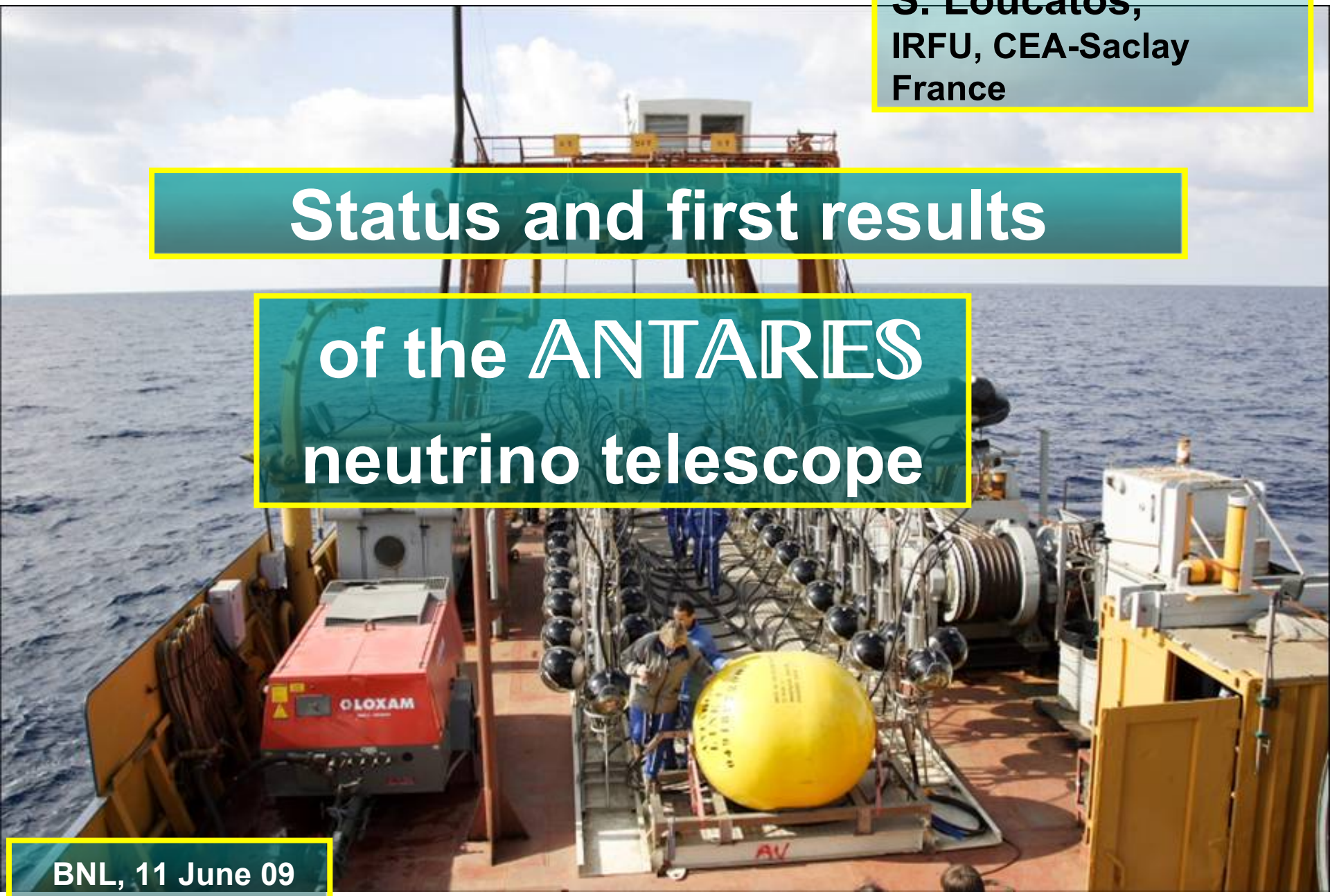
S. Loucatos,
IRFU, CEA-Saclay
France

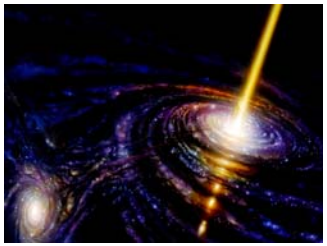
Status and first results of the ANTARES neutrino telescope

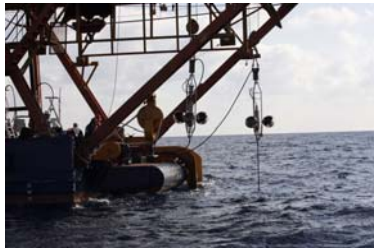


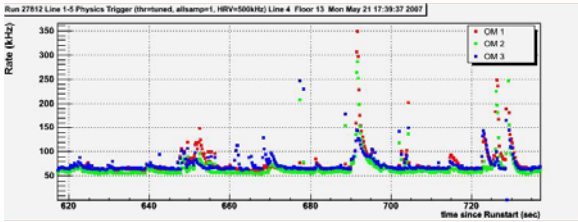
BNL, 11 June 09

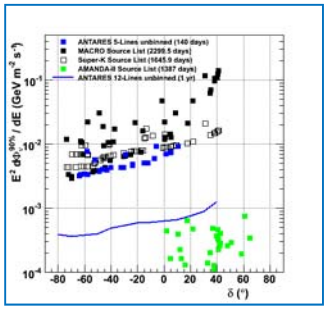
Outline

- Neutrino astronomy
  - The potential sources
- The ANTARES detector
  - Construction milestones
- Detector operation
  - The data taking campaign
- The first physics analyses
  - Atmospheric muons
  - Atmospheric neutrinos
  - Search for cosmic neutrino sources
  - Indirect dark matter detection
- R&D
- The future



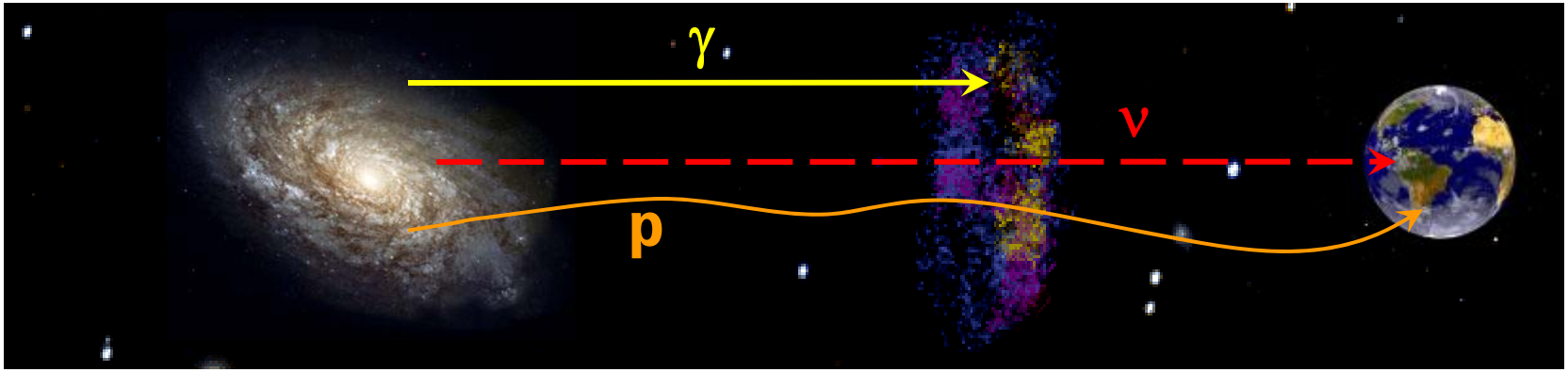


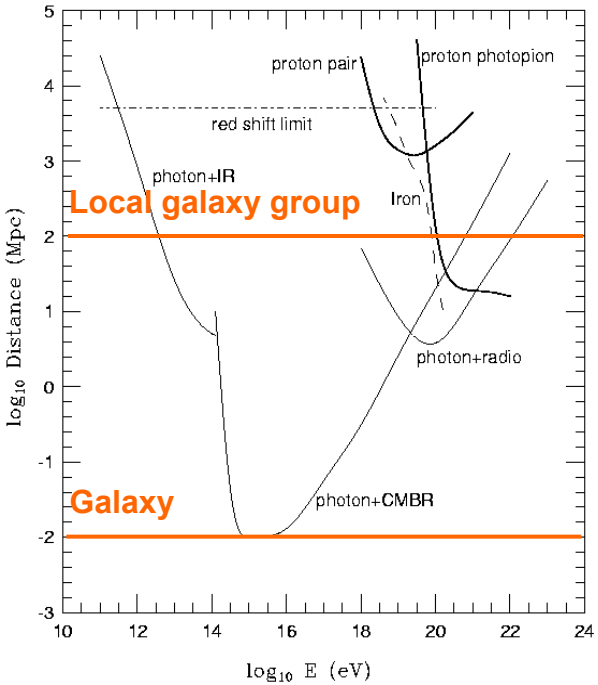




Neutrino Astronomy

Neutrino astronomy





- γ: interact with CMB and matter
- Protons: deflection by magnetic fields
- ν: weakly interacting
  - huge target needed (100Mton - Gton)

$$p/A + p/\gamma \rightarrow \pi^{\pm} + \pi^{0} + \ldots$$

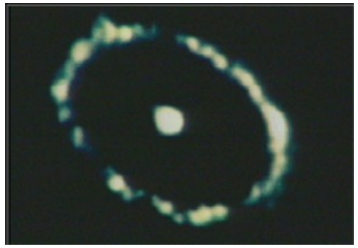
$$\pi^{\pm} \rightarrow \nu_\mu\ \mu \qquad \pi^{0} \rightarrow \gamma\ \gamma$$

$$\mu \rightarrow \nu_\mu\ \nu_e\ e$$

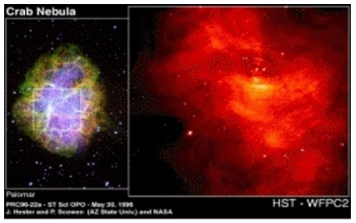
γ	< 2 10^9 l.y.	at 1 TeV	
	< 30 10^6 l.y.	at 100 TeV	→ local cluster
	< 30 000 l.y.	at 1 PeV	→ Galaxy

Galactique

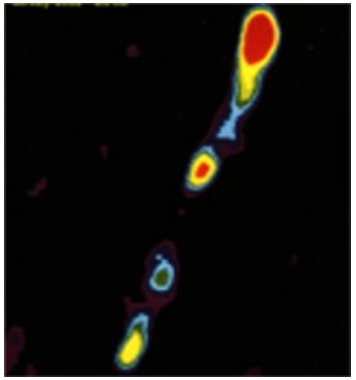
Restes de Supernova

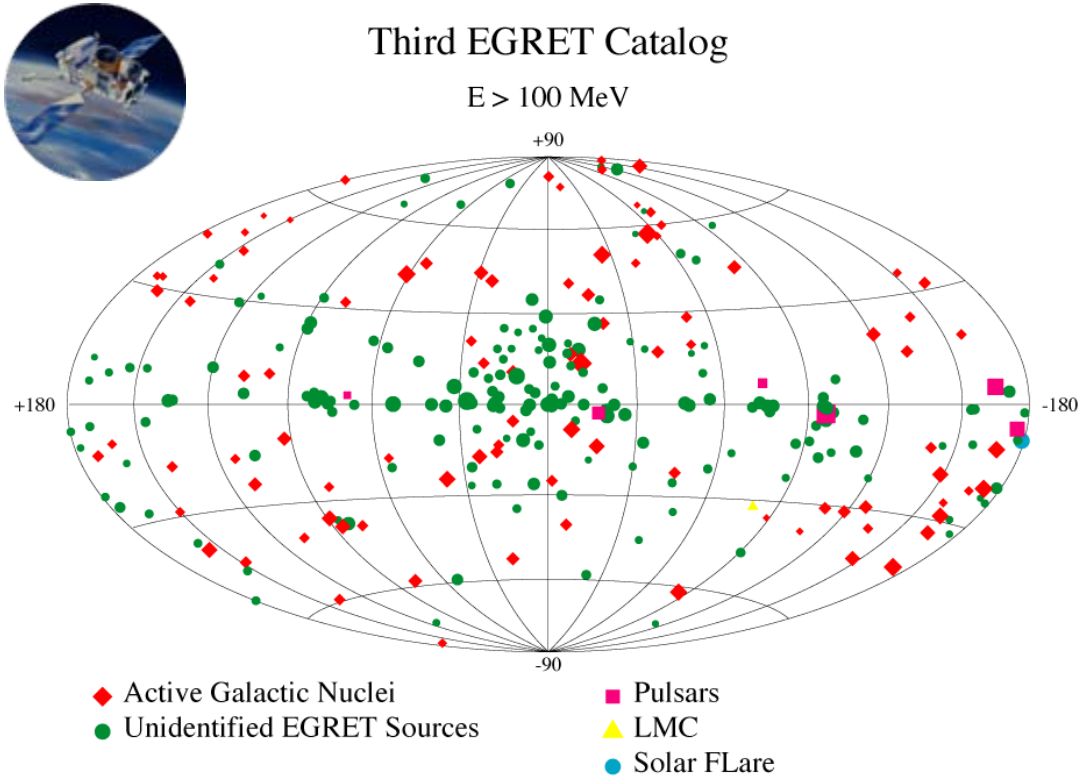


Pulsars



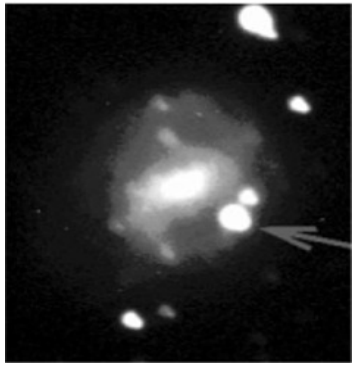
Microquasars



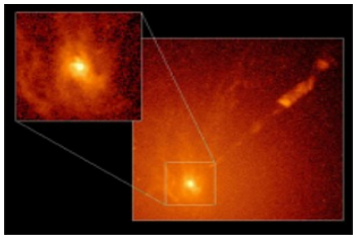


Extra-galactique

Sursauts gamma



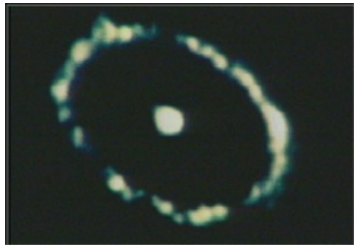
Noyaux actifs de galaxie



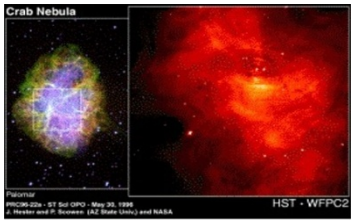
5

Galactique

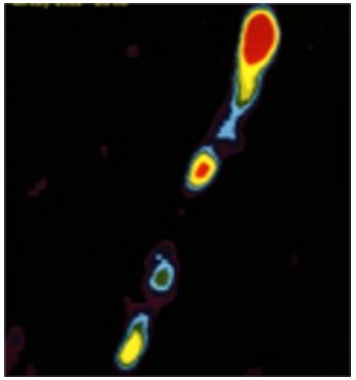
Restes de Supernova

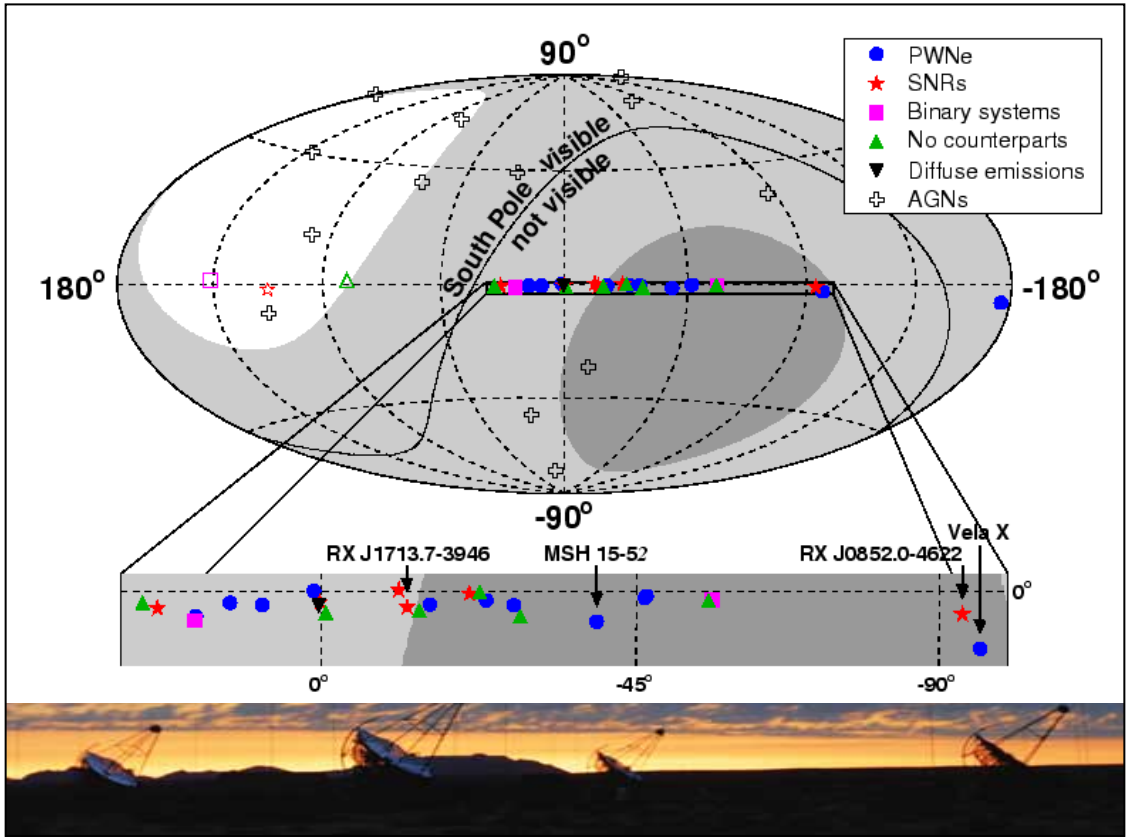


Pulsars



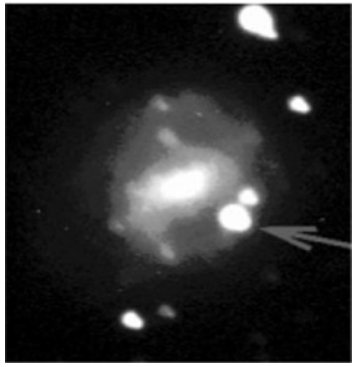
Microquasars



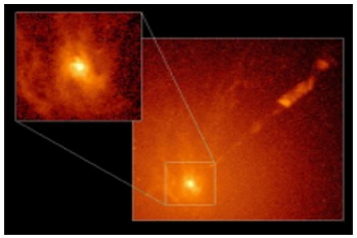


Extra-galactique

Sursauts gamma



Noyaux actifs de galaxie

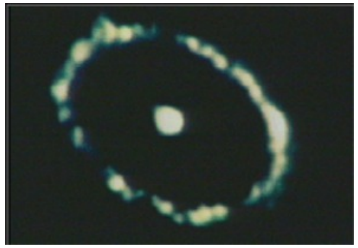


6

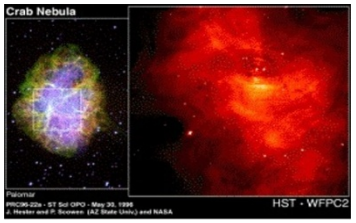
Galactique

Extra-galactique

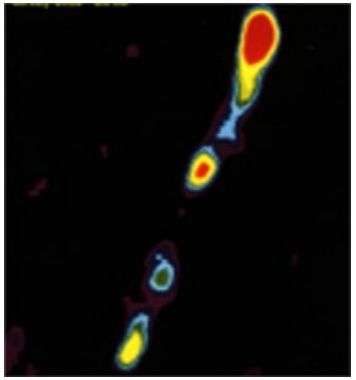
Restes de Supernova

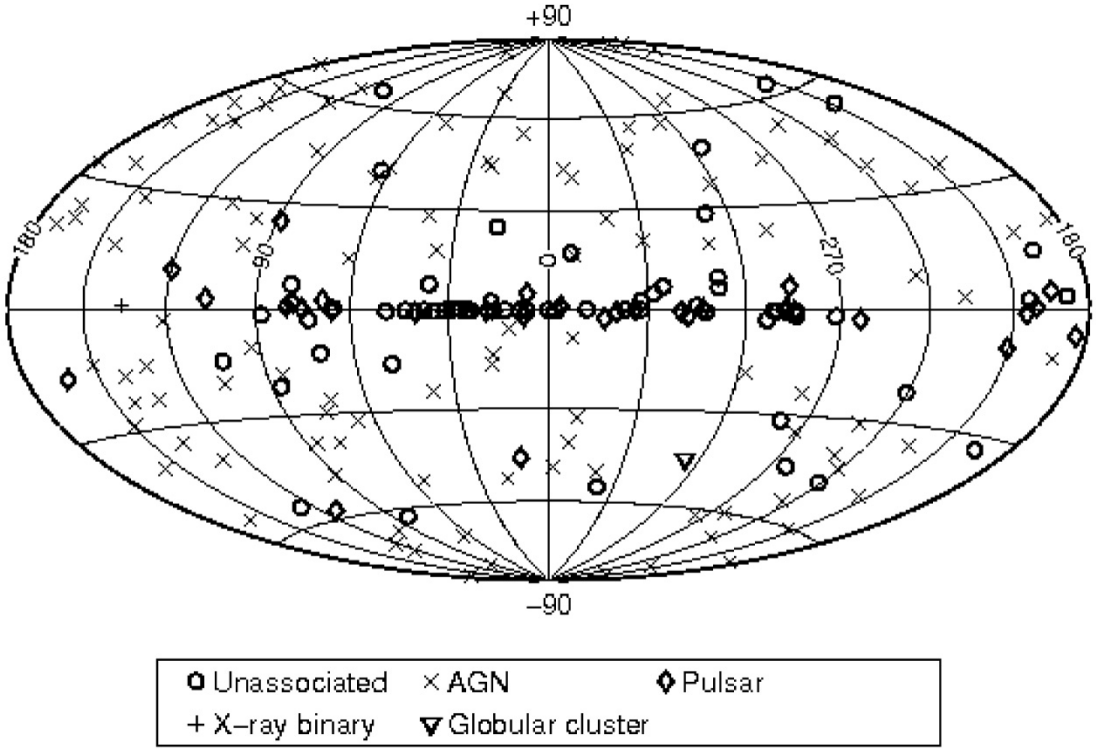


Pulsars

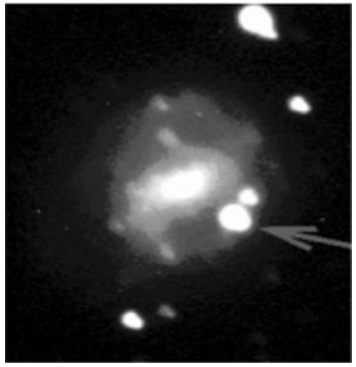


Microquasars

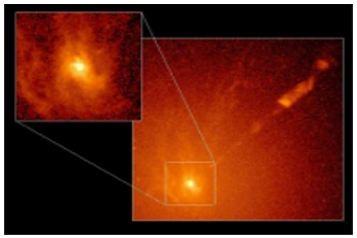




Sursauts gamma



Noyaux actifs de galaxie



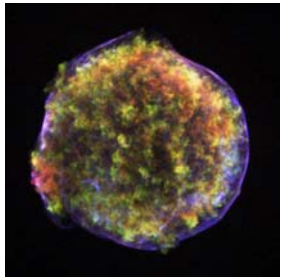
7

Potential sources

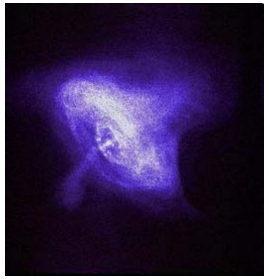
GALACTIC

EXTRAGALACTIC

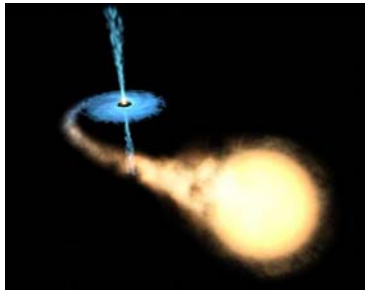
Indirect dark matter signal



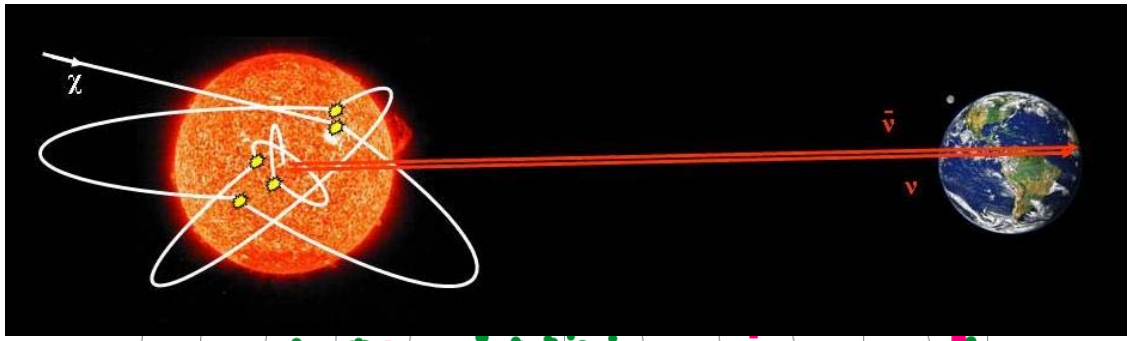
Supernova remnants

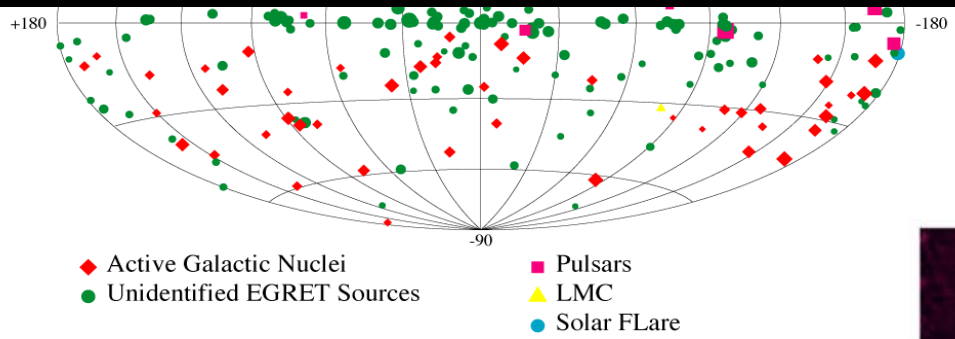


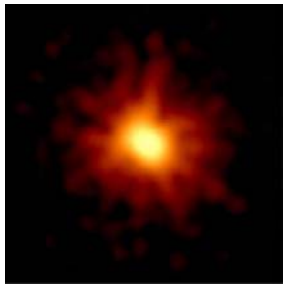
Pulsars



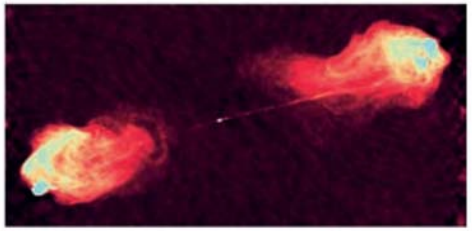
Microquasars



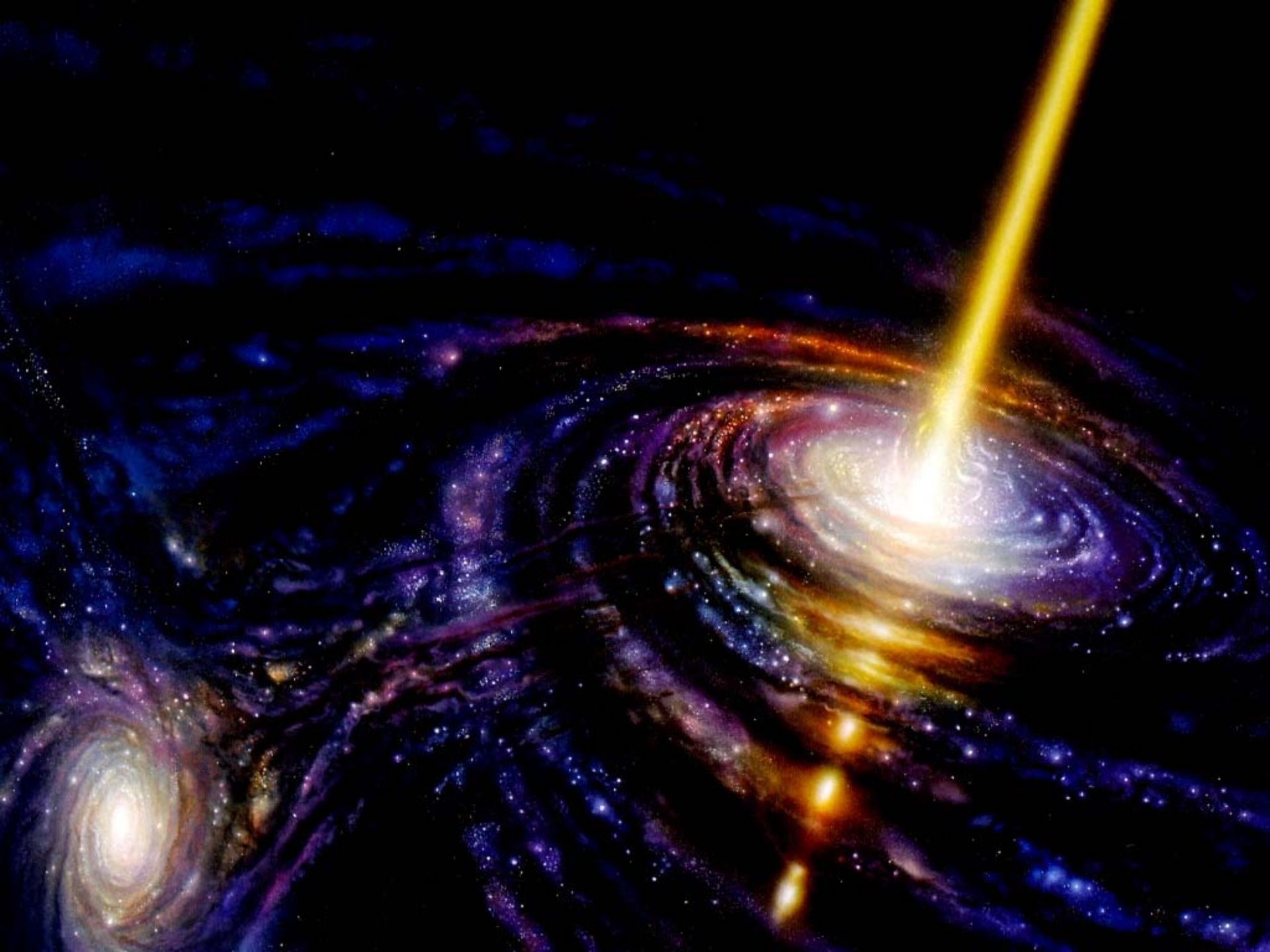




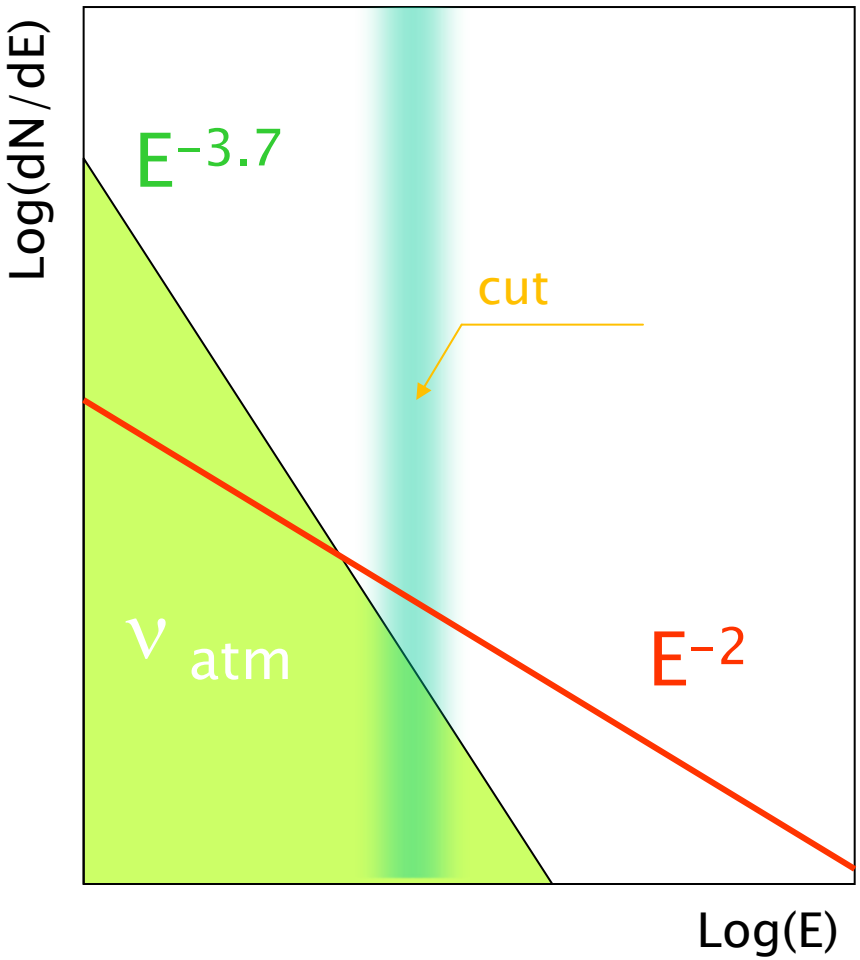
GRBs

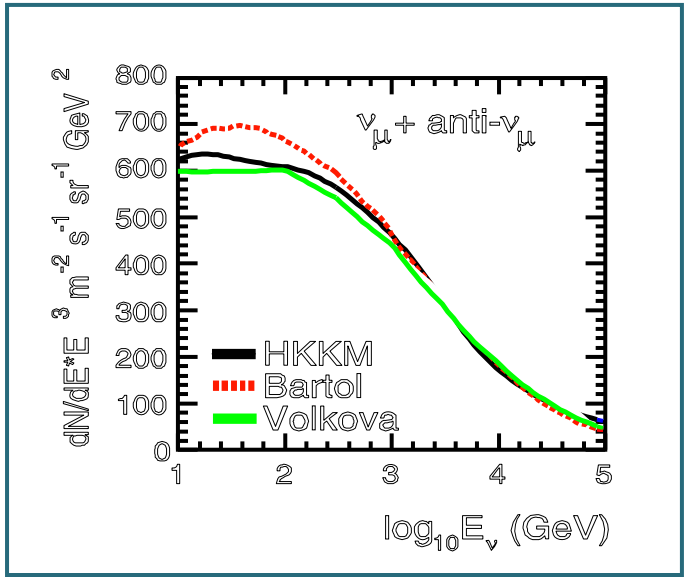


AGNs



High energy selection

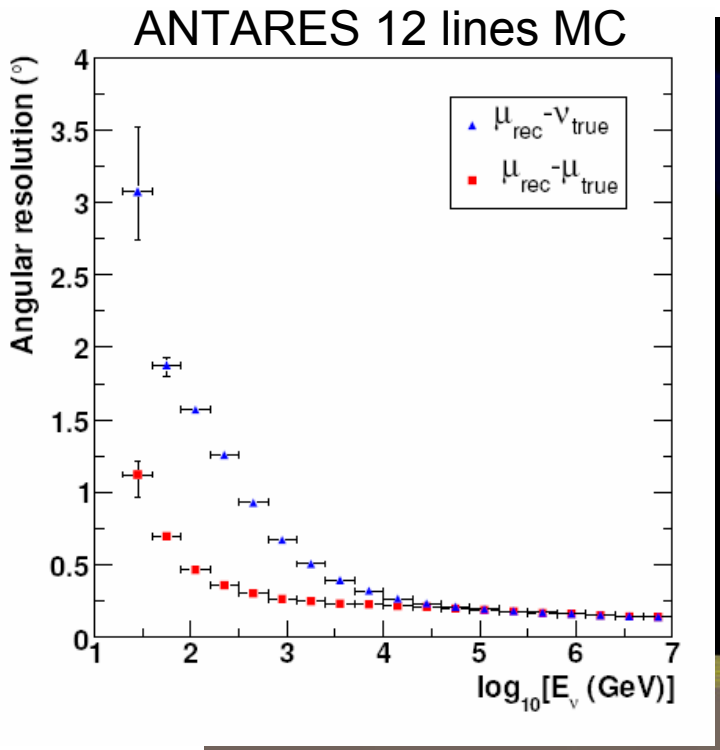


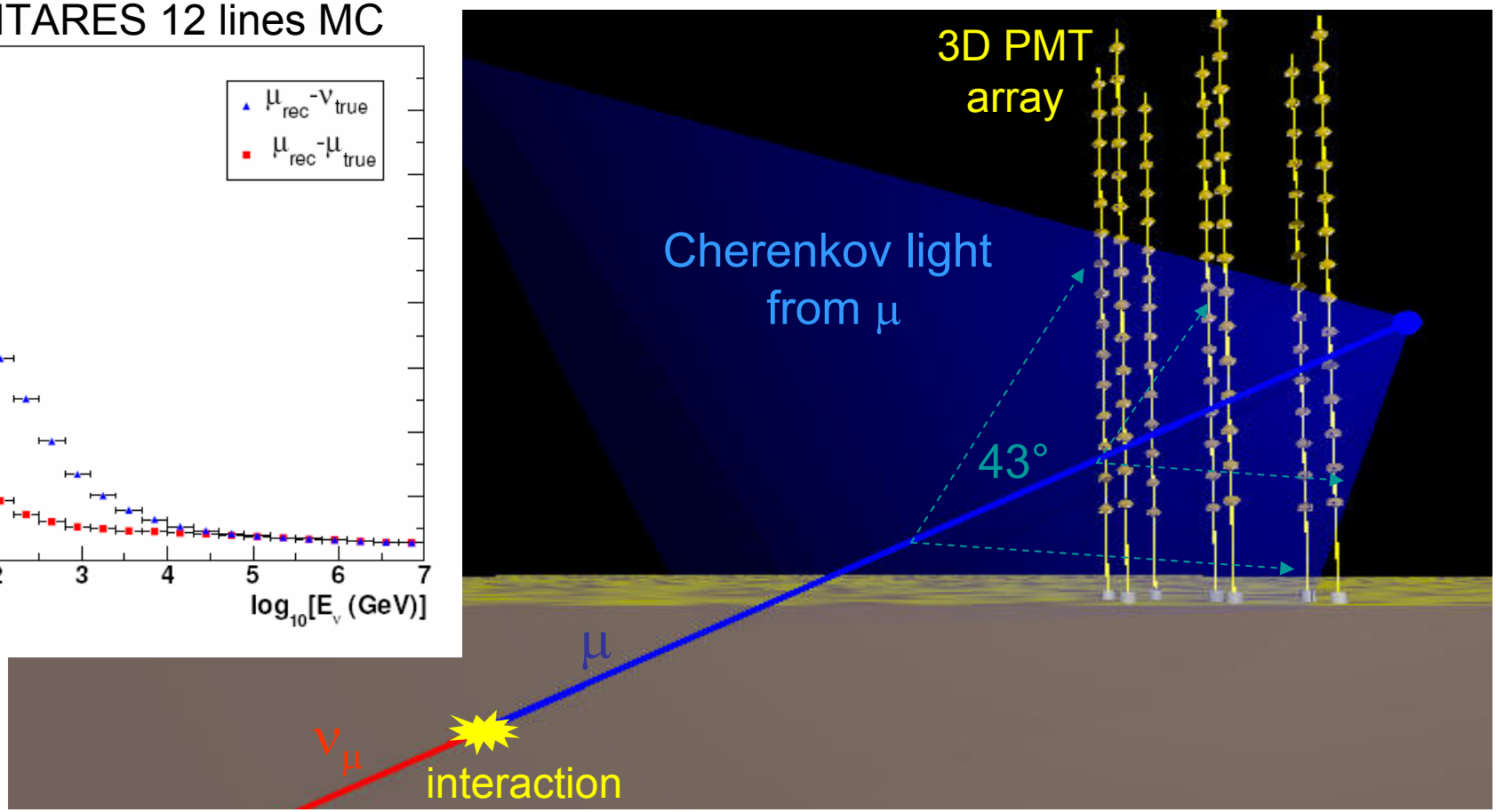


$E^3 \times dn/dE_{atm}$

10

Detection principle



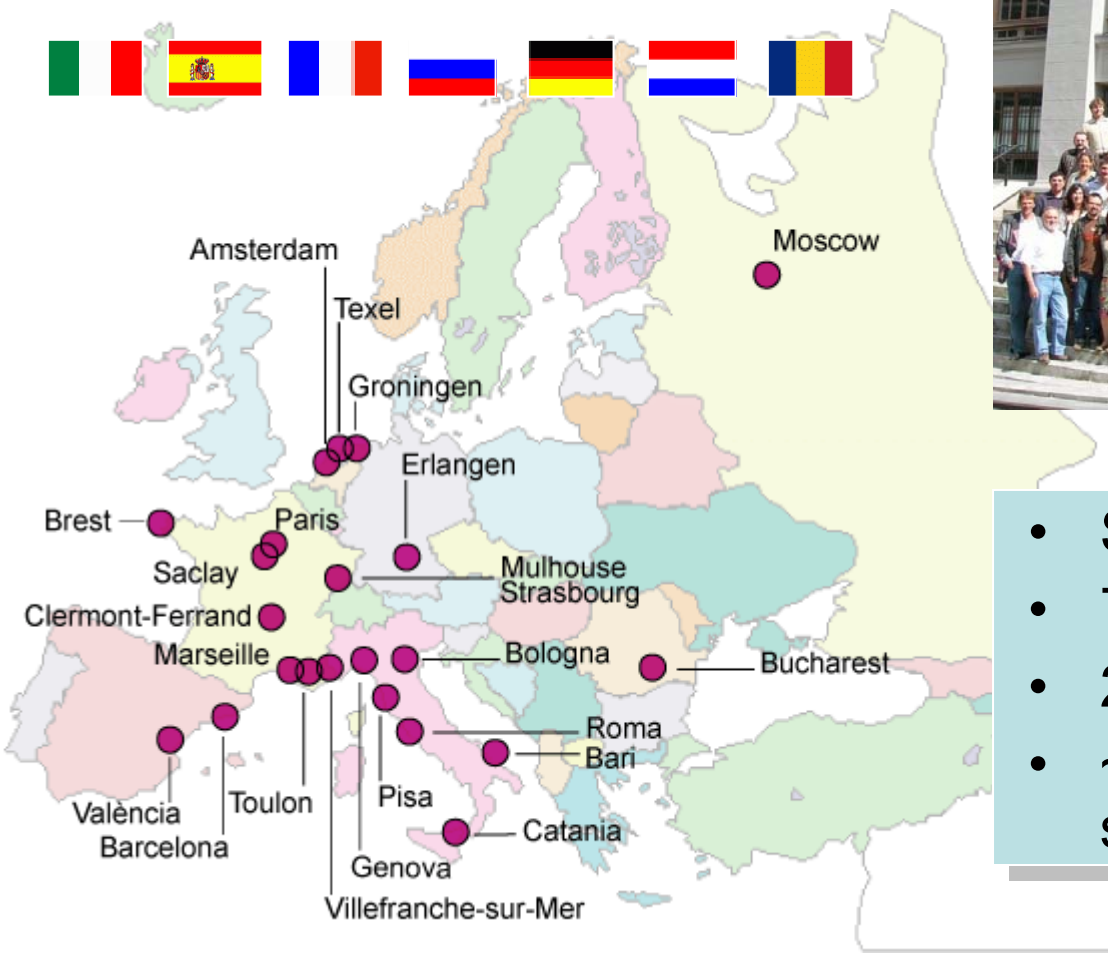


Main detection channel: charged ν_μ interaction giving an ultrarelativistic μ

Energy threshold: 10 GeV

The ANTARES detector

The collaboration



- Since 1996
- 7 countries
- 22 laboratories
- ~150 engineers and scientists

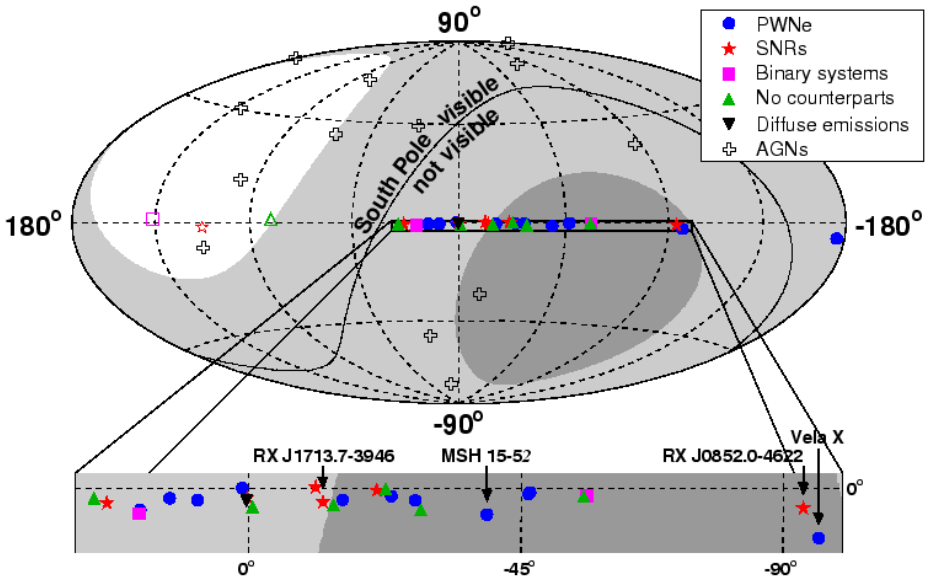
13

The ANTARES site

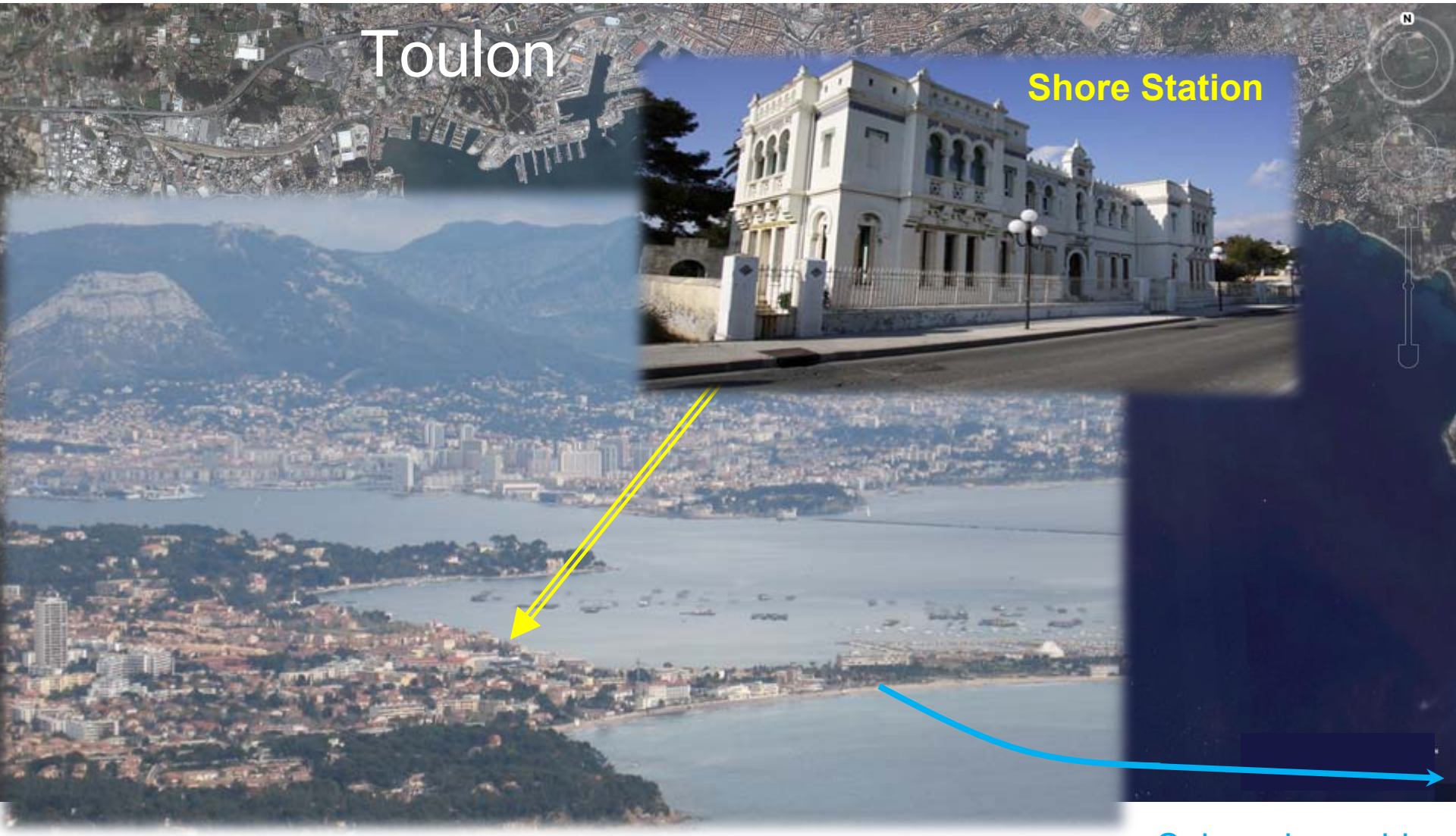
- 42°50’ latitude North
- 6°10’ longitude East

- Galactic Center
  - visible 75% of the day

Galactic coordinates

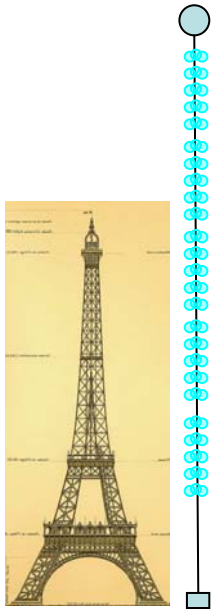


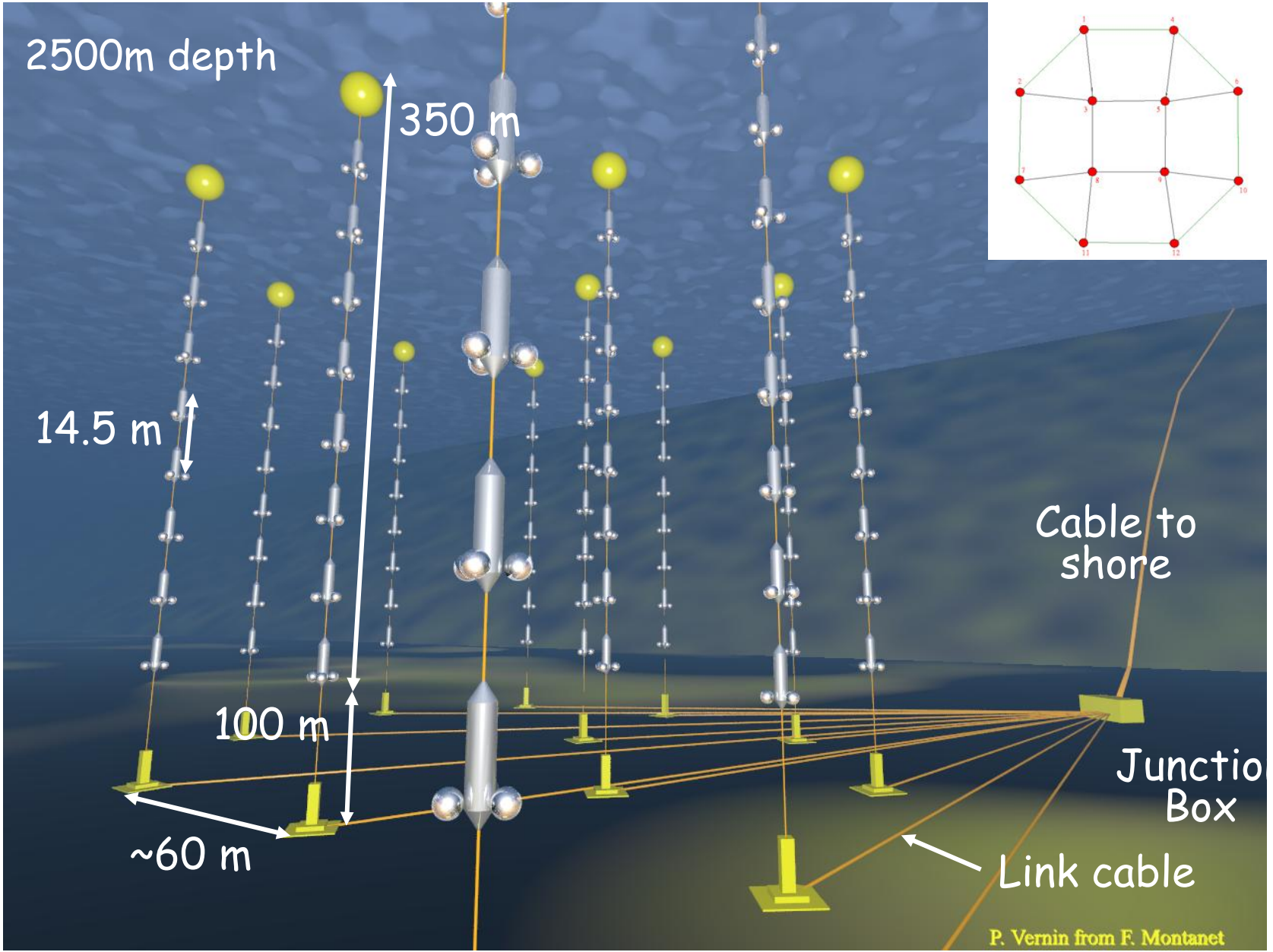
The ANTARES site

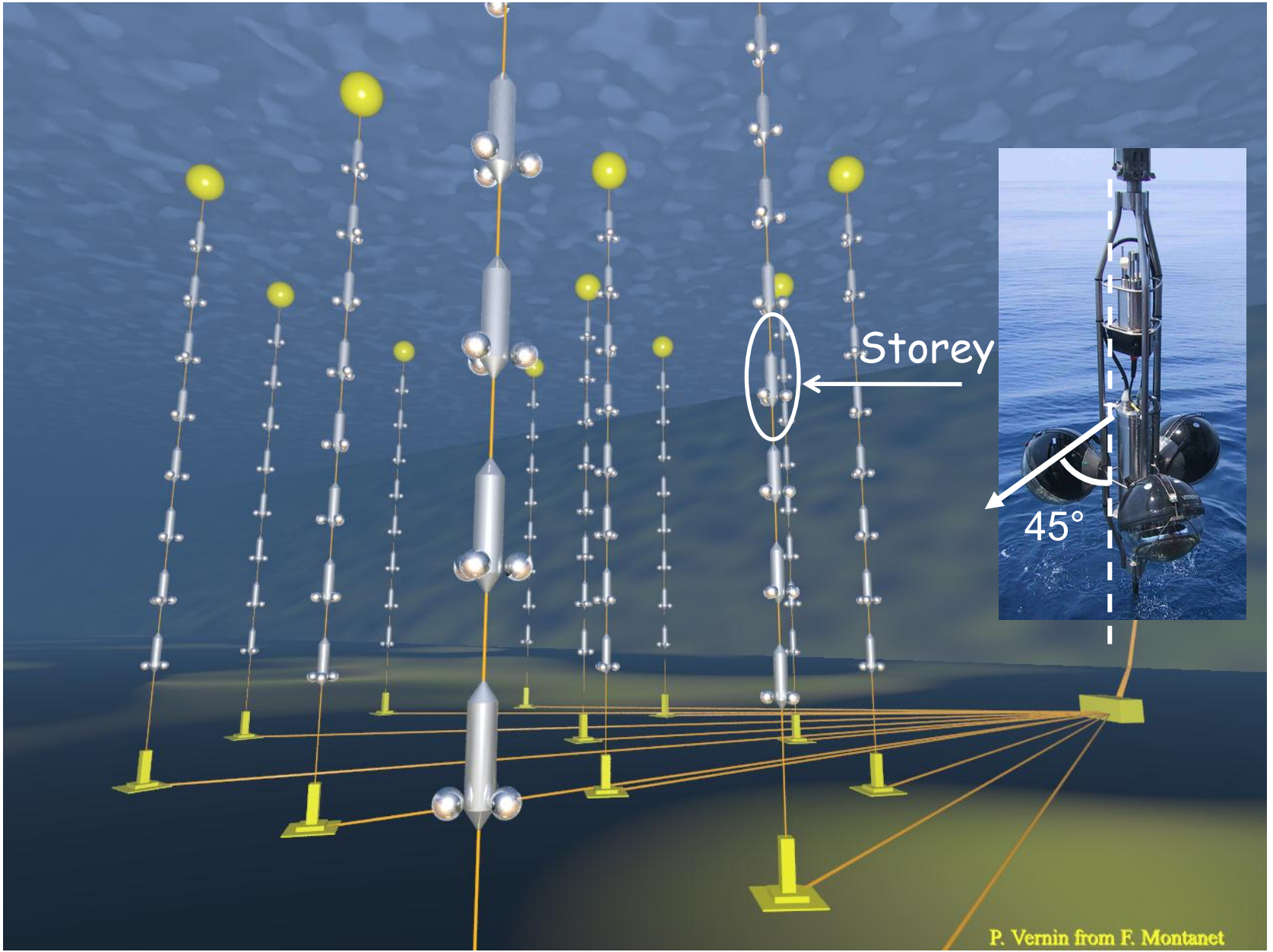


Submarine cable
(~40km)

The ANTARES detector



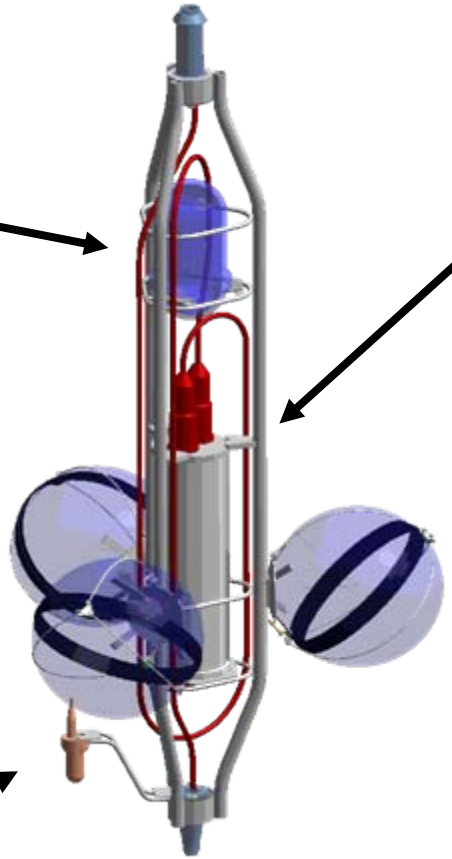



Storey
45°
P. Vernin from F. Montanet

A detector storey

LED
Beacon

~0.6 ns resolution



DAQ
Slow Control

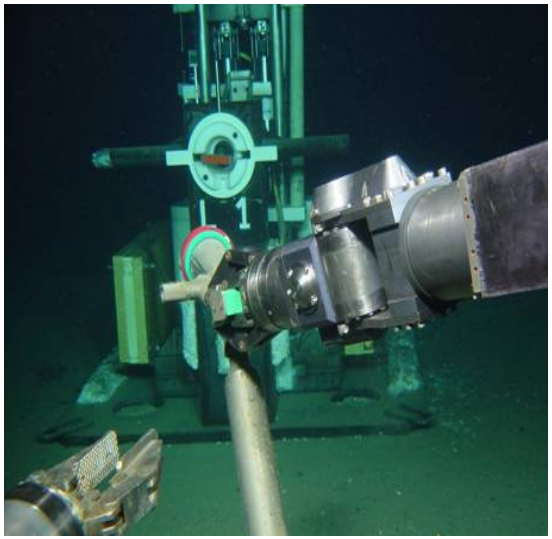
17'' glass sphere
10'' PMT

Hydrophone

~10 cm resolution

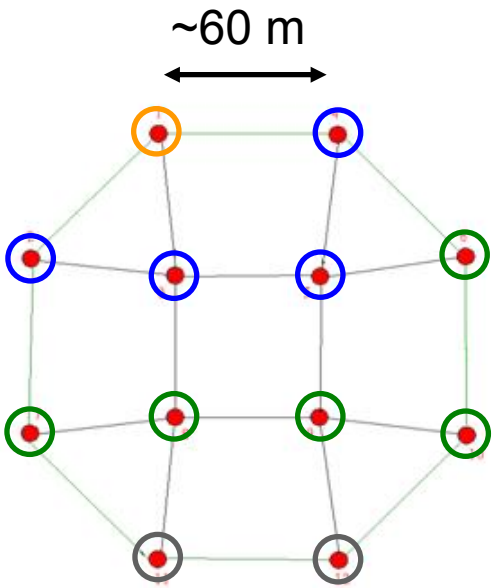
Titanium
frame

2005 – 2008: detector deployment

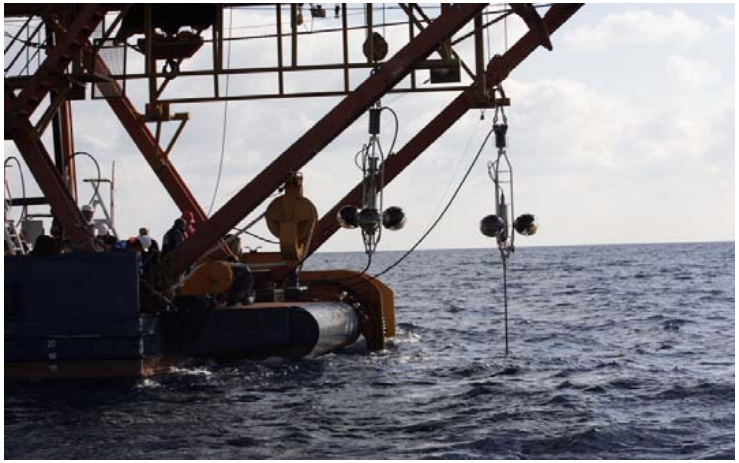


The detector is fully operational since the 30th May 2008

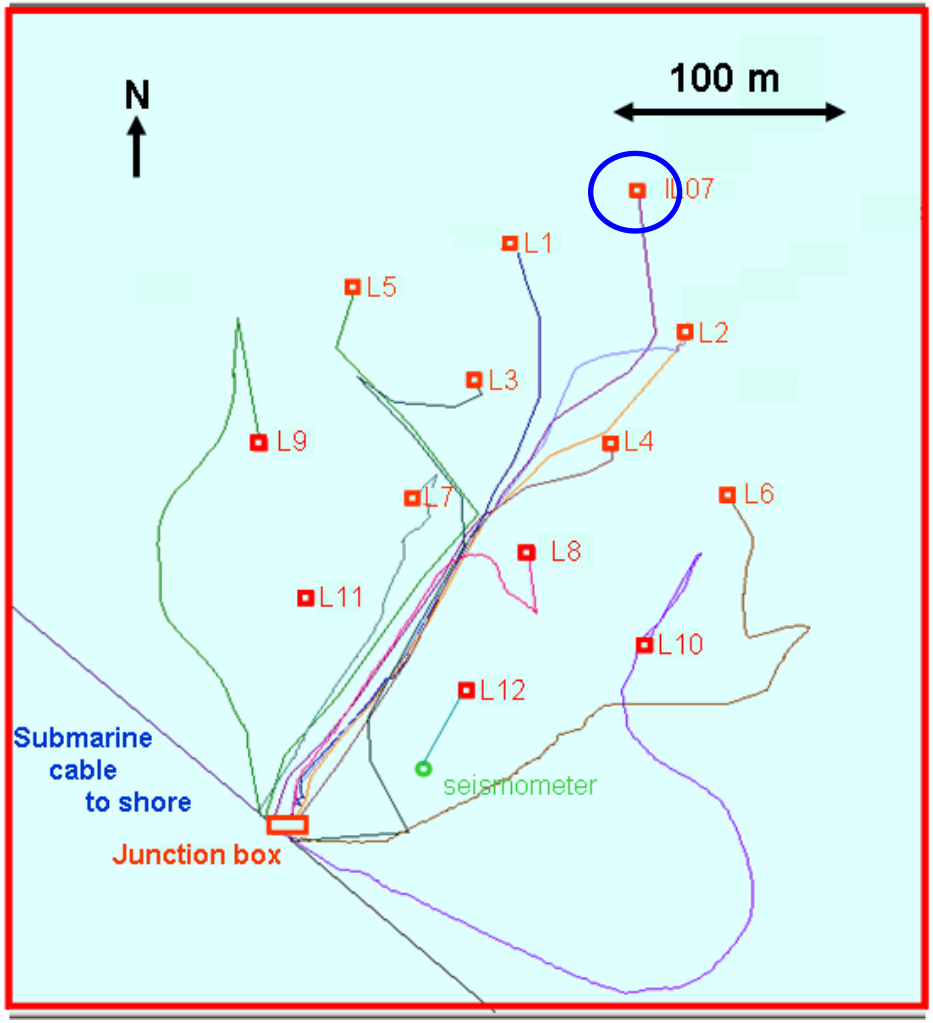
2006 – 2008: deployments of the detector lines



- **Line 1**: 03 / 2006
- **Line 2, 3, 4, 5**: 01 / 2007
- **Line 6, 7, 8, 9, 10**: 12 / 2007
- **Line 11, 12**: 05 / 2008



Detector layout



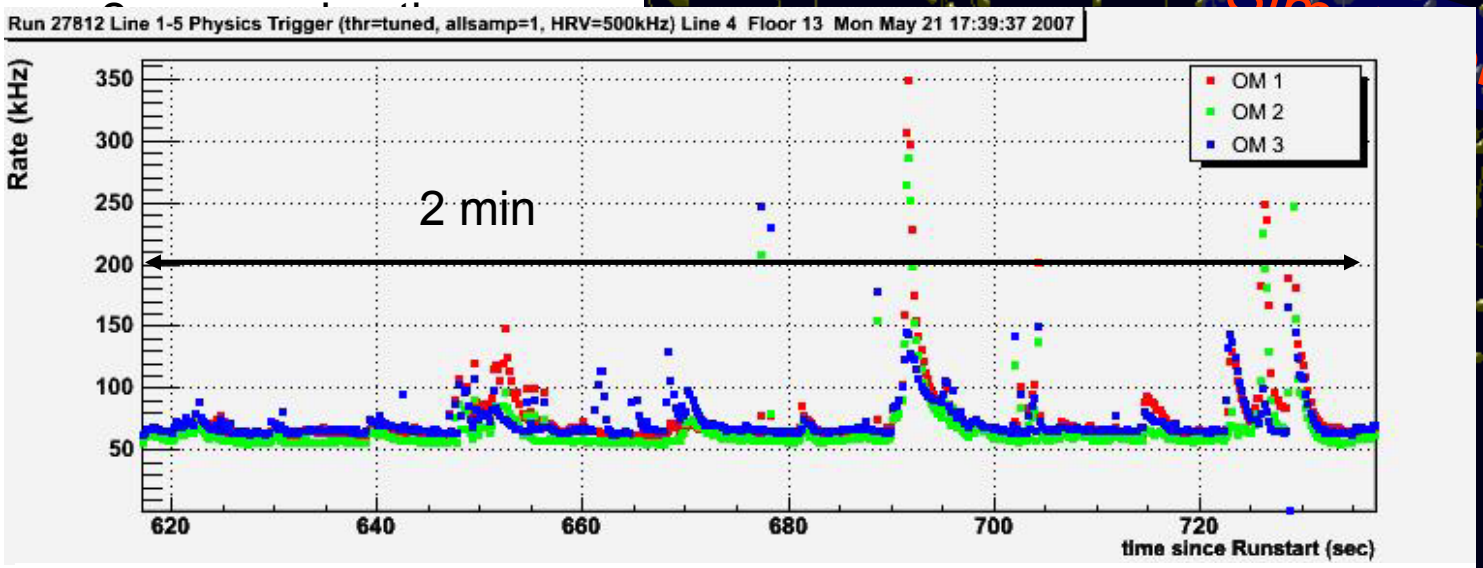
Acoustic storey

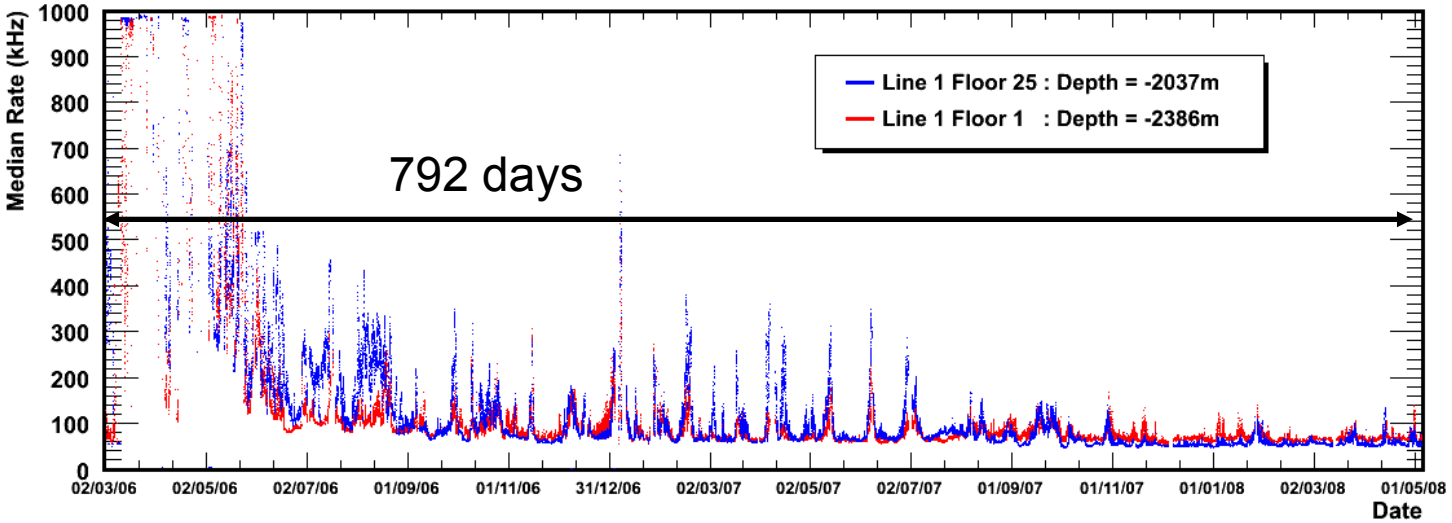
… and several instruments for environment studies with the ANTARES infrastructure

Detector operation

Signals and backgrounds

- Muon (Cherenkov)

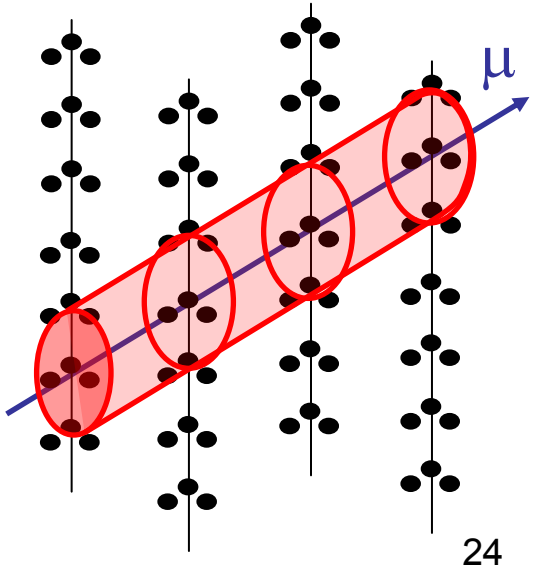




* 10

The on-shore filter

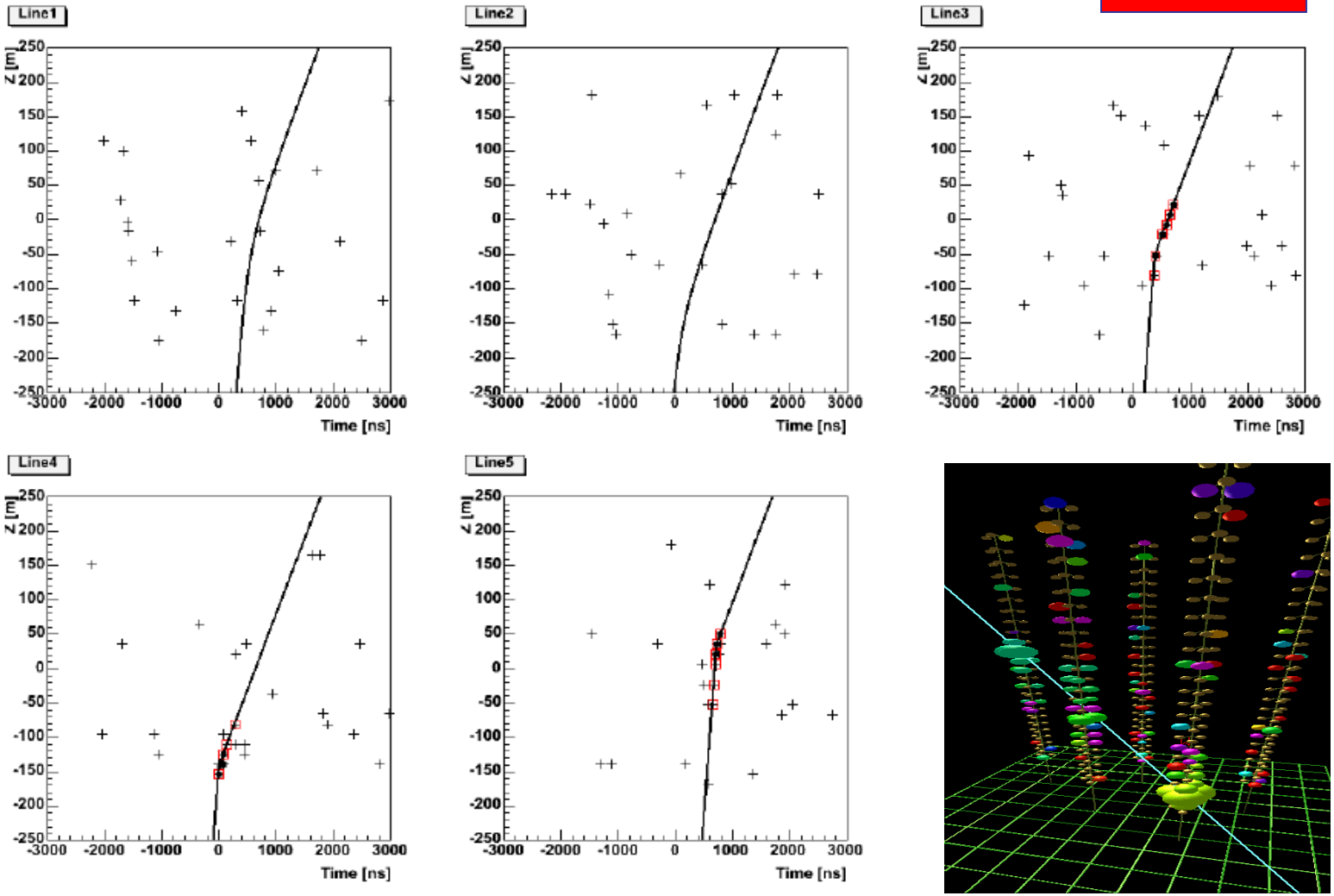
- All data to shore, no off-shore hardware trigger
- Front end chip digitizes charge and time of a light signal
- All data transmitted through multiplexed Gigabit links
  - the whole data flow can not be written to disk
- Computer farm running a software trigger:
  - look in all directions for light signals compatible with a muon track
  - when found, write a Physics Event
- Other triggers exist: cluster of storeys, GRBs, Galactic Center, …

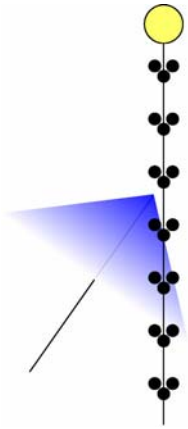


Track reconstruction

Run : 25929 Event : 6742 FrameTarget : 18 FrameIndex : 61770
a: 37.1598 b: 22.0721 t0: 164892932.2 θ: 0.61779 ϕ: -3.7146 fit : 1/4

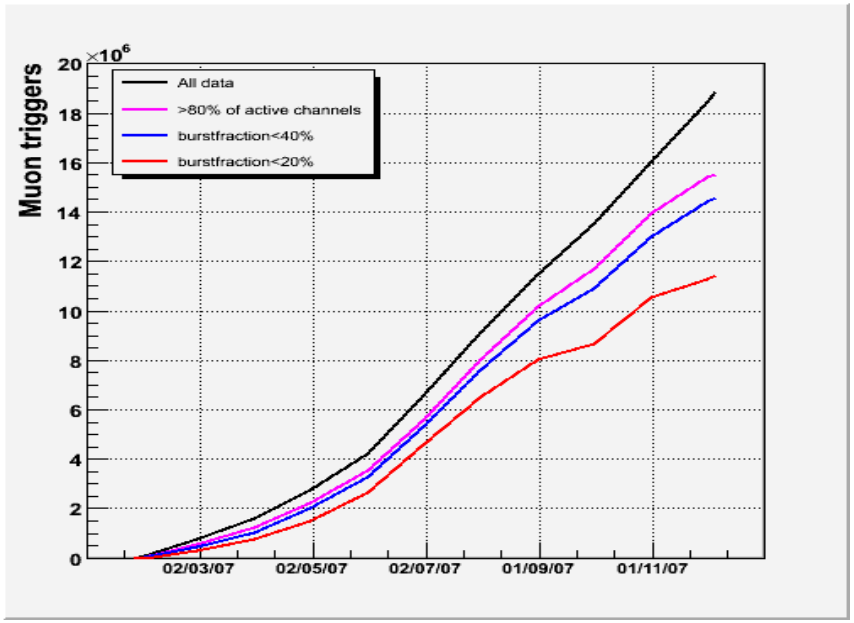
$\Theta = 35^{o}$



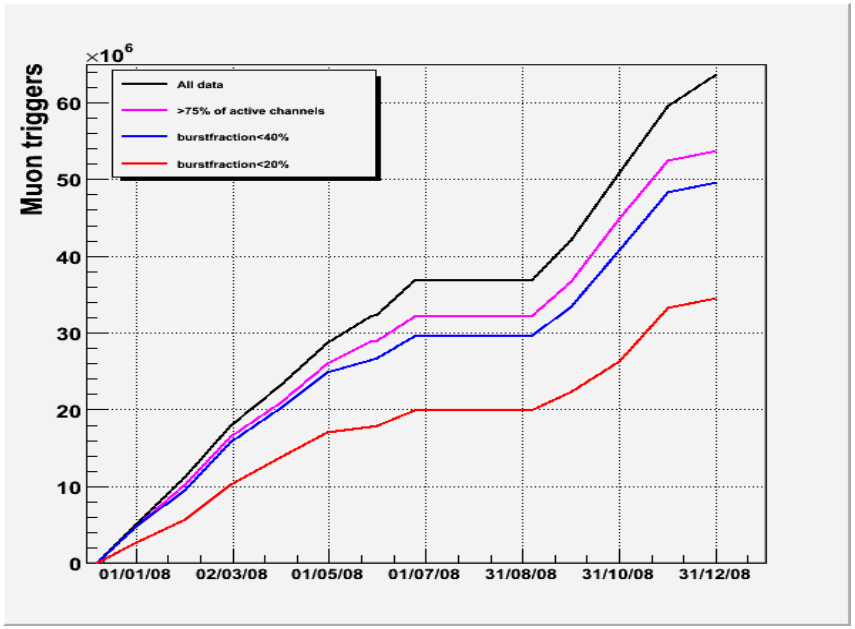


Number of triggers

5 lines (2007)



10 or more lines (2008)

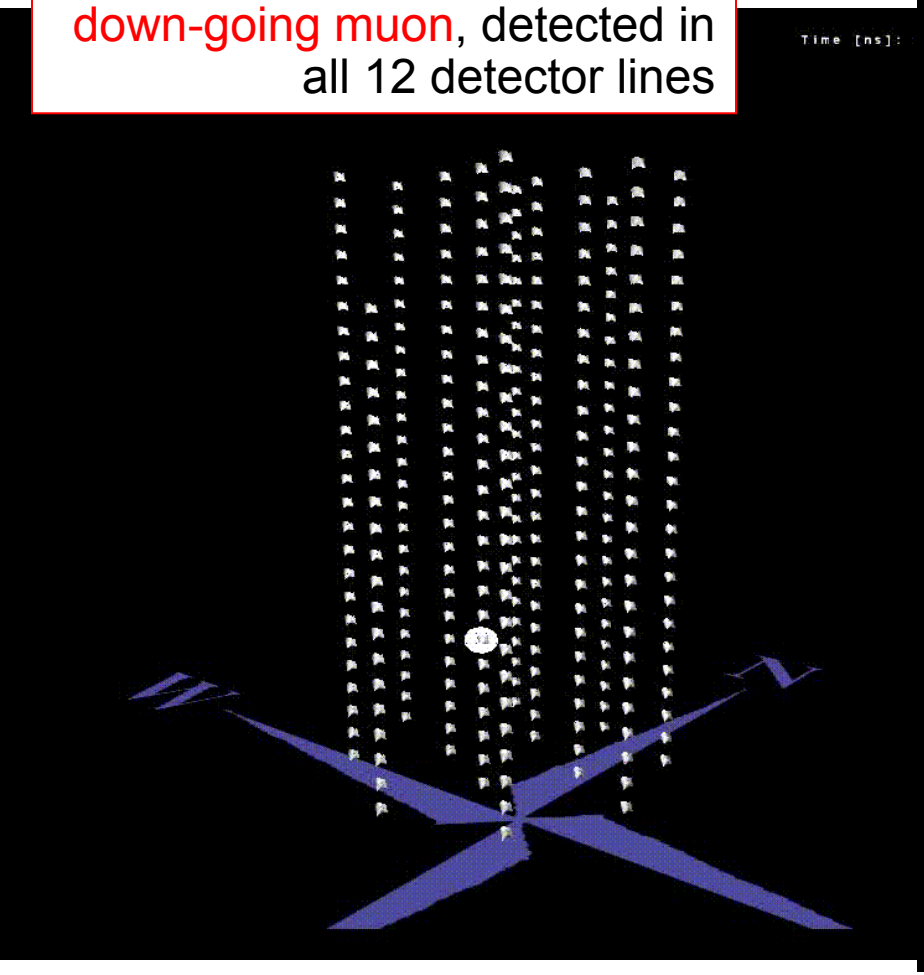


Data taking ongoing…

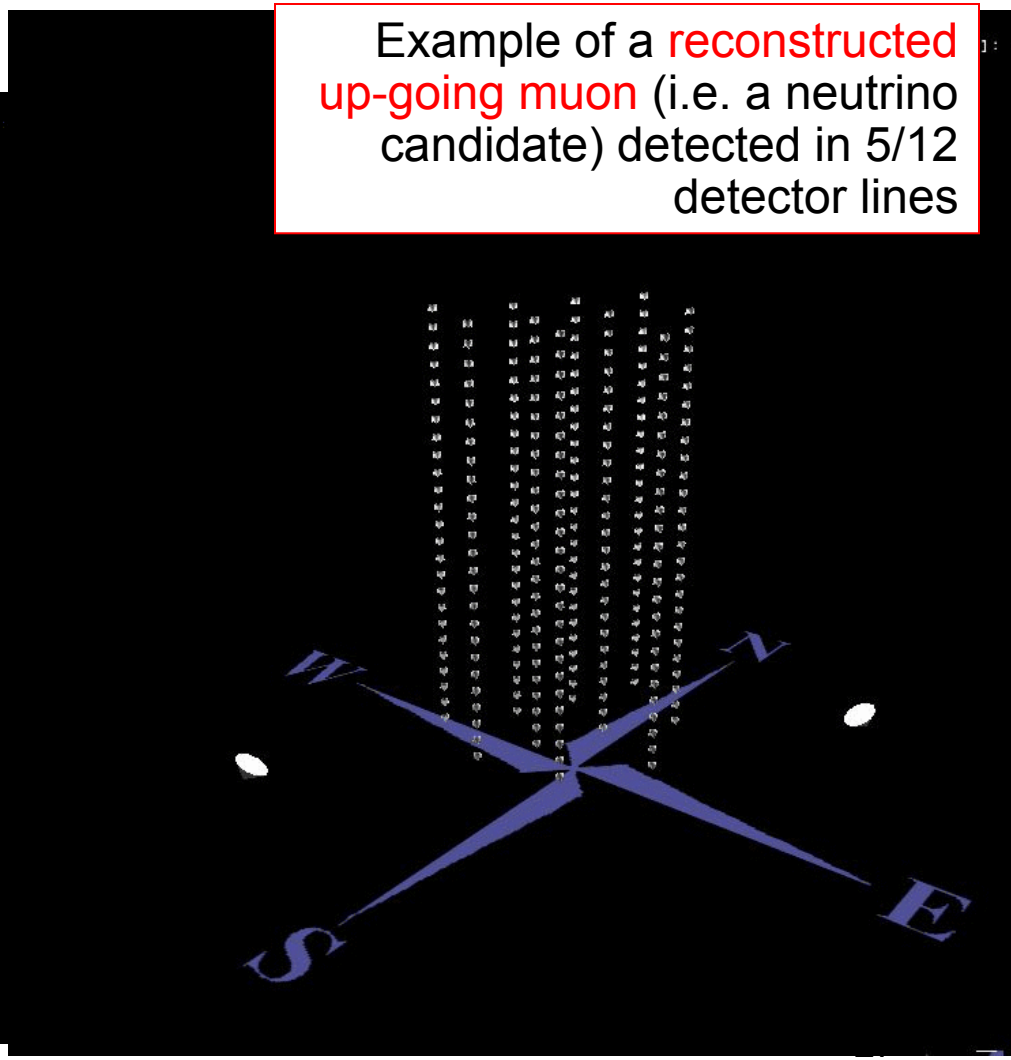
…accumulating neutrinos

Atmospheric muons and neutrino-induced muons

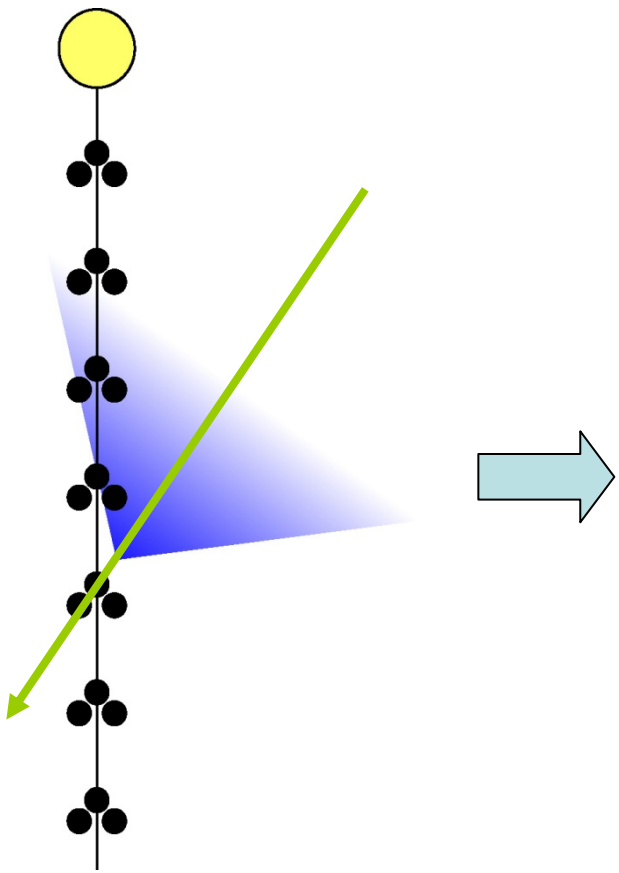
Example of a reconstructed down-going muon, detected in all 12 detector lines



Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 5/12 detector lines

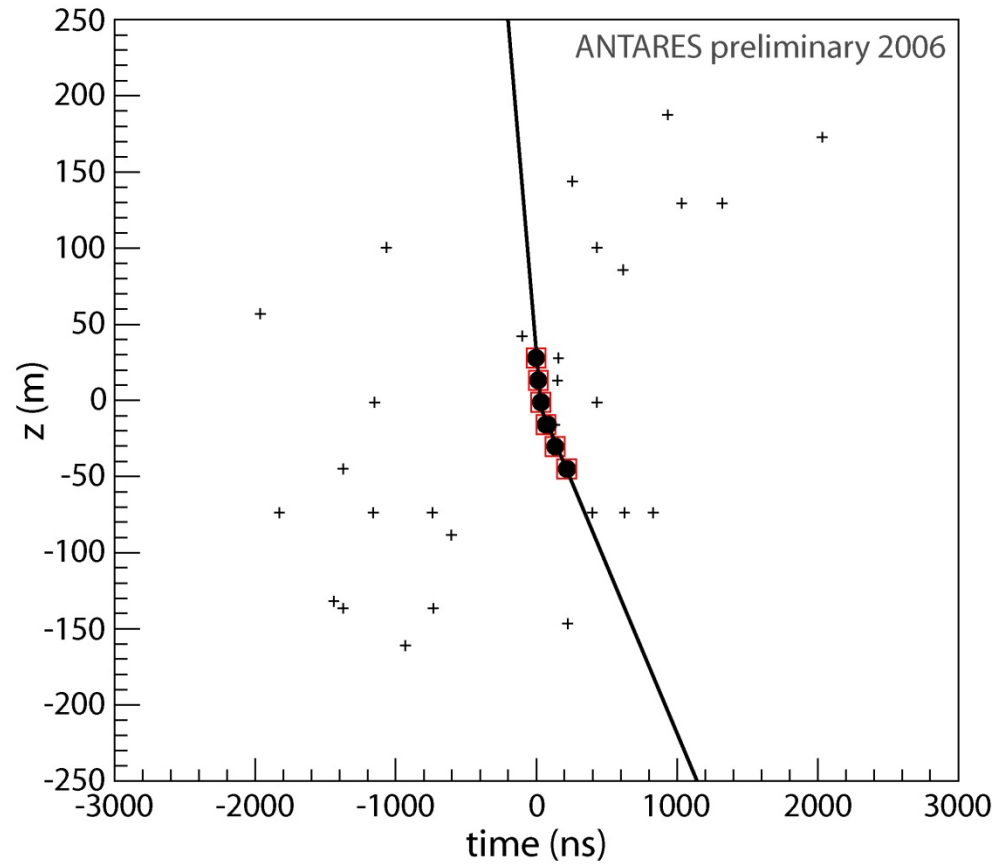


z (m)



r (m)

z (m)



t (ns)

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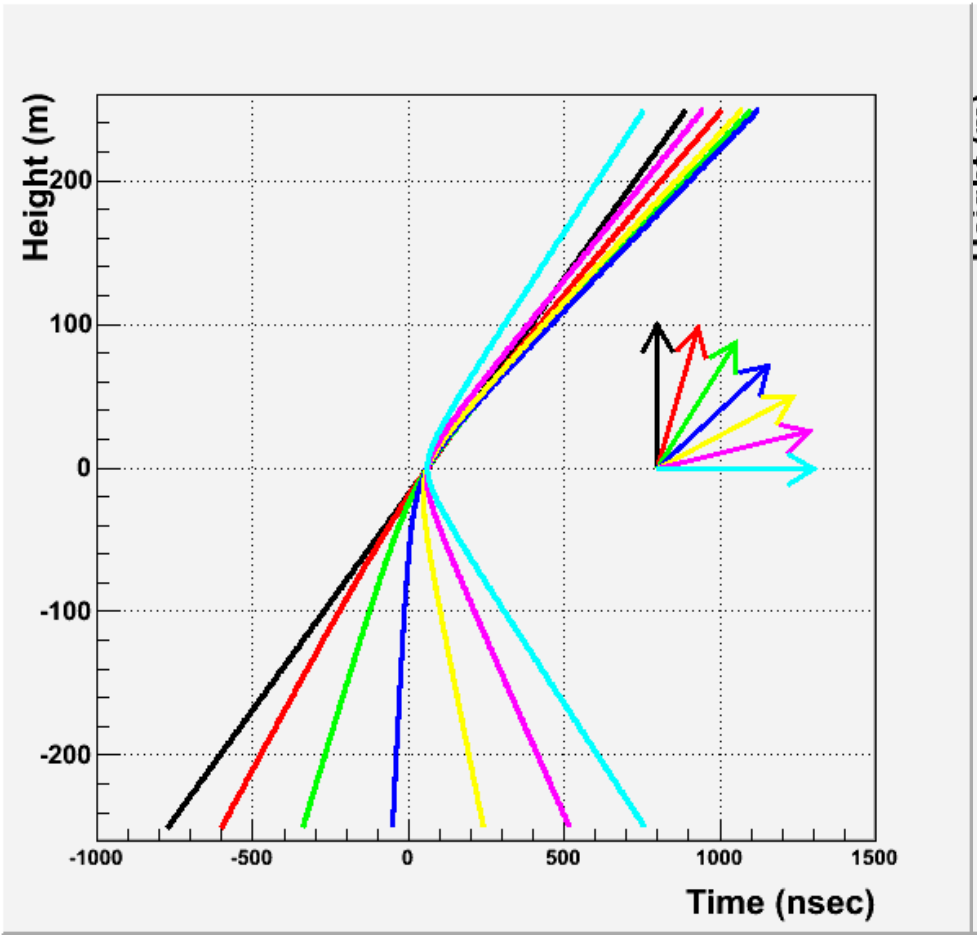
Time-Height representation

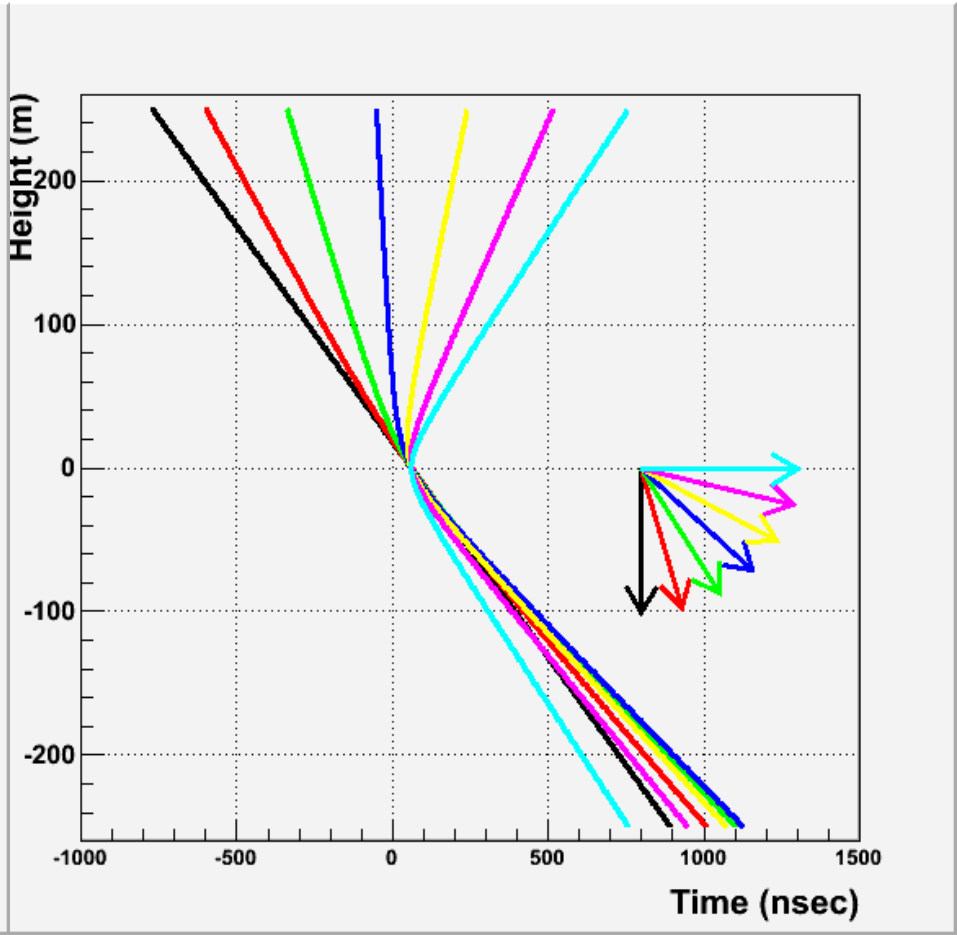
Intersection cone - plane = hyperbola

Form depends on zenith angle and point of closest approach between line and track

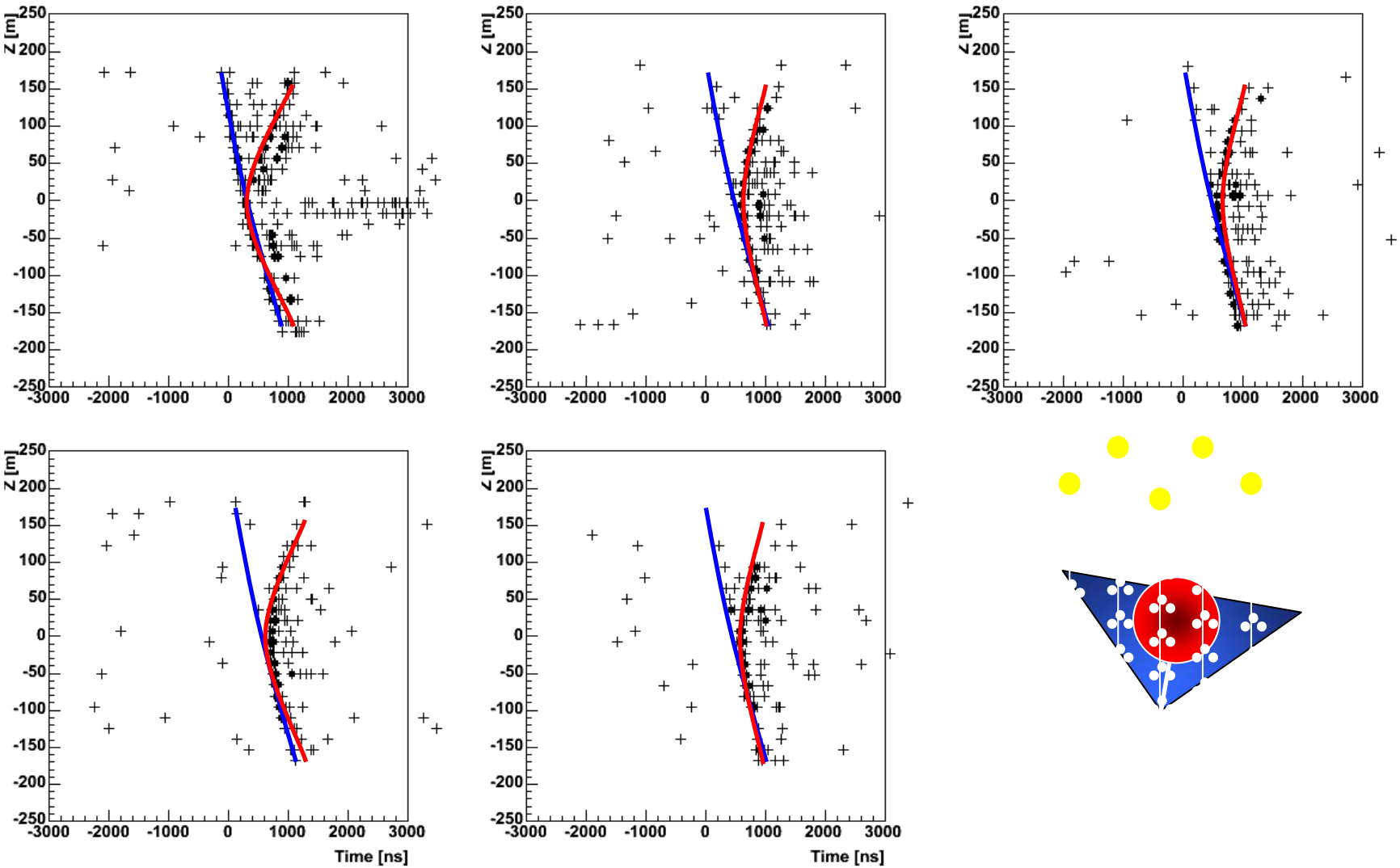
Up-going



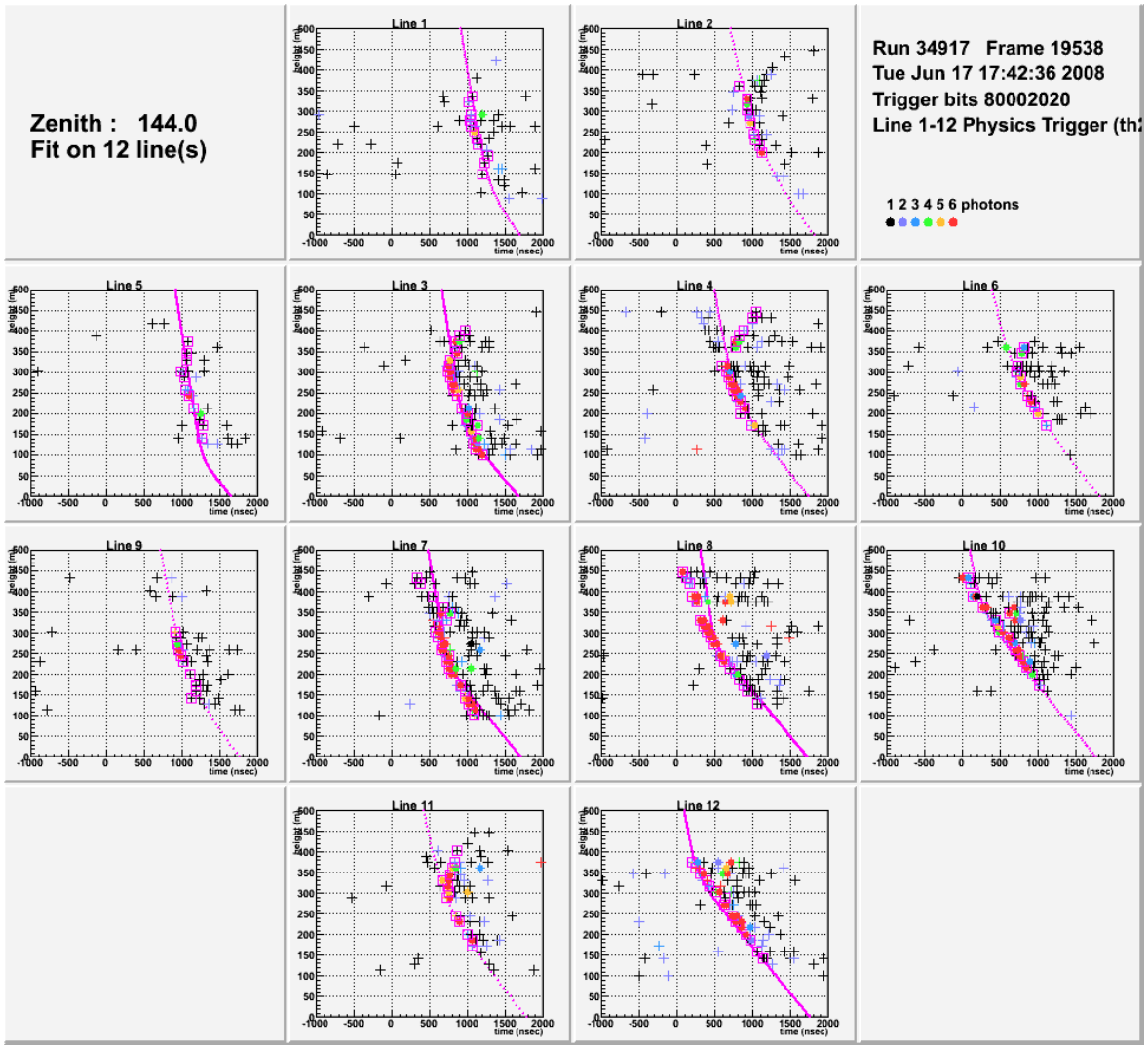
Down-going

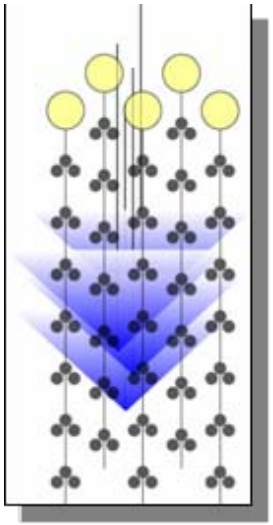


e.m. showers from HE μ's



Multi-muons





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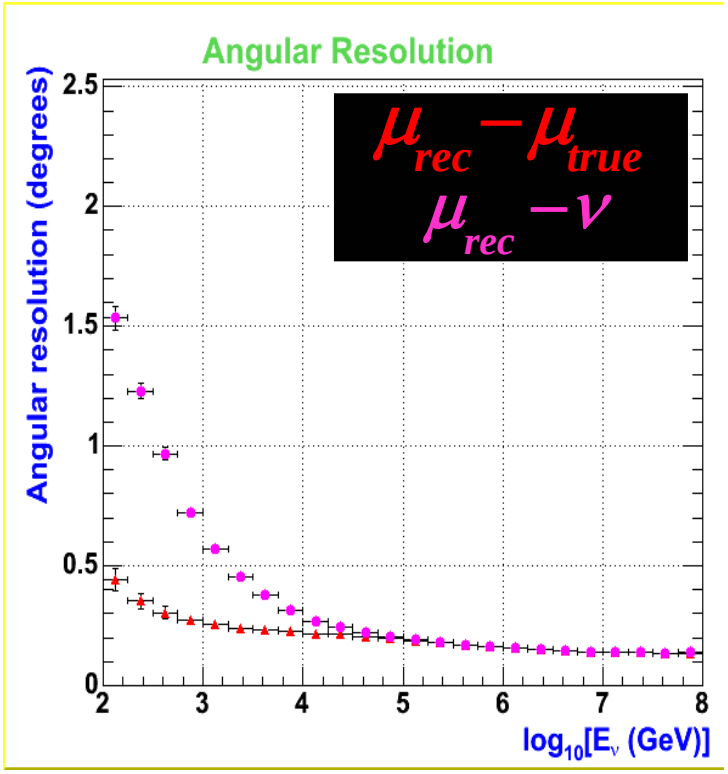
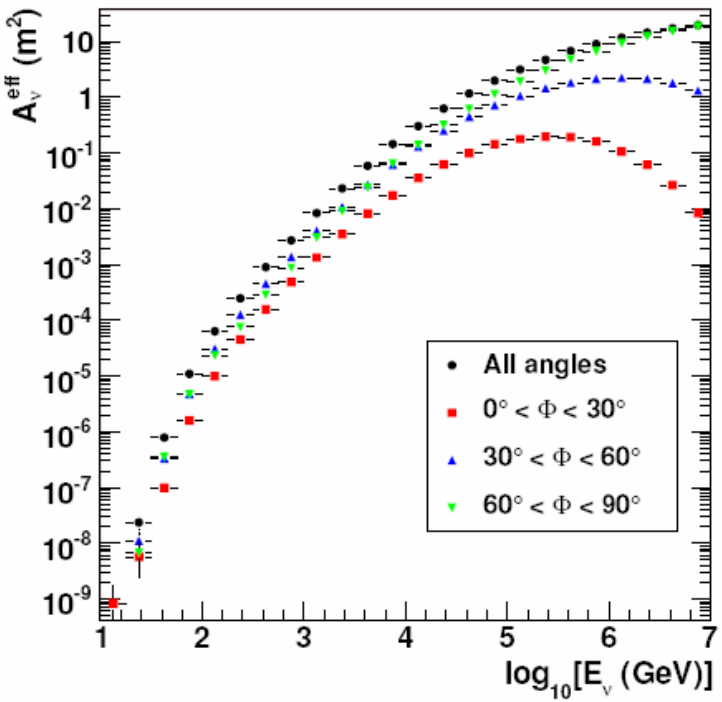
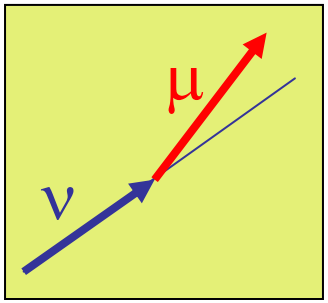
Expected performances







- Instrumented volume : 20 Mton (1/50 km^3)
- Muon effective area ≈ 20000 m^2 (E > 1 TeV)

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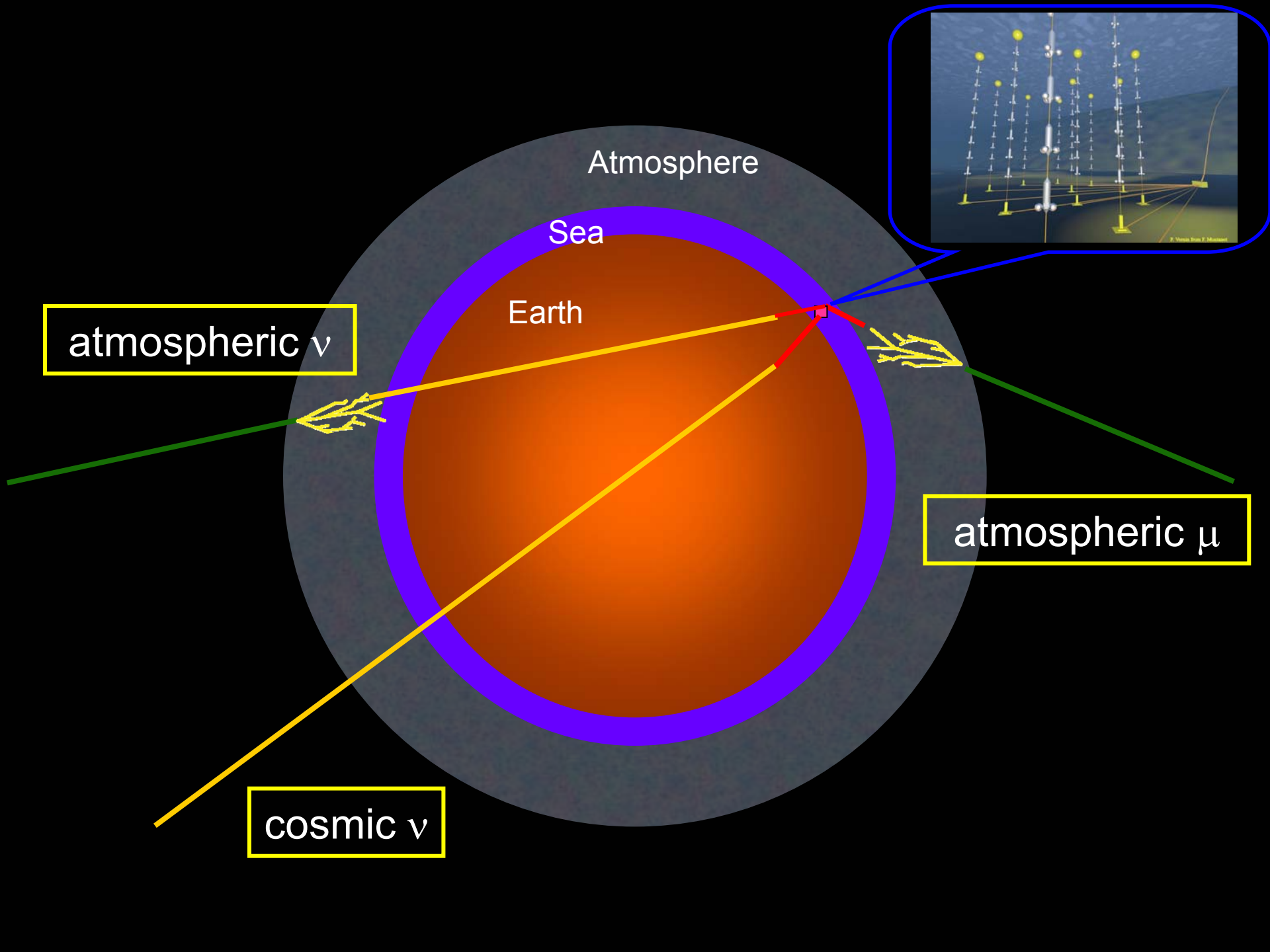
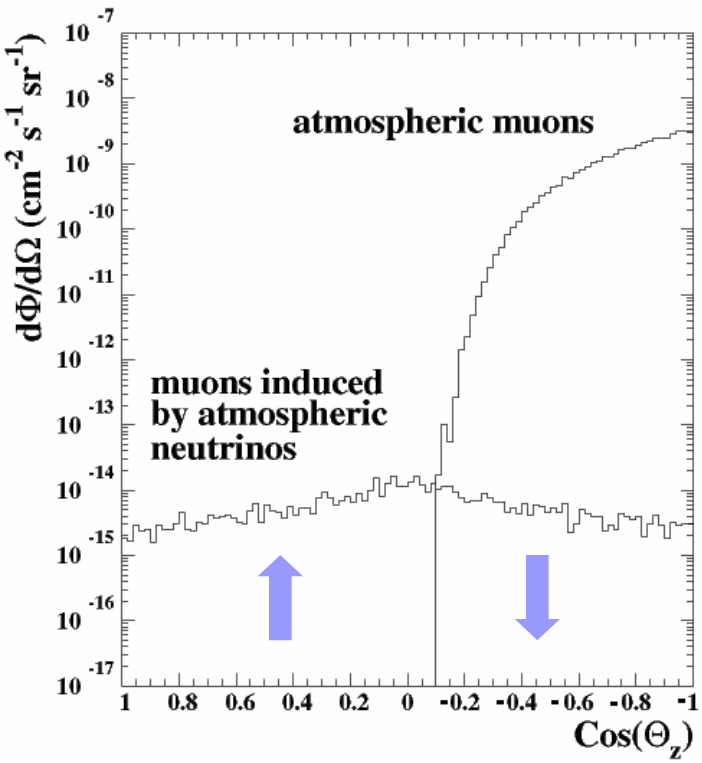
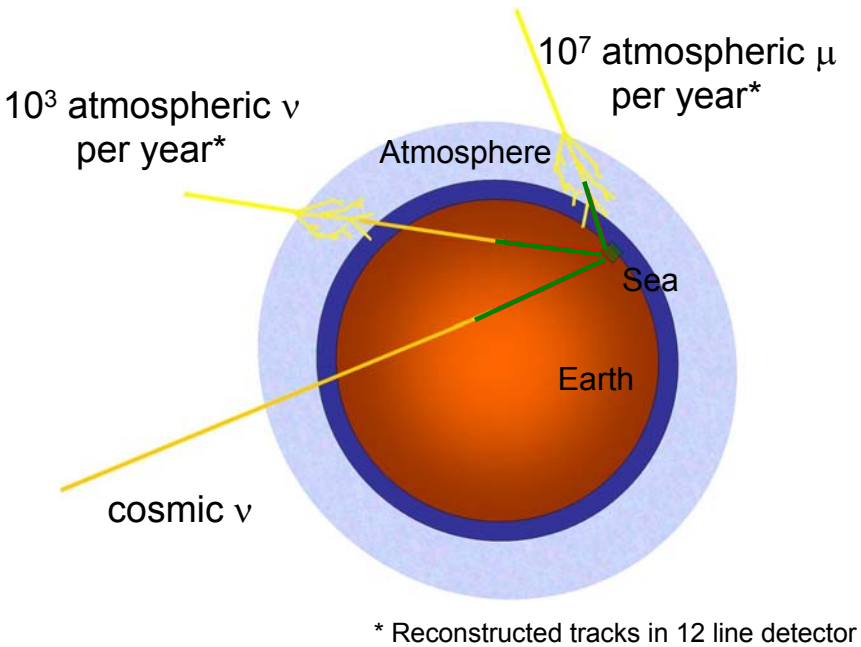
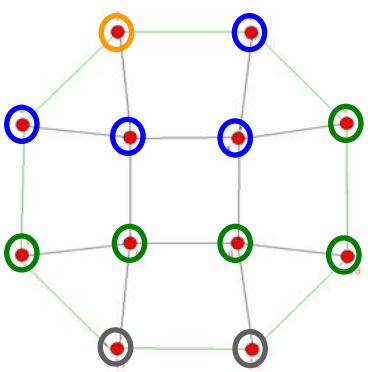
The first physics analyses


Atmosphere
Sea
Earth
atmospheric ν
atmospheric μ
cosmic ν

Muon flux at the detector







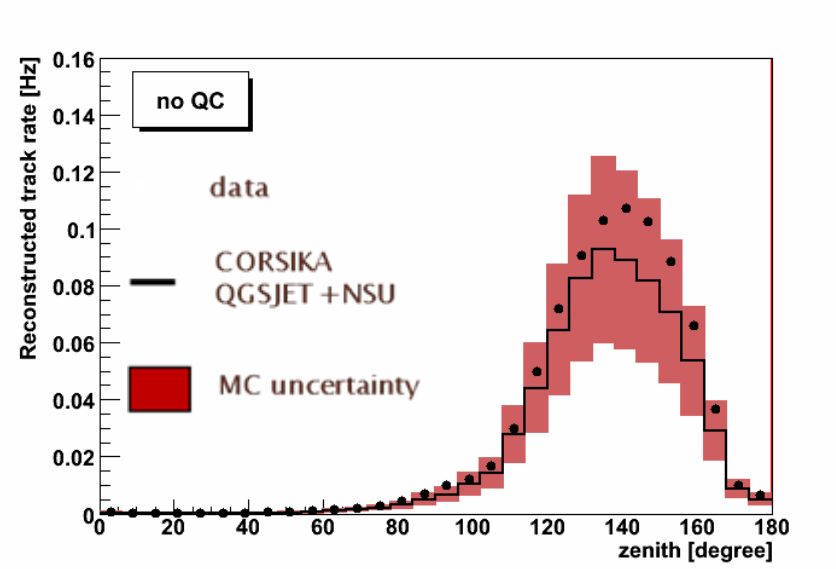
Line 1: 03 / 2006 → Performance paper submitted

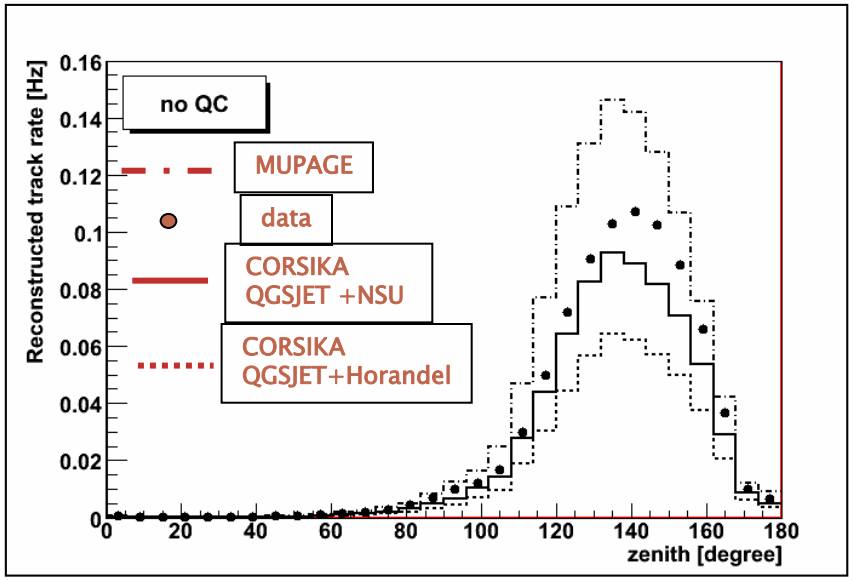
Line 2, 3, 4, 5: 01 / 2007 → First physics analyses completed

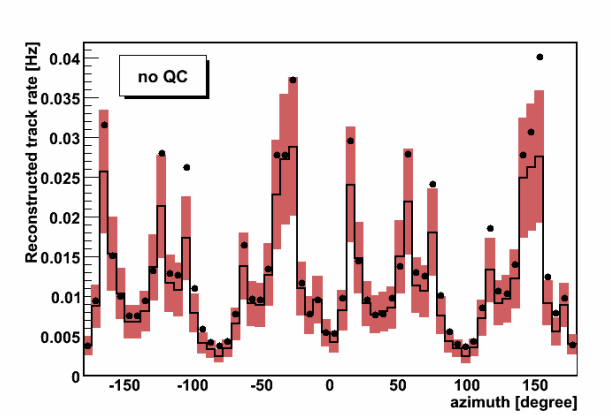
Line 6, 7, 8, 9, 10: 12 / 2007 → Ongoing analysis

Line 11, 12: 05 / 2008 → Data taking

μ flux study







- Systematic uncertainty ± 30%
- Main contributions
  - optical module response
  - absorption length of the light in water

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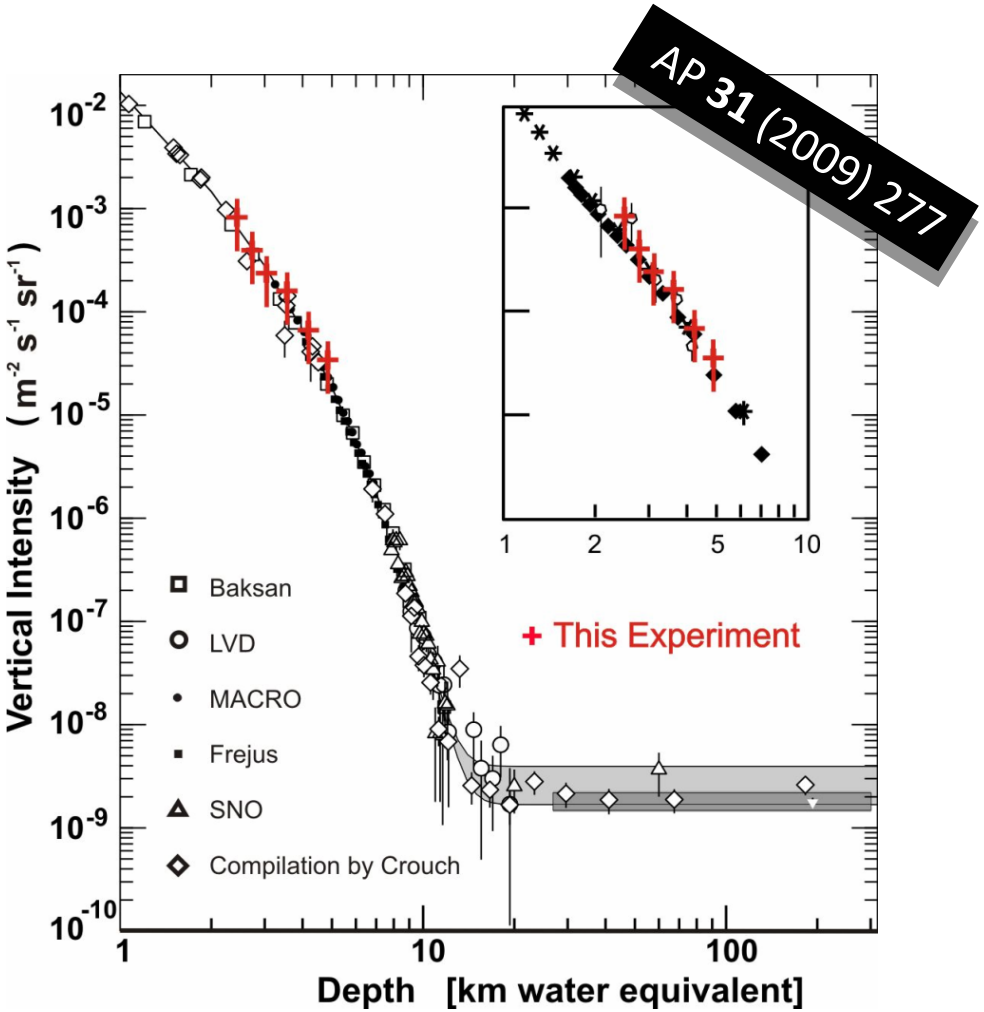
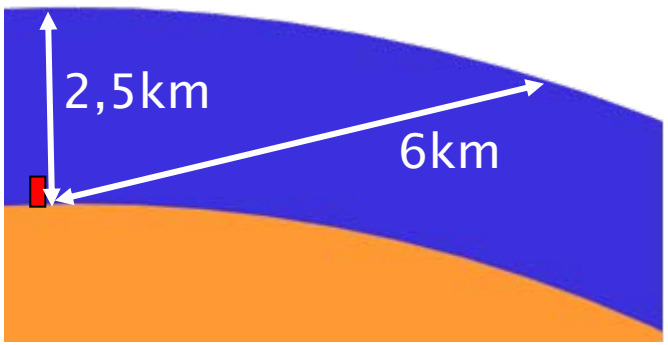
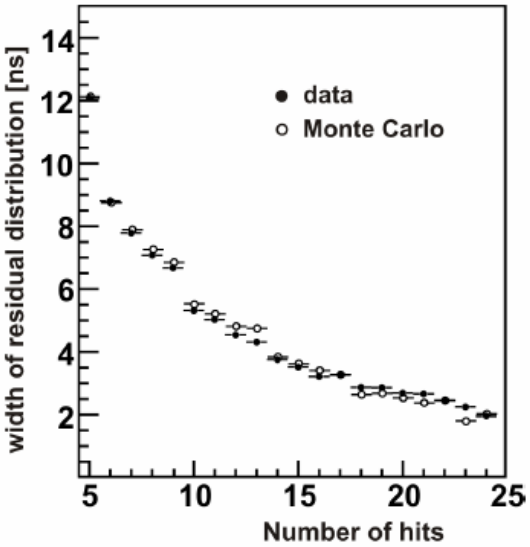
Line 1
Depth-intensity relation







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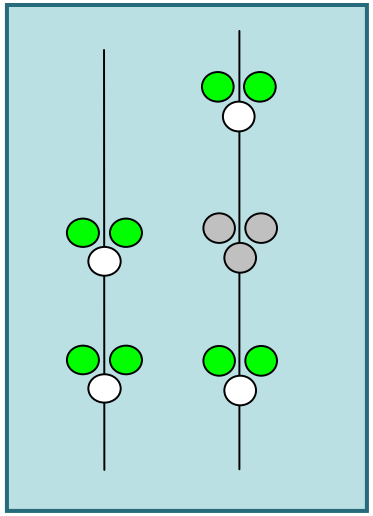
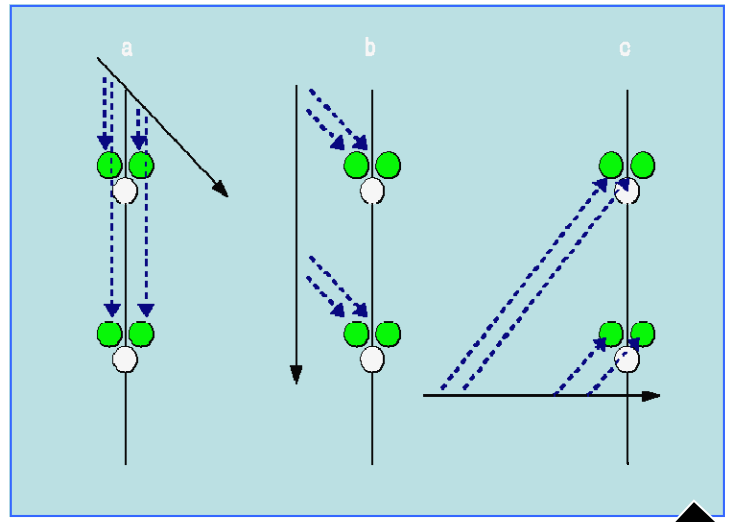
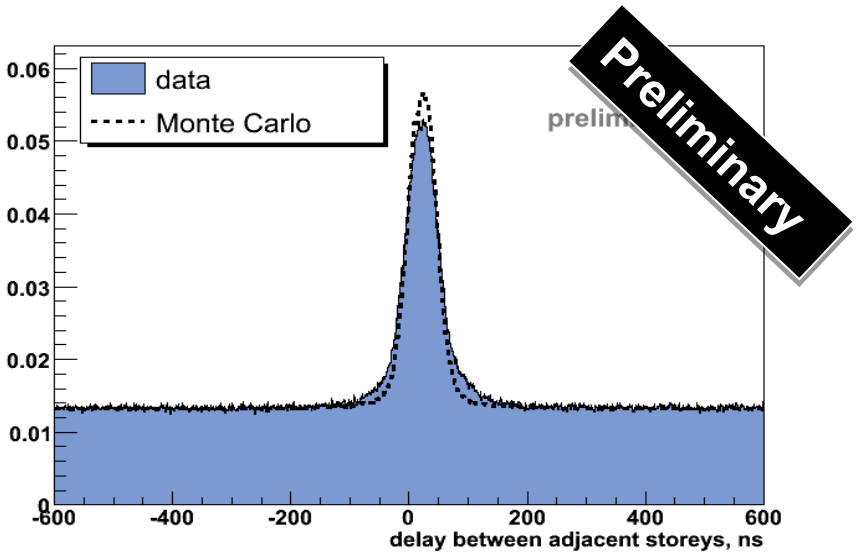
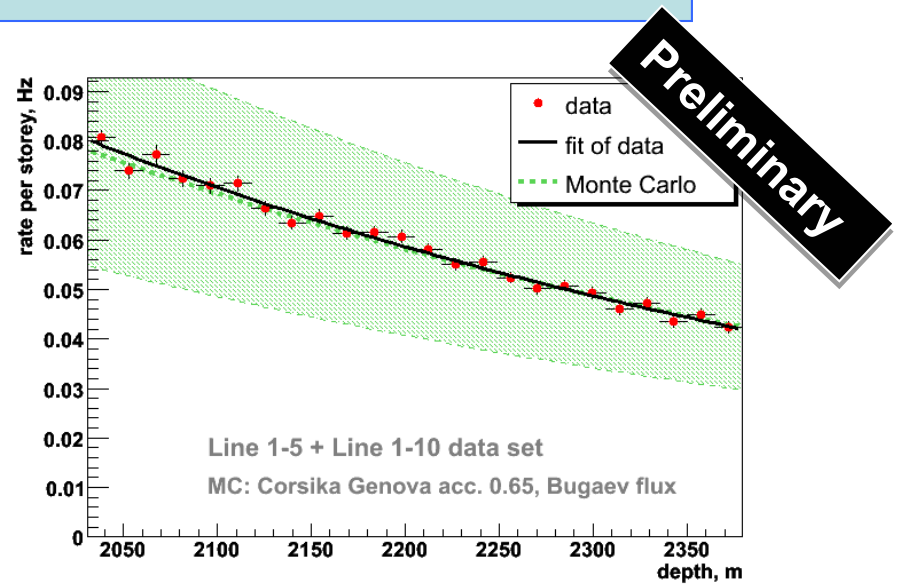
Simple depth-intensity relation

- No reconstruction
- Coïncidences between consecutive storeys









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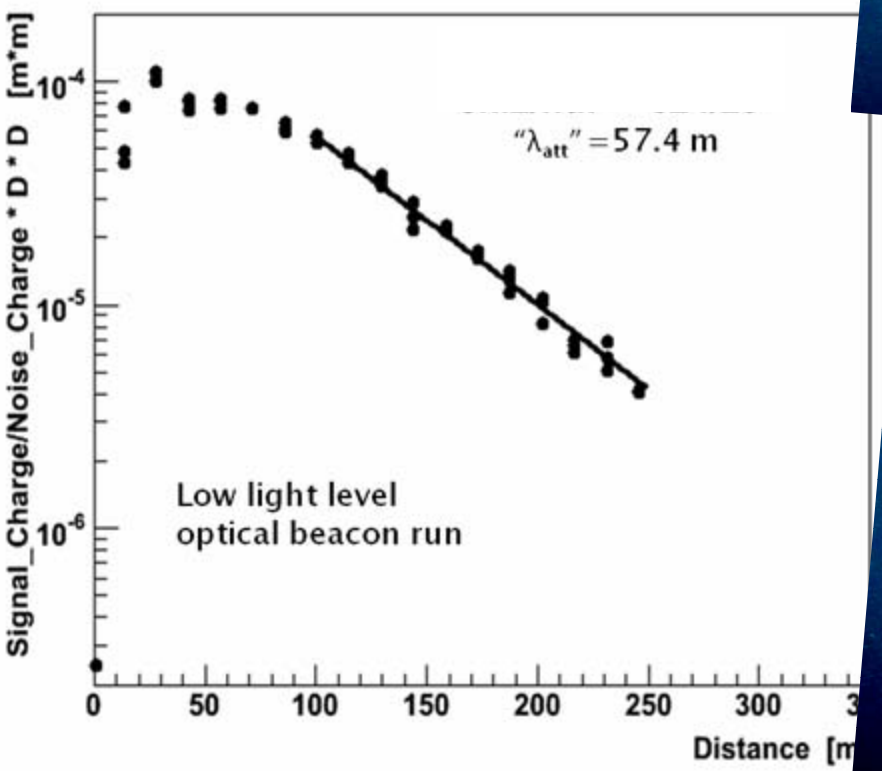
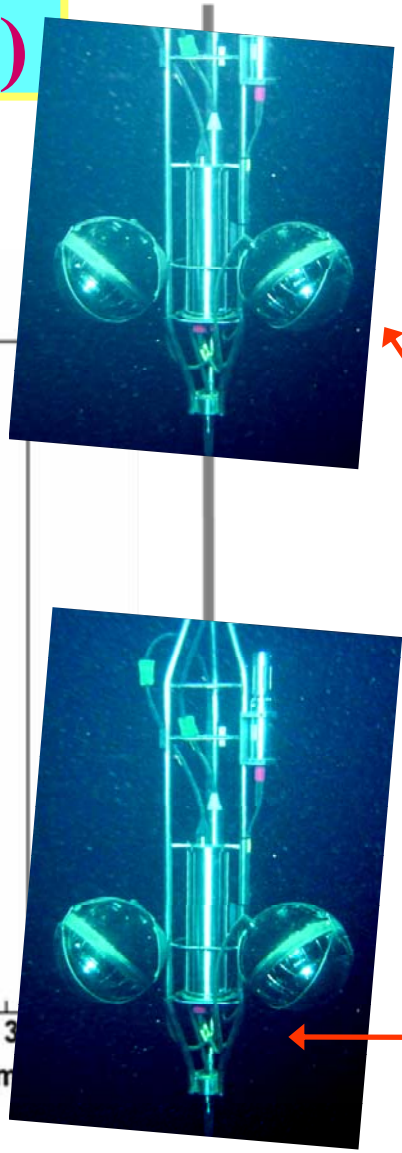
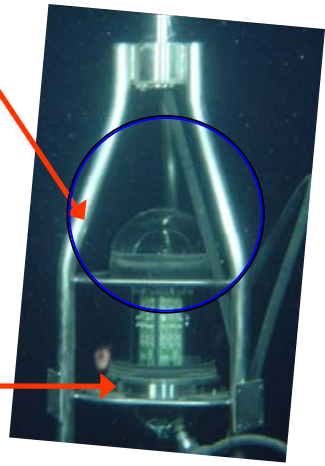
Attenuation (absorption ⊗ diffusion)





~150 m

~70 m



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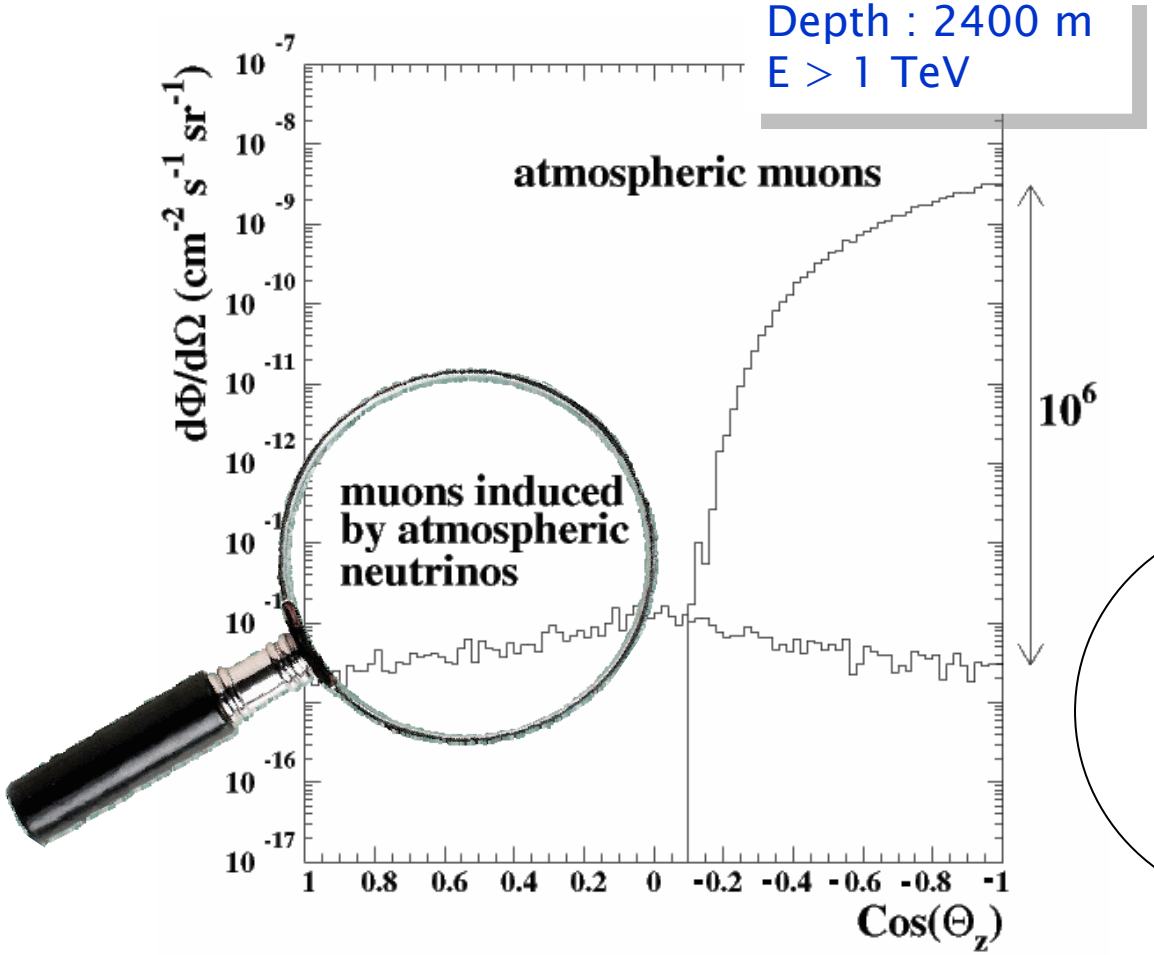
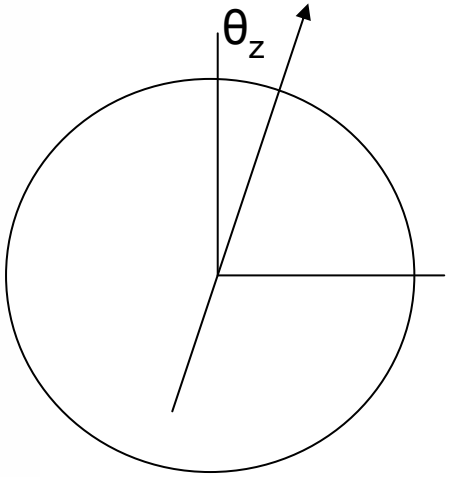
Atmospheric ν's





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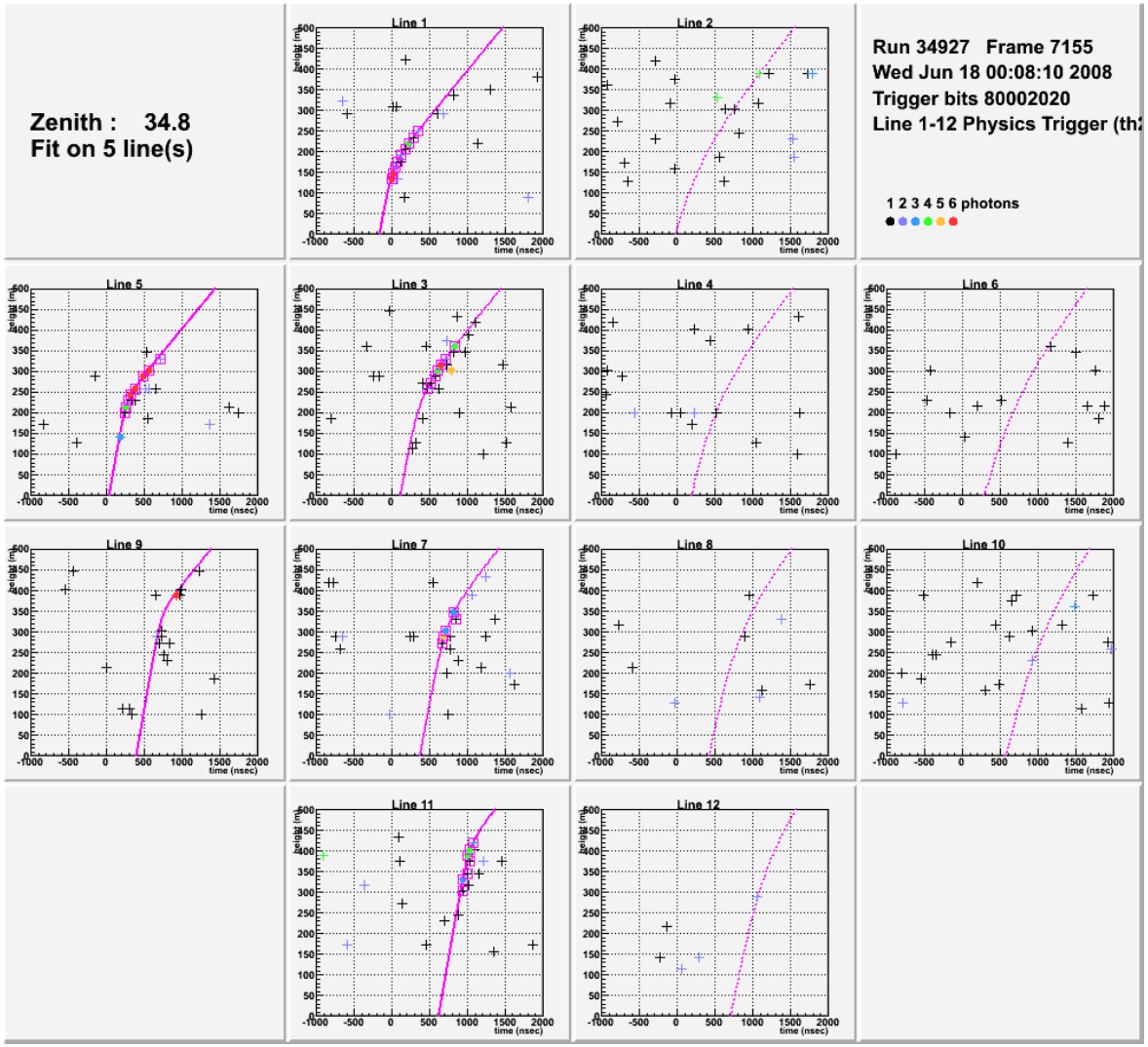
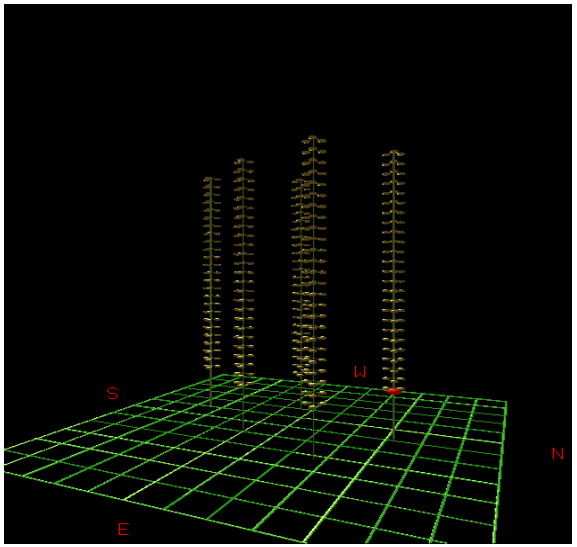
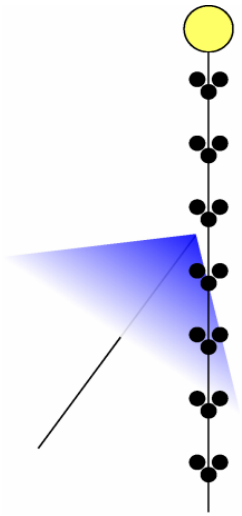
A neutrino event on 12 lines







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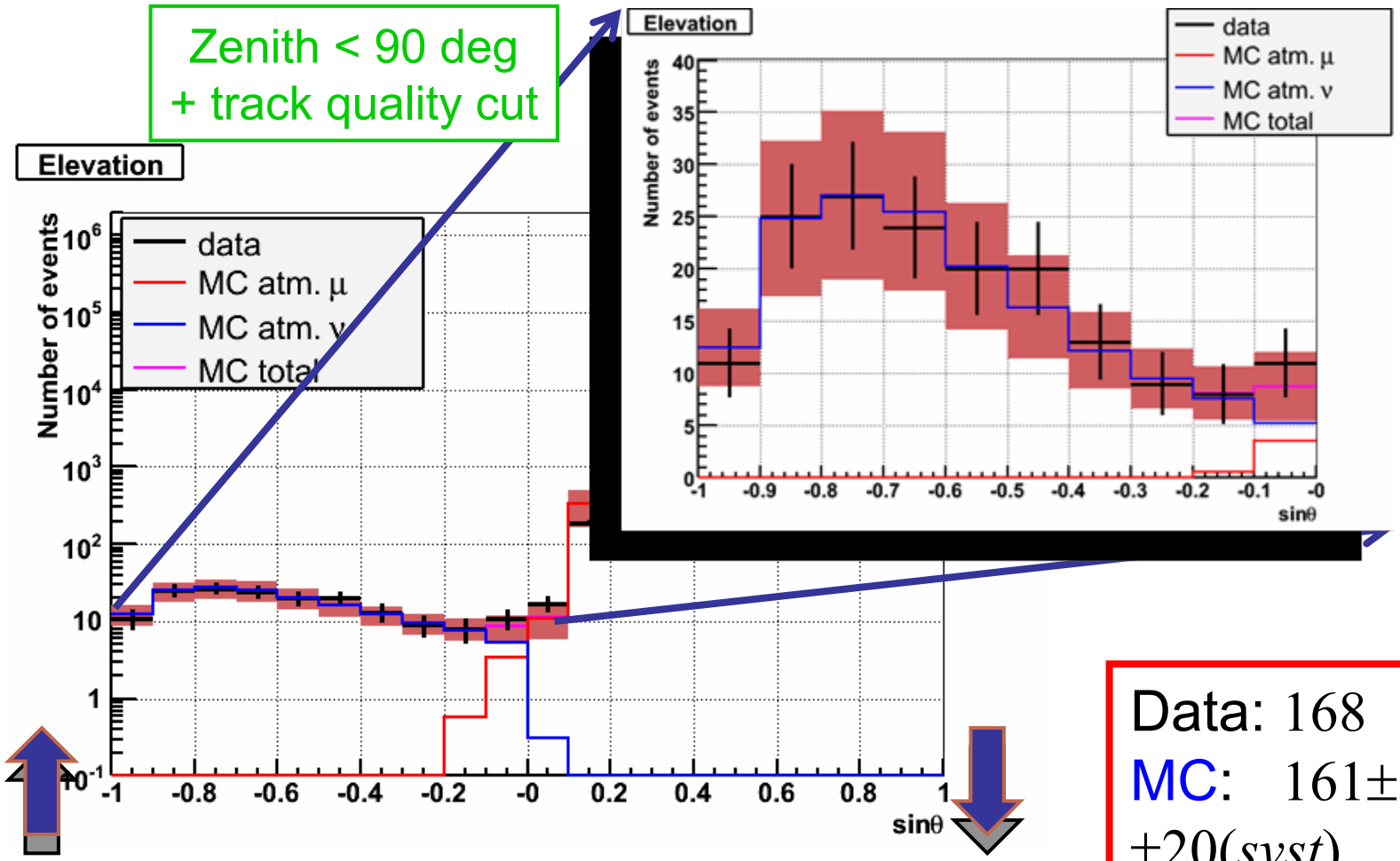
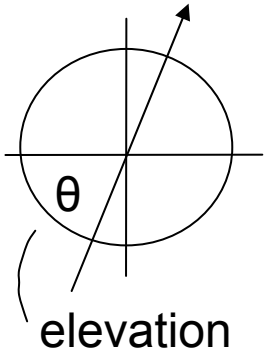
Feb - Dec 2007
140 active days

Atmospheric neutrinos with 5 lines detector

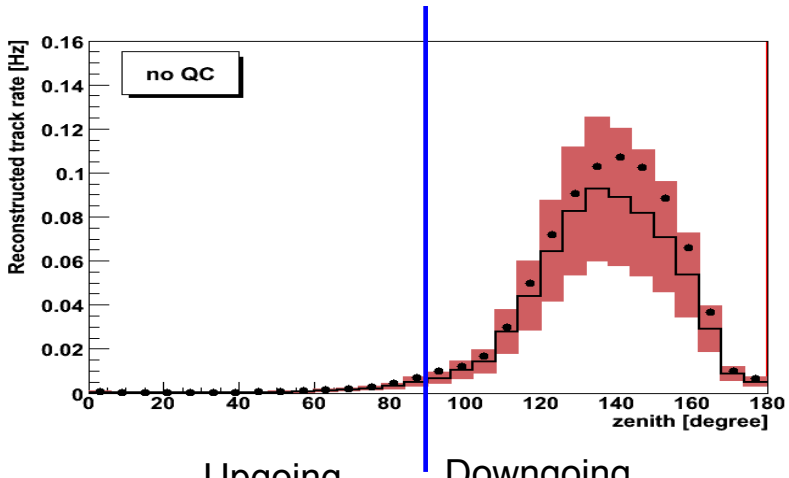
Zenith < 90 deg
+ track quality cut





Data: 168
MC: 161±32(*theor*) ±20(*syst*)

Selection of neutrino events

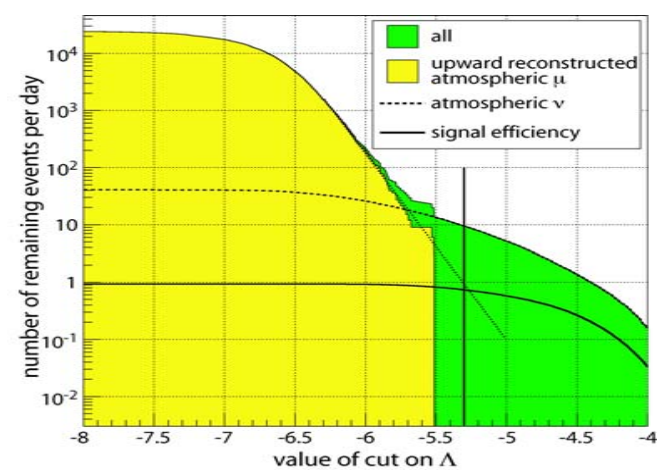


Upgoing Downgoing

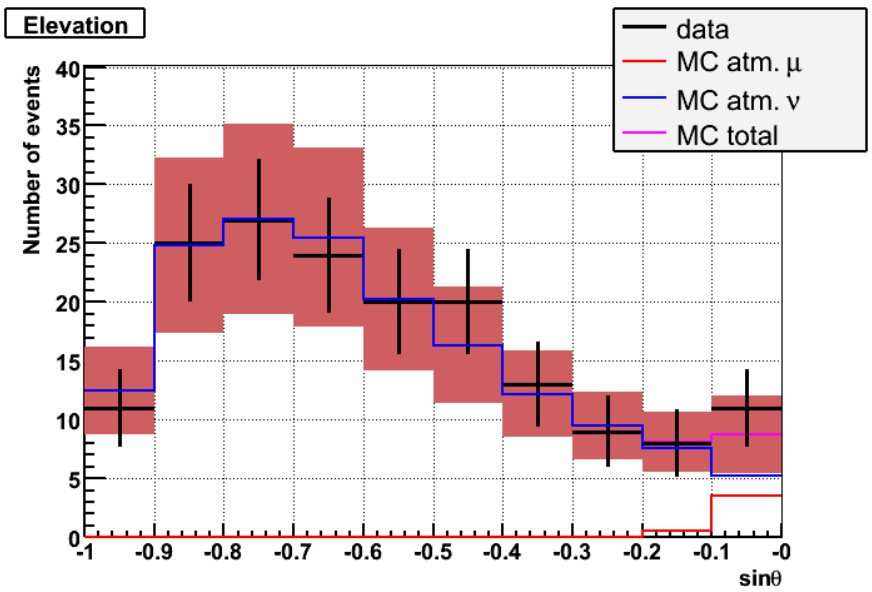
Upgoing events dominated by the tail of badly reconstructed atmospheric muons

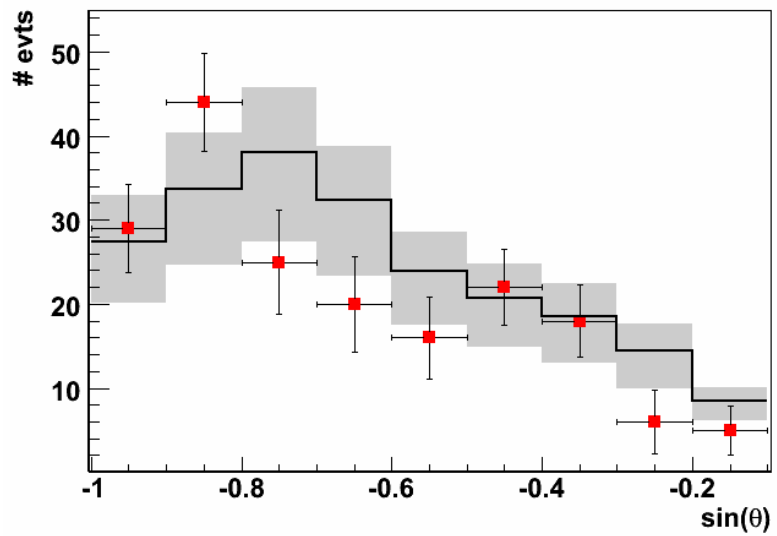
Λ: maximum likelihood of the track fit

MC



2 independent analyses





- **Observed** : 168
- **MC** : 164
  - ±3 (stat)
  - ± 33(théor)
  - ±16 (syst)

- **Observed** : 185
- **MC** : 218
  - ± 4 (stat)
  - ±41(théor)
  - $^{+3}_{-42}$ (syst)

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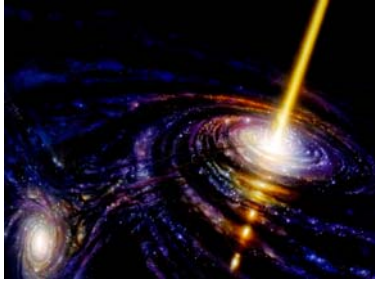
First search for point-like ν sources



- Definition of a potential source list
- Analysis optimization by MC, for E^{-2} flux
  2 methods: - unbinned EM [1] (main result)
  BIC[2]
  - binned, MRF [3] (as a check)
- No discovery 90% CL flux limit

1. Dempster et al, Maximul Likelihood for incomplete data via the EM algorithm, J.R.Stat Soc Series B,38 (1977) 1.
   Aguilar, Hernandez-Rey, The EM algorithm applied to the search of point sources, Astrop. Phys. 29 2 (2008), 117
2. Haughton, On the choice of a model to fit from an exponential family, Ann Stat 16 (1988), 342
3. Hill, Rawlins, Astrop Phys 19 3 (2003)

Unbinned: EM algorithm

- EM: a general approach to maximum likelihood estimation for finite mixture models.
- Mixture models: different groups of data are described by different density components.

$$p(\mathbf{x}) = \sum_{j=1}^{g} \pi_j p(\mathbf{x}; \boldsymbol{\theta}_j)$$

g = number of mixture models

π_i = mixture proportions, where $\sum_{j=1}^{g} \pi_j = 1$

First step: change from incomplete to complete data set.

$$\{\mathbf{x}\} \quad \mathbf{x}_i = (\alpha_i^{\mathrm{ra}}, \delta_i) \longrightarrow \{y\} \quad \mathbf{y}_i = (\alpha_i^{\mathrm{ra}}, \delta_i, \mathbf{z}_i)$$

The vector $\mathbf{z}_i$ is a class indicator that indicates if the event *i* belongs to the background or the source.

Expectation step

–Start with a set of initial parameters $\Psi^{(m)} = \{\pi_1, \pi_2, \mu, \Sigma\}$

–Expectation of the complete data log-likelihood, conditional on the observed data {x}

$$\mathrm{Q}(\boldsymbol{\Psi}, \boldsymbol{\Psi}^{(m)}) = \mathrm{E}[\log(g(\{\mathbf{y}\}; \boldsymbol{\Psi})) \mid p(\{\mathbf{x}\}; \boldsymbol{\Psi}^{(m)})]$$

Maximization step

–Find Ψ = Ψ(m + 1) that maximizes Q(Ψ, Ψ(m))

Signal & background

- A simple pre-clustering selects a set of candidates by using a cone of 1.25º around each event of the sample.

Background **Signal**

$$p(\mathbf{x}) = \pi_{BG} P_{BG}(\delta) + \pi_S P_S(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma})$$

position of event: $\mathbf{x} = (\alpha_{RA}, \delta)$

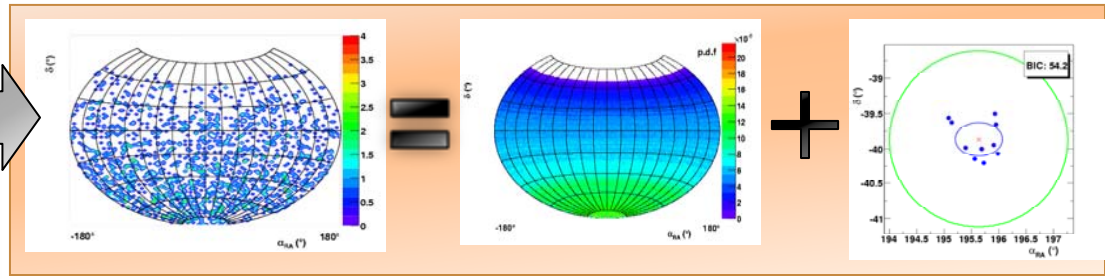
bg: only δ

signal : α_{RA}, δ

Sample

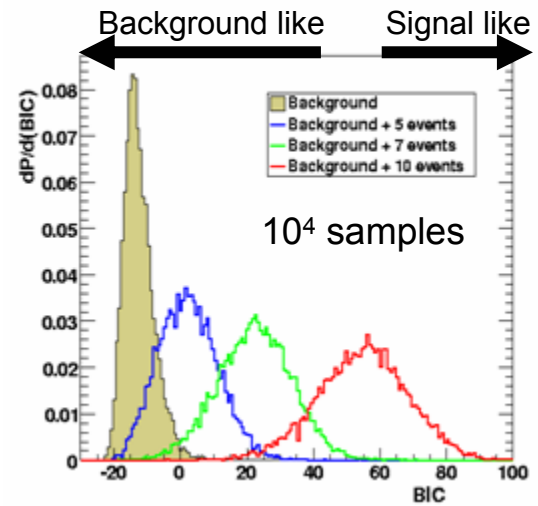
Background from real RA-scrambled data

Signal pdf model 2D-Gaussian



Samples simulation:

- 10^4 samples simulated.
- Each sample corresponds to the lifetime of 2007 data period.



- The **Bayesian Information Criterion (BIC)** is chosen as the test statistic of the method.

$$\mathrm{BIC}_k = 2\log p(D \mid \hat{\Psi}_k, M_k) - v_k \log(n)$$

Binned: Cone method

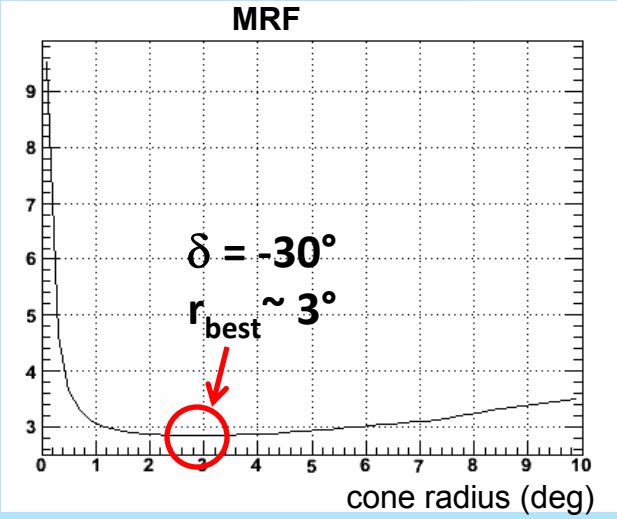
Cone size optimization

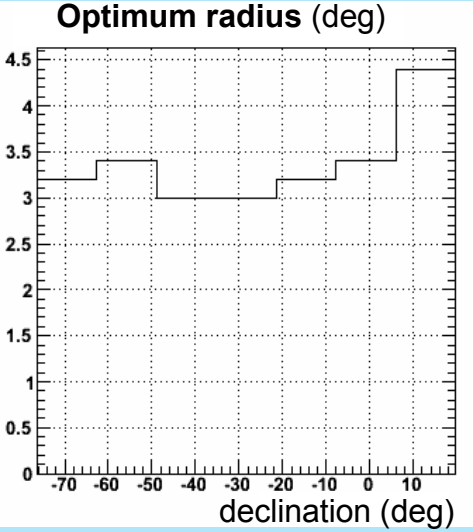
$$\bar{\mu}_{90}(n_b) = \sum_{n_{obs}}^{\infty} \mu_{90}(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{(n_{obs})!} \exp(-n_b)$$

Upper limit **Poisson weight**

MRF = $\frac{\bar{\mu}_{90}}{n_s}$

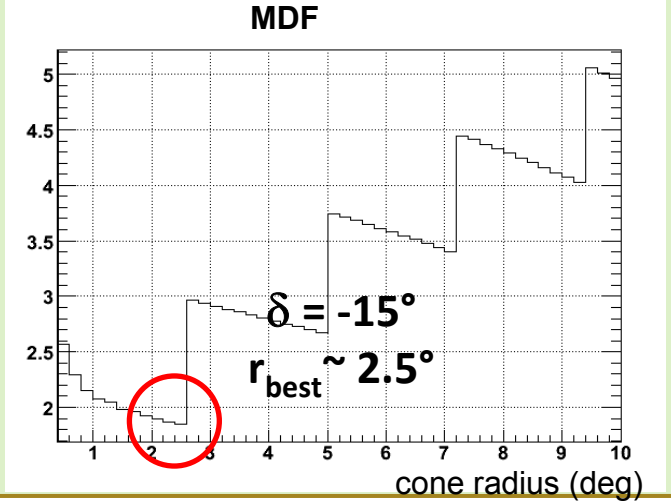
Model Rejection Factor used for **fixed-source** search

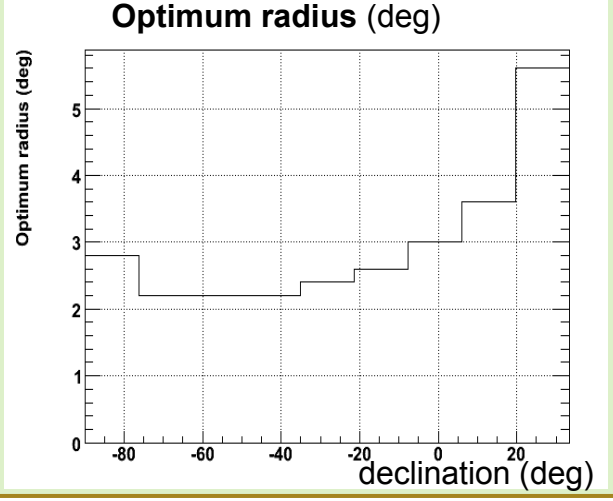




Model Discovery Factor used for **all-sky** search

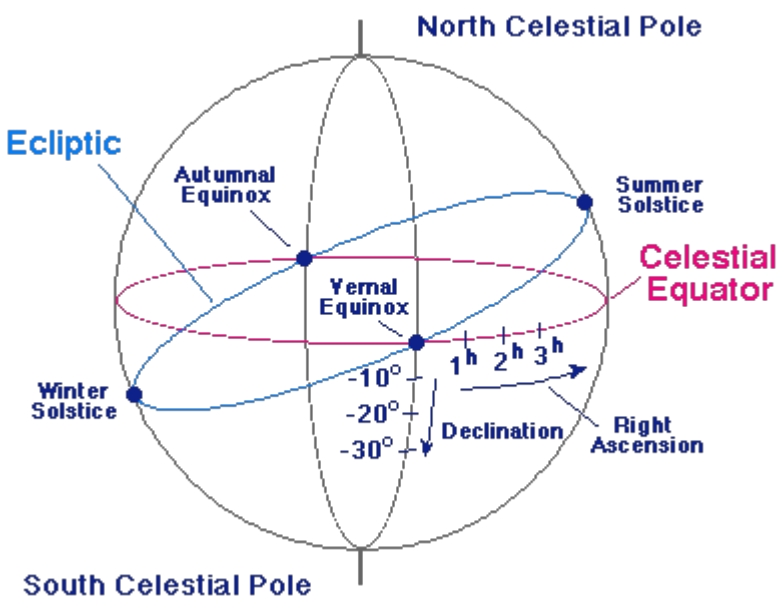
$$MDF = \frac{\mu(n_b, CL, SP)}{n_s}$$





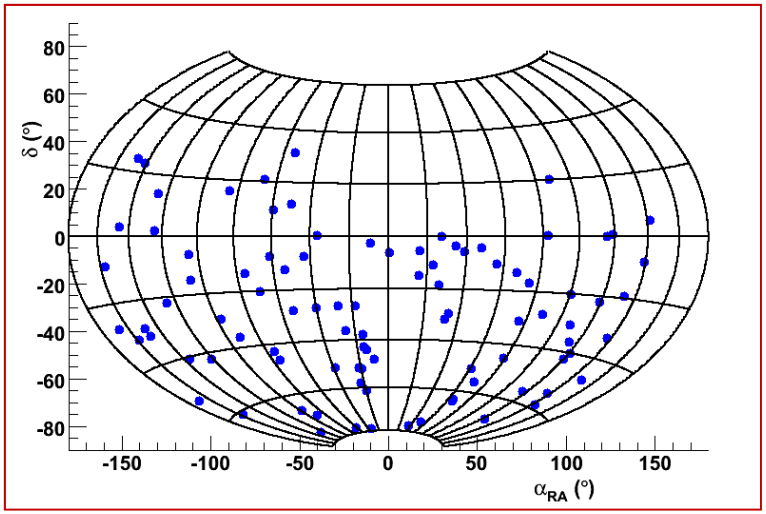
Point source search (2007)

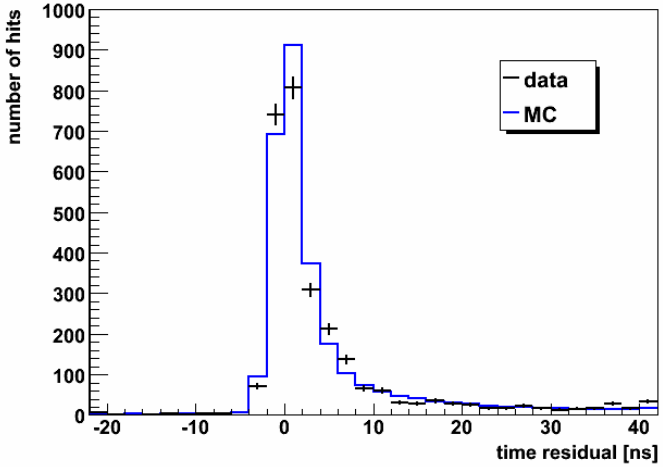
- Blind analysis
  - Strict cuts
  - Study on scrambled data
  - Final result on real data
- 94 candidate events
- Research applied to 25 sources

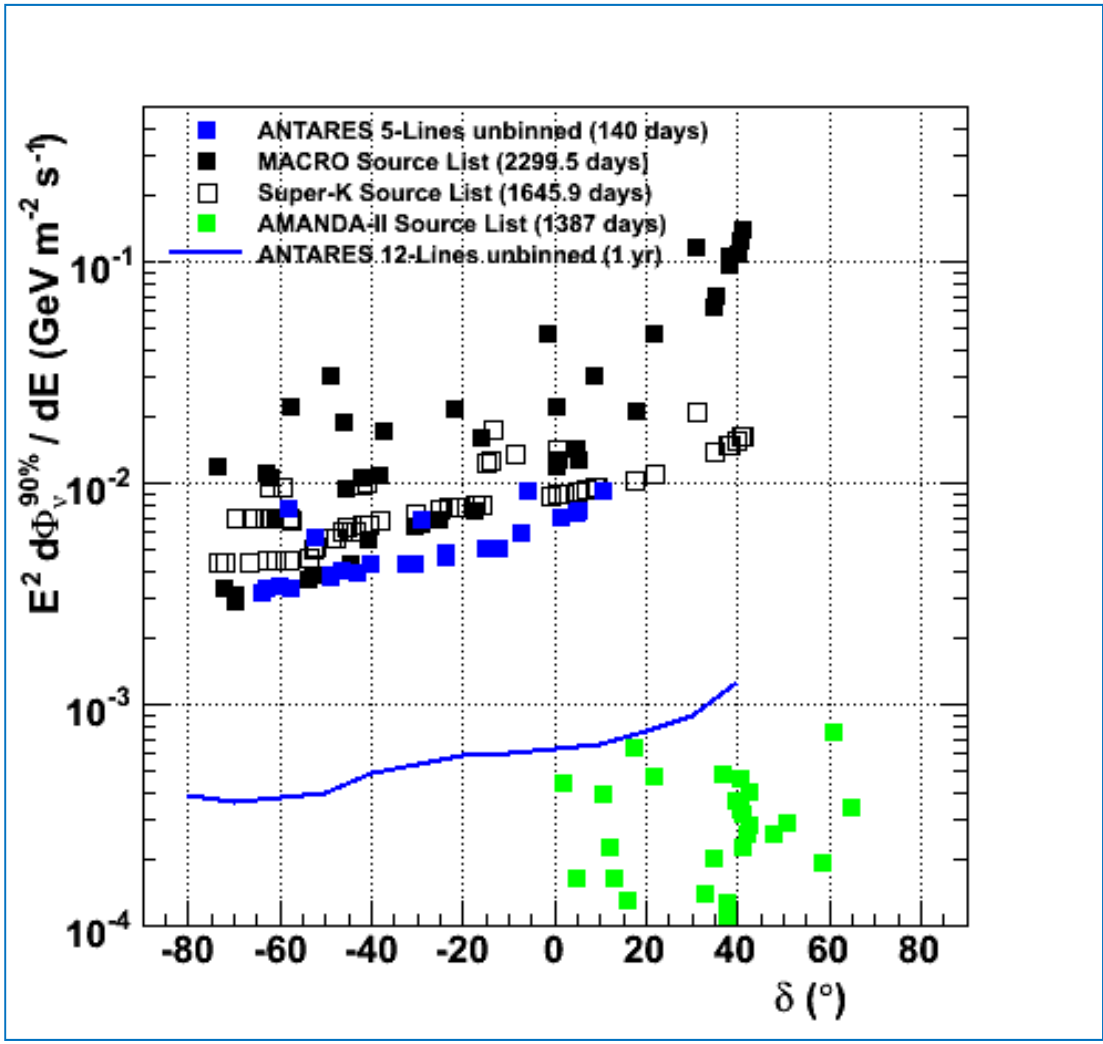


Source	DECL δ	α_{RA}	Nevents
PSR B1259-63	-63.8339	195.703	0
RCW 86	-62.4833	220.679	0
ESO 139-G12	-59.9414	264.414	0
HESS J1023-575	-57.7639	155.825	1
Cir X-1	-57.1667	230.171	0
HESS J1614-518	-51.82	243.579	1
PKS 2005-489	-48.8219	302.372	0
GX 339	-48.7897	255.704	0
RX J0852.0-4622	-46.3667	133	0
Centaurus A	-43.0191	201.364	0
RX J1713.7-3946	-39.75	258.25	0
PKS 0548-322	-32.2712	87.6692	0
H 2356-309	-30.6275	359.784	0
PKS 2155-304	-30.2217	329.721	0
Galactic Center	-29.0061	266.421	1
1ES 1101-232	-23.4919	165.909	0
W28	-23.335	270.425	0
LS 5039	-14.825	276.562	0
1ES 0347-121	-11.9908	57.3459	0
HESS J1837-069	-6.95	279.408	0
3C 279	-5.78917	194.046	1
RGB J0152+017	1.78861	28.1667	0
SS 433	4.98278	287.958	0
HESS J0632+057	5.80556	98.2416	0
IceCube HotSpot	11	153	0

Flux limits



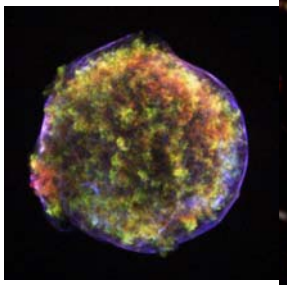




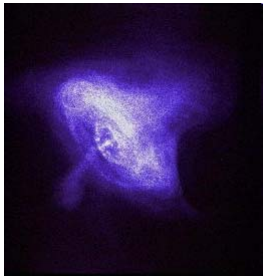
50

Potential sources

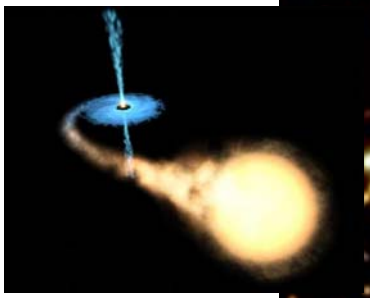
Indirect dark matter signal



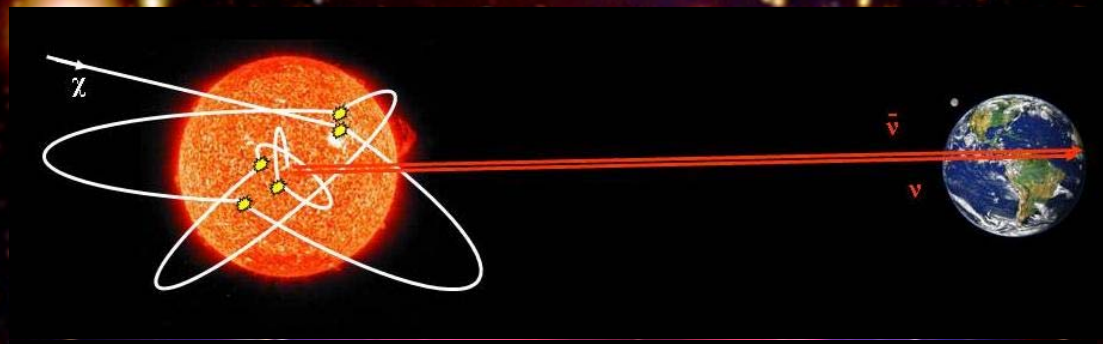
Supernova remn

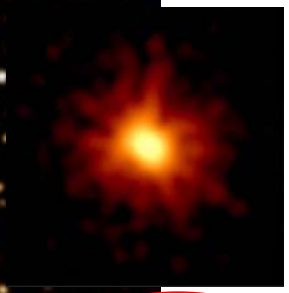


Pulsars

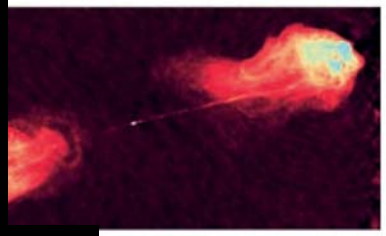


Microquasars





RBs



Ns

Relic WIMPs captured in celestial bodies

$\chi\chi$ self-annihilations into

c,b,t quarks, τ leptons or W,Z,H bosons

(prompt)

$\rightarrow$ significant

high-energy ν flux

Potential $\chi\chi \rightarrow \nu$ sources :

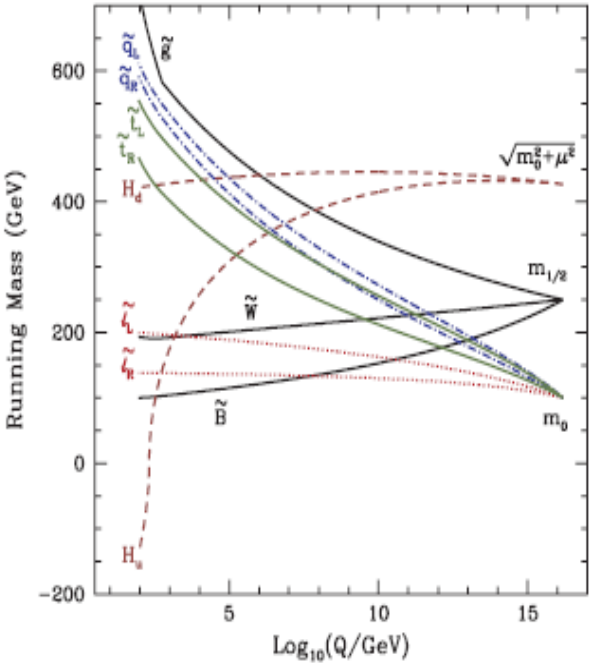
Sun, Earth, Galactic Centre

mSUGRA

Minimal Supergravity:5 free parameters. mSUGRA is a GUT including gravity, parameters defined at the GUT scale (10^{16} eV). All couplings converge at this scale,

free parameters:

- common masses for scalars (m_0) and gauginos ($m_{1/2}$)
- common trilinear coupling constant A_0
- ratio of vev's of the 2 Higgs fields $tan(\beta) = V_{top}/V_{bottom}$.
- Higgsino mixing parameter μ is fixed except for its sign (5th parameter).



From these parameters at the GUT scale, masses and couplings at the EW scale can be calculated using renormalization group equations (RGE), with ISASUGRA or SuSpect [2].. Depending on the parameters chosen, the LSP, stable from R-parity conservation, (-1 for superpartners and 1 for standard particles), could be the lightest of four neutralinos

Neutralino annihilations in the Sun in mSUGRA

Study of **neutralino Dark Matter** sensitivity within SUSY mSUGRA framework

Random walk scan within mSUGRA parameter space :

$0 < m_{1/2} < 2000$ GeV

$0 < m_0 < 8000$ GeV

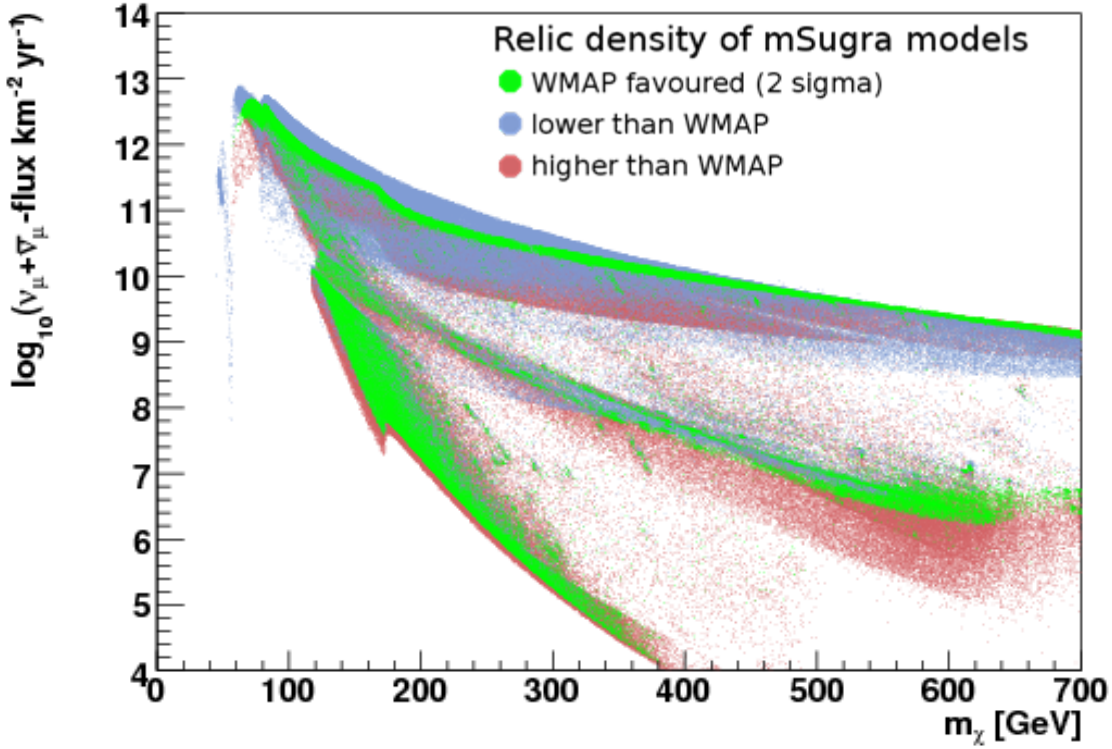
$0 < \tan\beta < 60$

$-3\, m_0 < A_0 < 3\, m_0$

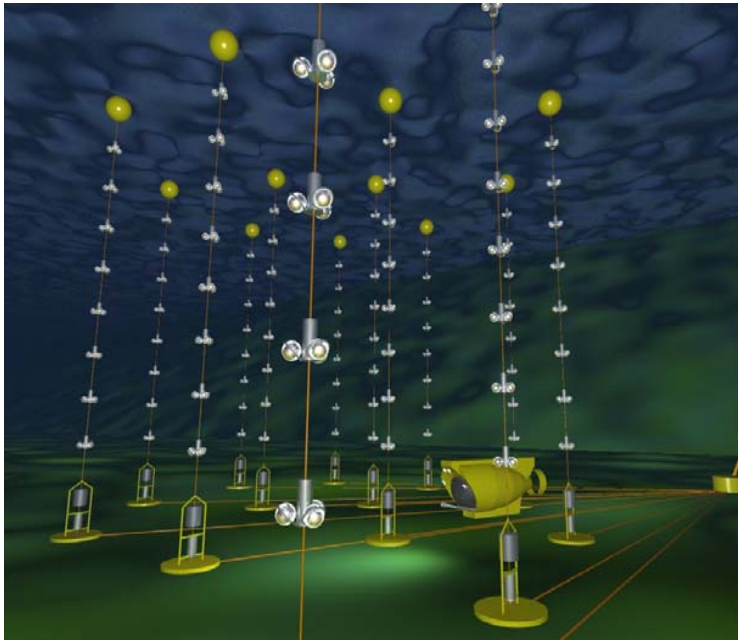
Calculated with DarkSUSY and ISASUGRA (RGE code) with $m_{top} = 172.5$ GeV

Includes ν oscillation effects inside and outside the Sun

Integrated neutrino flux for $E\nu > 10$ GeV

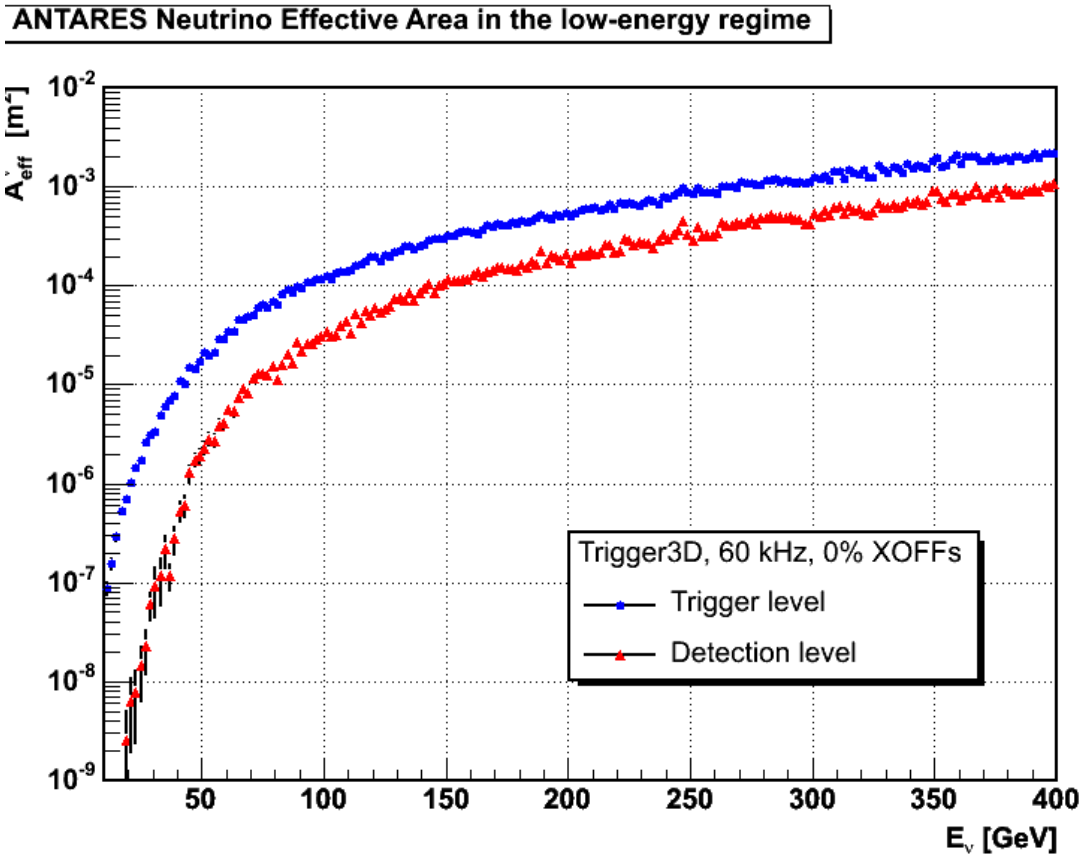


Low-energy performance



ANTARES Low-Energy Effective Area

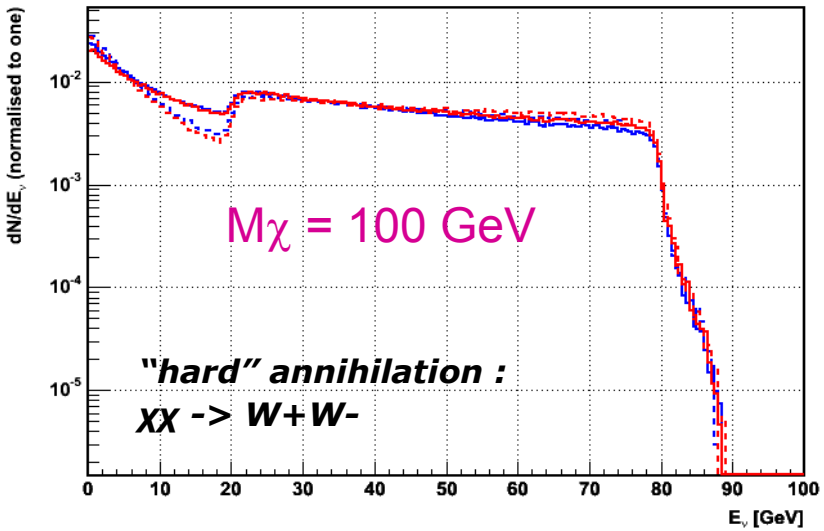
Assume 60 kHz of optical background mean rate

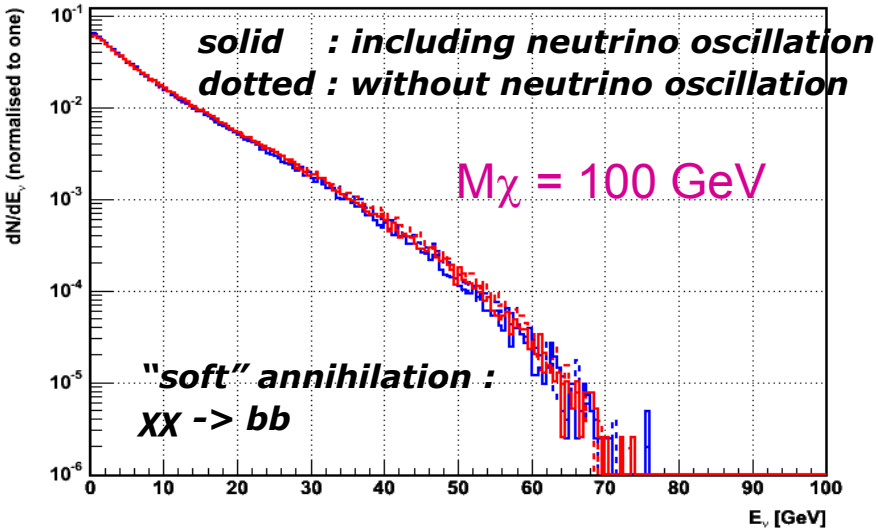


Trigger : Events with hits on at least 5 storeys in whole detector

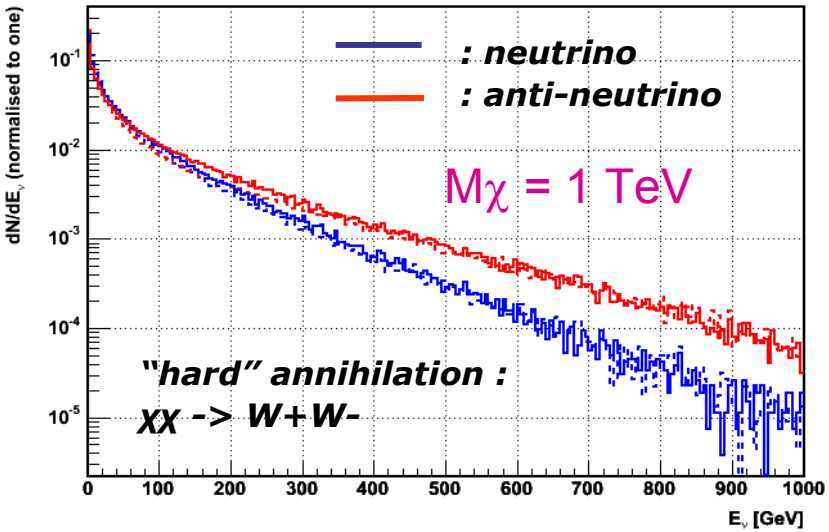
Detection : Selected after 3D reconstruction with quality cuts

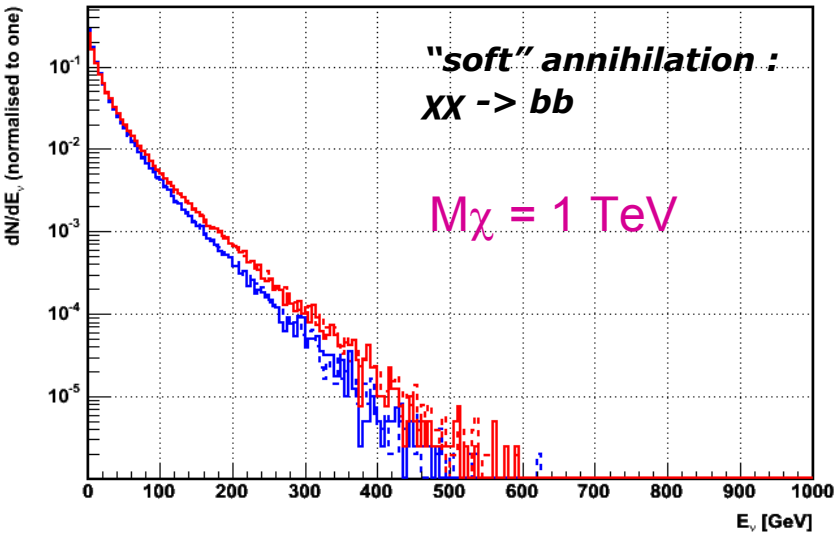
Neutrino spectra from neutralino annihilations





Neutrinos from $\chi\chi \rightarrow$ WW (hard spectrum) are more energetic and easier to detect

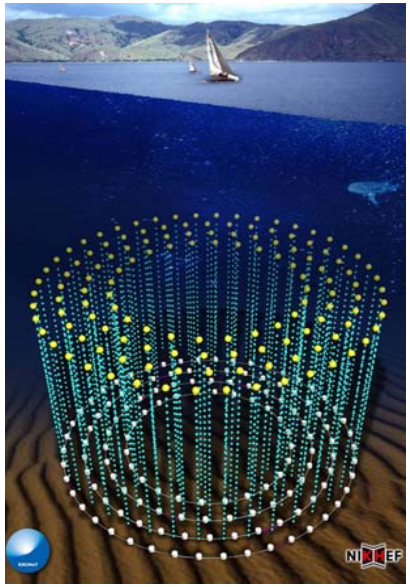




Neutralino annihilations in the Sun in mSUGRA

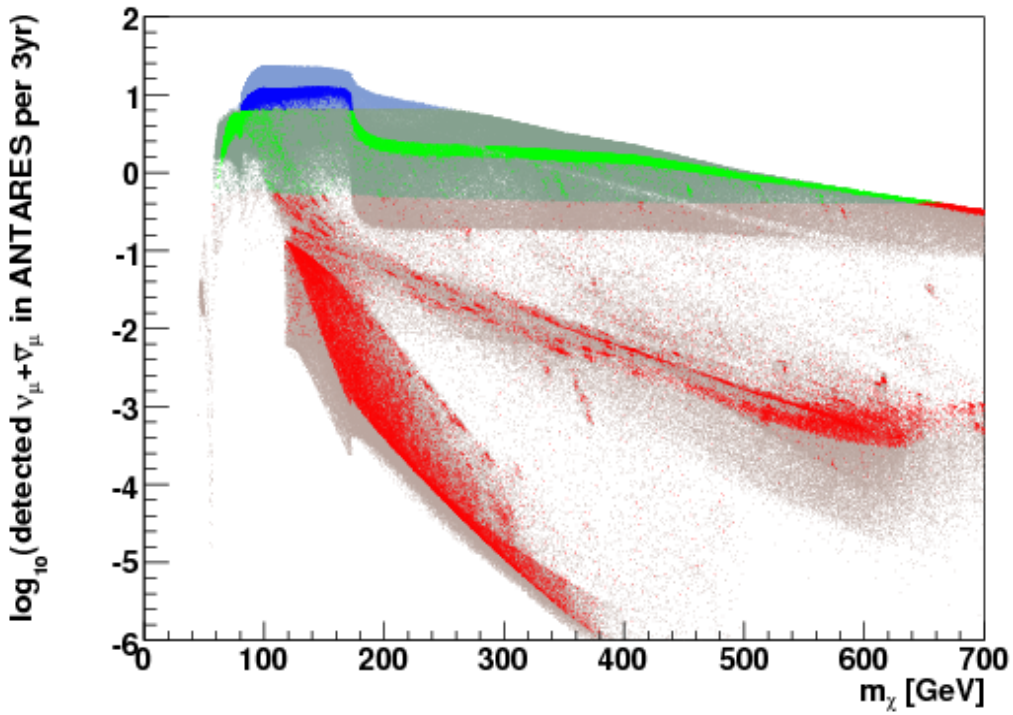
Sensitivity calculated for 3 years of data taking

Background from atmospheric neutrinos and misreconstructed atmospheric muons within 3° radius search cone around the Sun



KM3NeT detector

Detection rate with ANTARES and KM3NeT detectors

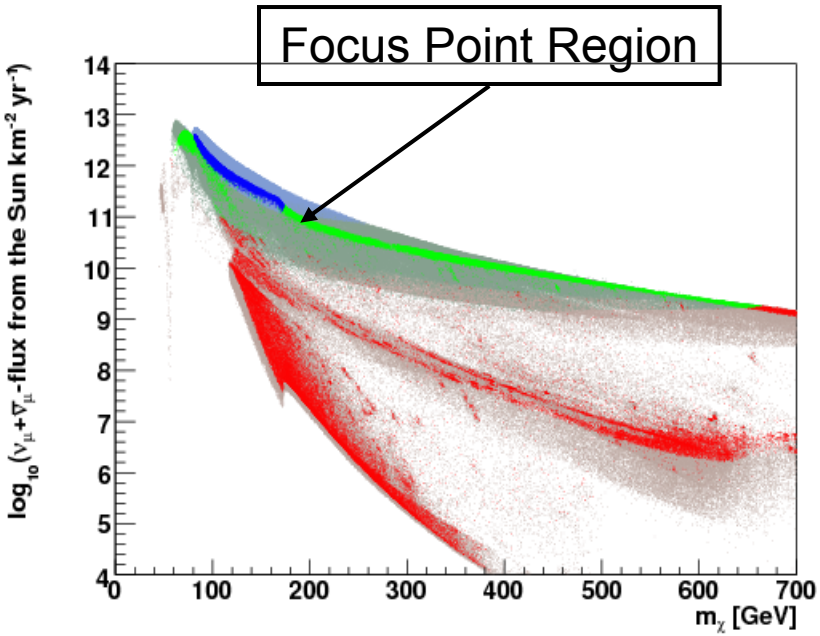


mSugra models favoured by WMAP
- 90% CL excudable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

mSugra models disfavoured by WMAP
- 90% CL excludable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

Neutralino annihilations in the Sun in mSUGRA

mSugra Parameter Space



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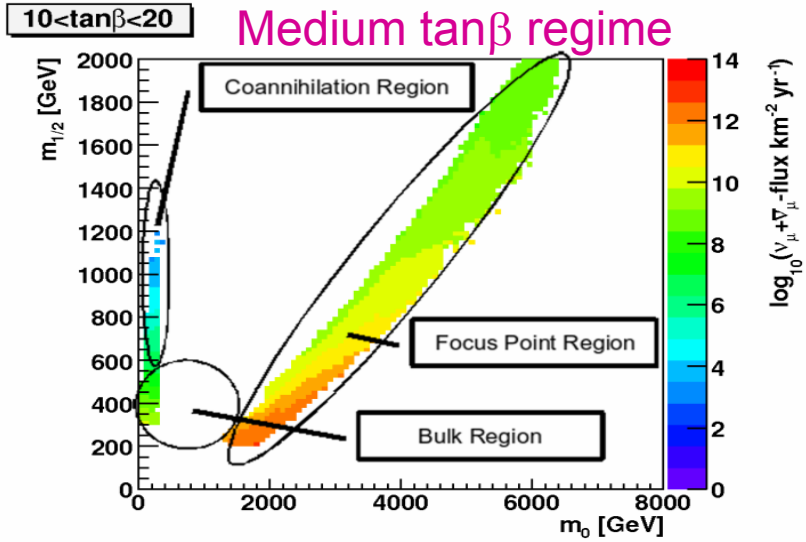
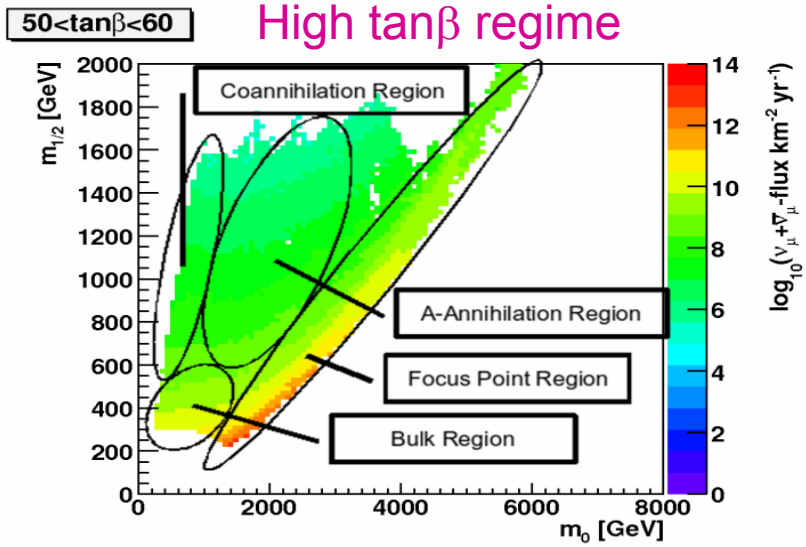
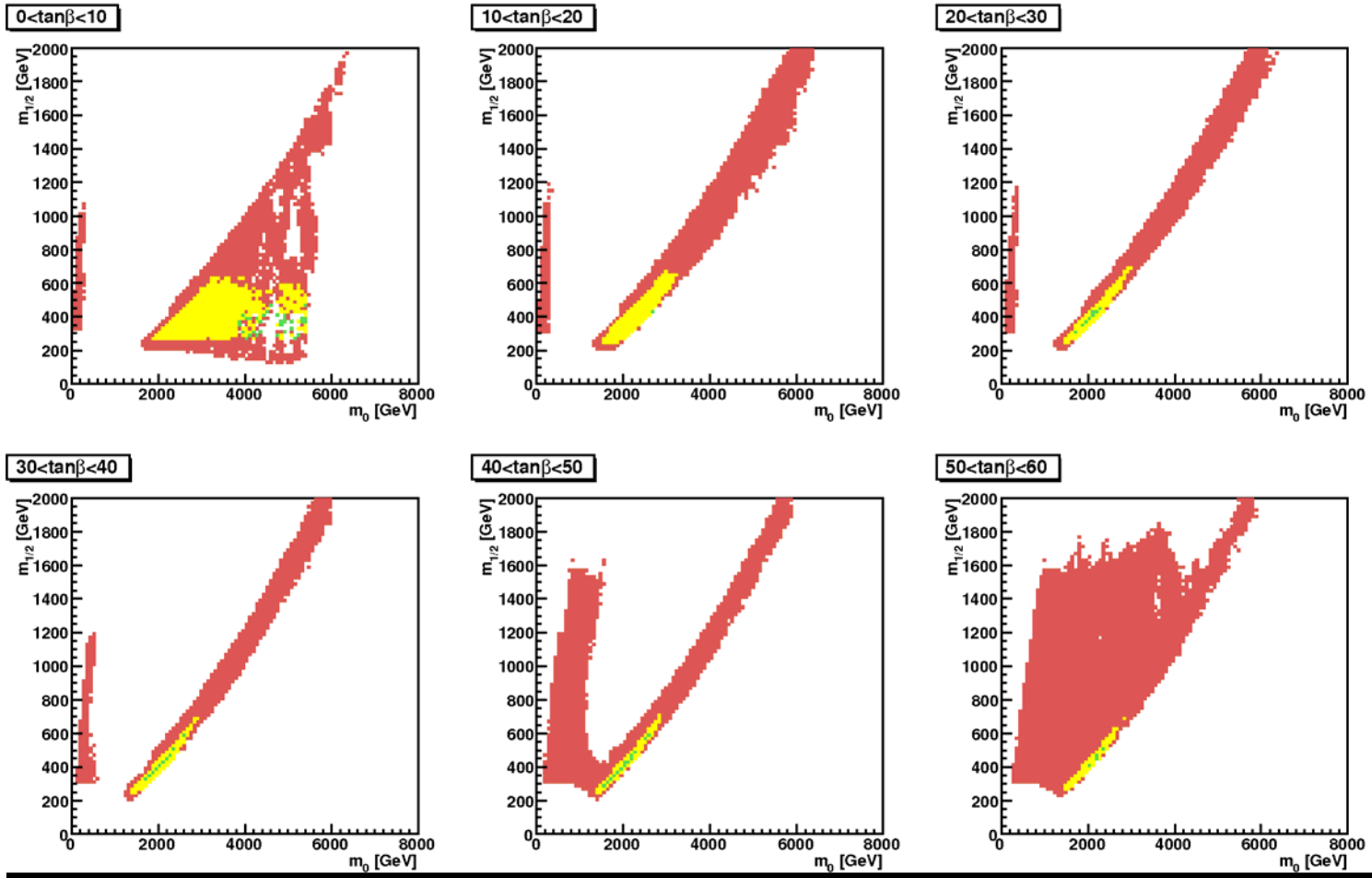


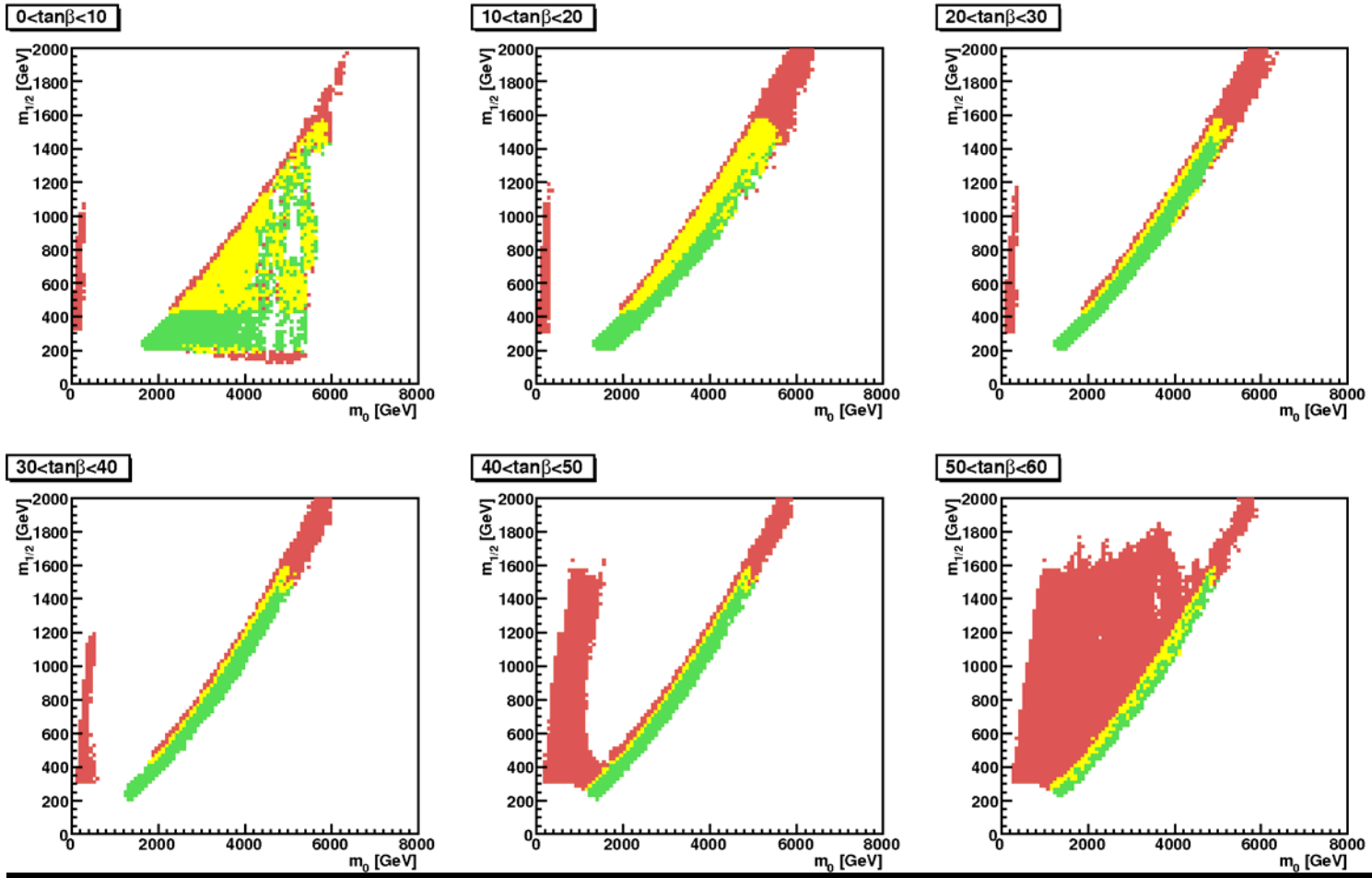


Exclusion capabilities of ANTARES for the mSUGRA parameter space



Excludable in 3 years at 90% CL: all some none
(A_0 varied between $-3m_0$ and $+3m_0$ and tan(β) within indicated slice)

Exclusion capabilities of km3 for the mSUGRA parameter space



Excludable in 3 years at 90% CL: all some none
(A_0 varied between $-3m_0$ and $+3m_0$ and tan(β) within indicated slice)

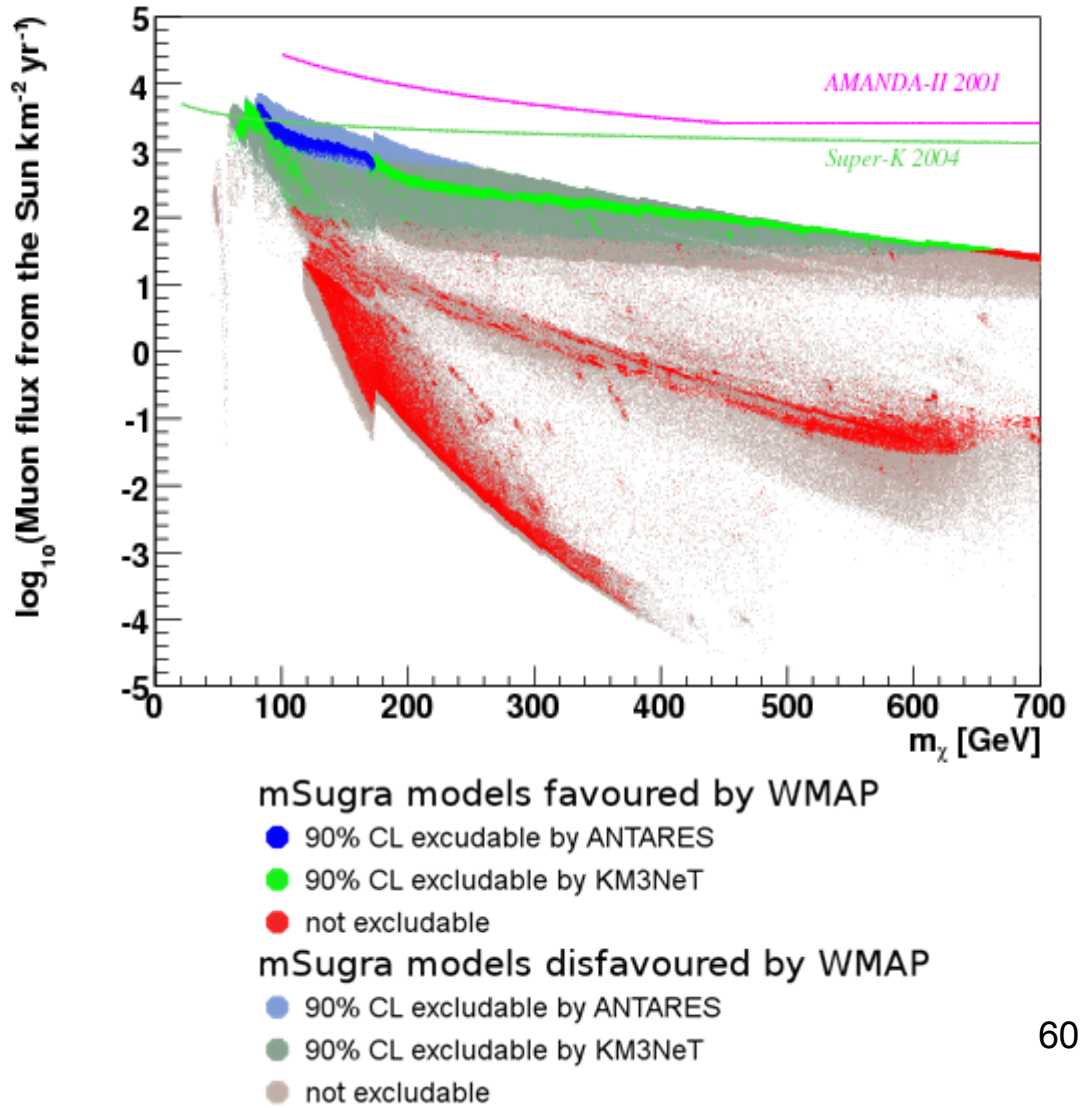
Muon flux from neutralino annihilations in the Sun

Used for comparison to other neutrino experiments

Site dependent quantity (ν propagation through Earth, target density at detector…)

Derived from neutrino flux through $\nu \rightarrow \mu$ conversion rate extracted from DarkSUSY for different m_χ

Muon flux from the Sun in mSUGRA



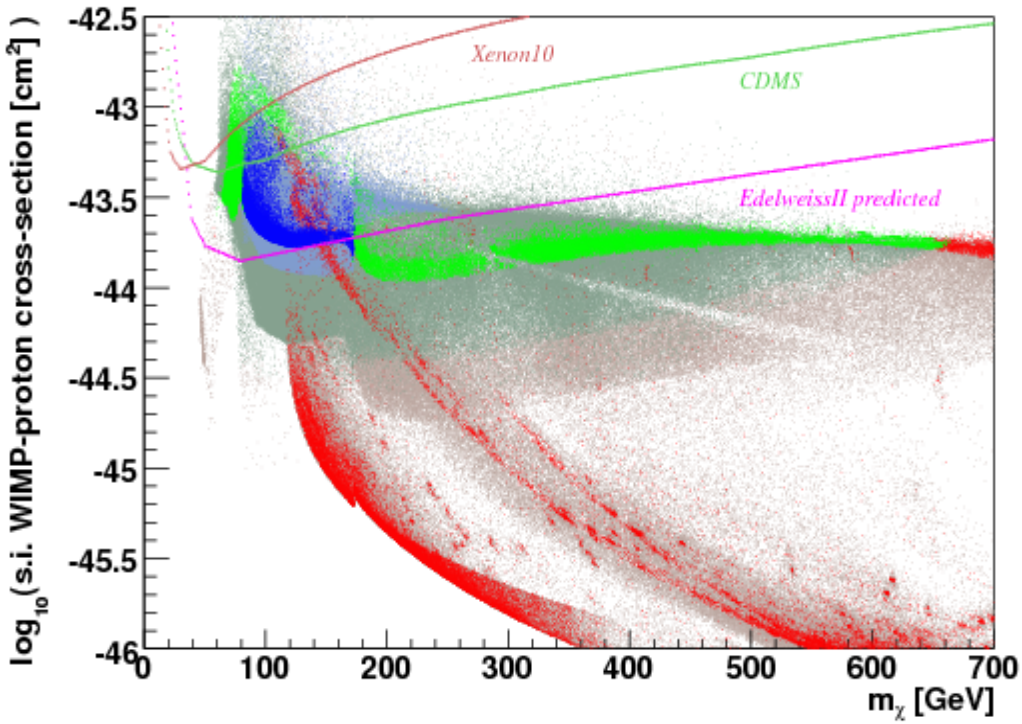
Comparison to Direct Detection sensitivity

Comparison to direct detection experiments sensitive to spin independent WIMP-nucleon cross section

Spin dependent scattering limits (direct search) not yet low enough to put constraints on mSUGRA Dark Matter

CDMS: arXiv:0802.3530

XENON: arXiv:0706.0039



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- 90% CL excludable by KM3NeT
- not excludable

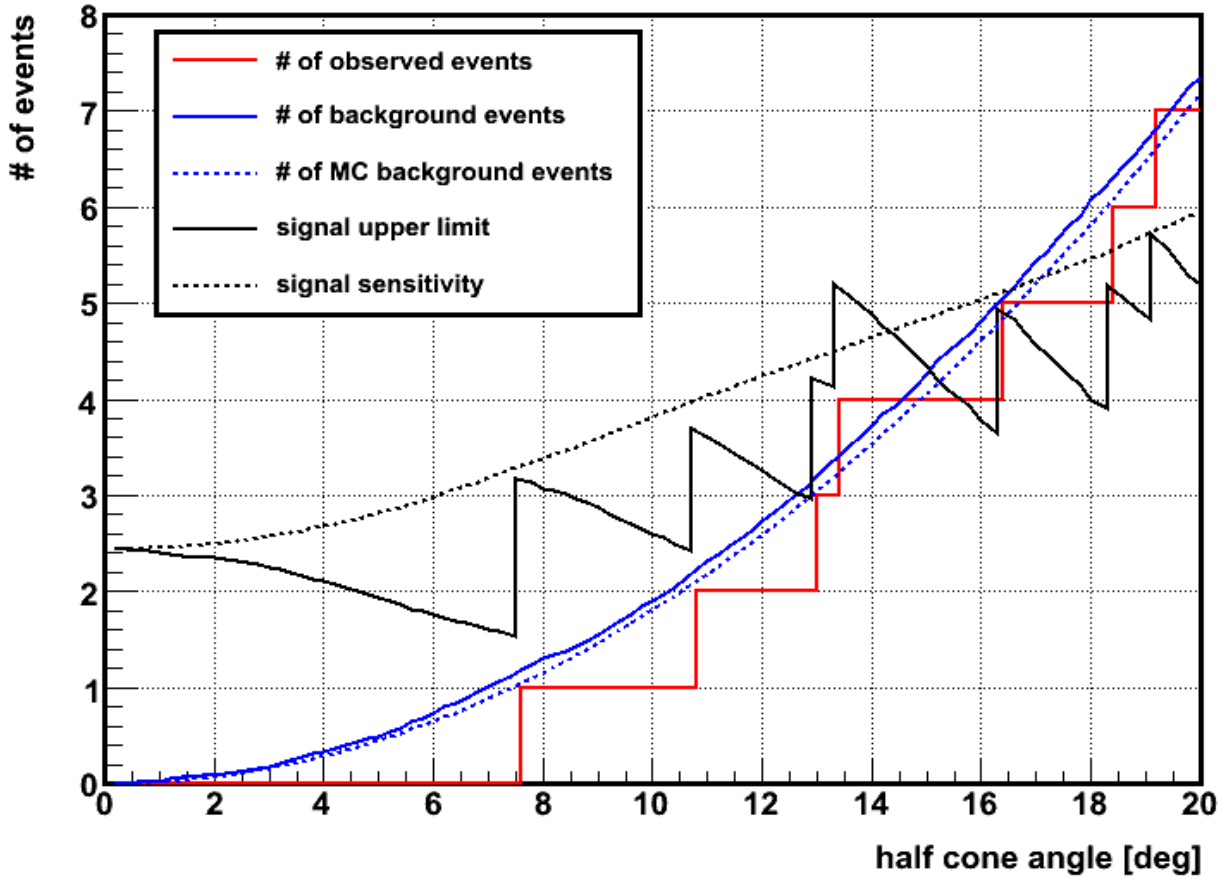
mSugra models disfavoured by WMAP
- 90% CL excludable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

Search for neutrino events coming from the Sun

Expected sensitivity and background in a cone around the Sun for the ANTARES 5-line upgoing neutrino sample

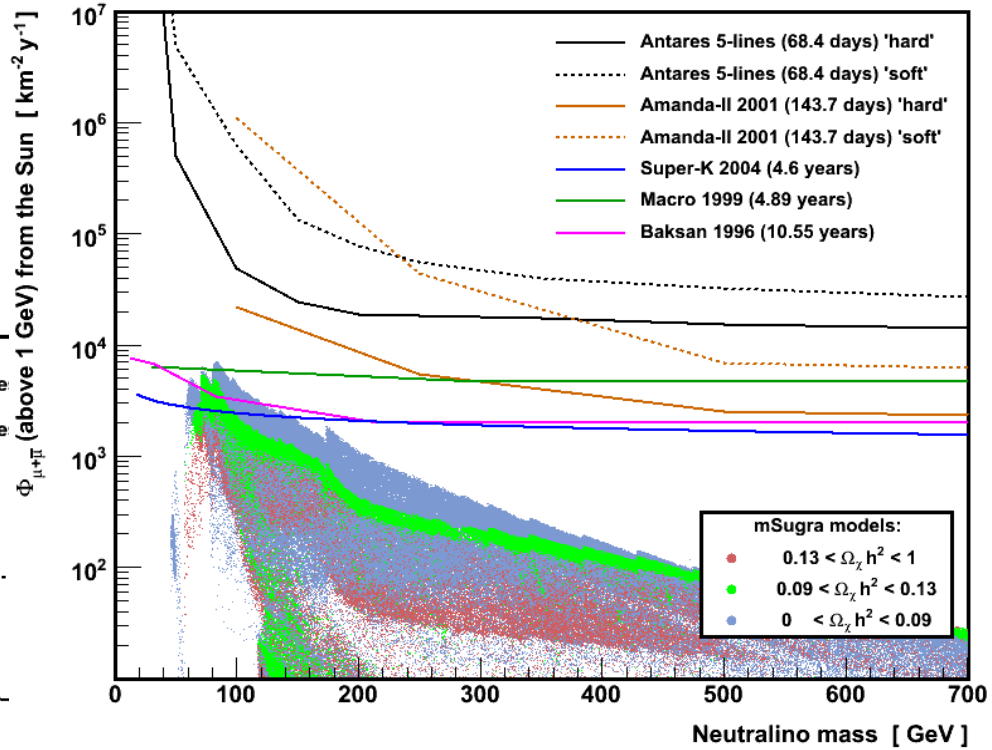
Good agreement for background estimation from MC and full sky data set

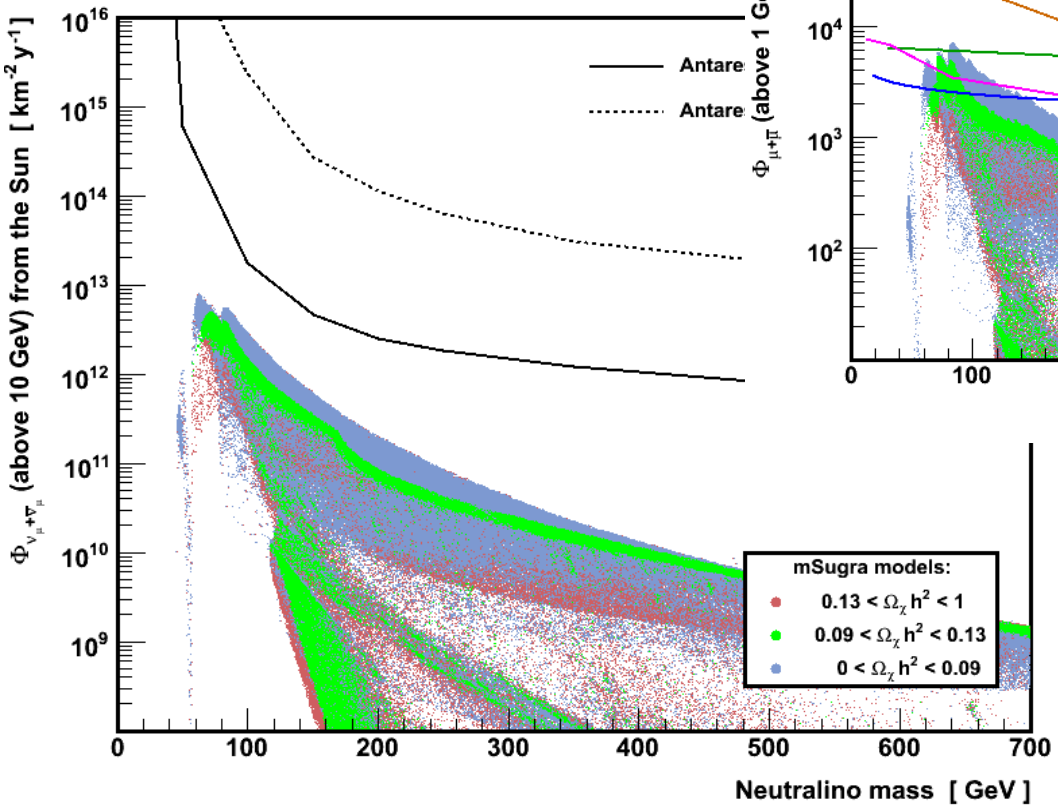
Size of search cone optimized on MC as a function of $M\chi$ and hard/soft spectrum



First ANTARES limit on ν/μ flux from the Sun

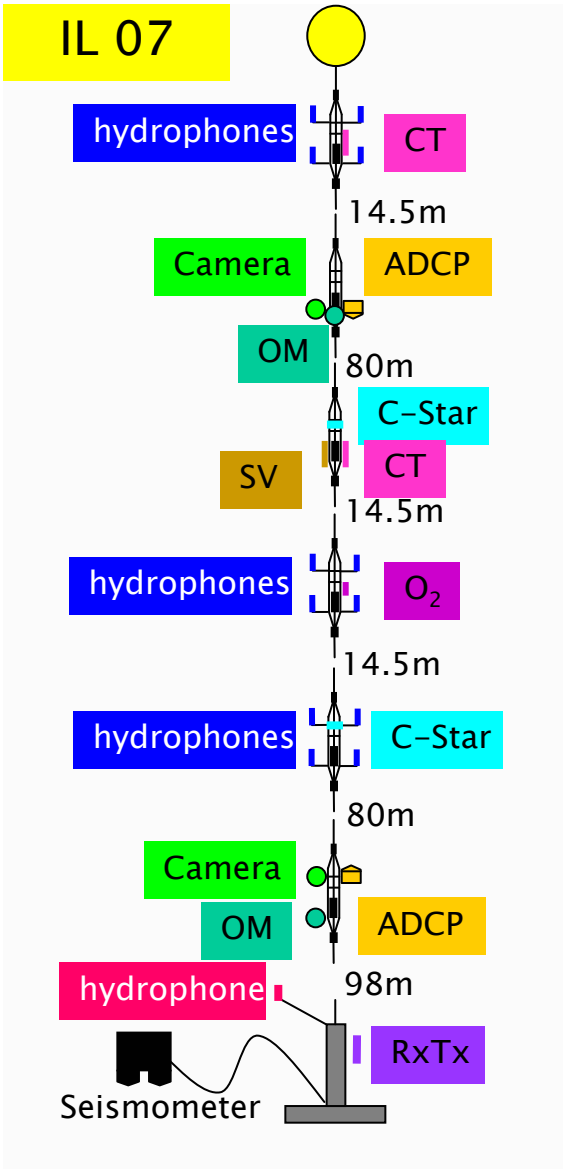
Promising limit based on data with ~ ½ of ANTARES detector in 6 months



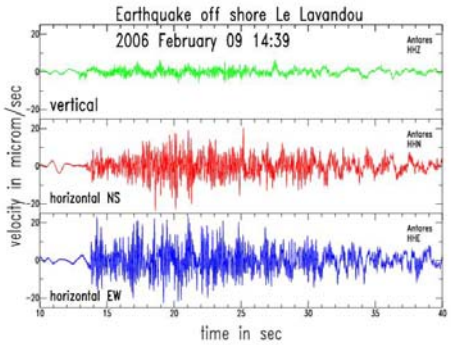


Limit with b-quark (soft) or W-boson (hard) annihilation channel

Other sciences



- Sismology
- Acoustic detection at VHE
- Oceanography
- Climatology



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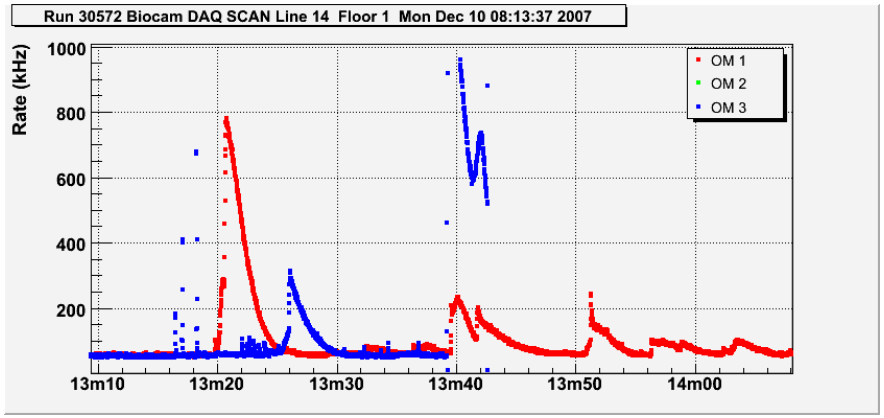
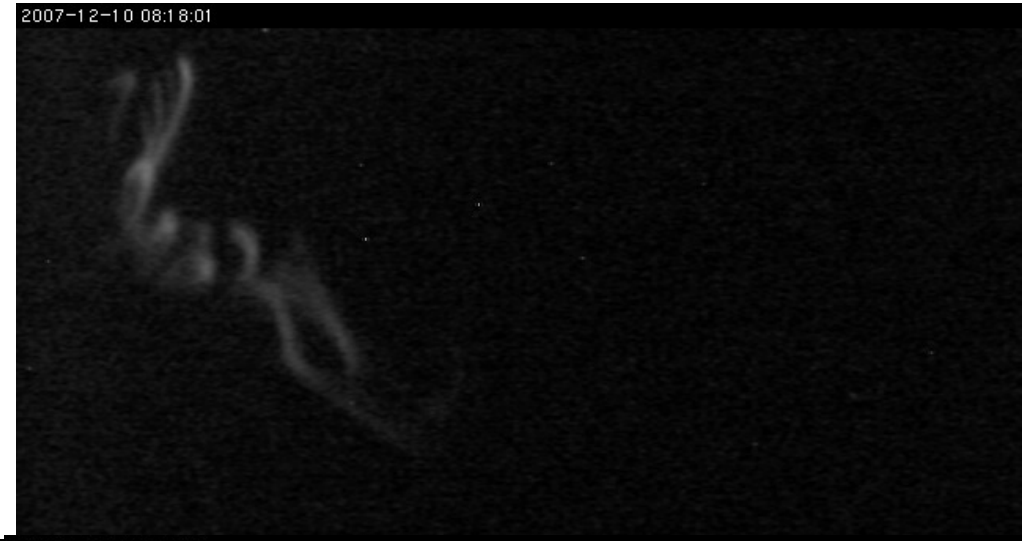
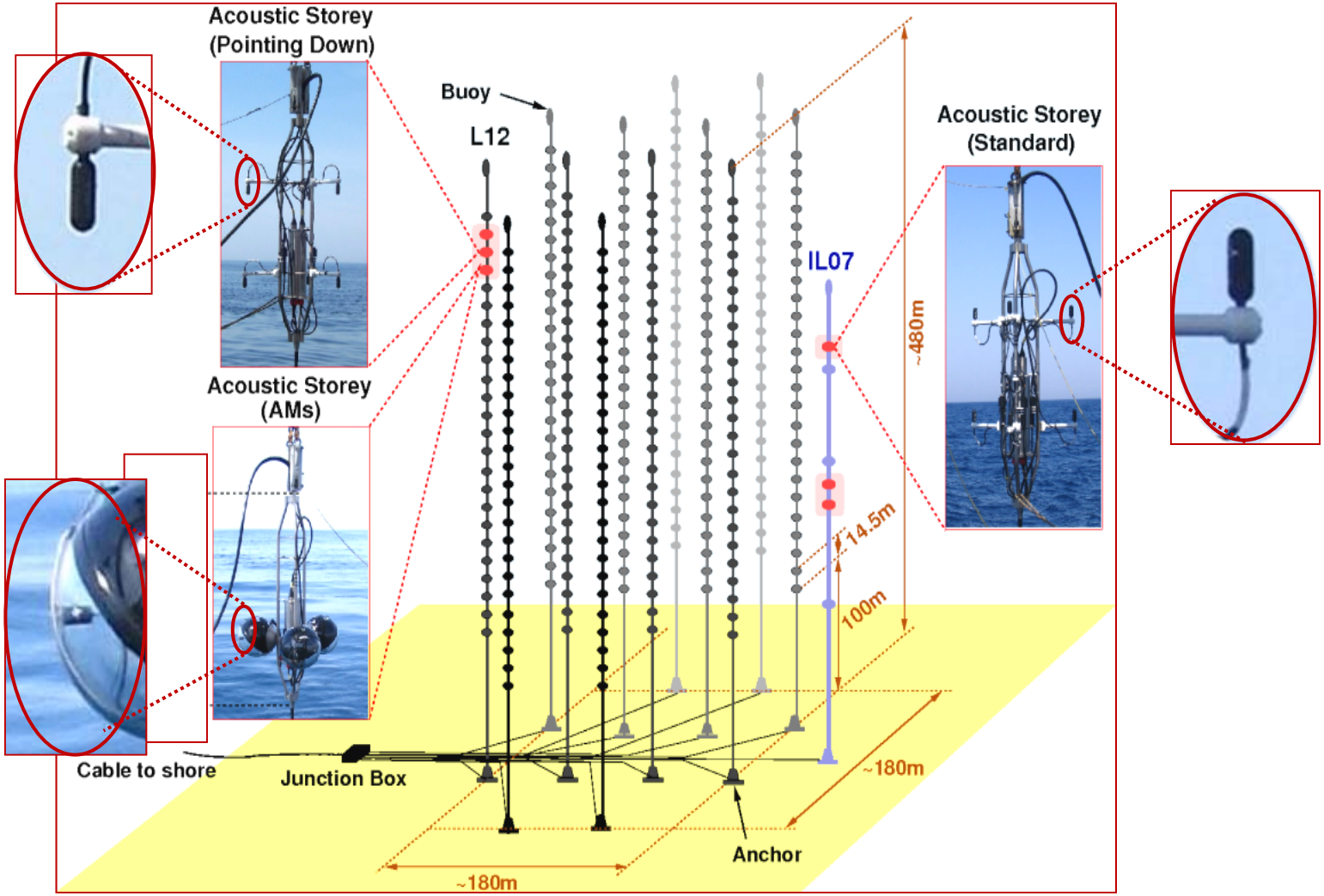


2007-12-10 floor5



Acoustic detection R&D



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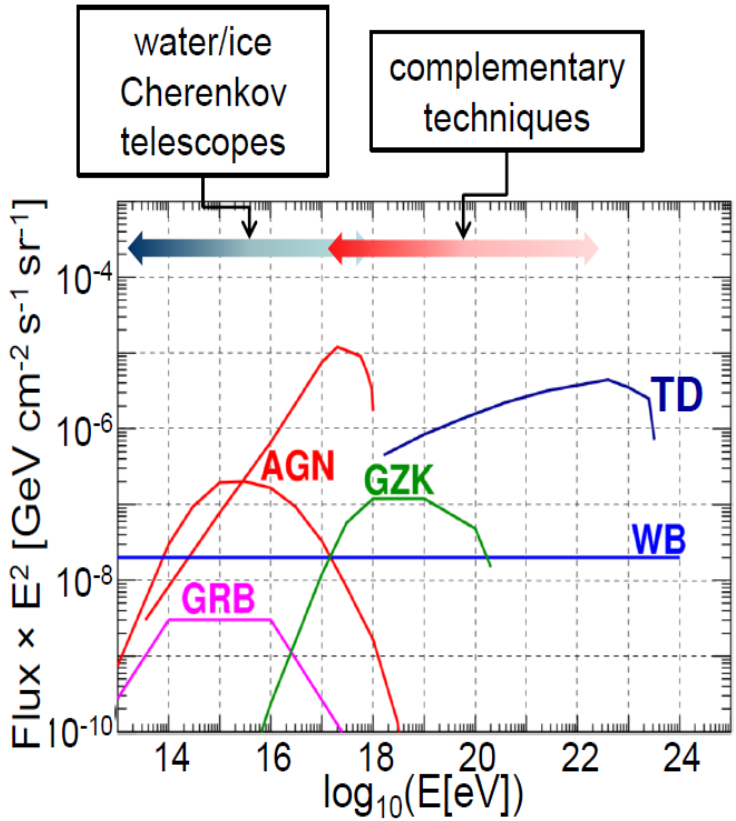
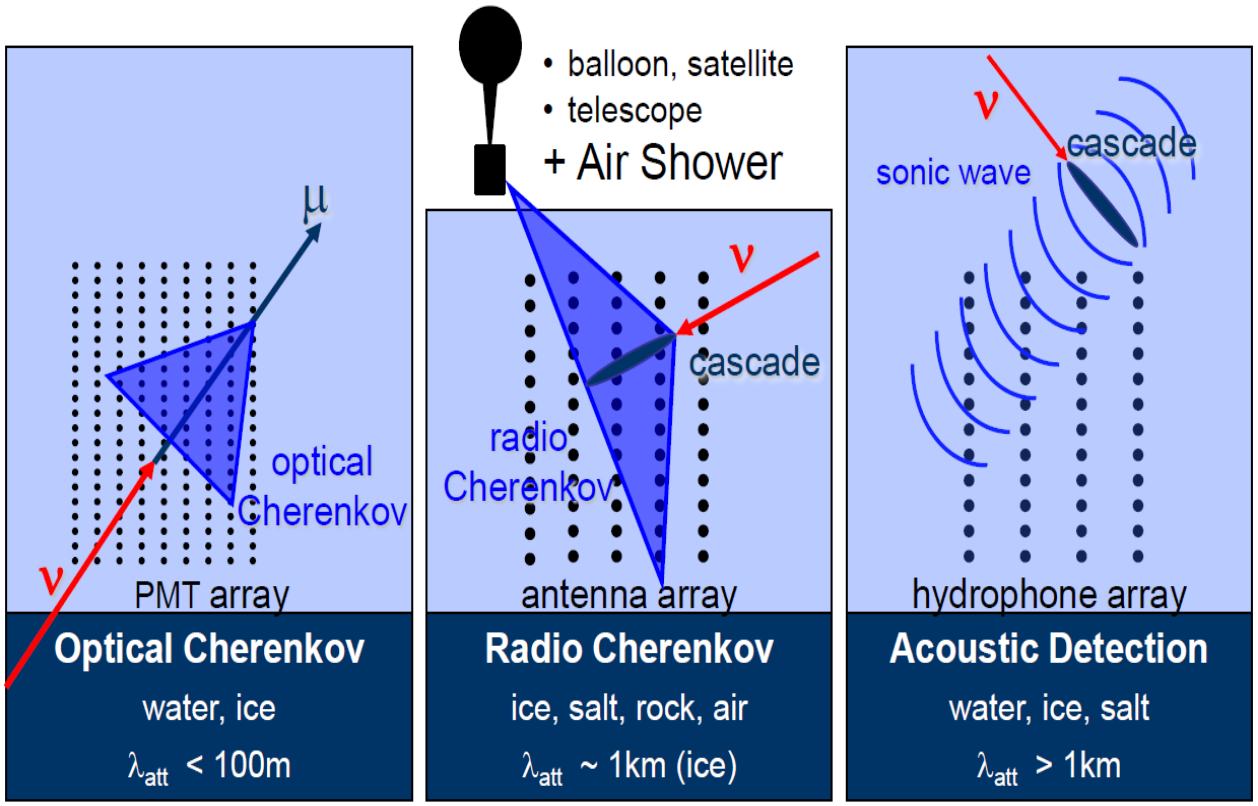
Highest Energy Neutrinos

- astrophysics:
  - origin of UHECR
  - GZK neutrinos
- cosmology:
  - top-down scenarios
  - topological defects
- particle physics:
  - neutrino cross section



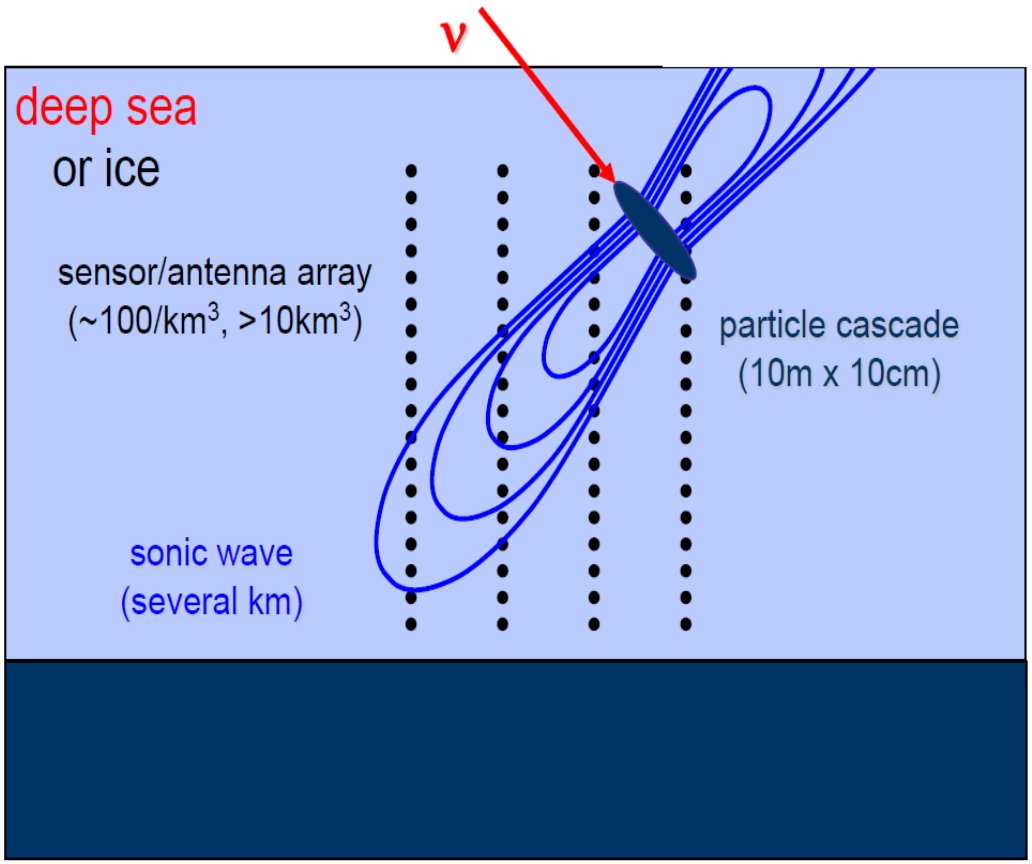
T. Karg, arXiv:astro-ph/0608312

(U)HE ν Detection Methods

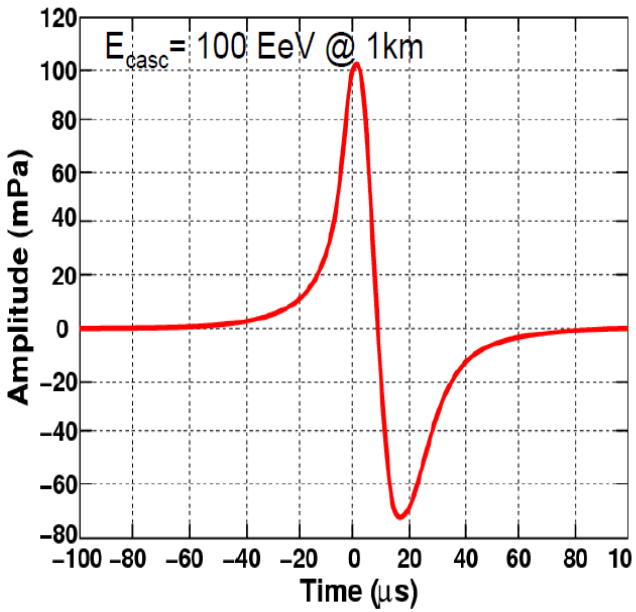


⇒ hybrid detectors possible

Acoustic Detection - Principle

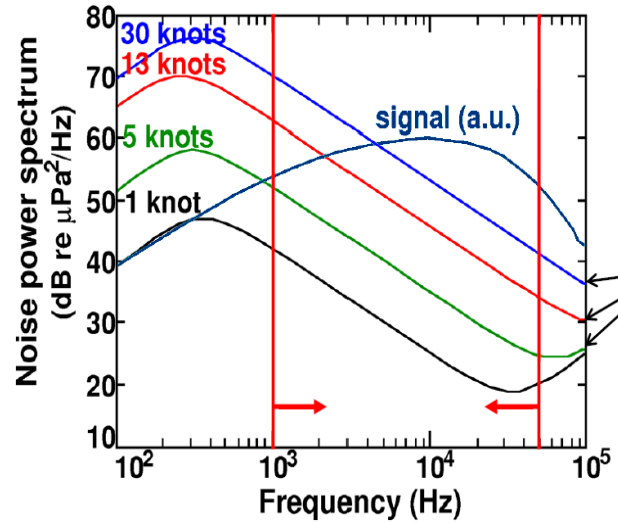


Acoustic Signal Properties



Acorne Coll. astro-ph/0704.1025

Persistant Ambient Noise



N.G. Lehtinen et al., astro-ph/0104033

noise level dominated by wind speed

~10mPa (RMS) ≅ P_ν(1EeV @ 200m)

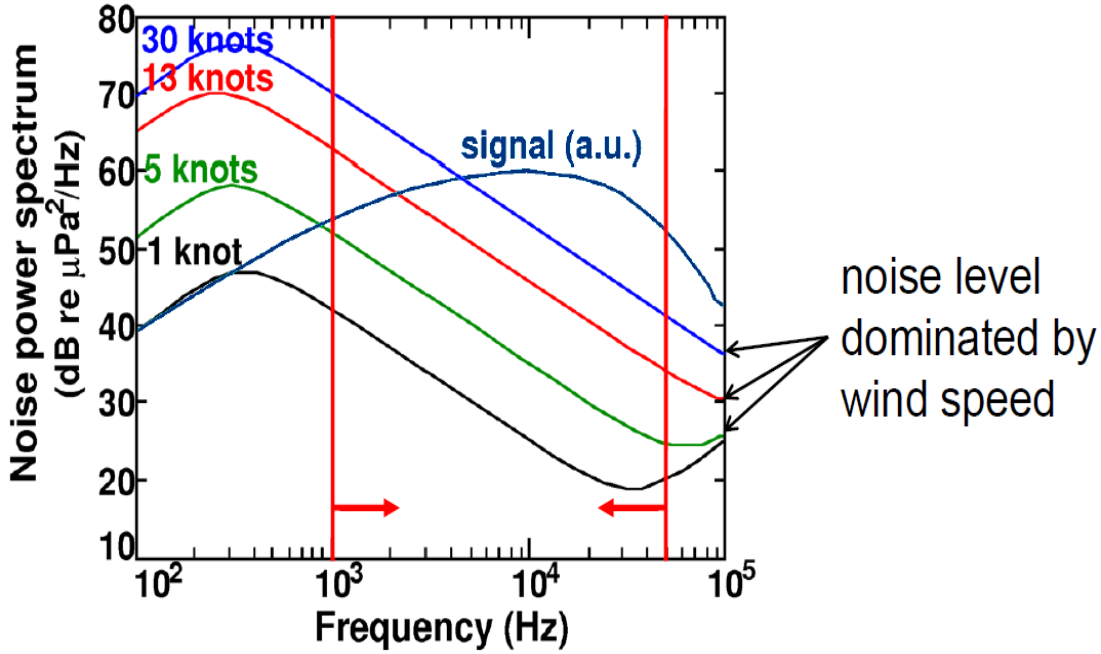
+ transient sources (fauna, anthropogenic)

bipolar signal (~10kHz) with disk-like geometry

$$P(r = 200\,\mathrm{m}) \approx 10\,\mathrm{mPa} \times \frac{E_{casc}}{1\,\mathrm{EeV}}$$

Acoustic signal and "noise"

Persistant Ambient Noise



N.G. Lehtinen et al., astro-ph/0104033

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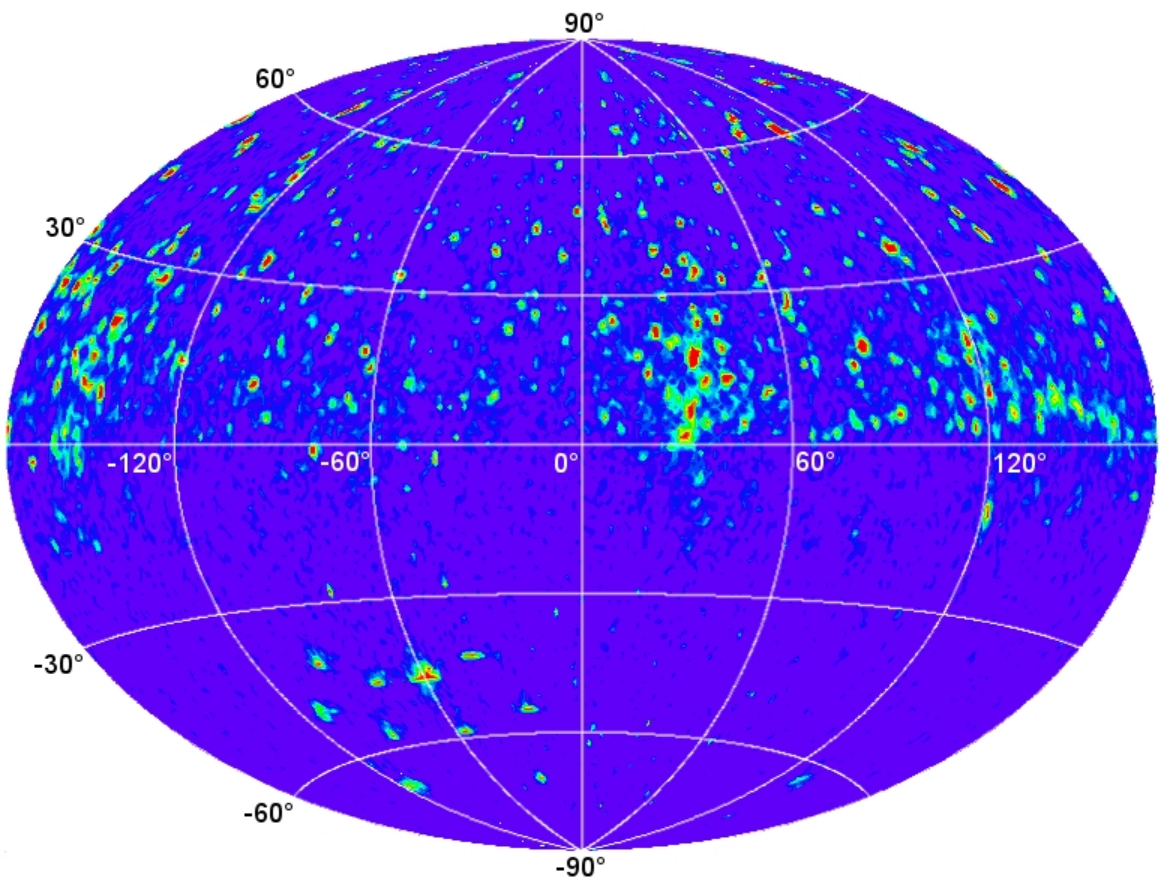
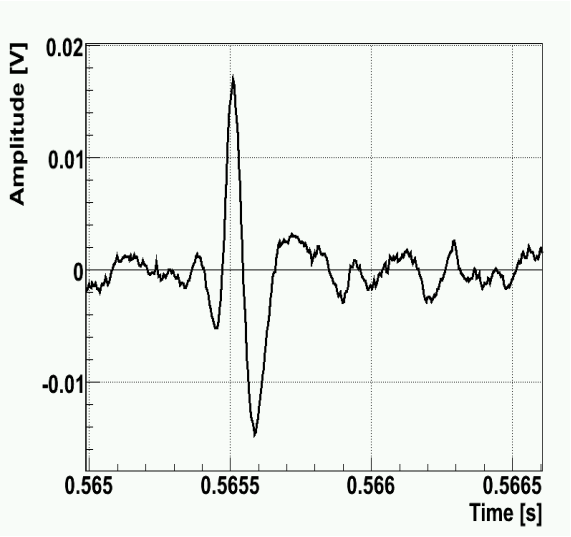
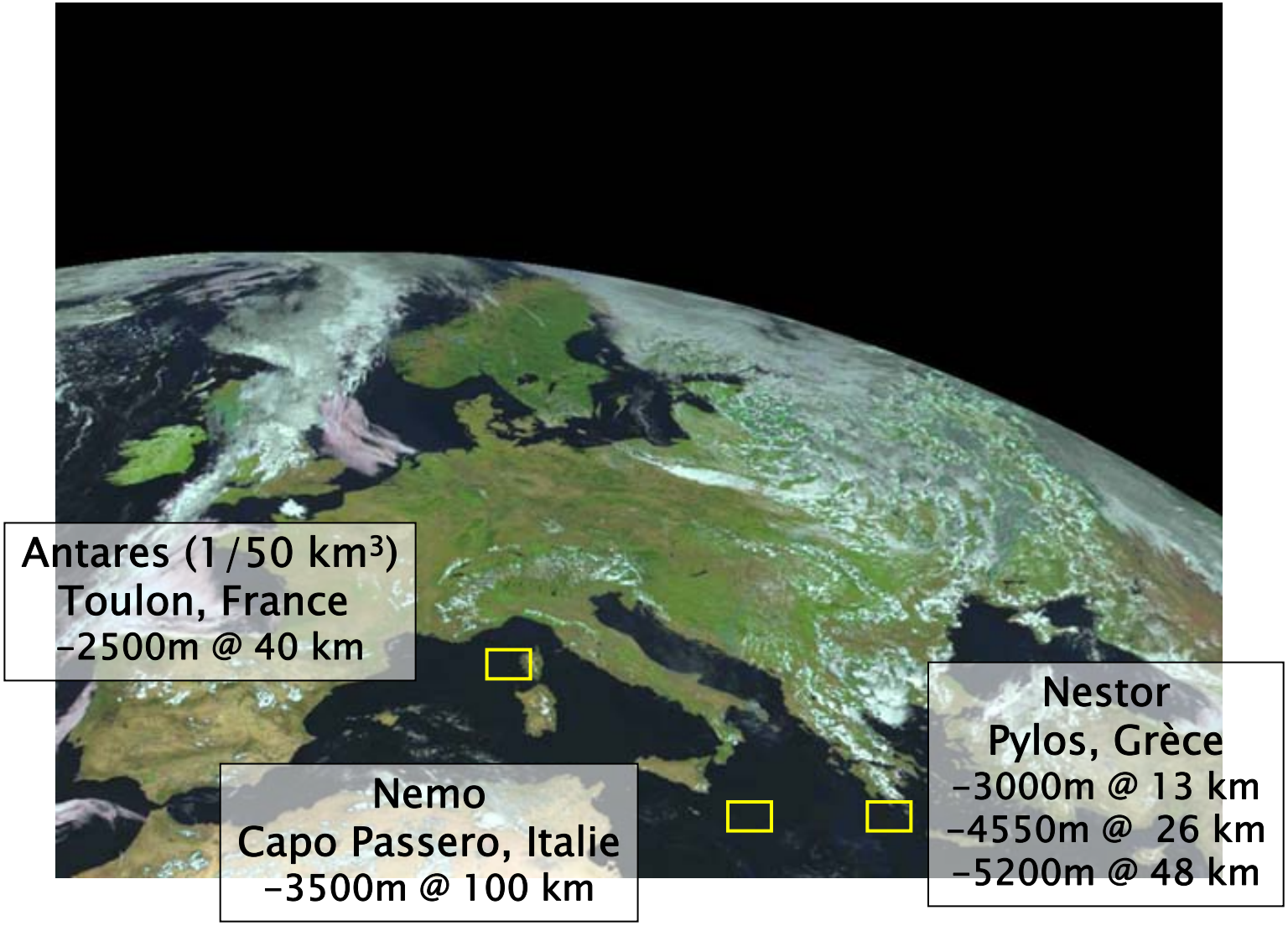
Acoustic detection R&D

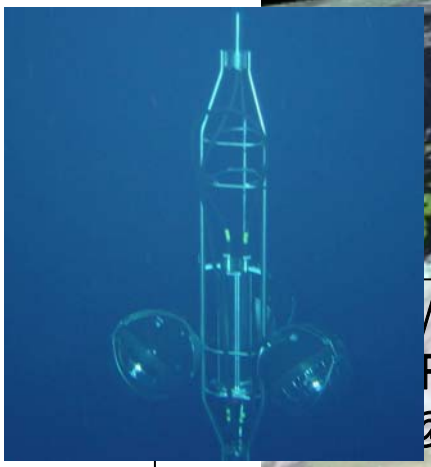


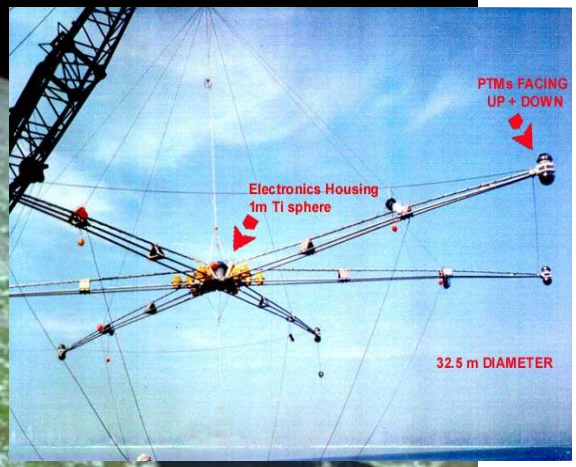


Detection of cetaceans

Towards a km^{3}detector in the Méditerranean







Since 1996
Neutrinos

Since 2000
R&D

Since 1990
R&D

Nemo
Capo Passero, Italy
-3500m @ 100 km

Nestor
Pylos, Grèce
-3000m @ 13 km
-4550m @ 26 km
-5200m @ 48 km

KM3NeT consortium

- 10 countries, ~ 40 laboratories, ~ 200 scientists

Cyprus: Univ. Cyprus, Nikosia

France
- CEA Saclay
- CNRS/IN2P3
  - APC, CPPM, IPHC
- GRPHE/Univ. Mulhouse
- Ifremer

Germany
- Univ. Erlangen
- MPIK-Heidelberg
- Univ. Kiel
- Univ. Tuebingen

Greece
- HCMR
- Hellenic Open Univ.
- NCSR Democritos
- NOA/Nestor
- Univ. Athens

Ireland :
- Institute for advanced studies, Dublin

Italy
- CNR/ISMAR
- INFN (Univ. Bari, Bologna, Catania, Genova, Pisa, Roma-1, LNS Catania, Frascati)
- INGV
- Tecnomare SpA

The Netherlands
- NIKHEF/FOM
- Univ. Amsterdam
- Univ. Utrecht
- KVI / Univ. Groningen
- NIOZ

Romania : ISS Bucharest

Spain
- IFIC/CSIC Valencia
- Univ. Valencia
- UP Valencia

UK
- Univ. Aberdeen
- Univ. Leeds
- Univ. Liverpool
- Univ. Sheffield

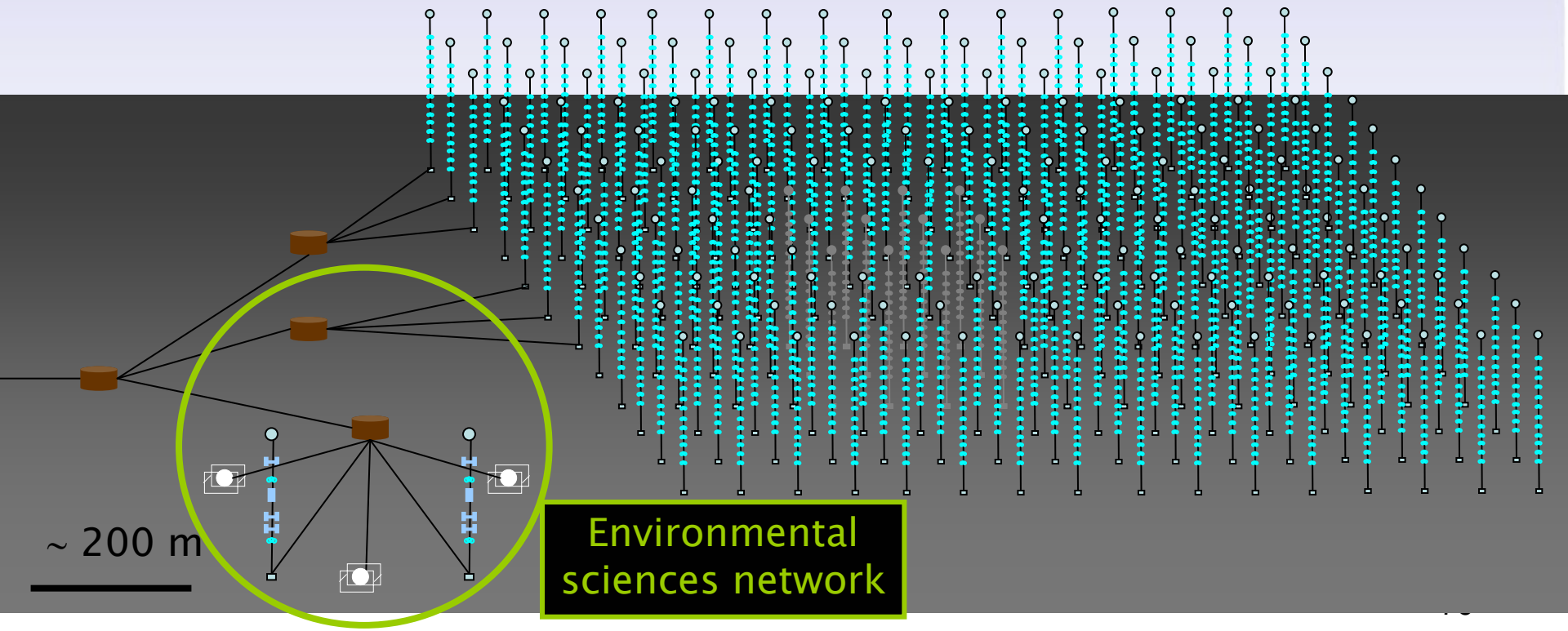
Pas dans Antares

KM3NeT (artist's view)

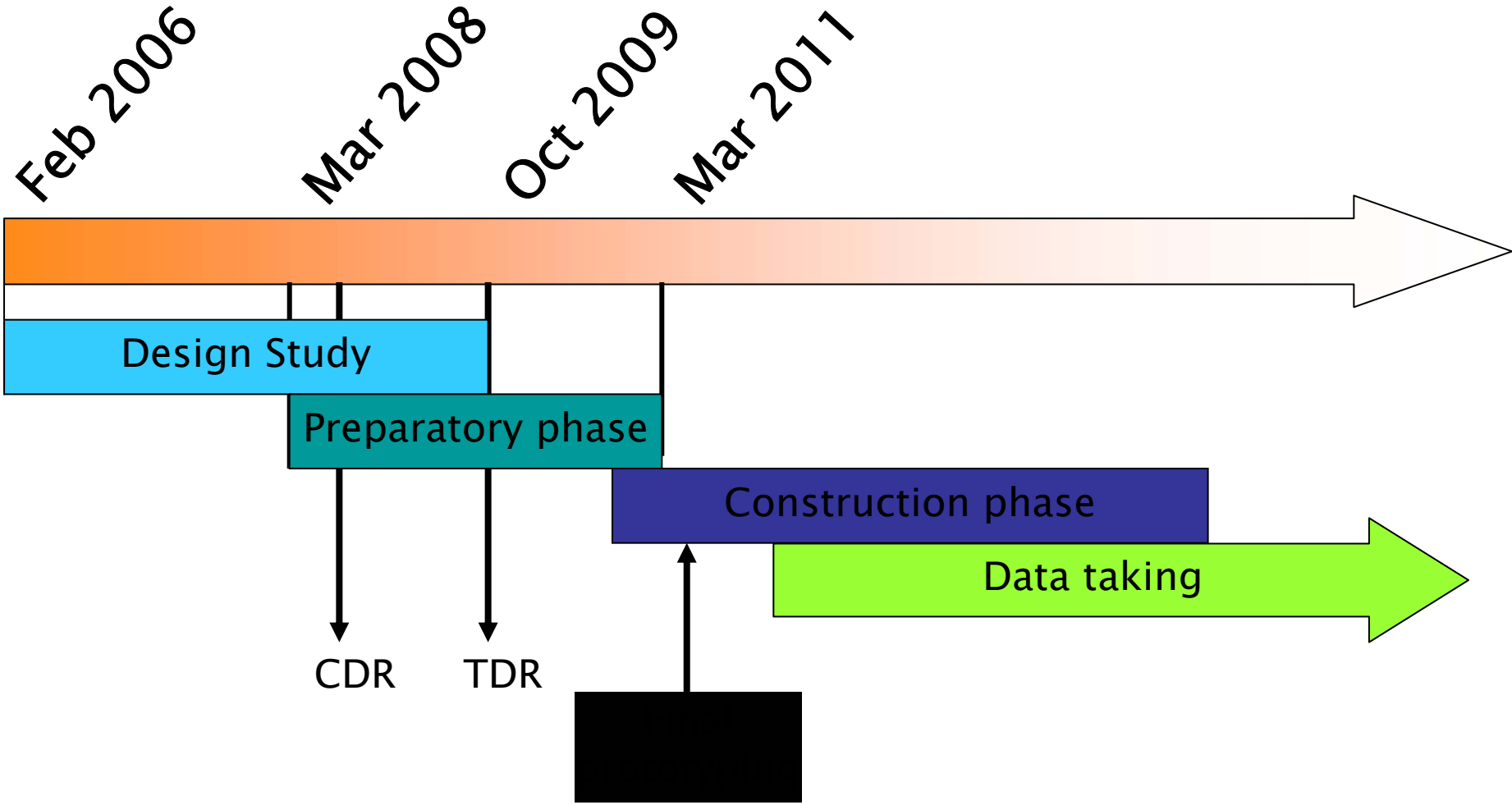
~ 100-200 "lines"
- Height : ~ 500 m
- Distance ~ 150 m
- ~ 20 stories at 25 m

~ 5000-10000 PM

Instrumented volume
~ 1 km^3
(or more)



Timeline towards construction



Note: “Construction” includes the final prototyping stage

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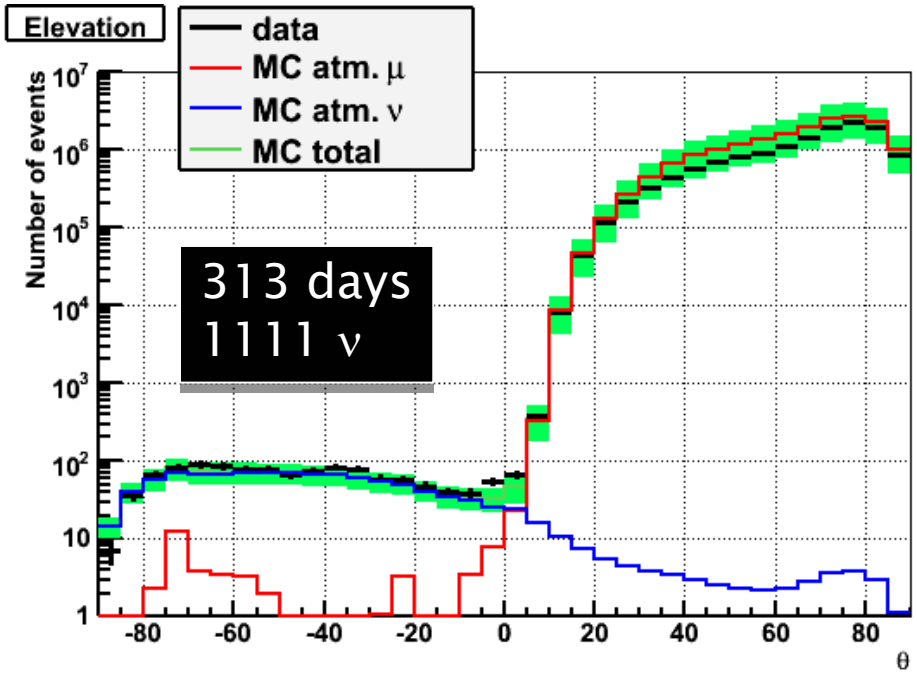
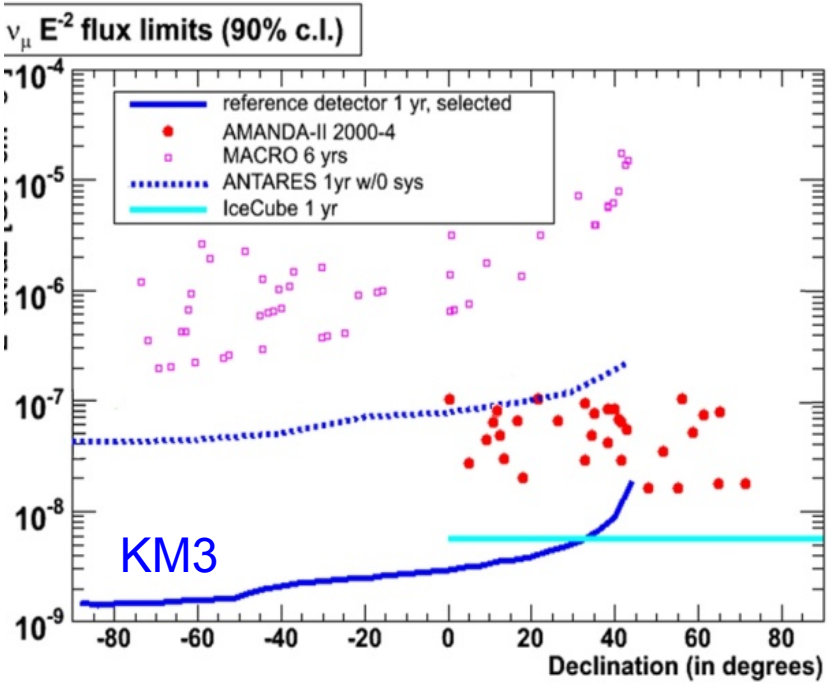
Summary

- ANTARES today
  - Successful end of construction phase
    - Technology proven
    - Data taking ongoing
  - First physics outputs
    - Atmospheric μ and ν, cosmic neutrino sources, dark matter
    - Neutrino oscillations, magnetic monopoles, VHE neutrino interactions, …
- On the road for the next step
  - KM3Net…

Present and future

Data 2007+2008





A view from ANTARES control room