High neutrino detection in the Mediterranea Sea

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Outline

1. High energy astroparticle physics
2. HE neutrino detection in the context of multi-messenger approach
3. Survey of a region of the supergalactic plane with ANTARES 2007 data
4. Detection of transient sources of HE neutrinos
5. Towards a km^3 scale detector in the Mediterranean sea: site evaluation in brief.

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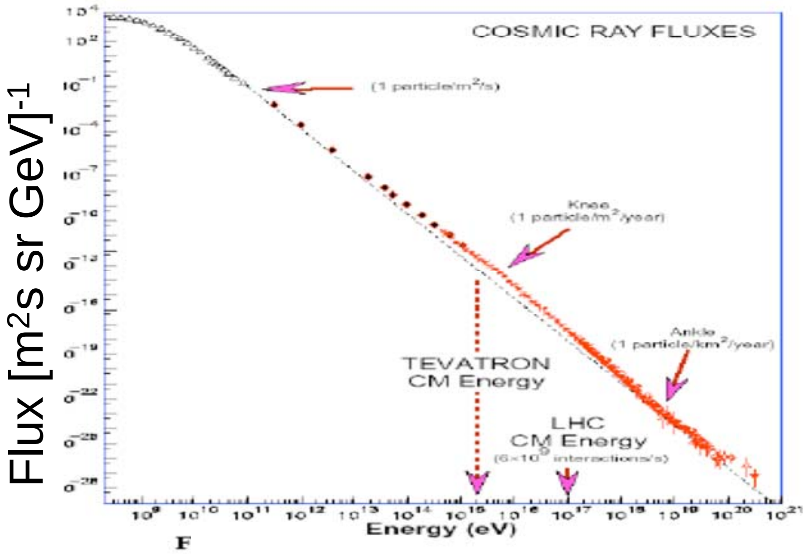
High Energy Cosmic Rays

<u>Starting point:</u>

observation of High Energy Cosmic Rays

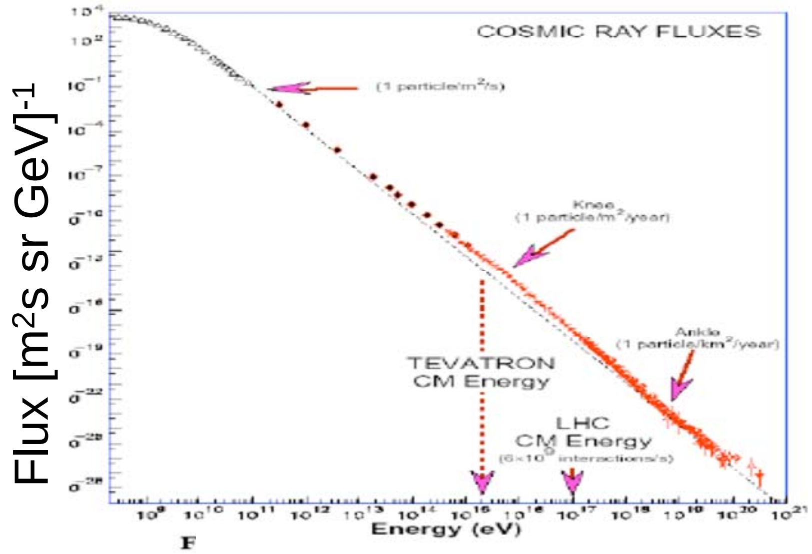


High Energy Cosmic Rays

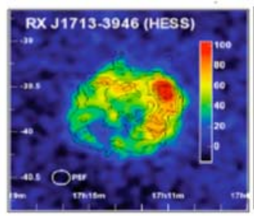
<u>Starting point:</u>

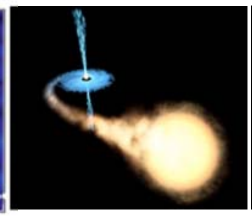
observation of High Energy Cosmic Rays

Where do they come from?



- Top-down: decay of super-heavy particles → disfavored
- Bottom up: acceleration in astrophysical sources → candidates?
  - Galactic:
    - Super Nova Remnants (SNRs)
    - Micro-quasars
  - Extra-Galactic:
    - Active Galactic Nuclei (AGN)
    - Gamma Ray Bursts (GRBs), …

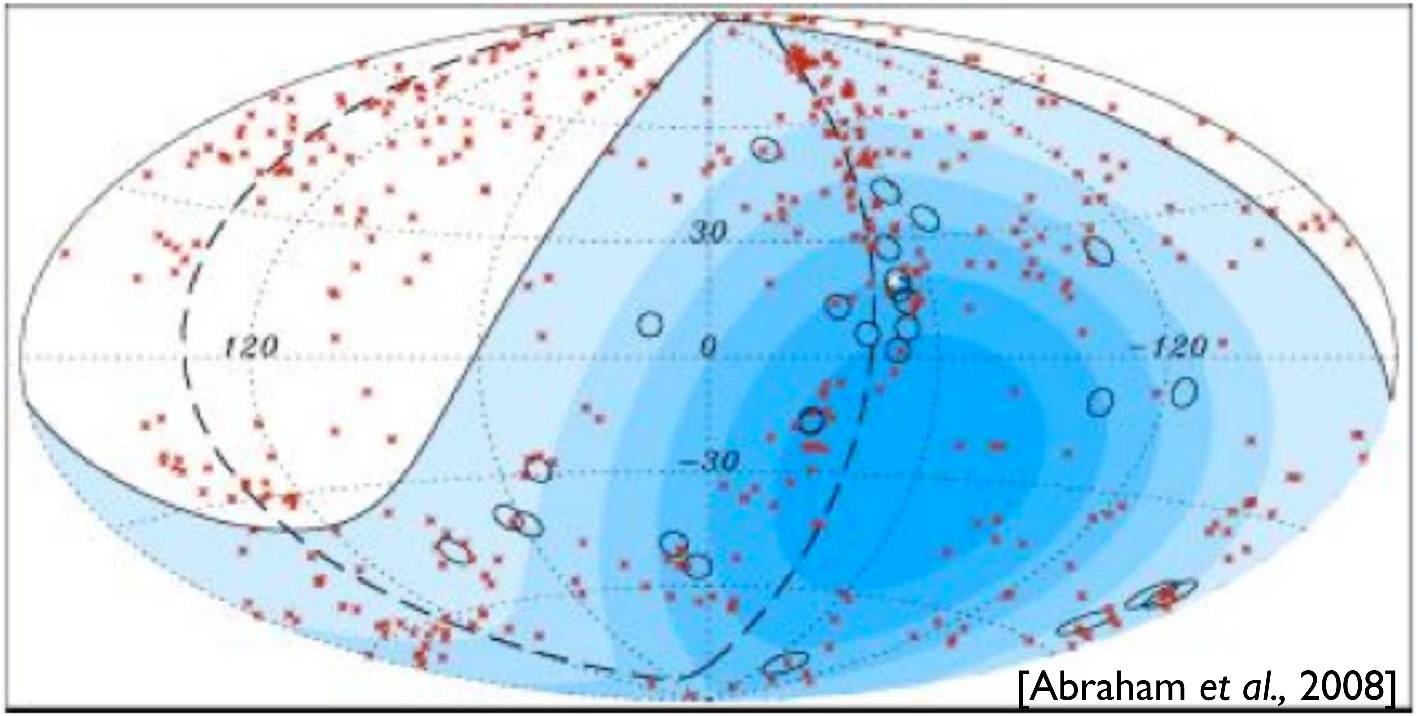




Recent UHECRs observations

Arrival direction of CRs($E>10^{20}$ eV) ⇔ position of nearby AGN: Correlation ??

Galactic coordinates

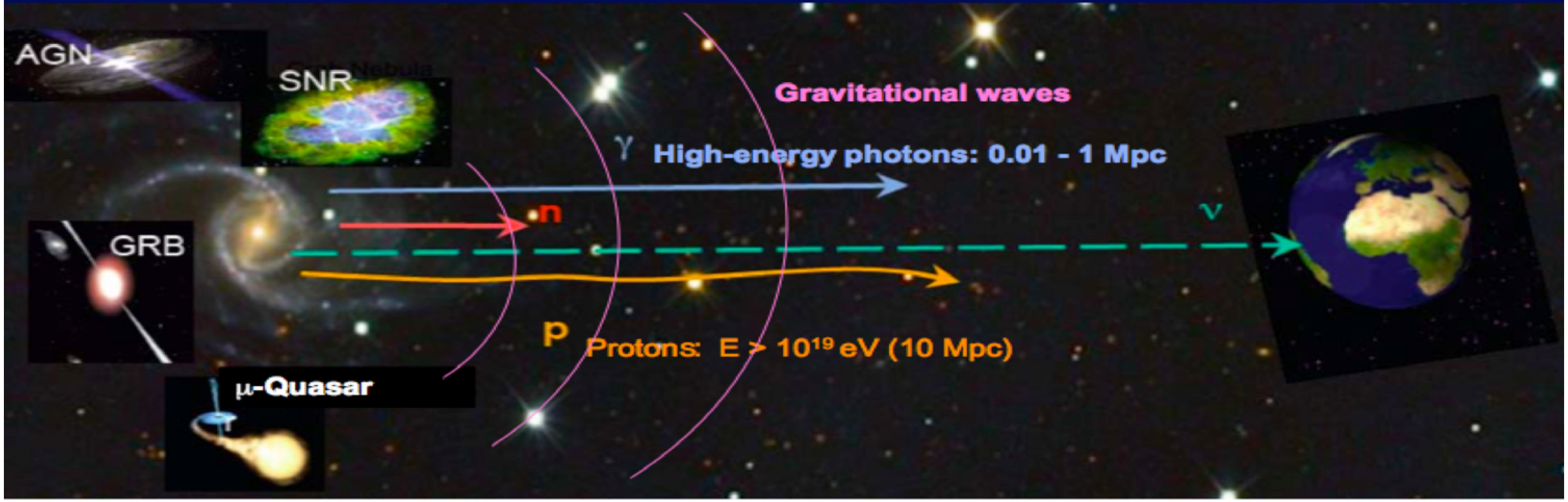


[Abraham *et al.*, 2008]

However:

- Pierre Auger Observatory results not confirmed by other experiments
- UHECRs propagation affected by unknown magnetic fields

Multimessenger astronomy



- CRs astronomy feasible at energies higher than 10^{19} eV → extra-galactic origin (B not well known)
- UHECRs horizon limited to 10 -100 Mpc due to interaction with CMBR (GZK effect)

Multi-messenger astronomy is likely to open new insights on the physics of the most violent events, combining results from CRs, γ-rays and *traditional astronomy*, neutrinos and gravitational waves.

Gamma Ray Astronomy

Advantages:

- γ-rays are expected together with UHECRs, e.g.

$$p + \gamma \rightarrow p + \pi^0 \rightarrow UHECRs + \gamma - rays$$

- Neutral particles ➔propagation not affected by B ➔point-back to the source
- γ -rays detection is successful !

- high energy photons strongly absorbed
  - In the source: *optically thick sources*
  - During propagation: *over extra-galactic distances the Universe is opaque to photons for E larger than hundreds of TeV*
- difficult to disentangle the origin
  - Hadronic: $p + \gamma \rightarrow p + \pi^0 \rightarrow UHECRs + \gamma - rays$
  - Leptonic: *synchrotron radiation of e⁻, inverse Compton scattering*

Neutrino Astronomy

Advantages:

- HE νs are expected together with UHECRs, e.g.

$$p + \gamma \rightarrow \pi^{+} + n \rightarrow UHECRs + \nu' s$$

- Neutral particles ➔propagation not affected by B ➔point-back to the source
- Only weakly interacting particles:
  - observation over cosmological distances ➔identify production sites
  - inner layers of astrophysical objects ➔understand production mechanisms
- Always of hadronic origin
- Flavor mixing

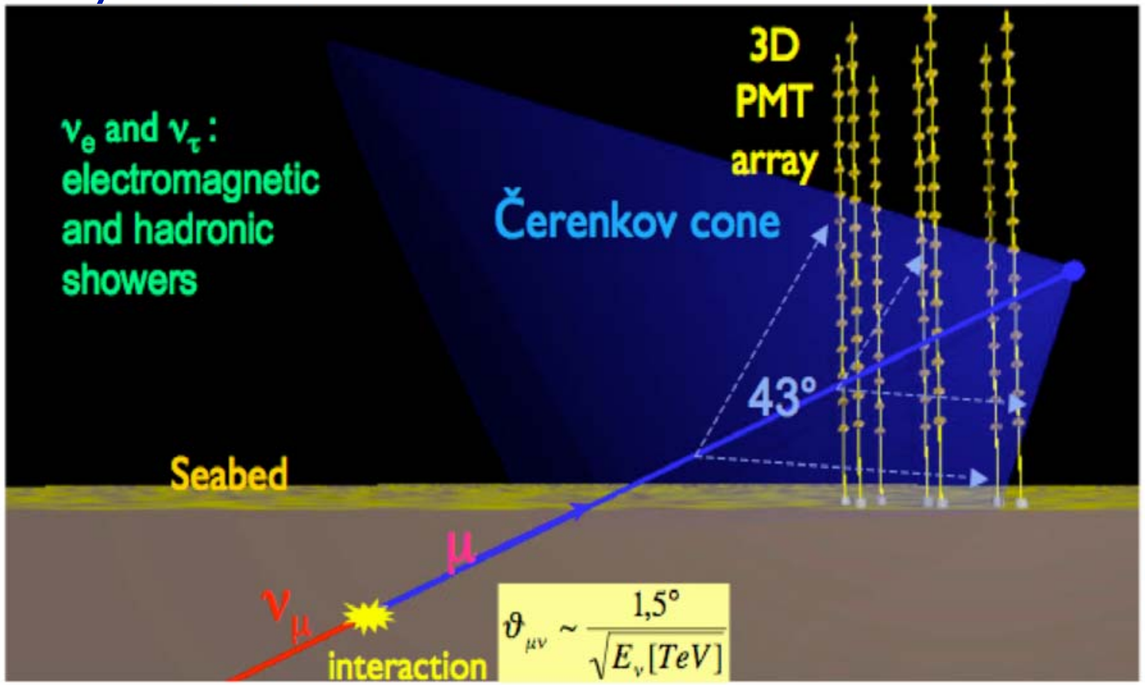
  even if at the source (ν_e: ν_μ: ν_τ) = (1:2:0) ➔at Earth (ν_e: ν_μ: ν_τ) = (1:1:1)

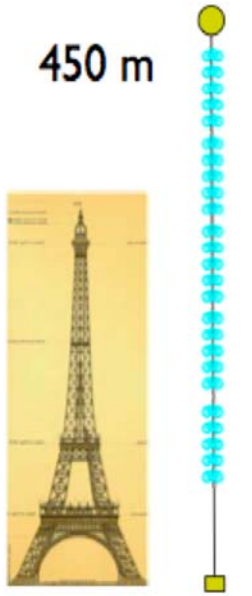
Only weakly interacting particles + Low fluxes expected from the sources

➔ Large detection volume (~km^3) is required

Neutrino Astronomy … how ?

Neutrinos can be detected using the visible Cherenkov radiation produced as the high-energy charged lepton (final state of CC interactions) propagates through a transparent medium with superluminal velocity.

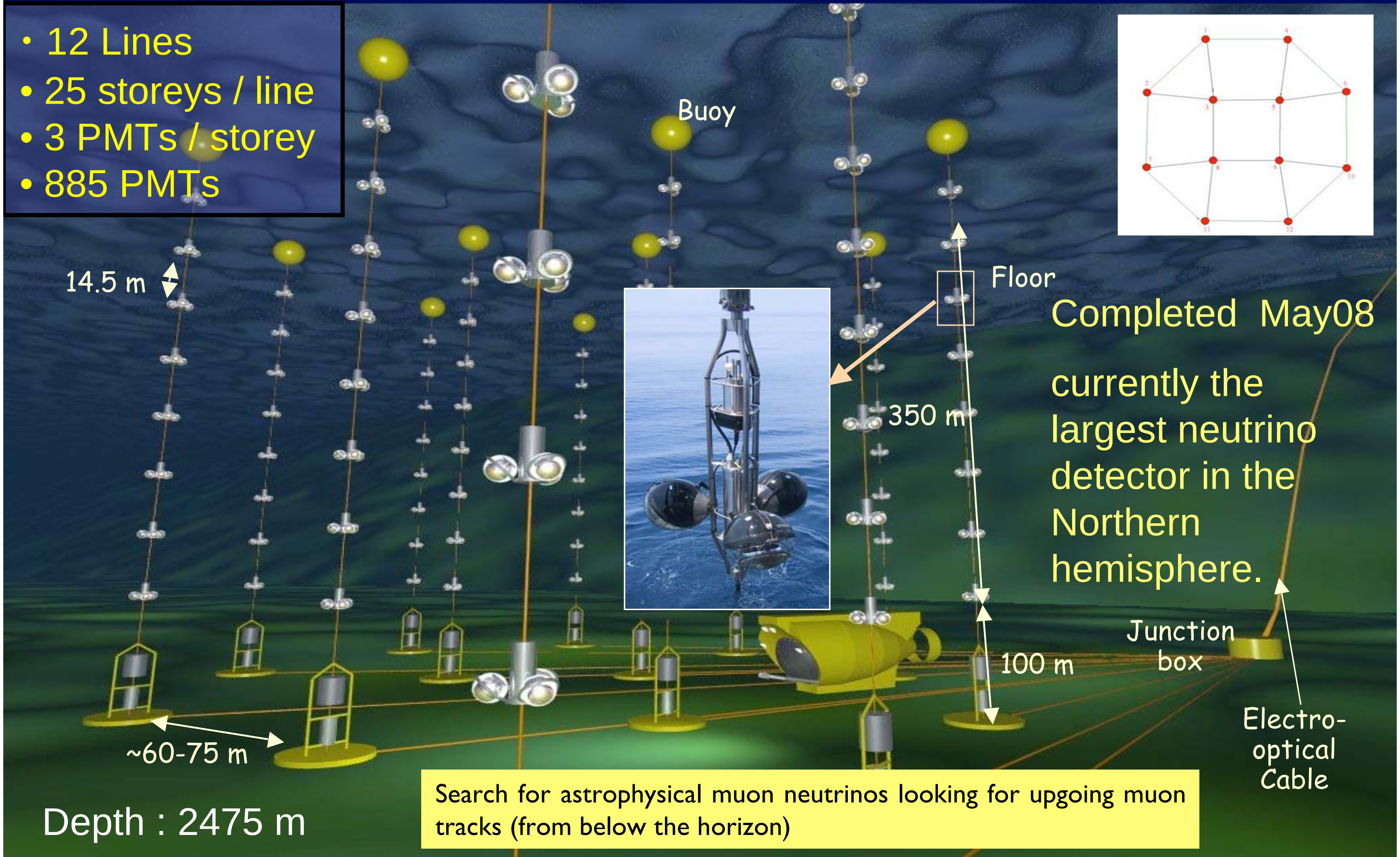




Due to low fluxes expected, cubic-kilometer scale detector are required to perform HE neutrino astronomy (E ~100GeV -10 PeV)➔prototype structures currently taking data.

The ANTARES detector

- 12 Lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs



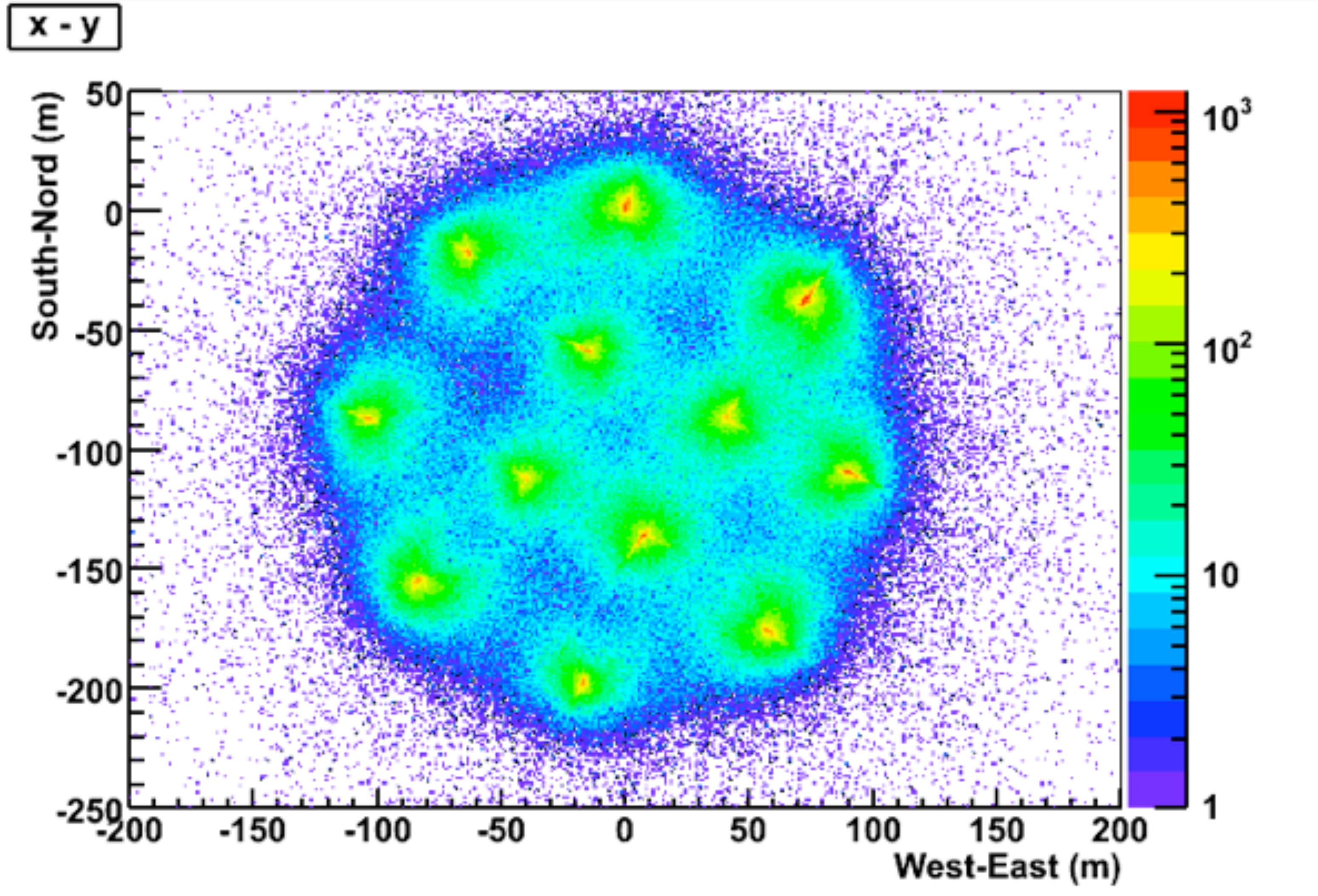
Completed May08

currently the largest neutrino detector in the Northern hemisphere.

Depth : 2475 m

Search for astrophysical muon neutrinos looking for upgoing muon tracks (from below the horizon)

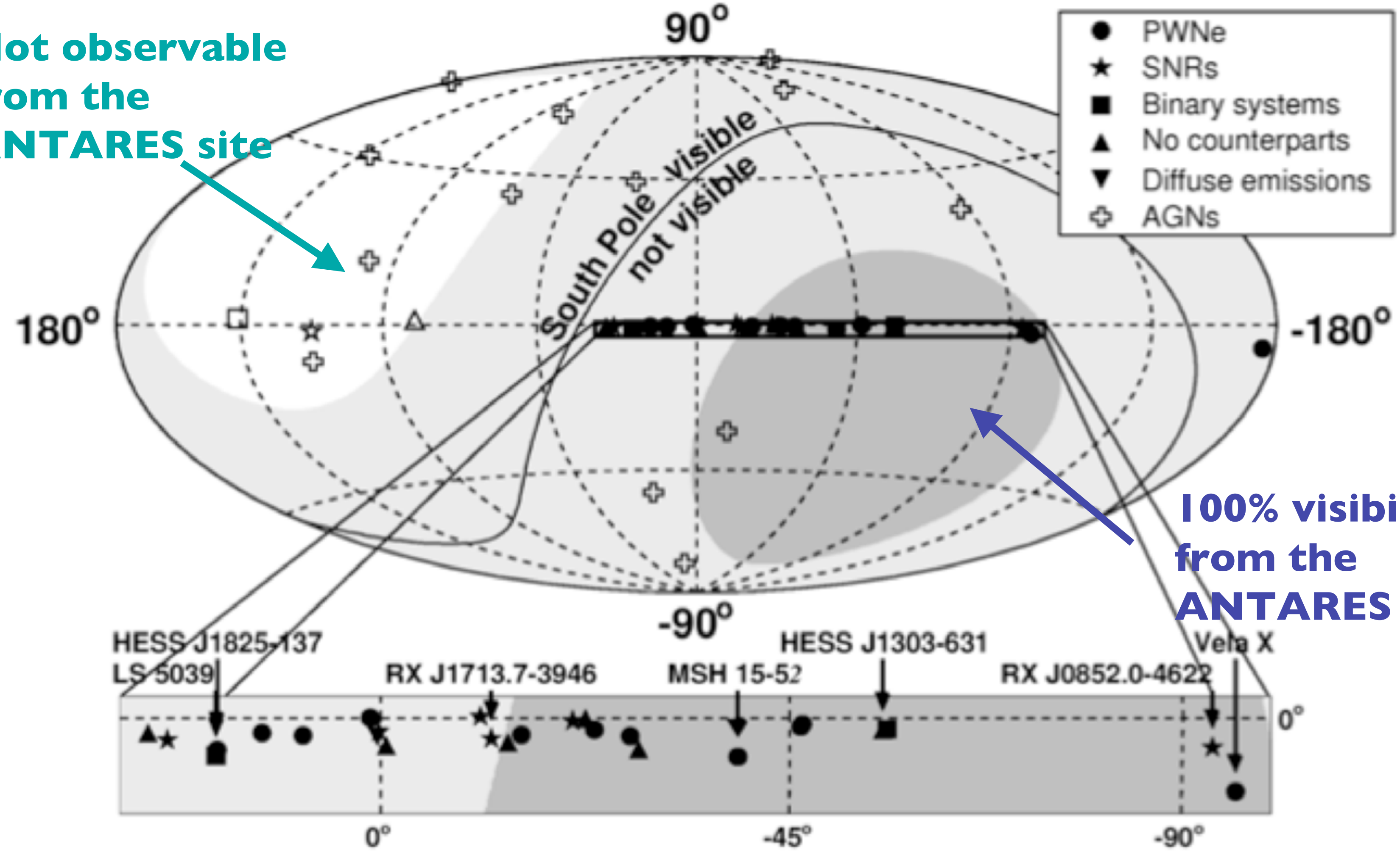
The ANTARES footprint



Reconstructed muon tracks at the time of the first triggering hit

Observable sky for ANTARES

Not observable from the ANTARES site

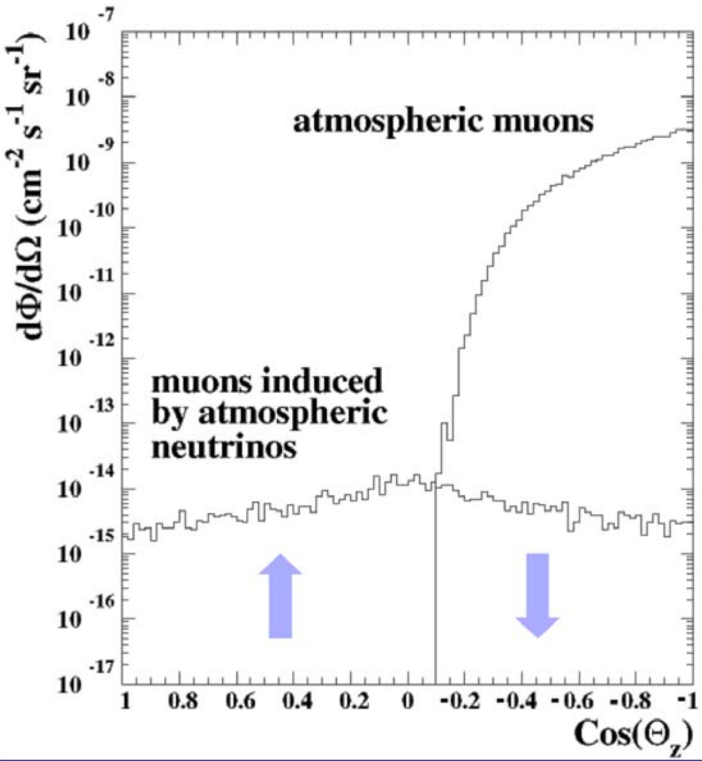


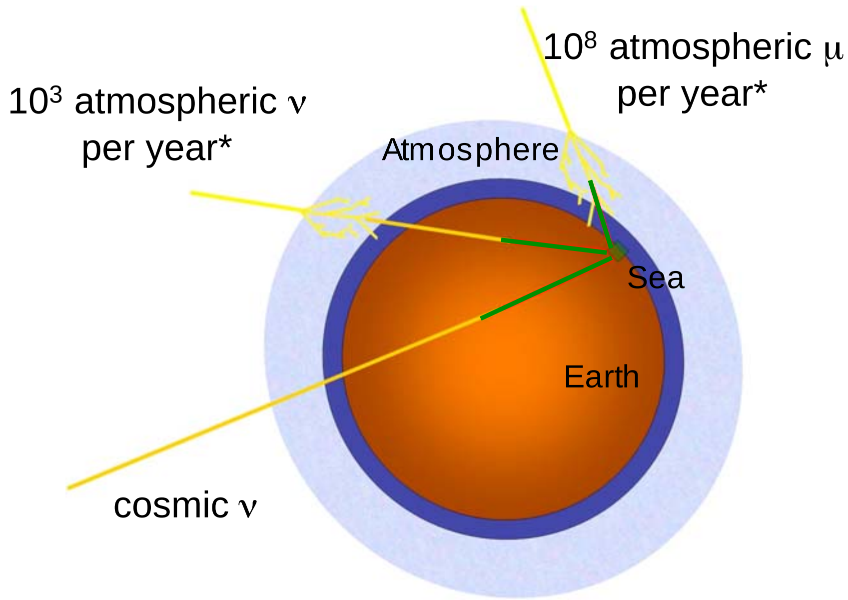
100% visibility from the ANTARES site

The region where the bulk of the Auger events lie is within the ANTARES field of view.

Muon flux at the detector

The data sample is dominated by the flux of atmospheric muons propagating downward through the detector. Atmospheric neutrinos, nearly isotropically distributed, contribute providing a flux that is 4-5 orders of magnitude less abundant than that of atmospheric muons. HE neutrinos from astrophysical sources will appear as a statistical excess from a defined position of the sky.





* Reconstructed tracks in 12 line detector

Survey of a region of SGP

Aim of the present work is the study of the distribution of the reconstructed neutrino events over several equally extended areas in the sky, searching for uniformity or excesses.

Why?

In view of the recent results by the Pierre Auger Observatory we have decided to study the distribution of neutrinos arrival directions in the sky region where the bulk of the UHECRs Auger events lie.

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Why?

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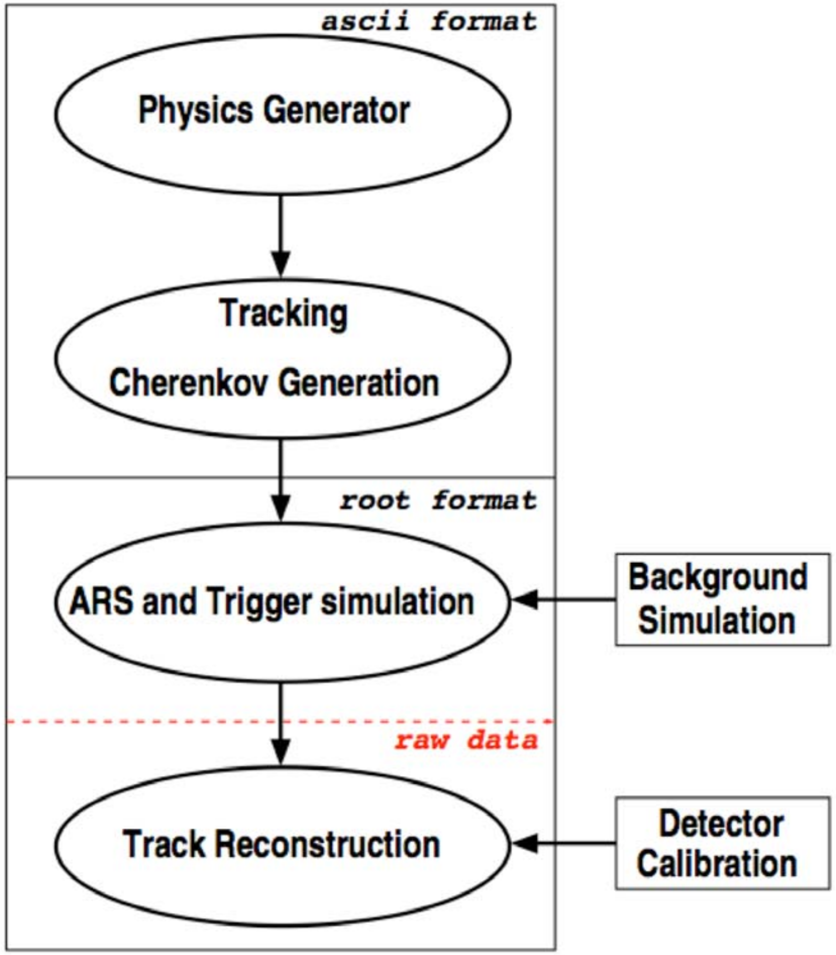
How ?

- Perform a dedicated simulation of signal and background events.
- Optimize the analysis strategy and selection criteria on simulated (signal + bkg) events.
- Apply optimised cuts to data.
- Study the distribution of neutrino events falling within the selected region (*ON region* in the following) searching for uniformity/excesses.
- Study the distribution of neutrino events in 11 regions (*OFF regions*) of equal exposure/declination, to characterize the background. The bkg is assumed to be the same in the OFF and in the ON regions.
- Compare the number of events found in the ON region with bkg expectations.
- In case no significant excess is found, an upper limit to the neutrino flux from the ON region will be set.
- Serendipitous search is performed in order to investigate the presence of a significant excess of signal in each of the 11 regions used to estimate the bkg.

Monte Carlo simulations



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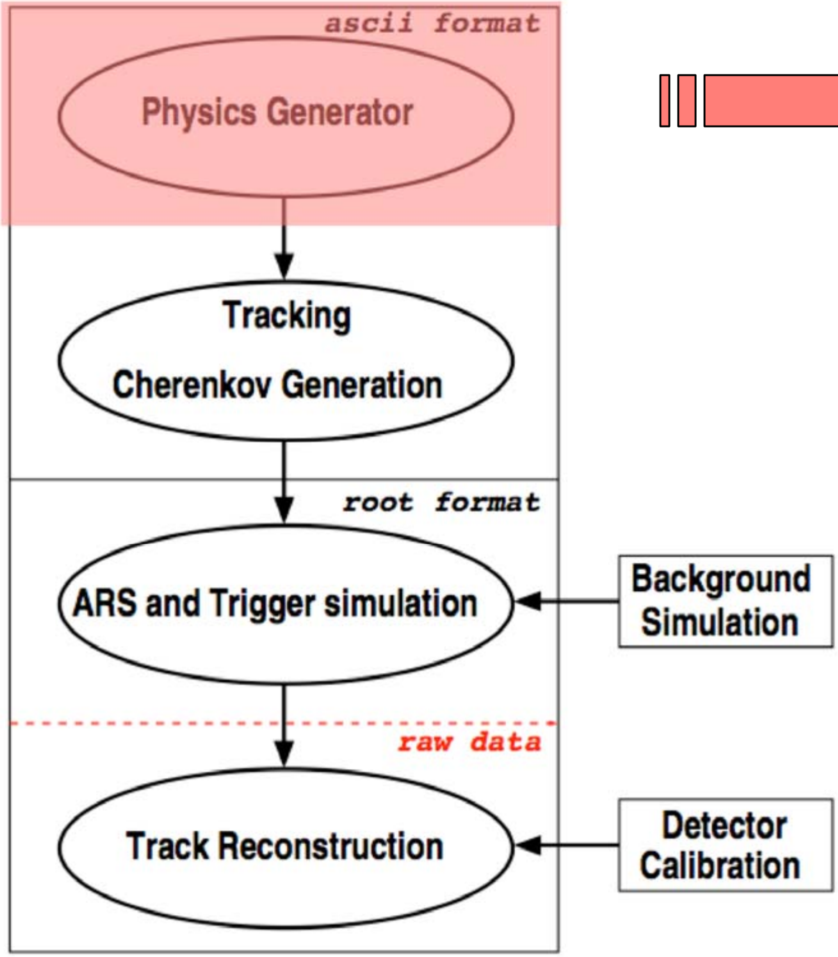
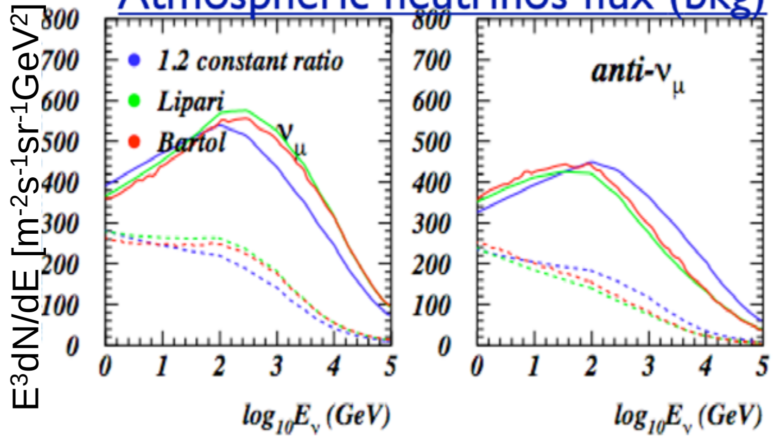
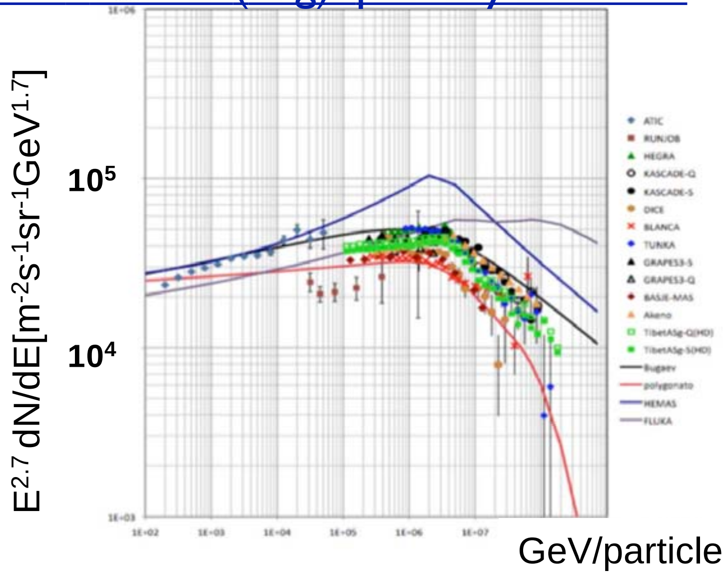


Atmospheric neutrinos flux (bkg)

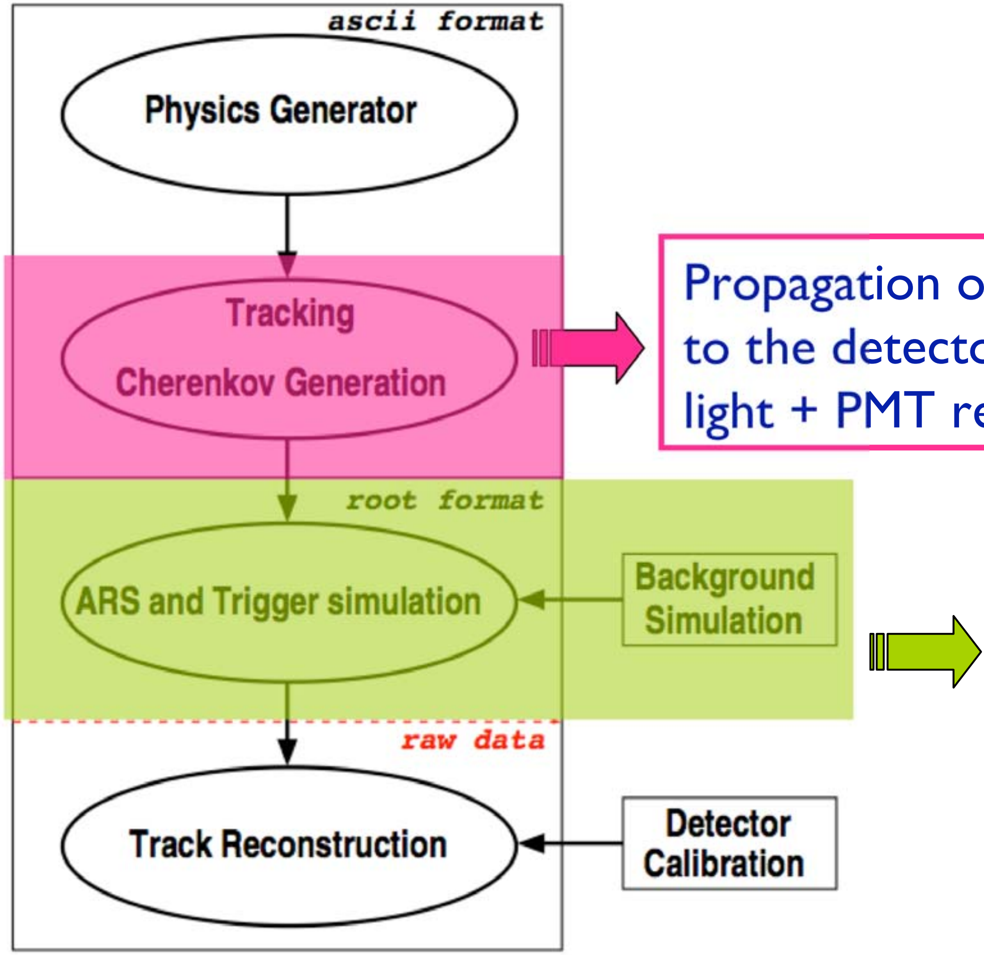


ν signal → power law spectrum E^{-2}

Atm. muons (bkg): primary CRs flux



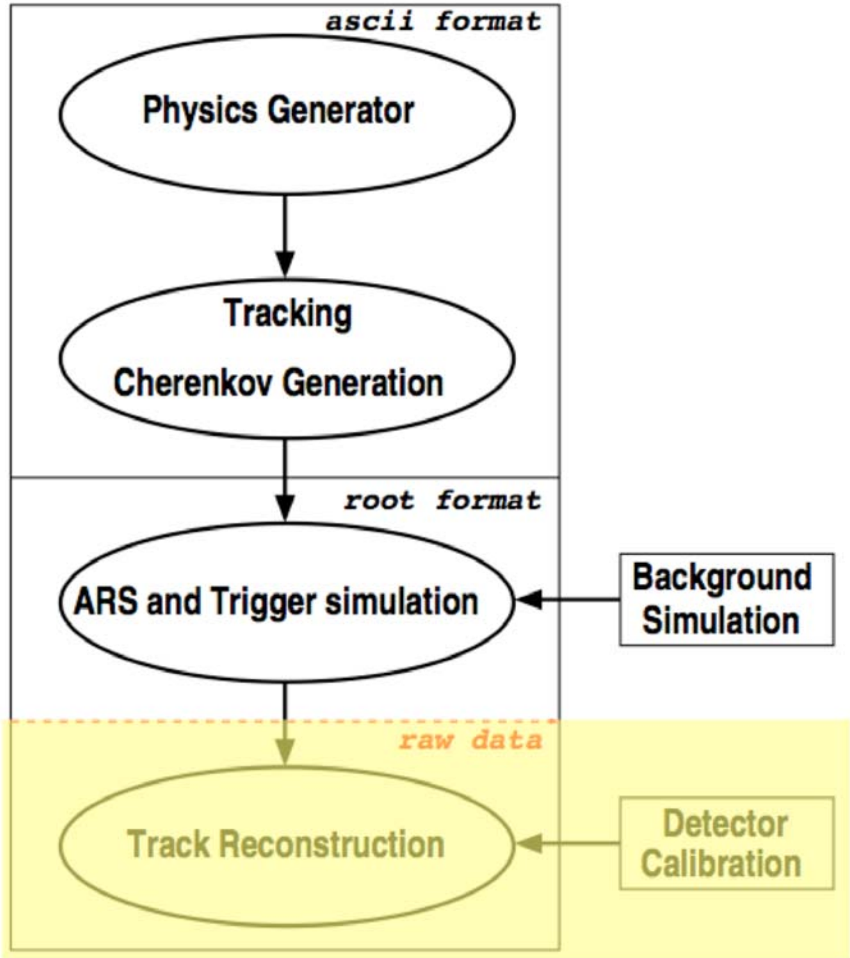
Monte Carlo simulations



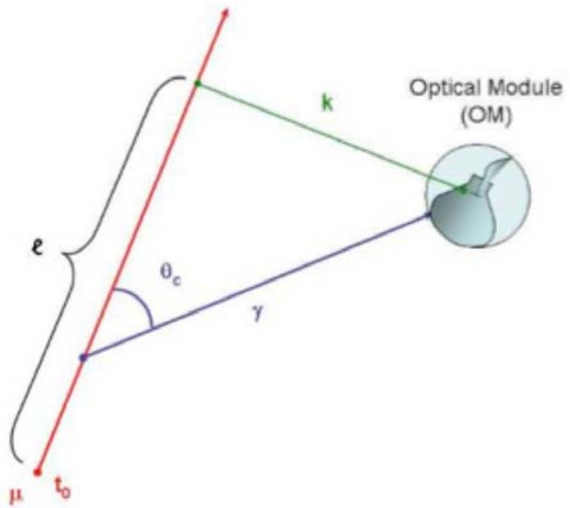
Propagation of muons in water up to the detector level+ Cherenkov light + PMT response is simulated

Front end electronics +data acquisition system is simulated and environmental bkg (~60KHz) is "added" to MC events.
Trigger algorithms are applied.

Monte Carlo simulations



Muon reconstruction



Arrival time and amplitude are stored for each hit on PMTs, together with their positions (Δx ~10cm).

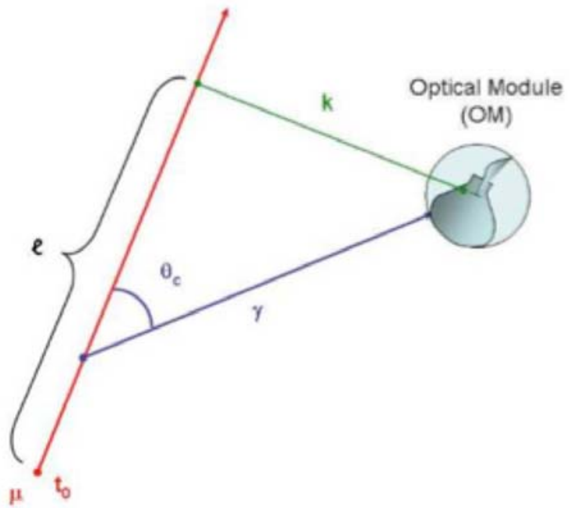
The arrival time of a photon on the OM is given by:

$$t^{th} = t_0 + \frac{1}{c}(l - \frac{k}{\tan\vartheta_C}) + \frac{1}{v_\gamma}(\frac{k}{\sin\vartheta_C})$$

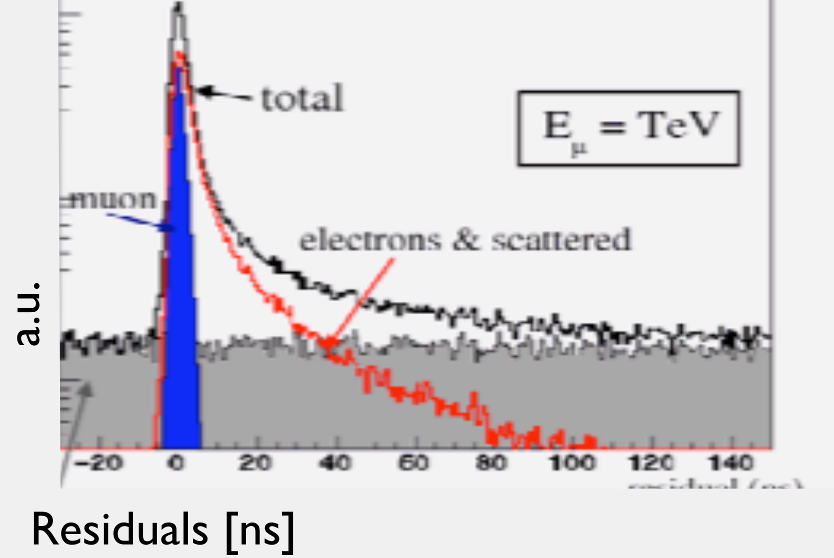
Time for the μ to reach the point of light emission (v_μ~c)

Time for the γ to propagate in water (v_γ=c/n).

Muon reconstruction



Time residuals = t^{th}-t^{i}



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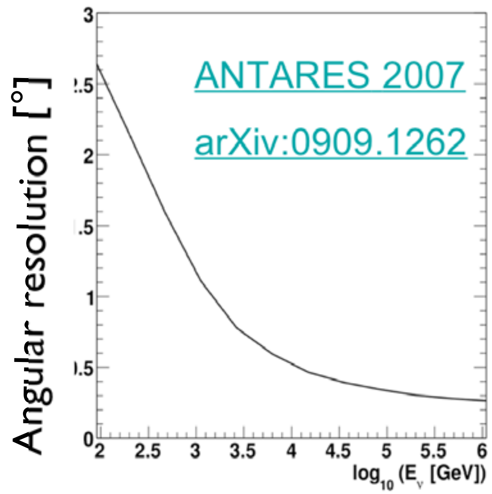
Full likelihood algorithm

- Time residuals pdf
- Alignment used



ANTARES 2007 data

The analysis that will be presented has been performed on data taken in 2007, when the detector was only composed of 5 lines.

2007 data -

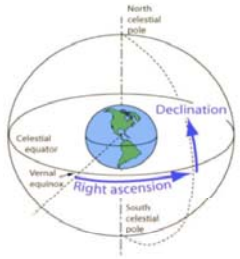
$19 \cdot 10^6$ μ triggers

Total: 245 days

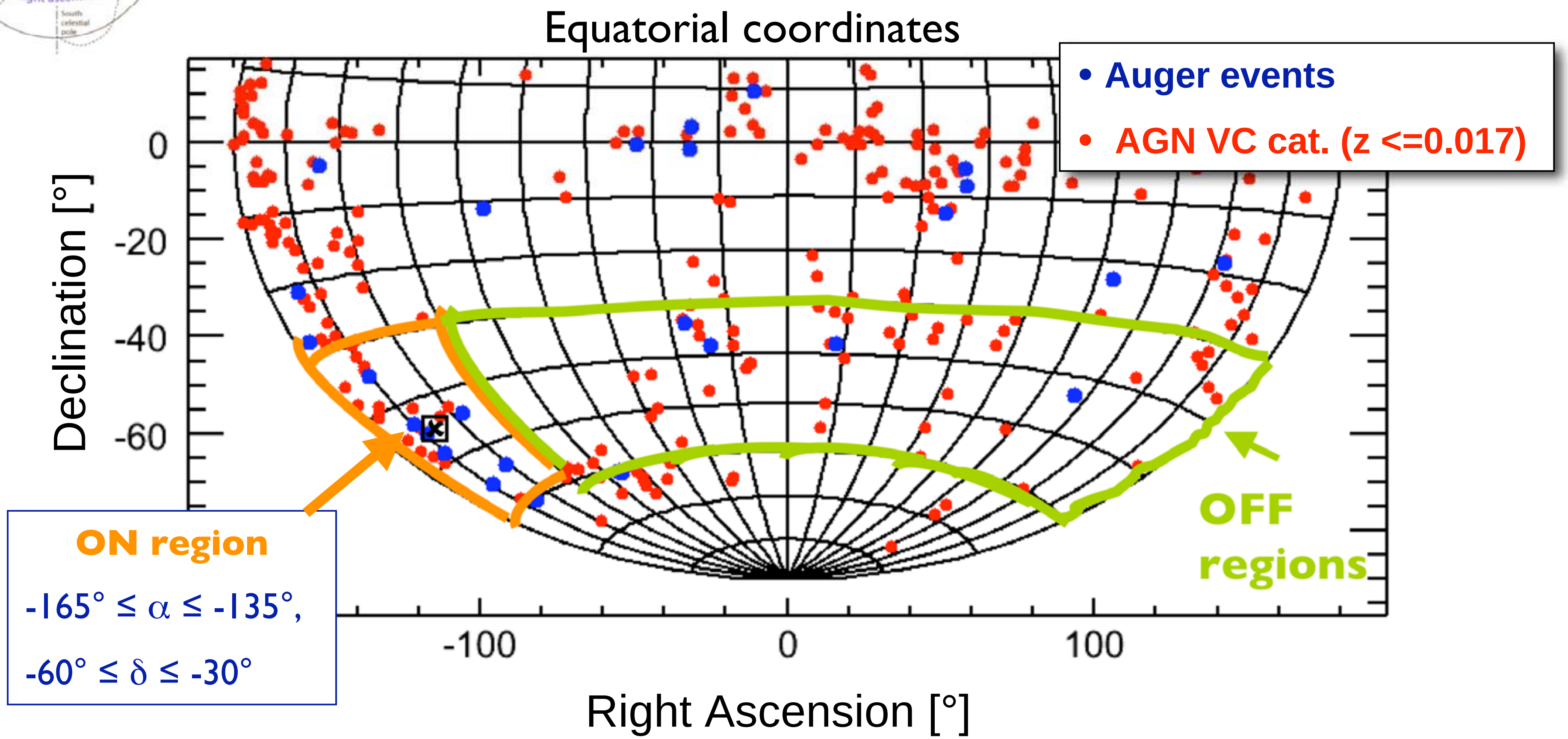
Selected: 168 days

N.B: The results that will be shown are very preliminary.

ON region



We have checked that the detector exposure and the detection rate is uniform within the choosen declination band (-60° ≤ δ ≤ -30°) . The background is estimated from eleven OFF regions that fall in the same declination band.



☒ Centaurus A recently detected in VHE γ rays.

Optimization of selection criteria

Likelihood L

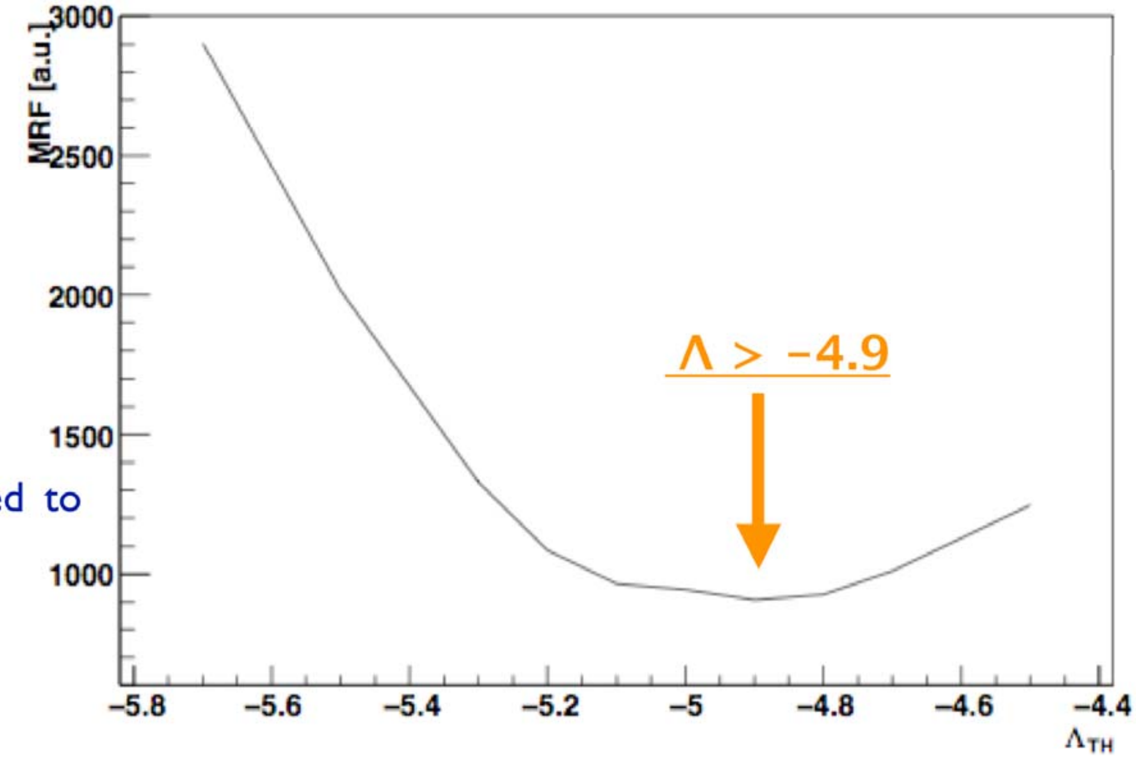
$$L = P(event|track) = P(hits|\vec{p},\vec{d}) = \prod_{i=1}^{Nhits} P(r_i|a_i,b_i,A_i)$$

The reco quality cut Λ

$$\Lambda \sim \frac{\log L}{N_{DOF}}$$

has been chosen in order to maximize the sensitivity of the search.

Model rejection factor (mrf) is used to choose the optimal cuts to be used in this analysis



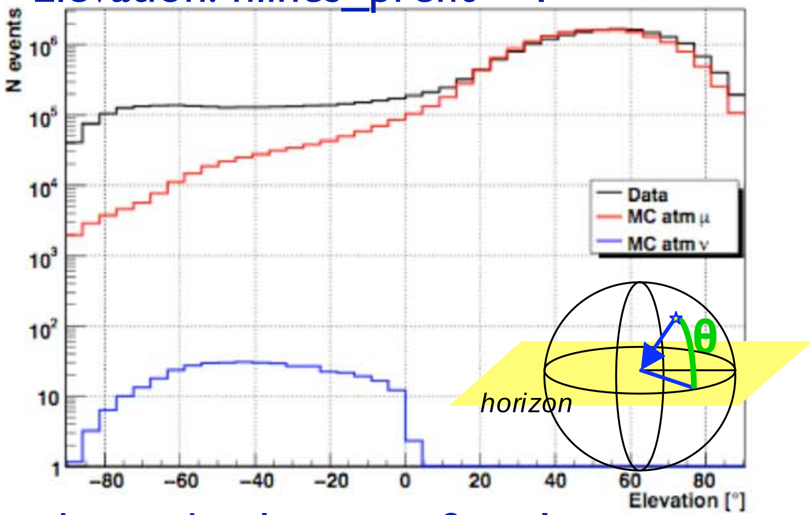
$mrf = \overline{\mu_{90}}/n_s$

The average upper limit $\overline{\mu_{90}}$ (90% C.L.) is calculated (Feldman, Cousins) from background events.

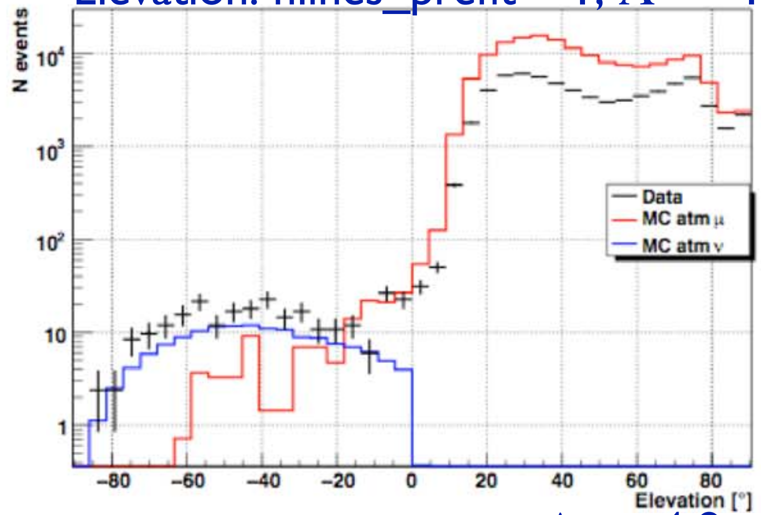
The number of expected signal events in the ON region, n_s, is obtained from a full MC simulation, assuming an E^{-2} power law, for the astrophysical neutrino flux.

Data - MC comparison

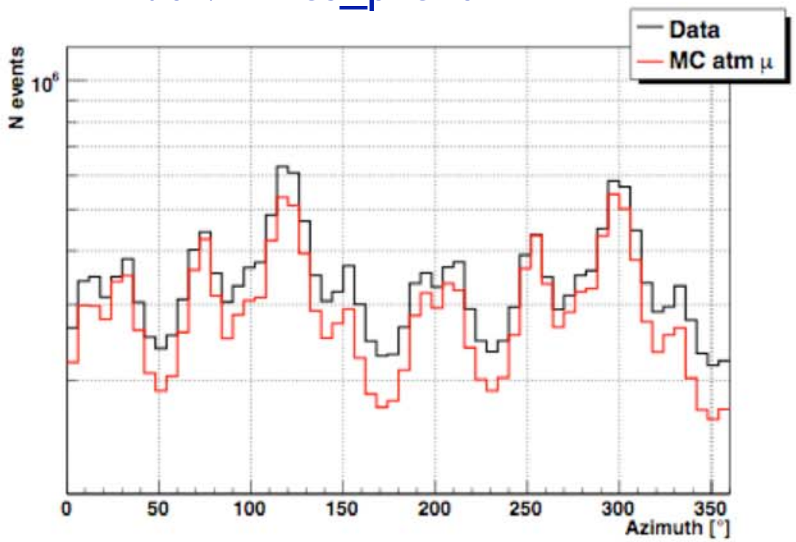
Elevation: nlines_prefit > 1



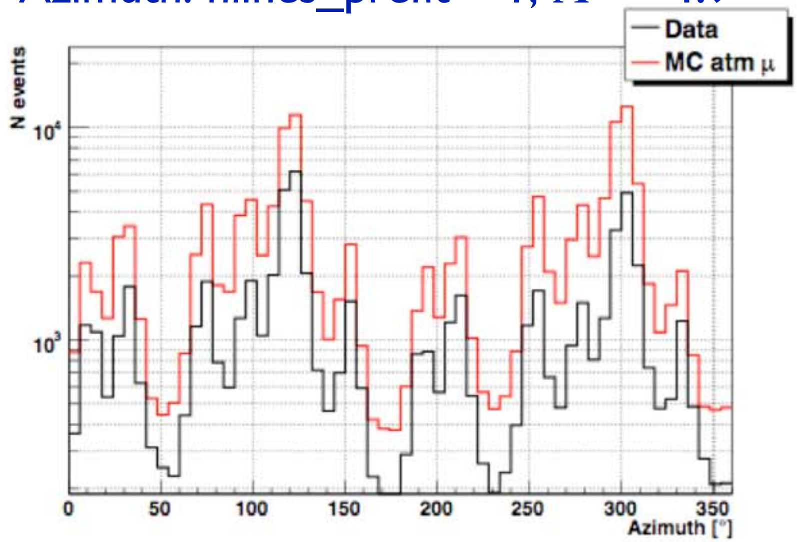
Elevation: nlines_prefit > 1, Λ > -4.9



Azimuth: nlines_prefit > 1

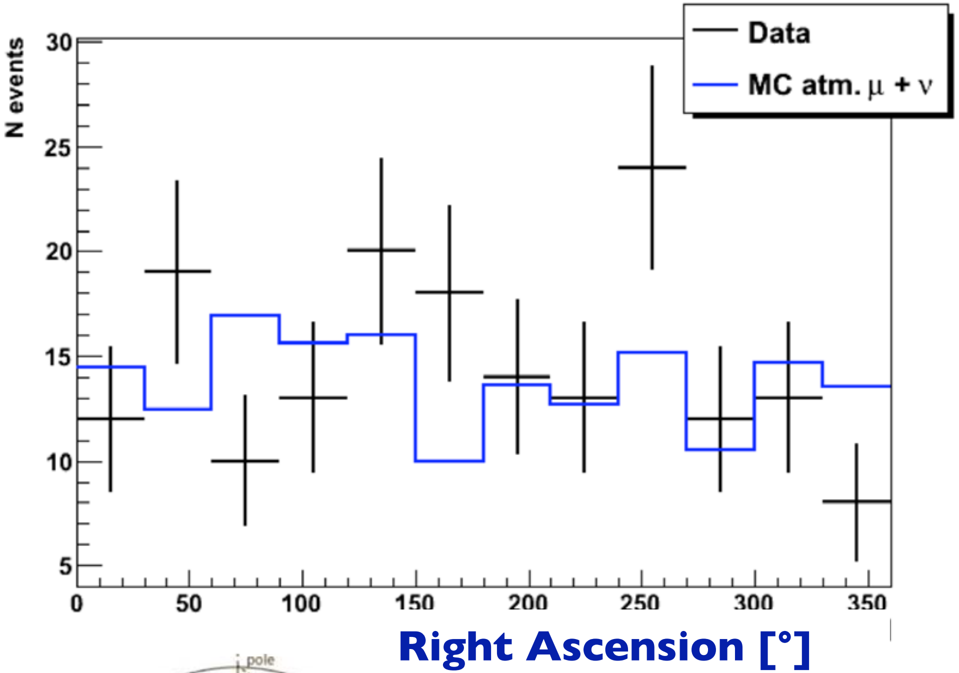


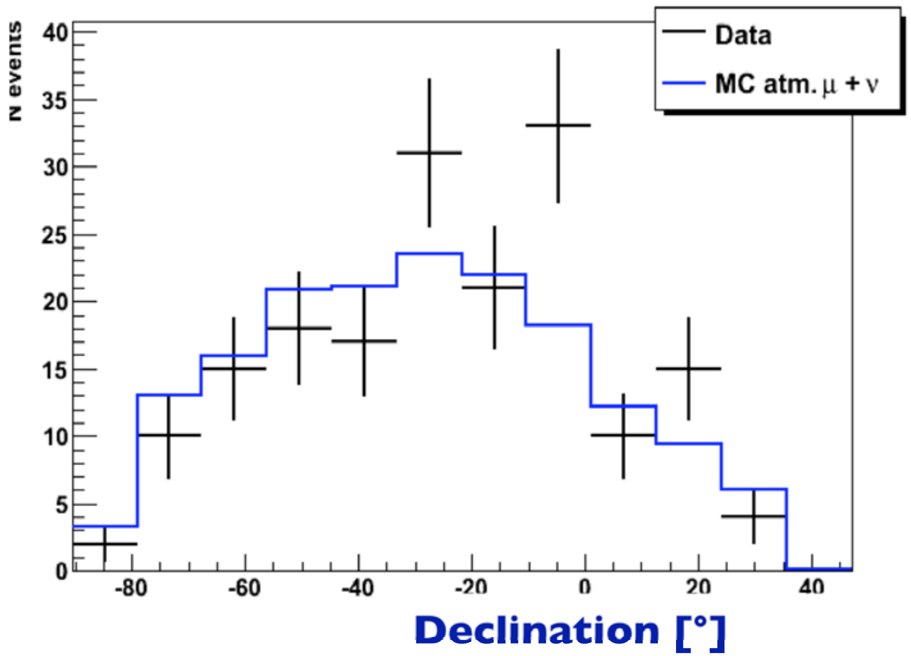
Azimuth: nlines_prefit > 1, Λ > -4.9

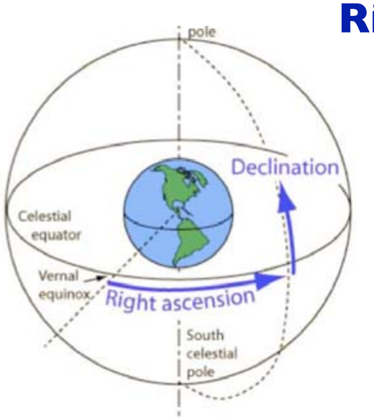


Data - MC comparison (2)

ANTARES 2007 unblind data, nlines_prefit > 1, elevation < -10° , Λ > -4.9

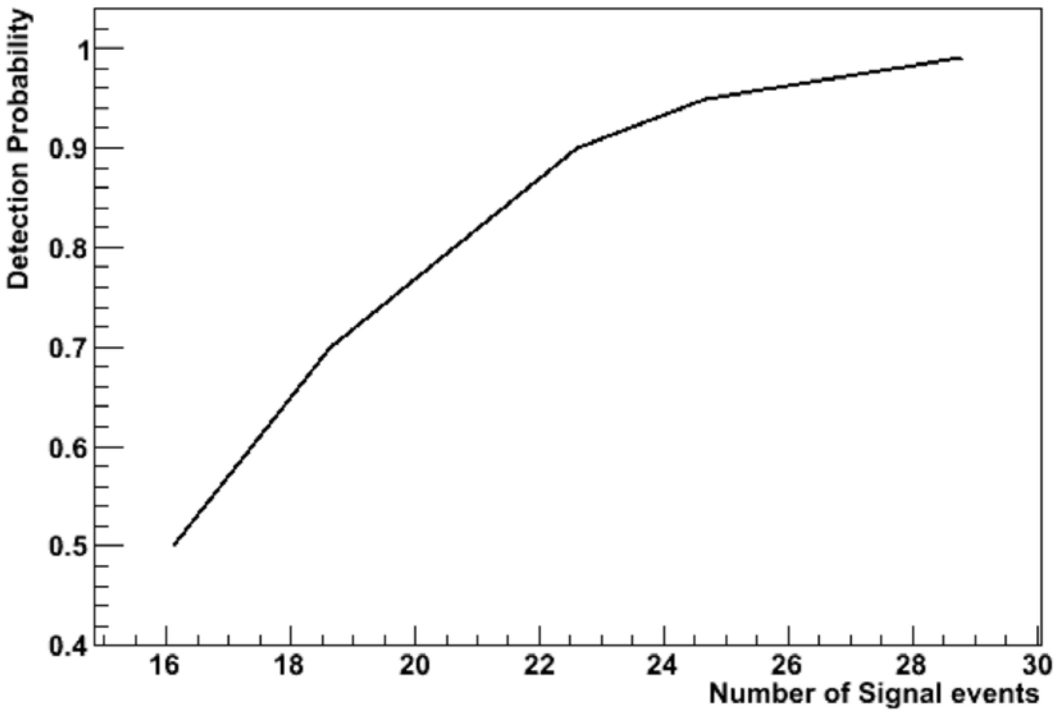






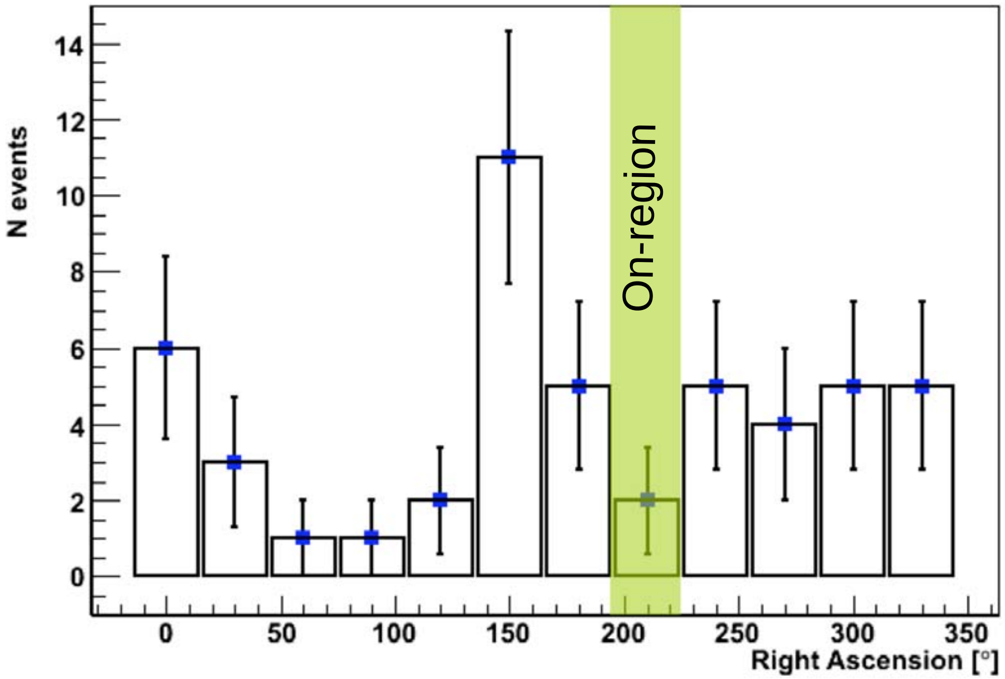
Detection Probability

Detection probability as a function of number of signal events for a 5 sigma discovery for the optimal lambda cut value (Λ > -4.9).



Events in the On-Off regions

nlines_prefit > 1, elevation < -10° , Λ > -4.9



Sky Region **-60° ≤ δ(declination) ≤ -30°**	Obs. events
(0° ≤ α (right ascension)< 15°) + (345° ≤ α < 360°)	6
15° ≤ α < 45°	3
45° ≤ α < 75°	1
75° ≤ α < 105°	1
105° ≤ α < 135°	2
135° ≤ α < 165°	11
165° ≤ α < 195°	5
195° ≤ α ≤ 225°	2
225° < α < 255°	5
255° ≤ α < 285°	4
285° ≤ α < 315°	5
315° ≤ α < 345°	5

Basic hypothesis H_0: data follow a Poisson distribution

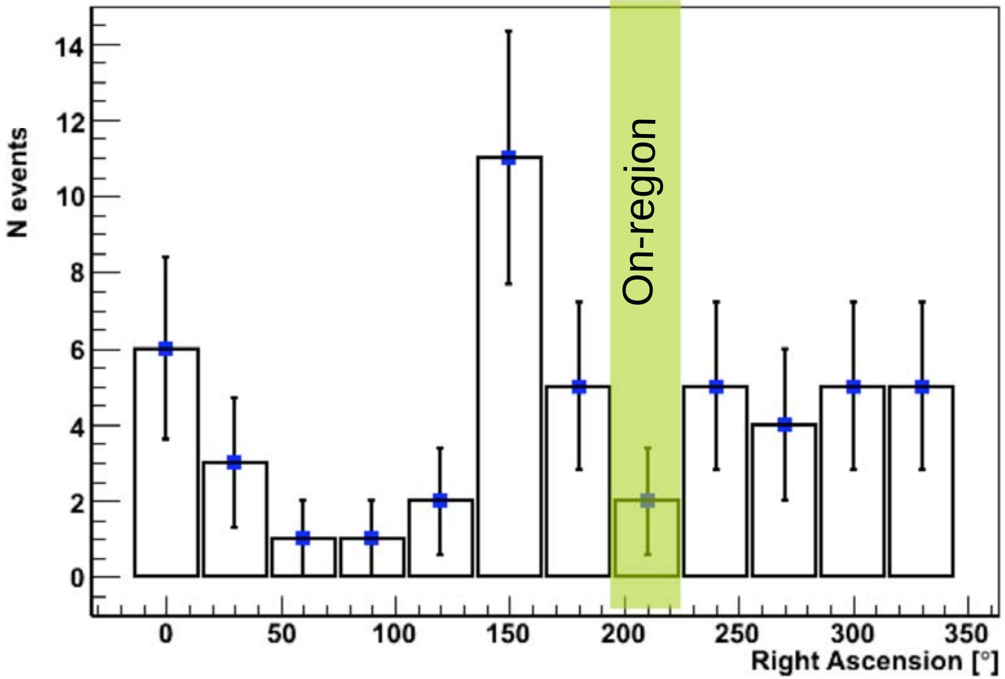
with mean value $\langle N_{off} \rangle$

$N_{on} = 2 \quad \langle N_{off} \rangle = 4.4$

p-value= $P(N \geq N_{obs} | H_0, \langle N_{off} \rangle) = 0.91$ ➔ the hypothesis is accepted

Events in the On-Off regions

nlines_prefit > 1, elevation < -10° , Λ > -4.9



Sky Region $-60° \leq \delta \leq -30°$	Obs. events
$(0° \leq \alpha < 15°)$ + $(345° \leq \alpha < 360°)$	6
$15° \leq \alpha < 45°$	3
$45° \leq \alpha < 75°$	1
$75° \leq \alpha < 105°$	1
$105° \leq \alpha < 135°$	2
$135° \leq \alpha < 165°$	11
$165° \leq \alpha < 195°$	5
$195° \leq \alpha \leq 225°$	2
$225° < \alpha < 255°$	5
$255° \leq \alpha < 285°$	4
$285° \leq \alpha < 315°$	5
$315° \leq \alpha < 345°$	5

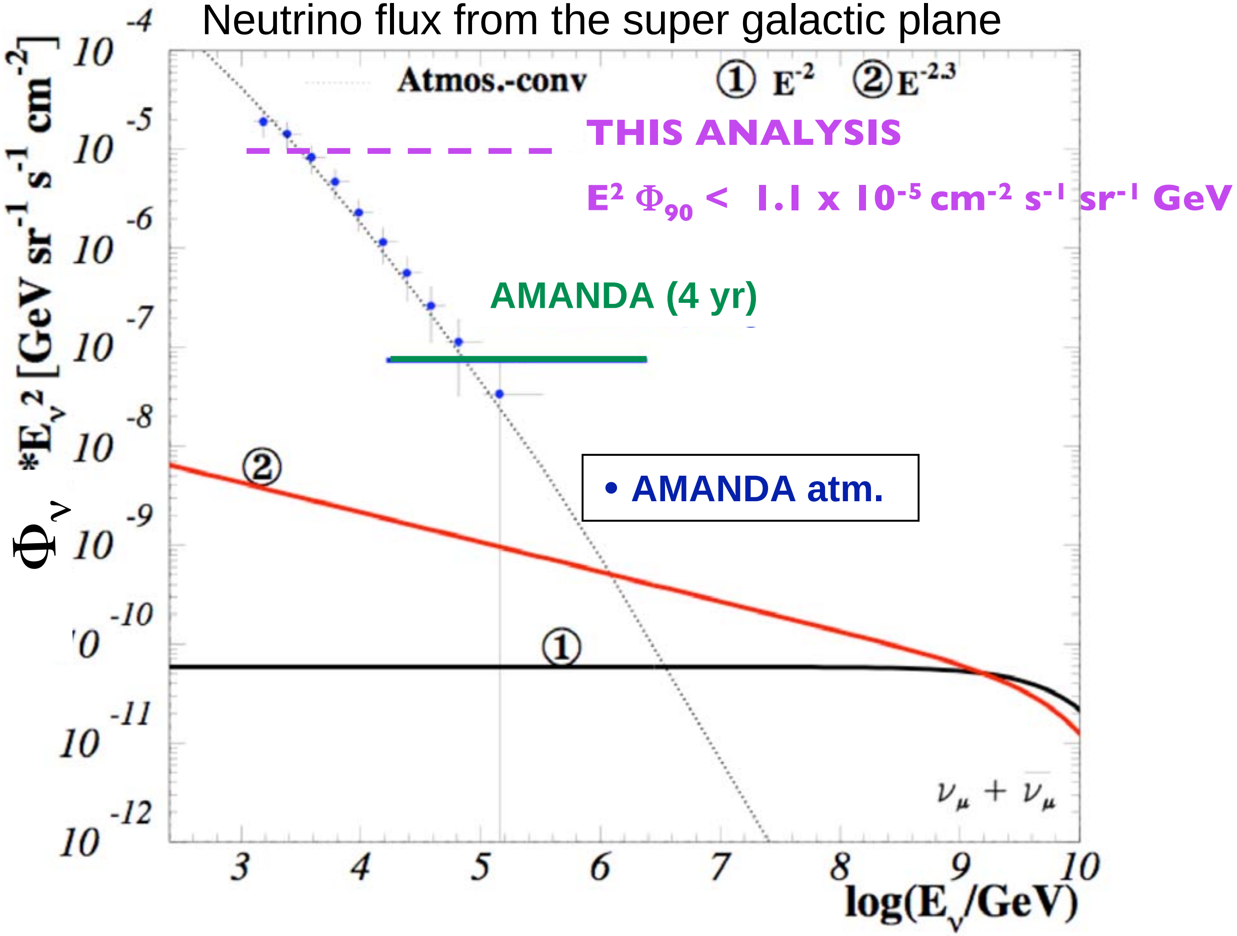
No significant excess is found.

We compute μ_{90} → the Upper Limit (90% C.L. - Feldman, Cousins) to the number of signal events → U.L. to the neutrino flux in the ON region, assuming an E^{-2} spectrum. **$E^2 \Phi_{90} < 2.1 \times 10^{-6}$ cm^{-2} s^{-1} GeV**

Diffuse neutrino flux

Assuming a uniform distribution of sources in the ON region, as well as in the SGP we obtain the following upper limit to the diffuse neutrino flux.

Neutrino flux from the super galactic plane



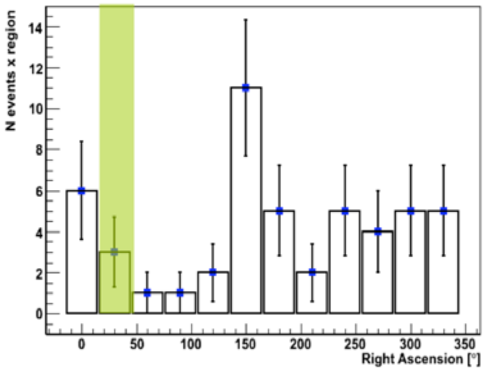
Theoretical predictions from: J.K.Becker, P. L. Biermann, AP 31 (2009) , arXiv:0805.1498

Serendipitous search

We iteratively consider as On region each of the eleven Off regions.

We evaluate an average background level, that will be compared to the number of events found in each region. The background, <N>=4.2, is the average number of events found in the 12 regions in which we have divided the declination band.

➔ On region

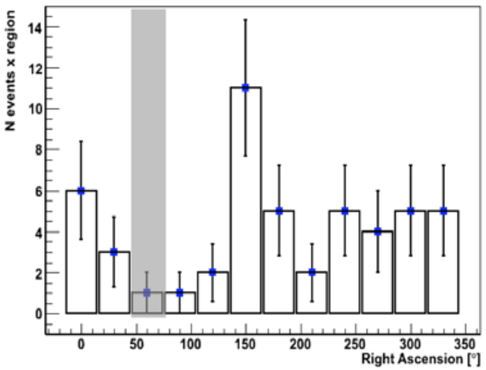


N_{on} =3 , <N> = 4.2

p-value= 0. 790

➔ H_0 accepted

➔ On region

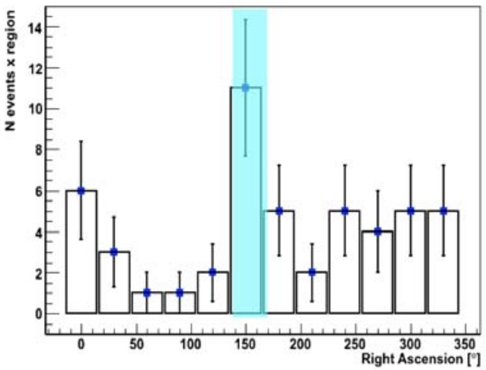


N_{on} =1 , <N> = 4.2

p-value= 0. 985

➔ H_0 accepted

➔ On region



N_{on} =11 , <N> = 4.2

p-value= 0.004 ➔

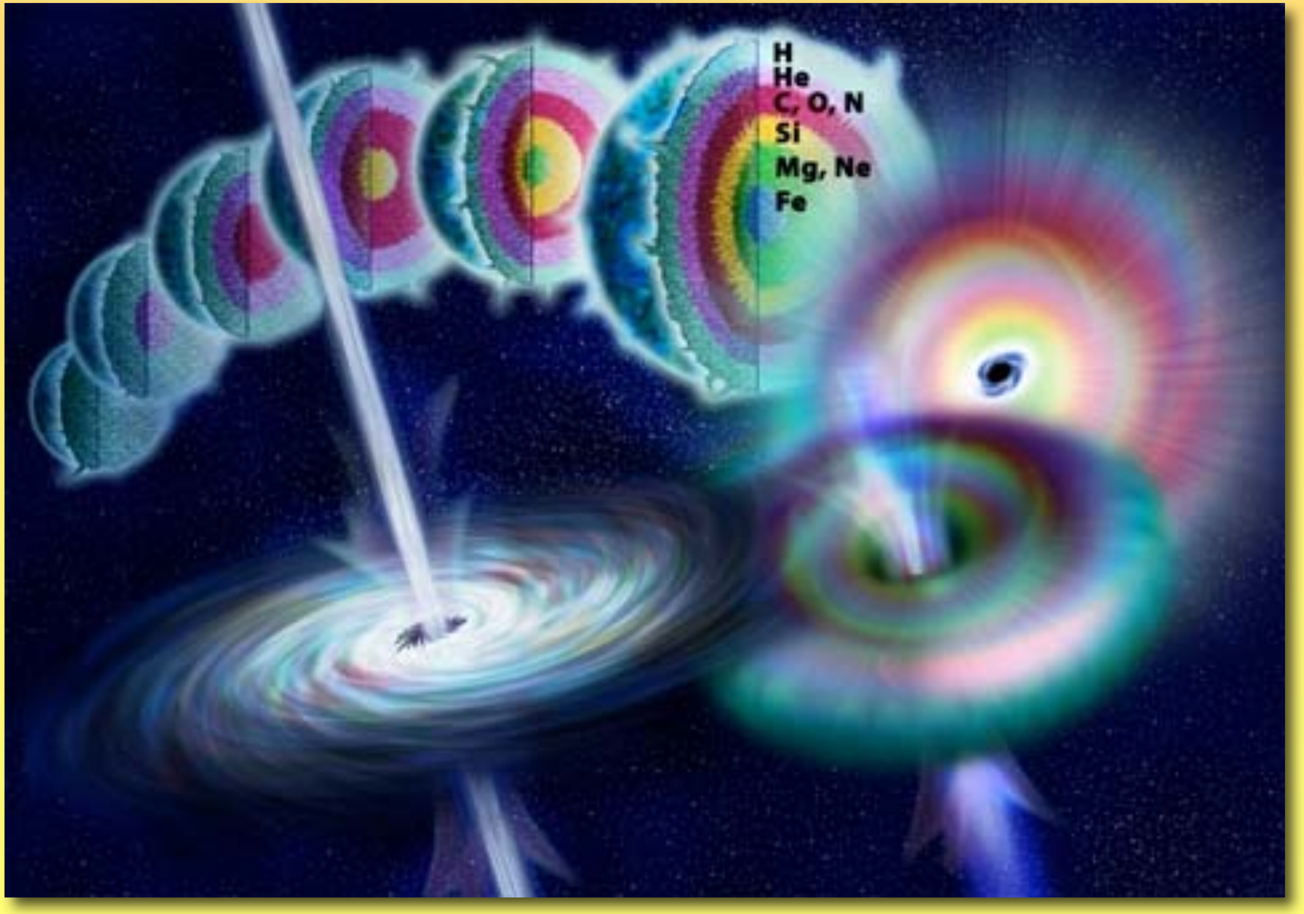
Post-trial probability 5%

H_0 = data follow a Poisson distribution with mean value <N> = 4.2

So far … so good

- This analysis has been performed on 2007 ANTARES data, searching for a neutrino signal excess coming from an extended sky region (ON region) around the supergalactic plane (SGP).
- No significant excess of signal has been found. Upper limit has been set to the total neutrino flux from the ON region.
- Under the assumption of uniform sources distribution in the ON region, as well as along the SGP, an upper limit to the diffuse neutrino flux has been set.
- Improvement expected from event classification in energy.
- Serendipitous search shows no significant post-trial excess of signal in any of the 11 OFF regions.
- The same analysis is going to be repeated on a larger data sample, and with a new and more powerful reconstruction algorithm.

neutrinos from transient sources with ANTARES



Neutrinos from transient sources

Why?

Several models predict the production of HE neutrinos from transient sources. The advantage is that time and directional correlation is used to reduce the background.

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Several models predict the production of HE neutrinos from transient sources. The advantage is that time and directional correlation is used to reduce the background.

How?

•Triggered search method: the informations from the satellites network are used.

•Rolling search method: the ANTARES detector is able to trigger the observation with an optical telescope in order to validate the observation.

Triggered search method

Detection principle:

– Whenever a GRB alert is received, a dedicated data taking strategy is performed: all raw data covering a 2 min window are saved to disk.

Advantages:

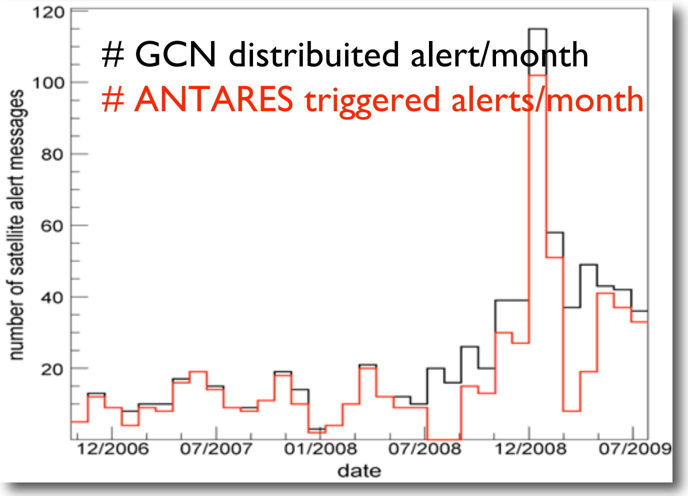
▪almost background-free due to the transient nature of the source.

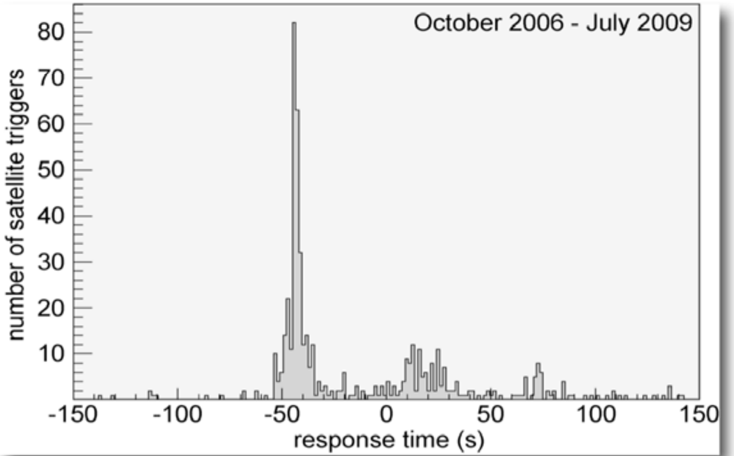
But …

oTime window is constrained by models.

oLimited by the satellite field of view.

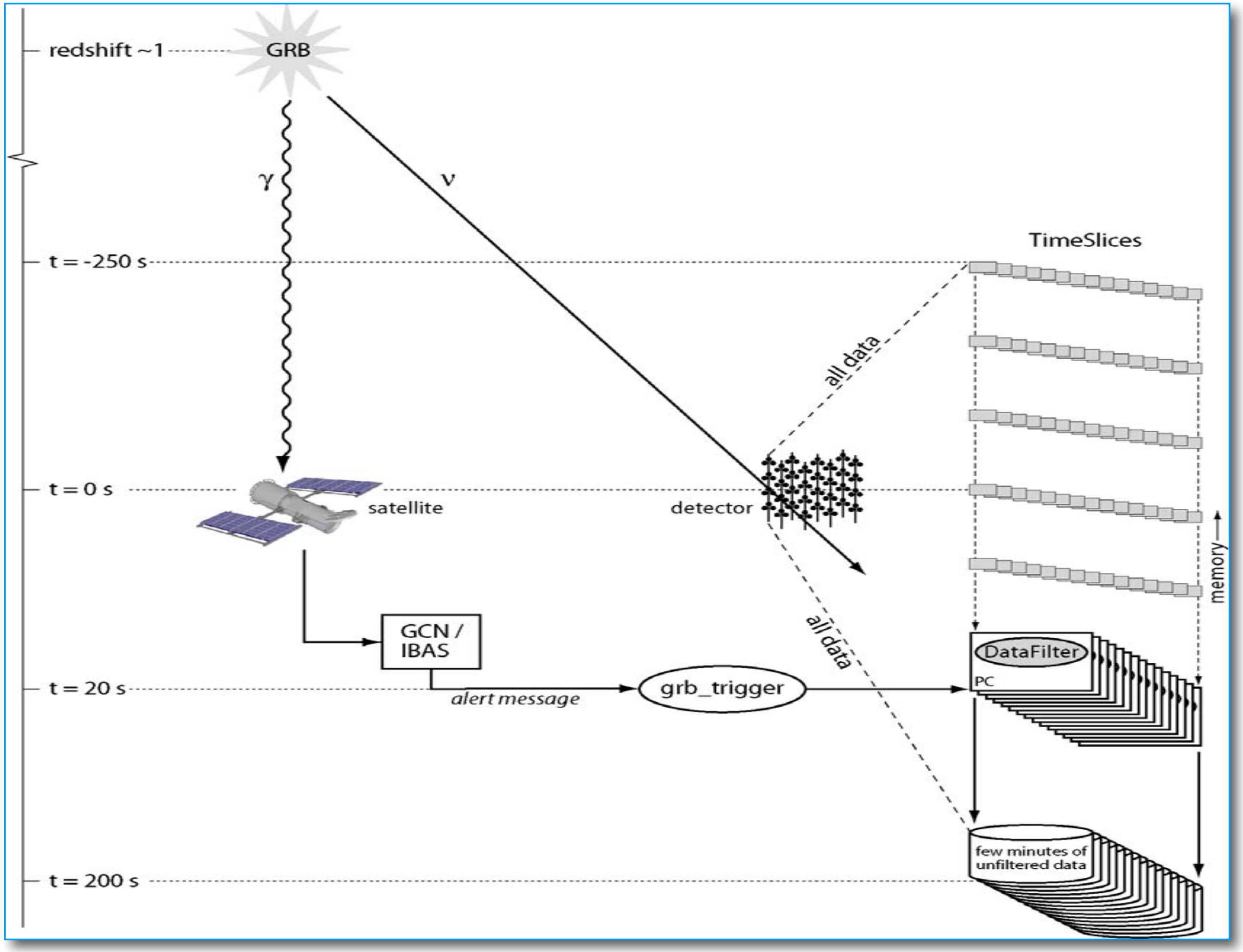
oDependant on external sources



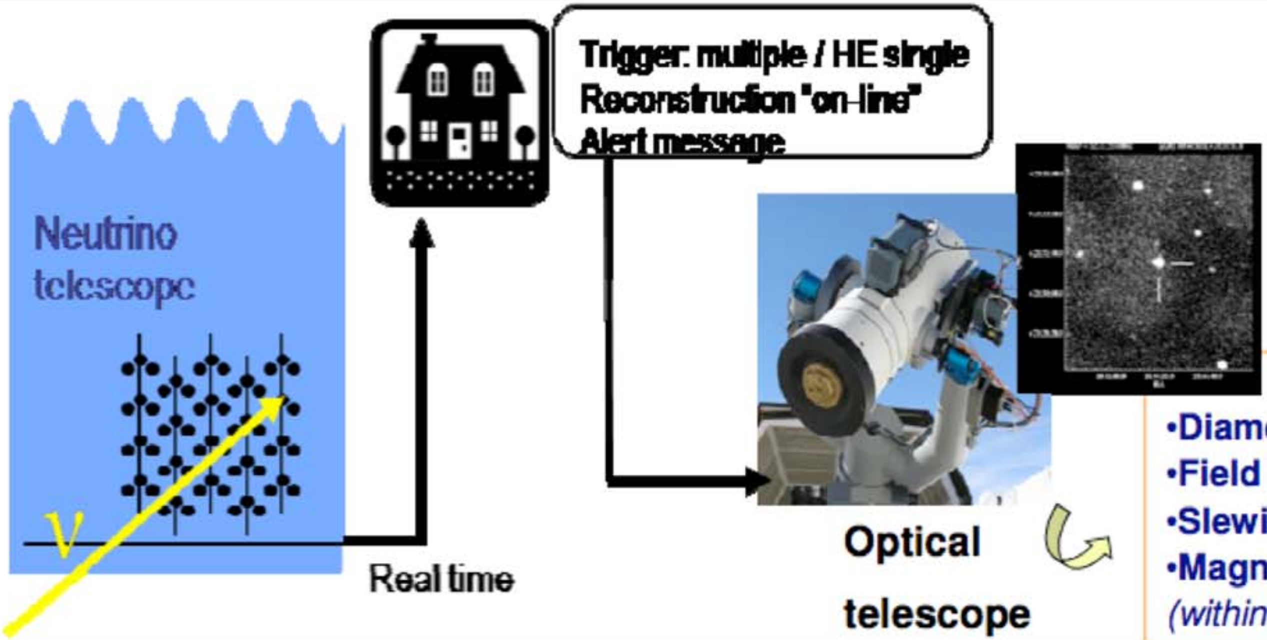


The response time of the satellite triggered data taking in Antares to a satellite alert message.

Triggered search method



Rolling search method



TAROT
- **Diameter**: 25 cm
- **Field of view**: 1.86°×1.86°
- **Slewing**: 5-10s
- **Magnitude limit**:18-19

(within 1-3 min image acq.)

Alert types and rates

HE singlets: cut on energy (nhits & amp) ➔ *expected ~ 2/month*

Doublets: 2 ν events within 3° Δt=15 min. ➔ *expected ~3.5x10^{-3}/yr*

Rolling search method

Detection principle:

– search for a burst of neutrinos in time and space coincidence or the detection of a single high energy neutrino event (E>10TeV).

Advantages:

- large field of view (~half an hemisphere) and duty cycle.
- Completely model-independent (time delay between γ and ν emission, source nature)

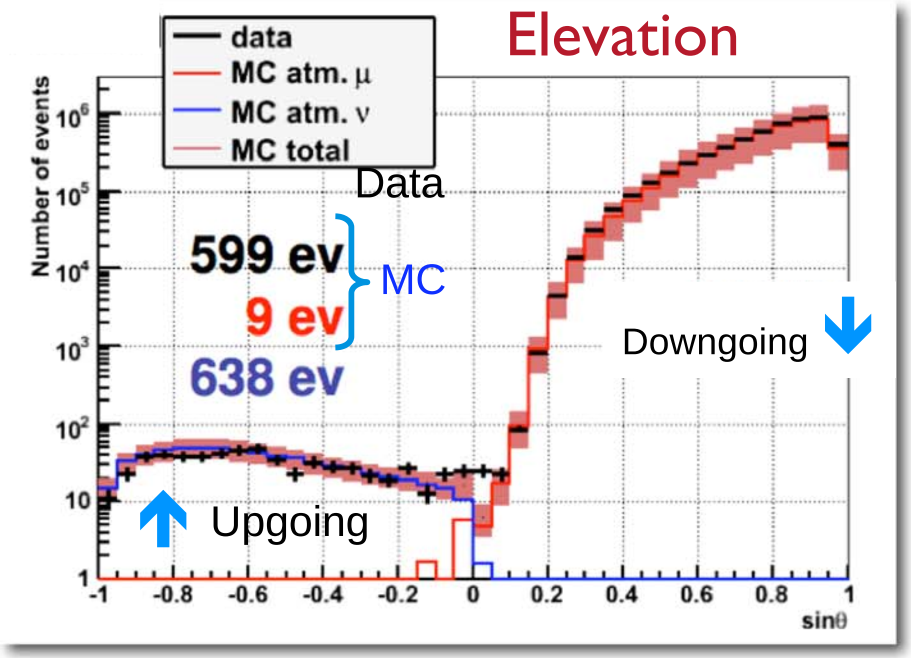
But … a detection is not necessarily associated to an astrophysical source:

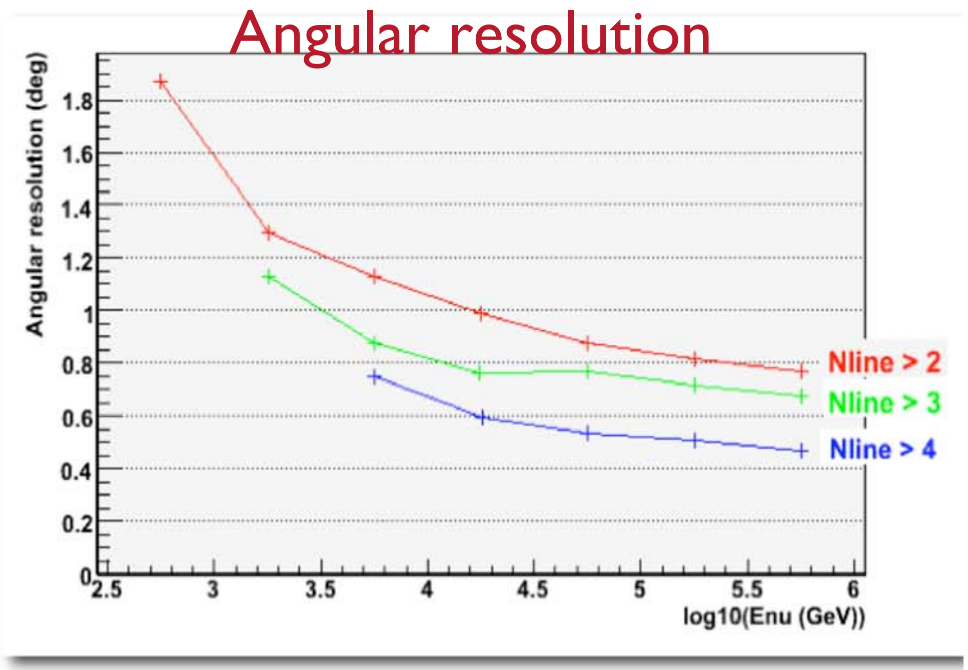
➔ necessary to organize complementary follow-up (optical, radio …).

➔ necessary to have fast reconstruction strategy and good angular resolution.

On-line reconstruction strategy

Golden neutrino events are identified by means of a quasi-online reconstruction algorithm: it takes 5-10 ms to reconstruct each event.

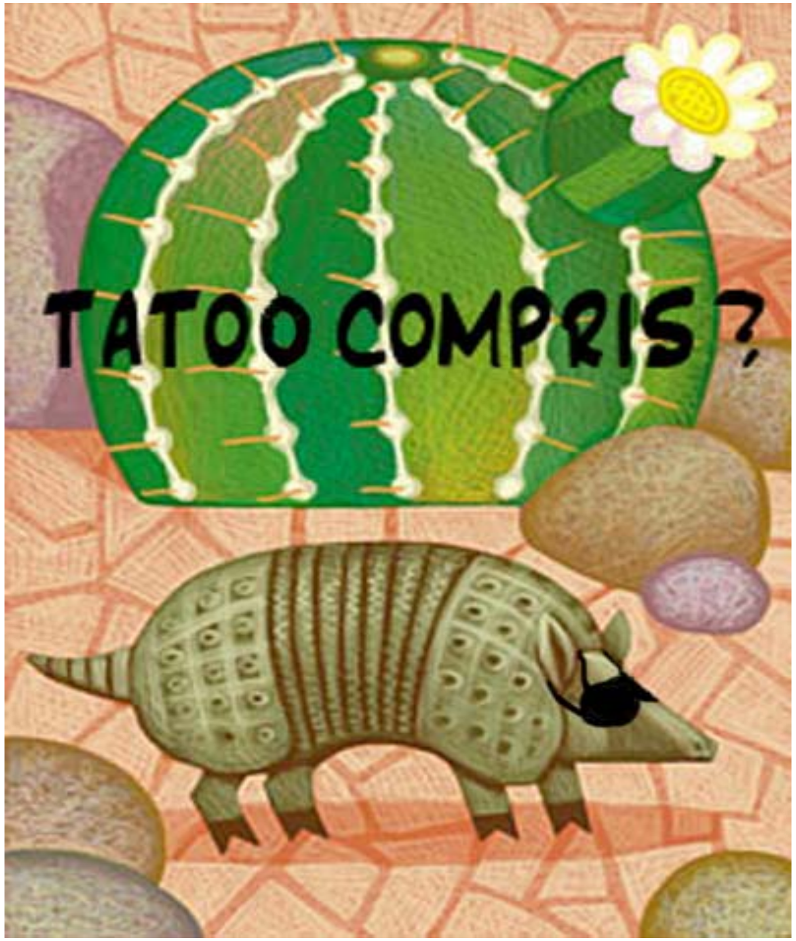




In order to achieve a better angular resolution a refined position can be obtained by means of an offline reconstruction algorithm.

Optical follow-up

The follow-up is performed by means of optical telescopes.



TAToO (TAROT ANTARES Target of Opportunity)

Optical follow-up

The follow-up is performed by means of optical telescopes.

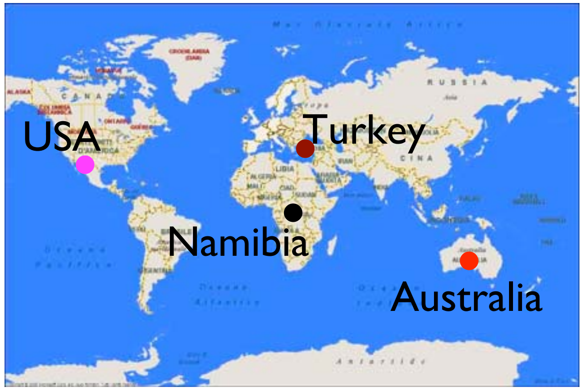
TAROT: two 25 cm telescopes

-fov 1.86° x 1.86°

- Magnitude V<17 (10s), V<19 (100s)
- sleewing time ~ 10s

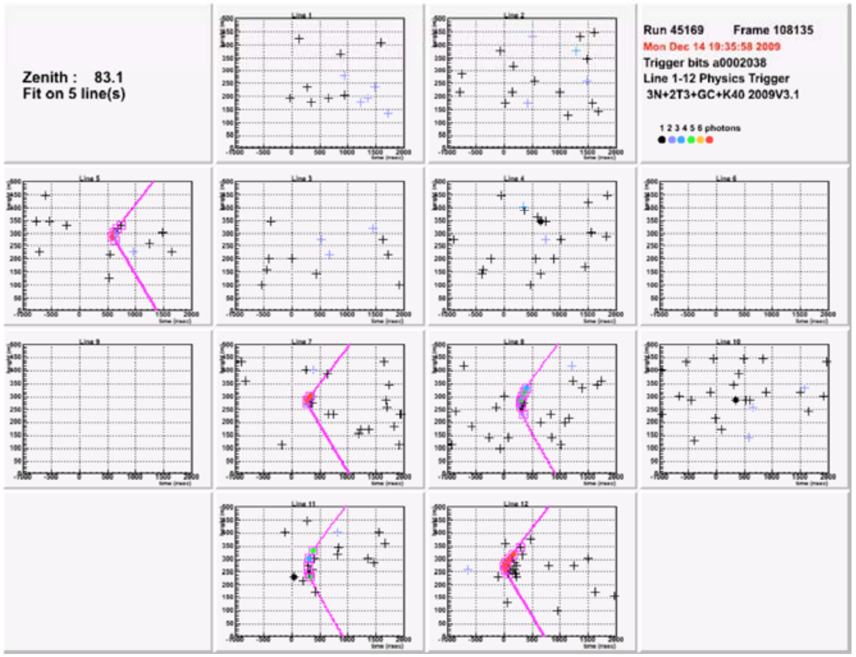
ROTSE: four 45 cm telescopes

- fov 1.85° x 1.85°
- Magnitude V~19 (60s)
- sleewing time < 6-8 s



Example: alert december 14th 09

Run_Number: 45169 Nframes: 108135
Amplitude: 296, nhit:28, nlines:5, tchi2: 2.3



ANTARES HE event

Optical Observation Strategy:

T_0

T_0+1

T_0+2

T_0+3

T_0+4

T_0+5

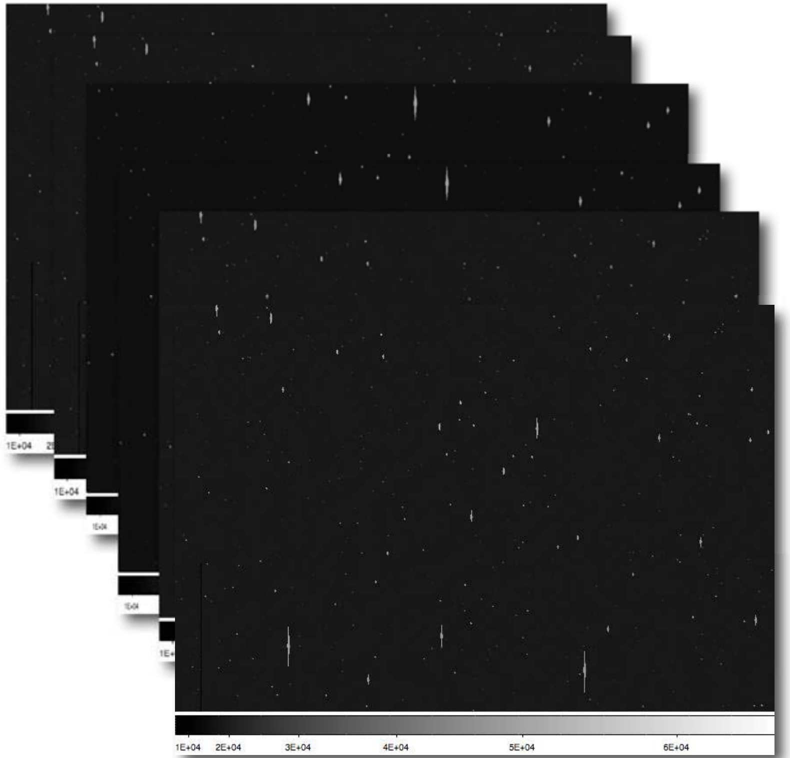
T_0+6

T_0+7

T_0+9

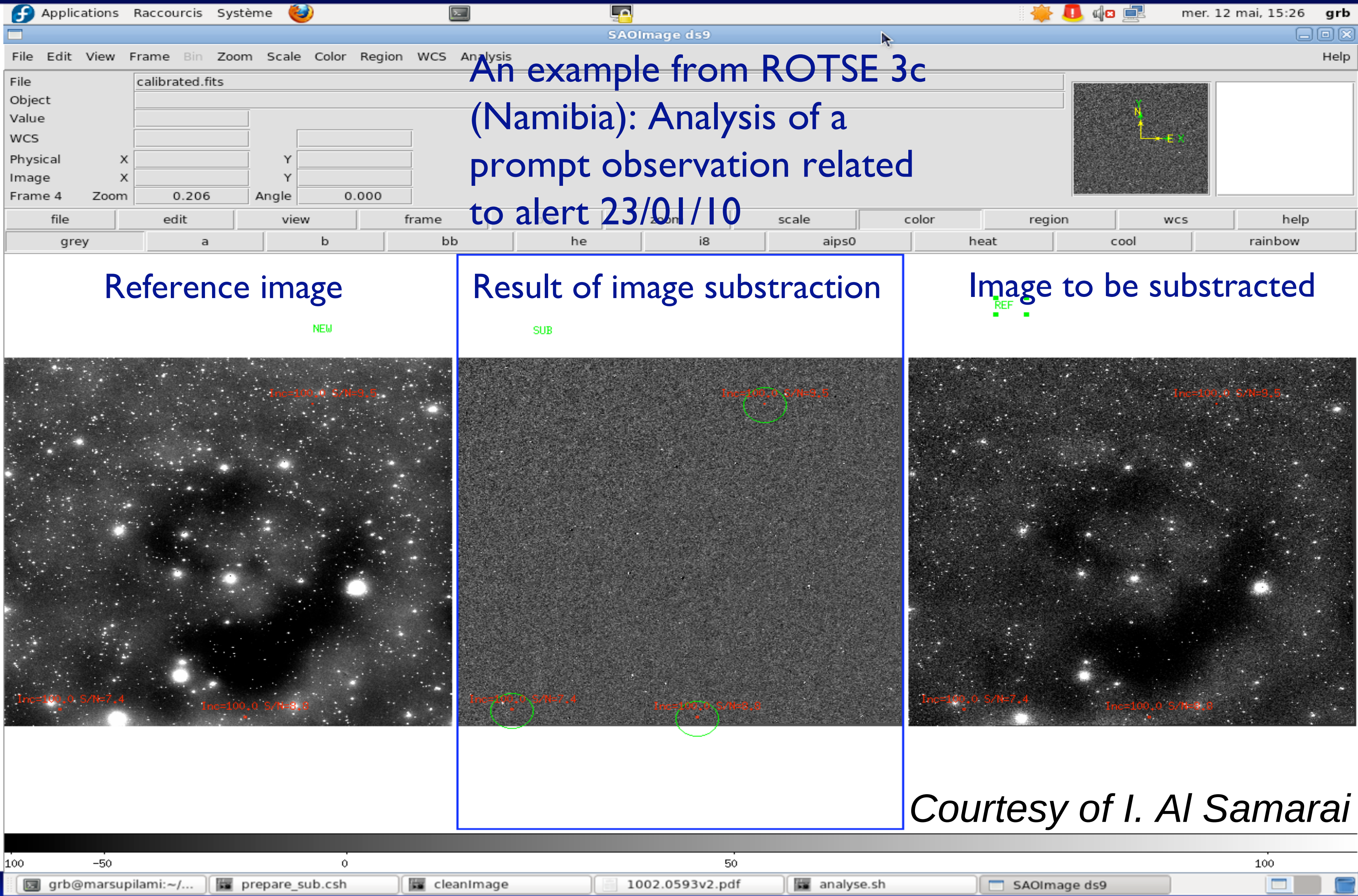
T_0+15

T_0+27



Analysis of optical images under development

Optical image analysis



An example from ROTSE 3c (Namibia): Analysis of a prompt observation related to alert 23/01/10

Reference image

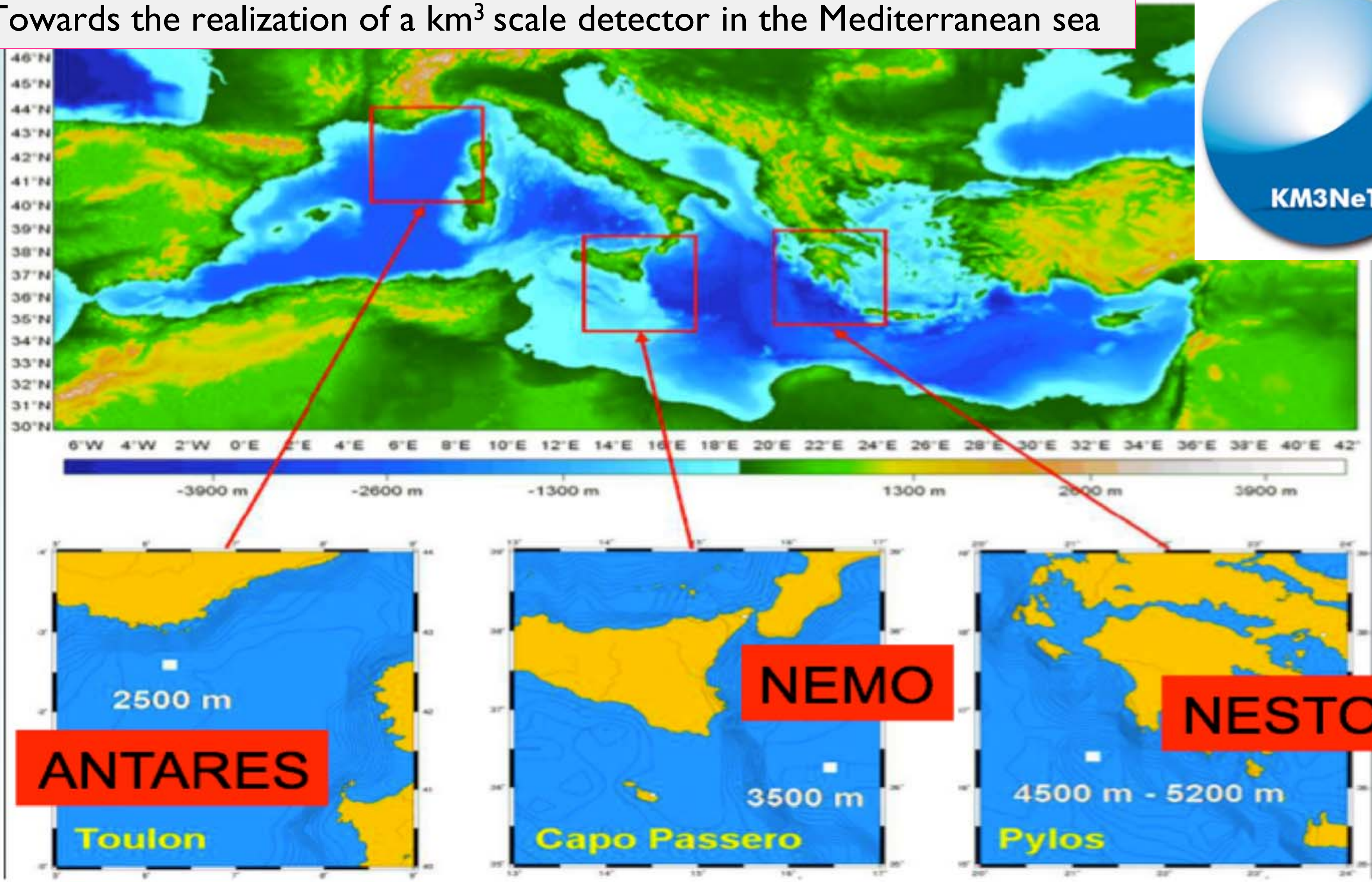
Result of image substraction

Image to be substracted

Courtesy of I. Al Samarai

What's next ?

Towards the realization of a km³ scale detector in the Mediterranean sea

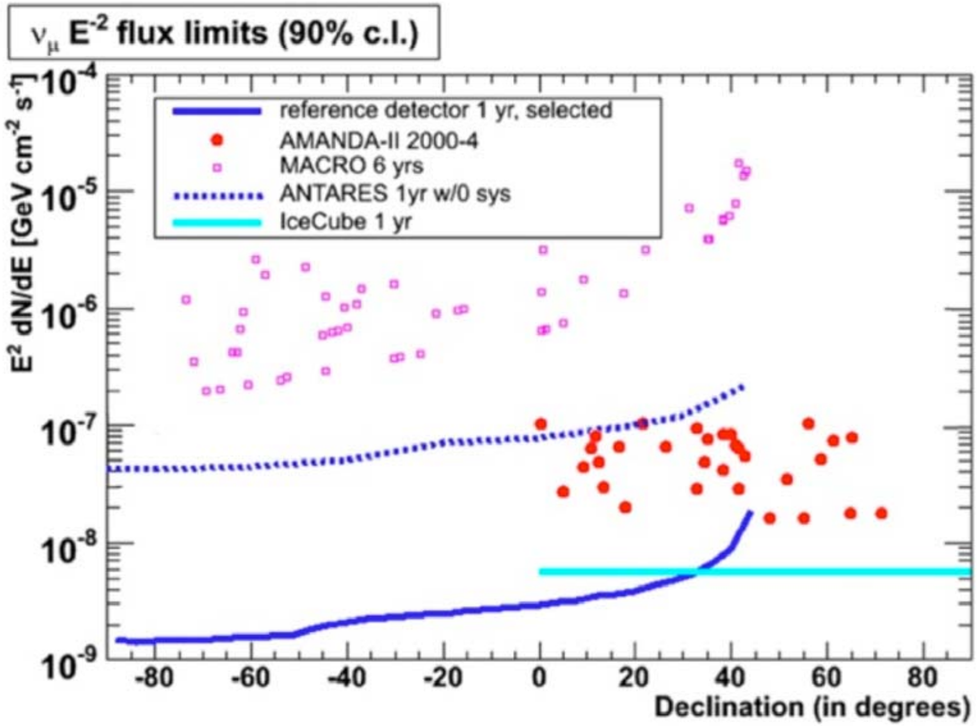


Km³-scale detector

+ + + …

DESIGN GOALS:

- Volume > 1 km^3
- Core process:
  $\nu_\mu + N \rightarrow \mu + X$ at ν_μ energies > 100 GeV
- Data taking period > 10 year
- Optimized for energy range
  - 1 TeV – 1 PeV
- Angular resolution < 0.1°



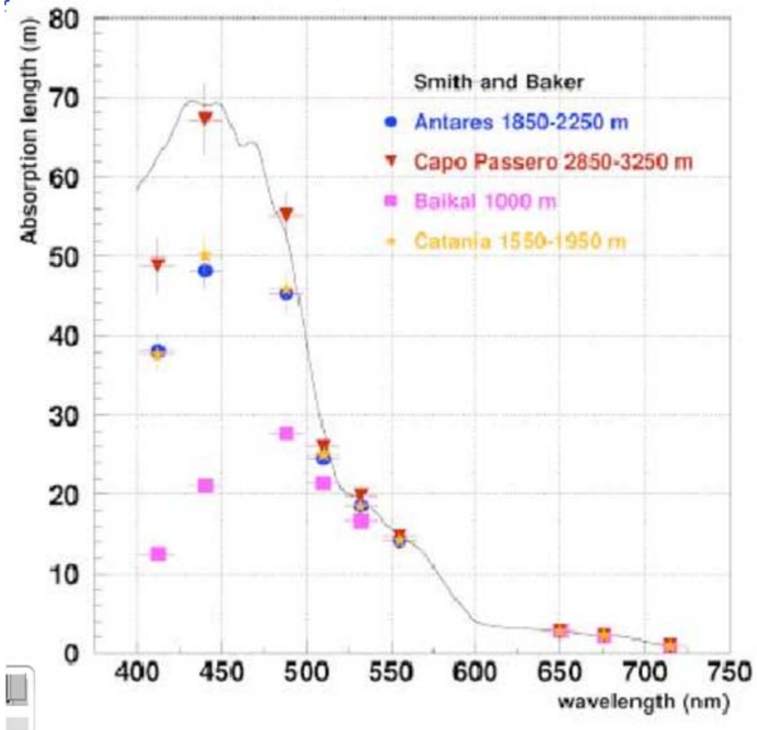
Site evaluation

Cherenkov light detection can be performed in a transparent medium.

The transparency of water can be evaluated by means of the absorbtion and scattering lenght.

A candidate site for the deployment of HE uderwater neutrino telescope should fulfill several criteria:

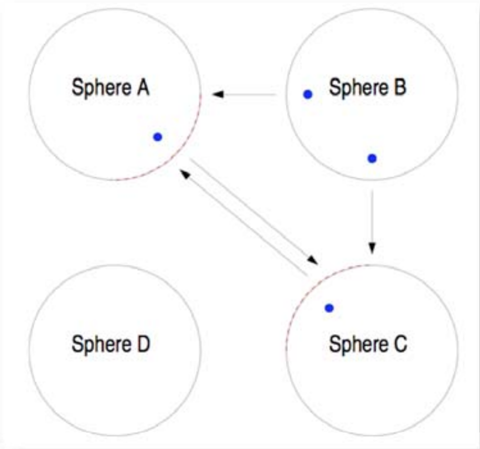
- deep underwater (shield atmospheric muons);
- large attenuation/scattering lenght;
- low sedimentation and fouling rate;
- …

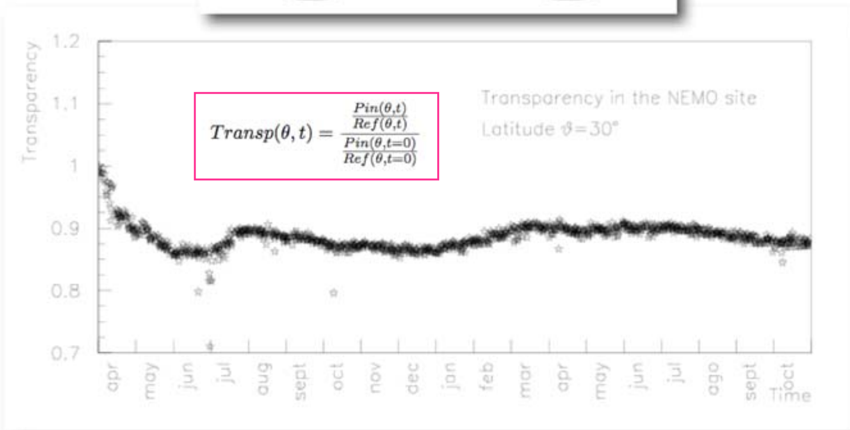


Biofouling effect

The transparency of Oms can be affected by the rise of bacteria colonies and sedimentation once they have been underwater.

A dedicated set-up has been put underwater in the Toulon and Capo Passero sites to evaluate this effect.





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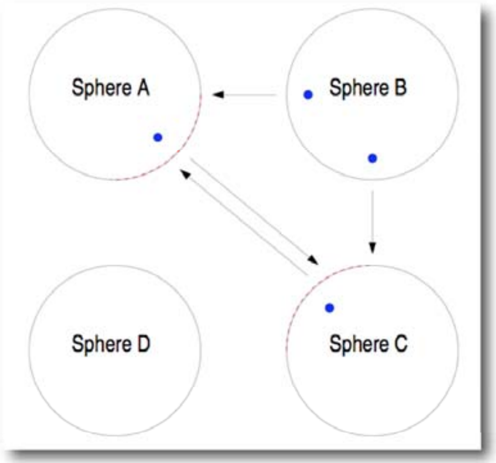
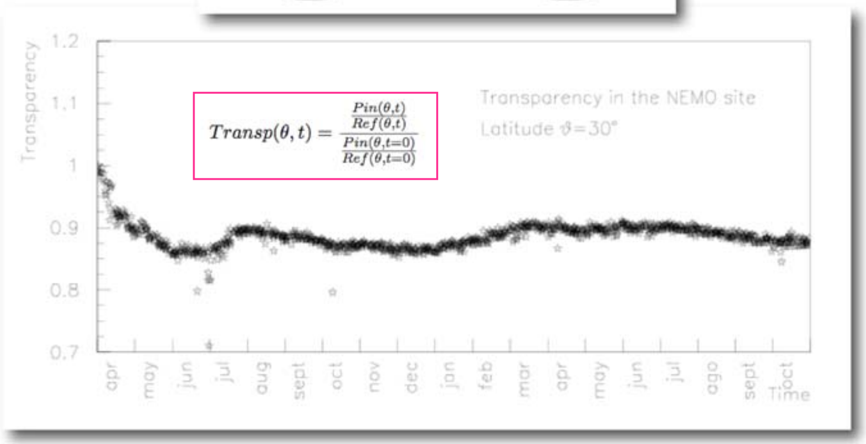
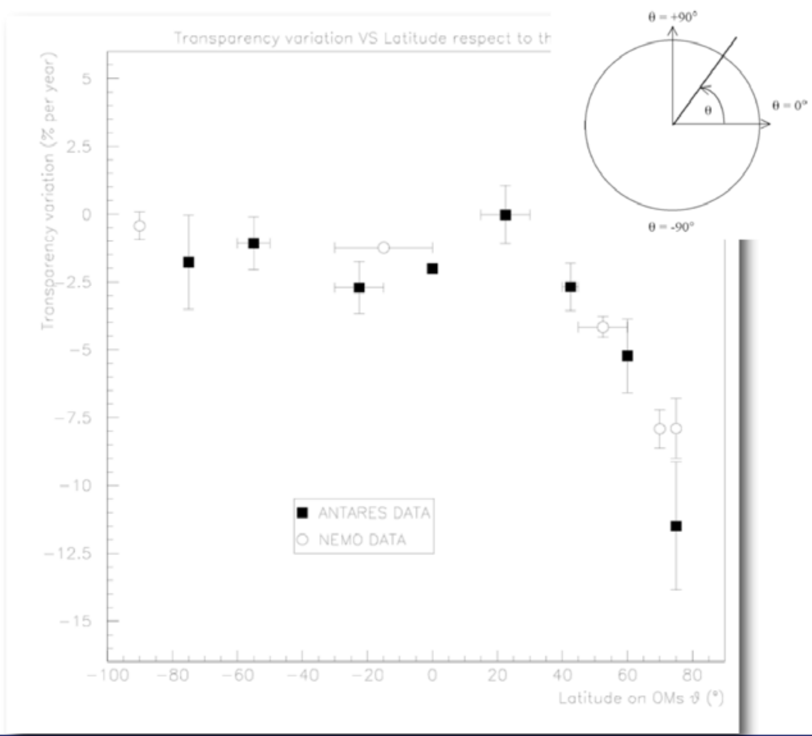






Summary

- The Mediterranean sea is an optimal location to search for HE neutrinos, due to deep sea water and optimal exposure (galactic plane visibility).
- The ANTARES detector is completed since 2008.
- …next step is the search for neutrino candidates with a cubic kilometer square detectors in the Mediterranean sea.

Summary

- The Mediterranean sea is an optimal location to search for HE neutrinos, due to deep sea water and optimal exposure (galactic plane visibility).
- The ANTARES detector is completed since 2008.
- …next step is the search for neutrino candidates with a cubic kilometer square detectors in the Mediterranean sea.

In this talk:

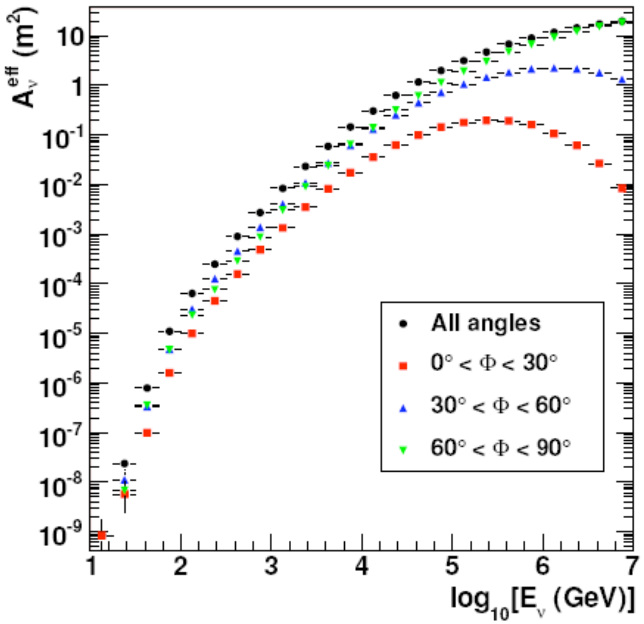
  - The search for a neutrino signal excess coming from an extended sky region (ON region) around the supergalactic plane (SGP) has not shown any significant excess of signal (2007 ANTARES data). Upper limit has been set to the total neutrino flux from the ON region.
  - Triggered search in ANTARES:
  - Dedicated data-taking configuration in addition to standard daq is performed in coincidence with alert send by GCN. On average ~ 1-2alert/day is received.
  - Rolling search in ANTARES:
  - Optical follow-up with TAROT telescope is well established and automatically working well since spring 2009.
  - Site evaluation in view of a cubic-kilometer scale detector in the Medirranean sea.


Thank you!

Backup slides

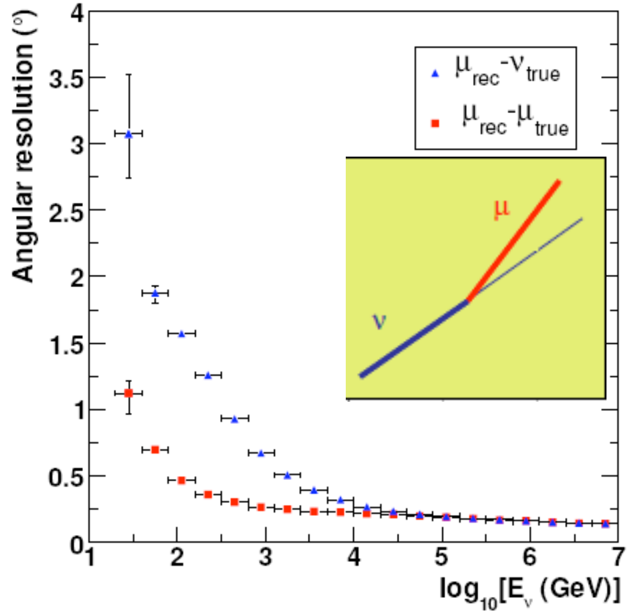
Expected Performance (full detector)

Neutrino effective area



$N_{det} = A_{eff} \times \text{Time} \times \text{Flux}$

Angular resolution



- For E_ν<10 PeV, A_{eff} grows with energy due to the increase of the interaction cross section and the muon range.
- For E_ν>10 PeV the Earth becomes

- For E_ν<10 TeV, the angular resolution is dominated by the angle between ν and μ.
- For E_ν>10 TeV, the resolution is limited by track reconstruction

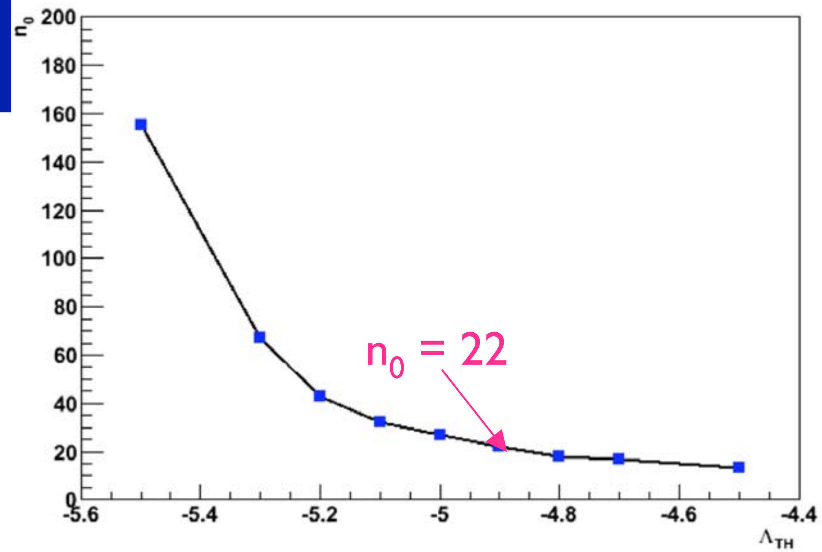
Discovery Potential …

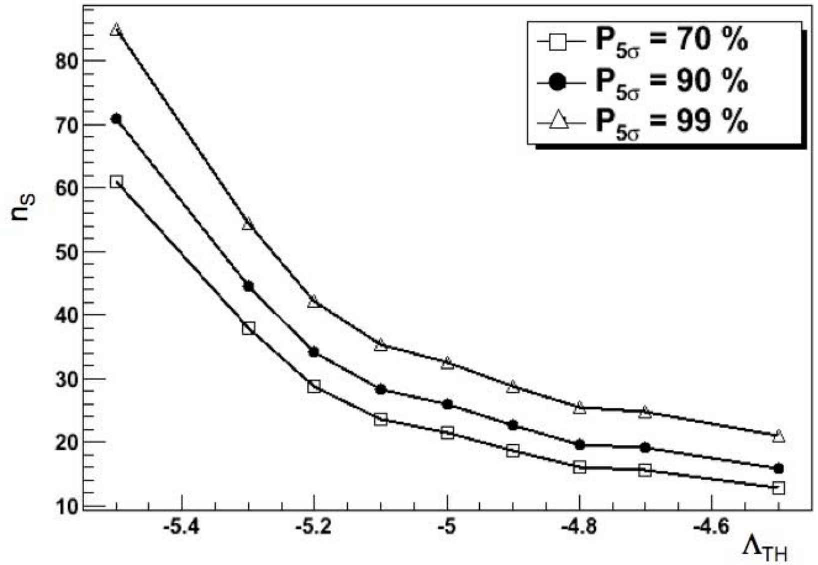
… and signal strength as a function of max. Likelihood cut

Discovery potential n_0: the number of events (signal + background) that are necessary, for a given $\langle n_b \rangle$, to lead to a discovery. There is evidence for a discovery when we find a 5σ excess of signal over the background.

$$5\sigma \Rightarrow \sum_{n_{obs}=n_0}^{\infty} P(n_{obs} \mid \langle n_b \rangle) \leq 2.85 \cdot 10^{-7}$$

Signal strength n_s such that with a 70%, 90 or 99% probability, we can observe a total number of events (signal + bkg) which is sufficient to claim a 5σ discovery.

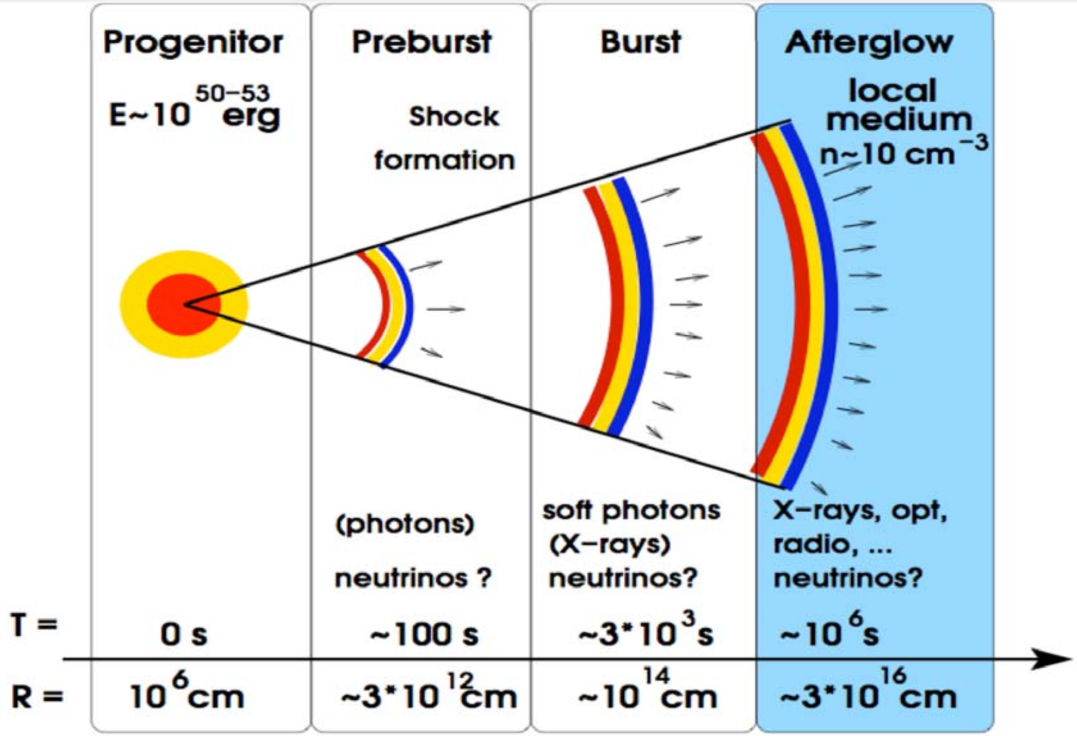




HE Neutrinos from GRBs

GRBs are between the most powerful sources in the Universe and they are thought to be also the sources of HE neutrinos.

The detection of HE neutrinos (typical energy above ~10 TeV) could unambiguously proof that GRBs accelerate protons $p + \gamma \to \pi^{+} + n \to \nu' s + \ldots$



The connection between the γ-rays and ν emission is not yet fully understood.

Data-MC comparison

The number of events observed in the several right ascention bins show fluctuations larger than the ones expected from MC simulation