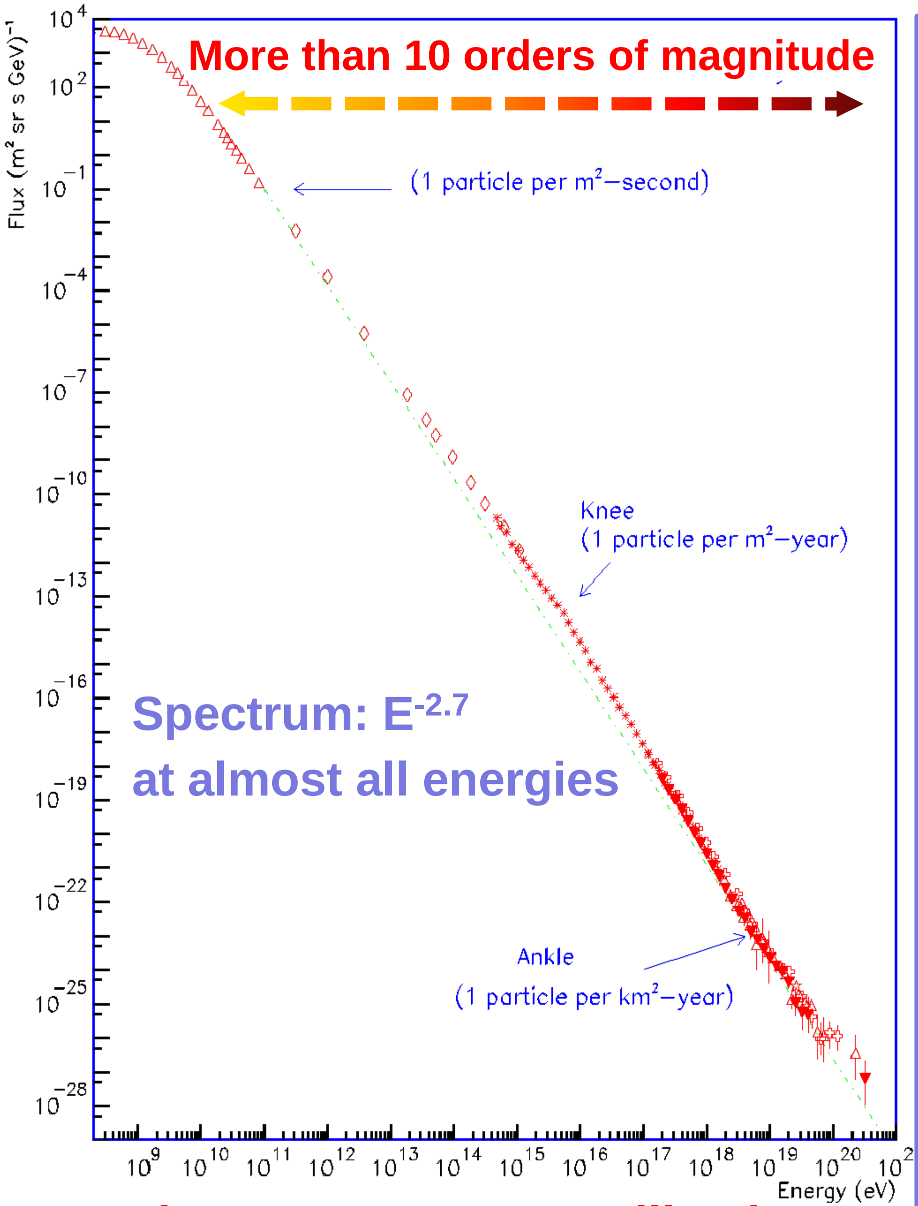
Telescopi per neutrini di alta energia

Giorgio Riccobene   INFN-LNS

IFAE 2010 - Roma “Sapienza”

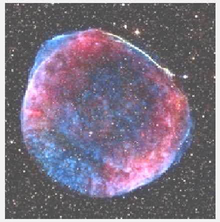
The Cosmic Ray (CR) Spectrum



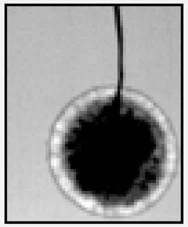
The CR sources are still unkown

Fermi's Idea:
Statistical acceleration of particles
Bell's model:
Charged particle acceleration in shocks

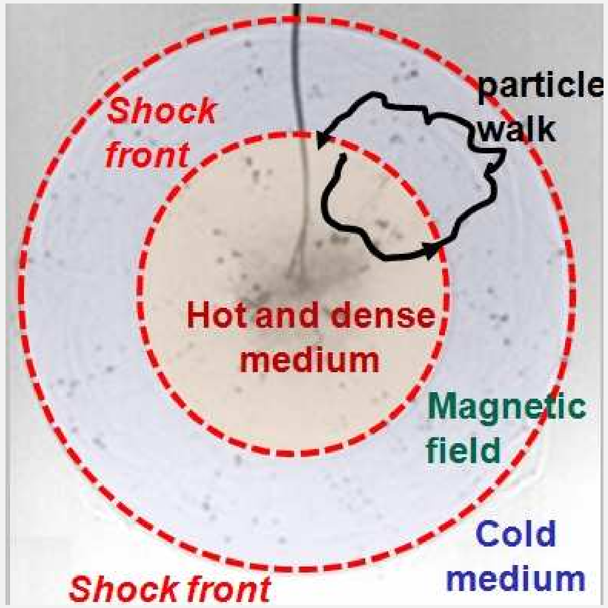
$E_{max} \propto$ *time spent in the source (BxR)*
$dN/dE \propto E^{-2}$



SN 1006

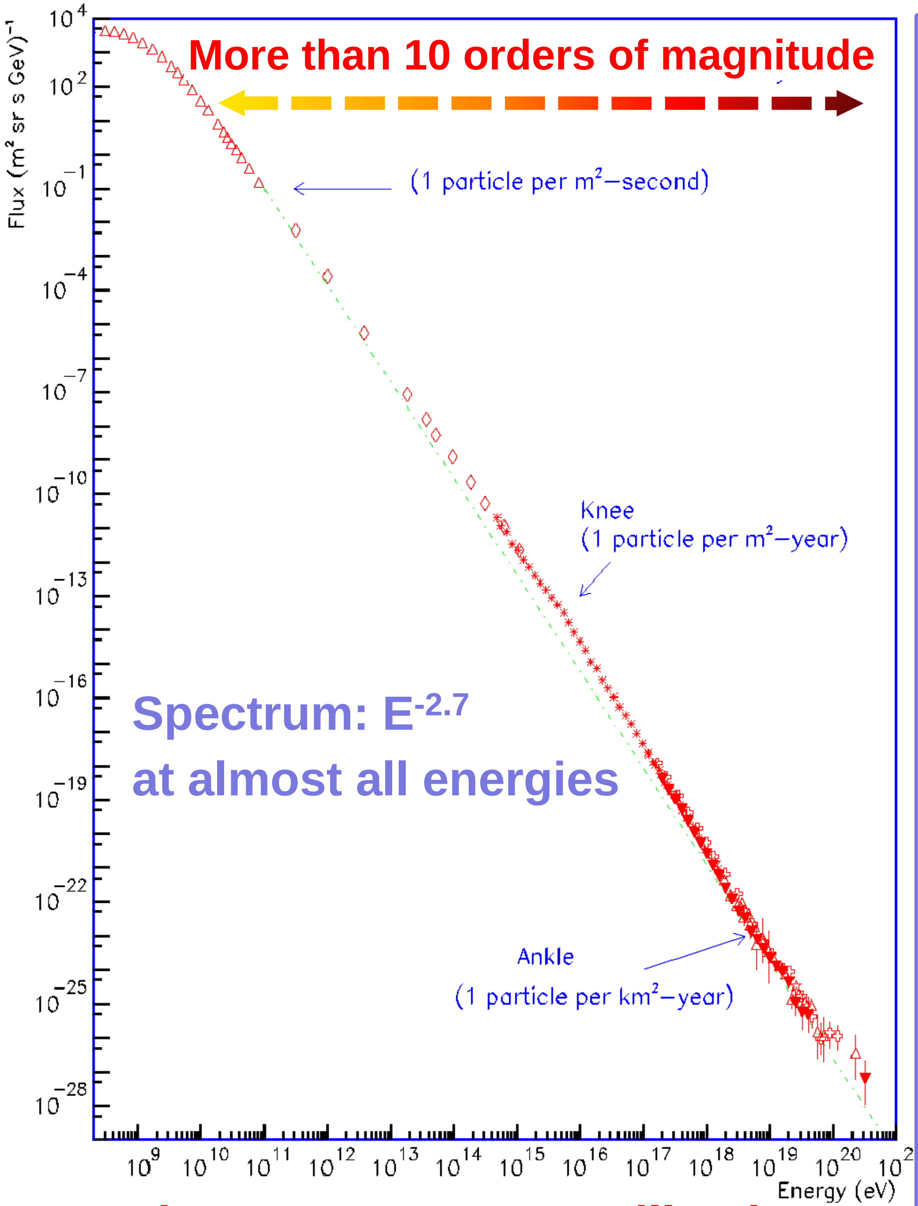


TNT detonation



E^{-2} (Fermi-Bell acceleration)
$E^{-0.6}$ (propagation in the Galaxy)

The Cosmic Ray (CR) Spectrum



Spectrum: $E^{-2.7}$

at almost all energies

The CR sources are still unkown

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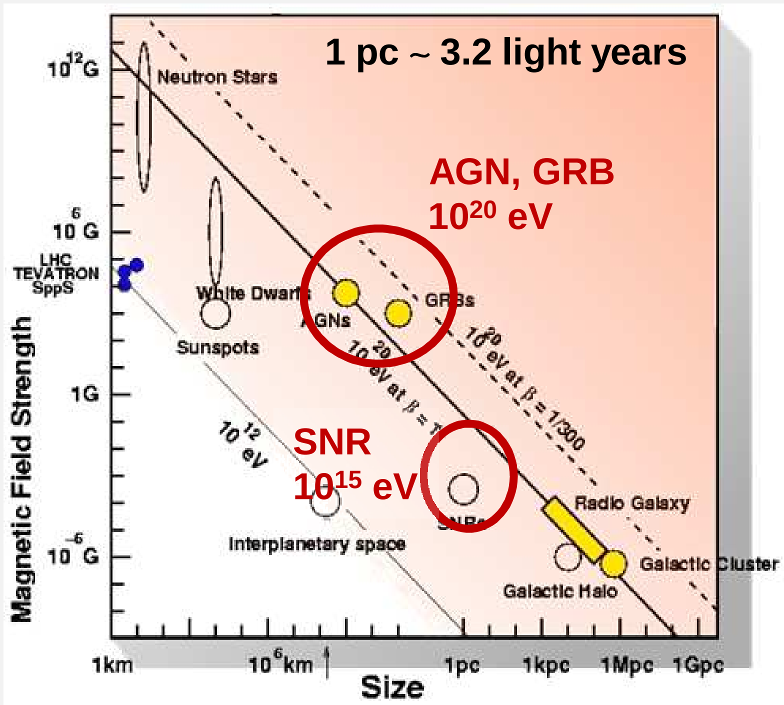
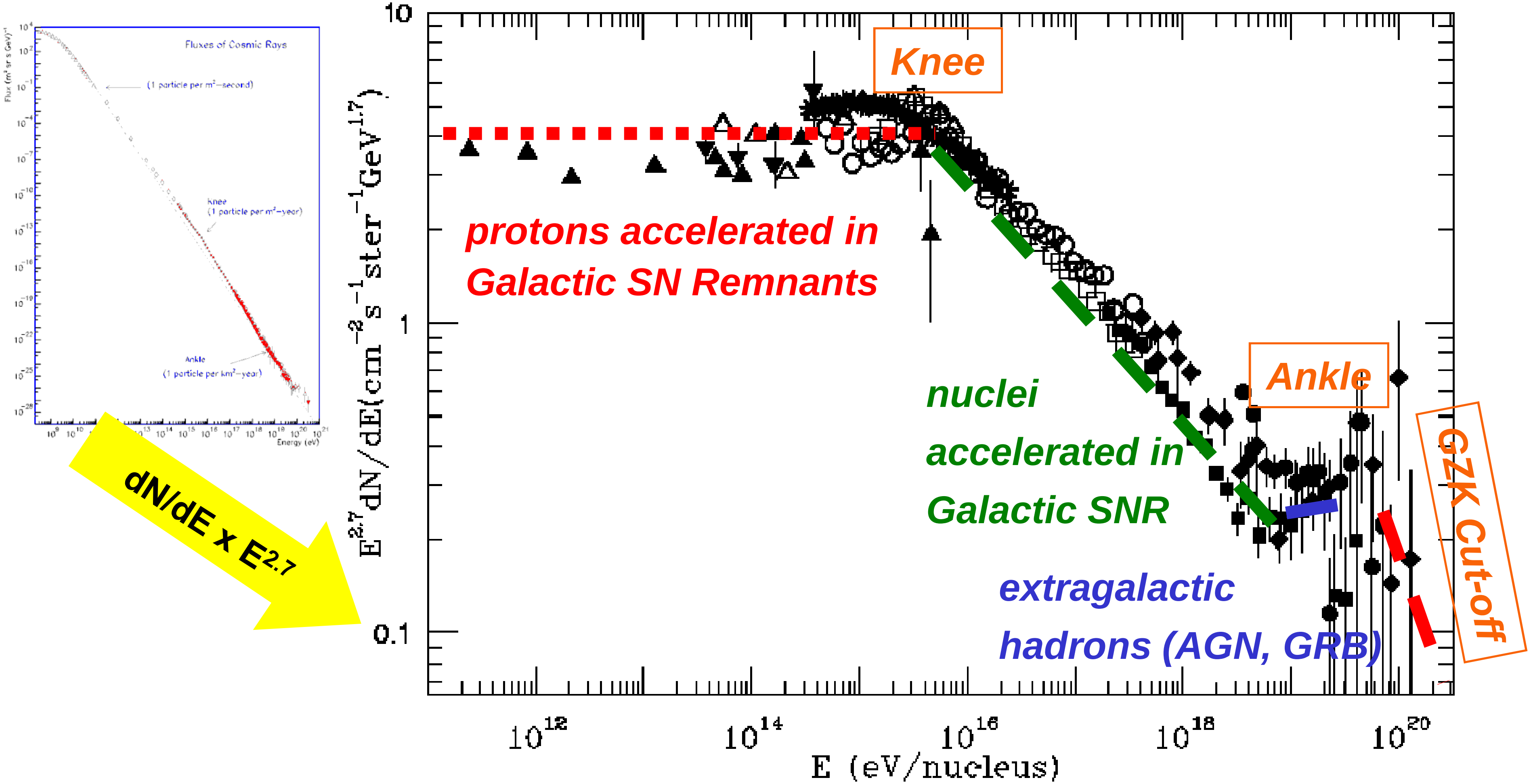
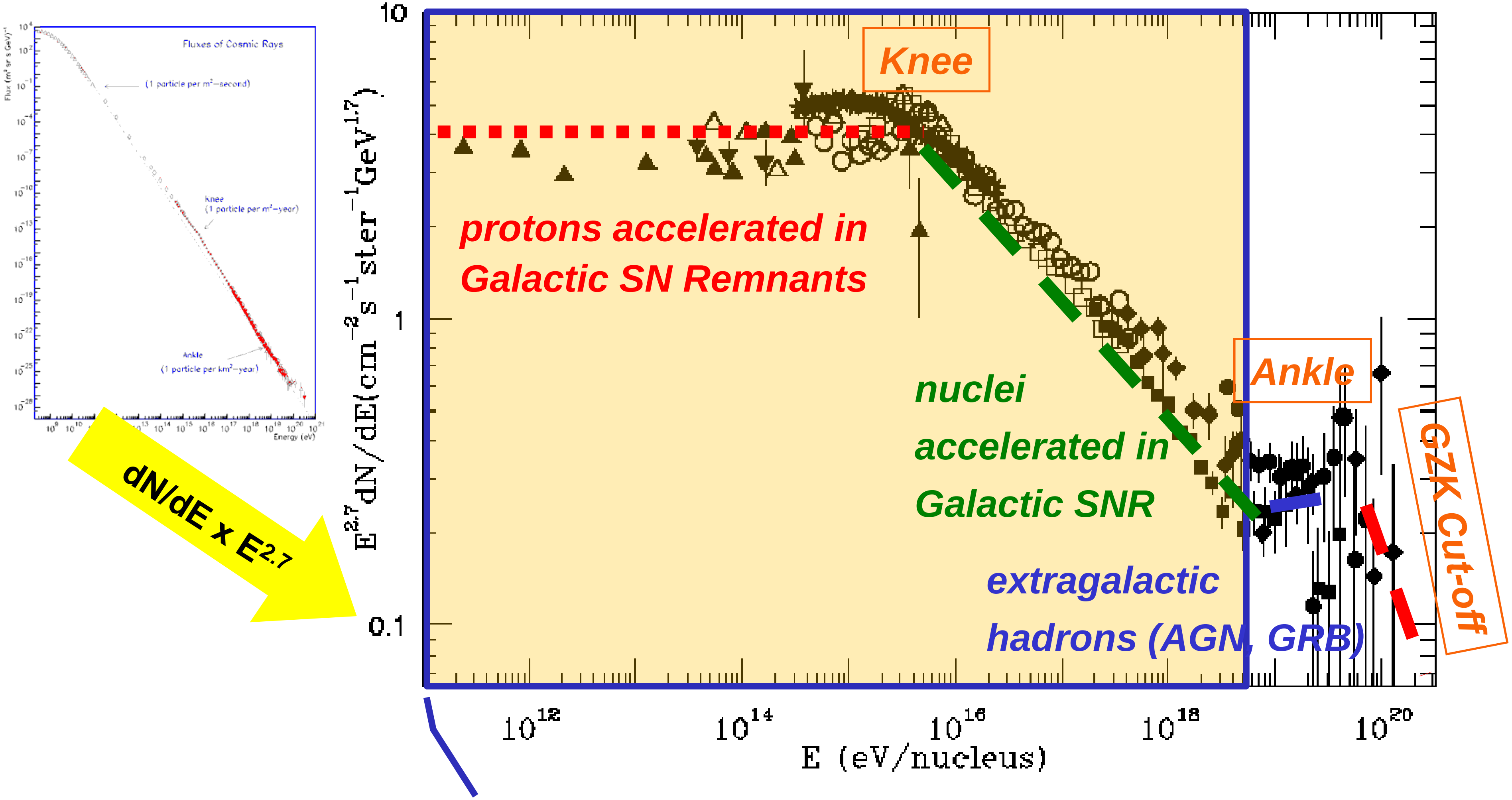


CR Origin: the standard scenario

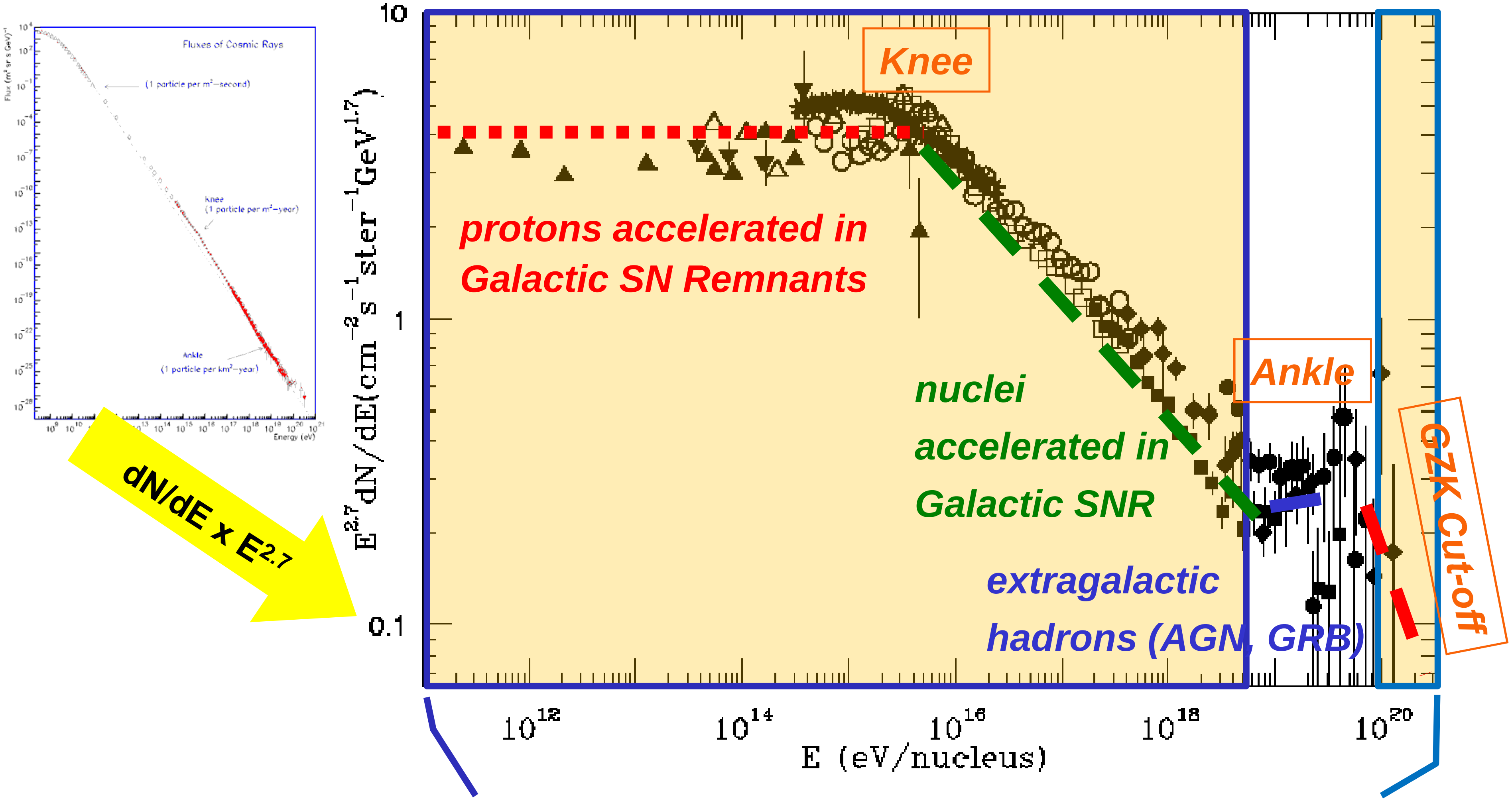


CR Origin: the standard scenario



Hadrons deflected by the Galactic magnetic fields

CR Origin: the standard scenario



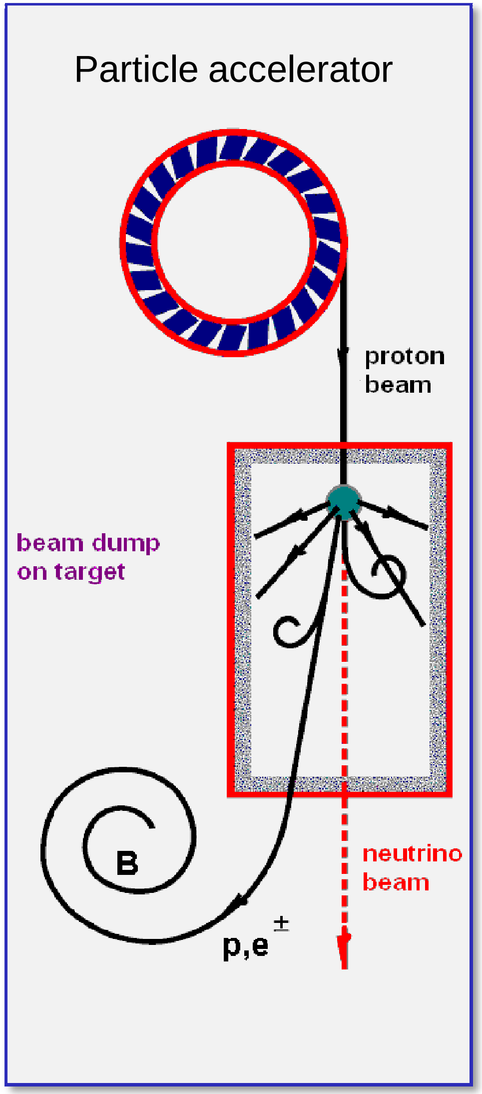
Hadrons deflected by the Galactic magnetic fields

Hadrons absorbed by the interaction with CMBR (GZK effect): p + CMBR → Δ^+ ($L^P_{attenuation}$ ~ 50 Mpc)

Astrophysical sources produce high energy hadrons

The astrophysical beam dump

Fermi acceleration of protons and electrons in astrophysical sources



Spectrum $dN_{p,e}/dE \propto E^{-2}$

Hadronic HE ν and γ production

$p + p$ (SNR, X-Ray Binaries) → X, π

$p + \gamma$ (AGN, GRB, μQSO) → N, π

Same interaction as GZK

Decay of pions

neutral pions* → HE *gammas

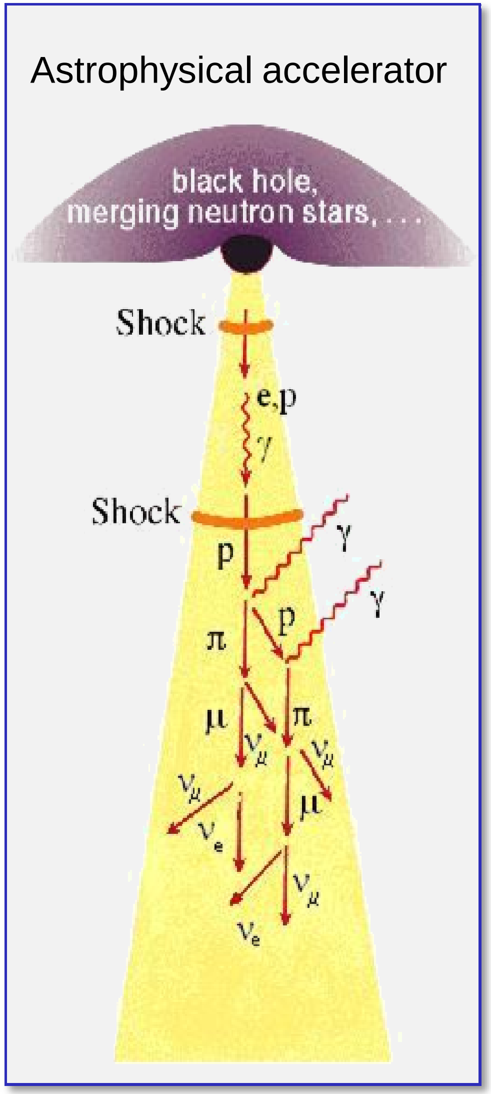
charged pions* → HE *neutrinos

Leptonic HE γ production

synchrotron radiation followed by IC

$e + \gamma_{Synchrotron} \rightarrow e' + \gamma'_{HE}$

$L_{attenuation}$ (γ_{HE} + CMBR) ~ 10 Mpc

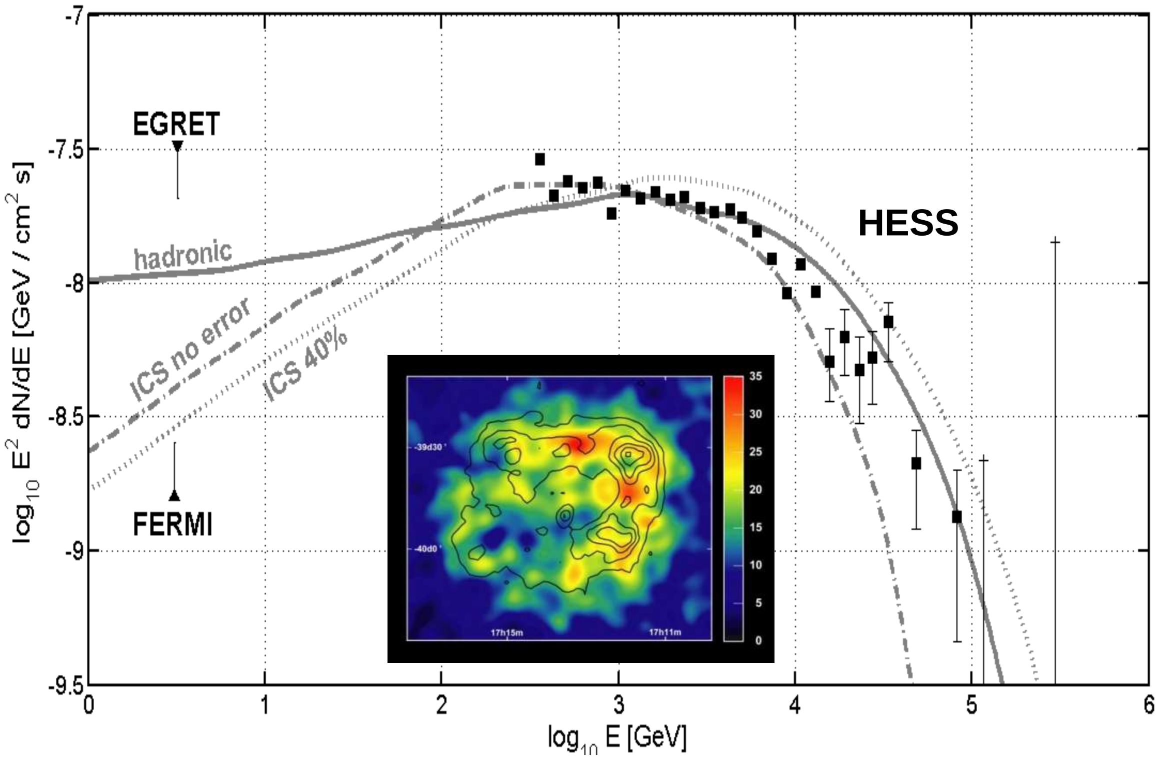


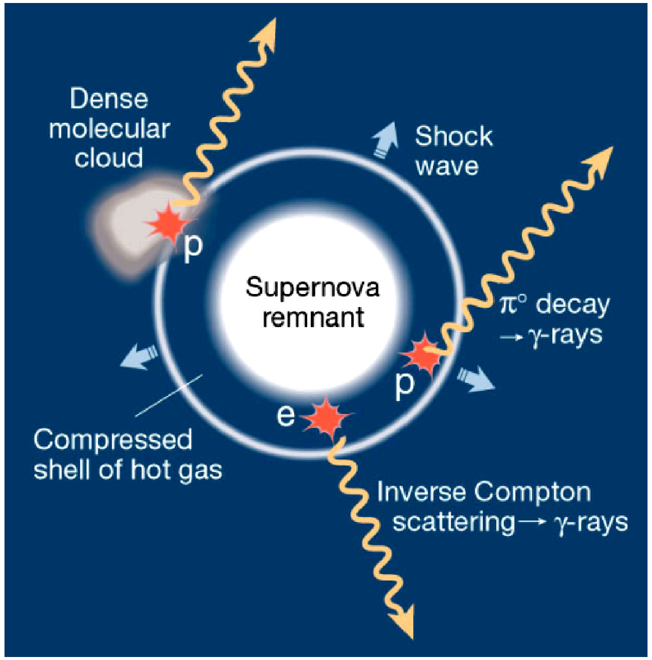
First Hadronic Gamma Ray Sources detection ? (HESS)

The Galactic SNR RXJ1713.7-3946:

proton acceleration + beam dump on nearby molecular clouds

- ***Power law spectrum $E^{-\gamma}$ observed up to 30 TeV***
- ***Spectral index $\gamma \approx 2$ implies acceleration of primaries up to 1000 TeV***
- ***Spectrum hardly explainable with IC mechanisms***





Neutrinos are the ultimate smoking gun for hadronic processes

Very large volume neutrino detectors

Neutrino astronomy can:
- ***disentangle between purely leptonic and hadronic source models***
- ***identify CR sources***
- ***probe the far and violent Universe***

→ **Low neutrino cross section**
→ **Faint astrophysical neutrino fluxes expected**

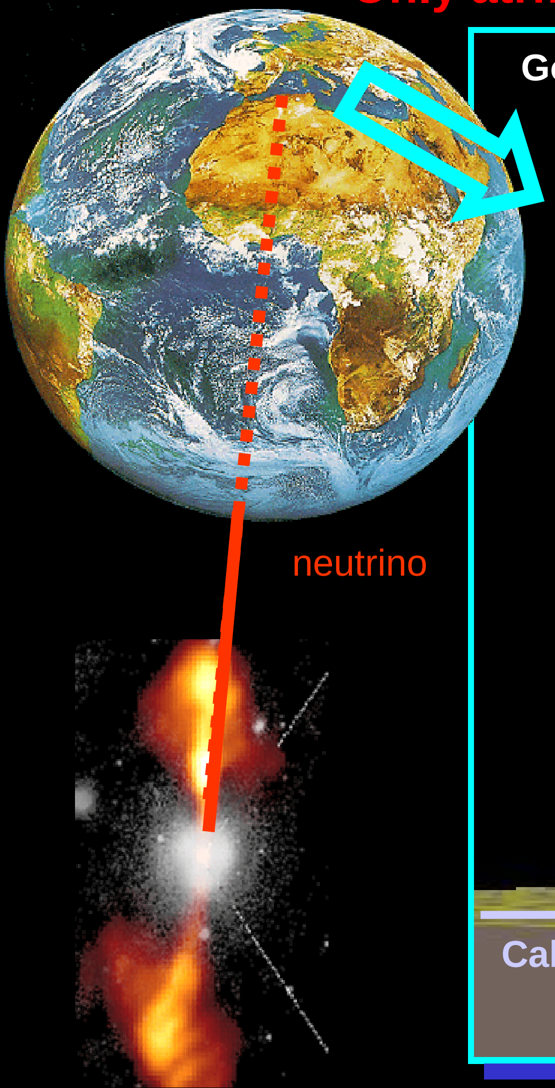
Detector size $\geq$ 1 km^3

Use natural targets. Deep seawater and polar ice cap offers:

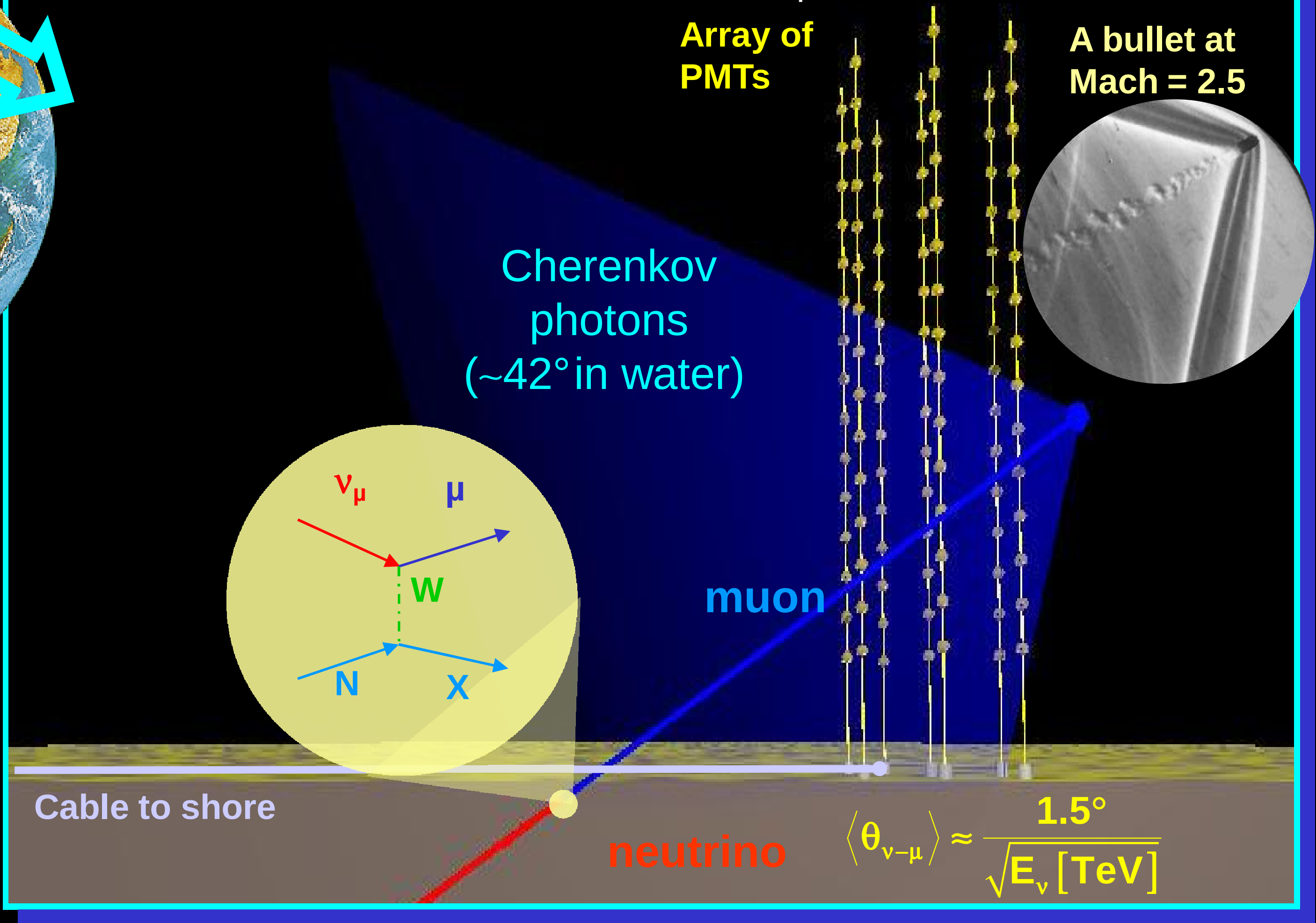
- ***huge (and inexpensive) target for neutrino interaction;***
- ***shielding from cosmic background;***
- ***good characteristics as optical and radio Cherenkov radiators;***
- ***good characteristics as acoustic wave propagators***

Underwater Cherenkov HE neutrino detectors

Look at upgoing muons: use the Earth as a filter
Only atrmopheric and astrophysical neutrinos can cross the Earth



Golden channel: througoing muon from CC ν_μ interaction



neutrino telescope !

IceCube:The first km3-scale neutrino telescope

Location: Geographic South Pole

Completion: January 2011

80 strings (60 PMT each)

4800 10”PMT (only downward looking)

125 m inter string distance

16 m spacing along a string

Instrumented volume: 1 km^3 (1 Gton)

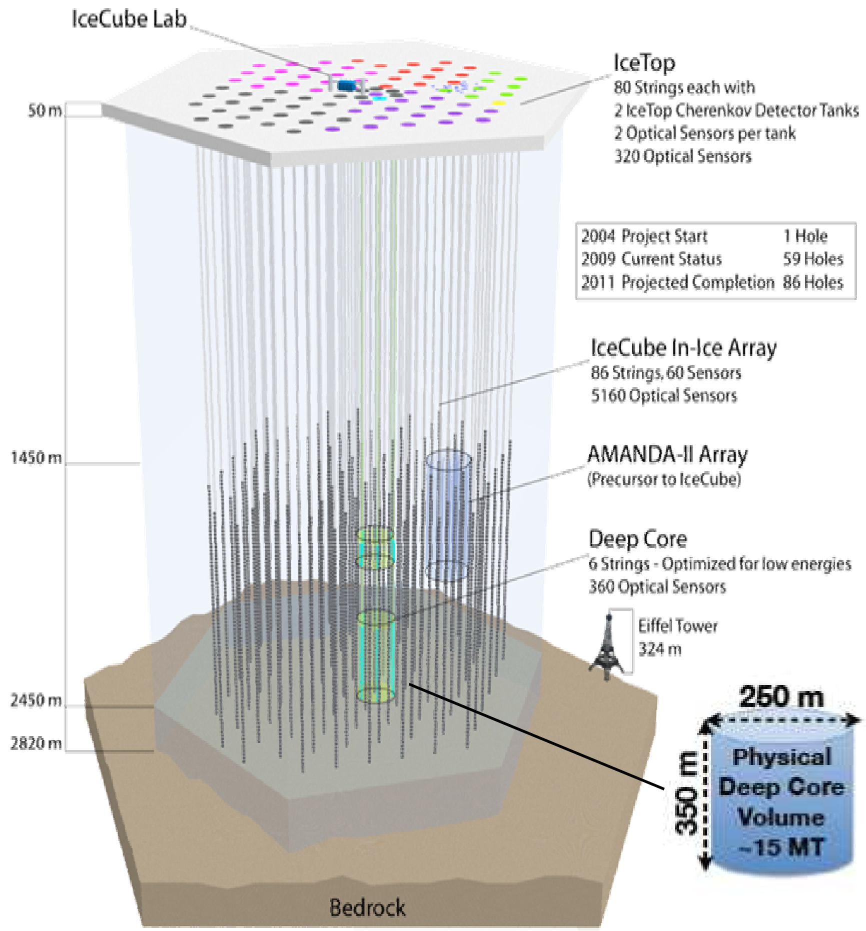
Technology and science goals proven by the small scale detector AMANDA (1996-2007)

IceCube is taking data during construction

This year:

73 IceCube Strings

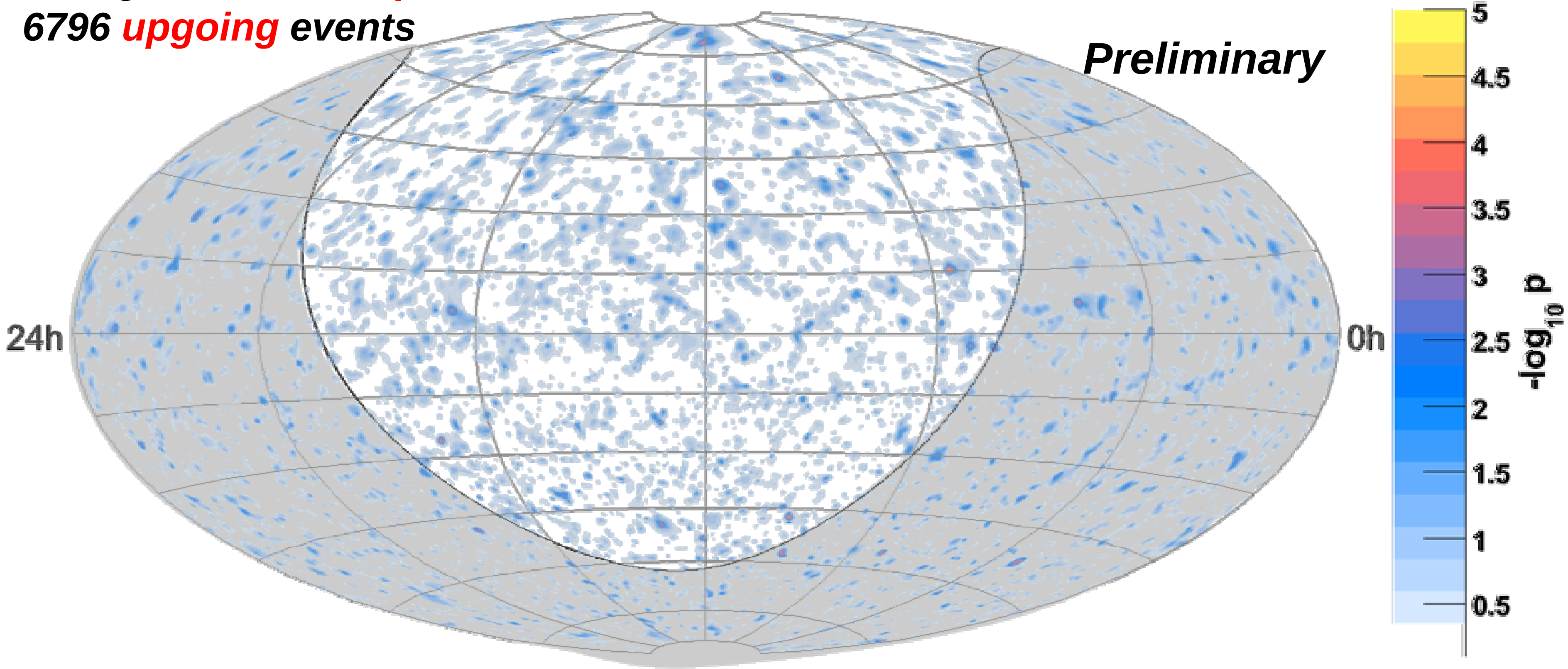
Deep Core (6 strings, High QE PMTs)



IceCube: Search for point sources

Northern hemisphere
Background: atmospheric neutrinos
6796 upgoing events

Adapted from A.Karle, 2009



IceCube 40 strings (IC-40)
175.5 days livetime
Angular resolution about 1
Muon rate: 1 kHz
Neutrino rate: 110/day

No ν source found yet

IceCube: Search for point sources

Northern hemisphere
Background: atmospheric neutrinos
6796 upgoing events

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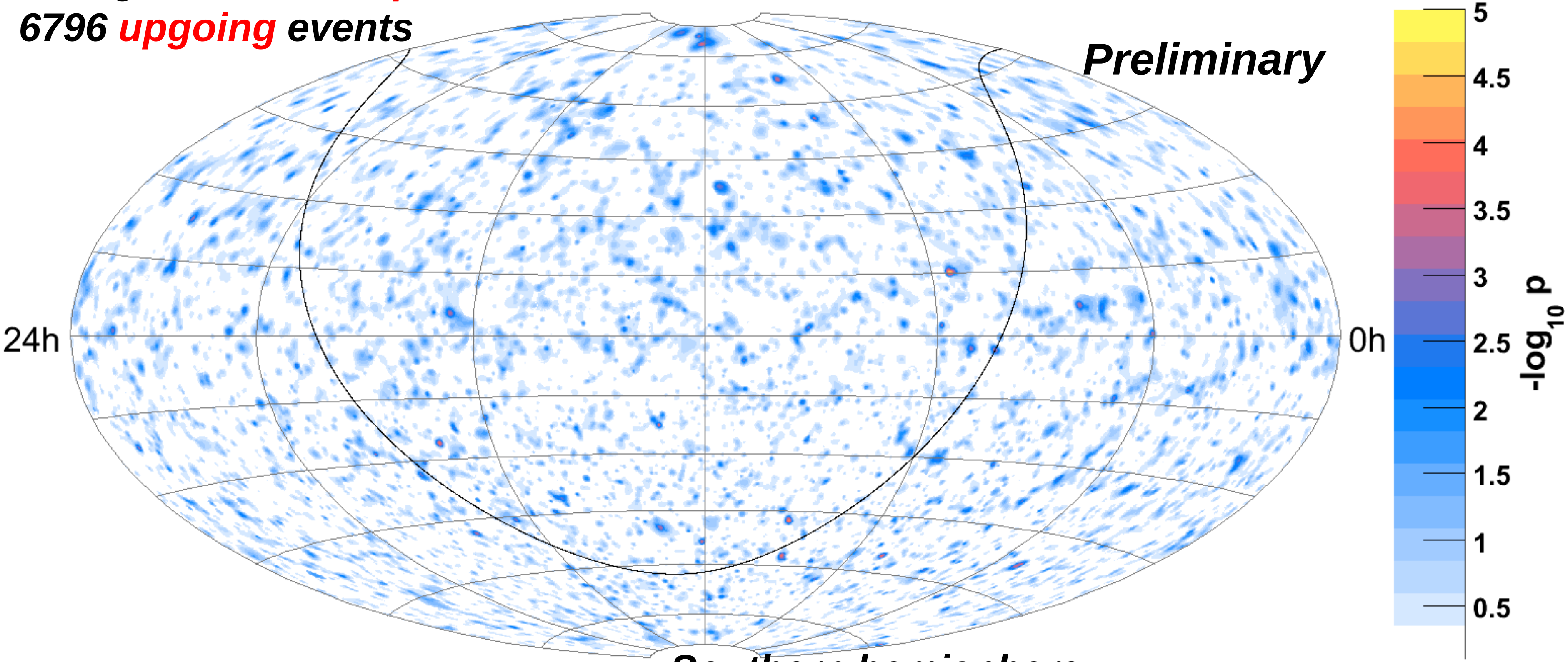
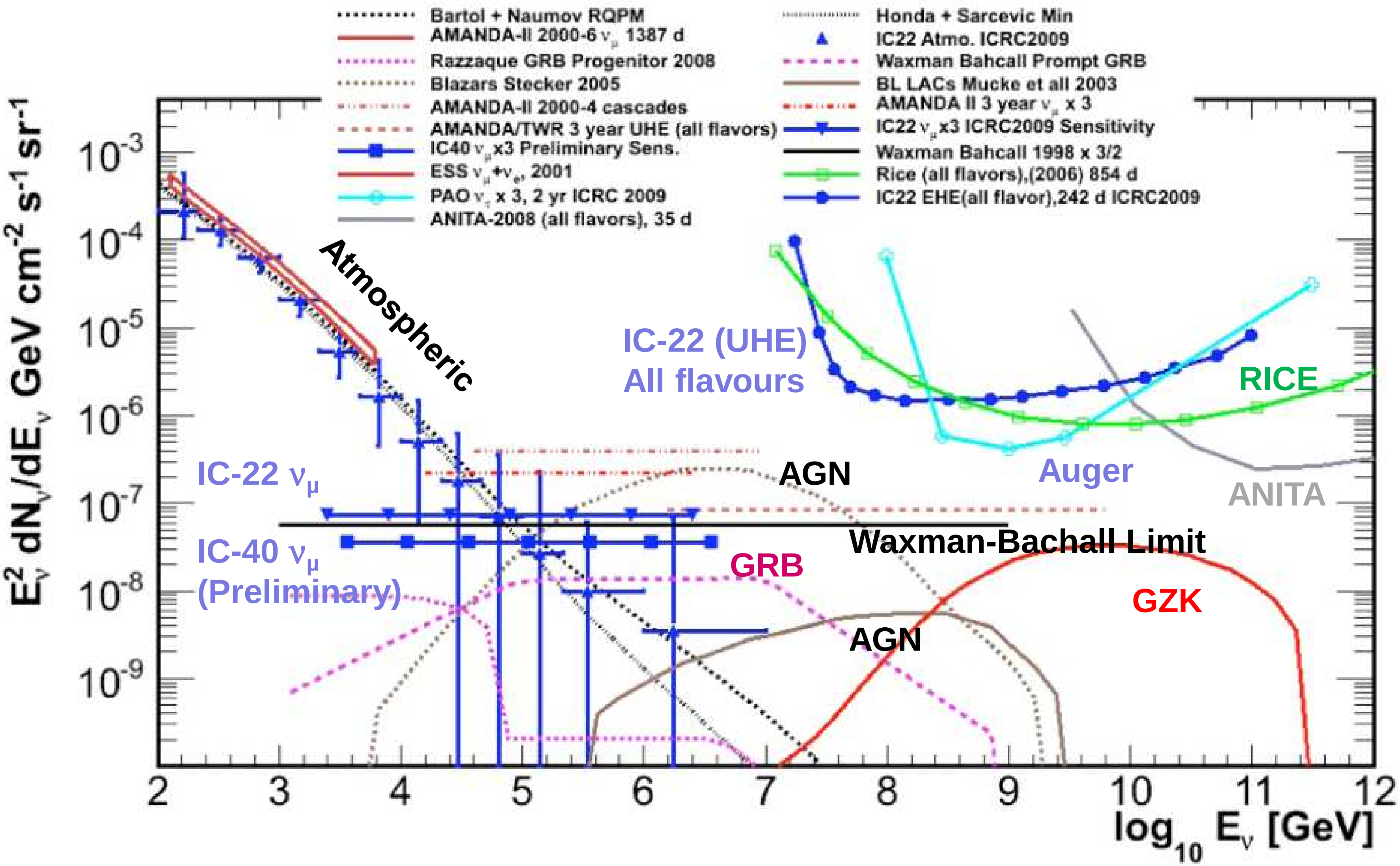


Southern hemisphere
Background: atmospheric muons
Reduced by 10^{-5} using energy cut
10981 downgoing (high energy) muon events

IceCube 40 strings (IC-40)
175.5 days livetime
Angular resolution about 1°
Muon rate: 1 kHz
Neutrino rate: 110/day

No ν source found yet

IceCube: limits to diffuse neutrino fluxes



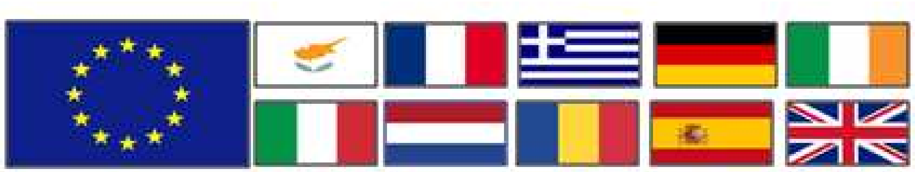
IC-40: $dN/dE \cdot E^2 < 1.17 \cdot 10^8$ GeV cm^{-2} s^{-1} sr^{-1} (3.7 TeV< E_ν <3.7 PeV)

Towards the Mediterranean km^3

→ **Need two telescopes (North and South Hemisphere) to cover the whole sky.**

→ **The Galactic Centre can be seen only from the Mediterranean telescope**

KM3NeT



Born from the experience of the Mediterranean pilot projects:

ANTARES
NEMO
NESTOR

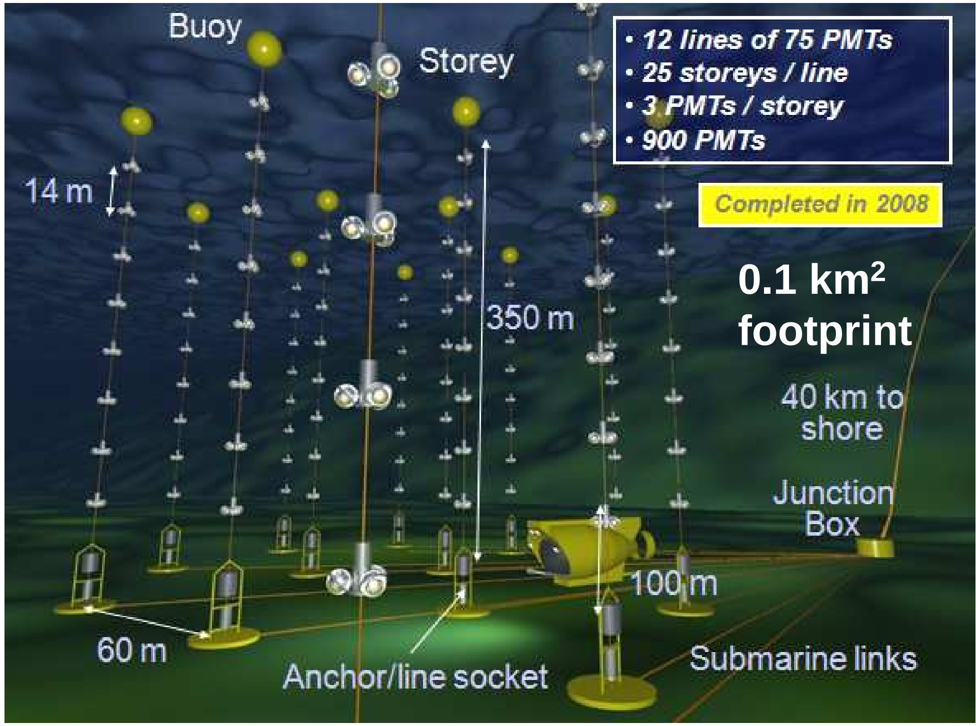
Intense technological R&D and coordination of Institutes

2006-2009	KM3NeT Design Study, Coordinated by Uni. Erlangen
2009-2012	Preparatory Phase, Coordinated by INFN

Goal: KM3NeT ~3 more sensitive than IceCube

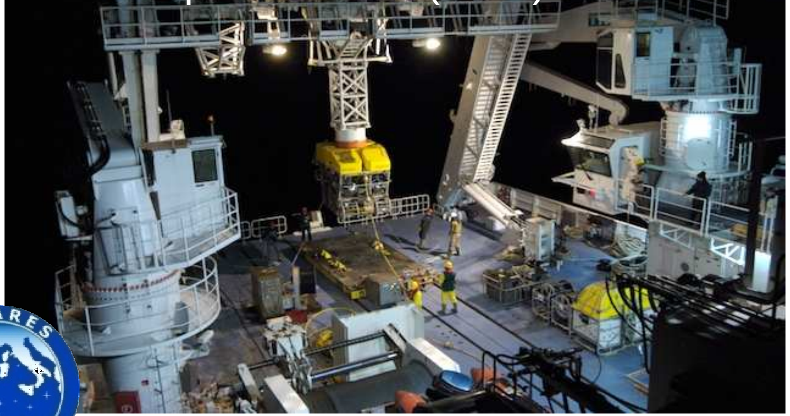
- larger total photo-cathode area (larger detector)
- better direction resolution (sea water)

Towards the Mediterranean km^3: ANTARES

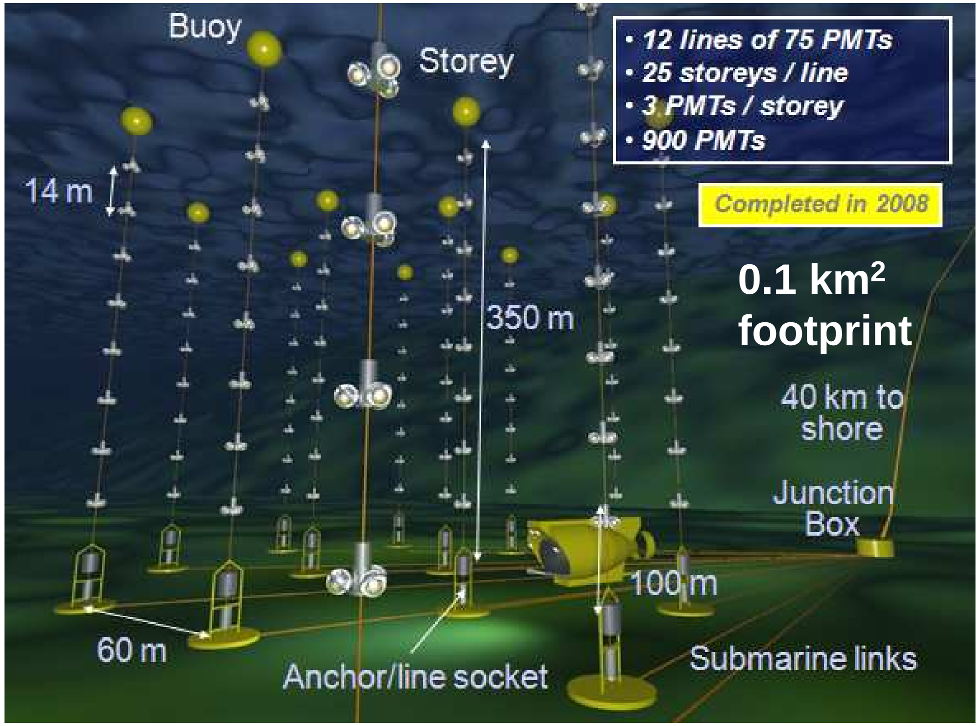


An ANTARES Line ready for the deployment

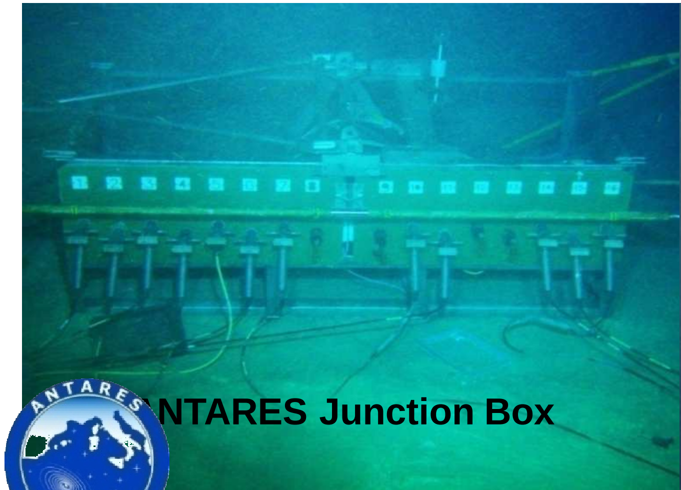
The deep sea Robot (ROV) VICTOR



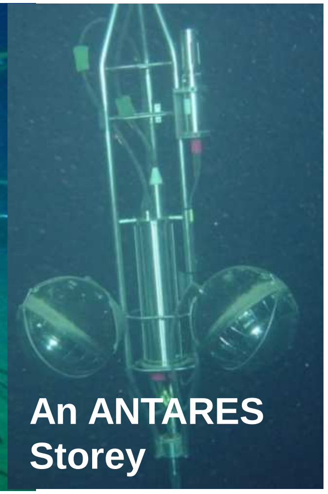
Towards the Mediterranean km^3: ANTARES



An ANTARES Line ready for the deployment

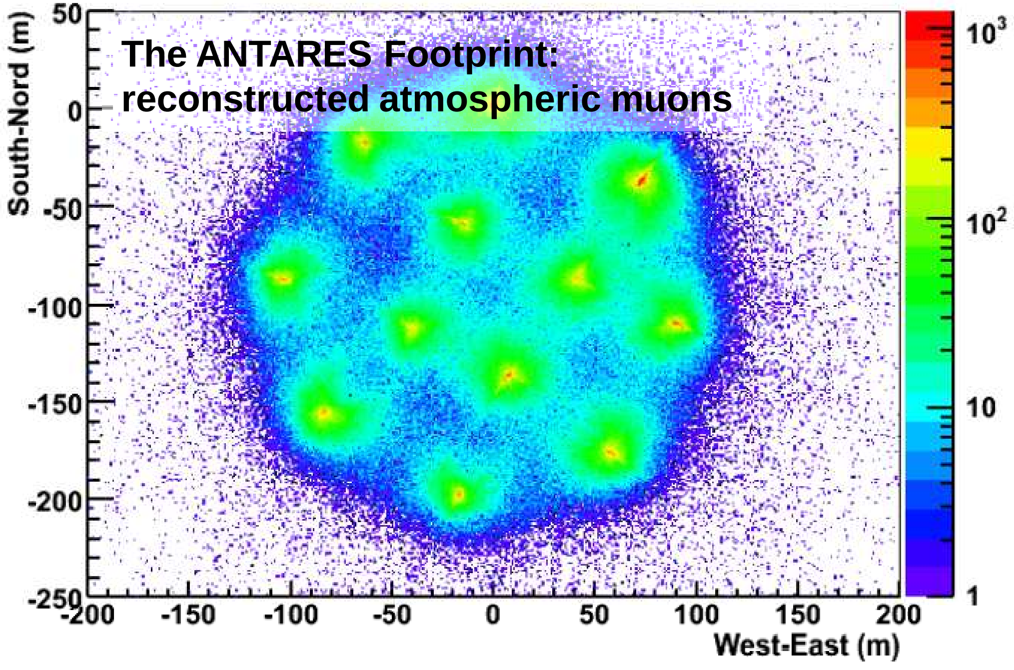


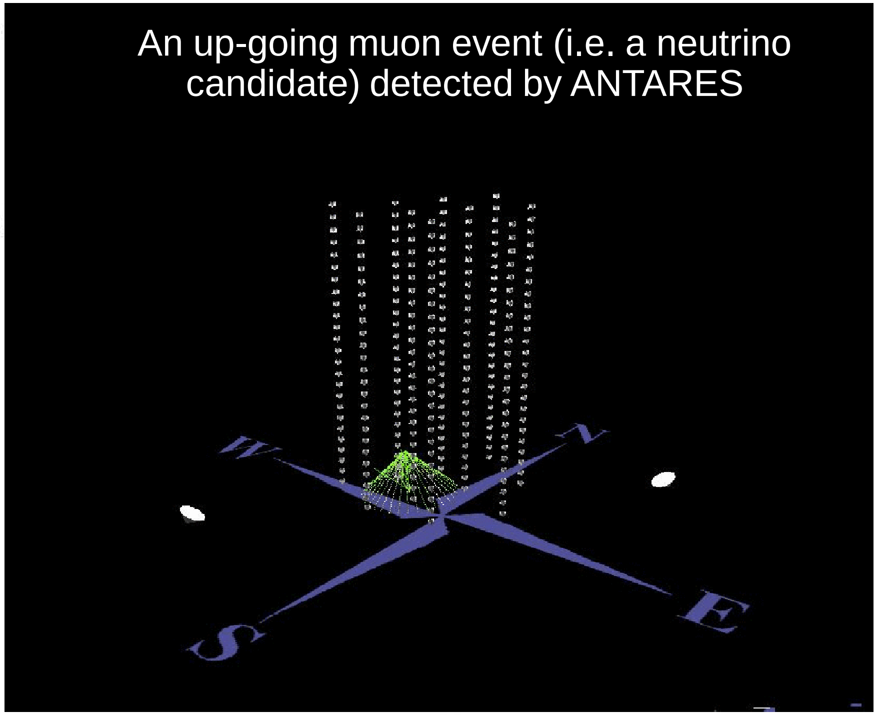
NTARES Junction Box

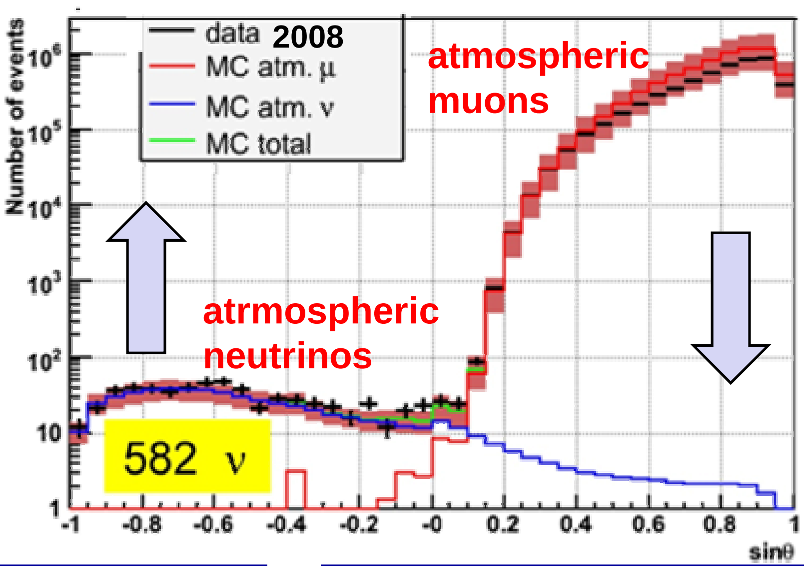


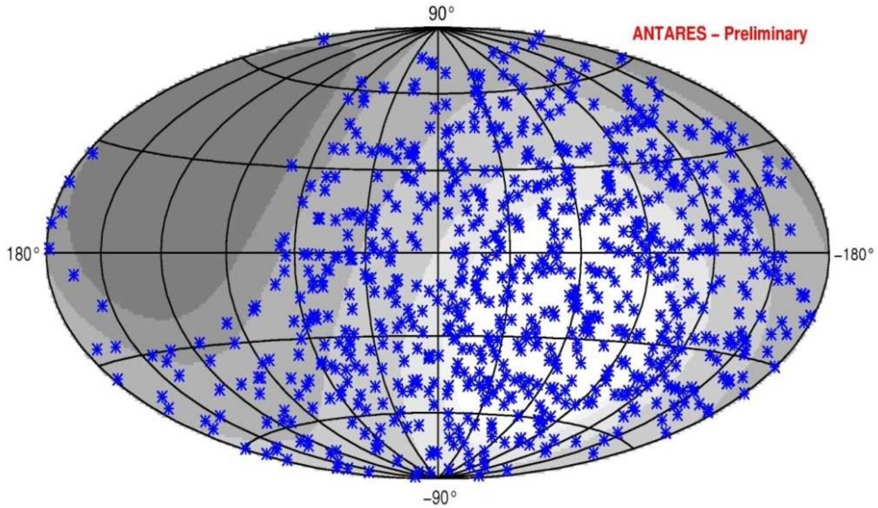
An ANTARES Storey

Towards the Mediterranean km³: ANTARES





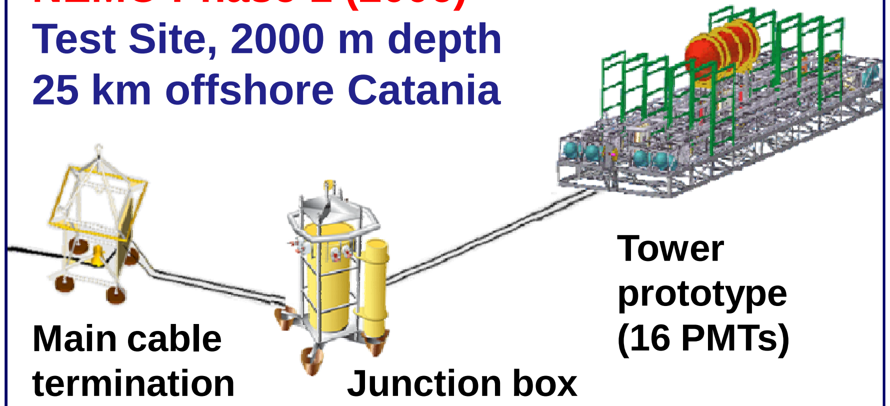


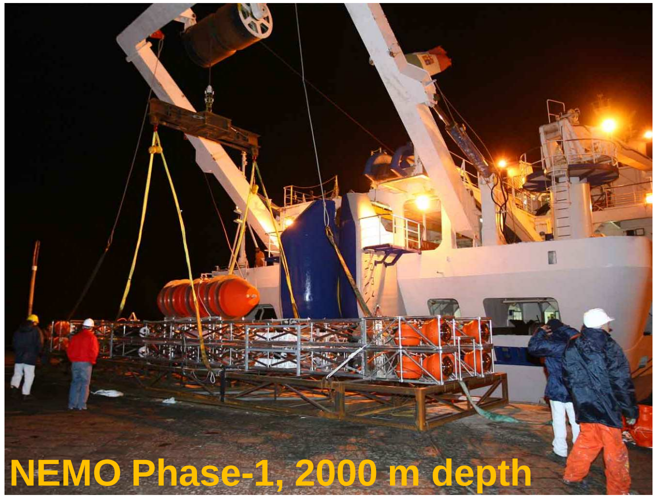


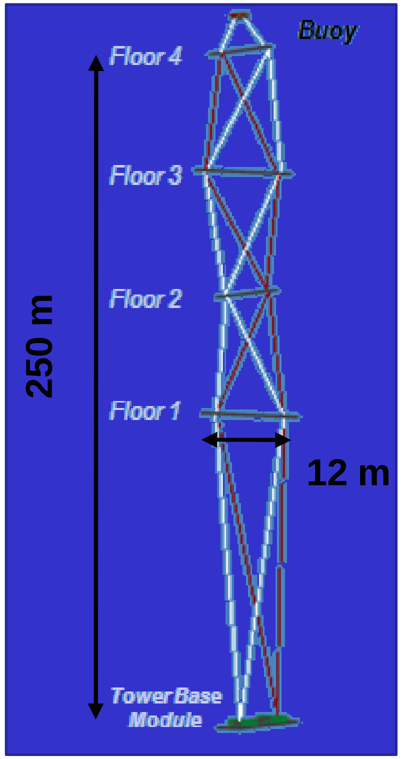
750 up-going neutrinos 2007+2008 data

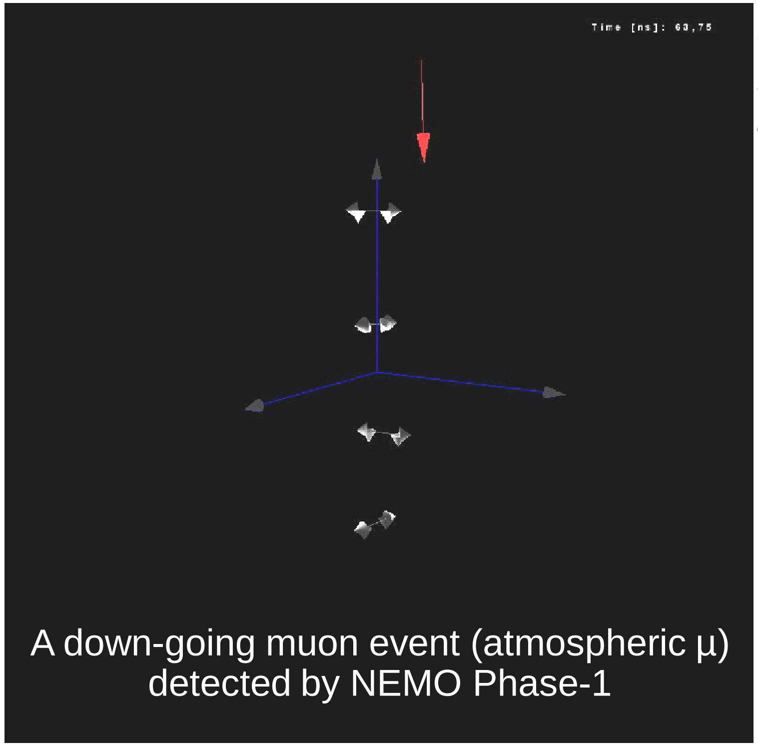
Towards the Mediterranean km^3: NEMO

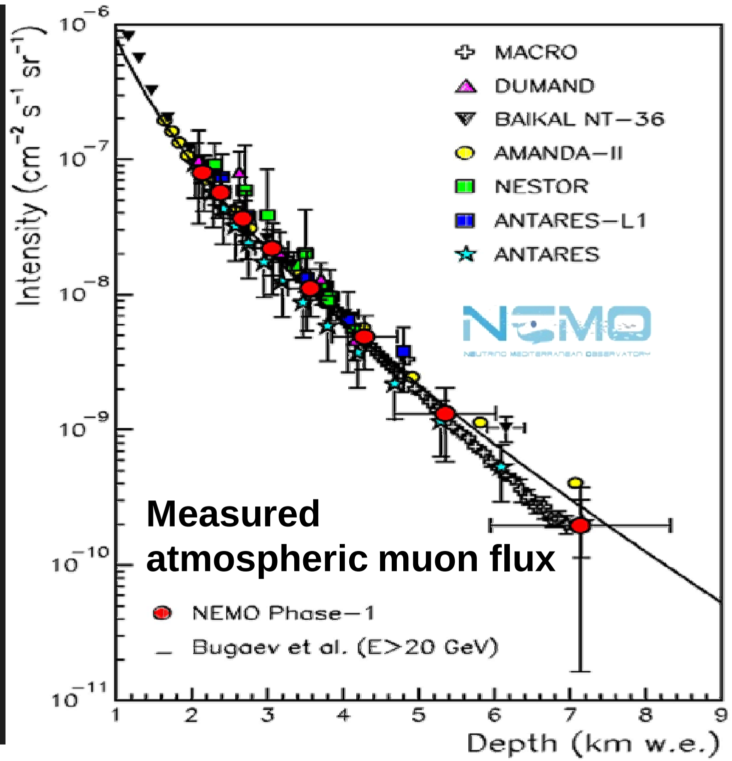
NEMO Phase 1 (2006)
Test Site, 2000 m depth
25 km offshore Catania







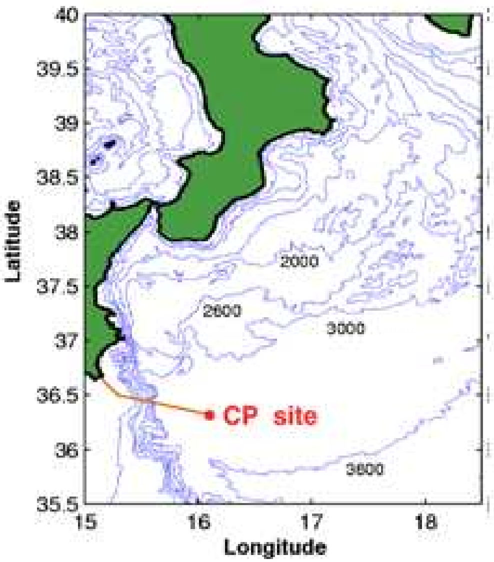




Towards the Mediterranean km³: NEMO

Capo Passero Site

- 3500 m depth, wide plateau, optimal water properties
- 100 km main electro-optical cable, laid and working
- 10 kVDC/400 VDC converter (MVC) installed and working
- Shore Lab completed
- Optical fibre link Capo Passero/LNS-INFN, in GARR-X
- Deep Sea ROV PEGASO (INFN-INGV)




Shore Laboratory in Capo Passero Harbour

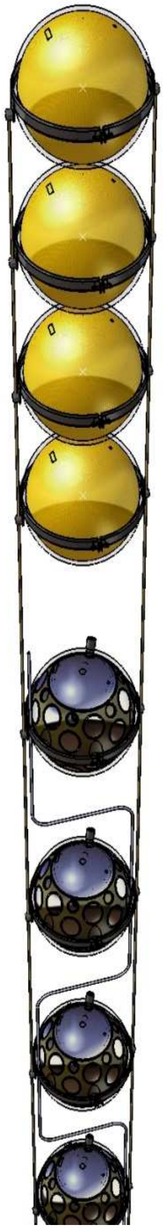

Installation of the ALCATEL MVC


The PEGASO ROV


The ANTARES Mini-Line ready for the deployment

Deployment of an ANTARES Mini-line (soon)
Deployment of the KM3NeT bar prototype tower (2011)

KM3NeT: Slender String vs. Flexible Bar Structure



Slender String (NIKHEF / NIOZ / NESTOR)

Evolution from the ANTARES string

1D displacement of OMs : 670 m, 20 storeys, 20 OM

Reduce connections (1 connector per OM)

Multi PMT optical module used

Unfurling from Sea bed

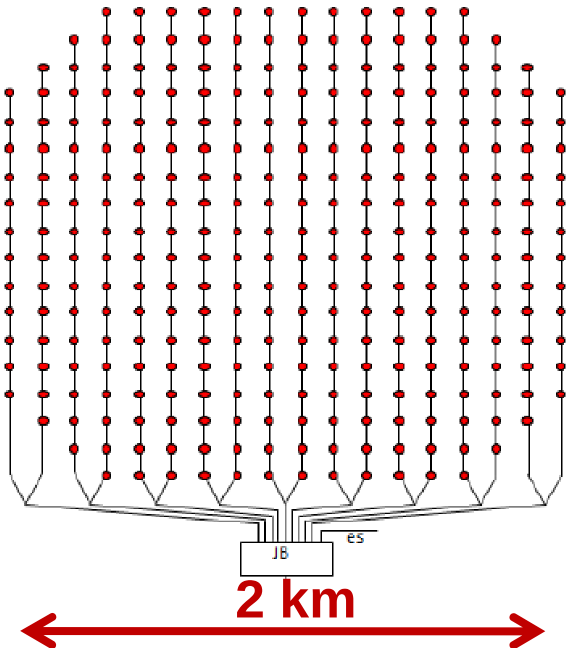
Unfurling method tested with few problems

New tests within 1 year

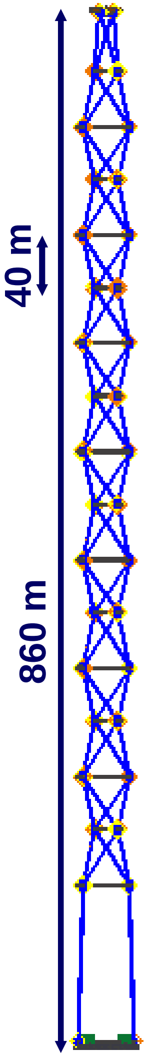
Multi PMT OM (32 x 4'' PMTs)

Detector Building Block

310 Detection Units @ 130 m



KM3NeT: Slender String vs. Flexible Bar Structure



Bar Structure

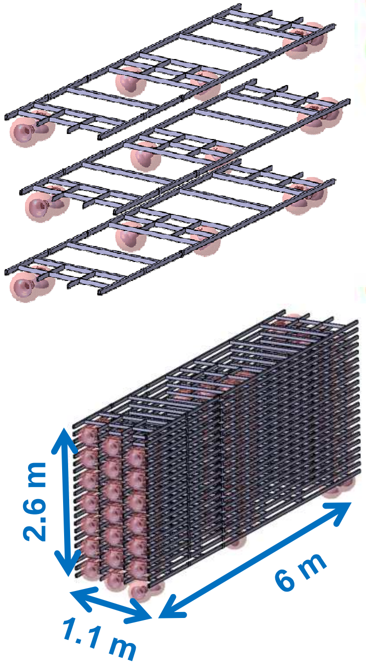
Bar Structure (INFN / IN2P3 / CEA): Evolution from the NEMO tower

3D displacement of OMs : 6 m-long storey, 6 OM/storey, 20 storeys
- Improve angular resolution at low energy
- Improve overall detector sensitivity

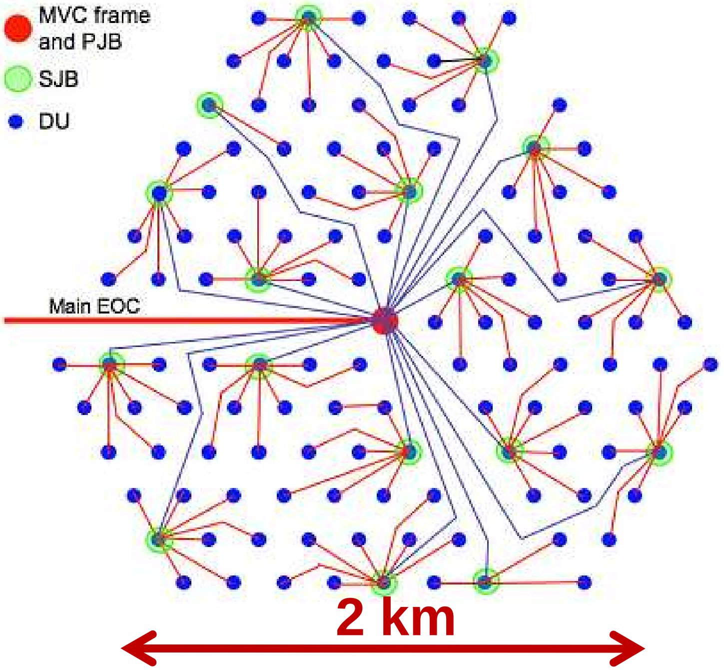
Unfurling from Sea bed
- Structure compact before sea operation
- Easier and faster deployment

Intense test activity:
5 deployments in next year

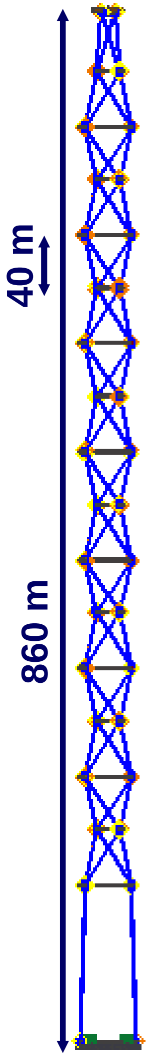
Feb 2010 - NEMO deployment
12 storeys, 10 m

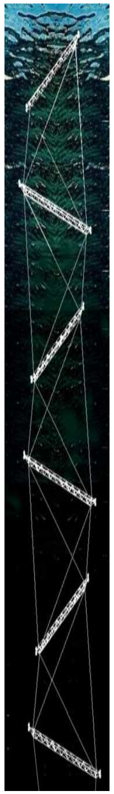


Detector Building Block
154 Detection Units @ 180 m



KM3NeT: Slender String vs. Flexible Bar Structure





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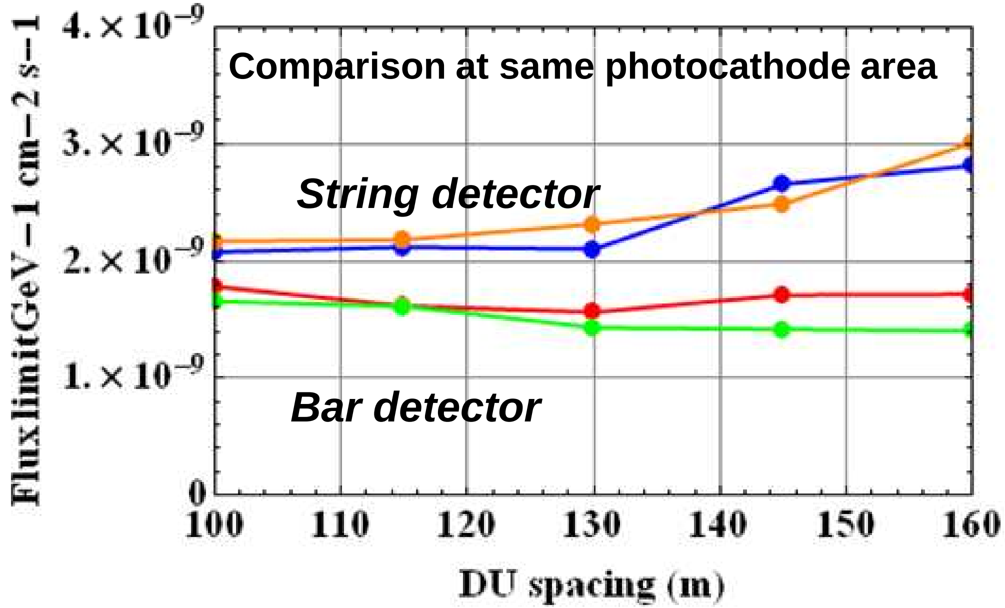
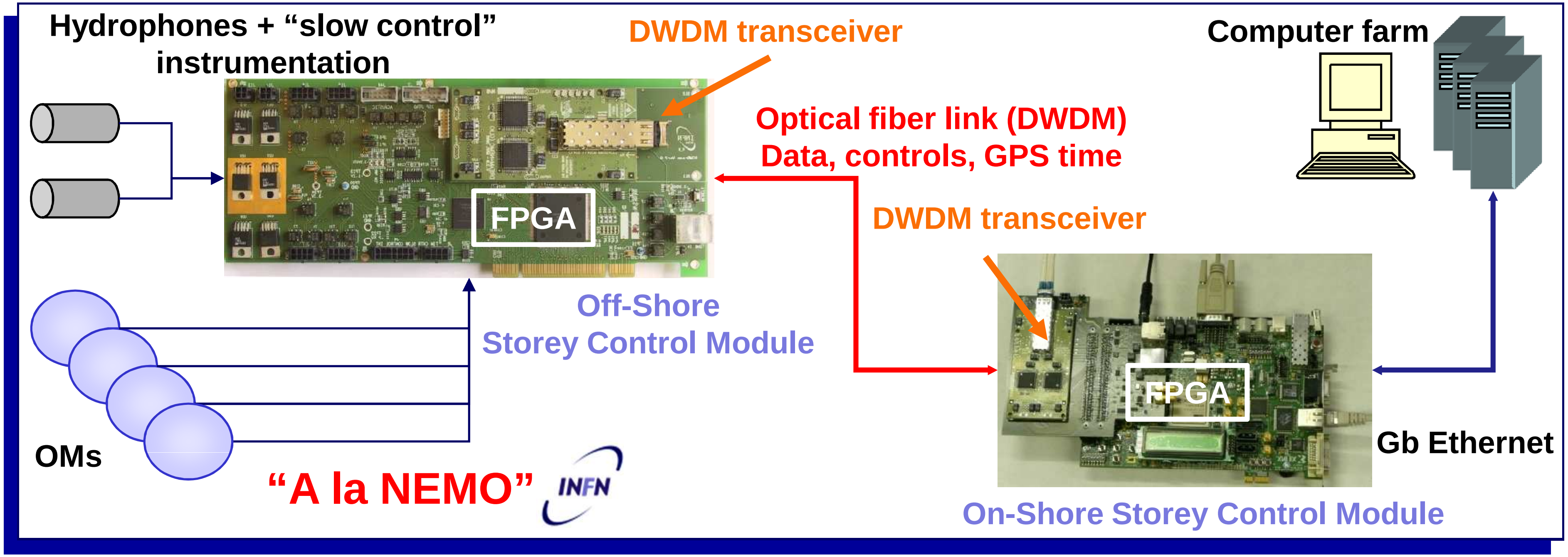
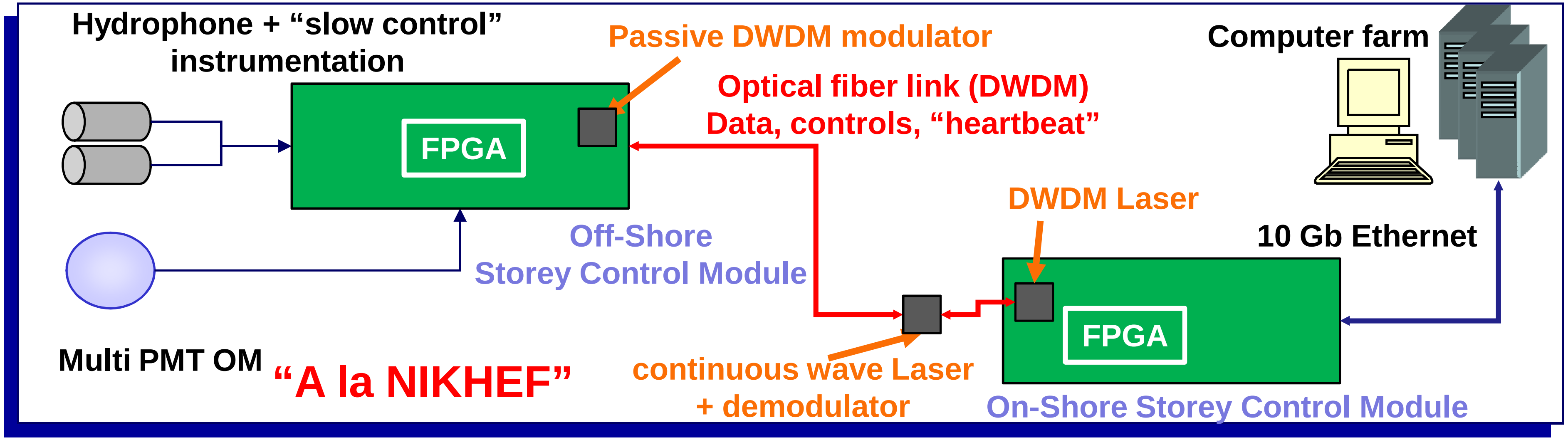


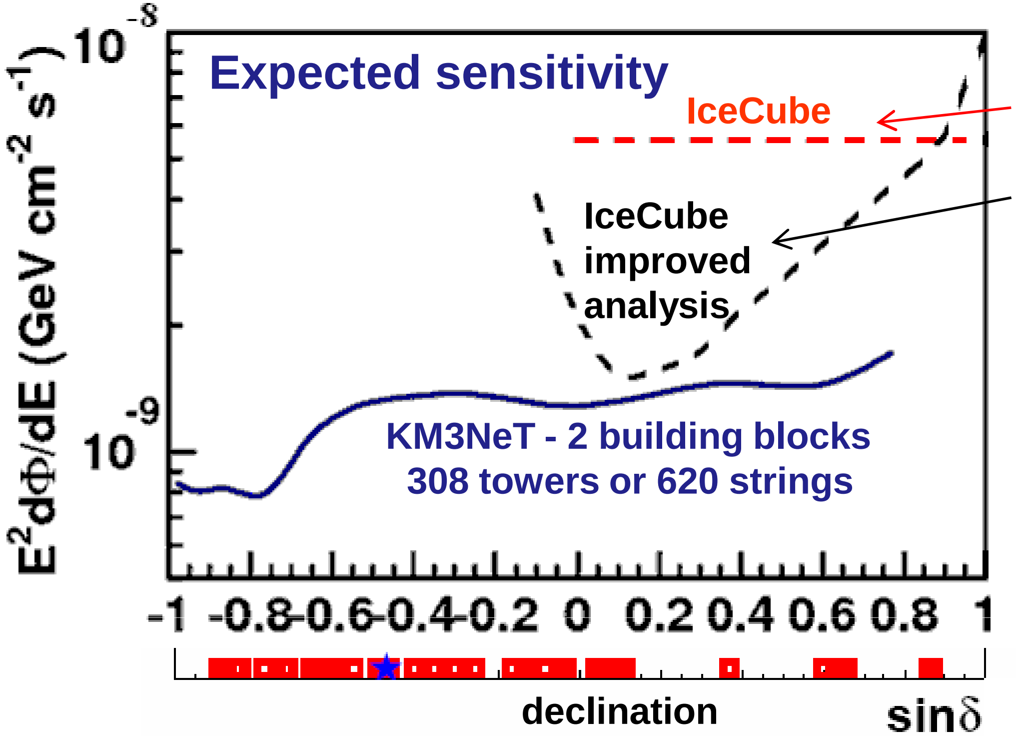
KM3NeT : Electronics

Point to point connection from each storey to shore





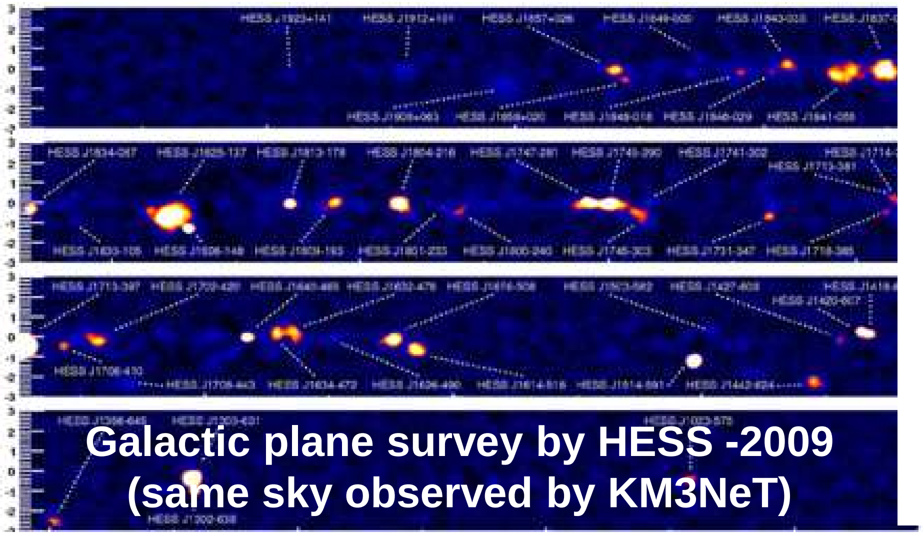
KM3NeT: Expected physics performances

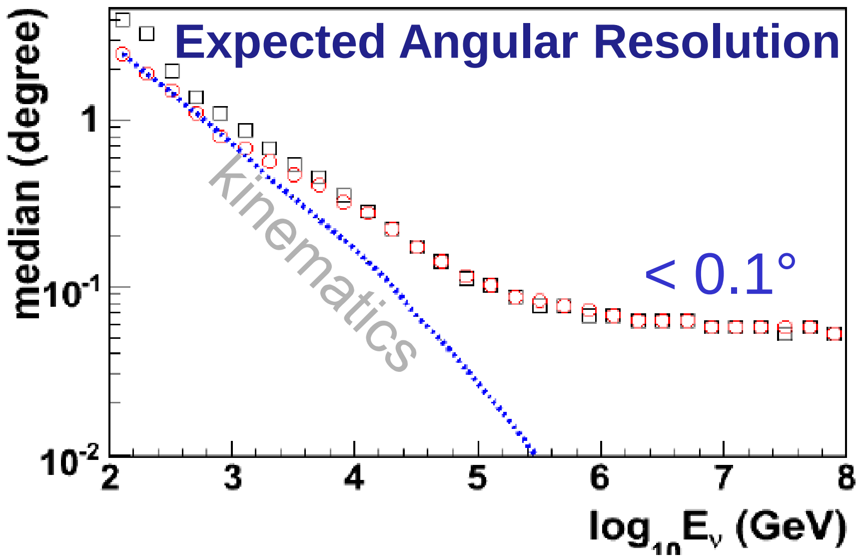


Aharens et al. AstroP. Phys.(2004)

Abbasi et al. Astro-ph (2009)

□ Observed Galactic sources
F. Aharonian et al. Rep. Prog. Phys. (2008) and
Abdo et al. Astrophys. Jour. 658 L33-L36 (2007)
★ Galactic center





KM3NeT: Earth and Sea Science

KM3NeT: a large deep sea infrastructure incorporating a VLV neutrino telescope

Deep sea covers the largest part of planet Earth and it is almost totally unexplored

Common efforts with the Earth and Sea Science Community

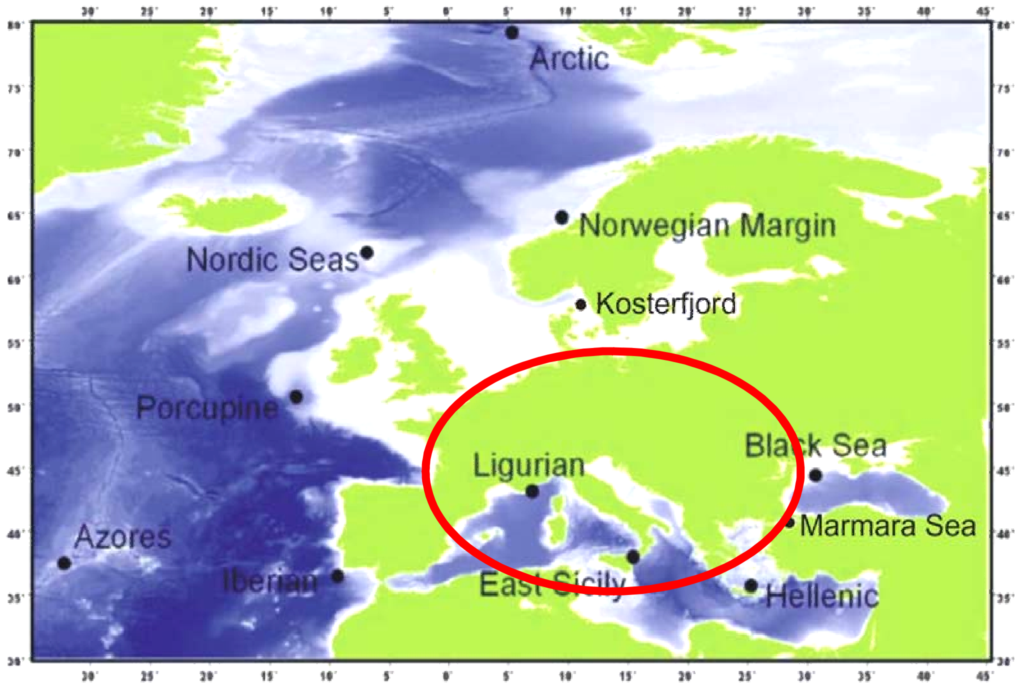
ESONET NOE

Coordinated by IFREMER (France)

european multidisciplinary seafloor observatory emso

Preparatory Phase

Coordinated by INGV (Italy)



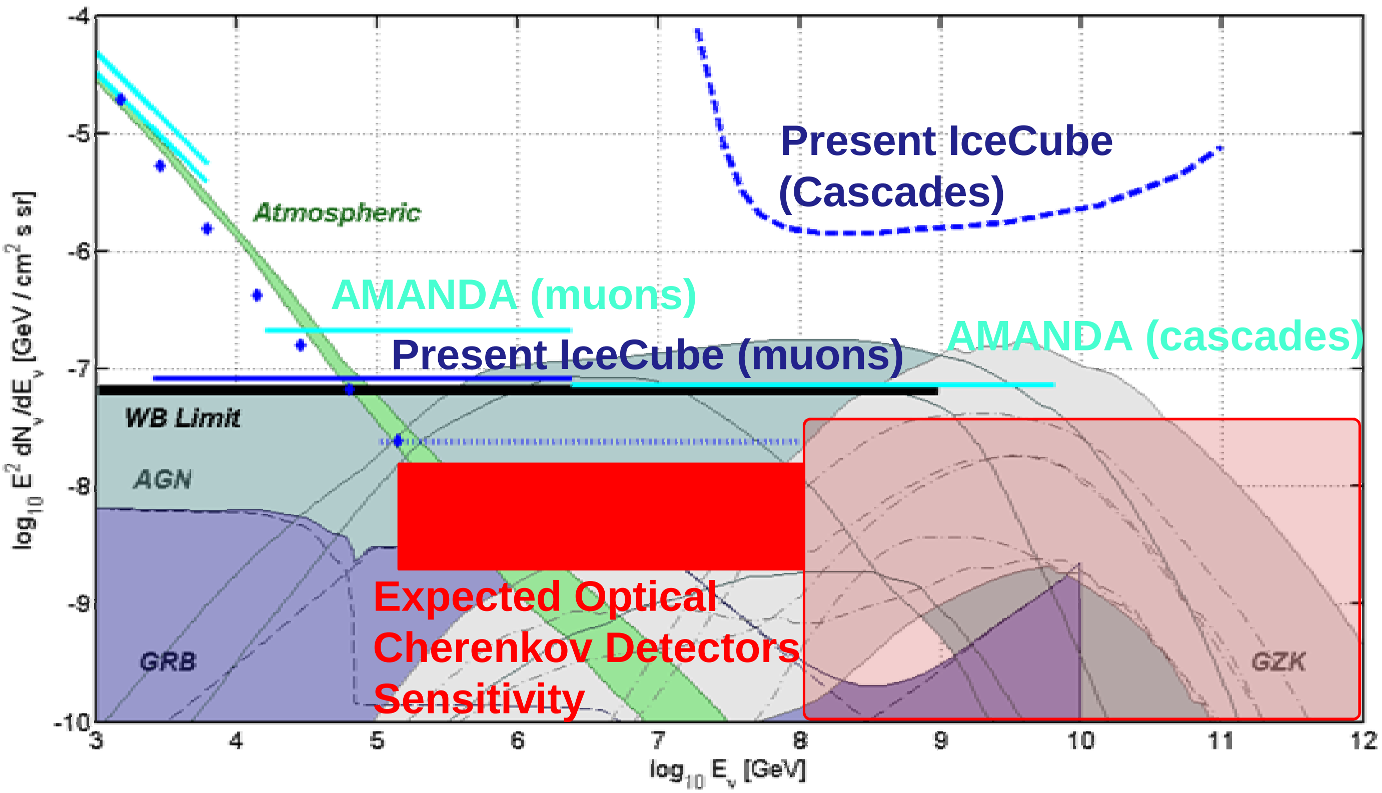
Real Time Envionmental Monitoring

Geophisics (geohazard):
Seismic phenomena, low frequency passive acoustics, magnetic field variations,...

Oceanography (water circulation, climate change):
Current intensity and direction, Water temperature, Water salinity ,...

Biology (micro-biology, cetaceans,...):
Passive acoustics, Biofouling, Bioluminescence, Water samples analysis,...

Looking for GZK neutrinos...



The obserbvation of the "guaranteed" GZK neutrinos requires larger detectors.

The optical Cherenkov technique is limited due to ligth absorption lenght in water and ice (<100 m).
Use different techniques to build larger (more sparse) arrays:
radio Cherenkov in ice (ANITA, IceRay) and acoustics in water (KM3NeT)

Conclusions

Clear science goal

Neutrinos are optimal probes to study far and violent Universe and identify the CR sources

IceCube

- **IceCube nearing completion (73 over 80 srings), Deep Core (6 srings) installed**
- **First results from AMANDA, IC-22 and IC-40 published:**
    - **Atmospheric Muon flux measured, Strong limits on HE neutrino fluxes and WIMPs**
- **IC40 and IC59 analyses under way**
- **Deep Core expected performances:**
    - **Reduce threshold to ~10 GeV**
    - **Increase reach for low mass dark matter**
    - **Extend searches to Southern Sky using veto techniques**

ANTARES

- **Detector Completed and taking data, Maintenance (recovery, substitution) proven**
- **2007-2008 data analysis under completion**

NEMO

- **Phase 1 completed: Deep sea technology (mechanics, electronics, ...) fully tested**
- **Bar structure physics performances demonstrated by the results of Phase 1 and KM3NeT MC**
- **Capo Passero Site infrastructure available and almost completed.**

KM3NeT

- **Scientific objectives fully met with 2 Detector Building Blocks (either 610 string or 308 towers)**
- **TDR (April 2010): common technology platform**
- **Final Prototypes and tests (2010-2011). Site decision (end of 2011)**

Beyond the optical Cherenkov detectors

Novel techniques under test for GZK neutrino search: Radio-Cherenkov (ice) and Acoustic (water)

Backup slides

The Fermi Acceleration Mechanism

Observed $E^{-2.7}$ spectrum

Non-thermal spectrum. Statistical acceleration

Fermi's idea:

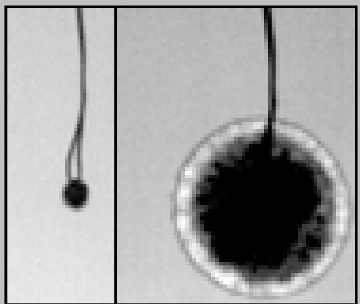
Particles gain energy hitting on clouds moving at V«c (inefficient)

Bell's shock acceleration: **$E^{-(2.0 \div 2.1)} \times E^{-0.6}$ (factor from confinement in the Galaxy)**

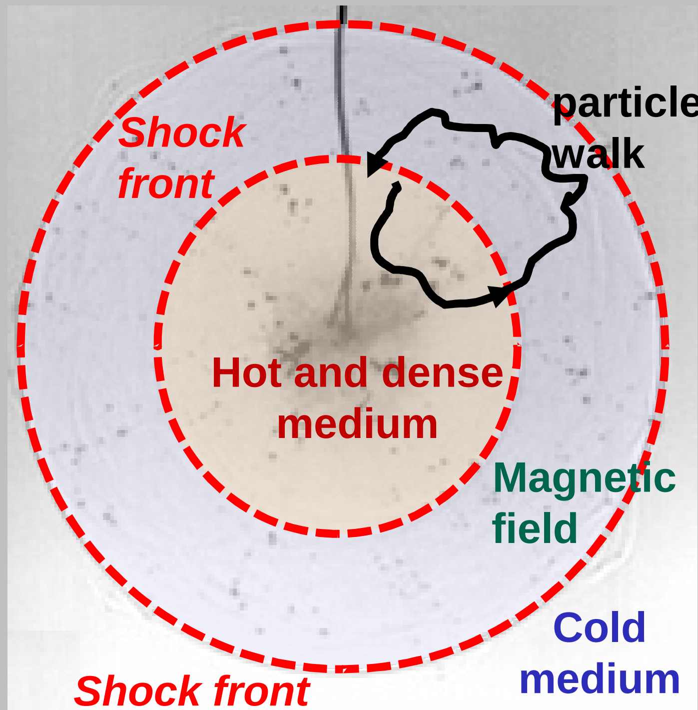
Each time a particle hit on the shock front it gains energy

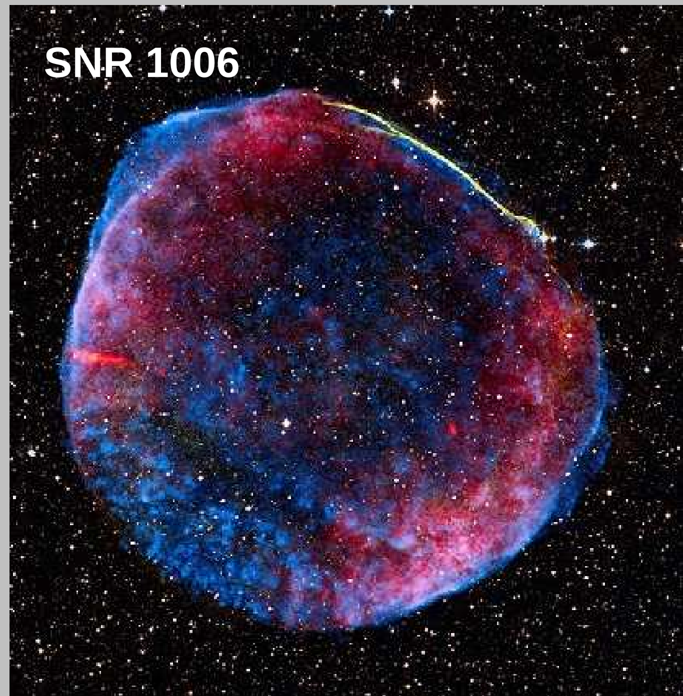
charged particles are confined by the object magnetic field

maximum energy $\propto$ number of hits $\propto$ (confinement) B x R



Shock wave produced by the detonation of a TNT charge





The Fermi Acceleration Mechanism

Observed $E^{-2.7}$ *spectrum*

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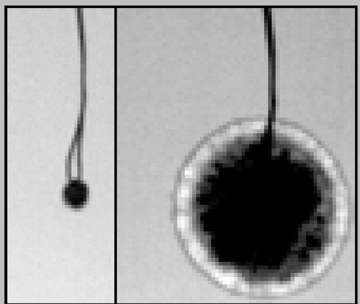

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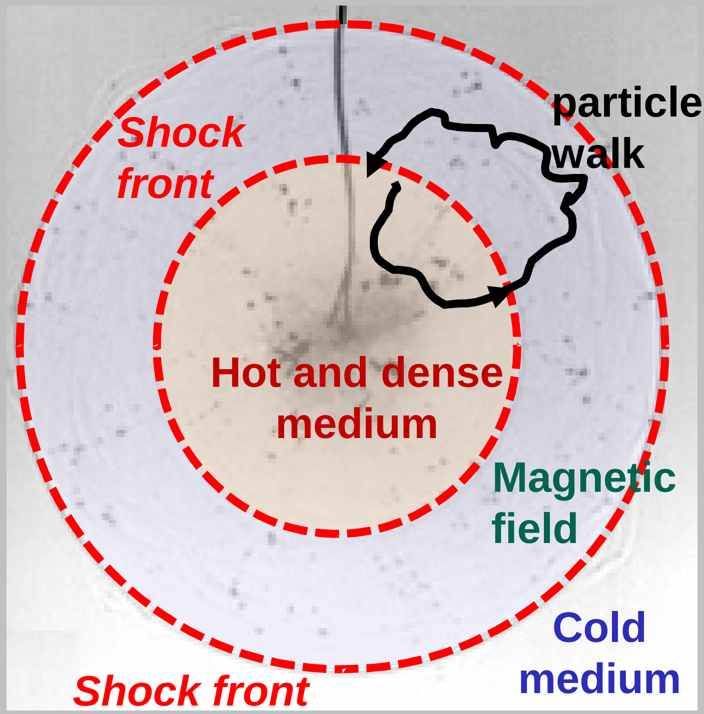
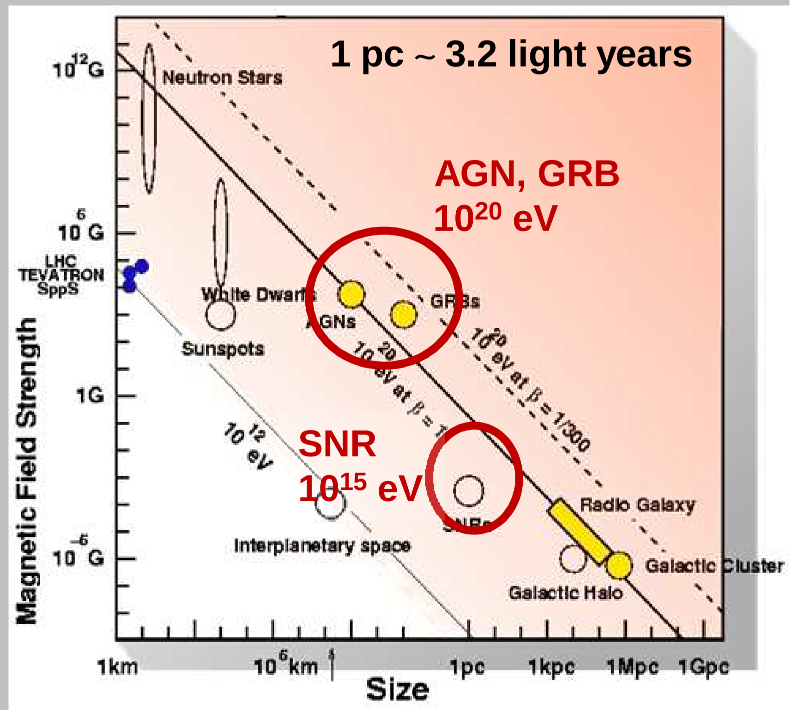
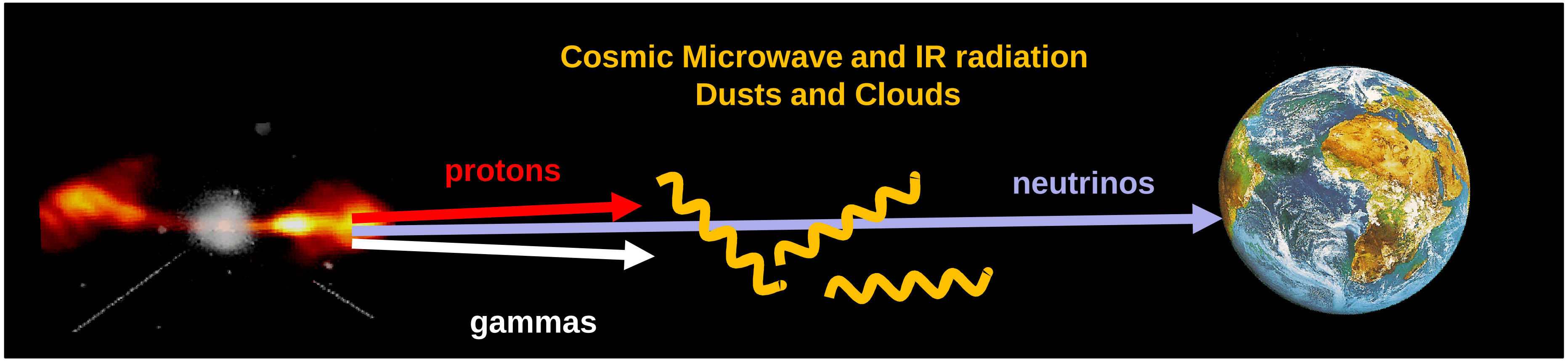
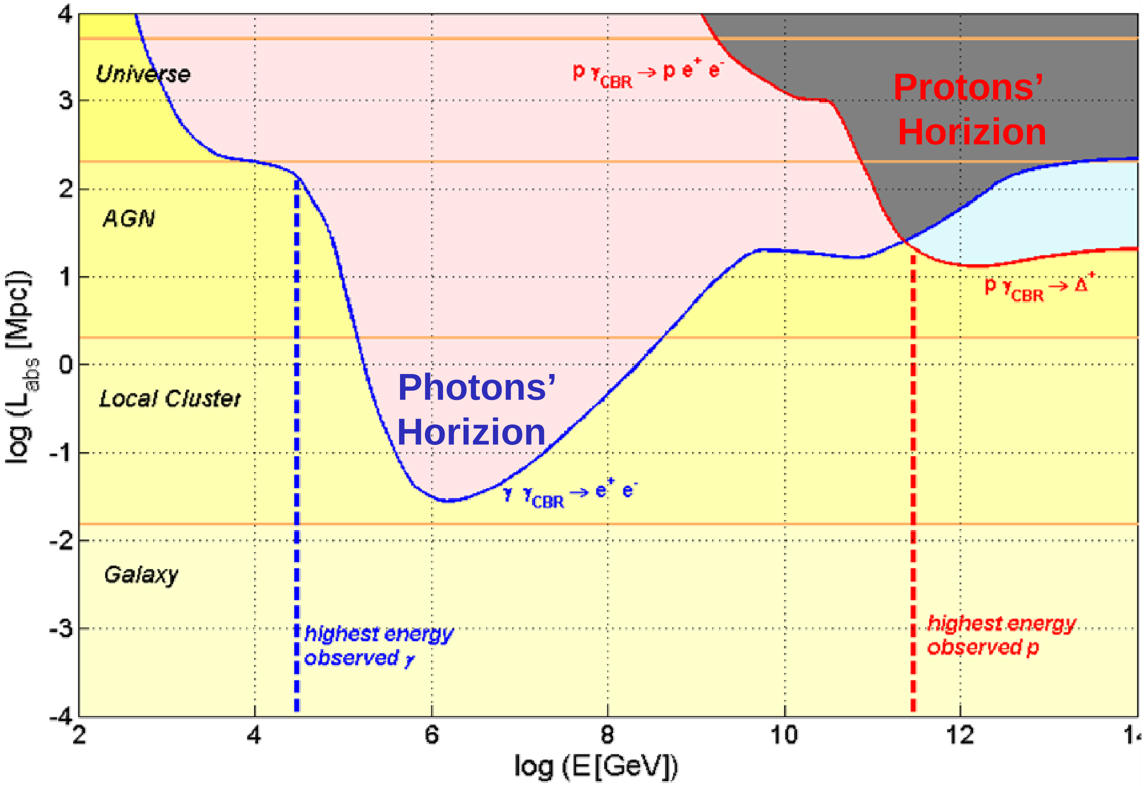




Absorption lenght of protons and gammas in the Universe

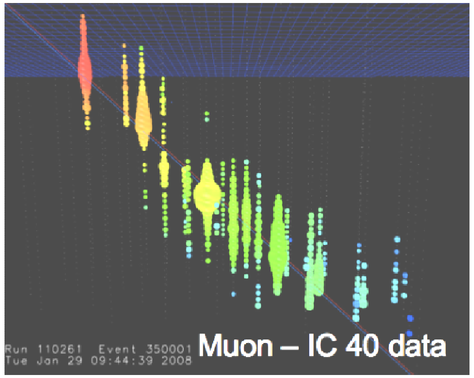




Neutrino astronomy can:

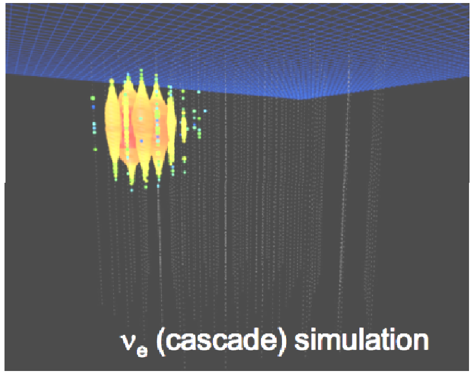
- ***probe the far and violent Universe***
- ***disentangle between pure leptonic and hadronic acceleration models***

Neutrino flavour identification



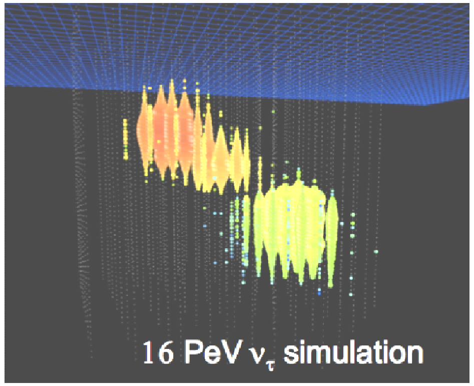
Tracks:
- **Golden channel for ν_μ (through-going muons)**

Pointing resolution <0.5°



Cascades:
- **All ν flavour (NC)**
- **ν_e and low-E ν_τ (CC)**

Energy resolution ~10% in log(E)



Composites:
- **High-E ν_τ (Double Bangs)**

Good directional and energy resolution

Event rates

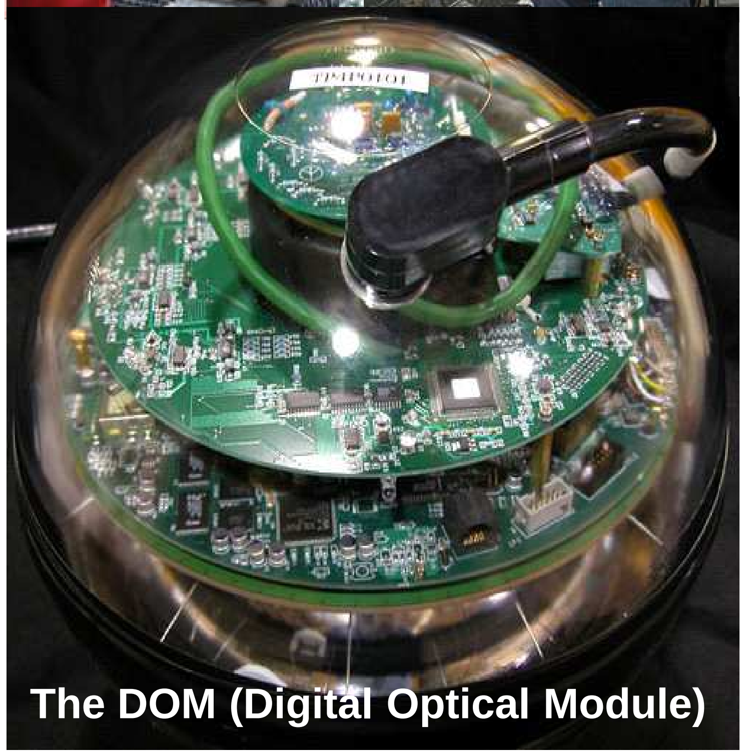
- *Low noise rates: 280Hz (SPE/sec)*
– *Noise is dominated by glass (housing and PMT)*

Supernova explosion detection is possible (Cherenkov light form intense MeV neutrino flux)

- *High duty cycle: >90%*
- *Event rates (40 strings)*
  – *Muons: ~1kHz*
  – *Neutrinos: ~100 / day*

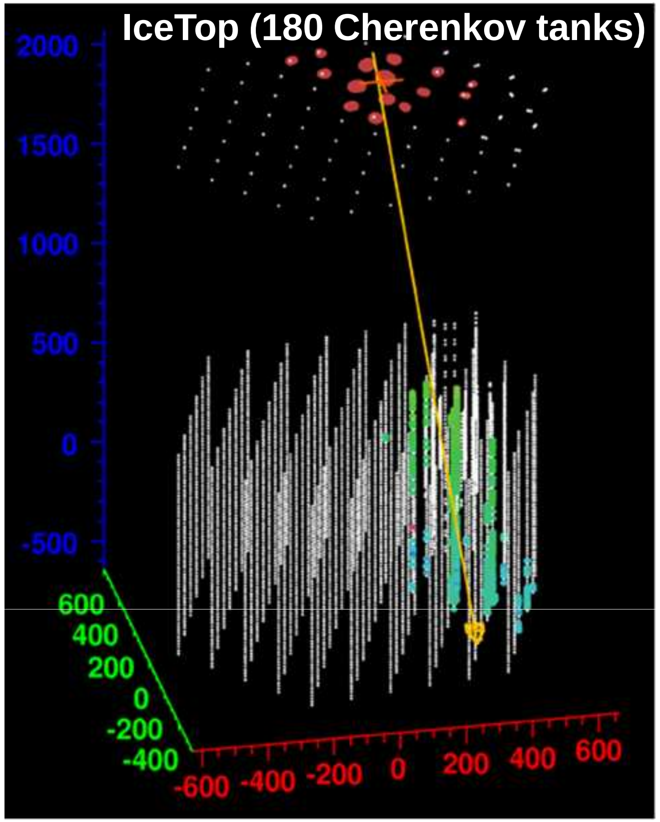
Adapted from A.Karle, 2009

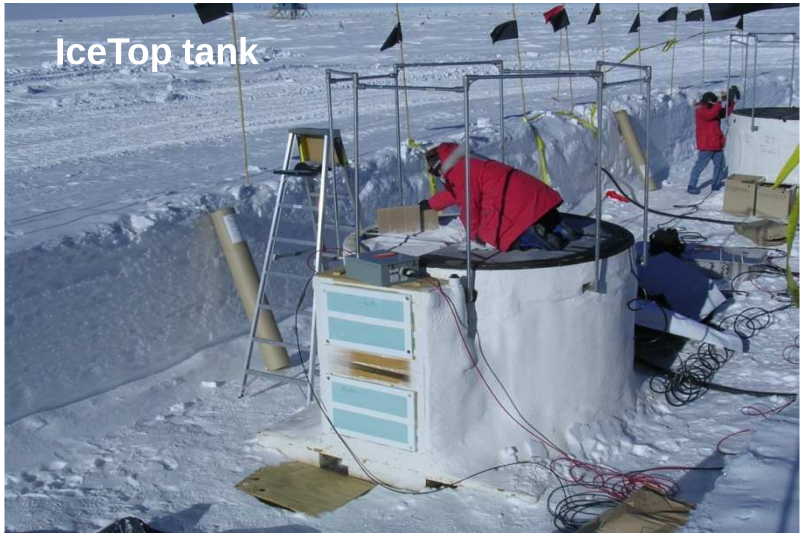
Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC80*	2011	~365 days	1650 Hz	220 / day



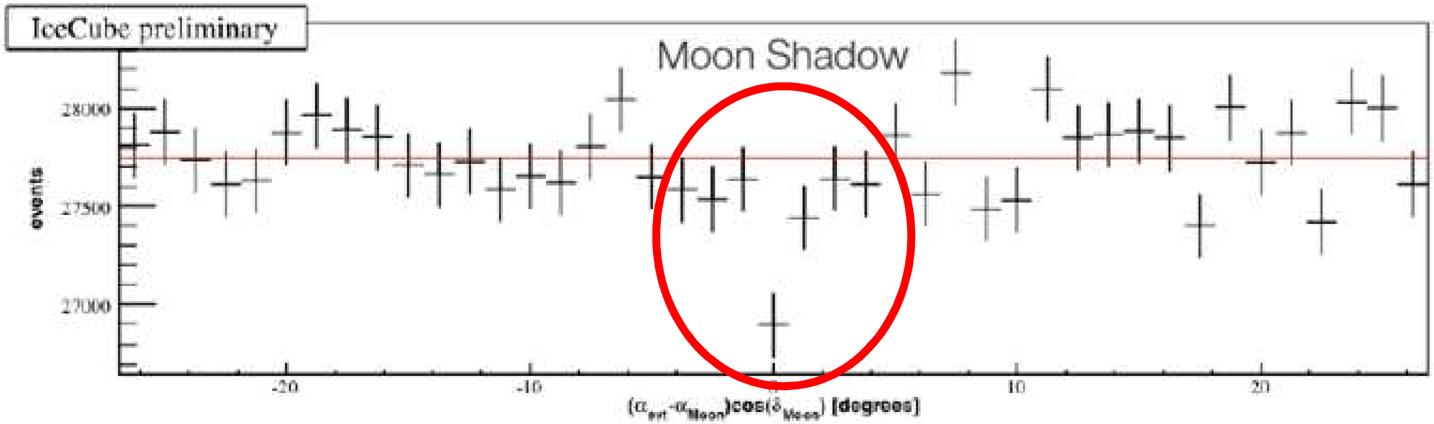
The DOM (Digital Optical Module)

IceCube: Angular Resolution





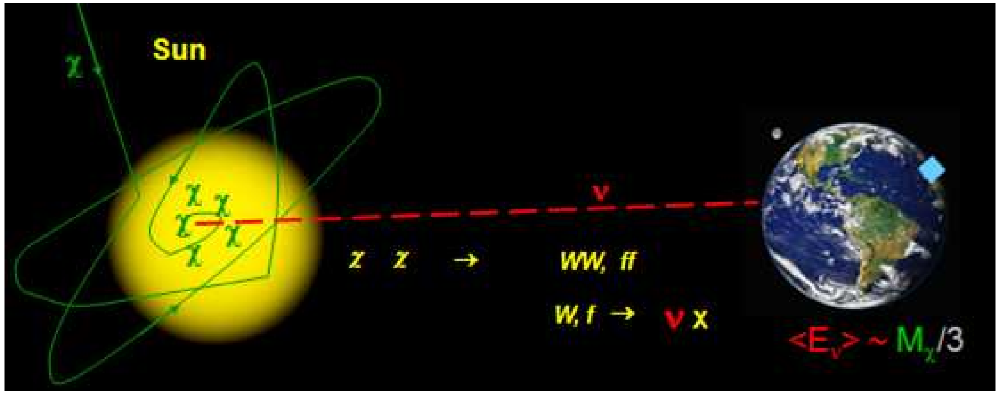
Icecube angular resolution evaluated with the surface shower array IceTop.
IC-22 : 1.5° | IC-40 : <1.0° | IC-80 : <0.5°



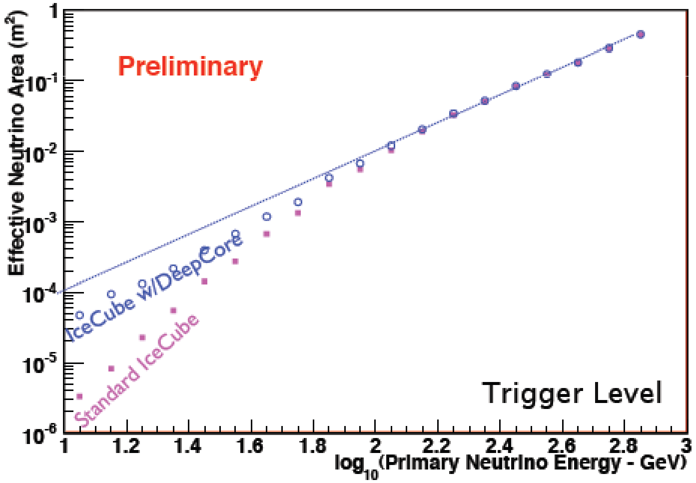
IceCube: WIMPs Detection

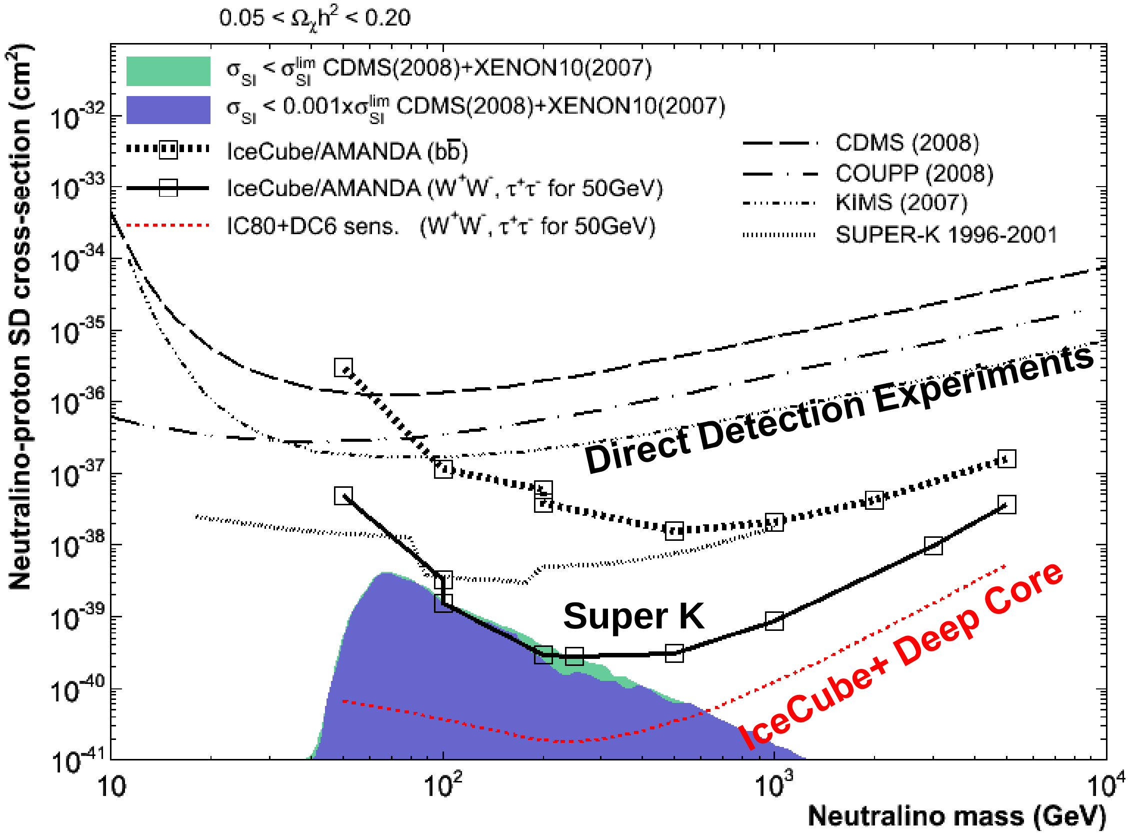
WIMPs gravitationally trapped via elastic collisions in the Sun.

Expected # of events: few to O(1000) per year



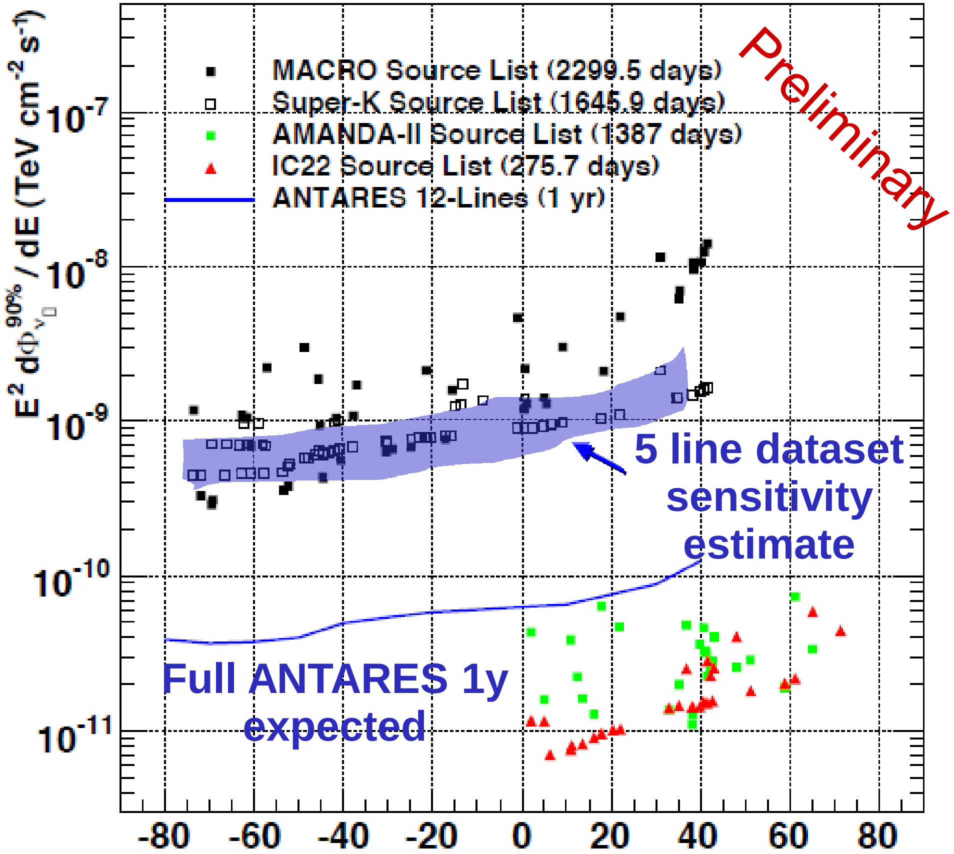
Deep Core will implement IceCube capabilities at low E



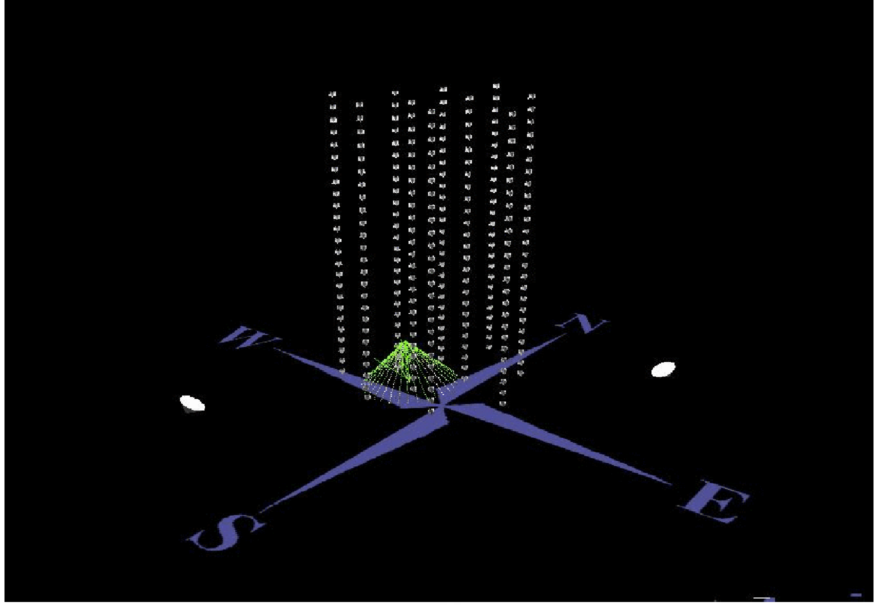


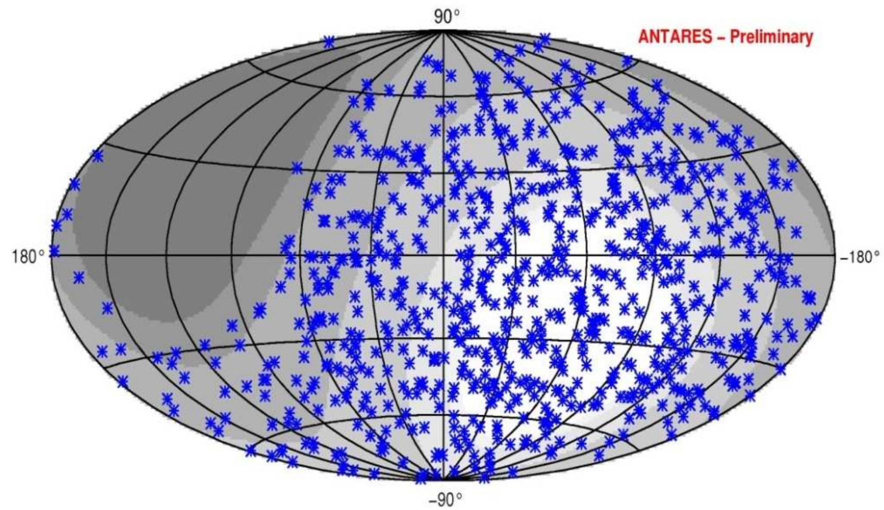
Deep Core + IceCube: veto for dowgoing muons (continuous Sun observation)

Towards the Mediterranean km³: ANTARES



An up-going muon event (i.e. a neutrino candidate) detected by ANTARES



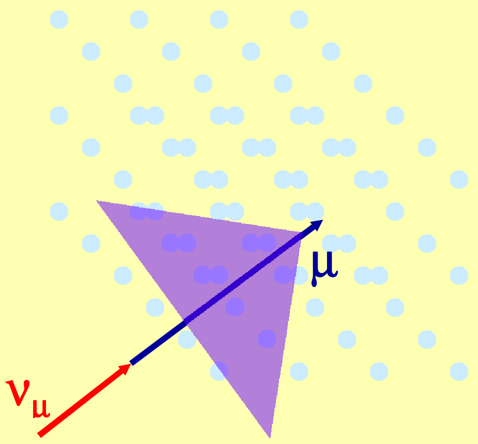


750 up-going neutrinos 2007+2008 data

Large Area Detectors for HE neutrinos

1 TeV — 100 PeV — 1000 ZeV

Optical Detection (ICECUBE-KM3NeT)



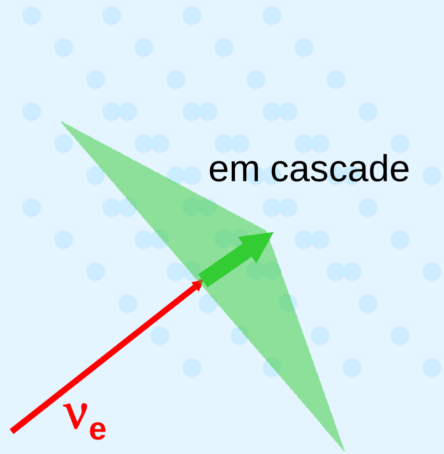
Medium: Seawater, Polar Ice

ν_μ (throughgoing and contained)
$\nu_{e,\tau}$ (contained cascades)

Carrier: Cherenkov Light (UV-visible)
Attenuation length: 100 m

Sensor: PMTs
Instrumented Volume: 1 km^3

Radio Detection (ANITA, RICE, ICERAY)



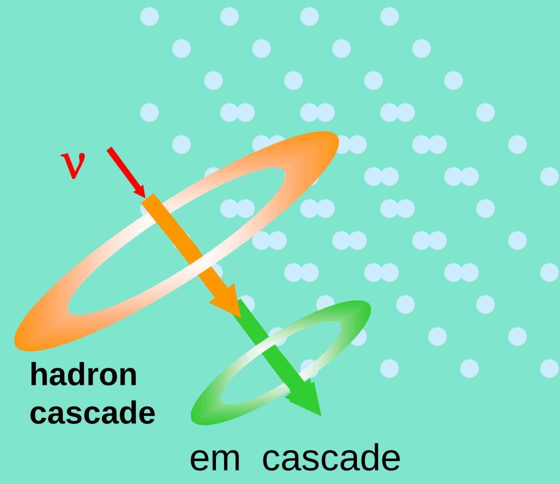
Medium: Salt domes, Polar Ice

ν (cascades)

Carrier: Cherenkov Radio
Attenuation length: 1 km

Sensors: RF-Antennas
Instrumented Volume: >>1 km^3

Acoustic Detection (SAUND, NEMO, AMADEUS)



Medium: Seawater (Salt)

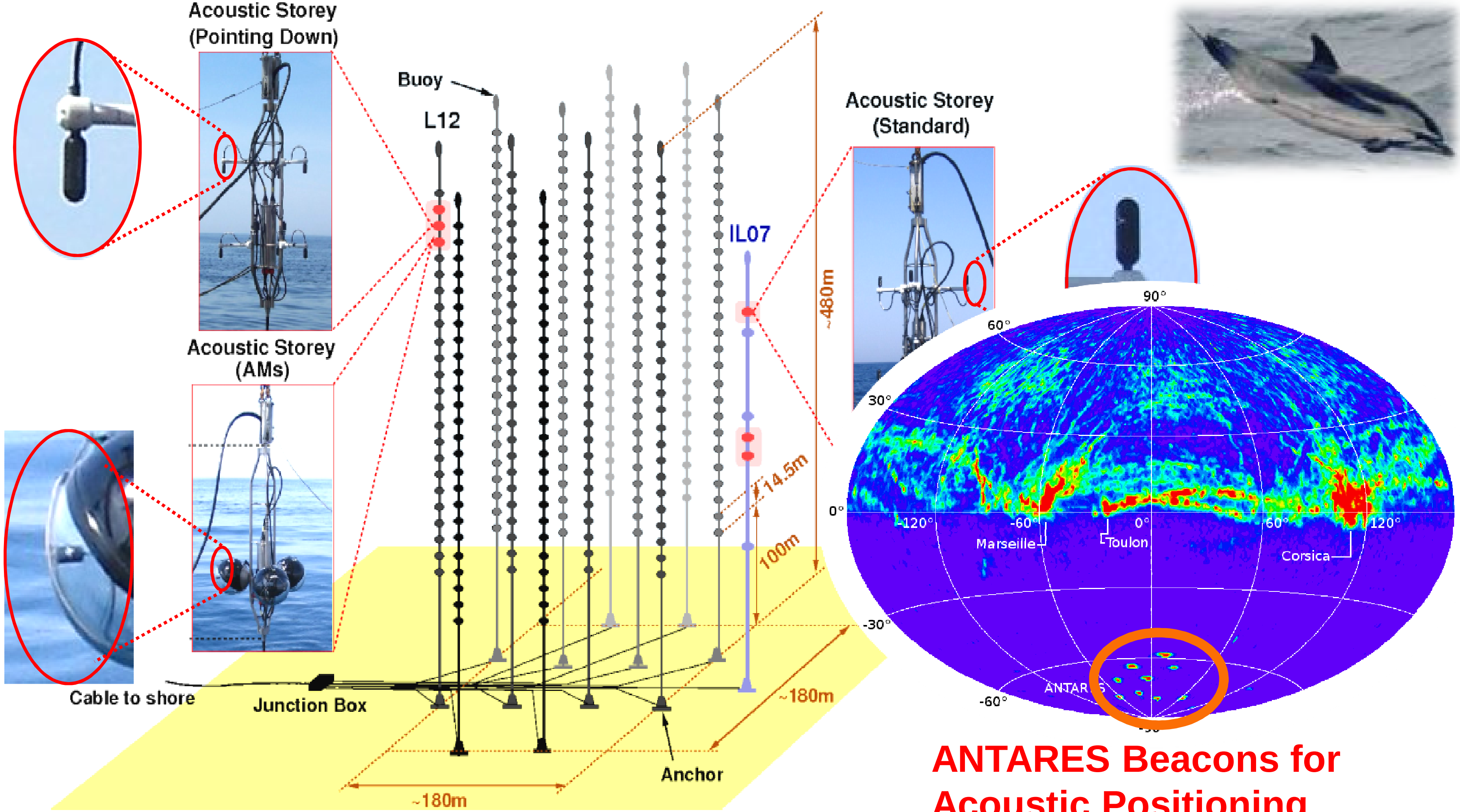
ν (cascades)

Carrier: Sound waves (tens kHz)
Attenuation length: ~ 1÷10 km

Hydro-phones
Instrumented Volume: >>1 km^3

Acoustic detection in ANTARES: AMADEUS

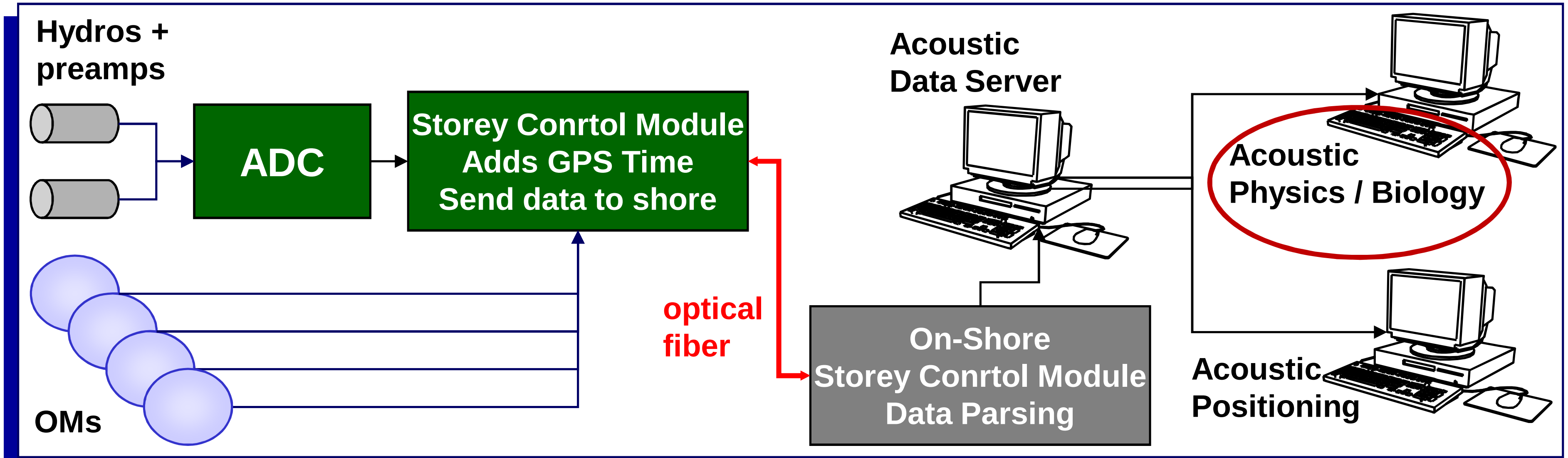
AMADEUS comprises a series of hydrophones on two ANTARES lines
A test bench to study the feasibility of a large acoustic UHE neutrino detector
Study of acoustic environment and backgrounds
Study of methods to reconstruct event direction

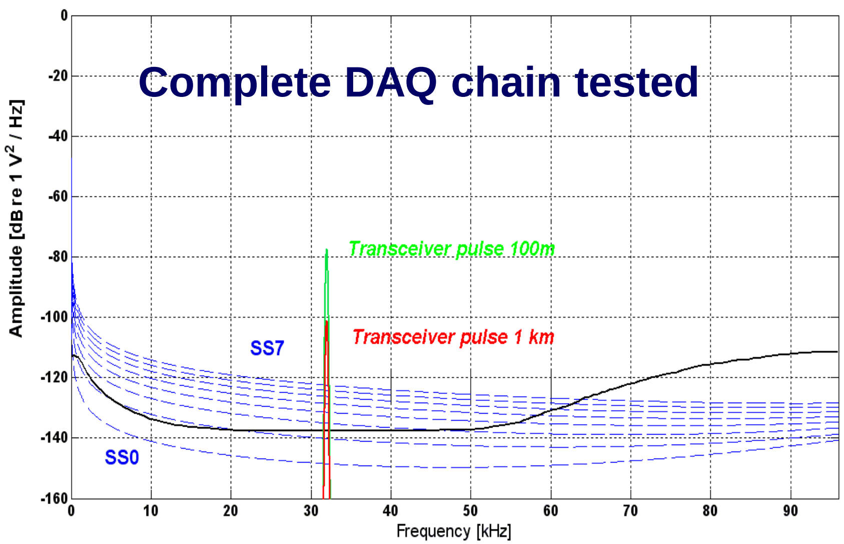


ANTARES Beacons for
Acoustic Positioning

KM3NeT prototype tower: “Acoustic” Electronics Chain

“All data to shore” philosophy | **data payload: 2 Hydros = 1 OM, fully sustainable**

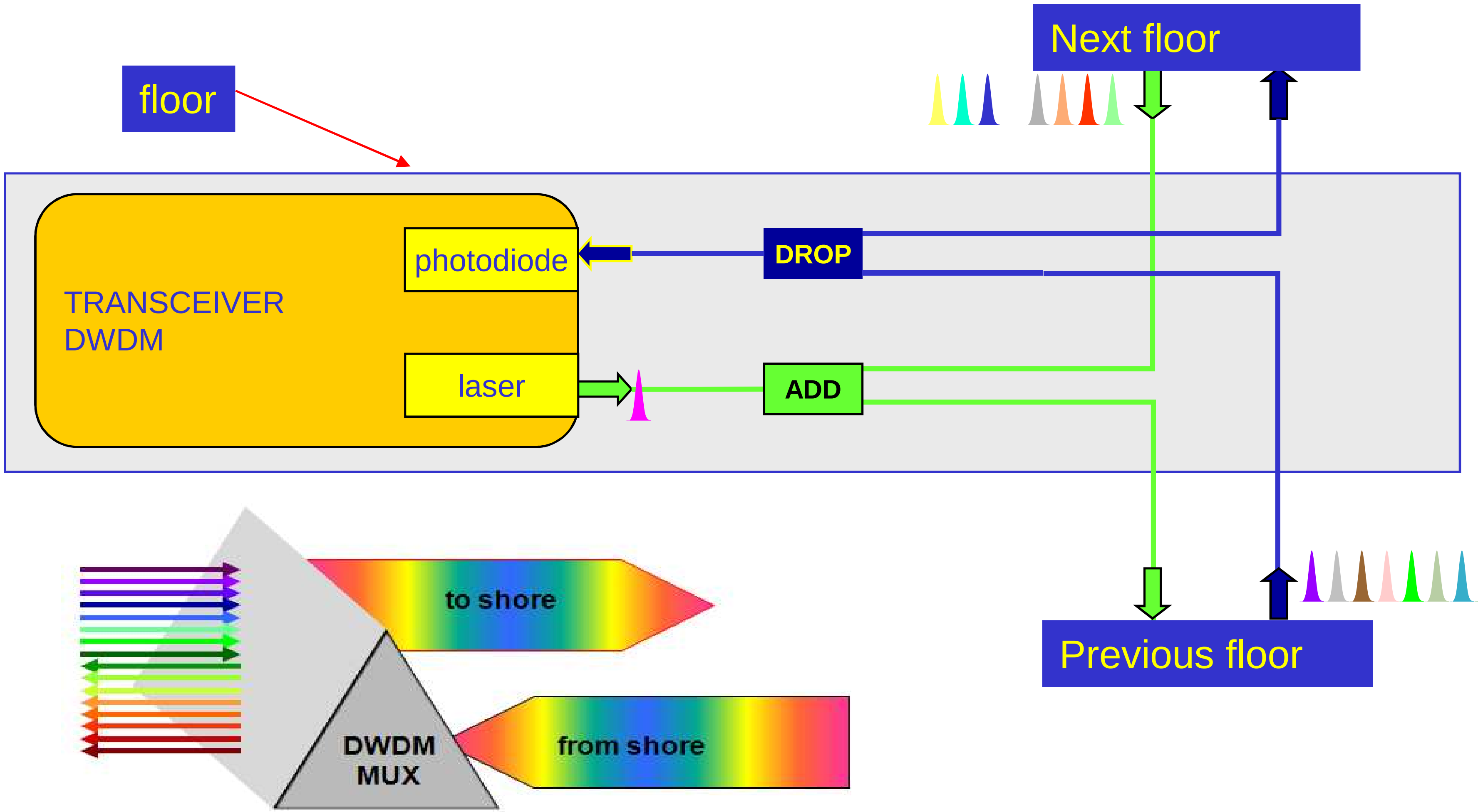




- R&D on hydrophones in collaboration with NATO Undersea Research centre and SMID (hydrophone manufacturer)
- Front end and data transmission chain electronics tested
- Obtained timing resolution 1 μs → 1 mm in water
- Expected overall resolution for positioning few cm: factor 10 better than present commerical systems (at 5 times less cost !)

NEMO Phase 1 Optical fiber transmission

Each break out contains an "add and drop" filter to add or subtract the specific optical wavelength (from/to shore) dedicated to the floor



The Size of Neutrino Acoustic Detectors

$E_\nu = 10^{20}$ eV

in water: p = 0.6 Pa @ 1 km → 20 mPa (neglecting attenuation)

in Ice : p = 6 Pa @ 1 km → 200 mPa (neglecting attenuation)

Underwater Cherenkov detectors
Upgoing events – 100 TeV

$$P_{\nu\mu}\left(E_\nu, E_\mu^{min}\right) = R_\mu^{eff}\sigma_{CC}N_A = 10^{-4}$$

$$\frac{N}{A_{eff}\cdot T} = \Phi_\nu P_{\nu\mu} 2\pi e^{-D(N_A\sigma_{Tot}\rho_{Earth})} \approx 100 \frac{events}{km^2 y}$$

WB flux

Underwater Acoustic detectors
Downgoing events – 10^{20} eV

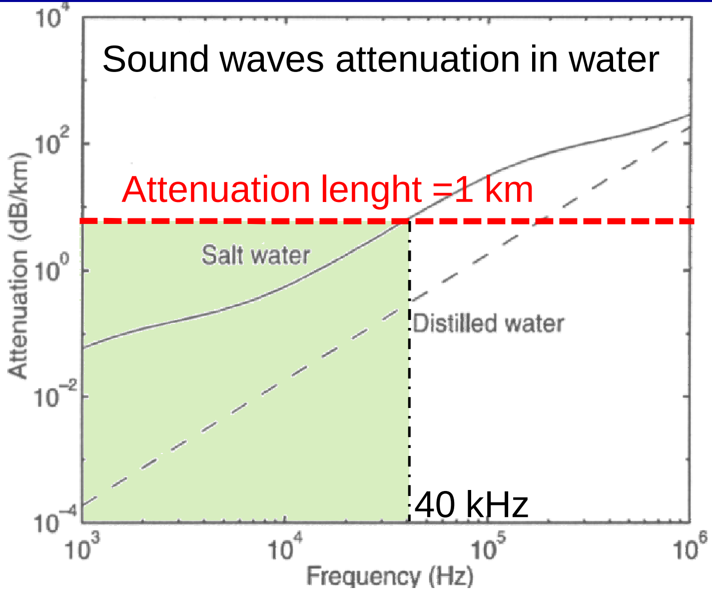
$$P_{det}(E_\nu, p_{min}) = H_{det}^{eff}\sigma_{Tot}N_A \approx 10^{-3}$$

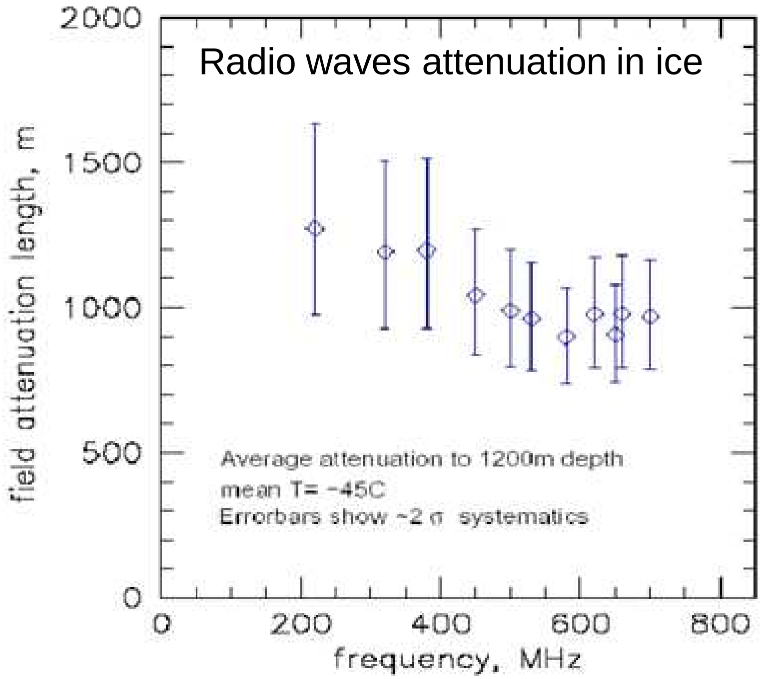
$$\frac{N}{A_{eff}\cdot T} \approx 10^{-3} \frac{events}{km^2 y}$$

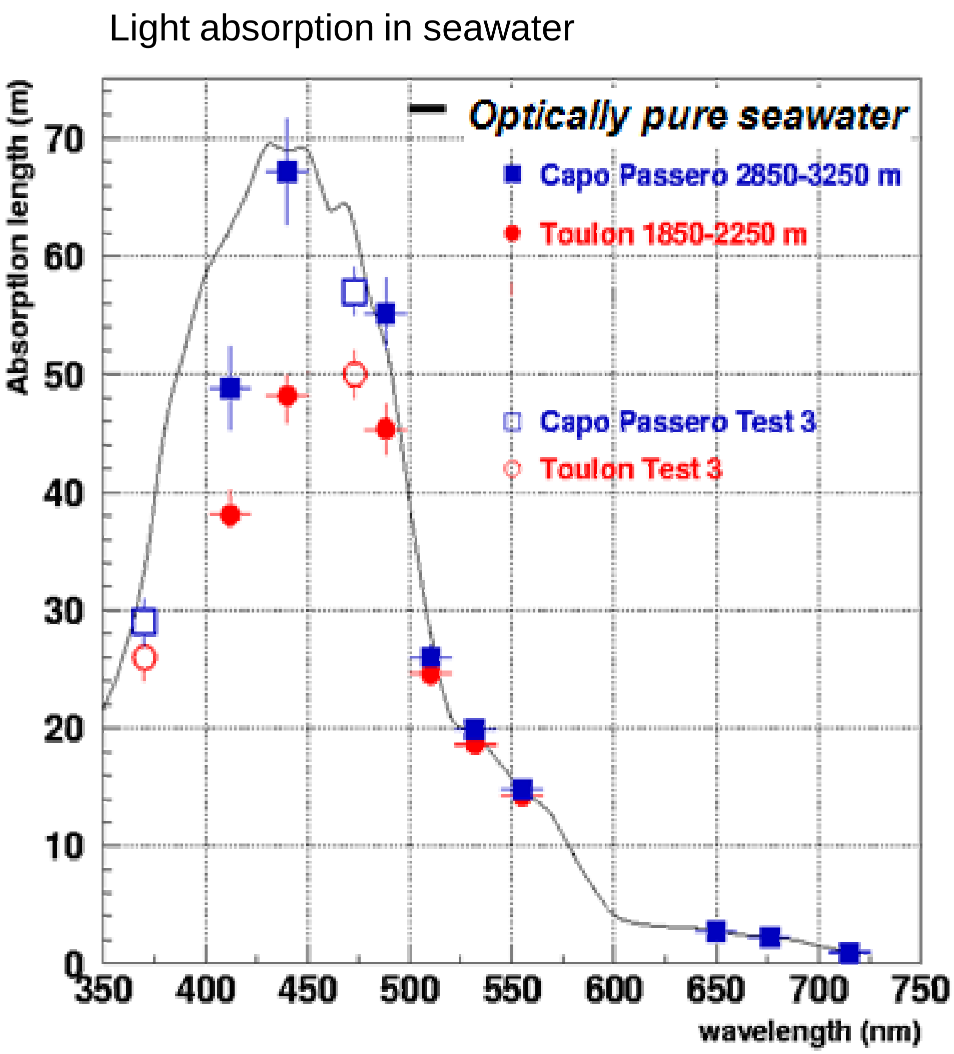
Sound absorption length in ocean O(10 km), noise O(10 mPa)

Several groups developing and improving simulation codes for large acoustic detectors
What we can do with 1 km^3 filled with hydrophones ?

Acoustic and e.m. waves paropagation in water and ice

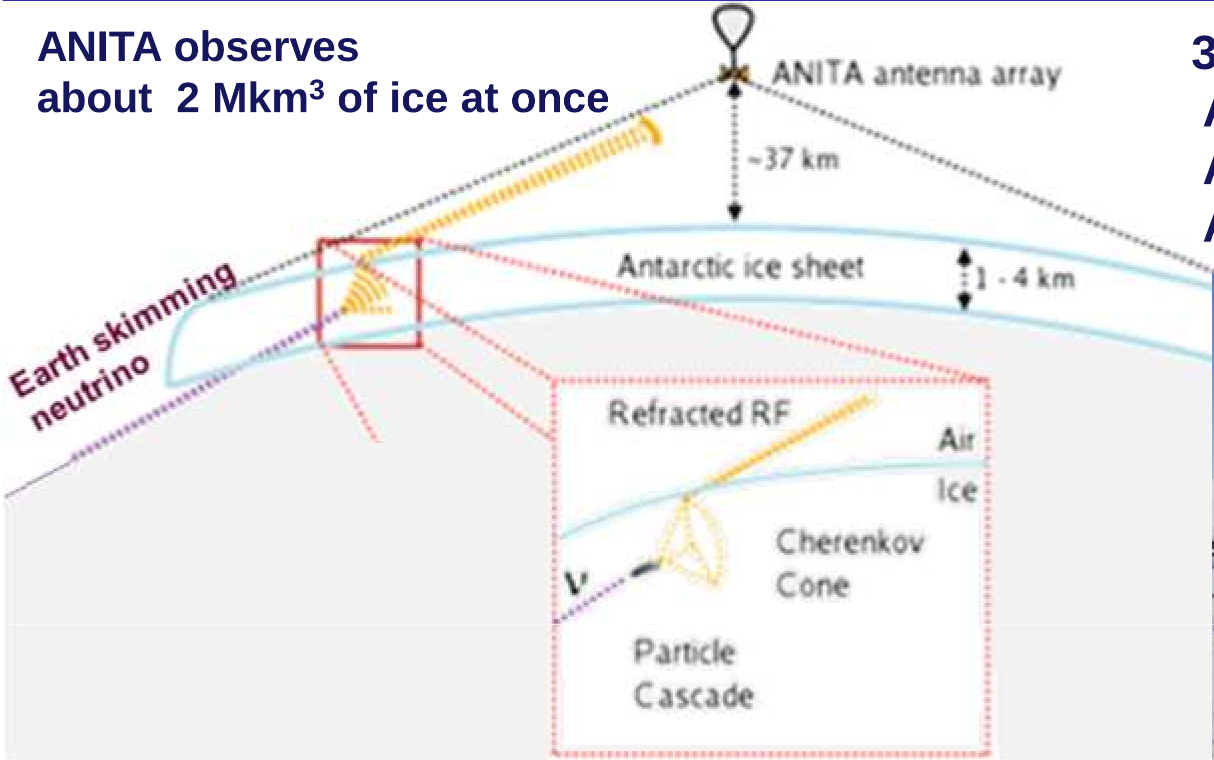






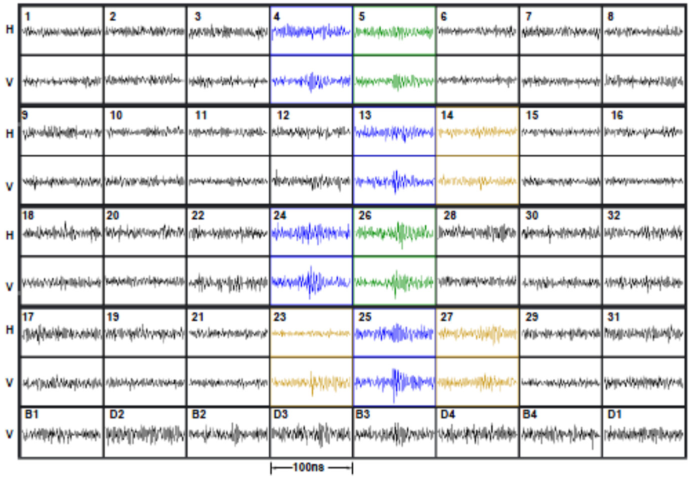
ANITA: Antarctic Impulsive Transient Antenna

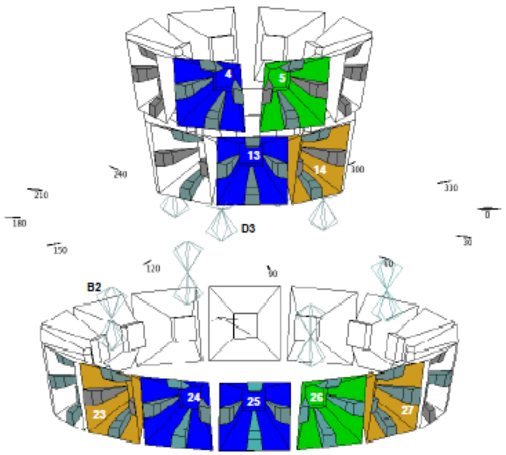
ANITA observes
about 2 Mkm^3 of ice at once



3 Baloon flights:
ANITA Lite Test (2004)
ANITA 1 (2006) 6 events
ANITA 2 (2008) under anlysis

- **-Two rings of 16 antennas (H and V polarization)**
- **Pointing at 10° below the horizon (skimming events)**
- **Bandwidth: 0.2÷1.2 GHz**
- **Threshold $10^{18.5}$ eV**

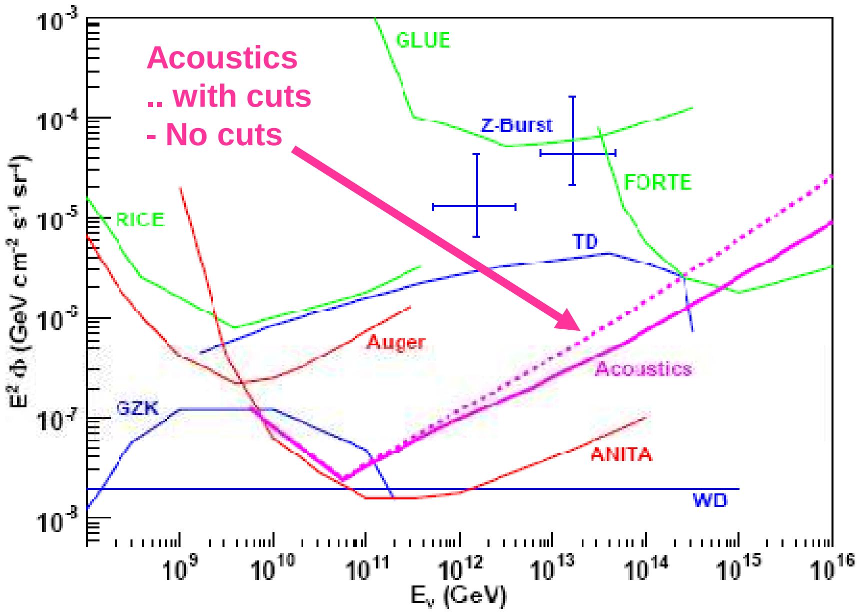




Acoustic detectors expected sensitivity

Standard approach

Largely spaced detectors for GZK neutrino detection

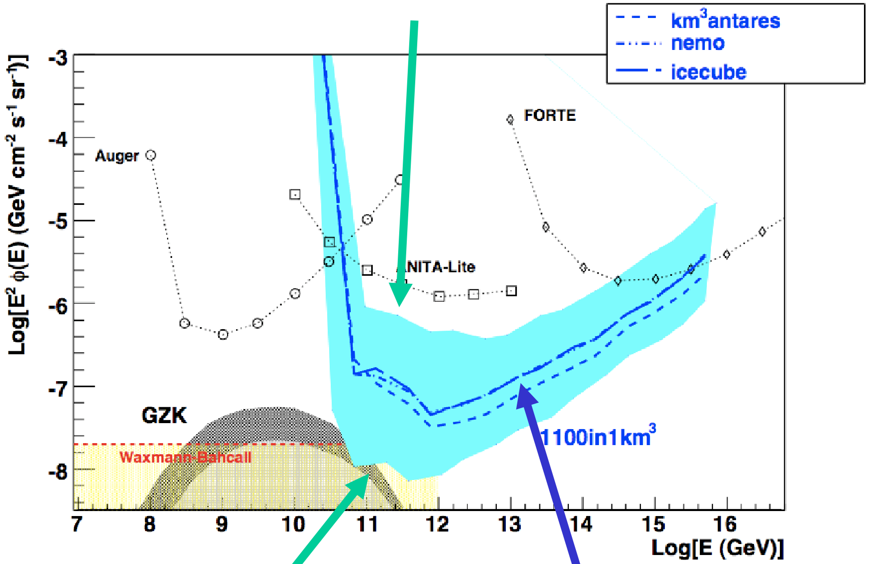


1500 km³, 200 hydros per km³
5 years
threshold 5 mPa

Calculation from ACORNE (Sheffield)

1100 hydros in 1 km³

1 year, threshold 35 mPa

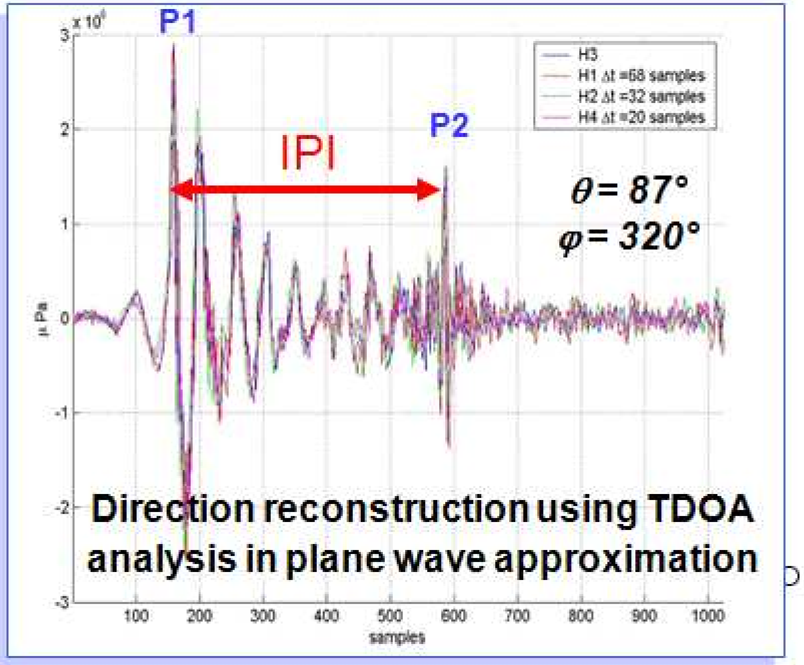


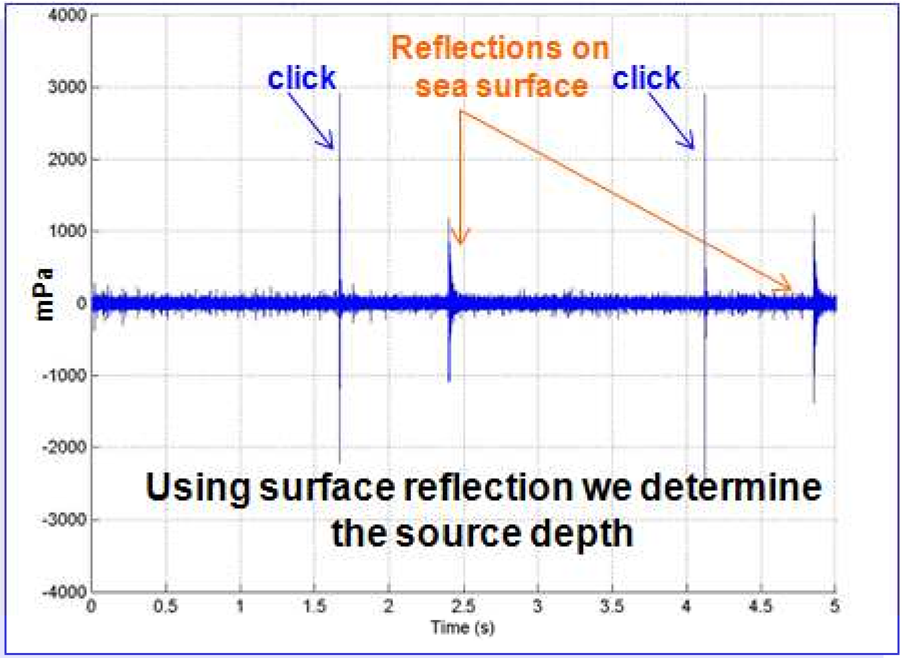
km³ regular geometries
5 years, 15 mPa, 95% CL

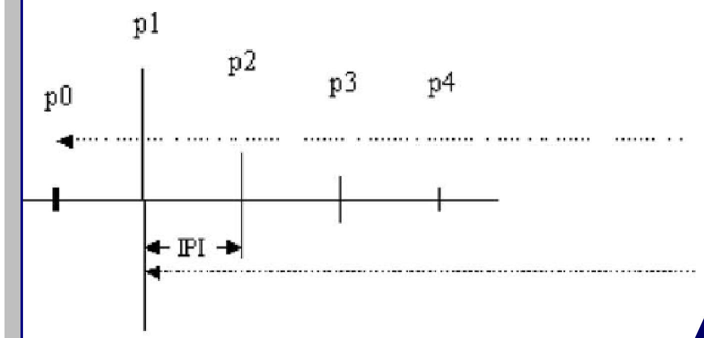
10 years, threshold 5 mPa

A “complementary” km³-scale detector ?

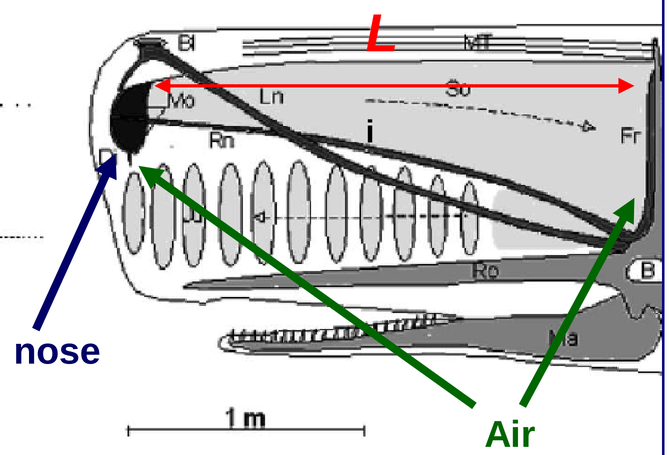
Bioacustics: Sperm-whale click analysis with the OνDE data







$$IPI = \frac{2L}{c_s}$$



Depth = 560 ± 5 m

L = 3.41 ± 0.05 m

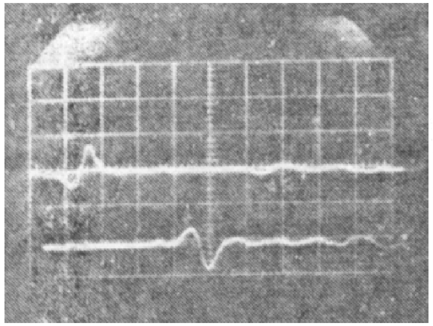
Size = 9.72 - 10.50 m

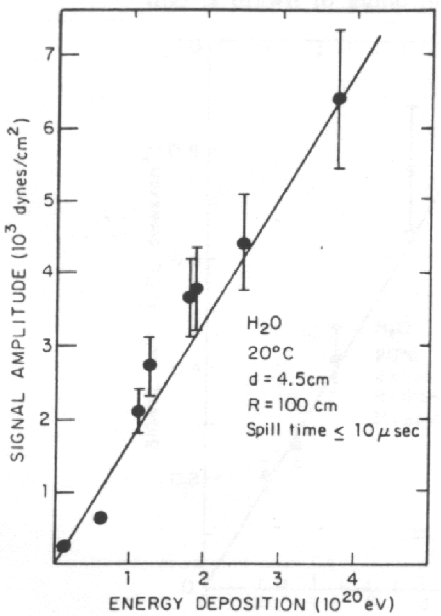
Young male or female

Accelerator experiments: results and open questions

Brookhaven NL (Harvard, SLAC) 1979

200 MeV proton beam (LINAC)
Spill time 3 to 20 μs
Beam diameter 4.5 cm
Energy deposited in water $10^{19} \rightarrow 10^{21}$ eV
Bipolar pulses observed
Dependency on C_p, T and on beam diameter confirmed (10% uncertainty)





Recent measurements (2000's)

Uppsala: 177 MeV p
E= 10^{16} – $10^{17.5}$ eV
Bipolar pulse observed
Unclear dependence on temperature
Other contibution to observed pulses ?

ITEP Synchrotron: 100, 200 MeV p
E= 10^{15} – 10^{20} eV
Measured pressure increses linearly with E

Erlangen Laser Nd-YaG
E= 10^{17} – 10^{19} eV
Dependence on C_p confirmed

A well calibrated shower energy vs. acoustic amplitude relation is still missing