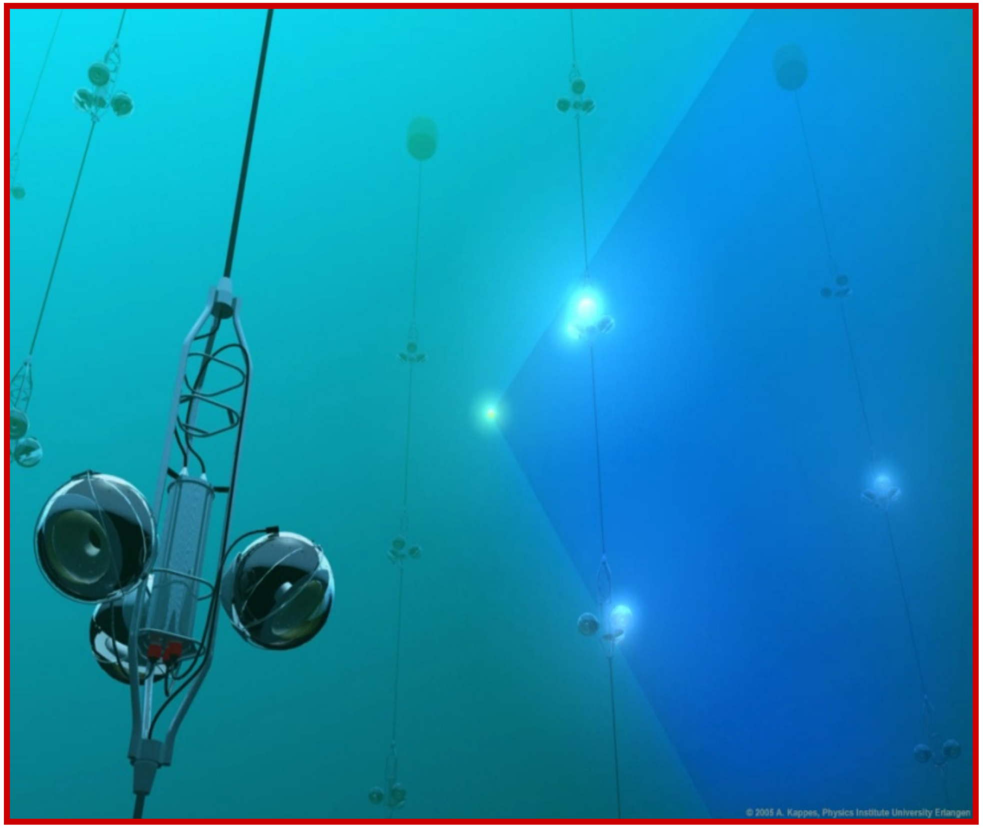
High Energy Neutrino Astronomy

Focusing on Water/Ice Cherenkov technique



Scientific Motivations
Detection principles
Status of Current projects
Selected analyses

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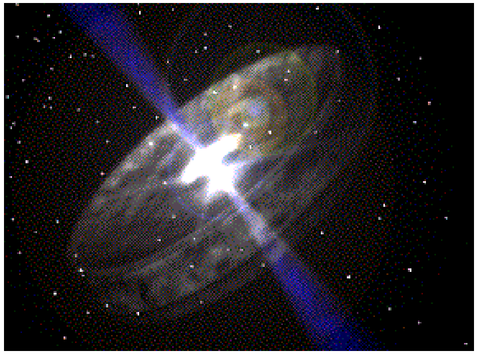
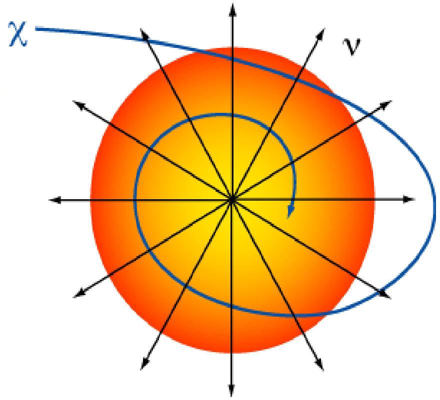
Financé par ANR

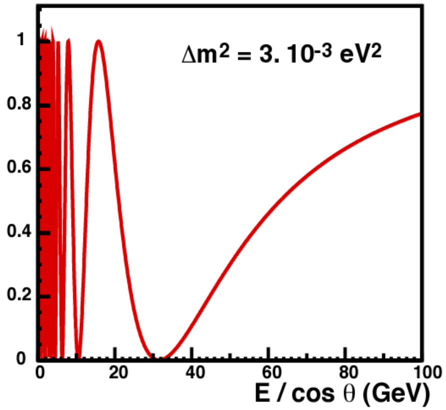
ECRS 2010

Turku

Neutrino telescopes science scope







High Energy $E_\nu > 1$ TeV	Medium Energy 10 GeV < E_ν < 1 TeV	Low Energy 10 GeV < E_ν < 100 GeV
ν from extra-terrestrial sources	Dark matter search	ν oscillations

Origin and production mechanism of HE CR

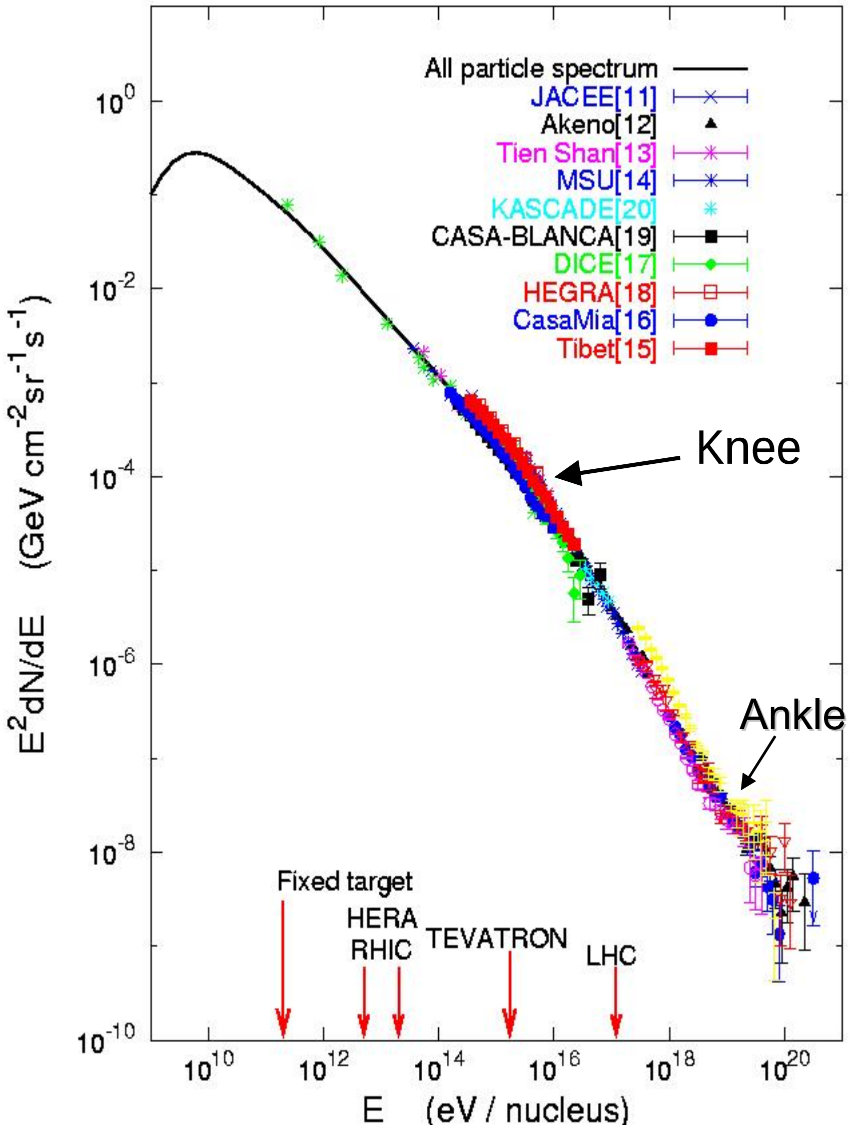
↓

Primary goal

Exotic particle physics
Monopoles, nuclearites,…

Marine sciences: oceanography, biology, geology…

High energy cosmic rays



From T Gaisser & F. Aharonian

Nature

Source ?

Production

Methods:

- Anisotropy studies of highest energetic CR air showers
  ☞correlations with AGN observed but not fully conclusive

- Gamma-ray astronomy
  ☞but γ-rays can be produced by electro-magnetic processes (eg. ICS)

- Neutrino astronomy !

Cosmic ray connection

- Primary acceleration («Bottom-Up»)
  - Stochastic shocks (Fermi mechanism)
  - Explosion /Accretion /Core collapse
- Hadronic cascades (as for atmospheric showers)

- GZK cut-off observed
  ☞'guaranteed' source of « cosmogenic » neutrinos E>~10^{17} eV

$$A + A/\gamma \rightarrow \pi^0 + \pi^+ + \pi^- + N + \ldots$$

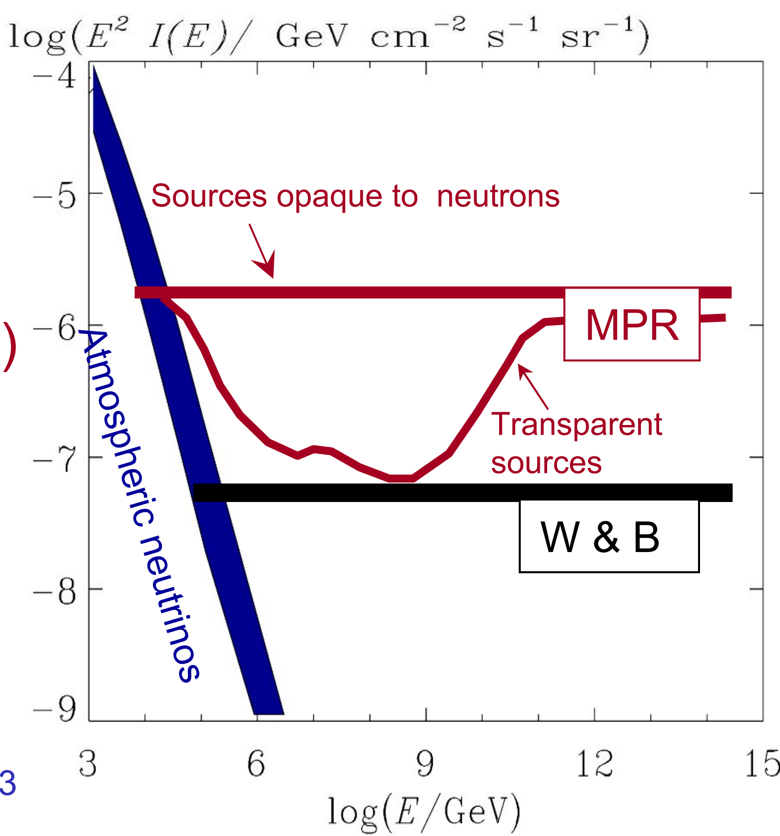
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

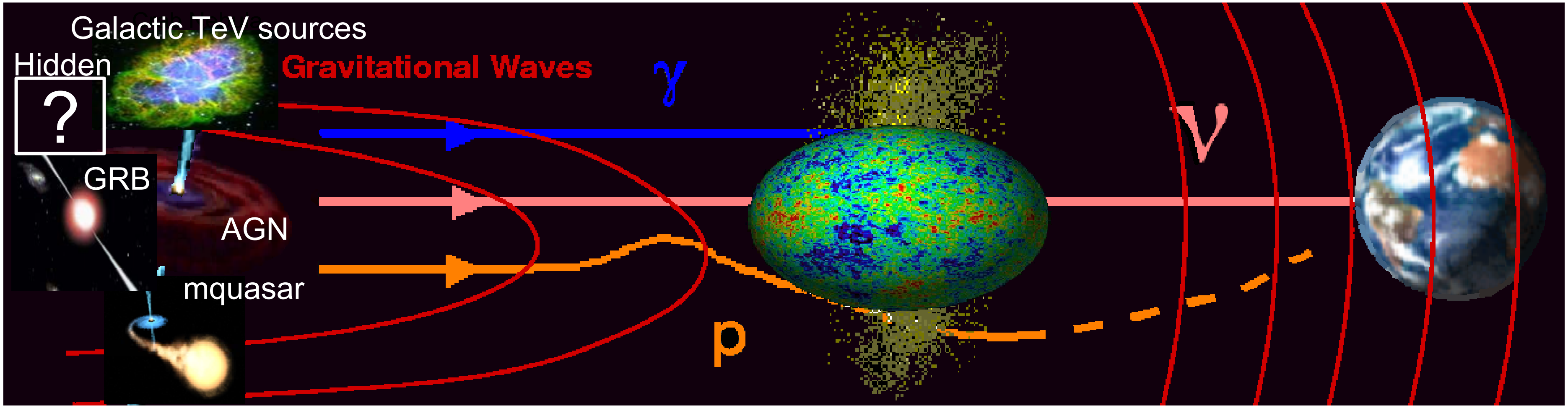
- Like γ-rays, ν are effectively produced ($\Phi_\nu \approx \Phi_\gamma$)
- But only in hadronic interactions unlike γ-rays

- Benchmark extragalactic muon neutrino flux
  - Waxman & Bahcall, 1999
  - Mannheim, Protheroe, Rachen 2001



⇒ Set the effective scale of ν telescopes to km³

Neutrinos as actor of the multi-messenger scene



- ✓ No absorption → **Cosmological distances**
- ✓ Weakly interacting → **Core of dense objects**
- ✓ No deflection by B → **Point sources**
- ✓ No delay → **Transient phenomena**

Neutrinos would open a new non-EM window on the Universe

But…so challenging to detect !
(so far only sun & SN1987A ~MeV)

DETECTION PRINCIPLES

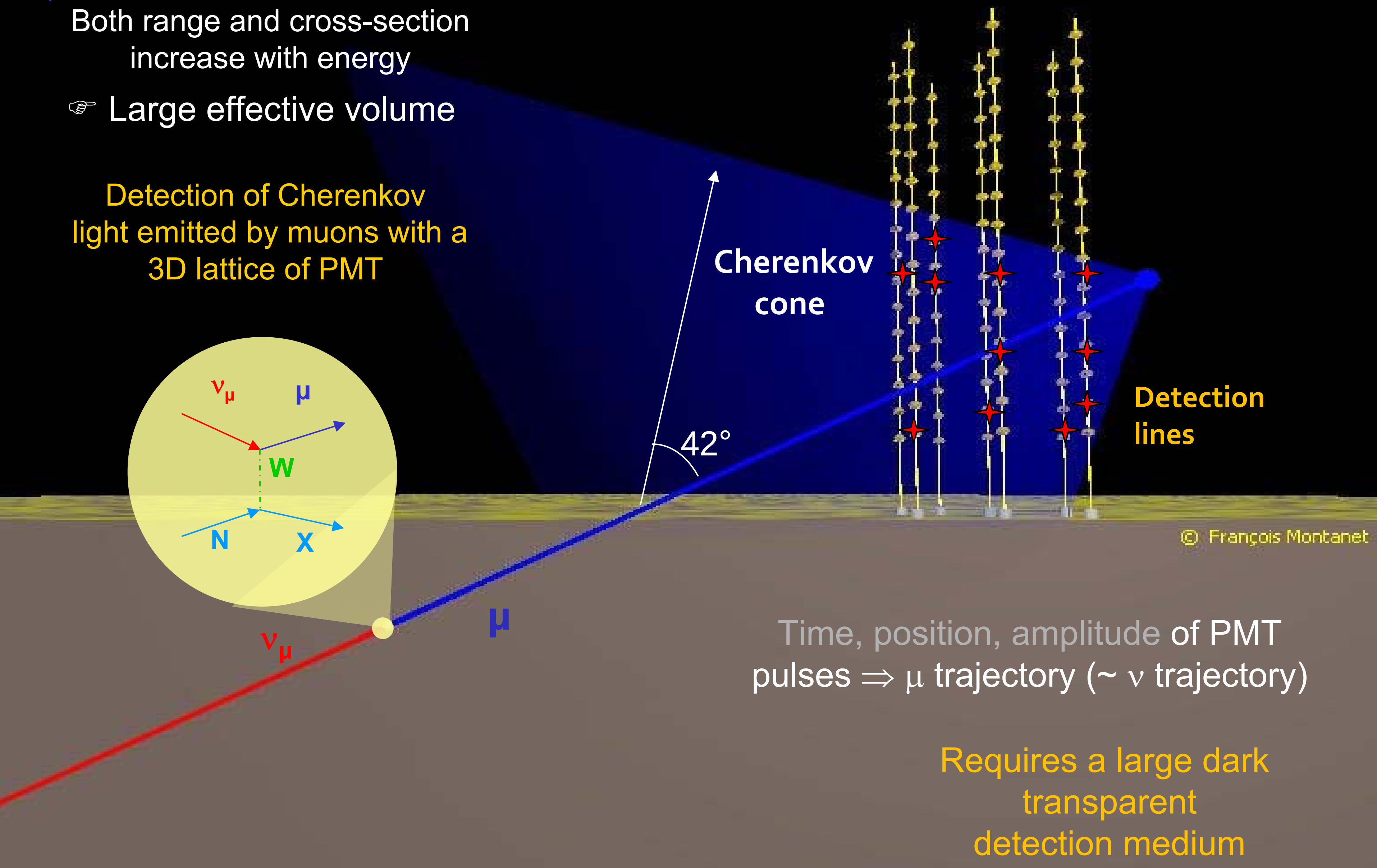
Detection principle

μ well suited for HE detection

Both range and cross-section increase with energy

☞ Large effective volume

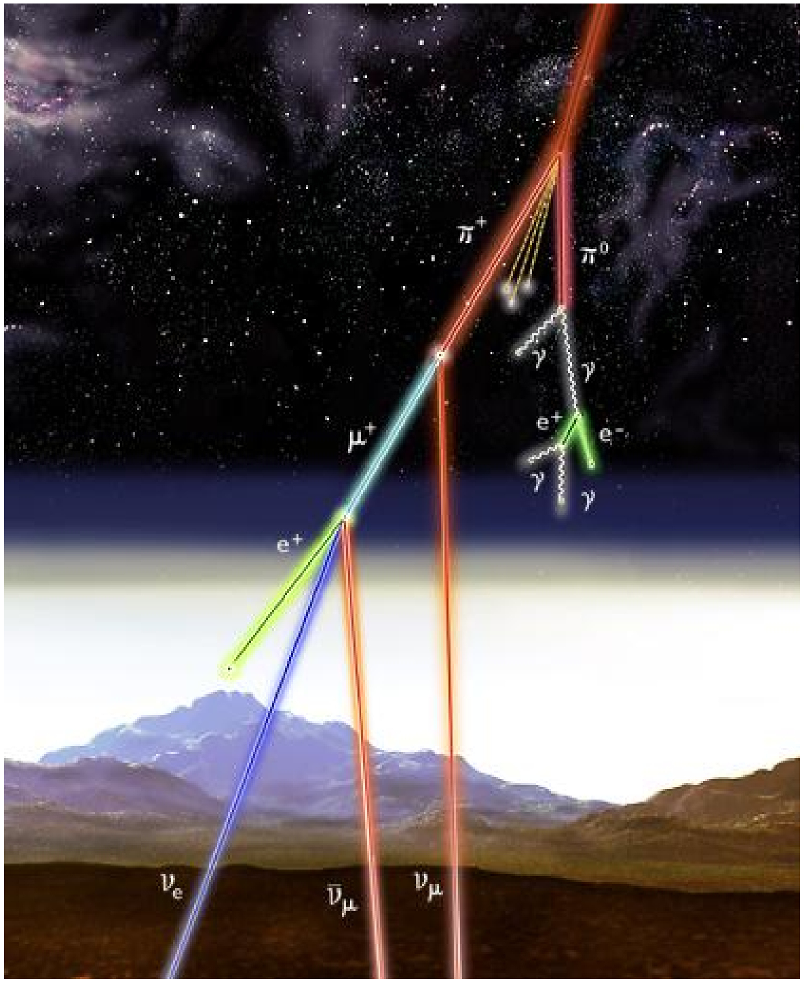
Detection of Cherenkov light emitted by muons with a 3D lattice of PMT

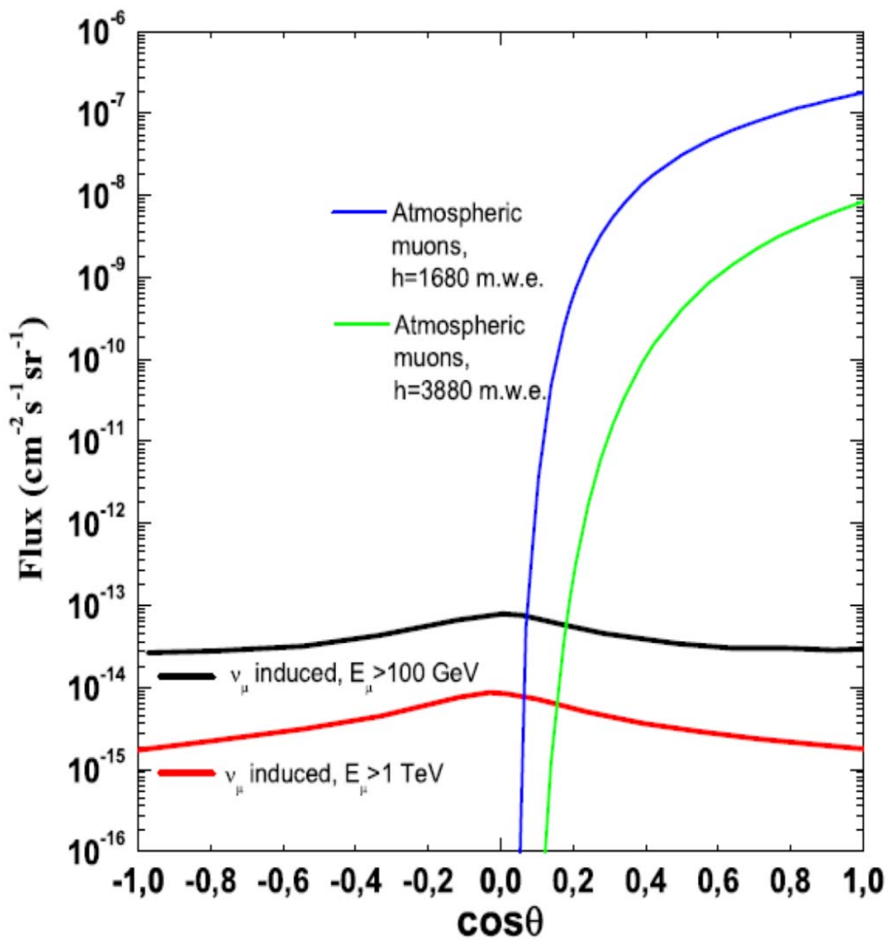


Time, position, amplitude of PMT pulses $\Rightarrow$ μ trajectory (~ ν trajectory)

Requires a large dark transparent detection medium

Physical background sources



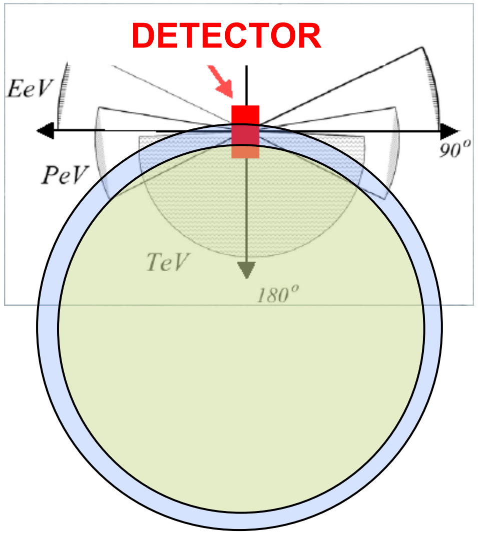


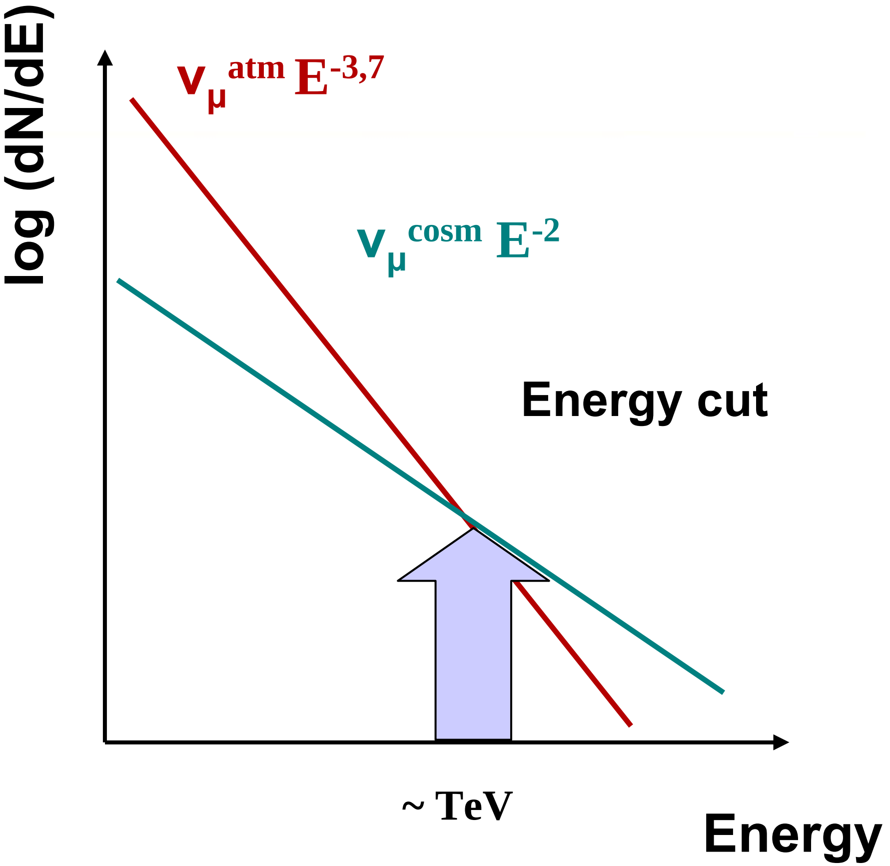
Atmospheric muons: only downgoing

Shield detector & define signal as upward muons

Atmospheric vs cosmic neutrinos

- **Cosmic neutrinos**: can be selected through dedicated cuts





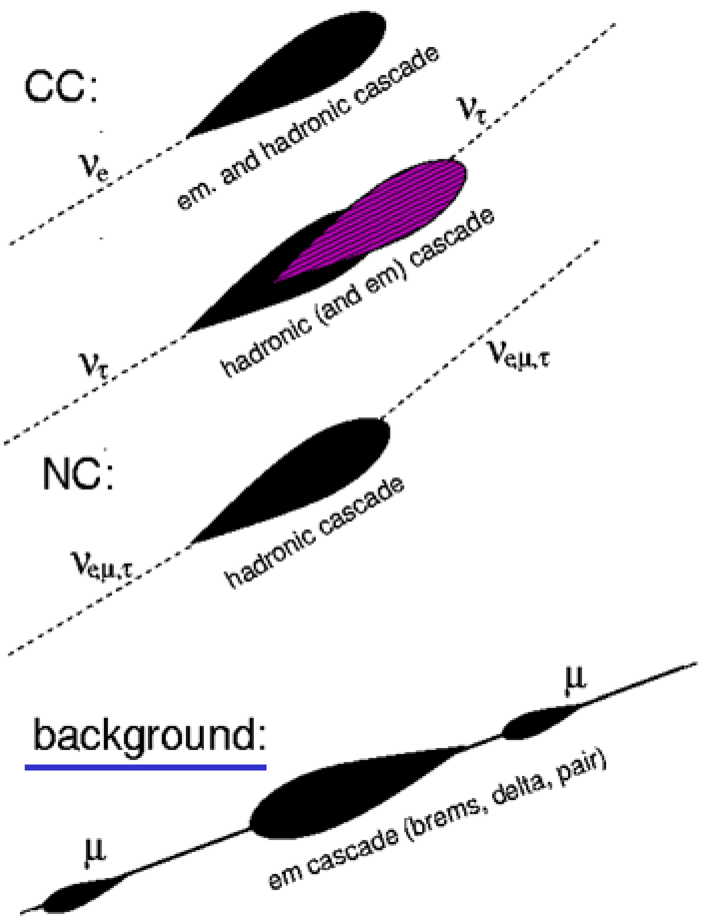
- Search for anisotropy

- Time and/or space coincidences with other cosmic probes

First signal for NT is atmospheric neutrinos

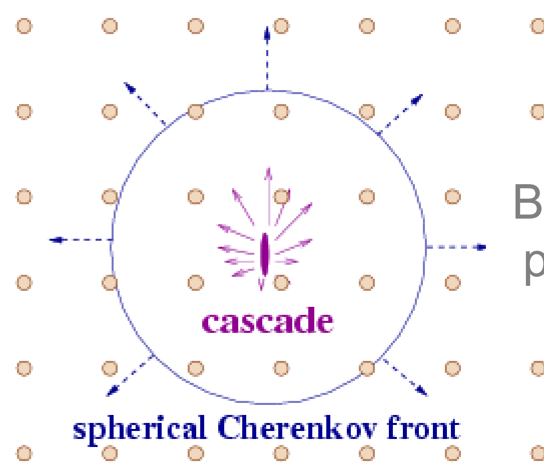
Other neutrino interaction topology

$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source $\xrightarrow{\textit{oscillation}}$ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !



So-called "cascade" events

Generic reconstruction:



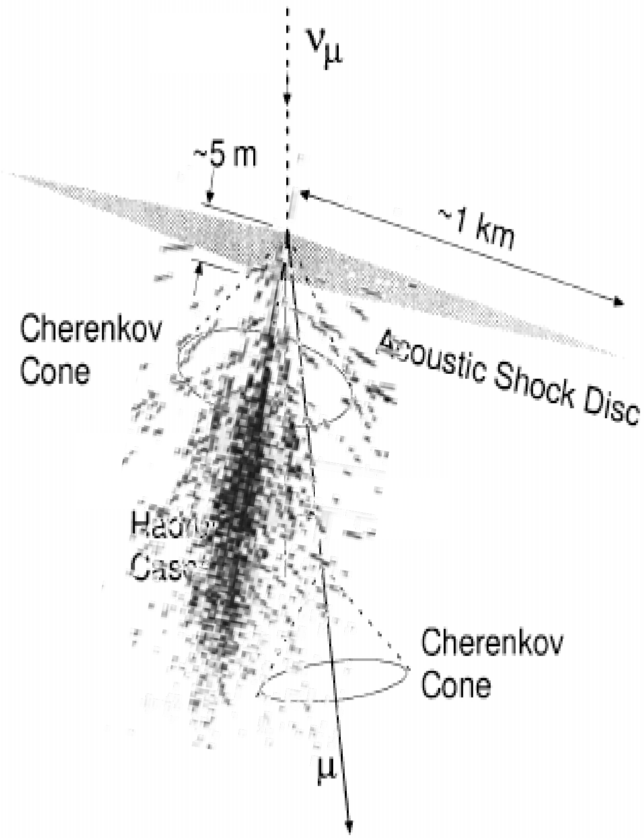
Bright point

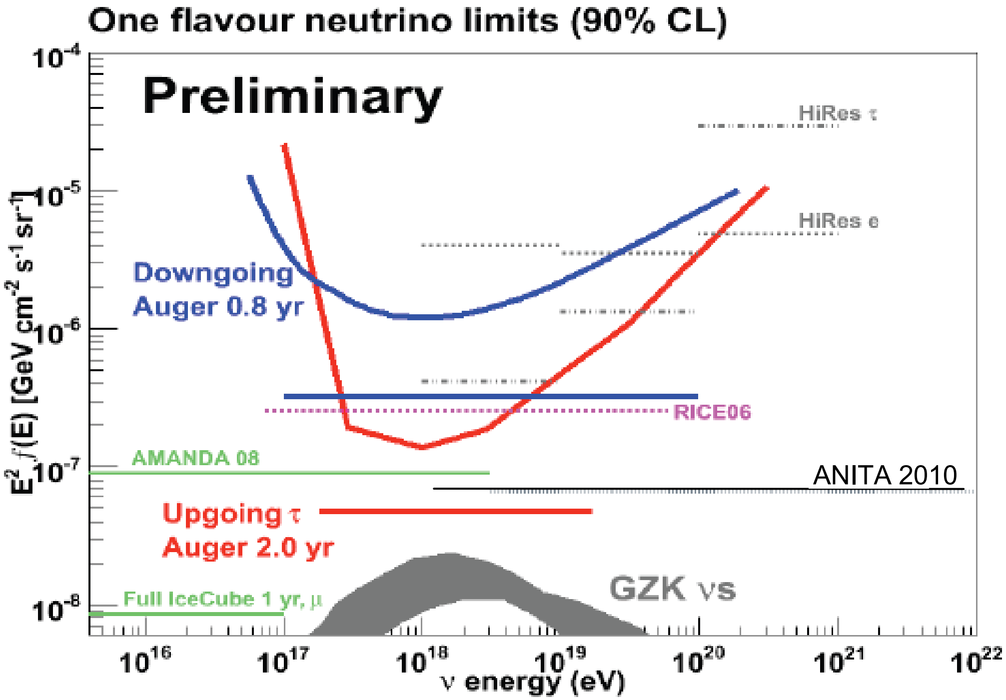
- Provide sensitivity to all neutrino flavors
- IceCube sees atmospheric ν_e ?

Other detection techniques

Acoustic shock, Optical, Radio (Askaryan Cherenkov), E.A.S, fluorescence

UHE neutrinos (not suited for TeV neutrinos)





Current limits disfavor « Top-Down » models

Exclude saturated model of GZK

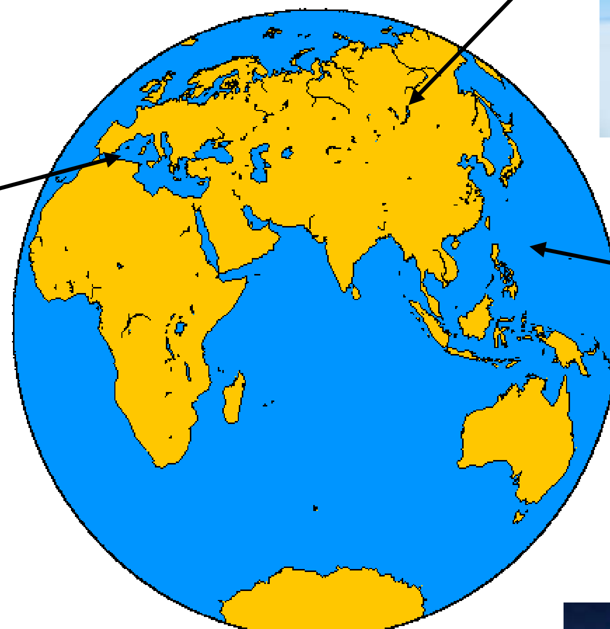
Cf O. Deligny's talk for AUGER (yesterday)

STATUS OF CURRENT PROJECTS

Cherenkov detectors world map

BAIKAL (1989) : Baikal Lake, Siberia
Gigaton Volume Detector GVD (~2017)

NESTOR (1989): Greece
ANTARES (1997) : France
NEMO (1999) : Italy



DUMAND : Hawaii
(cancelled 1995)

KM3NeT (2006): Mediterranean Sea
Consortium funded by EU

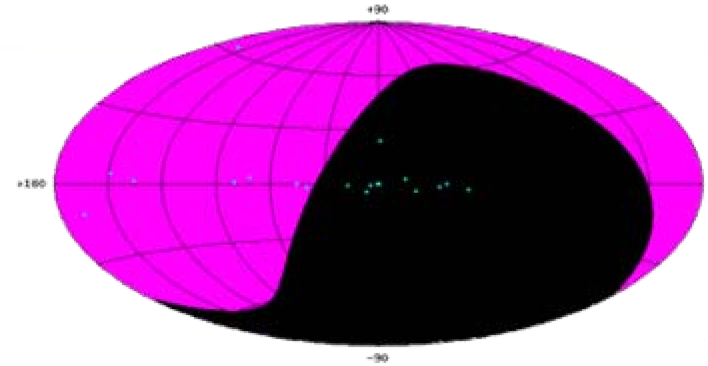
AMANDA (1993) /ICECUBE
South Pole, Antartica

Why the Mediterranean Sea?

- Obvious complementarity to South Pole
  - TeV sources, Galactic centre, galactic plane
- Deep sites - up to ~5000m
  - Reduces muon background contamination
- Infrastructure close to shore
  - Logistically attractive
- Re-surfacing and re-deployment of faulty/damaged detector elements is feasible
- Long scattering length
  - Good pointing accuracy
- Optical activity [quiet in ice and fresh water]

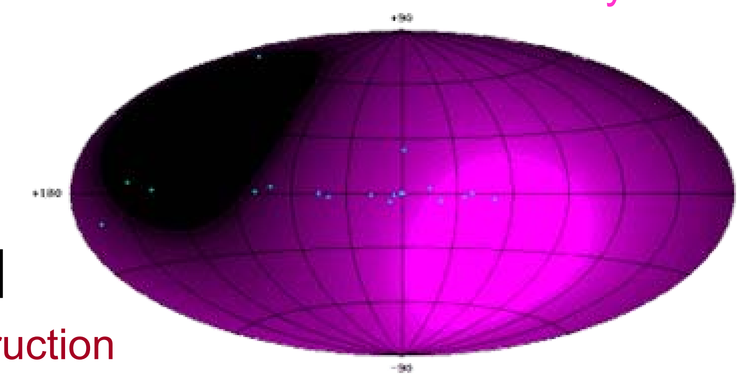
Living creatures/bacteria — Require causality filter for reconstruction
^{40}K decay — Used for calibration

South Pole visible sky

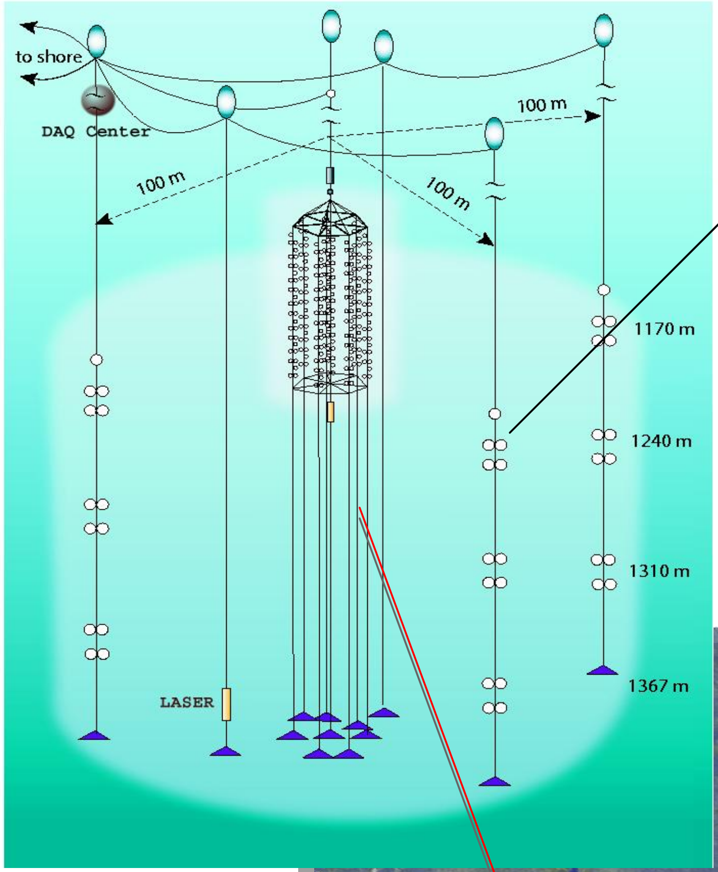


Most γ TeV sources in the field of view of northern NT !

Mediterranean visible sky



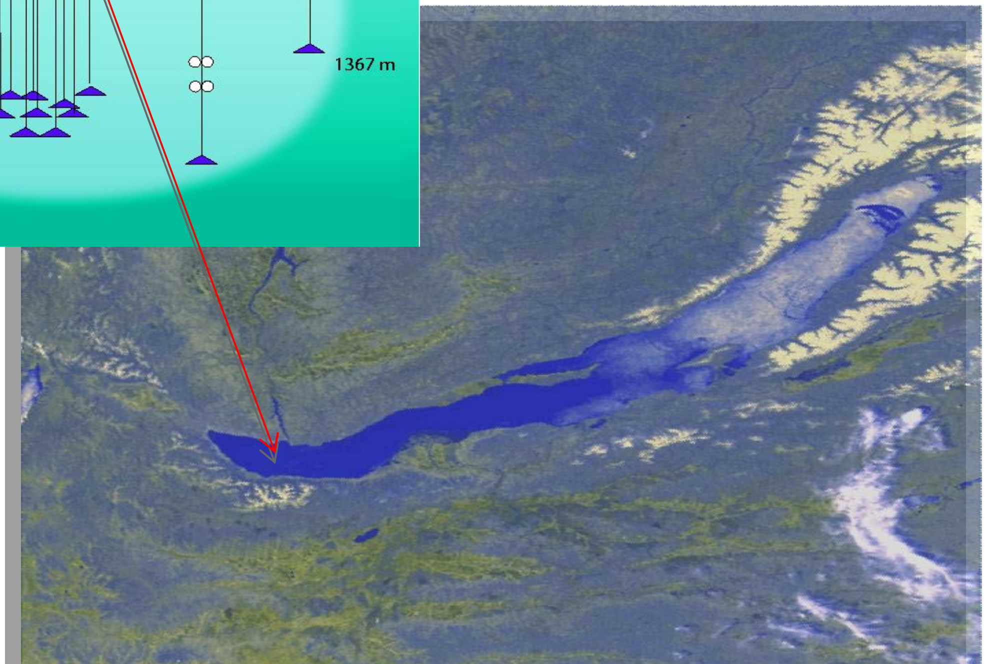
Baikal NT status



NT200+ is now operating

Quasar photodetector (∅=37cm)

GVD TDR expected in 2011



~ 3.6 km
to shore
1070m depth

NT200 +
8 strings (192 OMs) + 3 outer strings (36 OMs)
Height x ∅ 210m x 200m $V_{inst} = 4\times10^6 m^3$
Eff. shower volume: 10 PeV ~ 10 Mton
Includes 2 prototype strings for GVD New OM, DAQ, cabling triggering systems

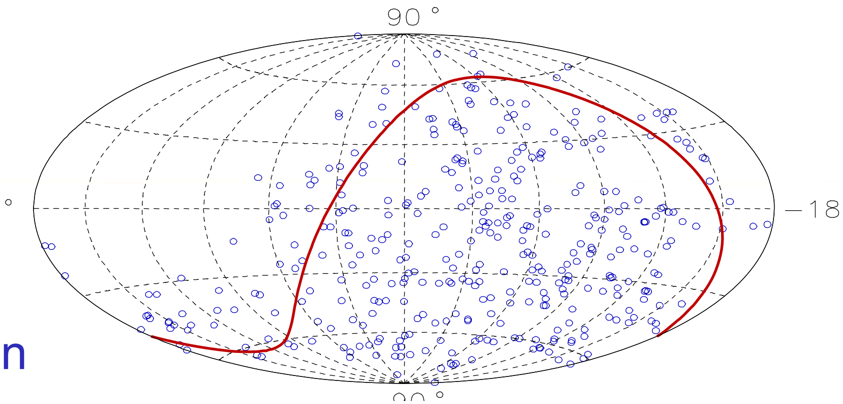
Baikal (NT200) physics studies

• Point sources / atmospheric neutrinos

• 372 neutrinos in 1038 days (1998-2003)
Expected 385 from Monte Carlo

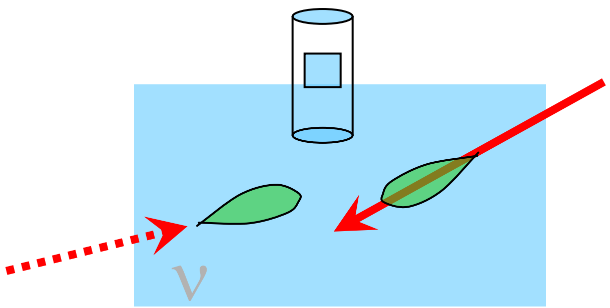
• Search for up-going μ correlated with 155 GRB in time and direction.

No excess, no significant cluster, no correlation



Skyplot of ν events for 5 years
E_{THR} 15-20 GeV (gal. coord.)

• Diffuse High Energy Neutrinos



• Studies of bright cascades detected in the telescope: a search for excess above the expected background from atmospheric muons.

The 90% C.L. "all flavor " (new analysis) limit, $\nu_e:\nu_\mu:\nu_\tau=1:1:1$

$E^2\,\Phi_\nu < 2.9 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} 20 TeV < E_ν <20 PeV

• Neutrinos from DM annihilations

• A search for possible signal from WIMP annihilation in the centres of the Earth, the Sun, the Galaxy ("indirect" WIMP search). ☞ Upper limits

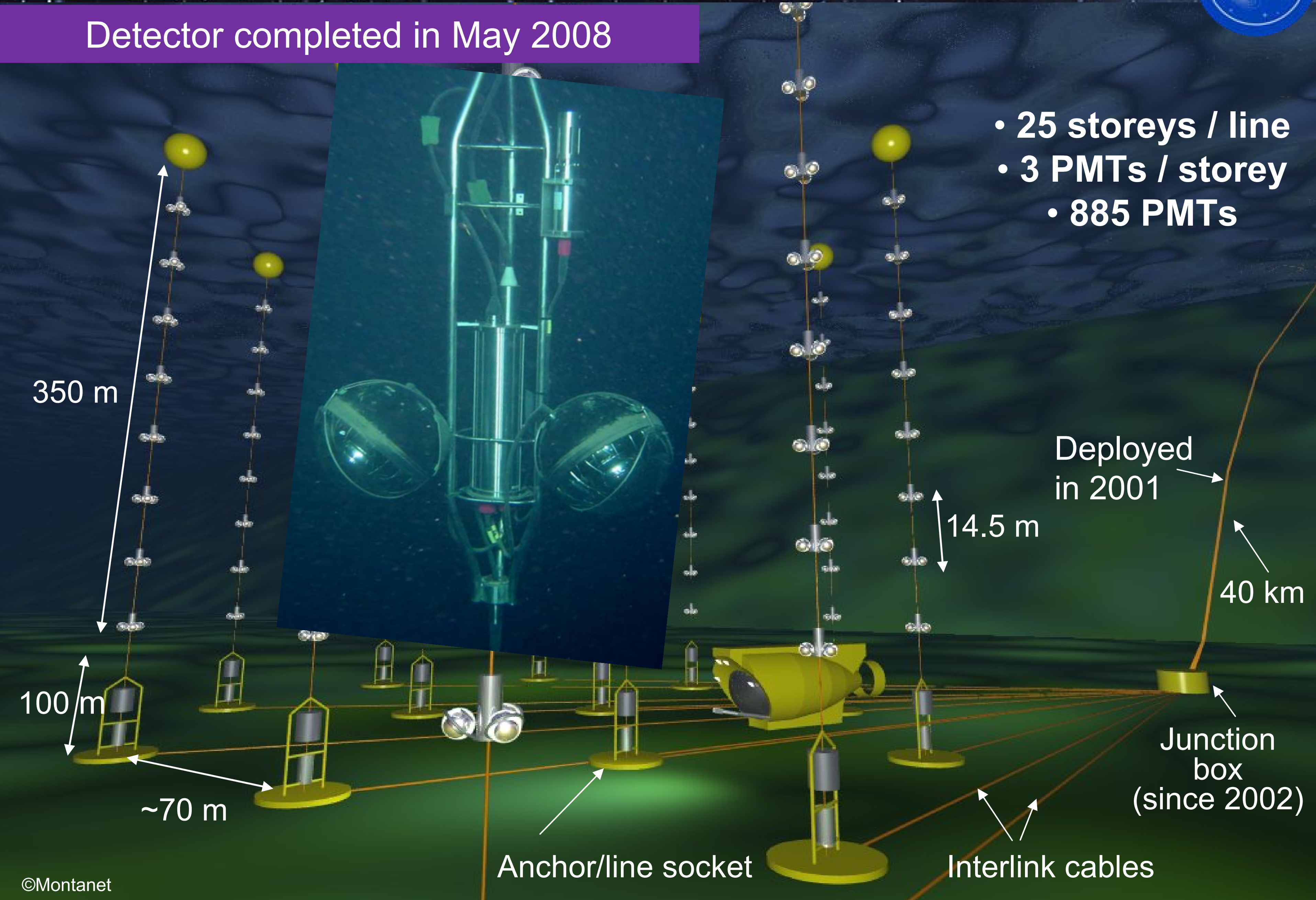
• Exotic physics

Search for fast and slow moving magnetic monopoles ☞ Upper limits

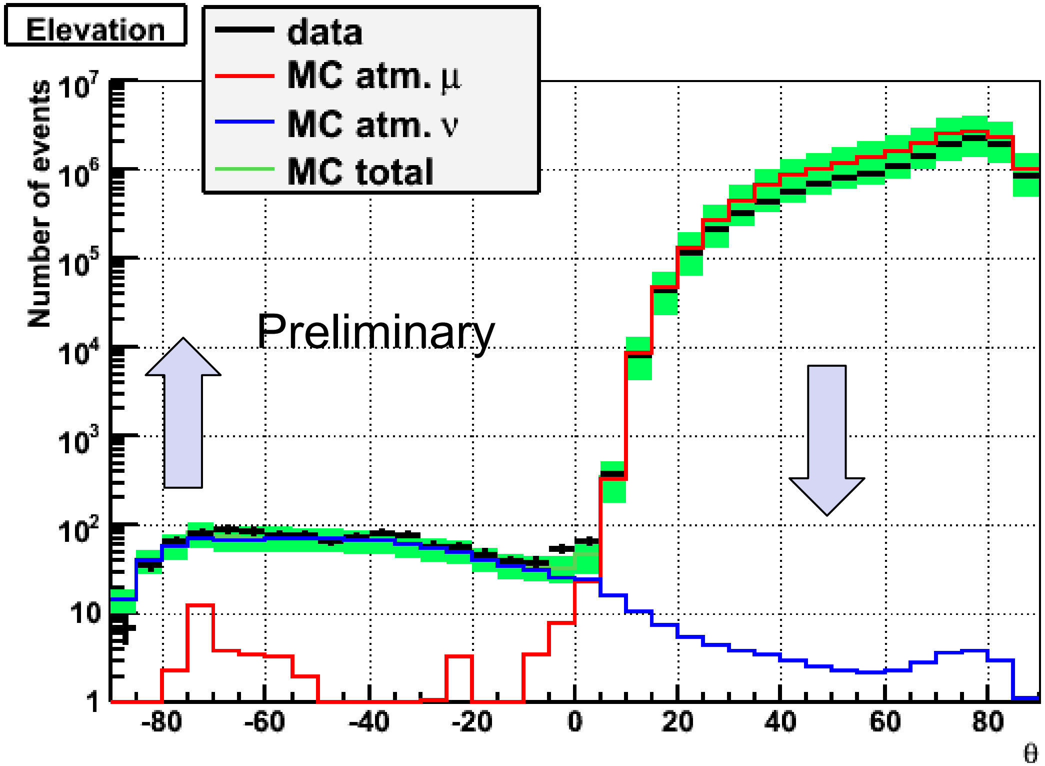
The ANTARES neutrino telescope

Detector completed in May 2008

- **25 storeys / line**
- **3 PMTs / storey**
- **885 PMTs**



ANTARES reconstructed data set



5-line data (May-Dec. 2007)
+
9-12 line data (2008)

341 days detector live time

1062 neutrino candidates:
3.1 ν candidates/day

Fair agreement with Monte Carlo
atmospheric neutrinos: 916 (30% syst. error)
atmospheric muons: 40 (50% syst. error)

Physics program started. First results presented.

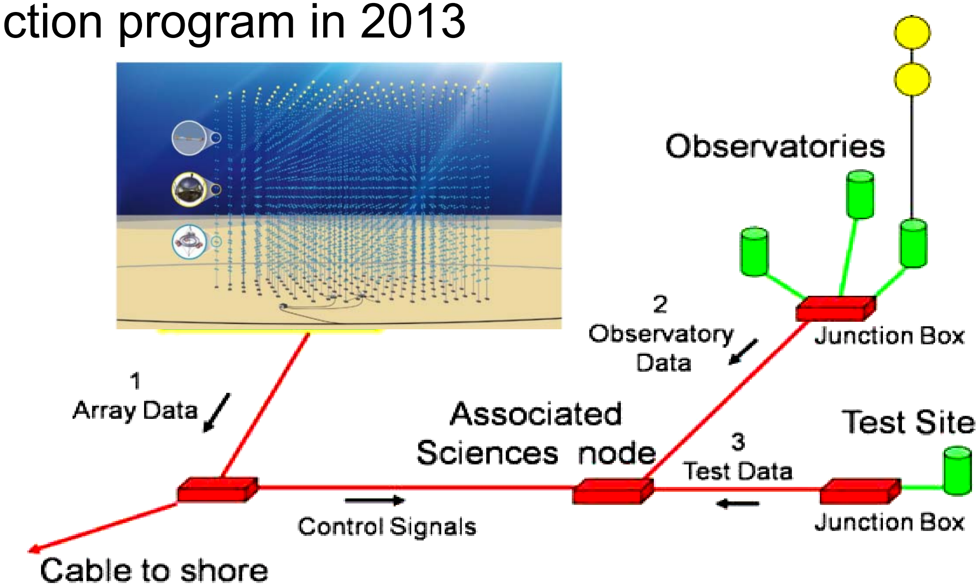
Cf A. Margiotta's talk (this morning)

KM3NeT activities

Consortium : 40 institutes from 10 European countries

Cf E. de Wolf's talk on Thursday

Objectives :
- Built a cubic-km scale NT in the Mediterranean that exceeds IceCube sensitivity by a substantial factor (target TeV galactic sources for an overall budget of ~ 250 M€)
- Provide node for Earth and marine sciences (real time multidisciplinary observatory)
- Start 5 years construction program in 2013



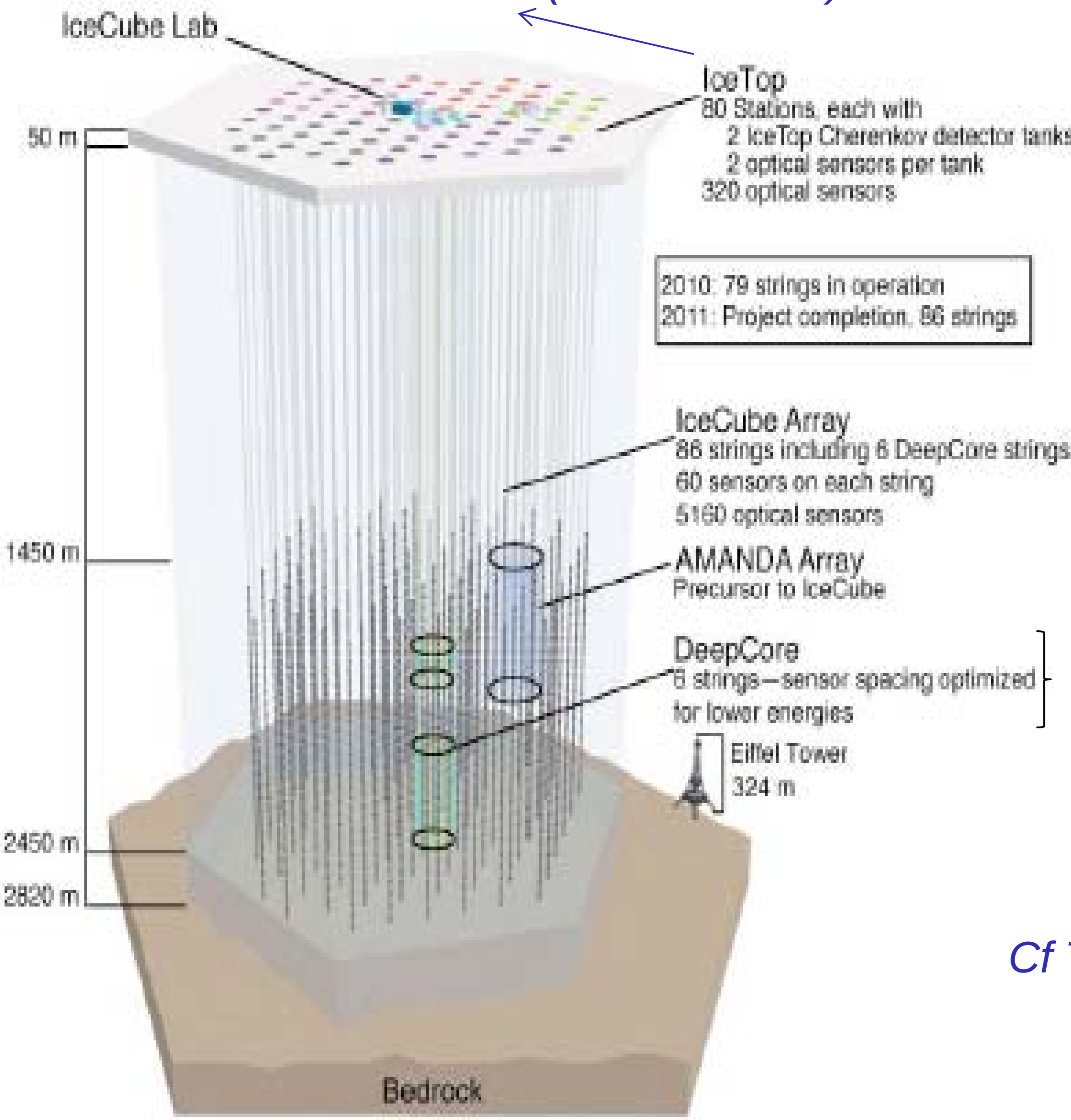
Achievements :
- Constructive gathering of "dispersed" forces
- Conceptual Design Report (CDR) published in 2008
- Technical Design Report (TDR) now available

http://www.km3net.org/public.php

Pending :
- Clarify the question of the site in the coming year

IceCube: a km^3 NT at South Pole

Cf Krislat's talk (this afternoon)



IceCube data taken during construction

2006-7 data set – IC9

2007-8 data set – IC22

2008-9 data set – IC40

2009-10 data set– IC59

Current configuration– IC79

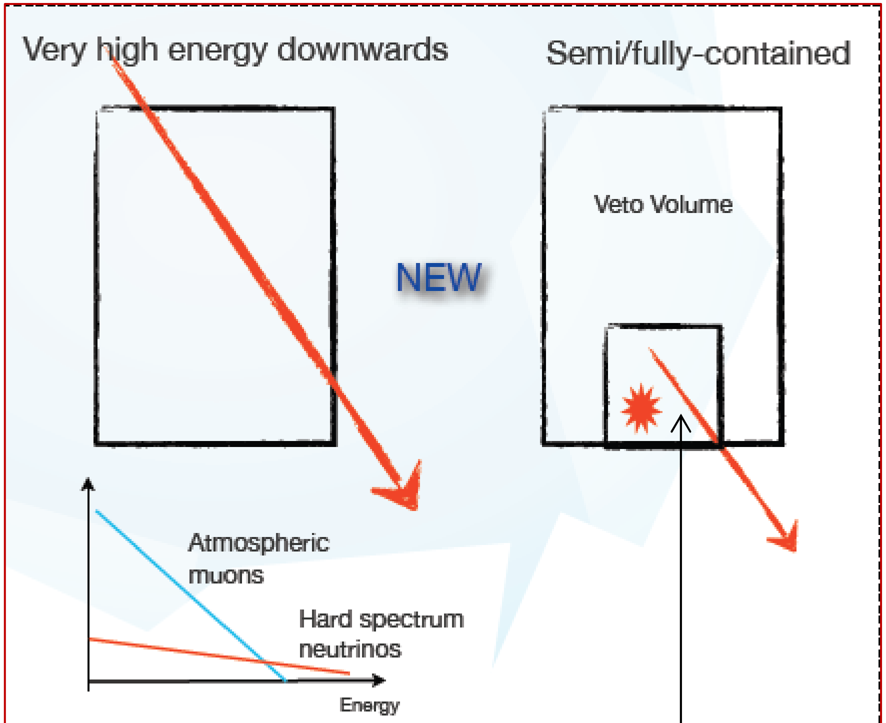
Enhances physics capabilities at low energy (~20 GeV) Dark Matter, Oscillation…

Only infill strings remain to be deployed

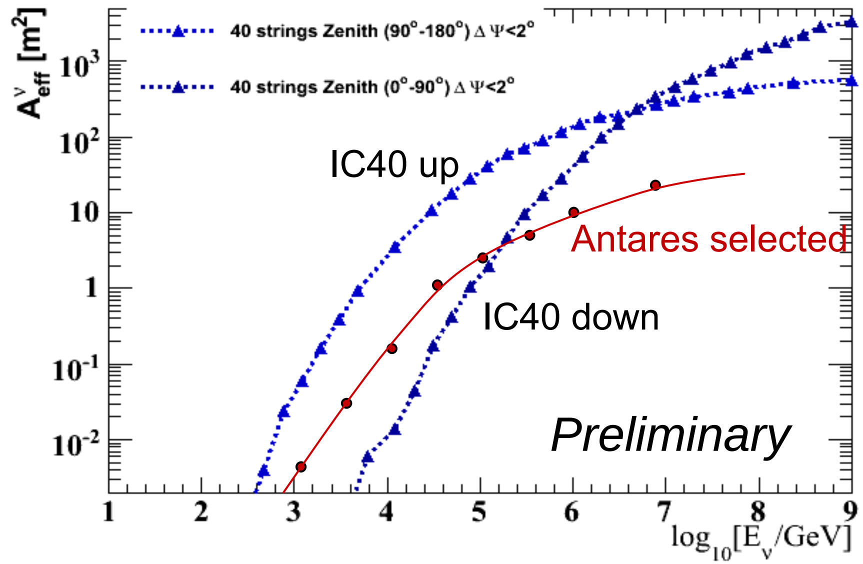
Cf T. Karg's talk (this morning)

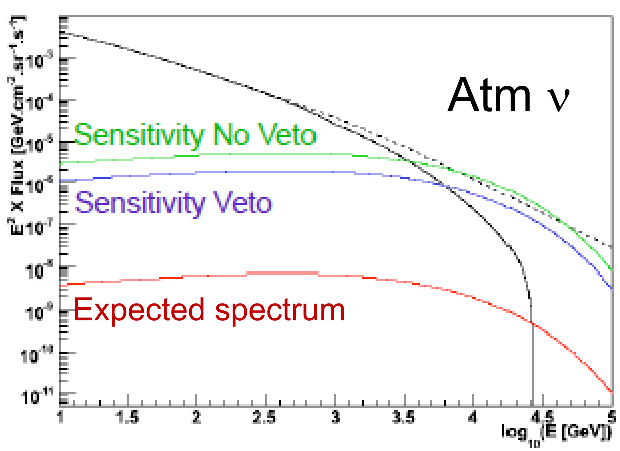
IceCube extension to 4π sky

The size of IceCube now allows to search for down going neutrinos at very high energy



Including DeepCore





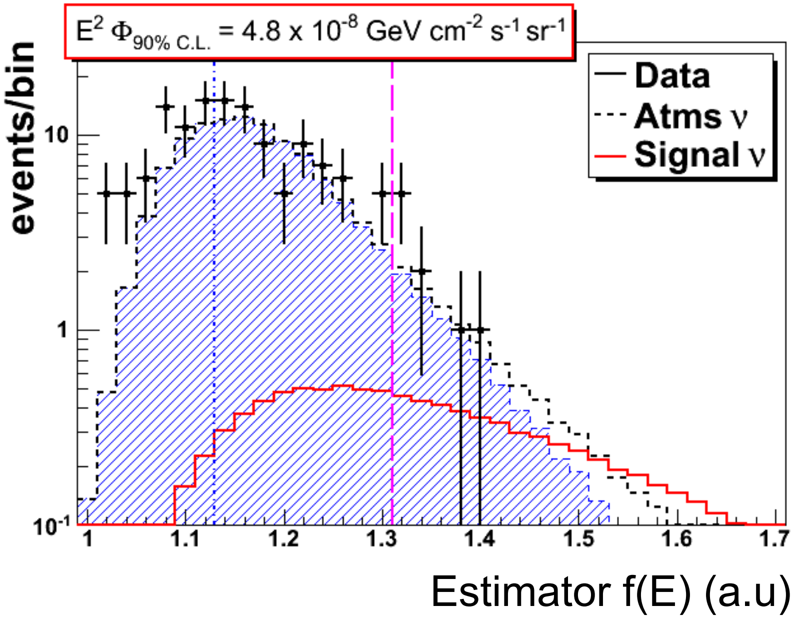
Sensitivity is reduced by:

- HE cut required to kill atmospheric background
- Vetoing against background (contained interactions)
- Difficult for TeV galactic sources like RX J1713.7-1936

Shonert et al. Phys.Rev.D79,043009 (2009)

SELECTED ANALYSES

Diffuse ν_μ flux – Upper limits (E^{-2})



334 days live time

9 observed events for 10.5 ± 2 expected

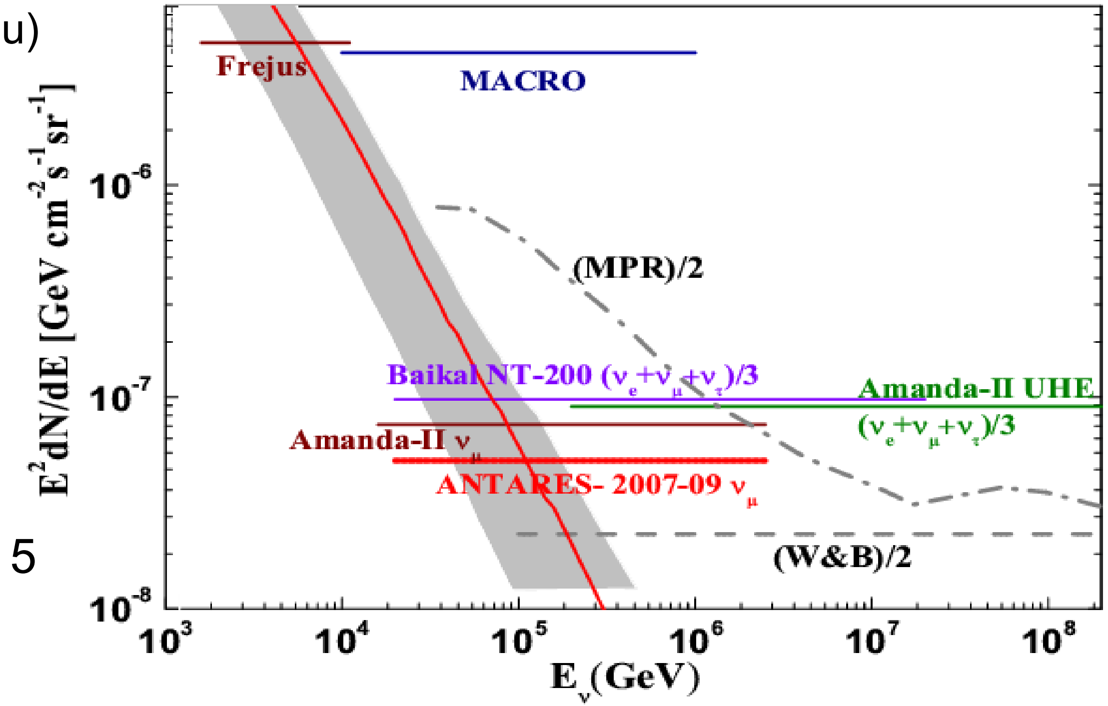
$\Rightarrow$ $E^2\Phi(E)_{90\%} = 4.8\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

20 TeV<E< 2.5 PeV

ANTARES limit currently the best established result …

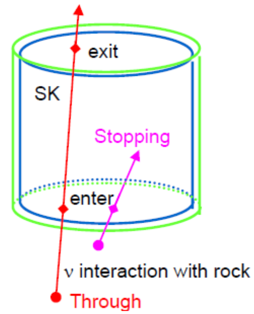
…but superseded by IC40 sensitivity (375 days) by a factor ~ 5

☞ below WB flux



Recent searches for neutrino point sources

- SK experiment (low energy threshold E>1.6 GeV)
  - All 3134 upward through going events in 2623 days

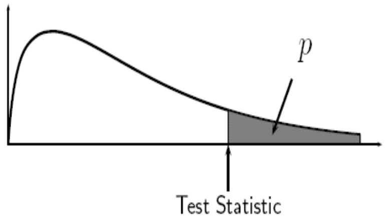


- ANTARES first analysis with 5 lines (TeV)
  - 2007 (140 days) data analyzed with simplified reconstruction

•ICECUBE with IC40 data set (375.5 days) in all sky

Summarized generic “blind” analysis (Optimized with scrambled data set)

- Use Clusterization algorithm
- Calculate a statistic given data (eg. Likelihood ratio)
- Compute *p-value* (probability to observe such statistic from bkg)
- Compute post-trial significance probability to observe *p-value* from many experiments



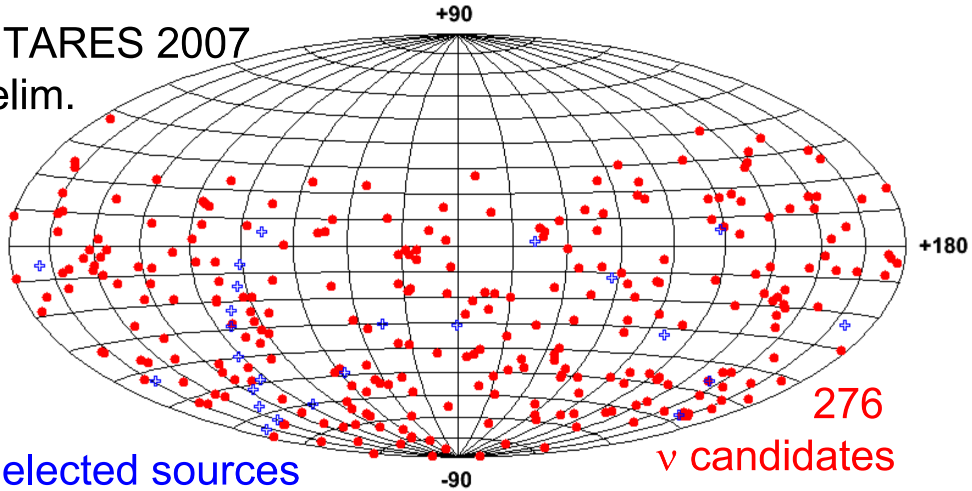
These analyses can be performed for :

- All sky search
- Predefined list of known sources
- Collection of sources of same kind summed up (stacking analysis)

Methods
- Neunhoffer and Kopke NIM A 558 (2006) 561
- Hill and Rawlins, Astrop. Phys., 19, 393, (2003)

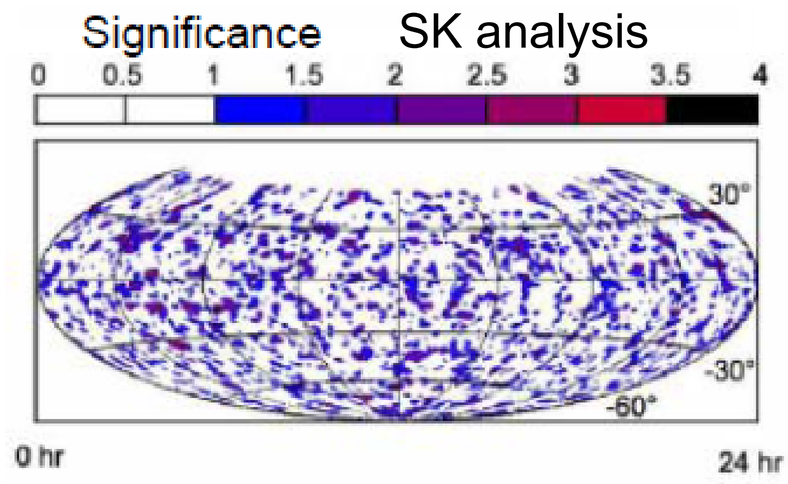
Selected results

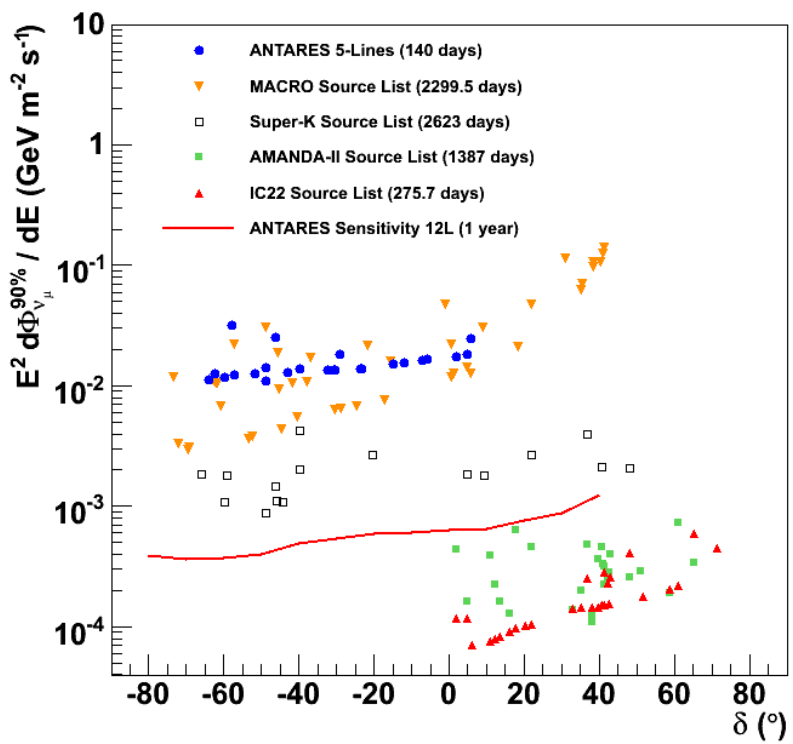
ANTARES 2007
Prelim.



Selected sources

276
ν candidates

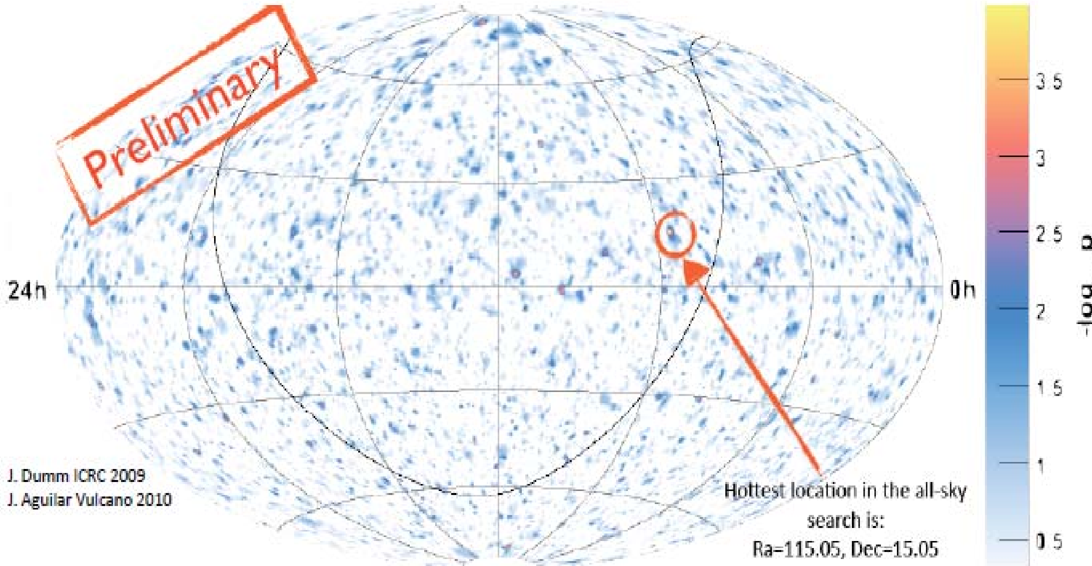




ANTARES lowest post-trial
p-value = 0.036 (1.8σ)
HESS J1023-575
No significant excess found

SK lowest post-trial
p-value = 0.025 (~2σ)
RX J1713.7-1946
No significant excess found

Updated searches (IC40)



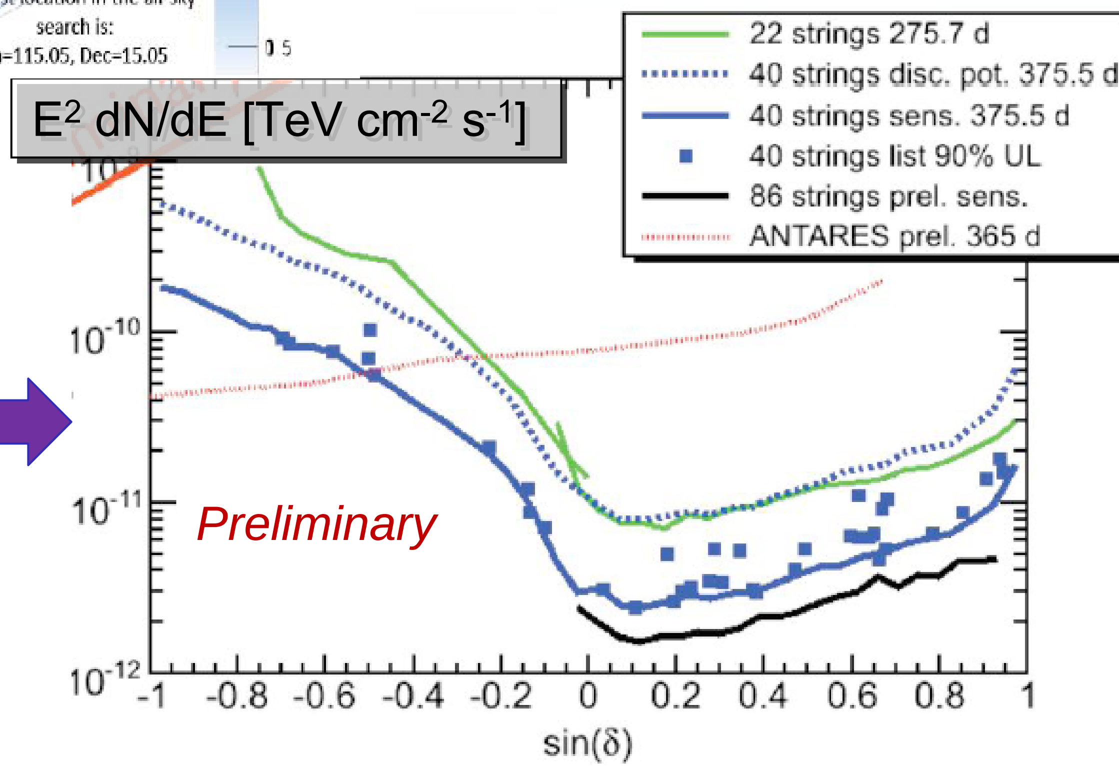
📖 J. Dumm et al., 31st ICRC, 2009
📖 J.A. Aguilar, Vulcano 2010

375 days
37290 events (14139 ↑ + 23151 ↓)
IC22 “hot spot” vanished

All sky post-trial *p-value* = 18%

No excess found ☞ limits

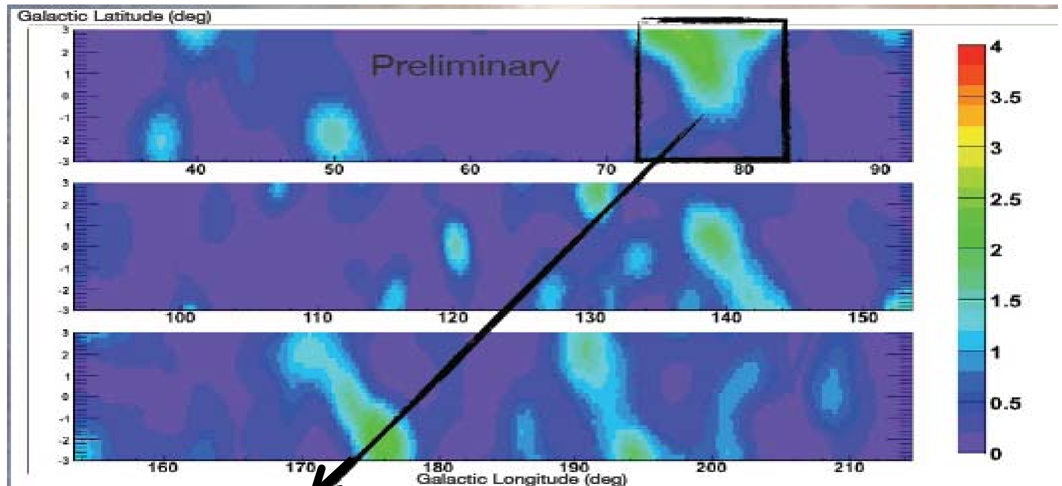
[E>PeV for IceCube at δ<0°]



Other analyses

• IC22+ AMANDA **scan of the accessible part of the galactic plane**
100 GeV < E < ~ PeV

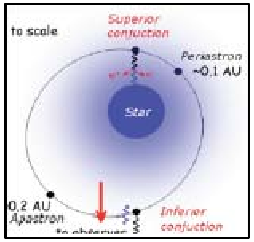
Cygnus region defined a priori

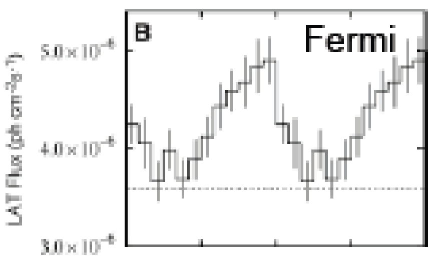


2.3 σ effect
Should be considered as background fluctuation
Ref: Sestayo VLVNT09

2-point correlation analysis in the entire region
(distance between couple of events compare to random case)

•**Time-varying sources (IC22):**
Analyses optimized by a priori information on the variability (e.g micro-quasars)





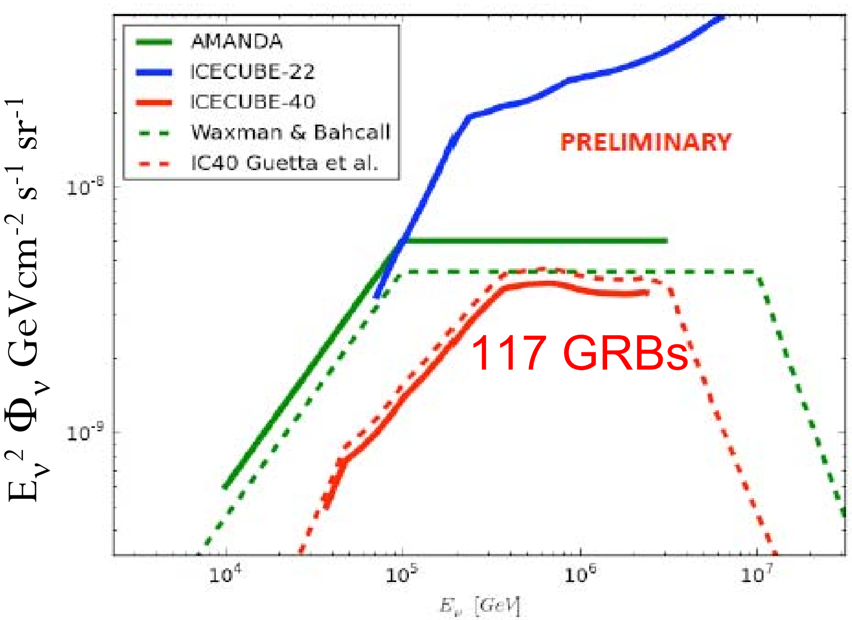
Post trial p-value = 1.8% for a catalogue of 7 objects, hence compatible with background
Preliminary

Another 2σ effect for Cygnus X3

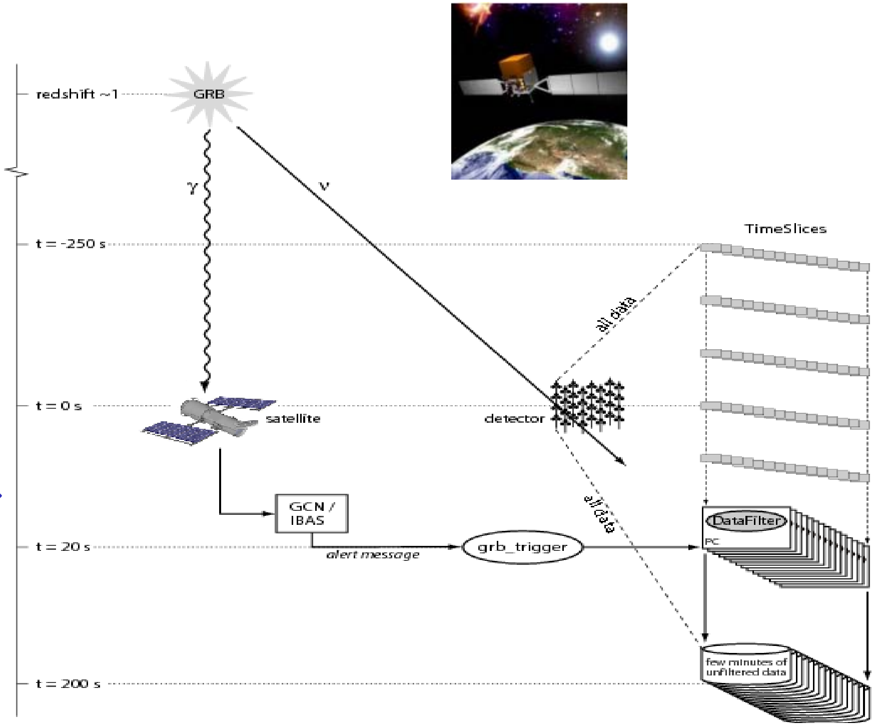
Ref: Montaruli PATRAS10

Multi-messenger analysis (1)

- Search for neutrino events in coincidence with observed GRB
  - Time and direction known ☞ background reduction ☞ improved sensitivity
  - Individual modeling of bursts using satellite data (fireball model)



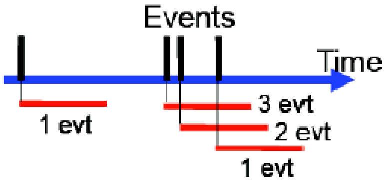
Best limit obtained with IC40 (supersedes recent Baikal x ~200)
Excludes optimistic predictions based on fireball model



- ANTARES dumps all buffered unfiltered data when receiving an alert (~1min)
  - Various analysis being performed

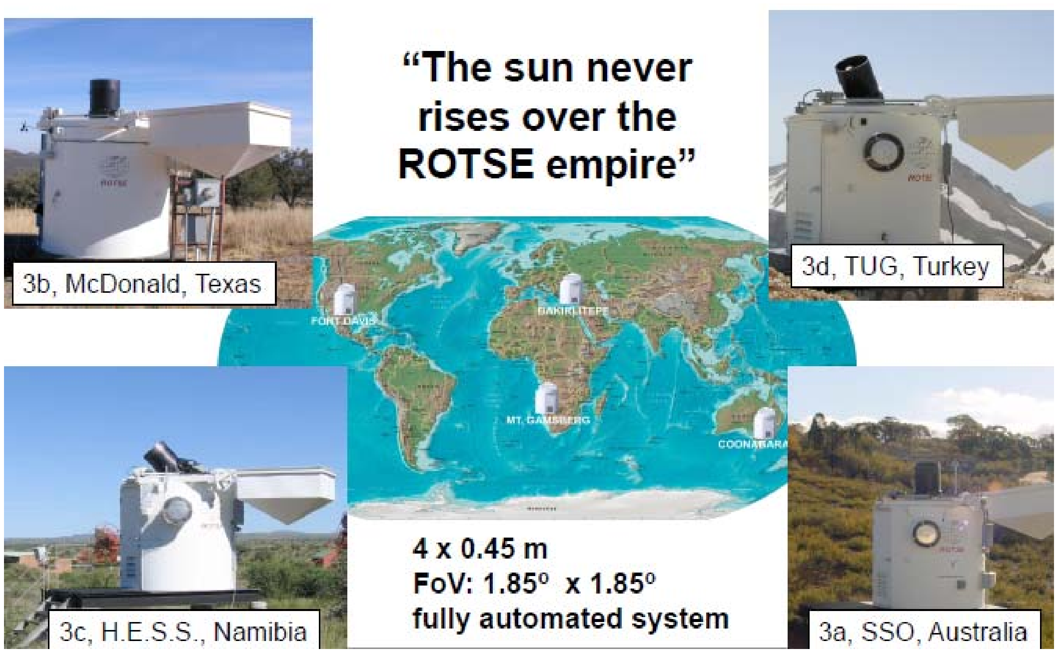
Multi-messenger analysis (2)

- Reversely, IceCube and ANTARES also send alerts for optical follow up
  - Could give confirmation of a detection
  - Triggers are VHE events or multiplets (rolling searches)



IceCube

Latency has been reduced to ~ minutes
Alarm rate ~ 30 /year
Alerts are sent to ROTSE
T_0, T_0 +1, 2,…14 days



Antares

Latency ~ sec
Alarm rate 1-2 / month
Alerts are sent to :
- TAROT (La Silla, Chile) since Feb 2009
  T_0, T_0 +1, 3, 9 and 27 days
- ROTSE for 3 months

IceCube is setting up a program with MAGIC (La Palma, E>25GeV)

System currently under commissioning

GWHEN working group

Objective: conduct a joint search for HE Neutrinos and Gravitational Waves

Motivations:

-plausible common sources GRBs (core collapse into BH or coalescing neutron stars), SGRs (magnetars), microquasars...

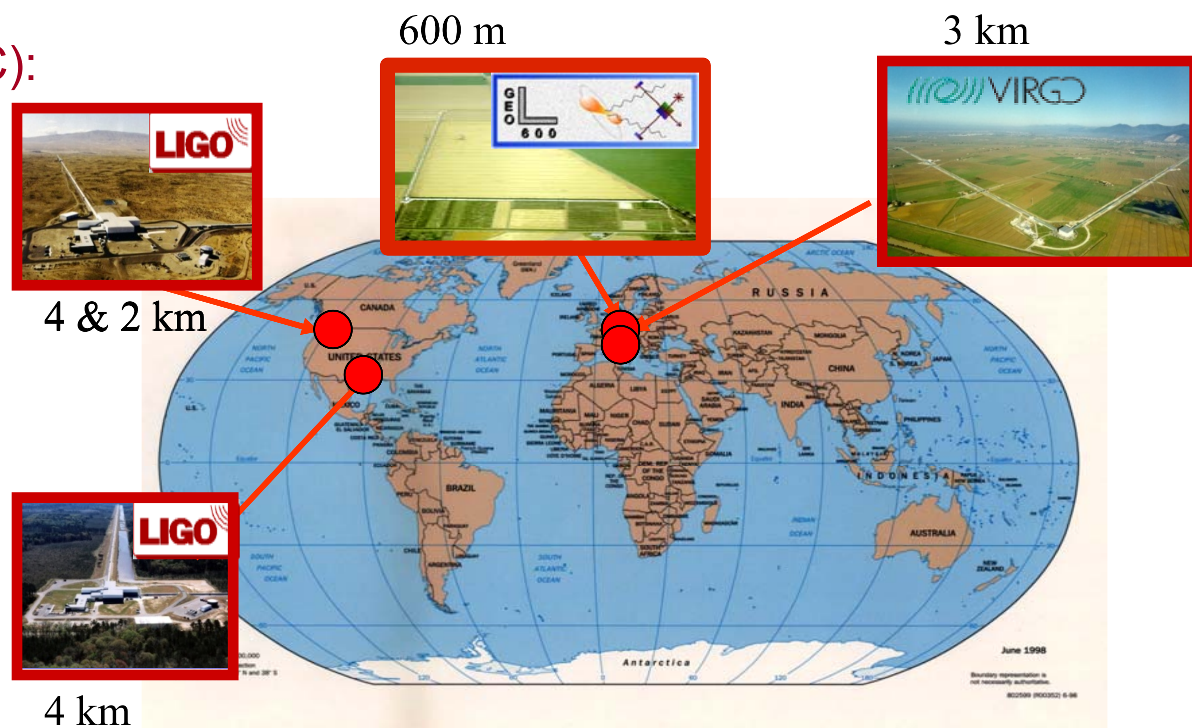
References : http://www.gwhen-2009.org

- potential for discovery of hidden sources (e.g. failed GRBs)

VIRGO/LIGO/GEO network (LSC):

Effective collaboration (MoU) between LSC and ANTARES (analysis started) since Sept 2009

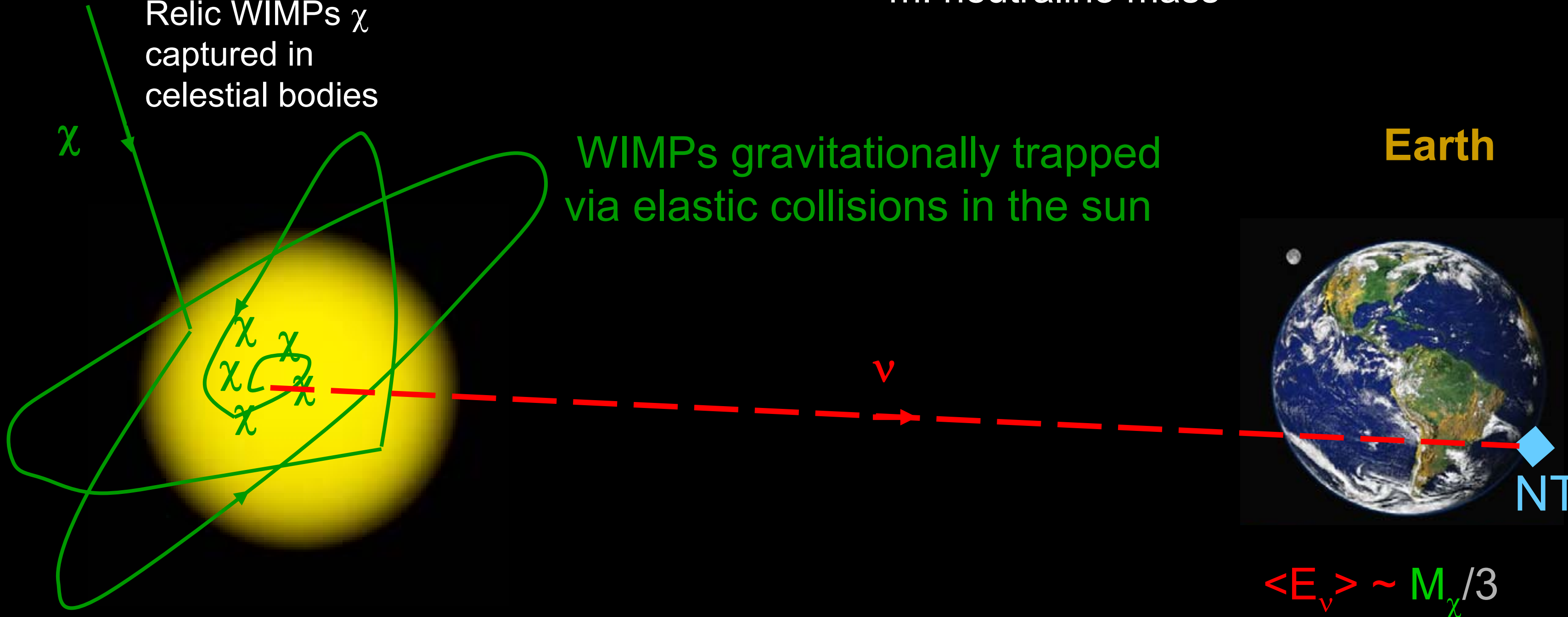
IceCube has recently joined the GWHEN group



Indirect Search for Dark Matter

$$\Gamma_{\text{ann}} = \frac{\sigma_{\text{ann}} v \rho^2}{m^2}$$

Γ_{ann}: annihilation rate per unit volume
σ_{ann}: neutralino-neutralino cross-section
v: relative speed of the annihilating particles
ρ: neutralino mass density
m: neutralino mass



Potential $\chi\chi \rightarrow \nu$ sources are Sun, Earth & Galactic Centre

$\chi\chi$ self-annihilations can produce significant high-energy neutrino flux

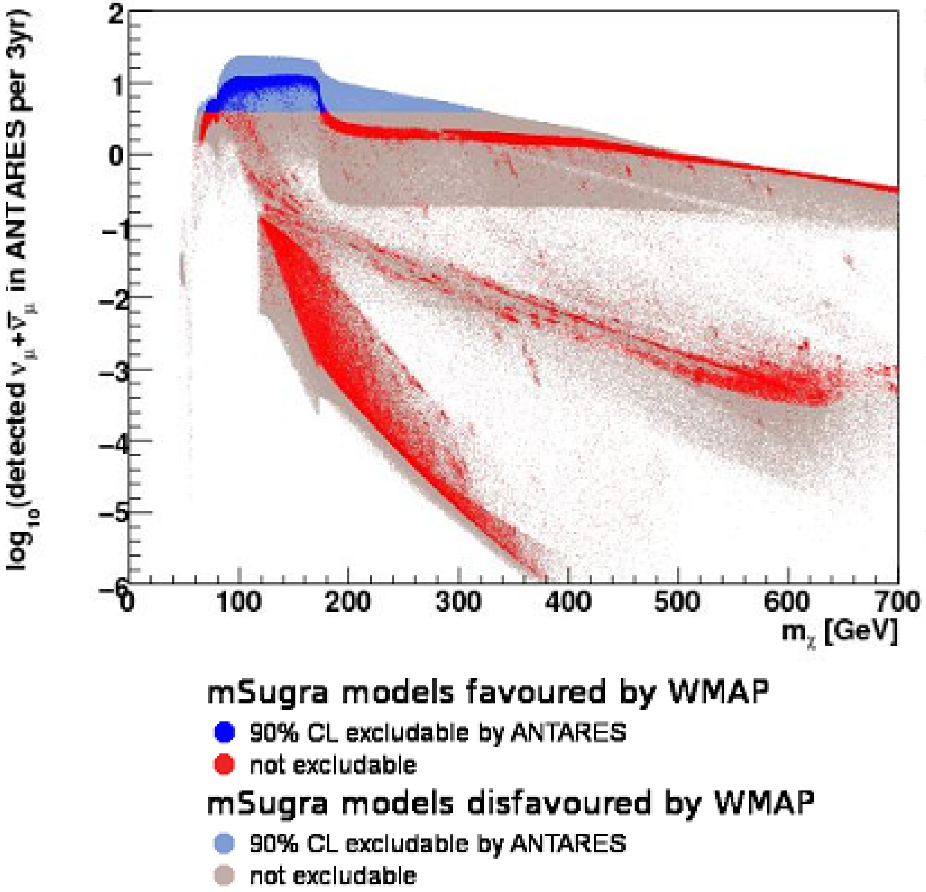
"hard" annihilation :
$\chi\chi$-> W+W-

"soft" annihilation :
$\chi\chi$-> bb

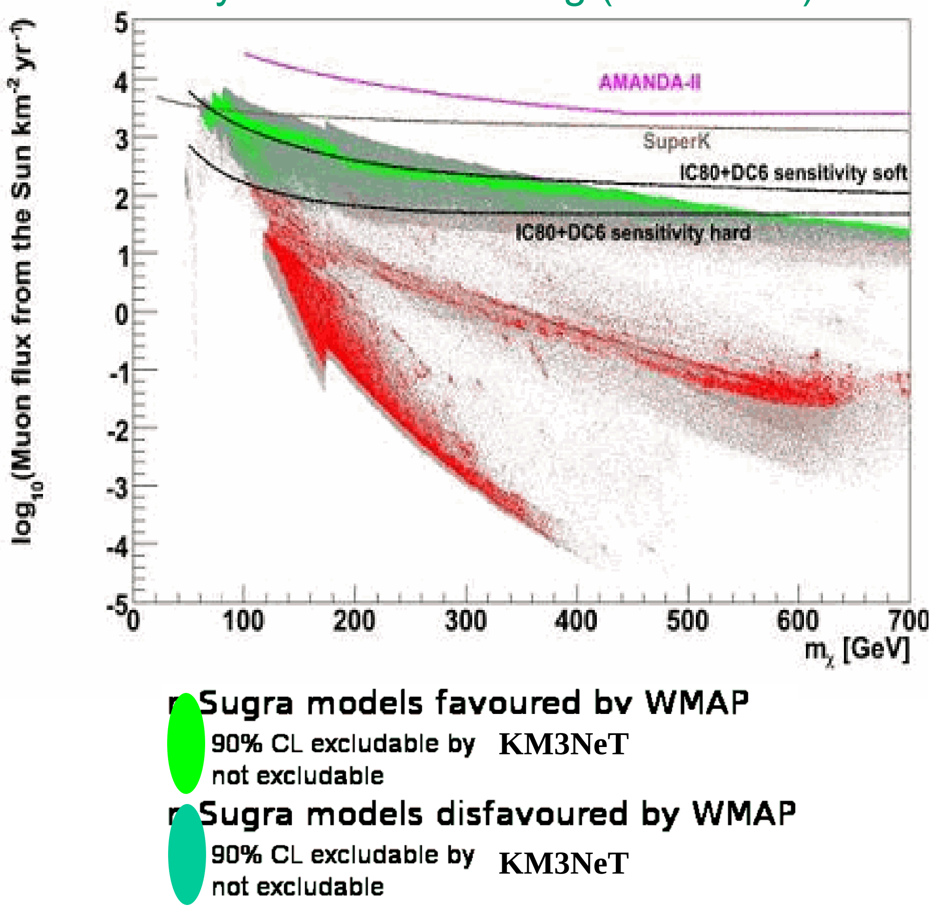
Prospects for dark matter

- Current limits do not constrain the WMAP favored models ($0.094 < \Omega_\chi h^2 < 0.129$)

ANTARES sensitivity calculated for 3 years of data taking (mSUGRA)



KM3NeT Sensitivity calculated for 10 years of data taking (mSUGRA)

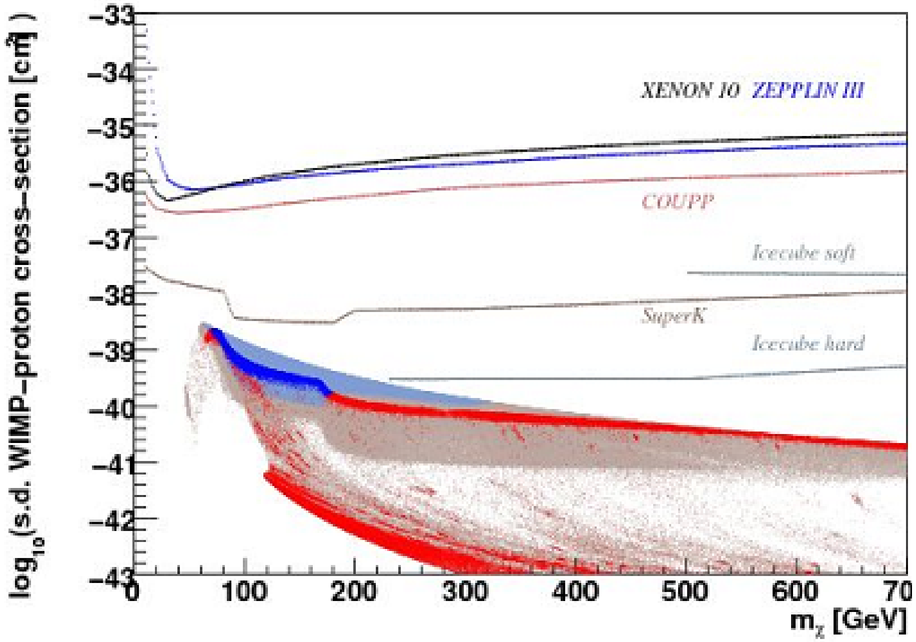


- Other models (e.g. mUED) have better prospects (direct LKP annihilation into neutrinos)

Spin-dependent scenarios

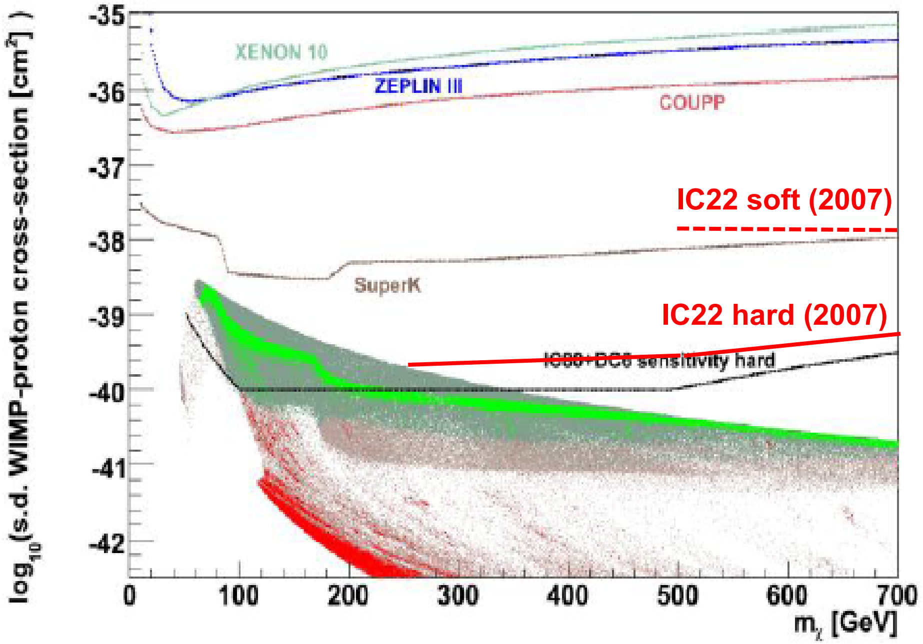
Very competitive sensitivity compared to direct detection experiments
in the case of spin-dependant neutralino interaction

ANTARES sensitivity calculated for 3 years of data taking (mSUGRA)



Current limits

Km-scale Sensitivity (10 years)



Conclusions

IceCube is almost 100% completed

- Available physics results from IC40 soon IC59
- Now probing theoretically interesting regions
- Intriguing fluctuations... Nothing else than that yet
- Deep Core component increases sensitivity at low energy
- Sensitivity to Southern sky does not reach ANTARES in TeV range

ANTARES detector completed in May 2008

- Largest neutrino telescope in Northern hemisphere
- First physics results
- A km-scale neutrino telescope in the deep-sea is feasible

KM3NeT has made serious progresses

- TDR released
- A possible start of the construction in 2013?
- A large program of synergetic multi-disciplinary activities

ANTARES/KM3NeT/IceCube have common meetings

Exciting physics program ahead

- Astronomical sources, multi-messenger approaches, CR physics, DM searches, exotic physics...
- Stay tuned!