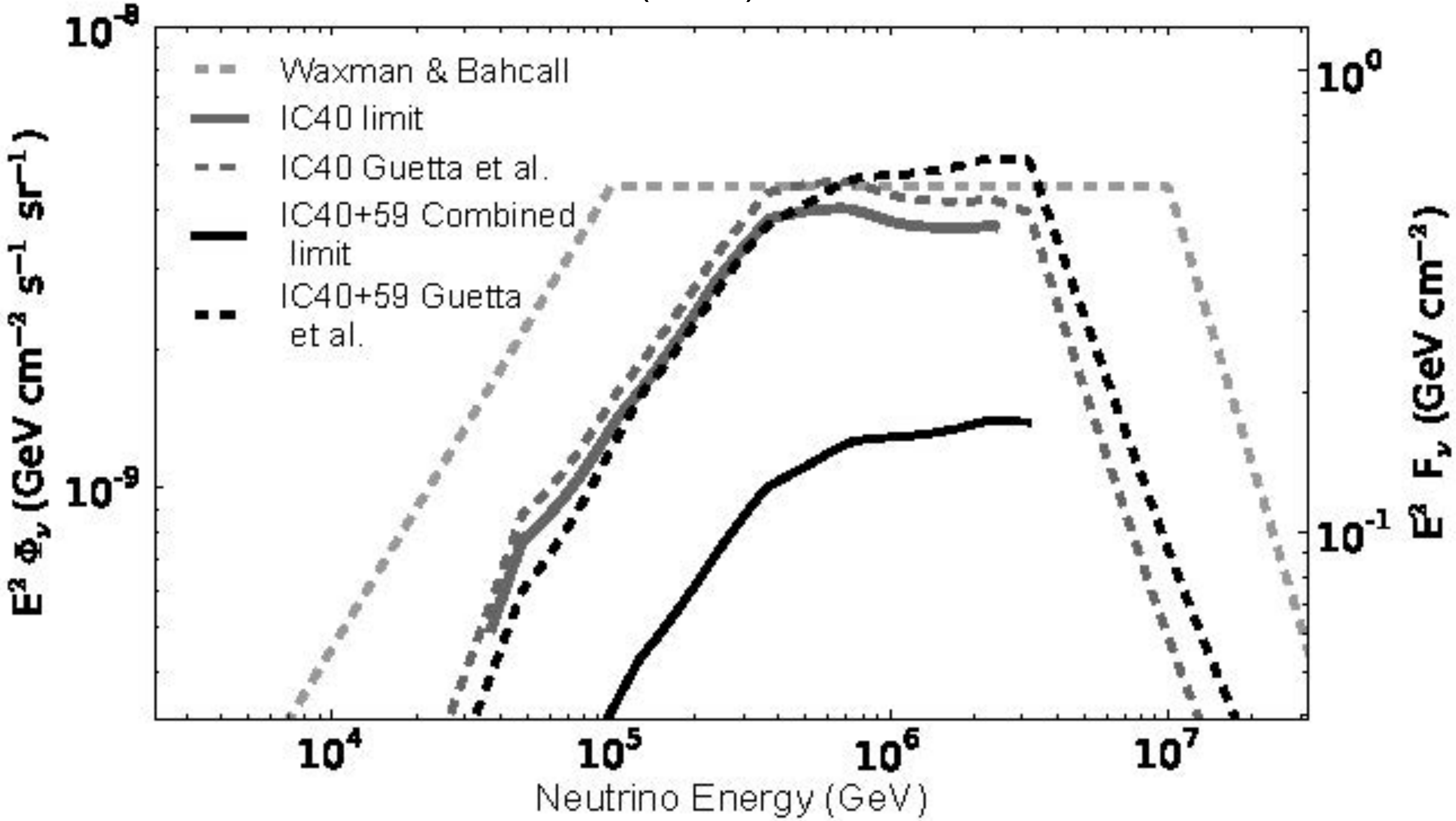




Transient point sources: GRBs

- New: IceCube analysis (40+59 strings)
- Result about factor 3 below model expectation
- Start to seriously cut into parameter space
- Beware: large model uncertainties (see Hümmer et al., arXiv:1112.1076)

Nature 484 (2012) 351-353; arXiv:1204.4219



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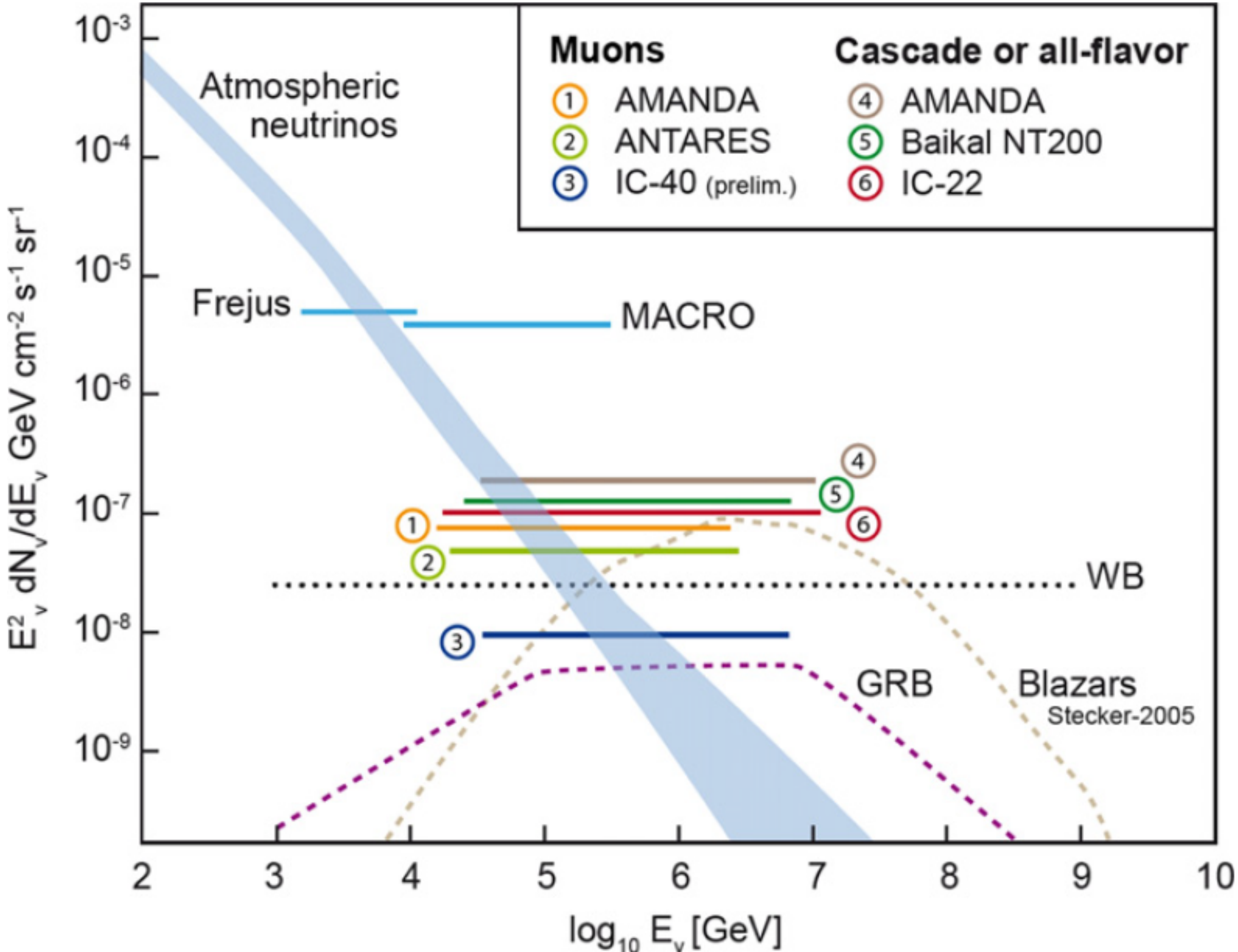
Diffuse fluxes

UK, C.Spiering, Prog. Nucl. Part. Phys. 67 (2012) 651

- Search for excess at high energies above atm. neutrino flux
- Assume E^{-2} energy spectrum
- No signal seen → limits
- Approaching regime of predictions



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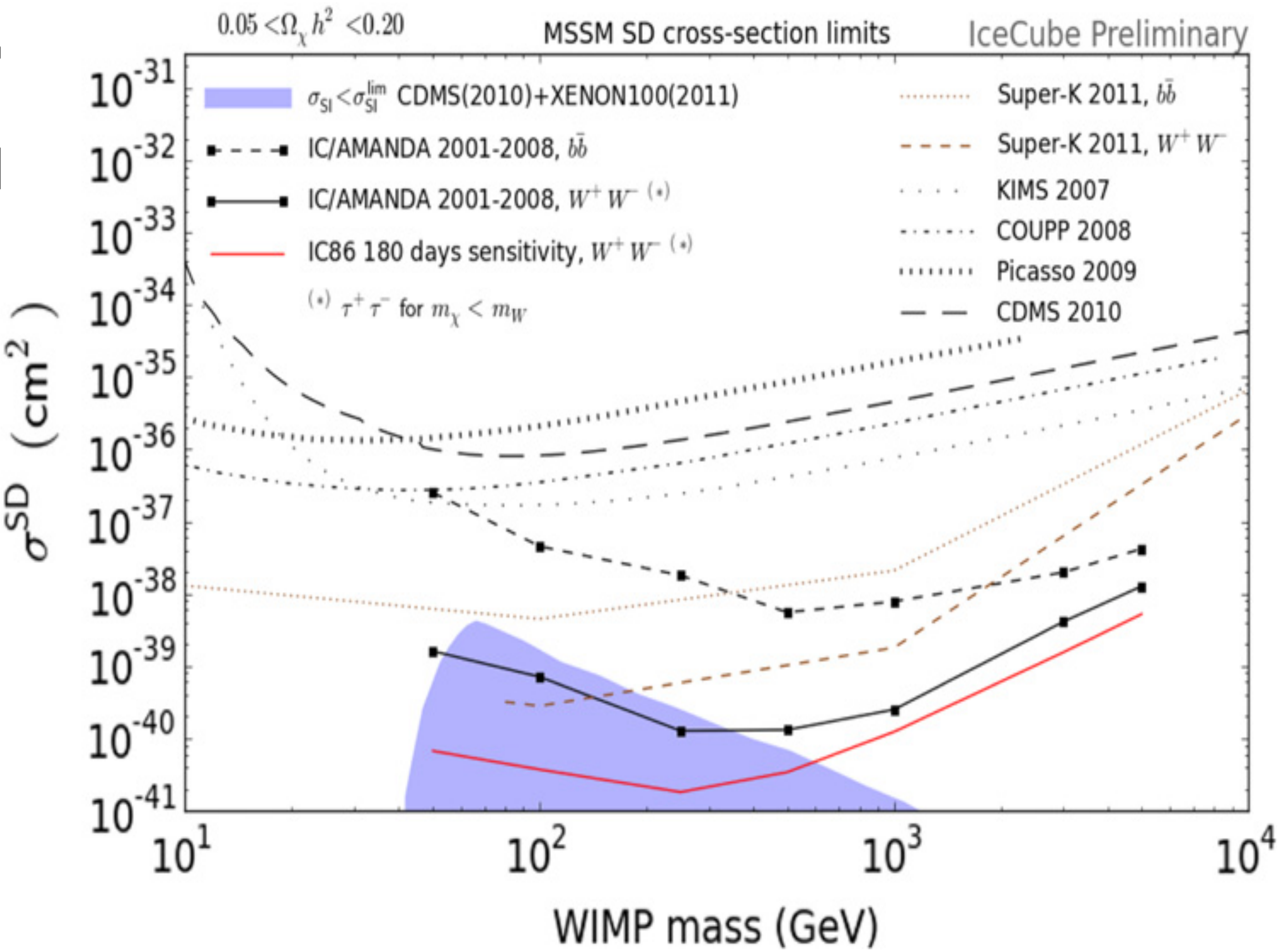
Sensitivity to dark matter (WIMPs)

- Assumption: WIN accumulation in Sun, subsequent annihilation
- Search for neutrino flux from the Sun
- Particularly sensitive to spin-dependent cross section (Sun = protons)
- Requires low energy threshold



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Where we are (summary)

… not yet there!

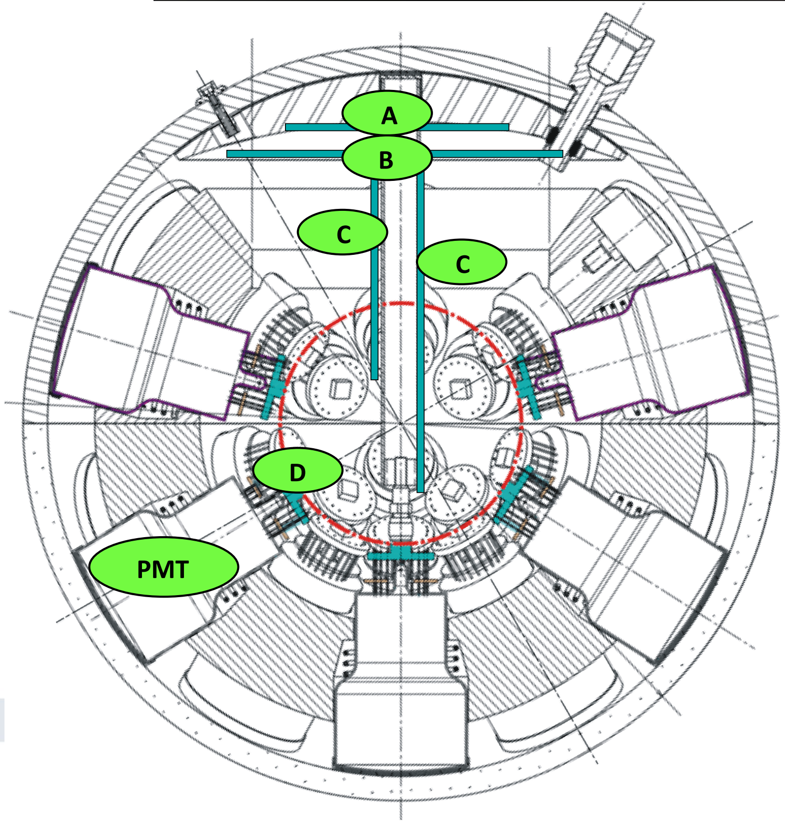
The Future: KM3NeT

The KM3NeT project

- EU-funded Design Study and Preparatory Phase (2006-2012)
- Multi-km^3 NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Central physics goals (by priority):
  - Galactic neutrino “point sources” (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- Current status
  - ~40 M€ available for first construction phase
  - final prototyping and last design decisions 2012/13
  - start of construction 2013/14

OM with many small PMTs

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



Recent developments:

- Detector will be constructed in 2 or more building blocks (technical reasons: power, data bandwidth, cables, deployment operations, complexity of se -floor network, …)
- Mechanical structure (towers vs. s der discussion
- Geometry according to Tec Report: Hexagonal blocks with n units each, at 180m distance
- Now: Optin ly for Galactic sources (energy cut-o ome 10 TeV)
  → Distance between detection units reduced to 100-130m
  → Effective area increases at intermediate and decreases at high energies

Footprint optimisation is ongoing

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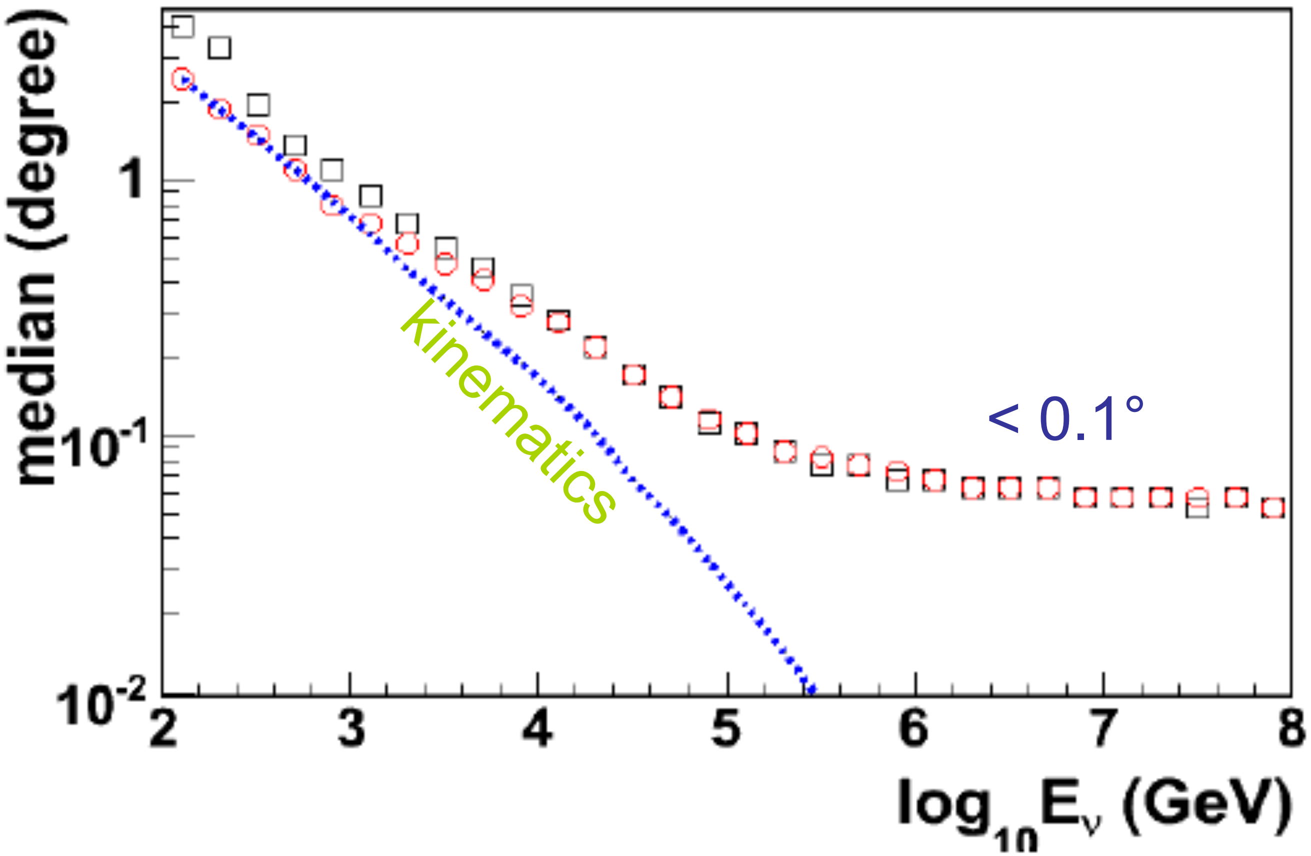
Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to ~1TeV



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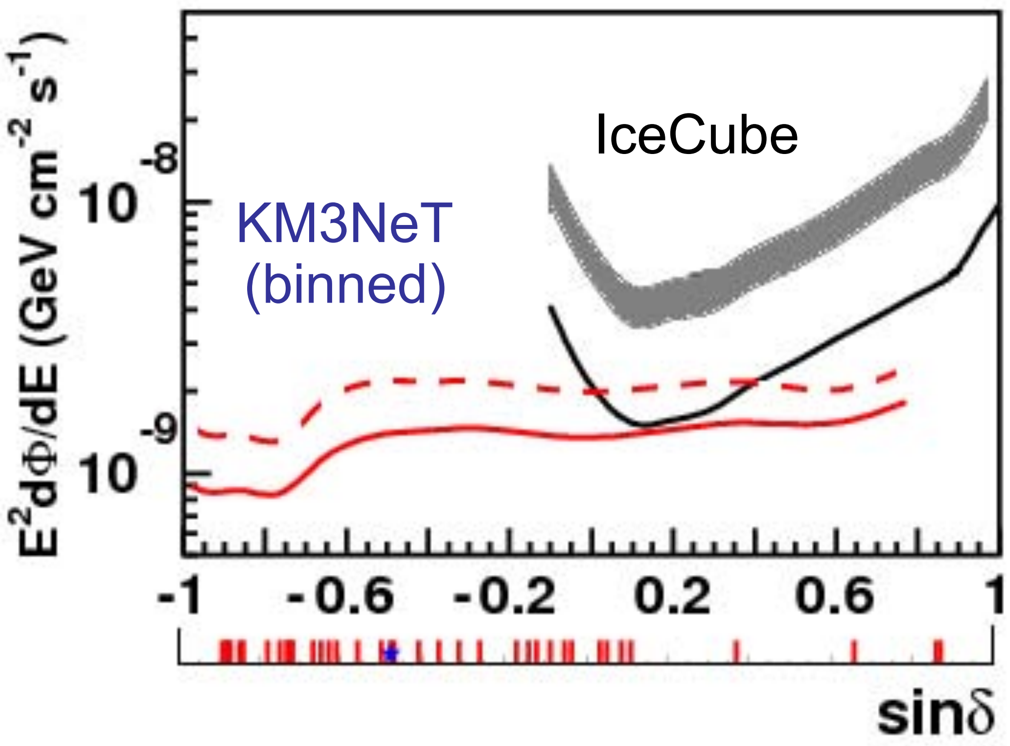
Point source sensitivity (1 year)

Expected exclusion limits / 5σ detection
(for E^{-2} source spectra, from Technical Design Report)



R. Abbasi et al. Astro-ph (2009) scaled – unbinned method

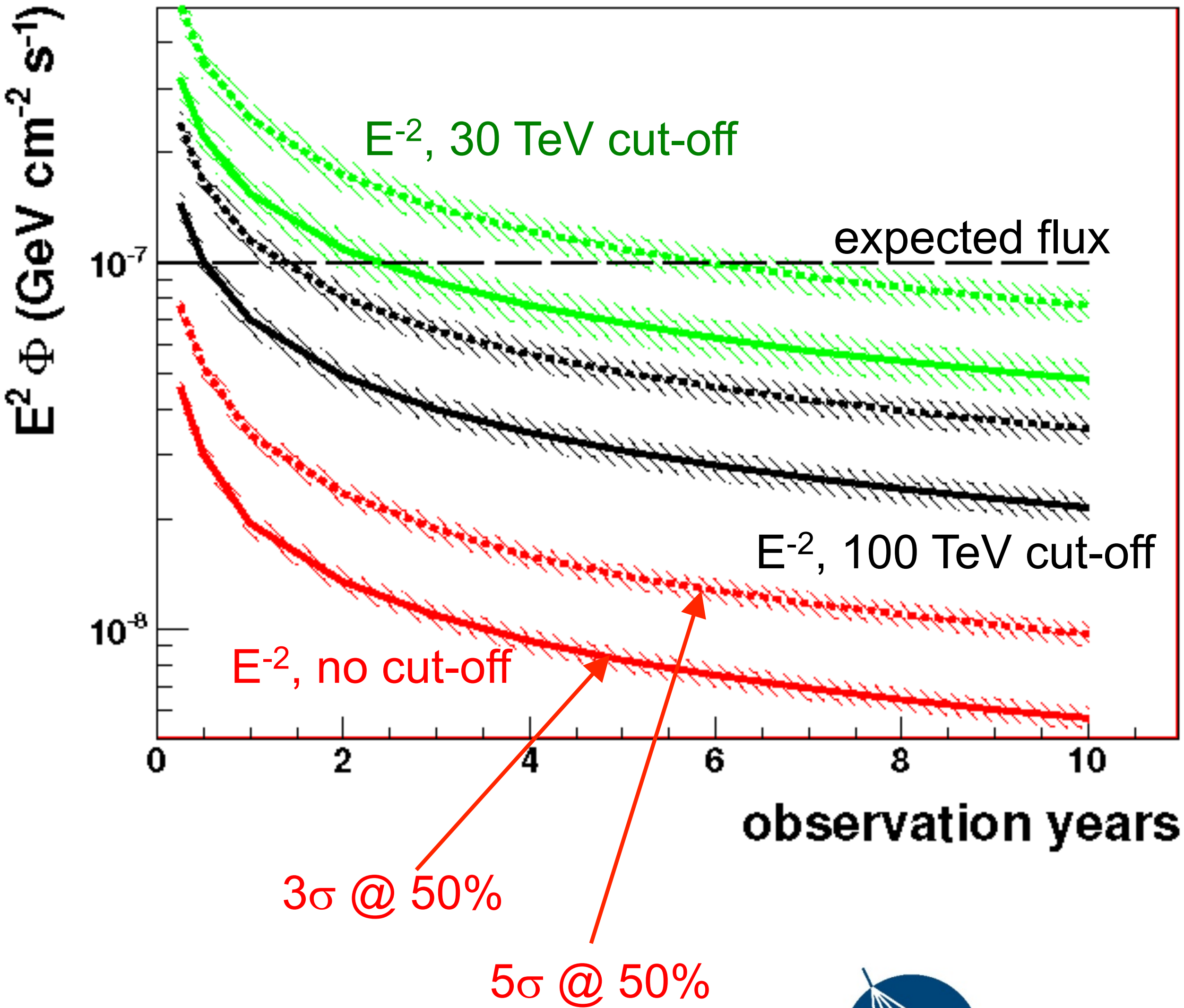
Discovery at 5σ with 50%

After optimisation for Galactic sources:
Observation of RXJ1713 with 5σ within ~5-7 years if γ emission fully hadronic

☐ Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)
F. Aharonian et al. Rep. Prog. Phys. (2008)
Abdo et al., MILAGRO, Astrophys. J. 658 L33-L36 (2007)

The Fermi bubbles

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



KM3NeT implementation parameters

- Overall investment ~220 M€
- Staged implementation expected;
  phase-1 sensitivity about equal to that of IceCube
- Science potential from very early stage of construction on
- Operational costs of full detector 4-6 M€ per year (2-3% of capital investment), including electricity, maintenance, computing, data centre and management
- Node for deep-sea research of earth and sea sciences

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Summary

- Neutrino telescopes in water and ice are taking data. The technology is proven.
- No discoveries yet …
  but they may be around the corner …
  we need patience and perseverance.
- KM3NeT will soon start construction
  and provide unprecedented sensitivity
- Hope to provide you with a discovery soon – stay tuned!

Technical Design

Objective: Support 3D-array of photo-detectors and connect them to shore (data, power, slow control)

- → Optical Modules
- → Front-end electronics
- → Readout, data acquisition, data transport
- → Mechanical structures, backbone cable
- → General deployment strategy
- → Sea-bed network: cables, junction boxes
- → Calibration devices
- Shore infrastructure
- Assembly, transport, logistics
- Risk analysis and quality control

Design rationale:

Cost-effective
Reliable
Producible
Easy to deploy

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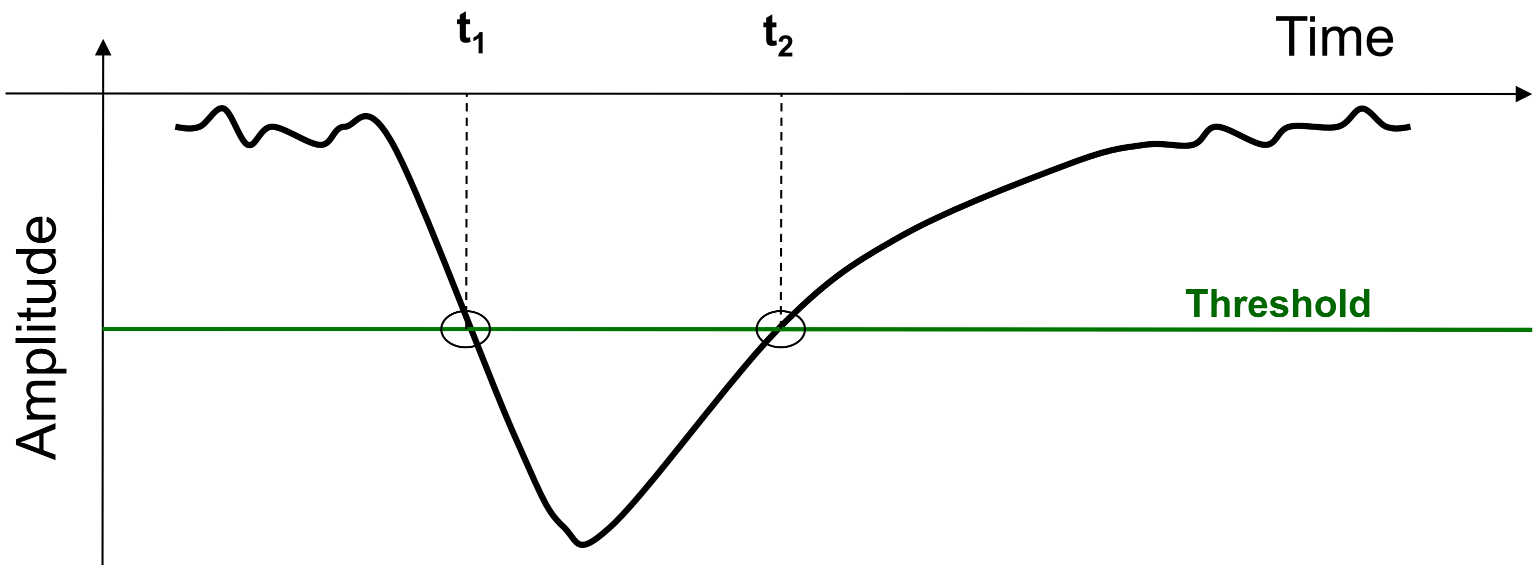
Front-end electronics: time-over-threshold

From the analogue signal to time stamped digital data:



…

- Implemented through FPGA & System on chip contained in optical module
- All data to shore via ethernet link
- Time synchronisation and slow control

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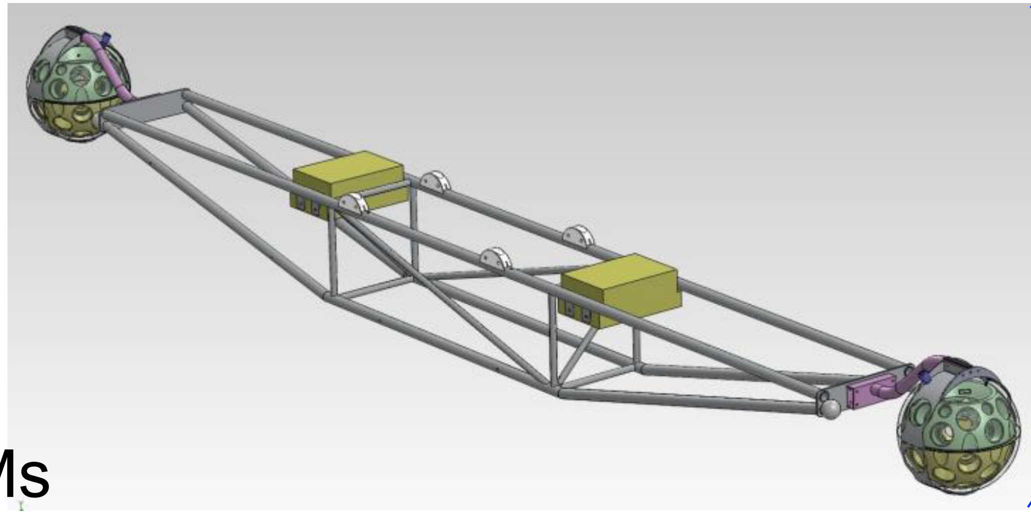
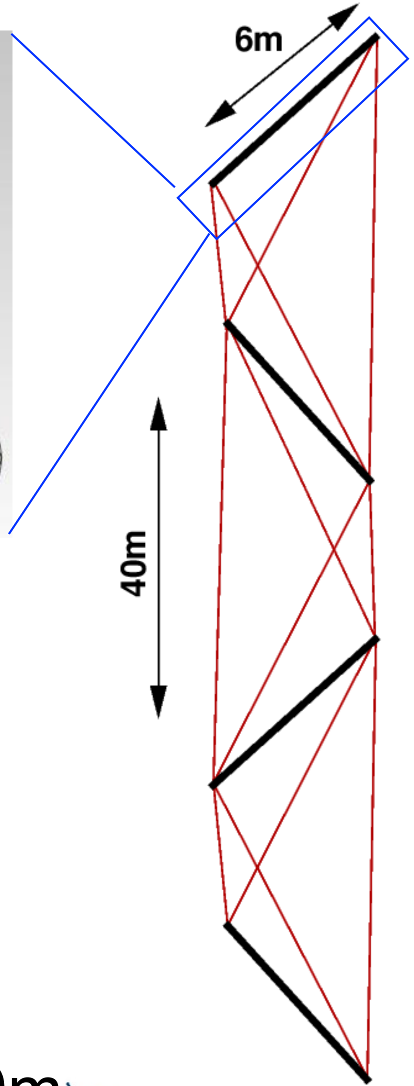
The Flexible Tower with Horizontal Bars





- 20 storeys
- Each storey supports 2 OMs
- Storeys interlinked by tensioning ropes, subsequent storeys orthogonal to each other
- Power and data cables separated from ropes; single backbone cable with breakouts to storeys
- Storey length = 6m
- Distance between storeys = 40 m
- Distance between DU base and first storey = 100m

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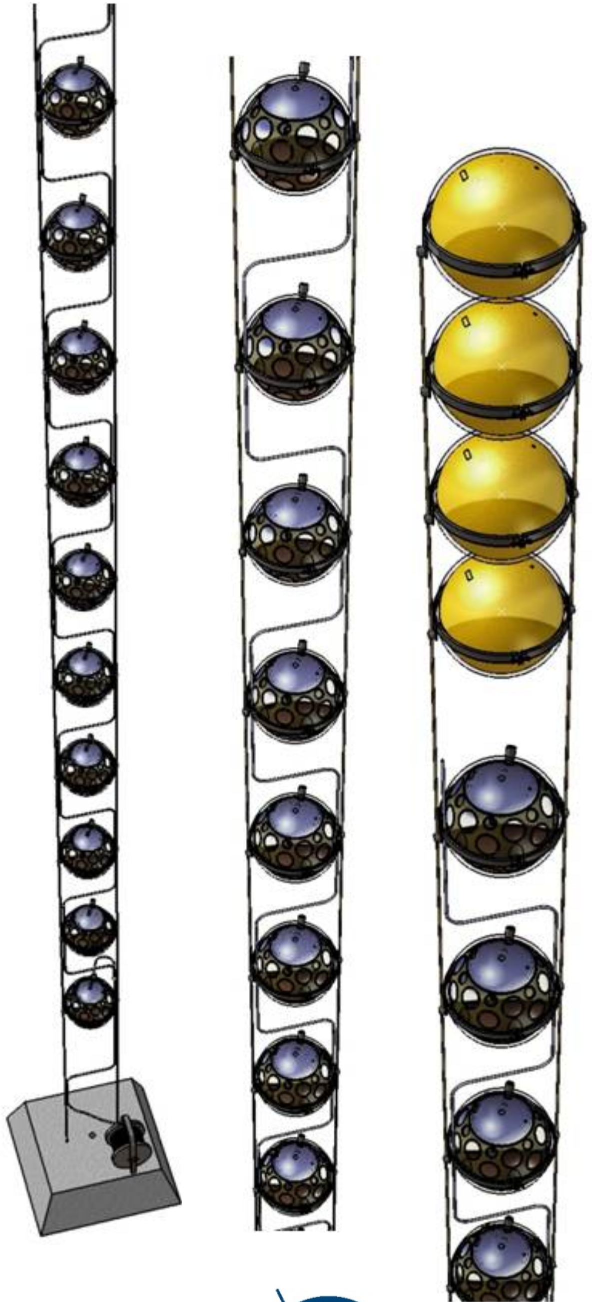
Backup solution: Strings

- Mooring line:
  - Buoy (empty glass spheres, net buoyancy 2250N)
  - 2 Dyneema ropes (4 mm diameter)
  - 20 storeys (one OM each), 30 m distance, 100m anchor-first storey
- Electro-optical backbone:
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - 11 fibres and 2 copper wires

New concept, needs to be tested. Also for flexible tower if successful

:

  - Star network between master module and optical modules



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Deployment Strategy

- Compact package – deployment – self-unfurling
  - Eases logistics
    (in particular in case of several assembly lines)
  - Speeds up and eases deployment;
    several units can be deployed in one operation
  - Self-unfurling concepts need to be thoroughly tested and verified
- Connection to seabed network by ROV
- Backup solution:
  "Traditional" deployment from sea surface

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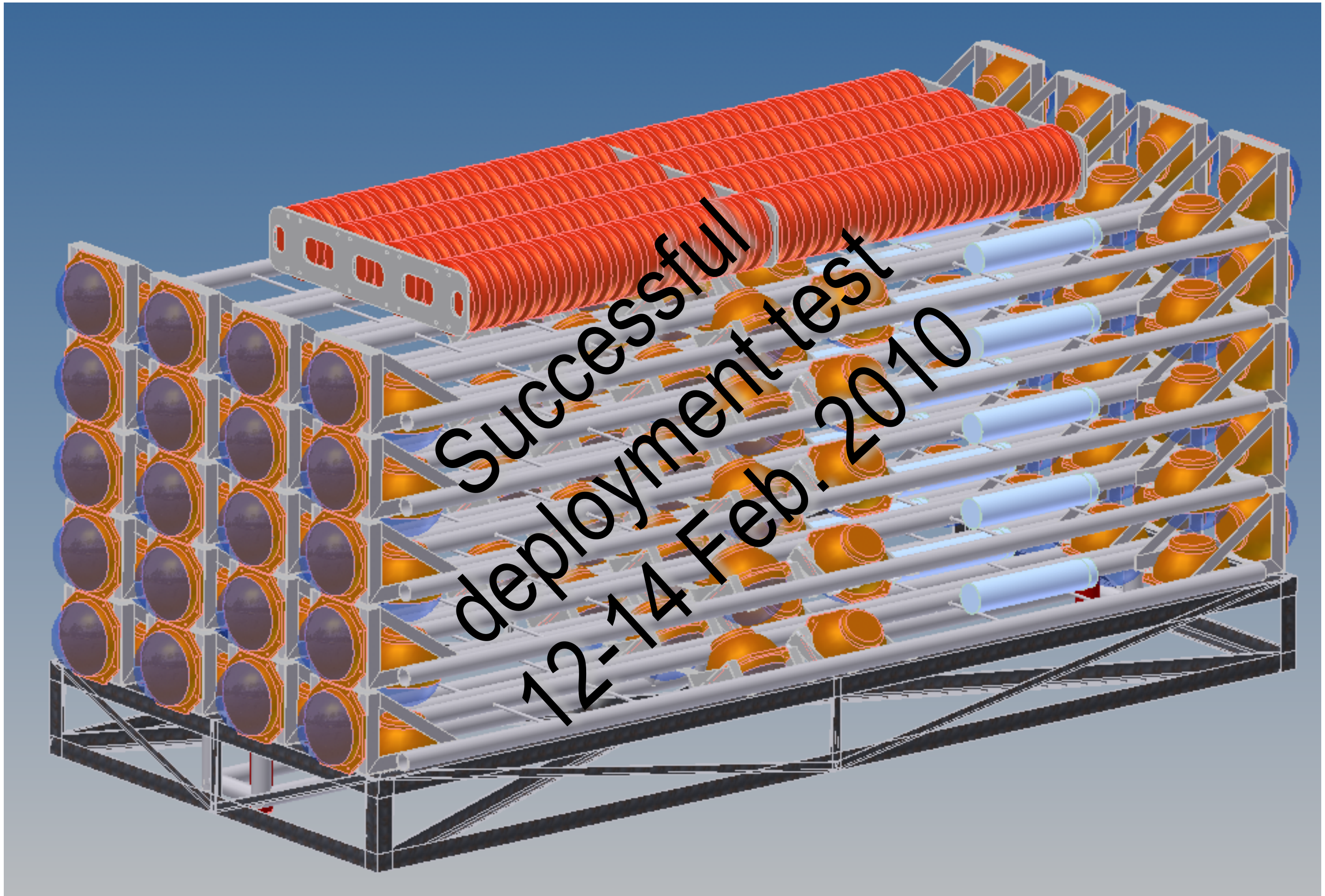
A Flexible Tower Packed for Deployment



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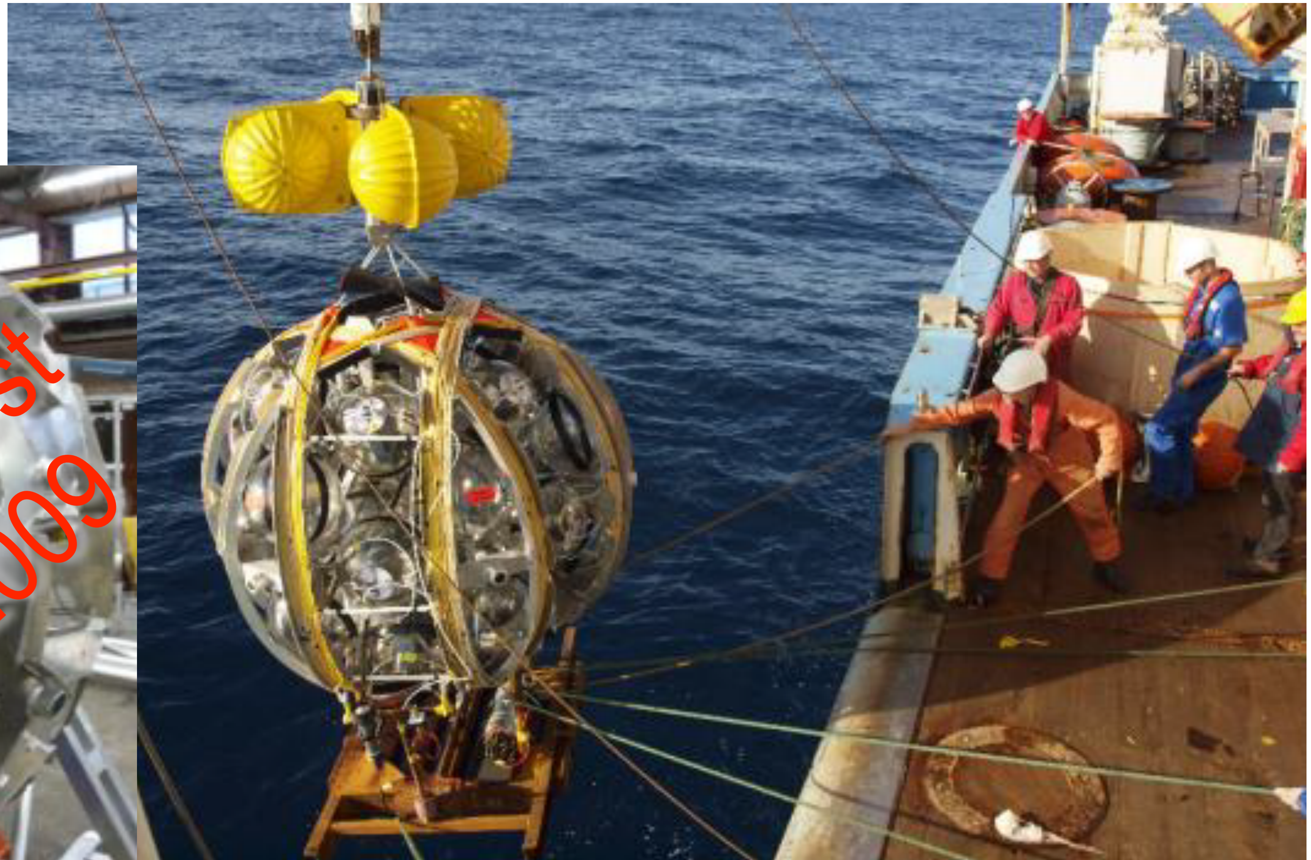
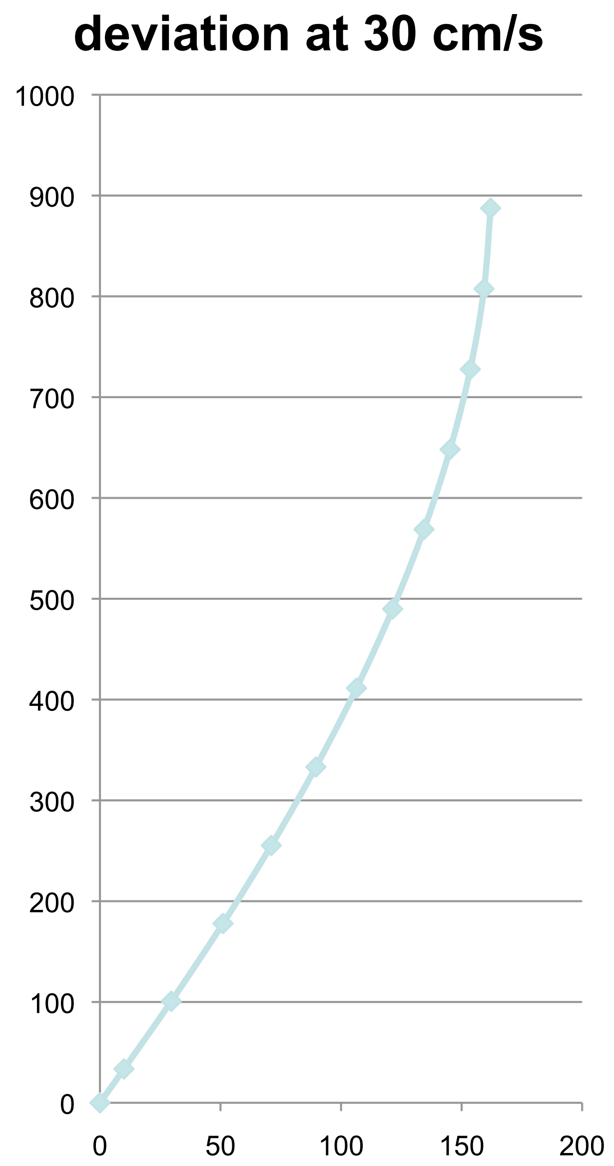
Compactifying Strings

Slender string rolled up for self-unfurling:



Hydrodynamic Stability

- DUs move under drag of sea current
    - Currents of up to 30cm/s observed
    - Mostly homogeneous over detector volume
    - Deviation from vertical at top about 150m at 30cm/s (can be reduced by extra buoyancy)
    - Critical current ~45cm/s (anchor starts to move)



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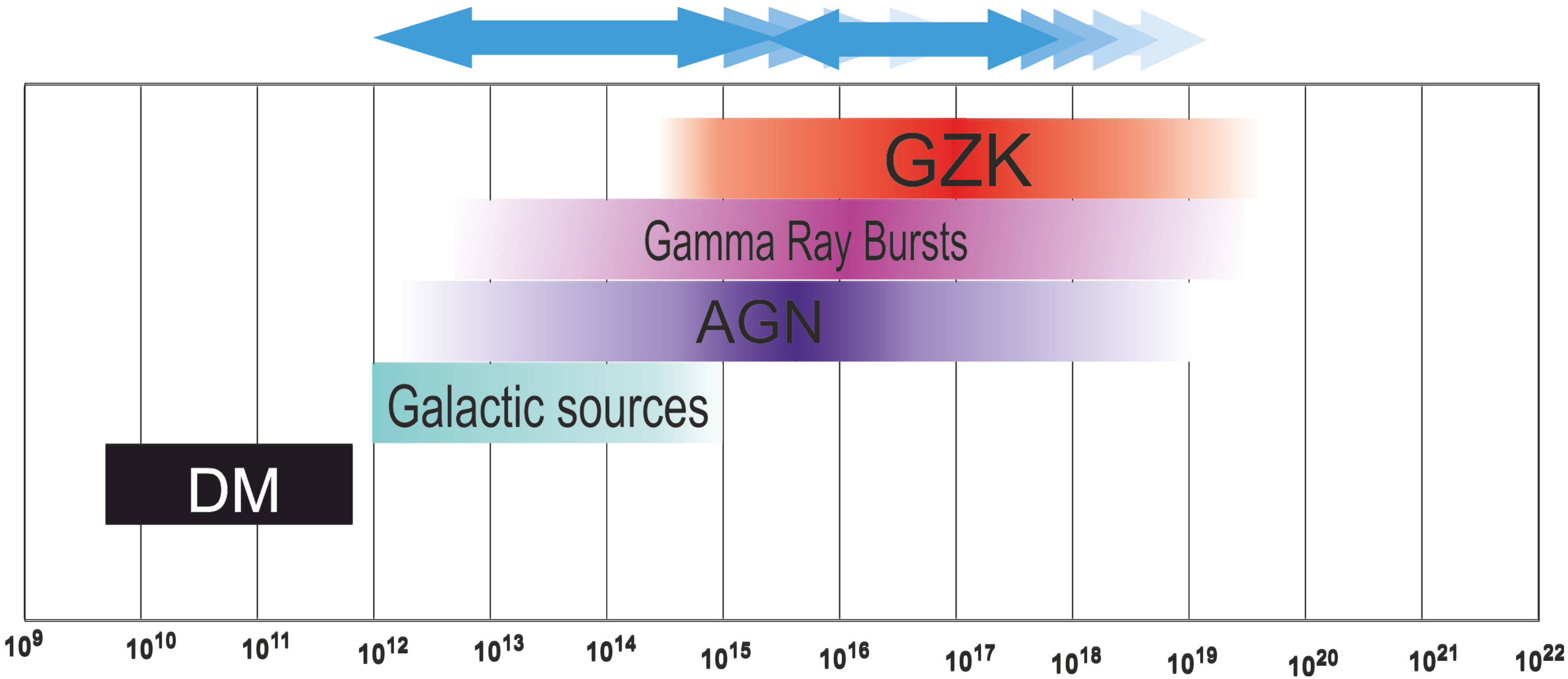
Sensitivity



For a fixed number of € we can optimise the sensitivity for different sources
Main parameter: photocathode density (area/volume)

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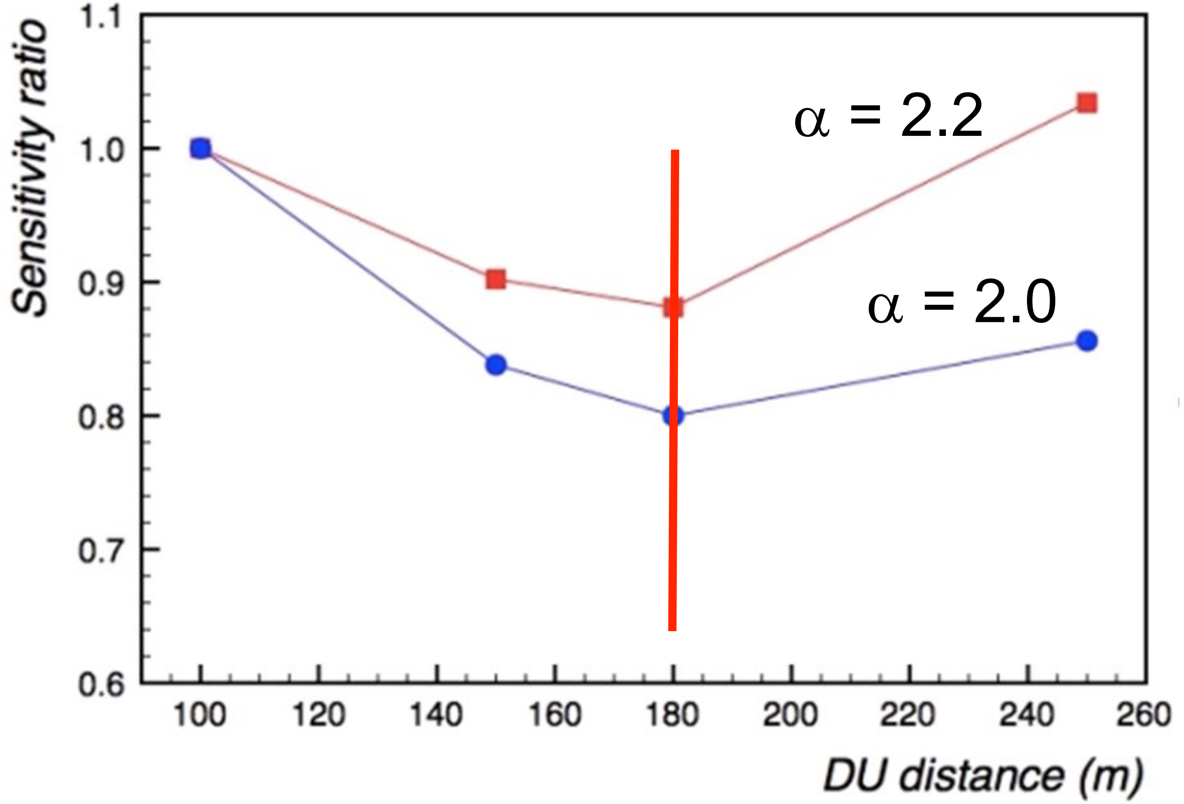
Optimisation Studies

<u>Example</u>: Sensitivity dependence of point-source search on DU distance for flexible towers (for 2 different neutrino fluxes ~$E^{-\alpha}$, no cut-off)



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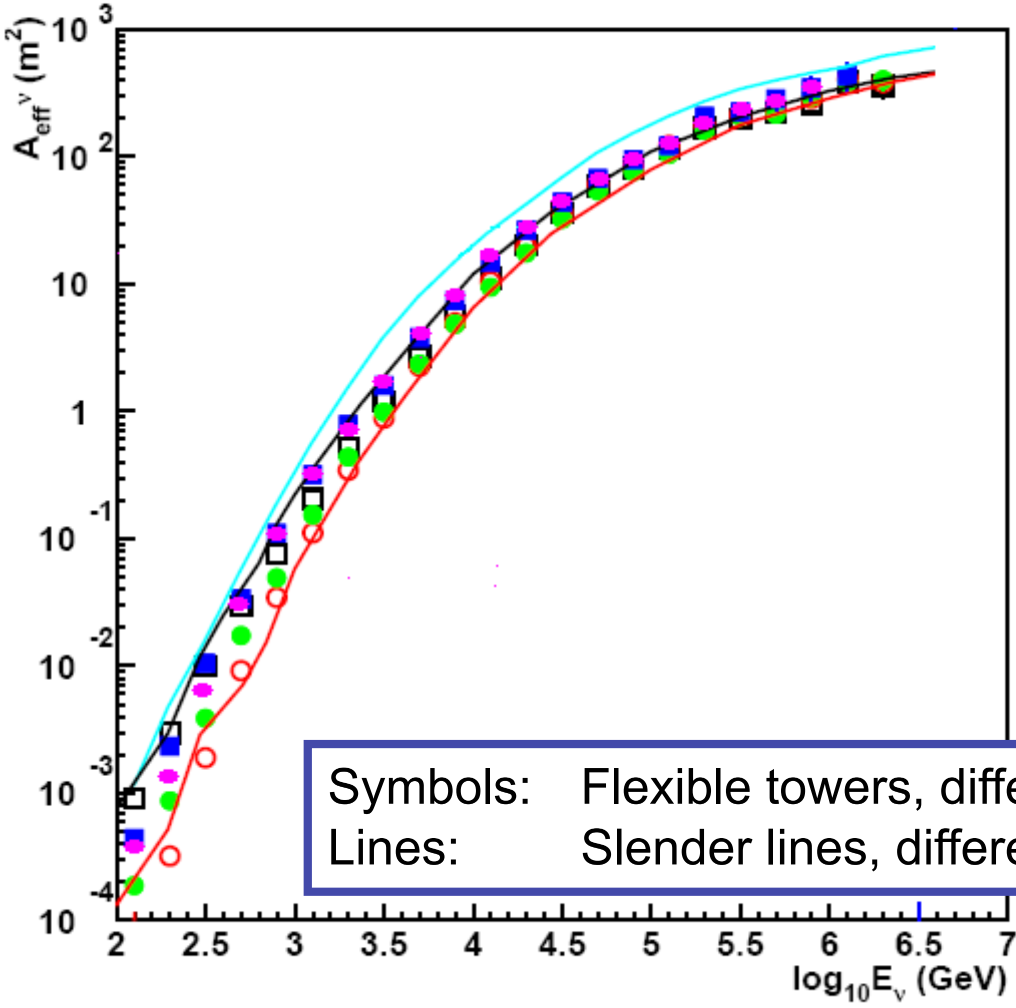
Effective Areas (per Building Block)



- Results very similar for hard quality cuts
- Flexible towers with bars and slender strings “in same ballpark”
- Driven by overall photocathode area

Symbols: Flexible towers, different quality cuts
Lines: Slender lines, different quality cuts

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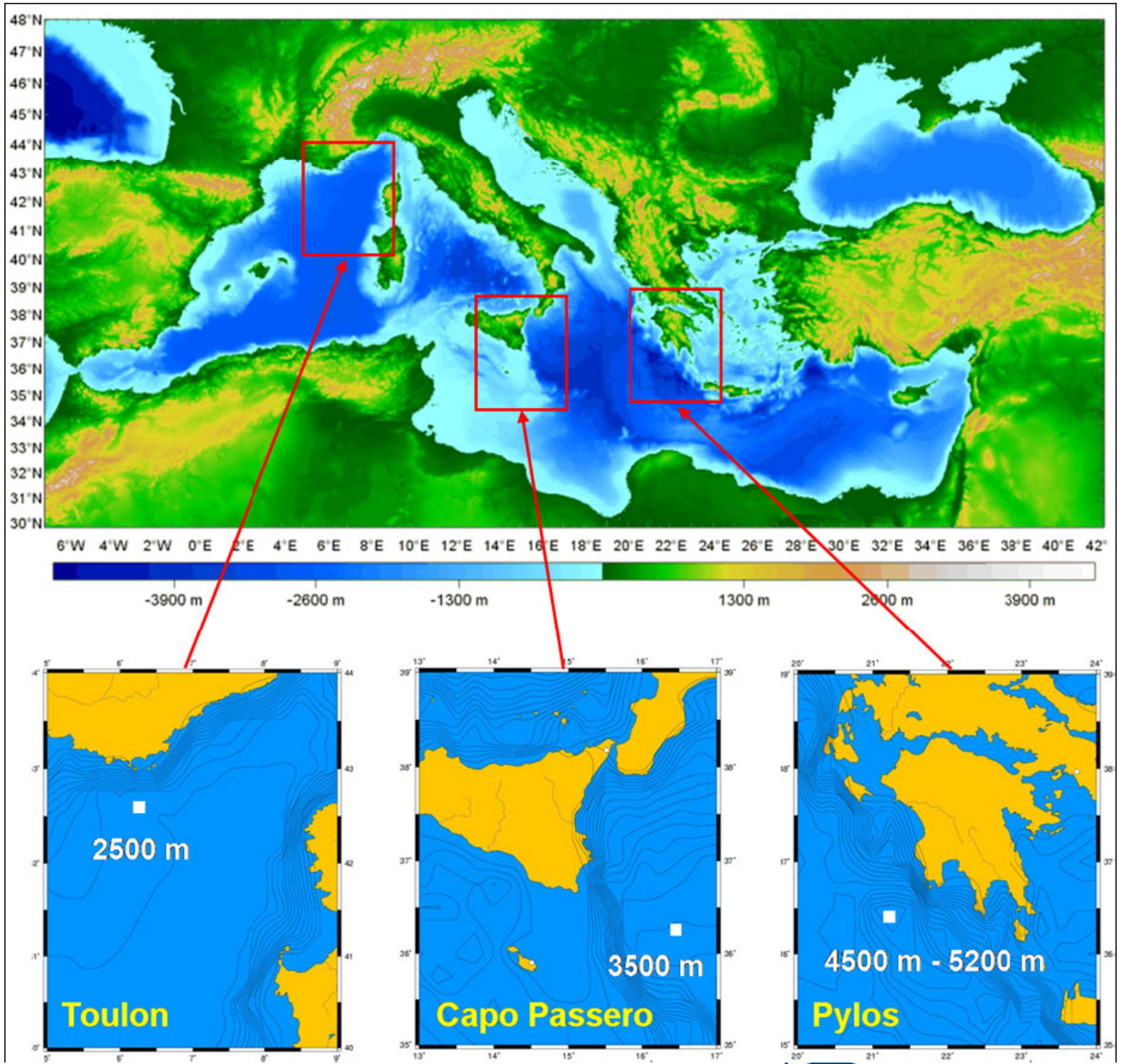
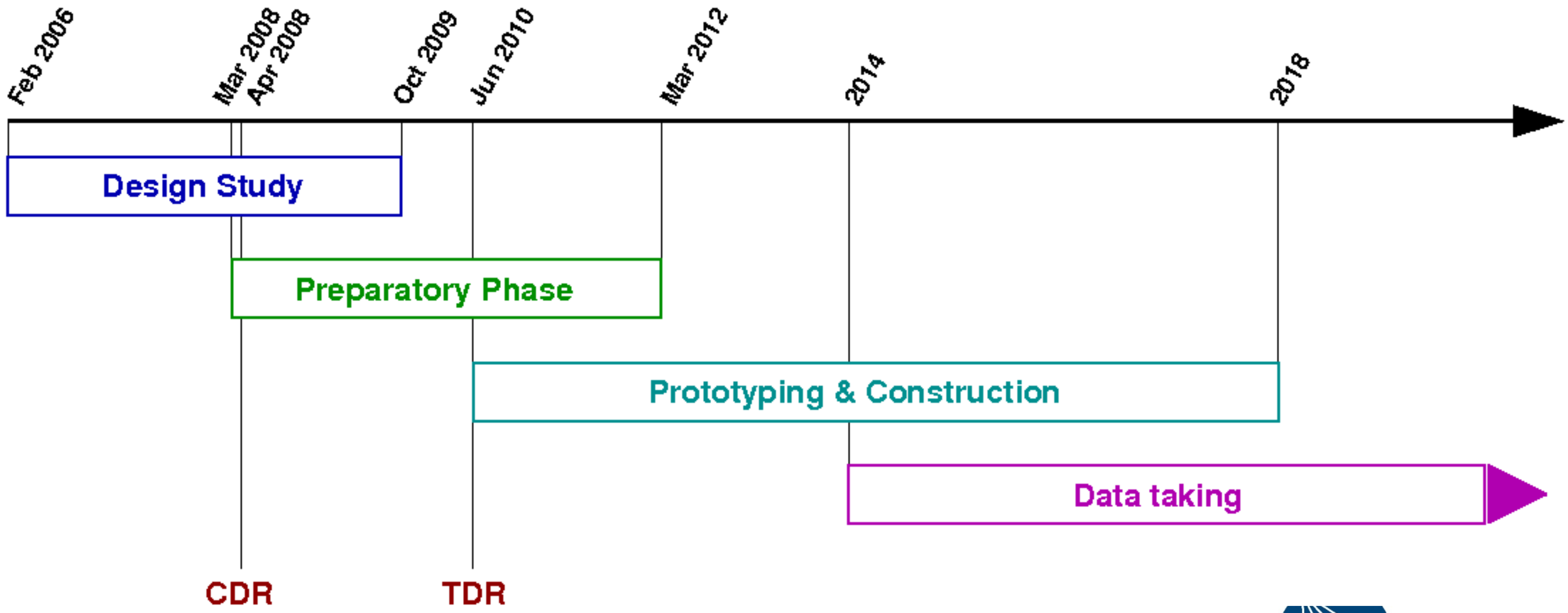
Candidate Sites

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



Next Steps and Timeline

- Next steps: Prototyping and design decisions
  - TDR public since June 2010
  - convergence of technical design
  - site decision in preparation
- Timeline:



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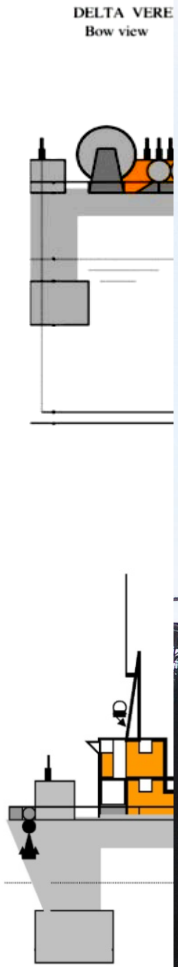
NESTOR: the Delta-Berenike Platform



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NeT

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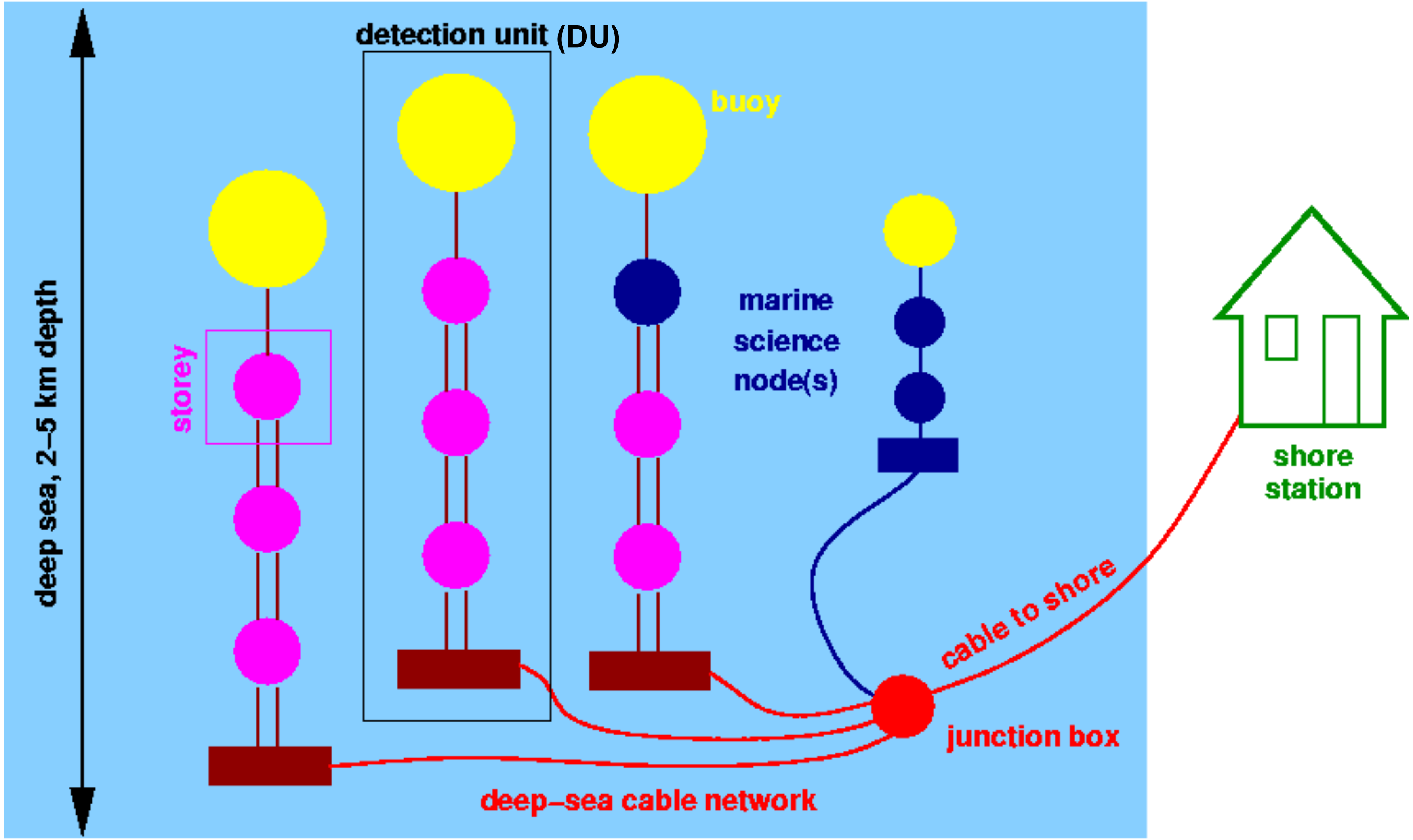
The KM3NeT Research Infrastructure (RI)



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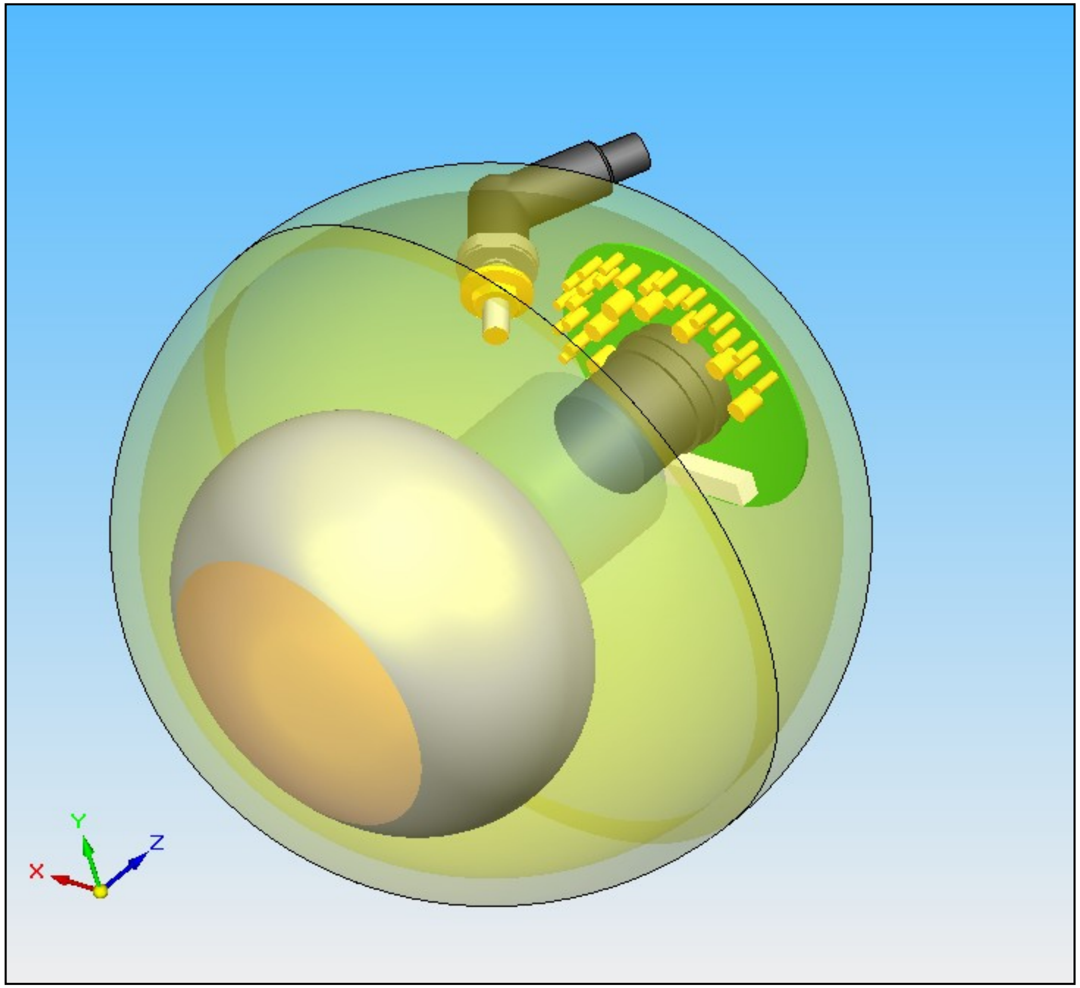
OM “classical”: One PMT, no Electronics

Evolution from pilot projects:

- 8-inch PMT, increased quantum efficiency (instead of 10 inch)
- 13-inch glass sphere (instead of 17 inch)
- no valve (requires “vacuum” assembly)
- no mu-metal shielding



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Data Network

- All data to shore:
  Full information on each hit satisfying local condition (threshold) sent to shore
- Overall data rate ~ 25 Gbyte/s
- Data transport:
  Optical point-to-point connection shore-OM
  Optical network using DWDM and multiplexing
  Served by lasers on shore
  Allows also for time calibration of transmission delays
- Deep-sea components:
  Fibres, modulators, mux/demux, optical amplifiers
  (all standard and passive)

A first Deep Core result

- Identification of cascades, mainly from

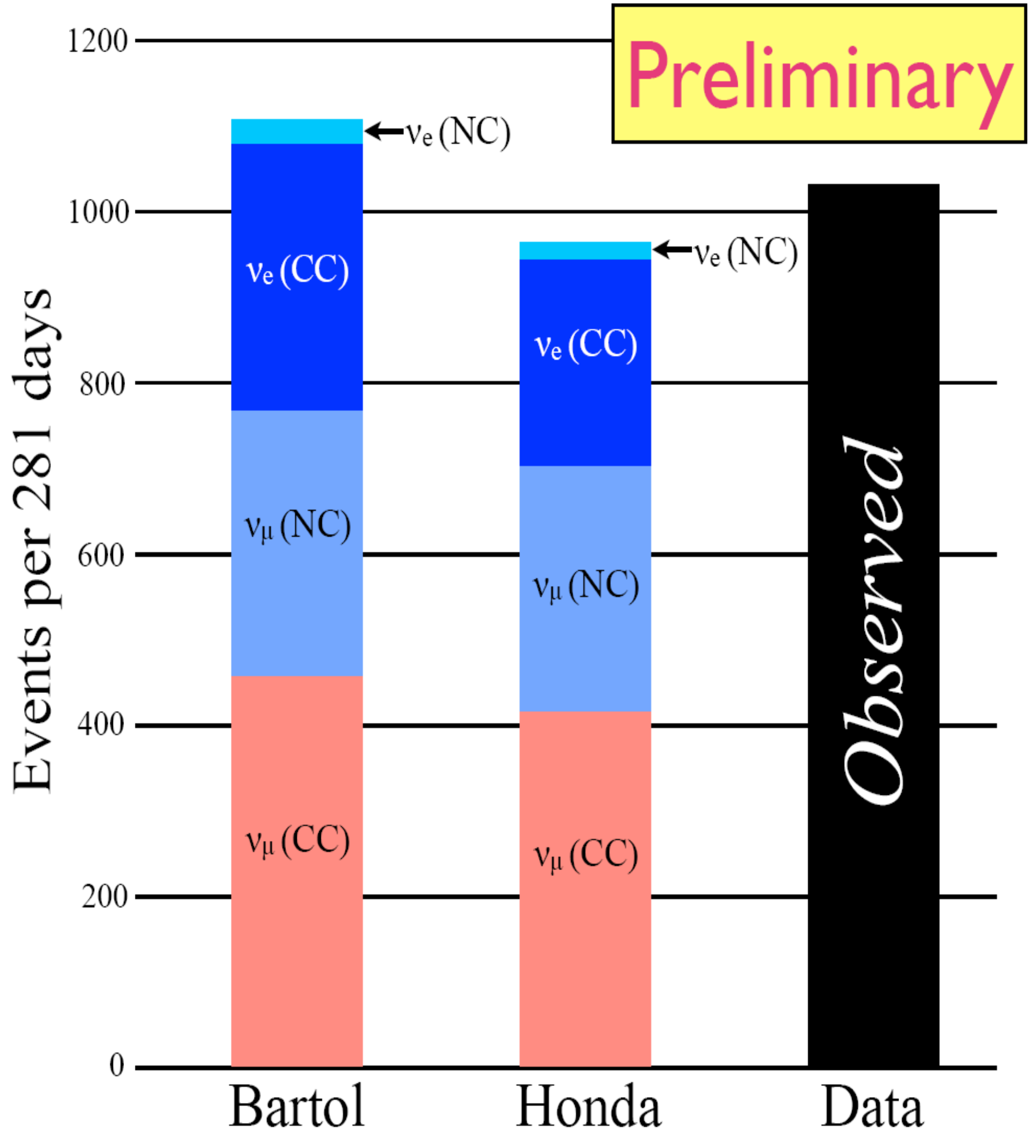
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

- Main background:

$$\nu_\mu + N \rightarrow \mu + X$$

with short μ track
- Very difficult in IceCube
- Success in Deep Core! (see arXiv:1201.0801)



What we learn from Deep Core

- A close look at neutrino events above O(10 GeV); event identification and reconstruction possible.
- The atmospheric muon veto works well.
- New physics results (see also arXiv:1112.1053):
  - Flavour composition of atmospheric neutrinos
  - Neutrino oscillations (ν_μ disappearance)
  - Neutrino oscillations (ν_τ appearance)
  - …

In the pipeline

Can we build on this success and go one step further?
→ The PINGU project

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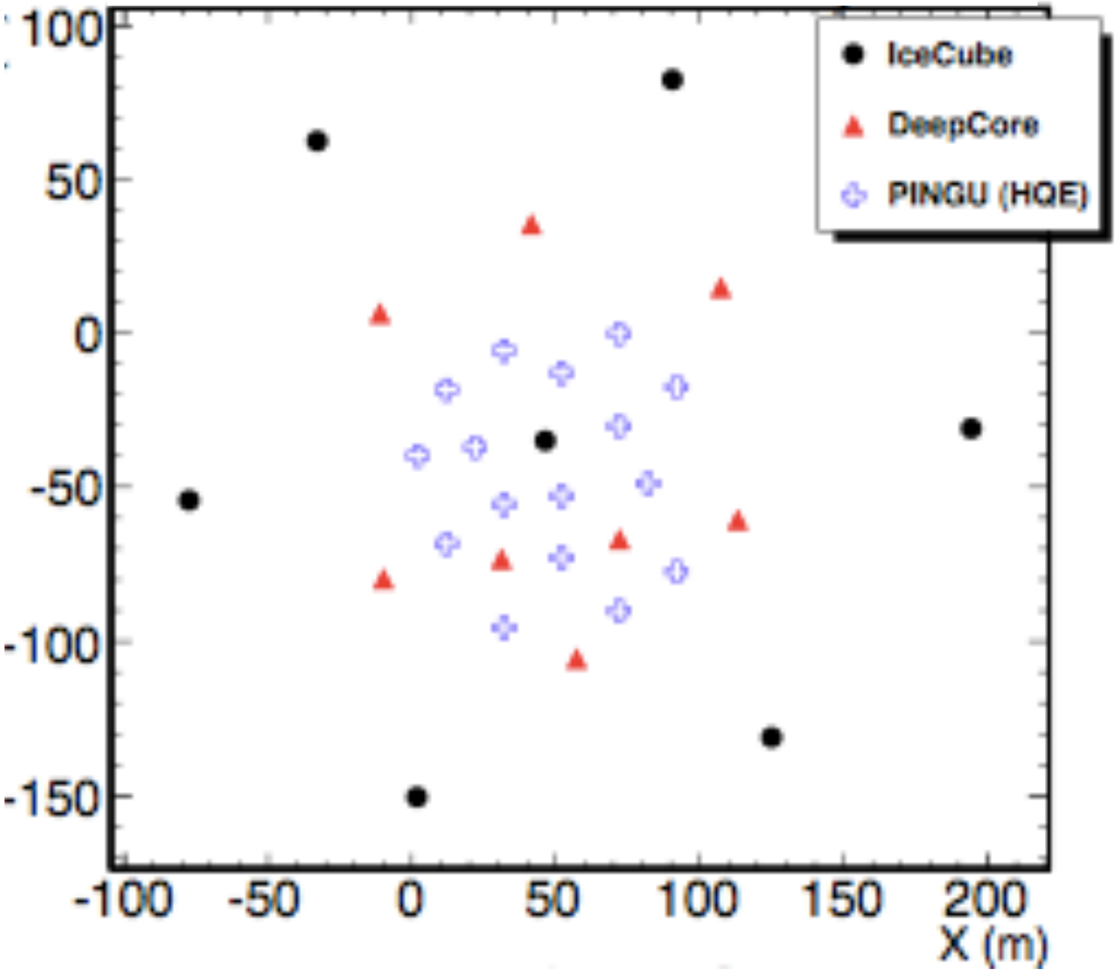
The PINGU fact sheet

- Phased IceCube Next-Generation Upgrade
- Add 20 strings in Deep Core region
- Expected energy threshold at 1 GeV
- R&D opportunity for future developments
- IceCube plus further groups

PINGU geometry
(more compact version also studied)



Physics opportunities with PINGU

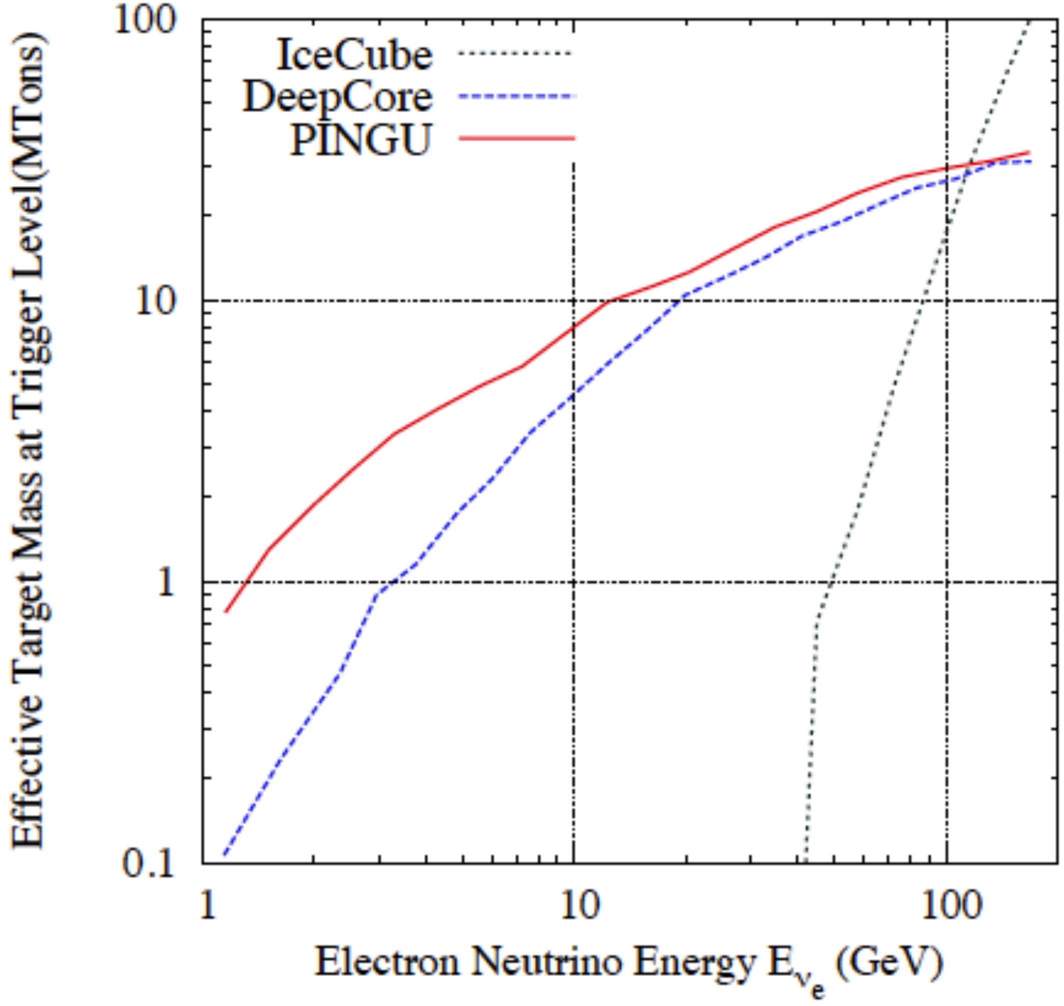
Theorists are very interested:
Alexei Smirnov
Walter Winter
…

- Neutrino physics:
  - Oscillations (in particular deviation of 2-3-mixing from maximal)
  - Mass hierarchy
  - Sterile neutrinos
  - Additional option: Neutrino beam-line to PINGU
  - CP violation ??
- Indirect Dark Matter searches
- Supernova neutrinos
- …

Sensitivity example

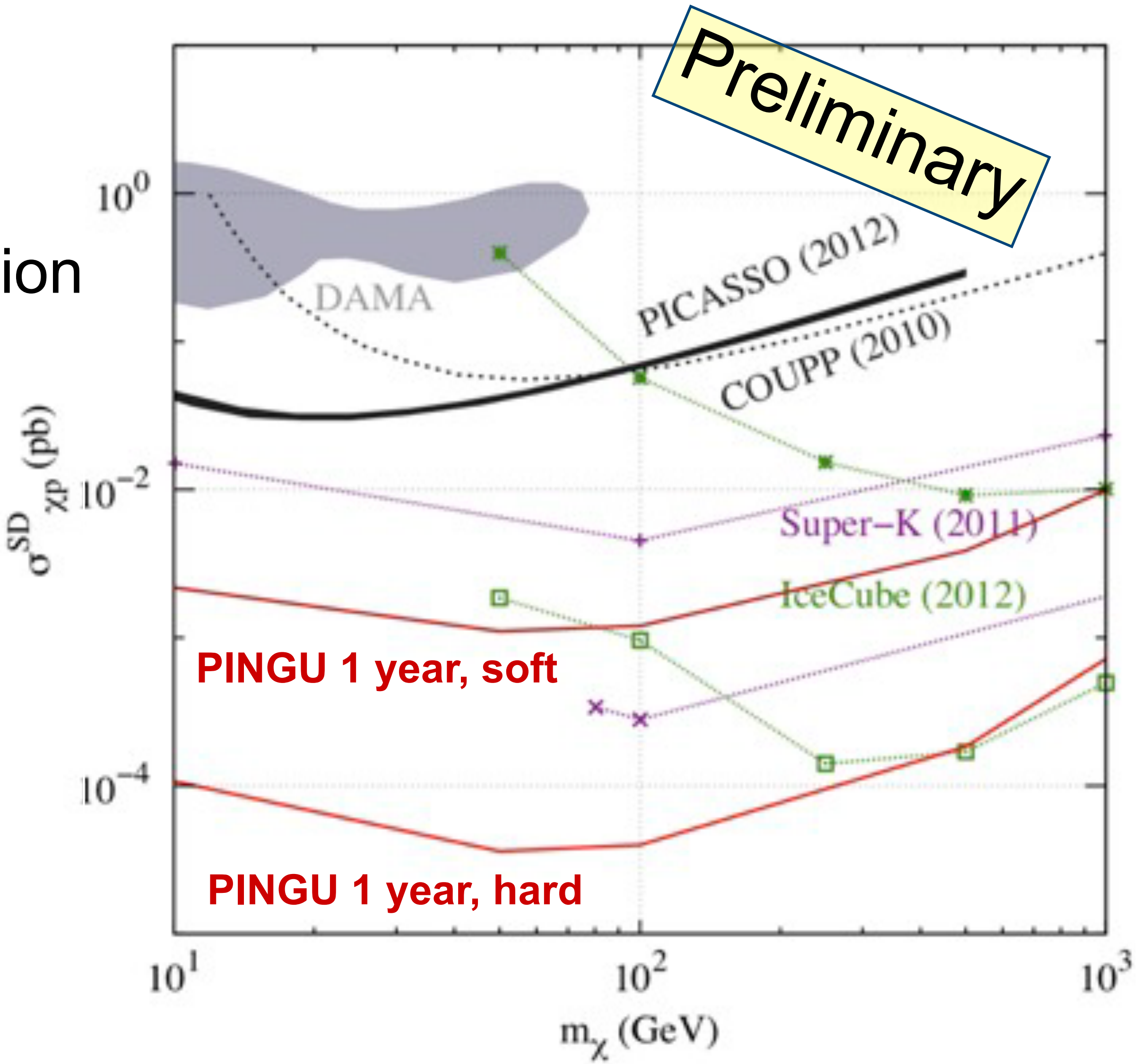
- Study sensitivity to ν_e
- Particularly important for WIMP searches (low atm. background)
- Improved trigger level sensitivity compared to Deep Core (factor 2-10 at 1-10 GeV)
- Even more at analysis level
- Megaton-scale effective volume

Trigger level effective volume (ν_e)



WIMP searches

- Expected exclusion limits for spin-dependent cross section
- Assumptions see C.Rott, JCAP(2011)029
- Atmospheric muons not yet included
- Low-mass WIMP region in reach



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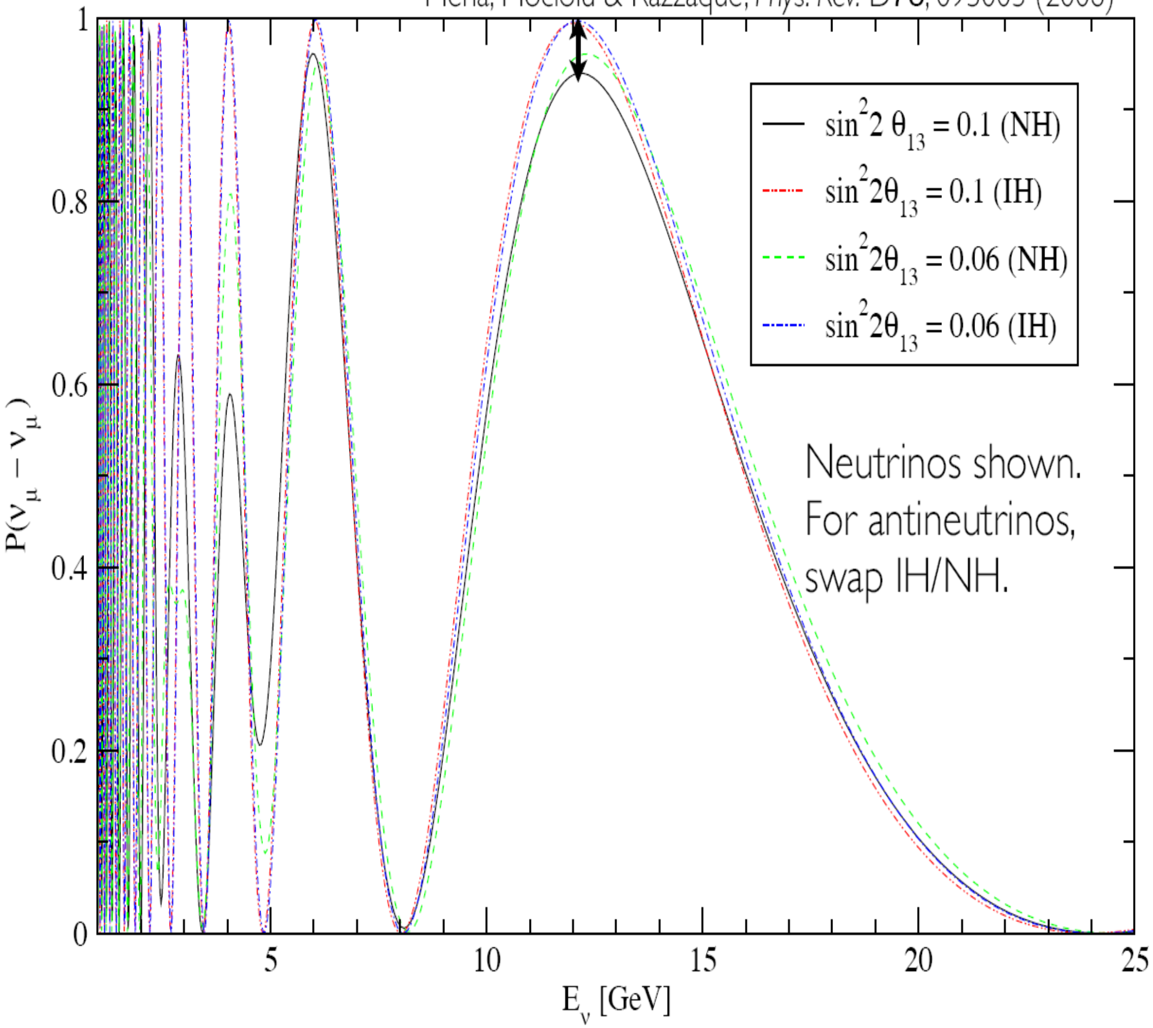
Mass hierarchy (atmospheric ν)

- MSW effect in Earth induces $\nu/\overline{\nu}$ difference in ν oscillations
- Note: first maximum for $\mu \longrightarrow \mu$ is at 12 GeV for $L = d_{\text{Earth}}$
- Could be measurable since $\sigma(\nu) \approx 2\sigma(\overline{\nu})$ at these energies
- Advanced analysis: "oscillograms" (Alexei Smirnov)

Mena, Mocioiu & Razzaque, *Phys. Rev.* D78, 093003 (2008)



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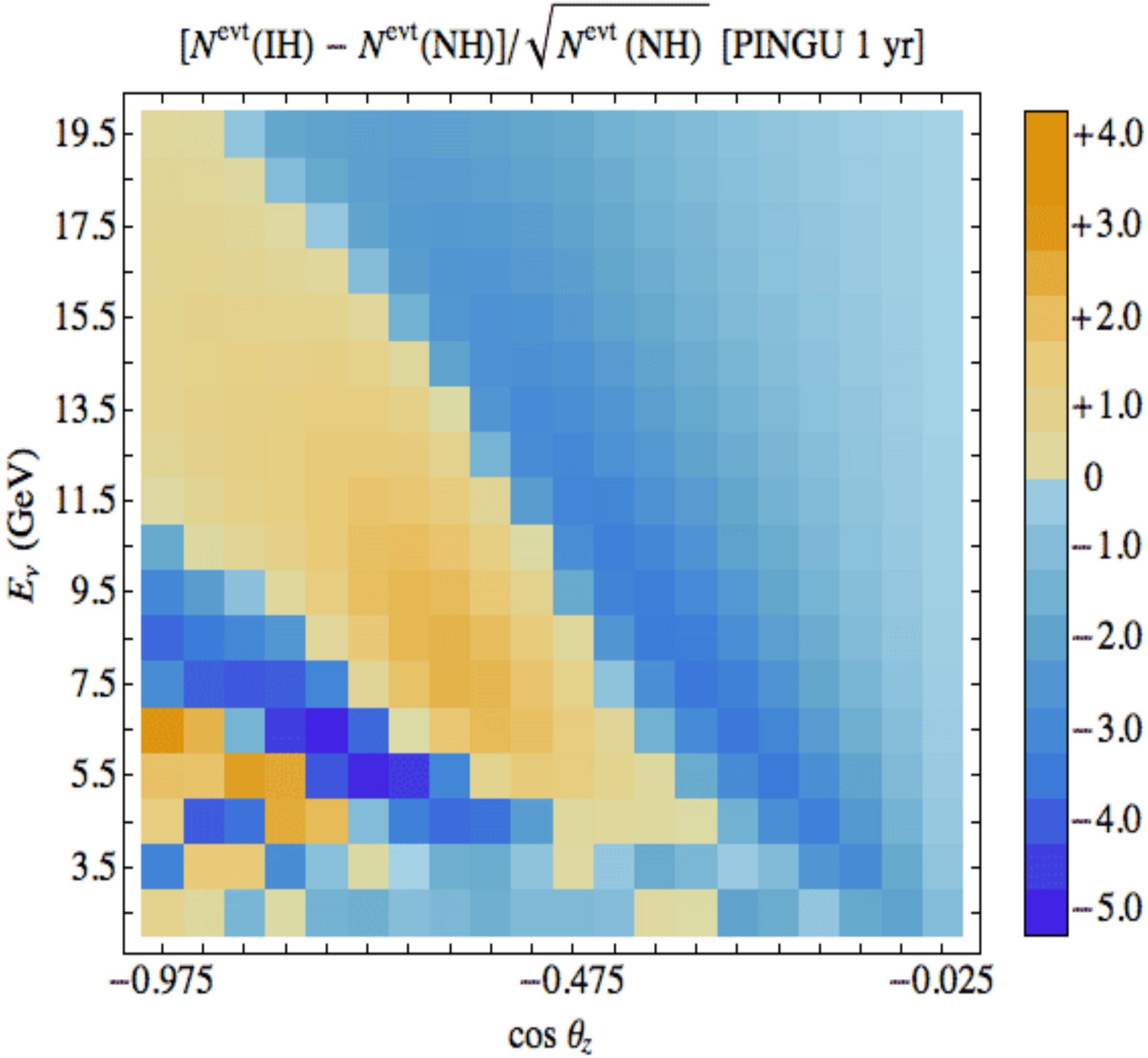
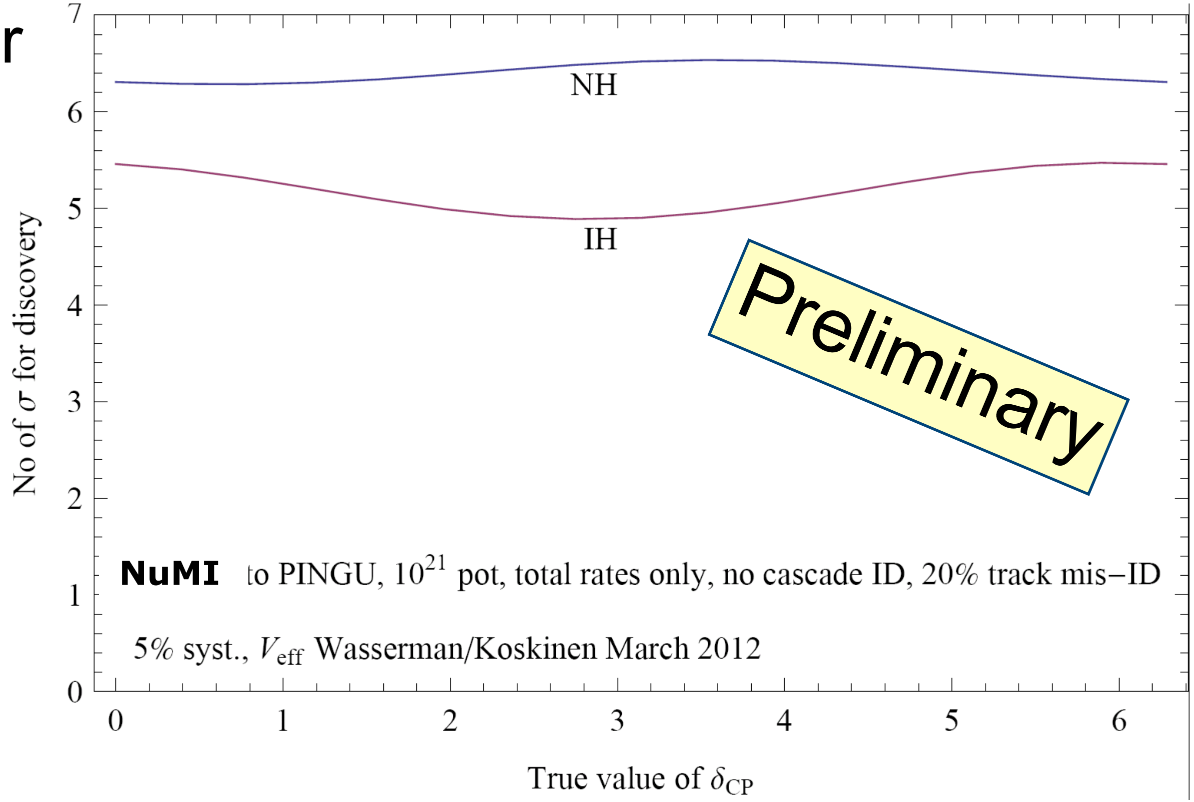
Mass hierarchy oscillogram

- Expected signal significance in energy vs. zenith
- Required energy and directional resolution appear to be realistic
- Analysis and plot courtesy of Alexei Smirnov



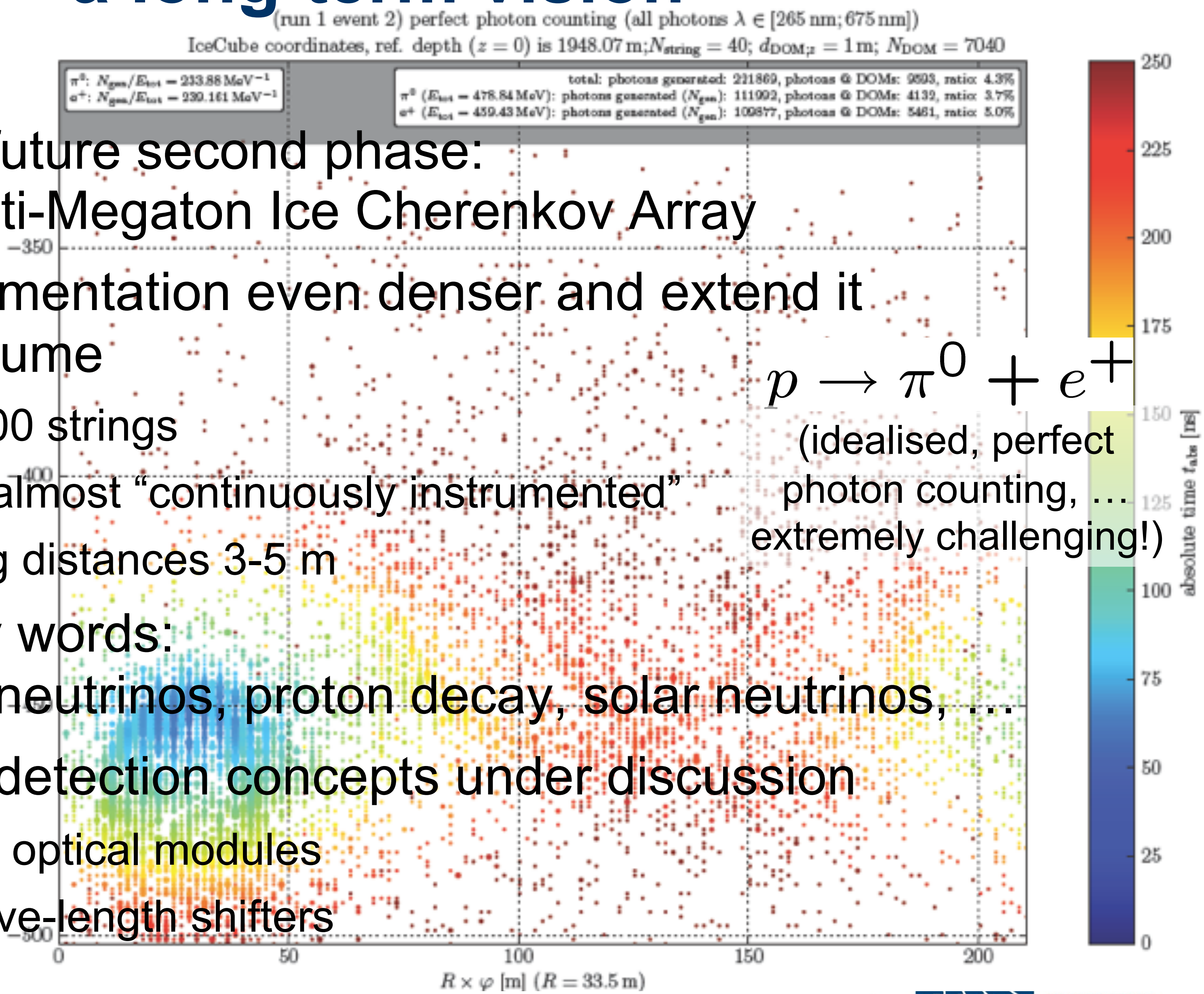
Mass hierarchy with a accelerator beam

- Idea by Walter Winter
- Accelerator beam (beta, super, …) provides clean initial state
- Hierarchy measurement could be possible using event counts only
- Requires beam pointing to the South Pole ….



MICA – a long-term vision

- Vision of a future second phase:
  MICA = Multi-Megaton Ice Cherenkov Array
- Make instrumentation even denser and extend it to larger volume
  - Several 100 strings
  - Vertically almost “continuously instrumented”
  - Inter-string distances 3-5 m
- Physics key words:
  Supernova neutrinos, proton decay, solar neutrinos, …
- New photo-detection concepts under discussion
  - Multi-PMT optical modules
  - Use of wave-length shifters

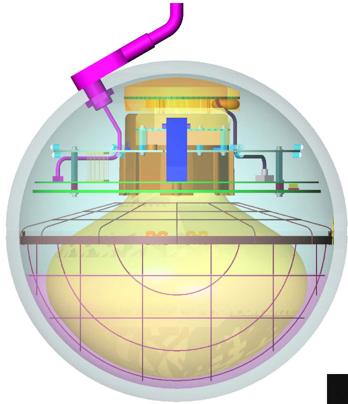


$p \rightarrow \pi^0 + e^+$

(idealised, perfect photon counting, … extremely challenging!)

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

R&D in PINGU



- PINGU offers opportunities for R&D towards MICA
- Example: Optical Module with many small PMTs
- Advantages:
  - Increased photocathode area per OM
  - Precise single-photon counting
  - Directionality
  - Intra-OM coincidences
- Prototype in preparation

KM3NeT: 31 3” PMTs in 17” sphere

PINGU: 3”-PMTs in cylindrical vessel