Dark matter search with the ANTARES neutrino telescope

RICAP

Rome, May 25 , 2011

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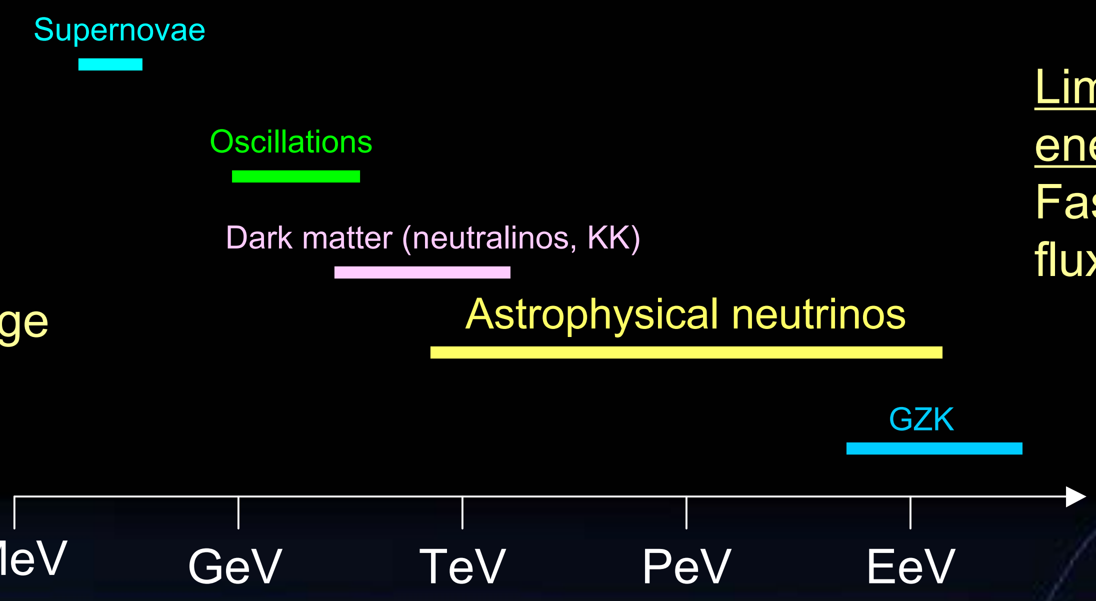
Scientific scopes

- Origin of cosmic rays
- Hadronic vs. leptonic signatures

Detector size

<u>Limitation at high energies:</u>
Fast decreasing fluxes E^{-2}, E^{-3}

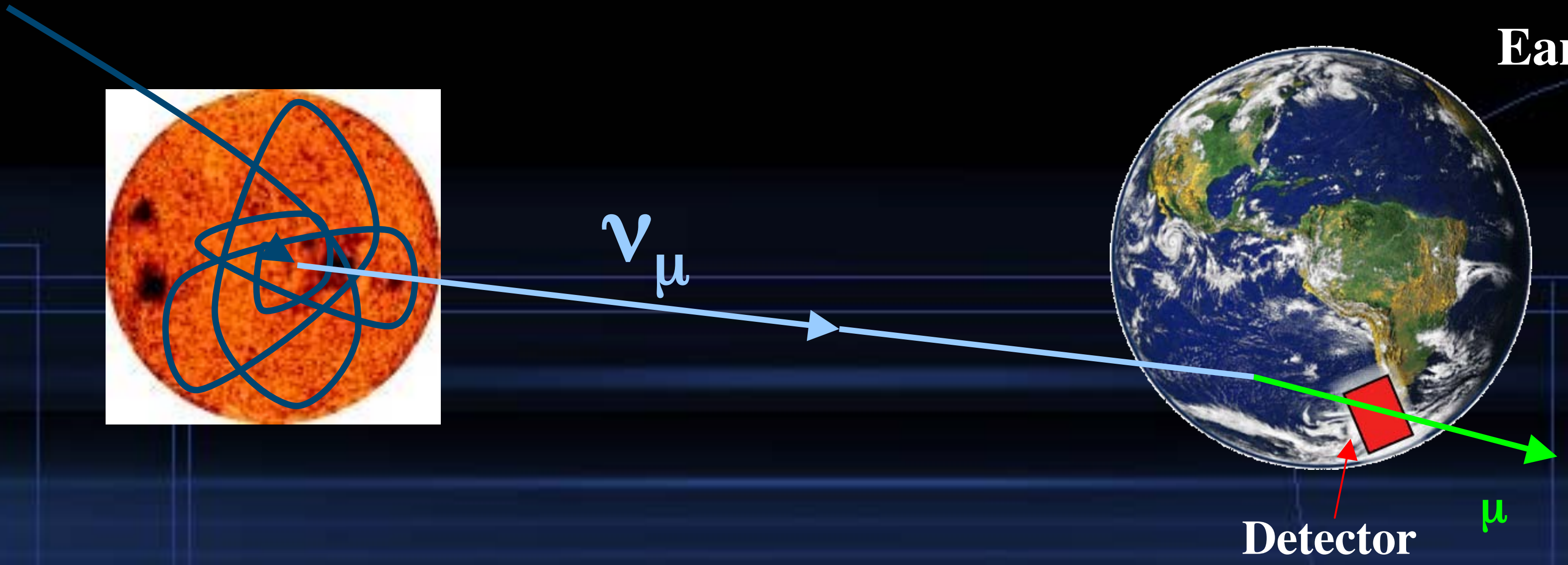


<u>Limitation at low energies:</u>
-Short muon range
-Low light yield
-^{40}K (in water)

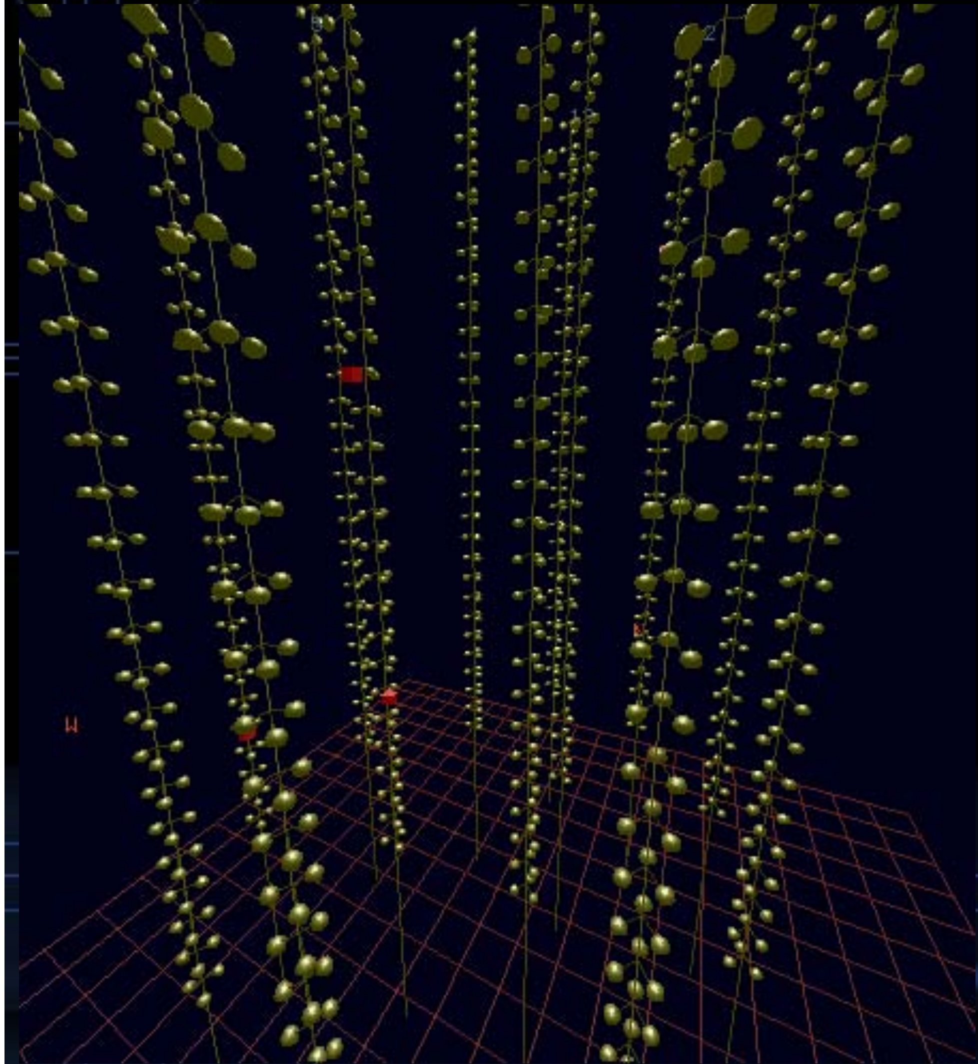
Detector density

Dark matter

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would accumulate in massive objects like the Sun, the Earth or the Galactic Center
- The products of such annhiliations would yield “high energy” neutrinos, which can be detected by neutrino telescopes
- In the Sun a signal would be very clean (compared with gammas from the GC, for instance)
- Sun travel in the Galaxy makes it less sensitive to non-uniformities

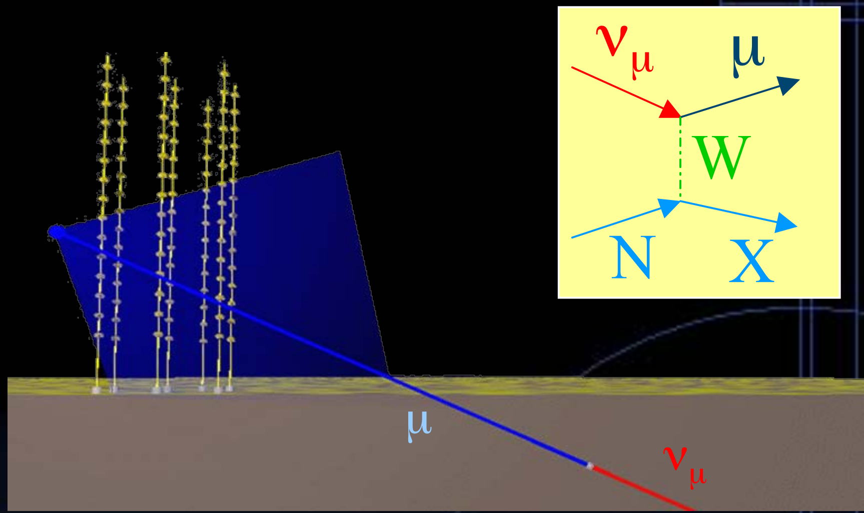


Detection principle of optical Cherenkov detectors



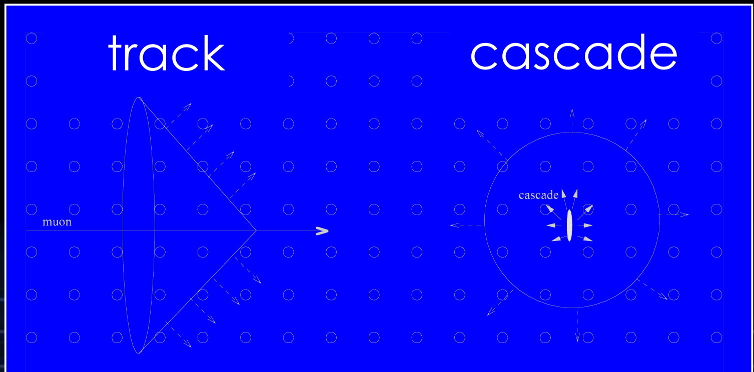
1.2 TeV muon traversing ANTARES

- The neutrino is detected by the Cherenkov light emitted by the muon produced in the CC interaction.



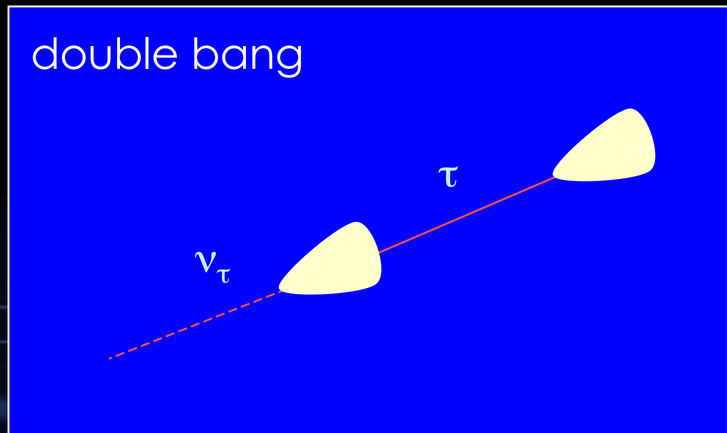
Other Signatures

- Cascades are an important alternative signature: detection of electron and tau neutrinos.
- Also neutral interaction contribute (only hadronic cascade)

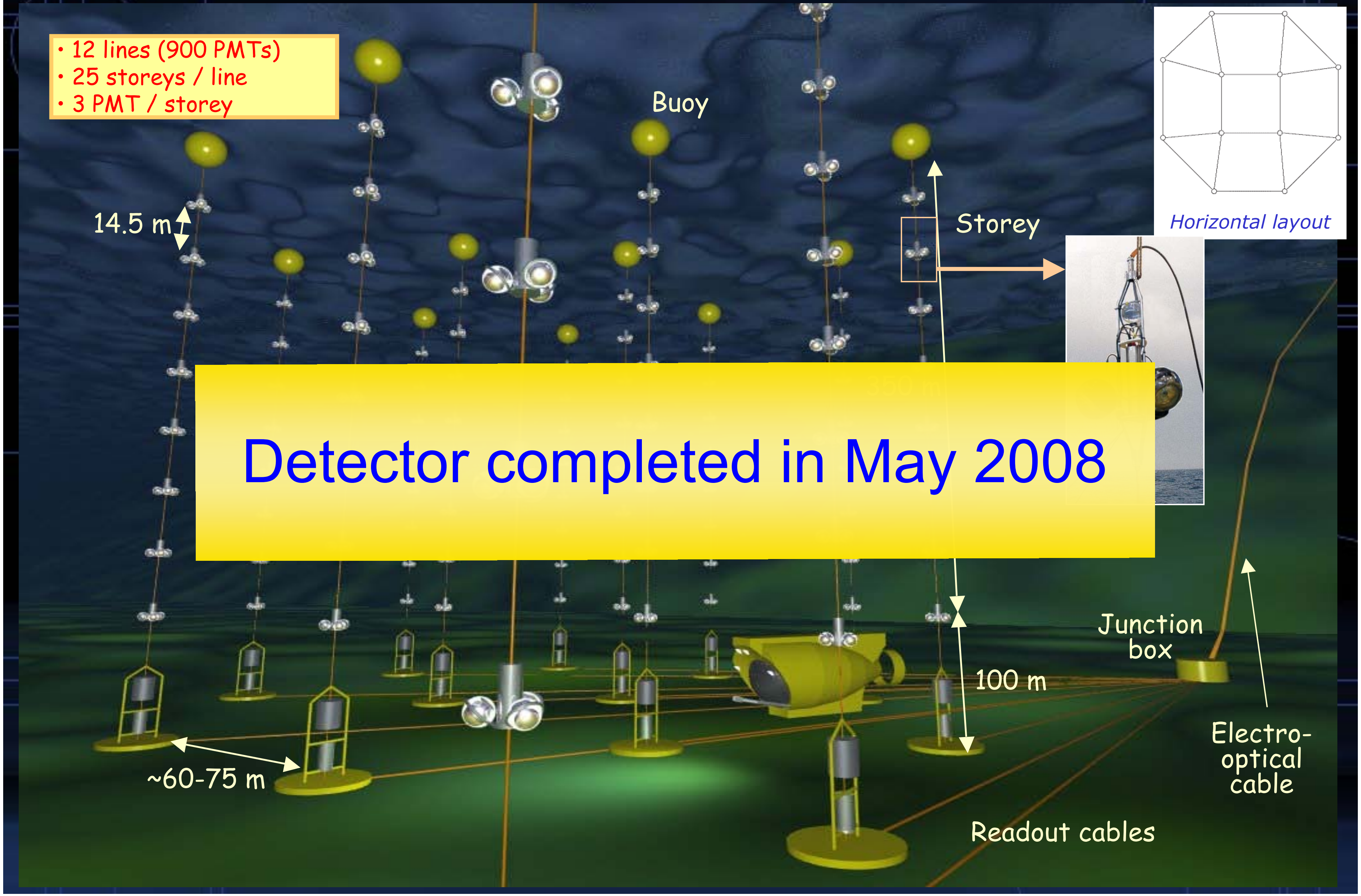


1 km at 300 GeV 25 km at 1 PeV	5-10 m long diameter ~ 10 cm

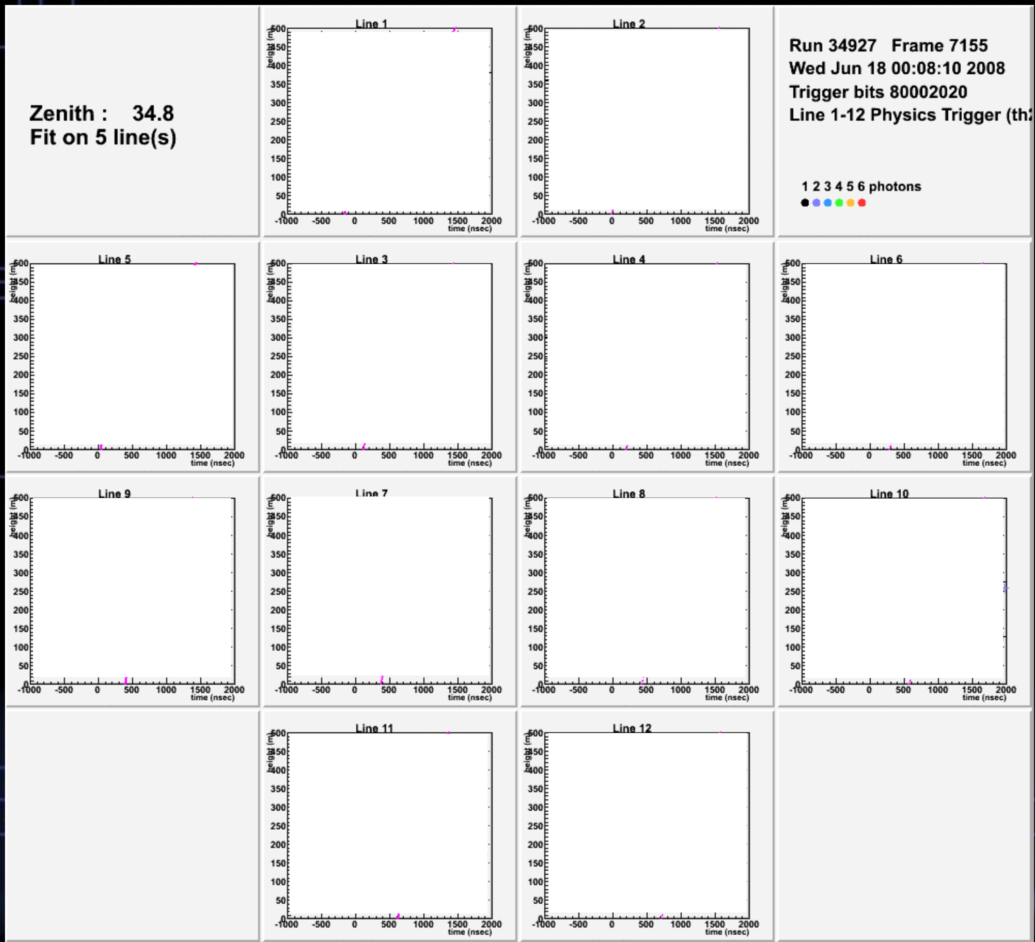
- Clear signature of oscillations.
- ANTARES & AMANDA are too small to detect double bang signature (they are too rare)
- However, cubic-kilometer telescopes could detect them.
- Maximum sensitivity at 1-10 PeV



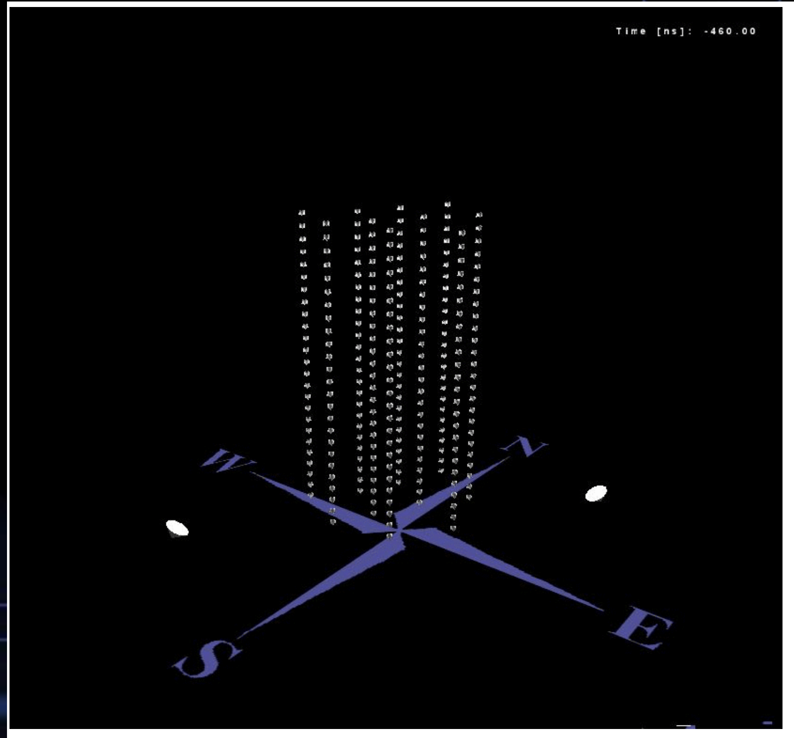
The ANTARES detector



Neutrino candidate



Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:

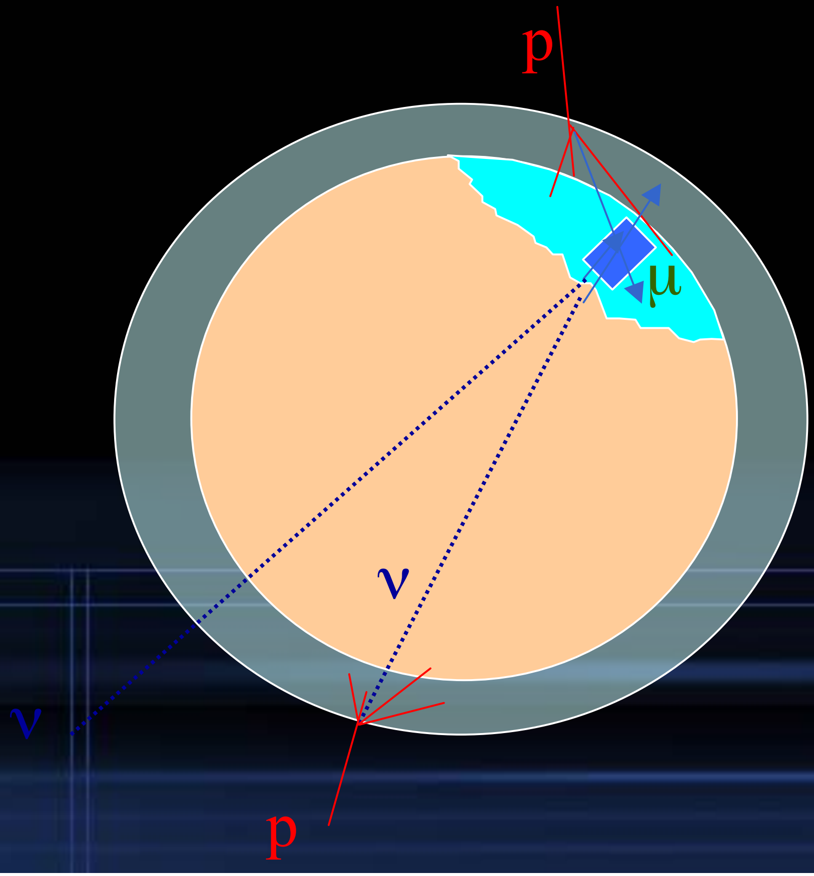


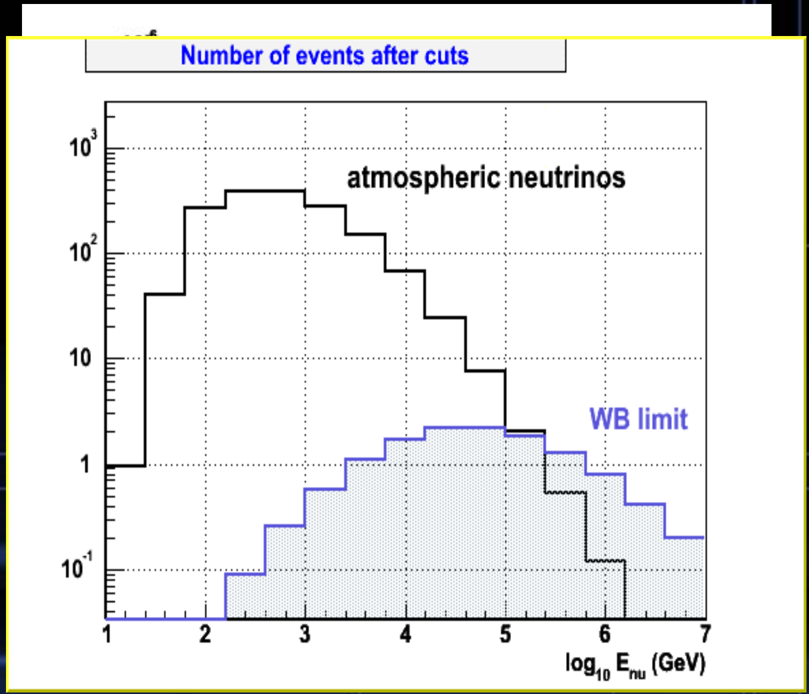
Physical Background

- There are two kinds of background:
  - -Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events).
  - -Atmospheric neutrinos (cut in the energy).

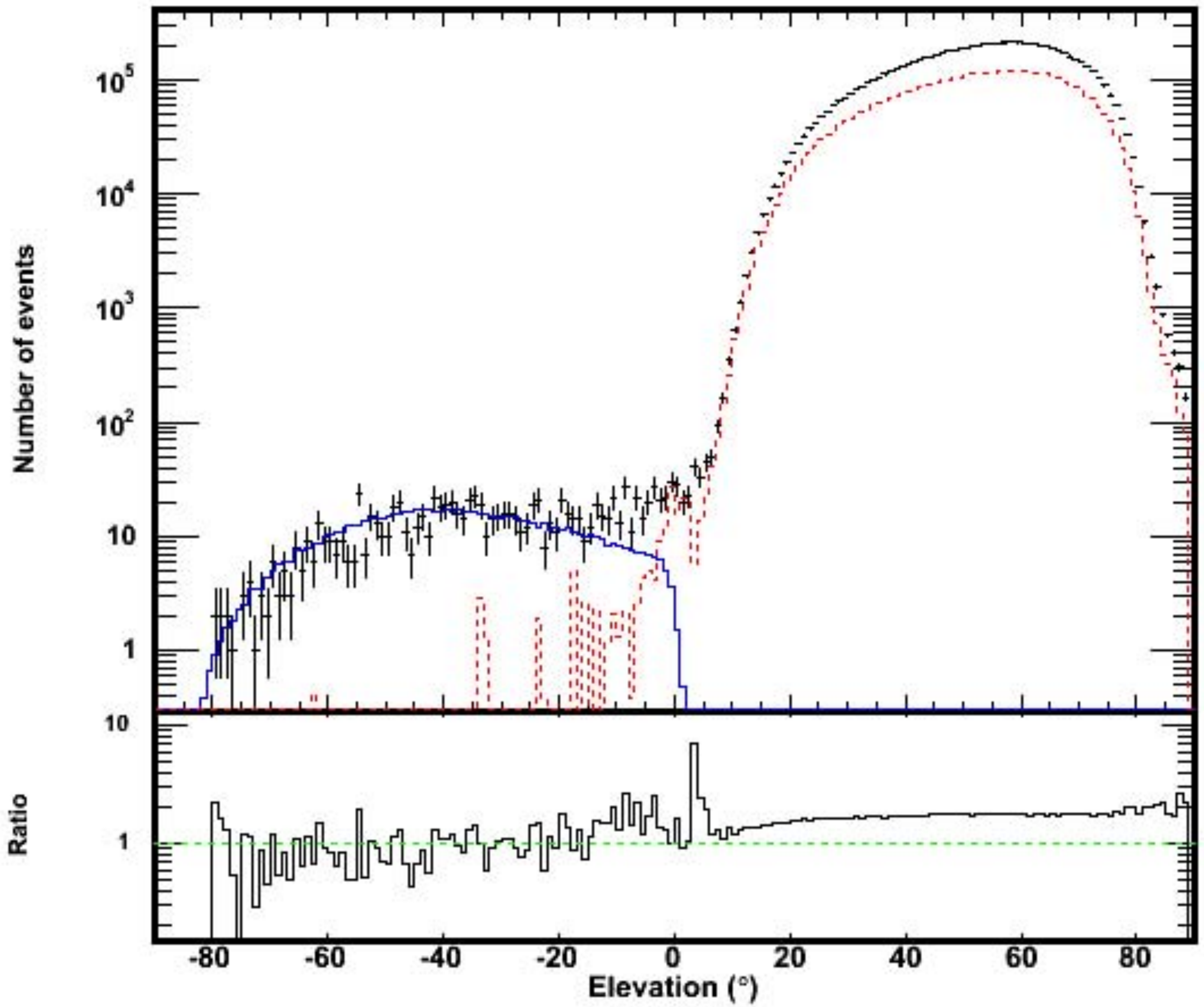
$$p \rightarrow \pi^+(+K^+...) \rightarrow \mu^+ + \nu_\mu$$
$$\mapsto e^+ + \bar{\nu}_\mu + \nu_e$$

$$n \rightarrow \pi^-(+K^-...) \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mapsto e^- + \nu_\mu + \bar{\nu}_e$$

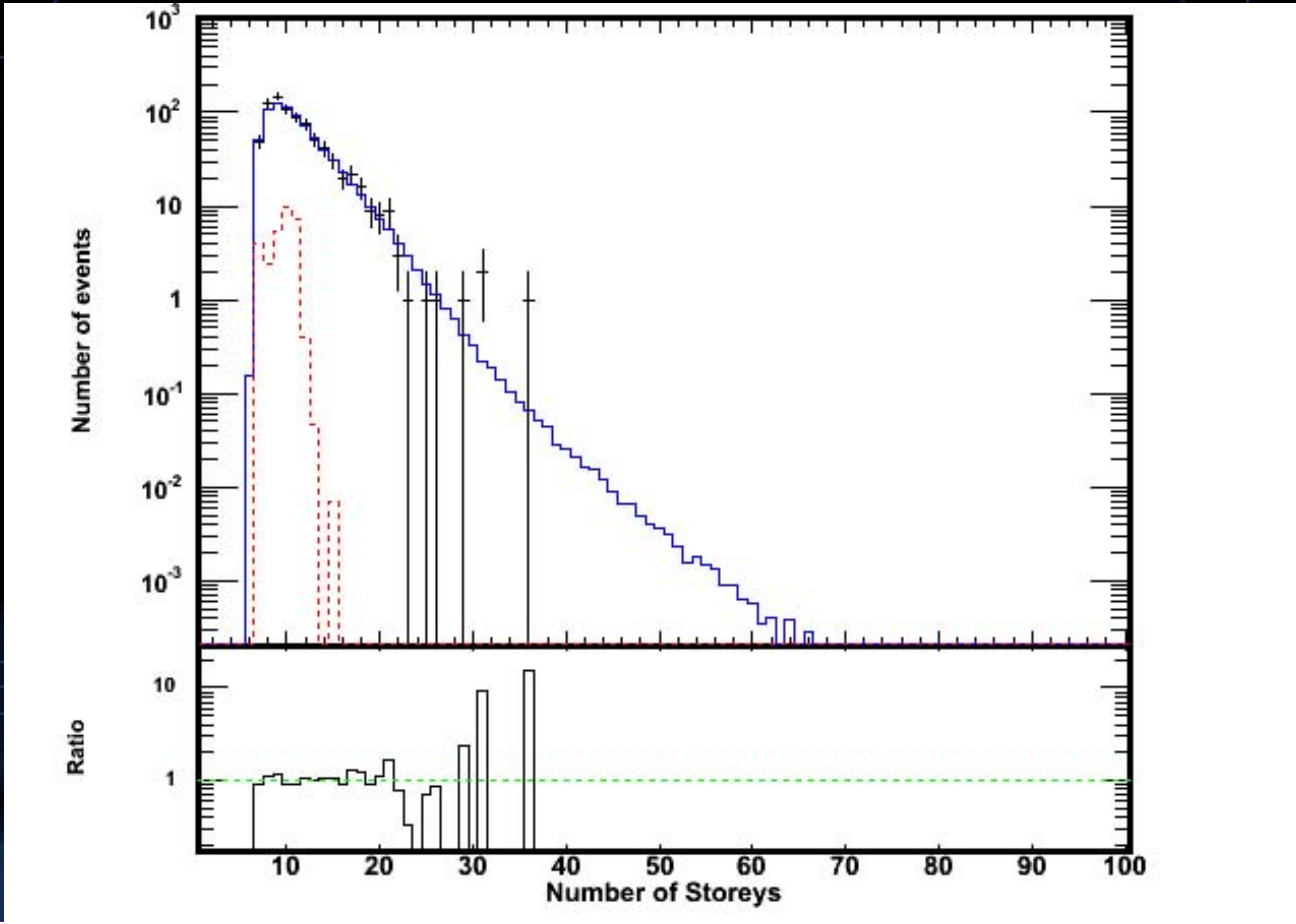




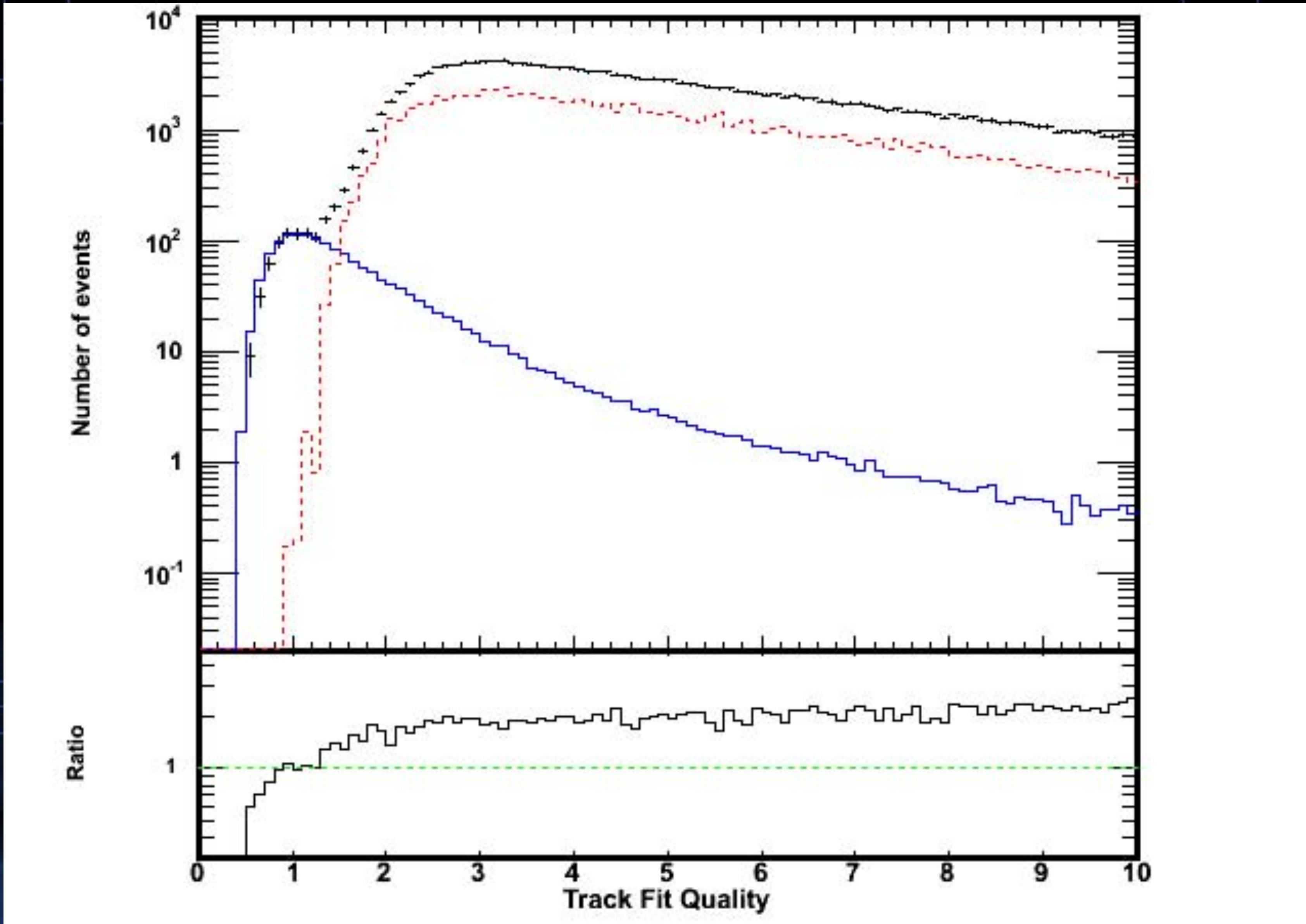
Data vs MC: elevation



Data vs MC: amplitude

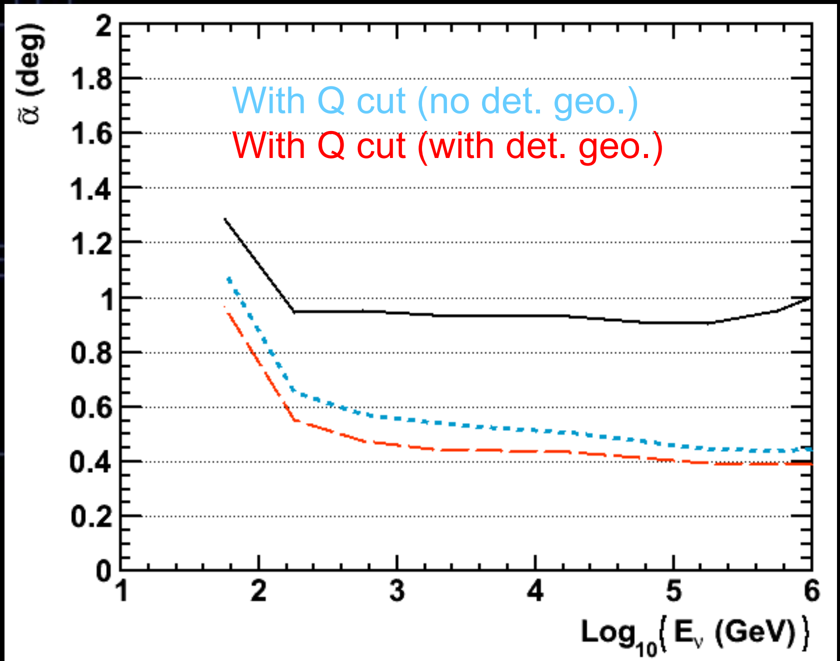


Data vs MC: fit quality

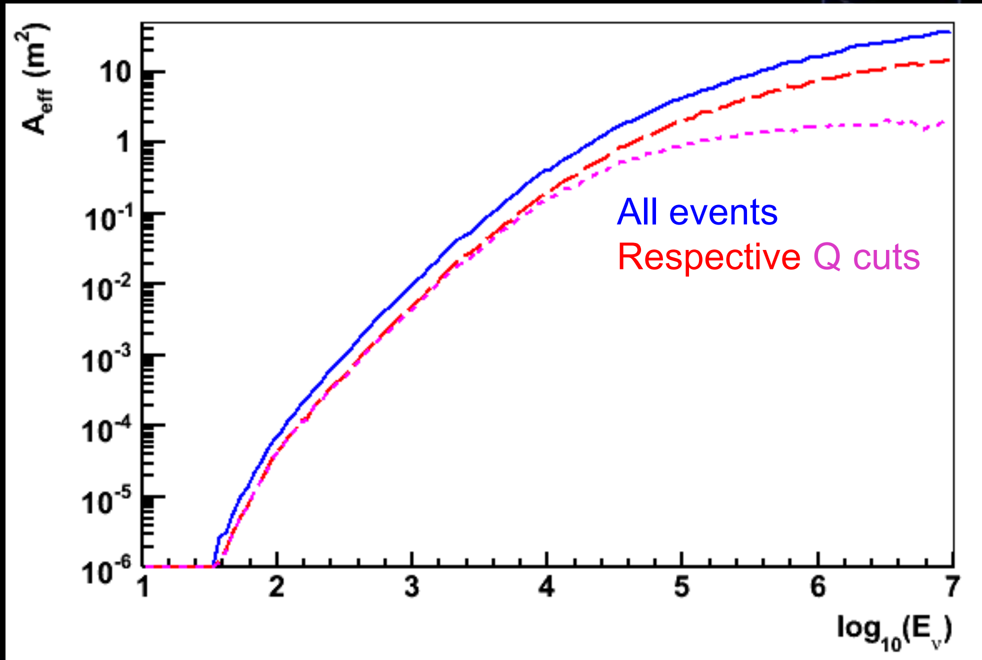


Detector performance

Angular resolution



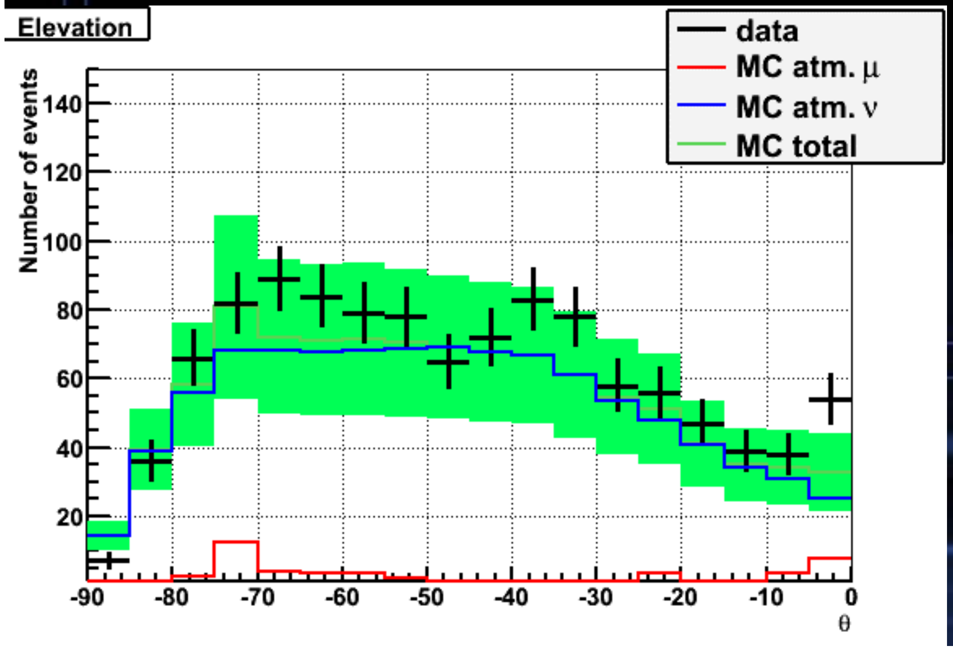
Effective area



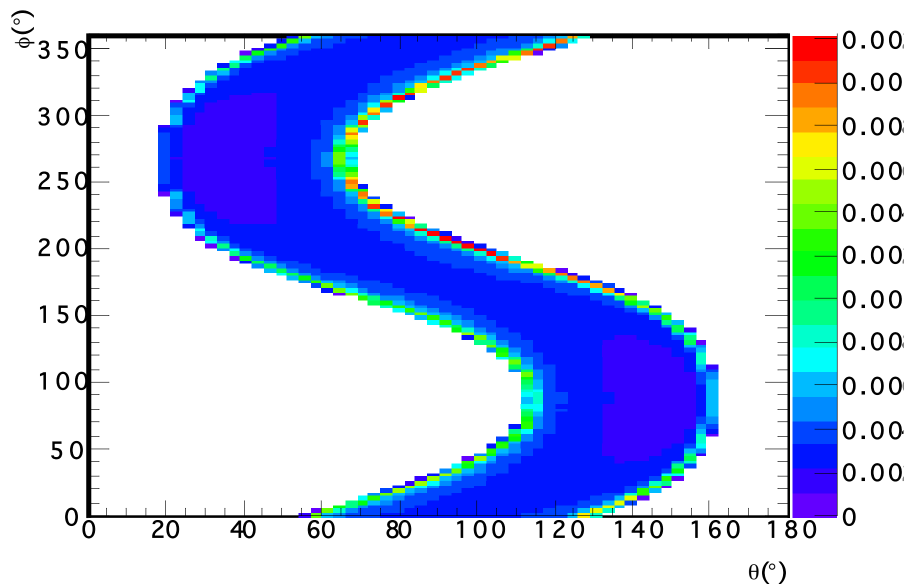
Data scrambling

- Cut are optimized using scrambled data:
  - Less systematic effects
  - Blinding policy to avoid bias
- Data scrambled in (theta, phi), time (Modified Julian Date)
- Sun distribution is weighted by its visibility for ANTARES

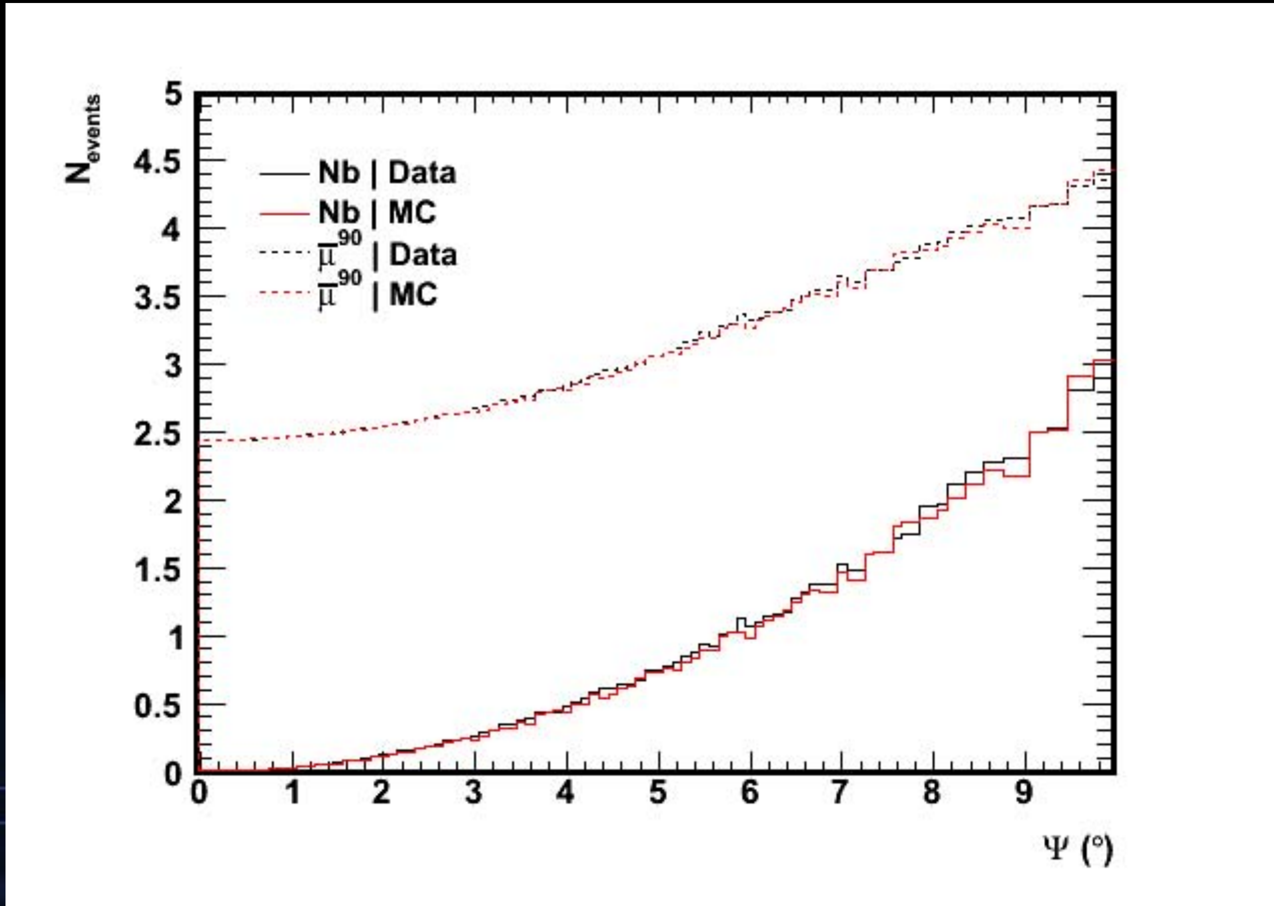
All upward-going events from 2007-2008 data



Example of Sun tracking in horizontal coordinates

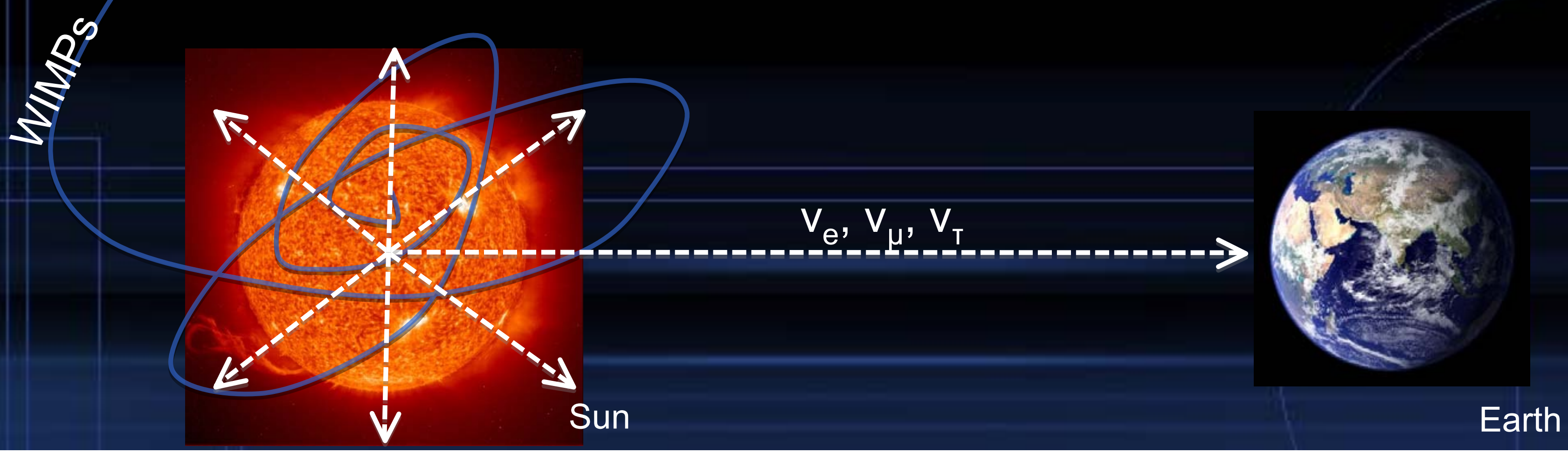


Data analysis in the Sun direction



Dark Matter Simulation

- The WIMPSIM package (Blennow, Edsjö, Ohlsson, 03/2008) is used to generate events in the Sun in a model-independent way.
- Great statistics: with 3×10^6 WIMPs annihilations
- Capture rate and annihilations in equilibrium at the Sun core
- Annihilations in c,b and t quarks, τ leptons and direct channels
- Interactions taken into account in the Sun medium
- Three flavors oscillations, regeneration of τ leptons in the Sun medium (Bahcall et al.)
- Available parameters: WIMPs mass, oscillations parameters, ...

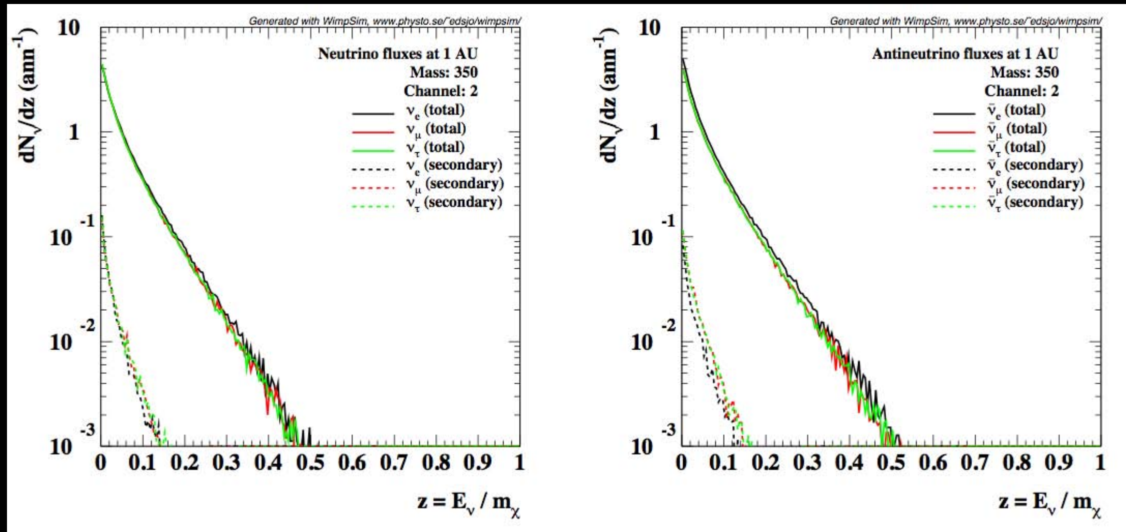


Main annihilation channels (I)

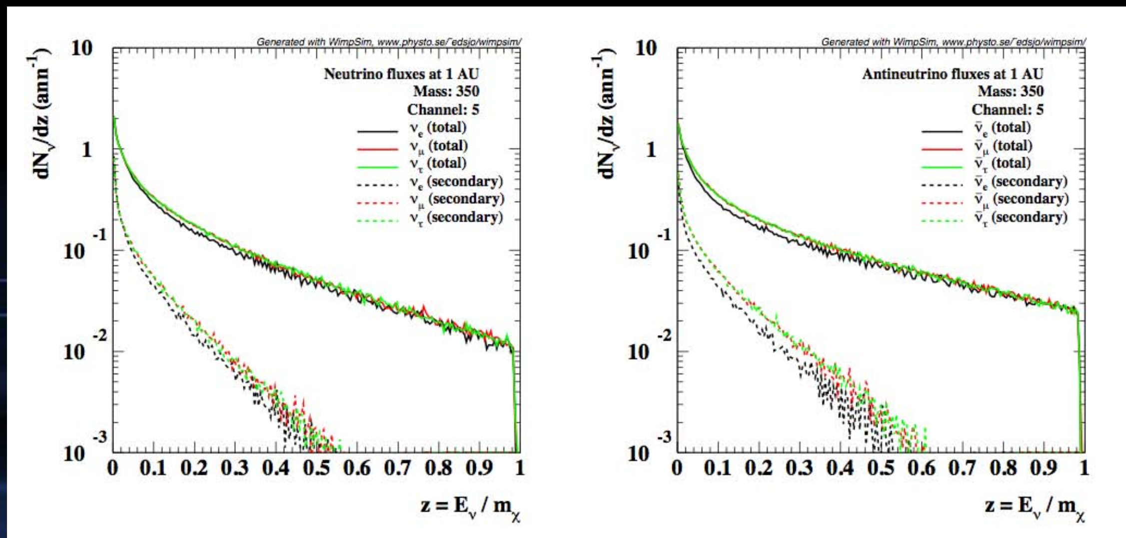
nu anti-nu

M_{WIMP} = 350 GeV

bb →



WW →



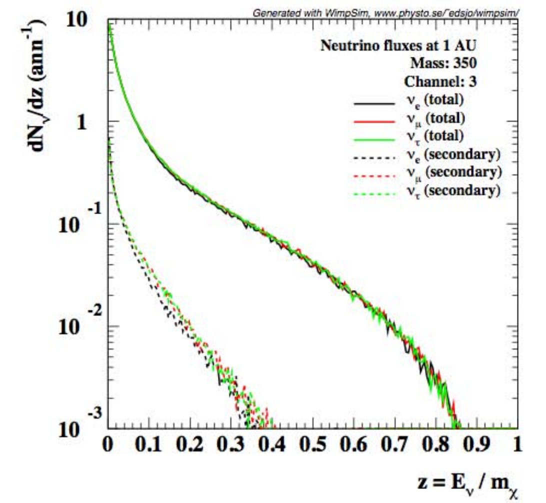
Main annihilation channels (II)

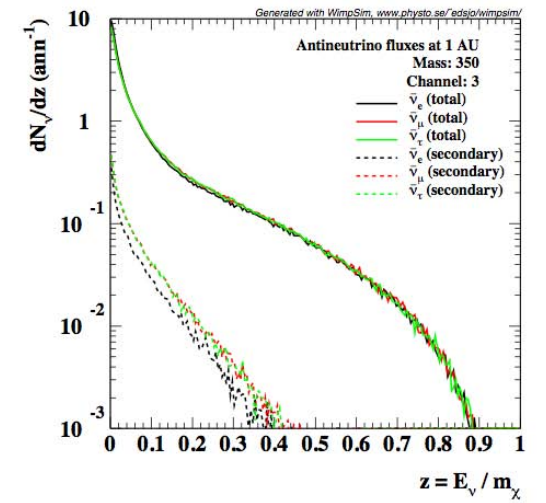
nu

anti-nu

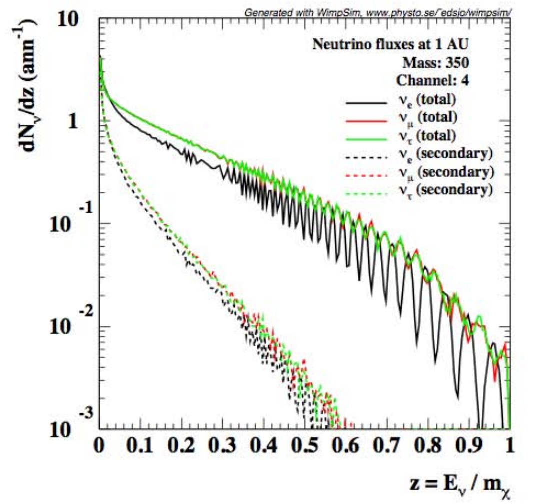
M_{WIMP} = 350 GeV

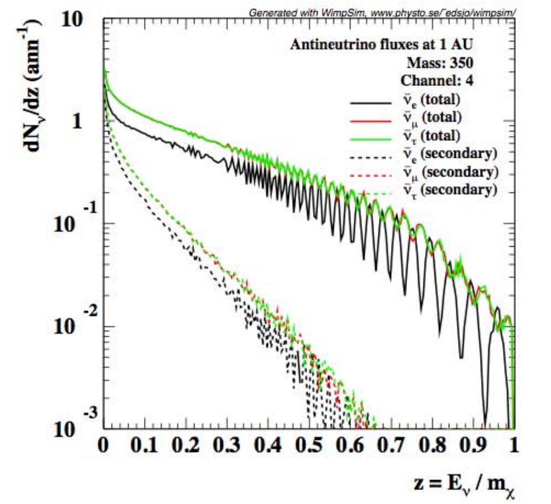
$t\bar{t}$ →





$\tau\tau$ →





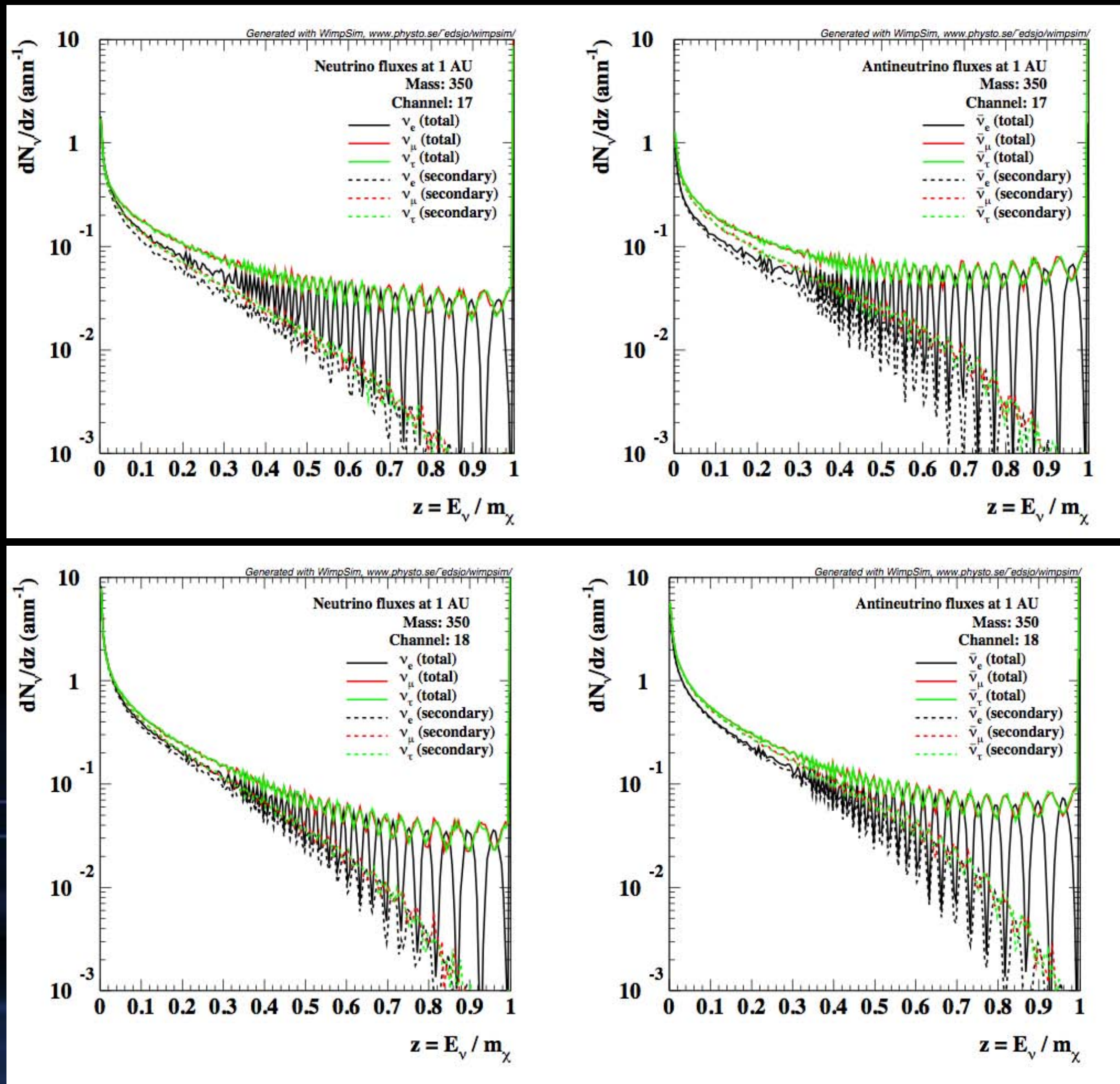
Main annihilation channels (III)

nu anti-nu

M_{WIMP} = 350 GeV

$\nu_\mu \nu_\mu$ →

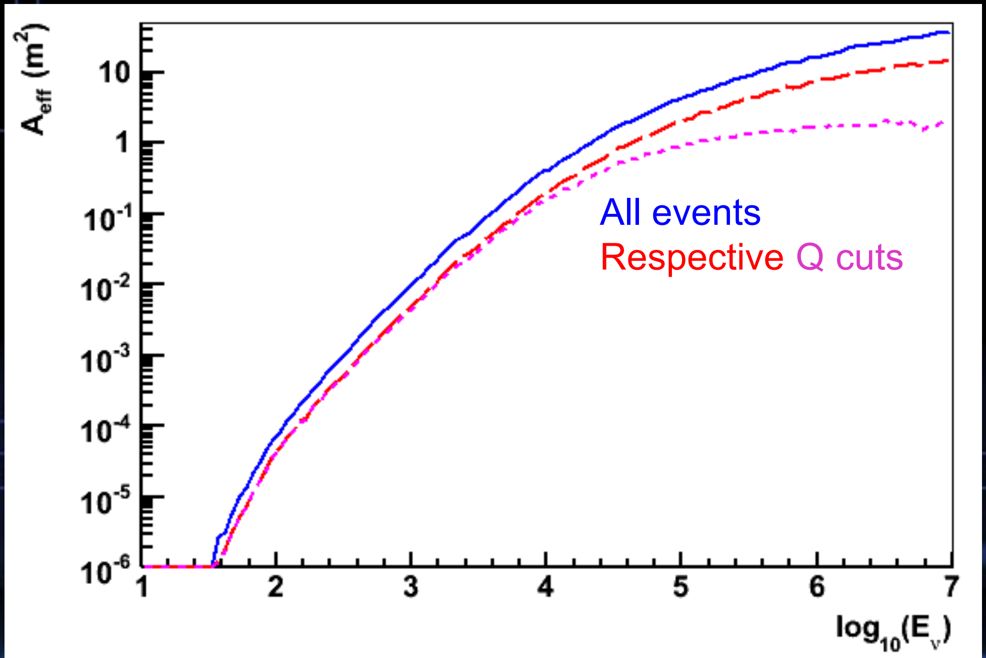
$\nu_\tau \nu_\tau$ →



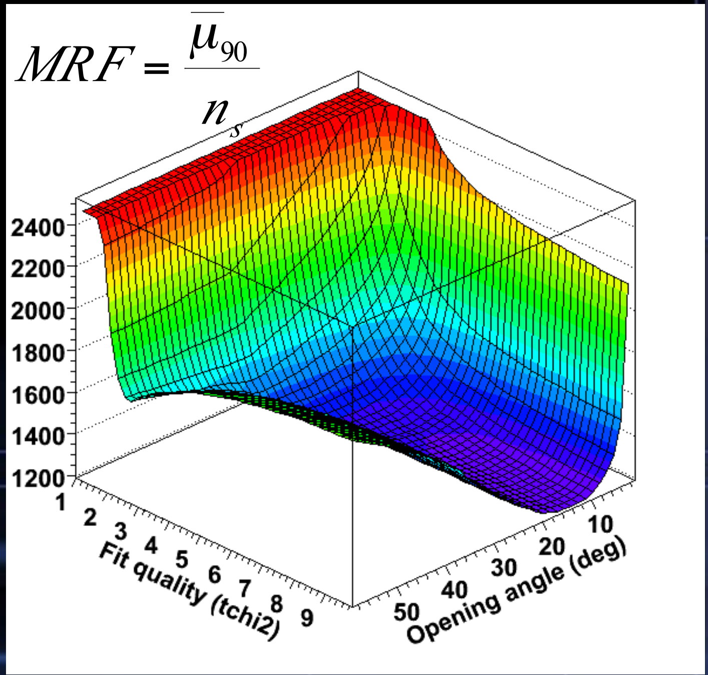
Dark Matter Signal and cuts optimisation

- Neutrino flux at the earth, from the dark matter annihilation, are convoluted with the efficiency of the detector for a cuts parameter space (Q,cone)
- Neutrino background from the scrambled data in the Sun direction is evaluated in the same space
- Optimize cuts by minimizing the Model rejection Factor (ratio between the average upper limit and the dark matter signal evaluated)
- A set of (Q,cone) is defined for each value of WIMP mass…

Effective area to be estimated for different sets (Q,cone)



MRF minimization in (Q,cone) plan



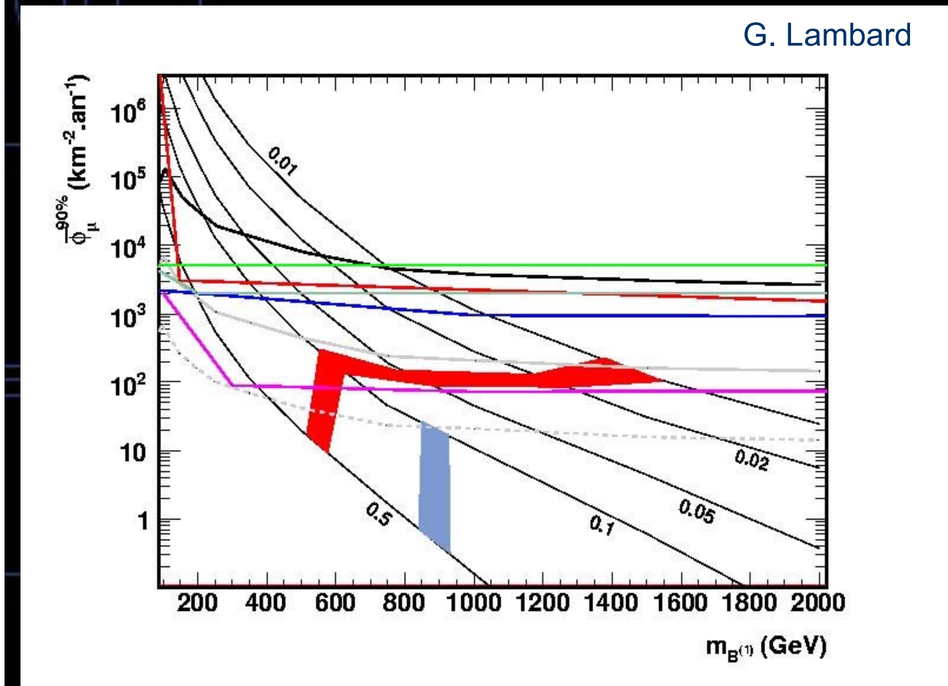
Signal computation method

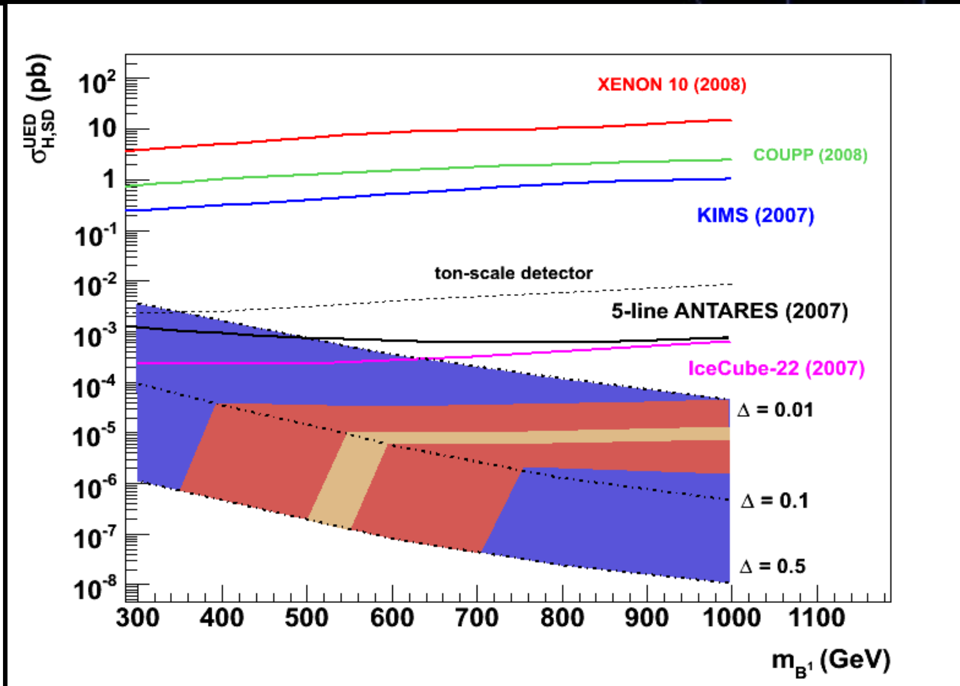
- Usually, we need :
  - Flux at the surface of the Earth
  - Capture rate into the Sun, dependent on the SD, SI cross-section
  - Annihilation rate ~ 0.5 * C (equilibrium condition)

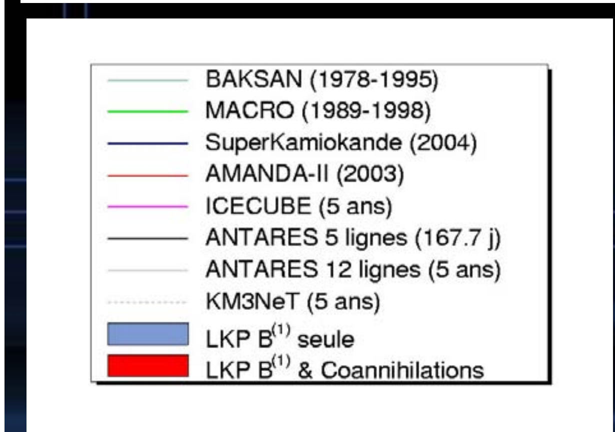
$$\frac{d\varphi}{dEd\Omega} = \frac{\Gamma}{4\pi d^2}\sum_{\iota} B_{\iota}\frac{dN_{\iota}}{dE_{\iota}}$$

  - Flux from WIMPSIM (see previous plots)
  - Cross-section from analytic computation or simulation in the parameter space of the models
  - Branching ration:
    - For Kaluza-Klein, branching ratio not so dependent on the location in the parameter space R, Δ, and SM Higgs mass m_h
    - For CMSSM: equilibrium in the Sun well/not reached, SD/SI very dependent on the parameter space, branching ratios very dependent, main channel chosen is not so obvious -> large systematic errors from the sensitivity computed

Kaluza-Klein (5 lines)







From 5-line scrambling data constraints in (Δ,m_{LKP})

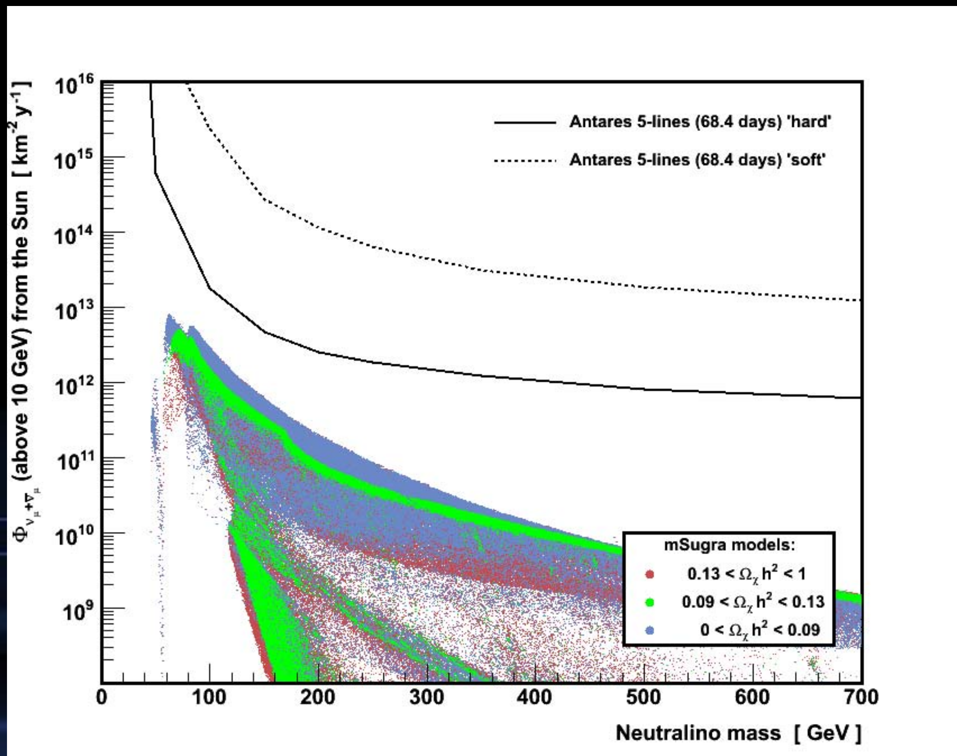
Prospectives for 12-line (5 years)
Closed to the WMAP constraints

Allowed (Δ,m_{LKP})
$0.05 < \Omega_{CDM}h^2 < 0.20$
$0.1037 < \Omega_{CDM}h^2 < 0.1161$ (WMAP, 1σ)

IceCube-22 (~104 days)
ANTARES 5-line (~135 days)
XENON 10, COUPP (2008)
KIMS (2007)

Neutralino (5 lines)

- mSUGRA parameter space not reached yet but…
  - only 68 active days included in this analysis and
  - only ~half of the detector

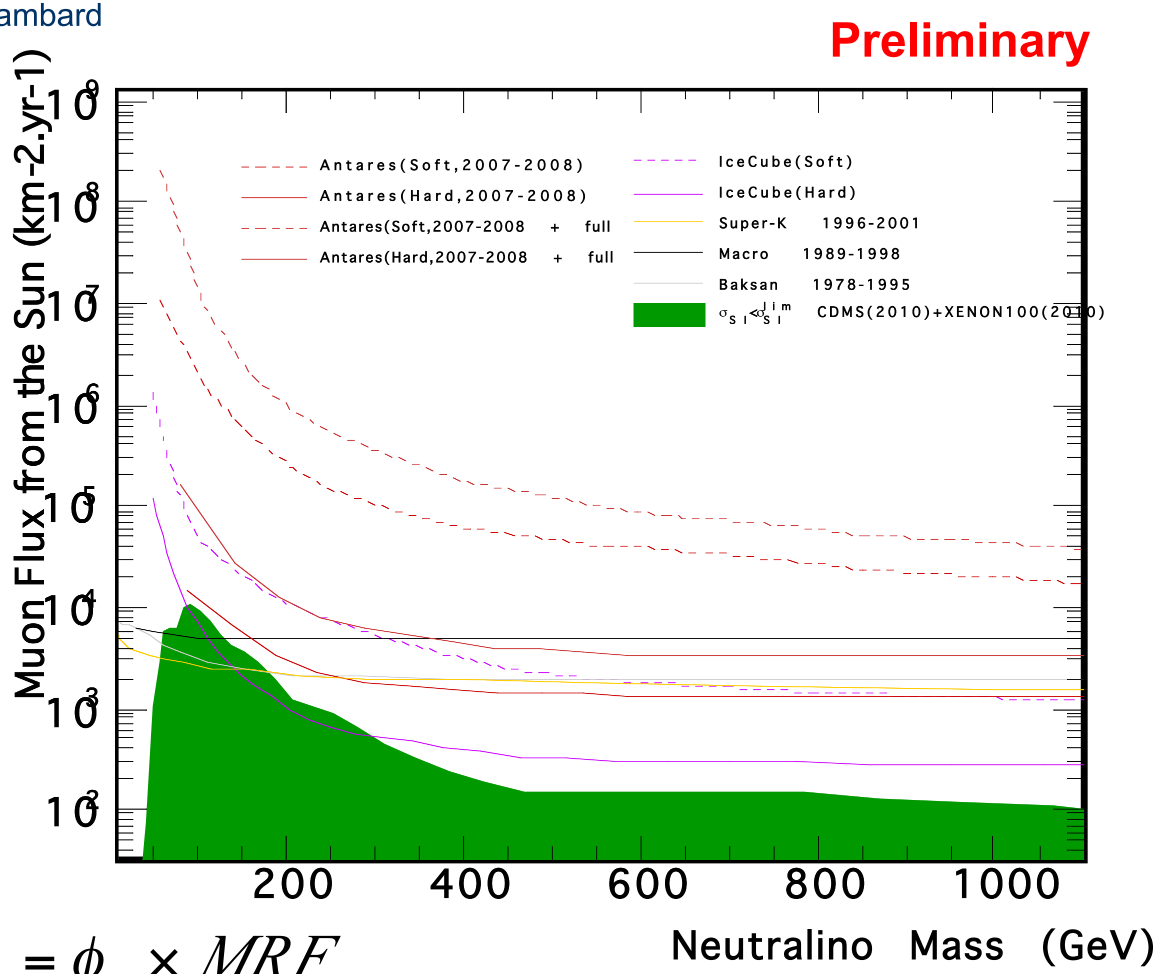


hard=WW
soft=bb

Dark Matter muon flux sensitivity

- Dark Matter neutrino flux multiplied by the MRF minimized reaches to the best sensitivity with ANTARES using 2007-2008 scrambled data

G. Lambard

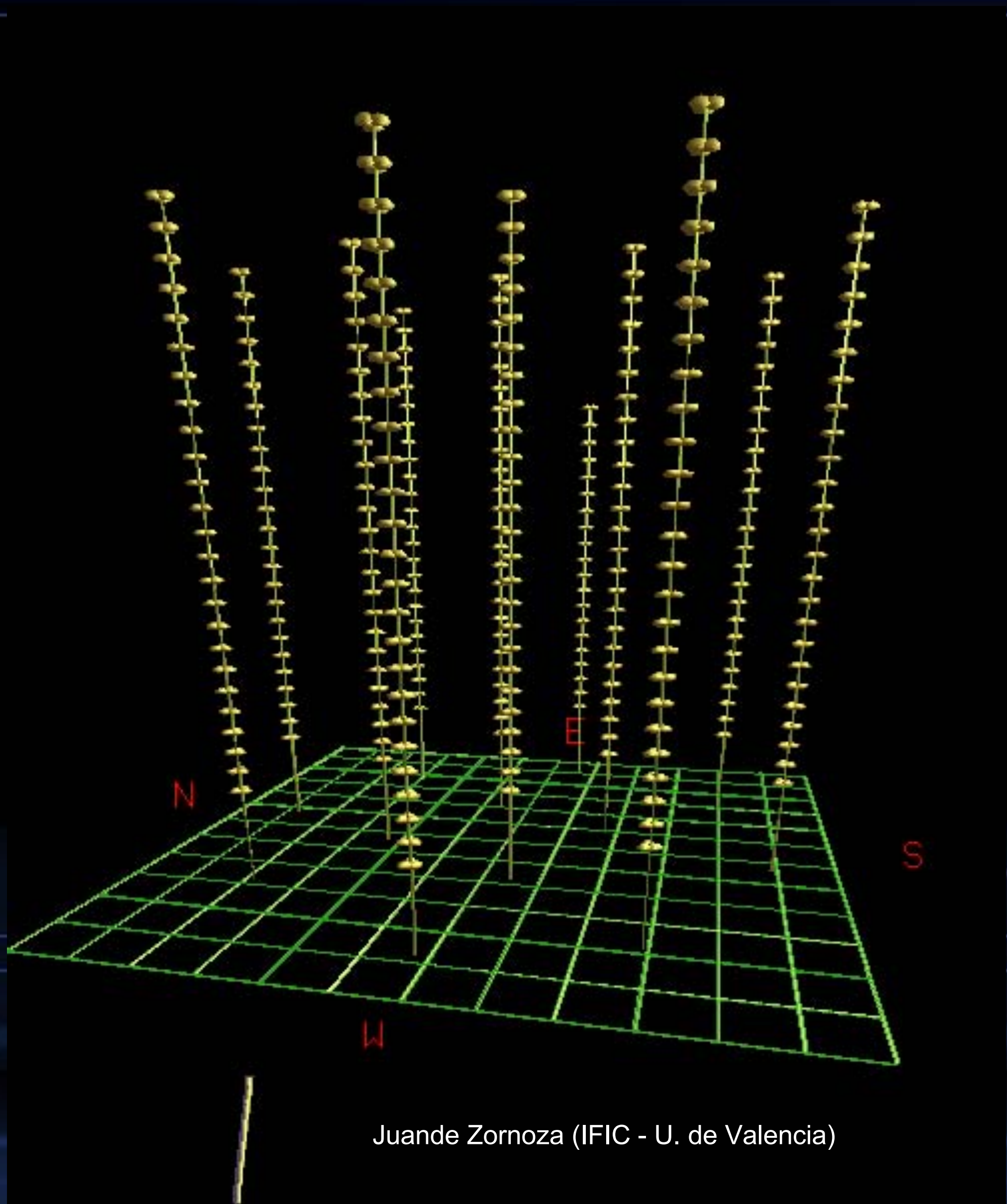


$$\overline{\phi}_{\mu}^{90} = \phi_{\mu} \times MRF$$

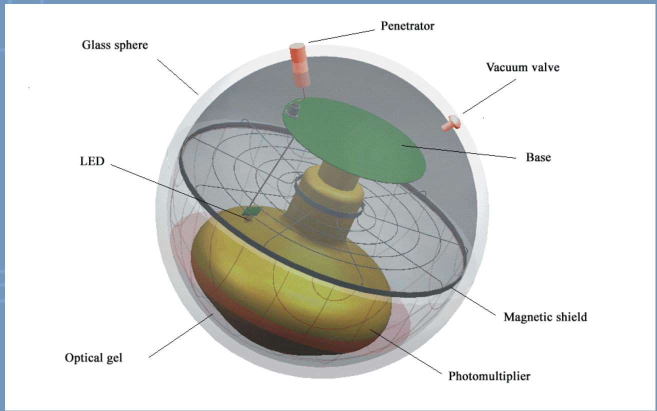
Conclusions

- Dark matter is a major goal for neutrino telescopes
- ANTARES is a technical success, after three years of data taking with the whole detector
- Several analysis possible: Sun, Earth, Galactic Center, Galactic Halo, dwarf galaxies
- Both neutralino and Kaluza-Klein models can be probed
- First limits with 5 line data already set
- Limits with the whole detector will come soon (this summer)

Neutrino candidate with 12-line detector

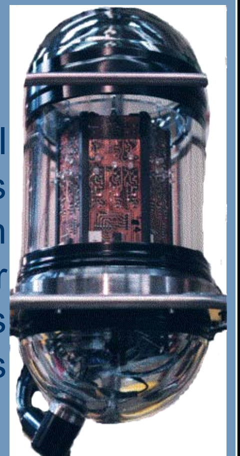


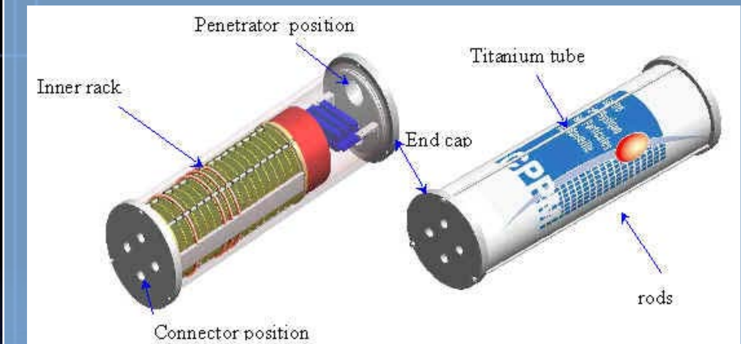
Detector elements



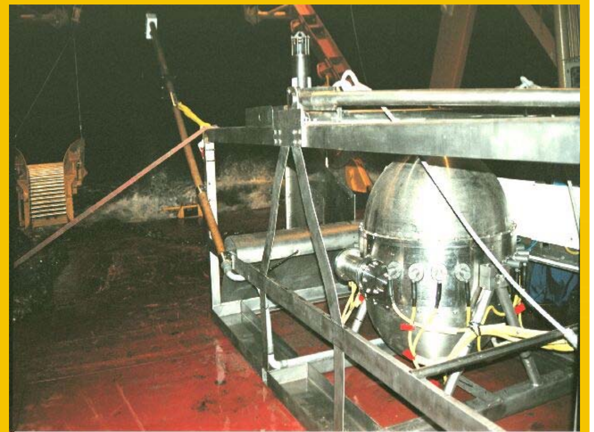
The Optical Module contains a 10” PMT and its electronics

The Optical Beacons allows timing calibration and water properties measurements





The Local Control Module contains electronics for signal processing



It receives power from shore station and distributes it to the lines. Data and control signals are also transmitted via the JB.

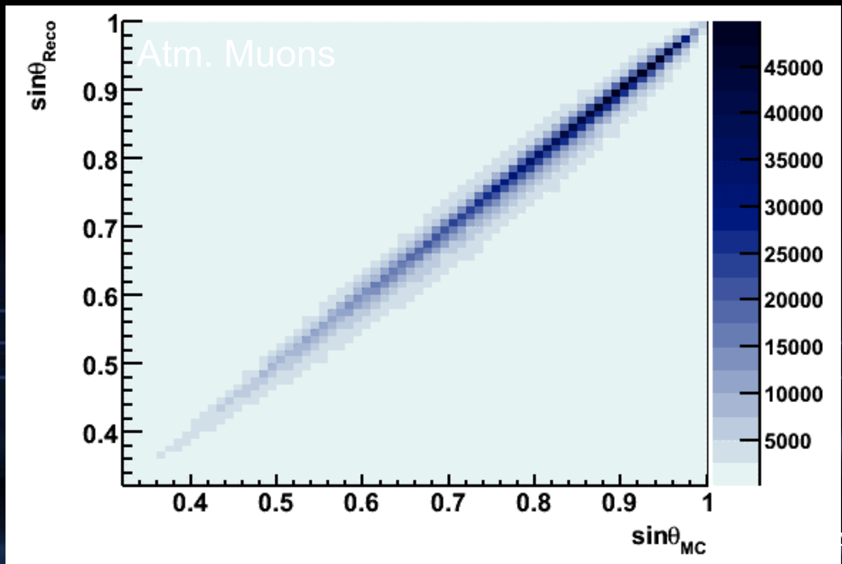
It provides power and data link between the shore station and the detector (40 km long)

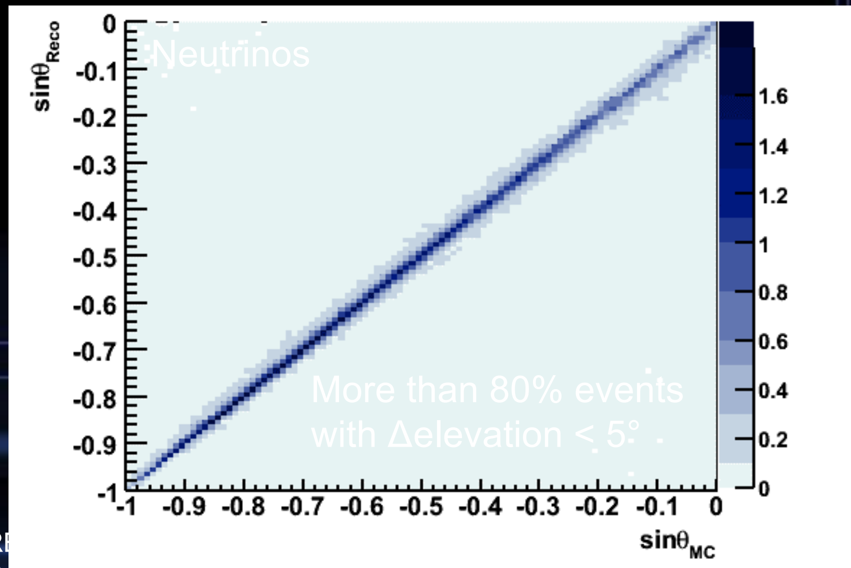
Fast algorithm and Monte-carlo/Data comparions I

- Fast and robust reconstruction of neutrino induced upward-going muons discriminated from downward-going atmospheric muon background
- Algorithm of reconstruction is employed to a hit merging and hit selection procedure by fitting steps for a track hypothesis and a point-like light source
- Point-like light source in the detector approximate light from hadronic and electromagnetic showers, to be discriminated from muon tracks
- Main quality function Q simillar to a standard χ^2 fit based on the arrival hit times from a track or a bright point

For more details: « A fast algorithm for muon track reconstruction and its application to the ANTARES neutrino telescope », Astro. Phys. 34 (2011) 652-662

FROM MC

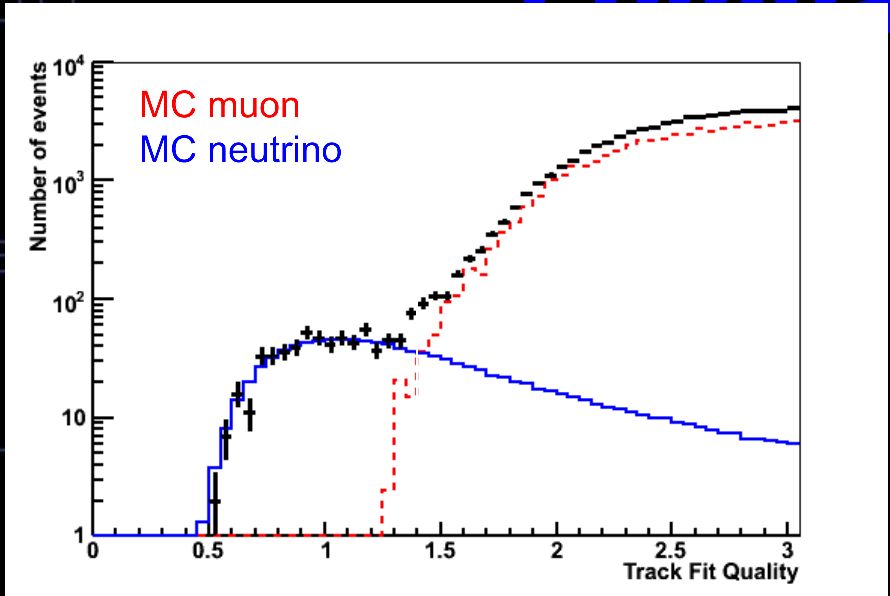




Fast algorithm and Monte-carlo/Data comparisons II

Comparison MC(μ+ν)/Data

In the Track Fit Q plan



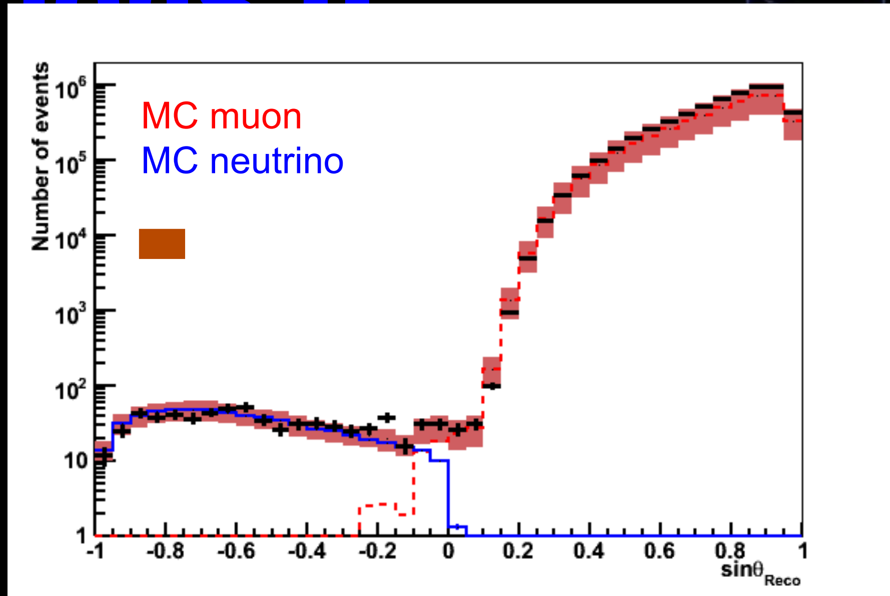
Just upward-going multi-line tracks are considered

For example : for Q < 1.4, purity at 90% in neutrino

All systematics taken into account, data are compatible with the chosen flux models for the atm. neutrinos and muons

The reconstruction procedure is enough robust to be used for the present study

As a function of Sin(Elevation) reco.

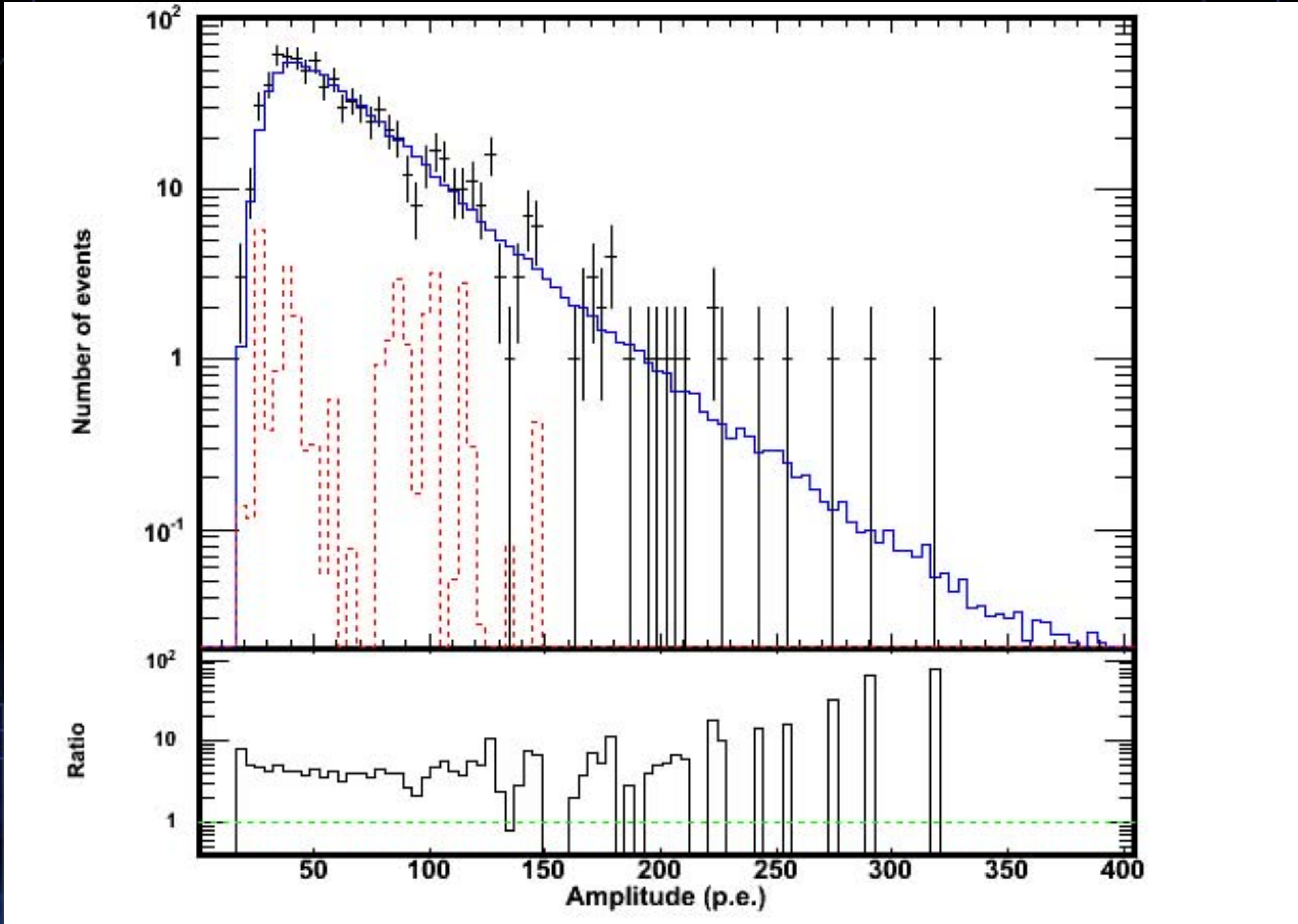


Excellent agreement atm.ν_{MC}-data is observed in the upward-going dial

30% excess of data observed with respect to the atm.μMC

Systematic errors from PMTs effective area, water absorption, PMTs angular acceptance

Data vs MC: hit amplitude



SuperBayes v1.35

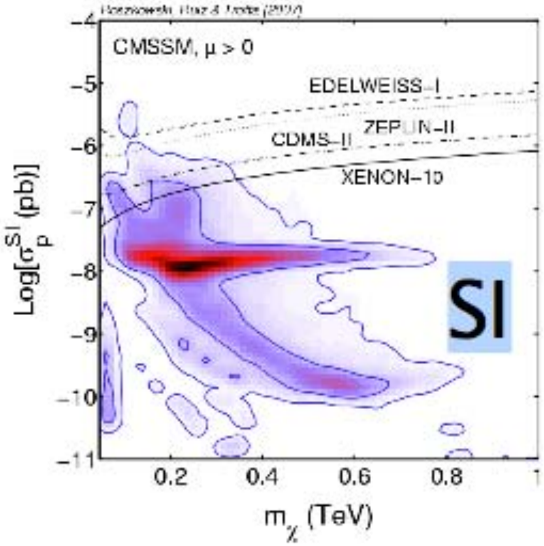
Supersymmetry Parameters Extraction Routines for Bayesian Statistics

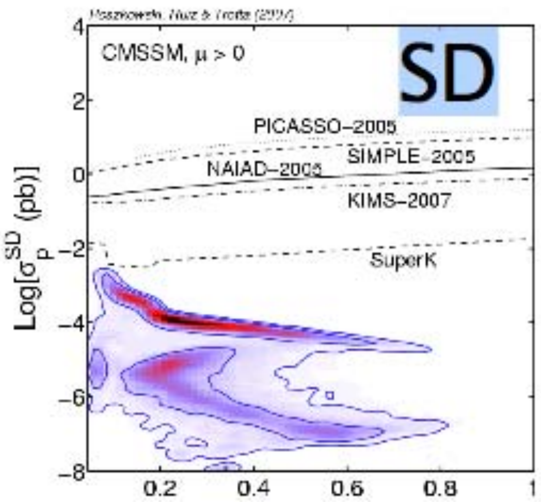
- Multidimensional SUSY parameter space scanning
- Compare SUSY predictions to observables as sparticles masses, collider observables, dark matter relic density, direct detection cross-sections, …
- Using a new generation Markov Chain Monte Carlo for a full 8-dim scan of CMSSM
- Using PISTOO farm at cc-Lyon to run it

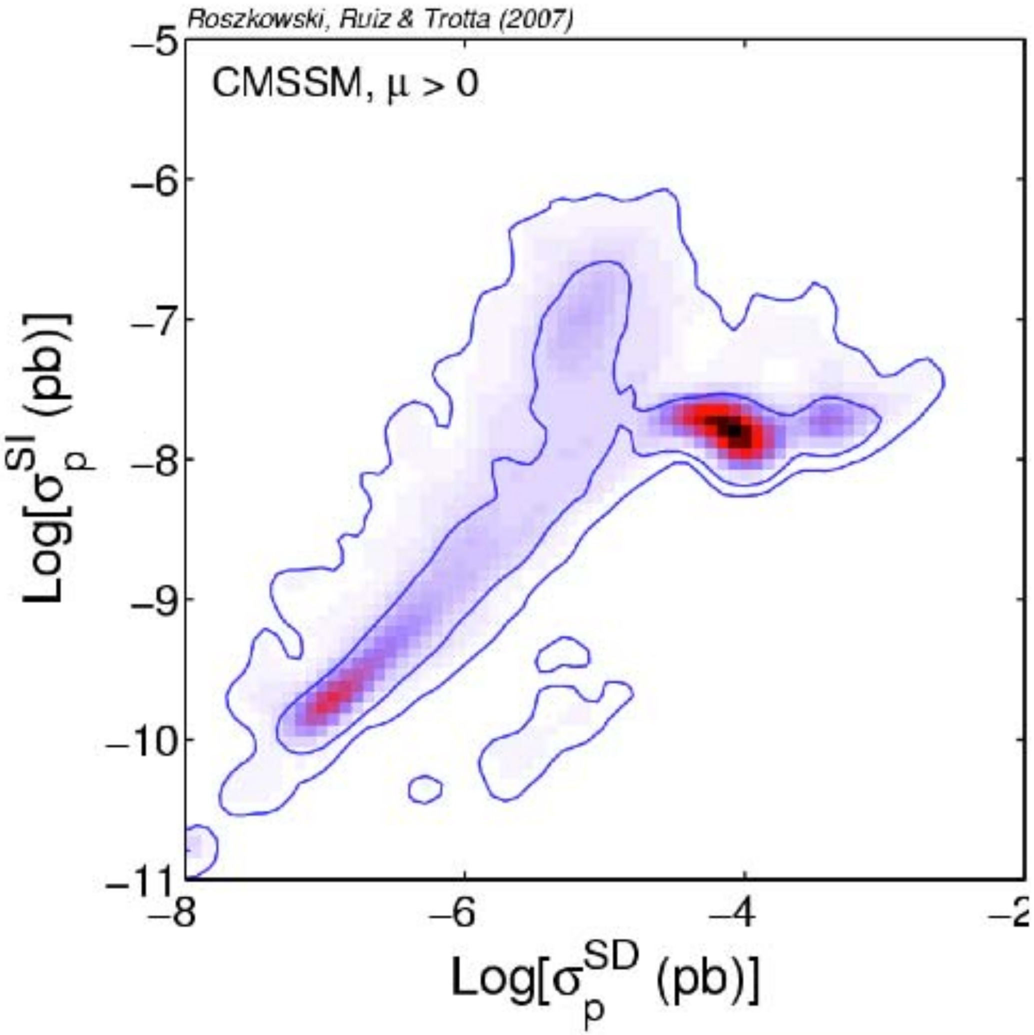
- Well documented (articles, Website), as DarkSUSY package

- Parameter set of CMSSM (m_0, $m_{1/2}$, A_0, $\tan\beta$)
- Nuisance parameters from SM (m_t, m_b, α_{em}, α_s)

SuperBayes v1.35







Dark Matter,

Phenomenological model UED

- First gravity-electromagnetism unification : T. Kaluza, 1921

➔ 1 metric extra-dimension

- models evolution, taken into account : weak and strong fields.
  ADD (Arkani-Hamed, Dimopoulos, Dvali) and RS (Randall-Sundrum) models
  ➔ 1 or n metric extra-dimensions compactified with a radius R
- gravity propagation inside the extra-dim can explain its weakness
- if R is enough tiny, each field can propagate in the extra-dim

- UED (Universal Extra-Dimension) model : space-time with (3+1) dimensions (brane) evoluates in 3+1+(δ = 1) (bulk), all SM fields propagate in the bulk
  ✓ mass hierarchy problem : Planck scale reduced around electroweak scale
- field decomposition in Fourier modes in the bulk, Kaluza-Klein (KK) states appear in the brane like KK towers such a mass spectrum

$m_n \alpha\ n / R$, n modal index

Interest : production of stable candidates for the dark matter nature…

Dark Matter,

Phenomenological model UED

Mass spectrum of KK states at first level :

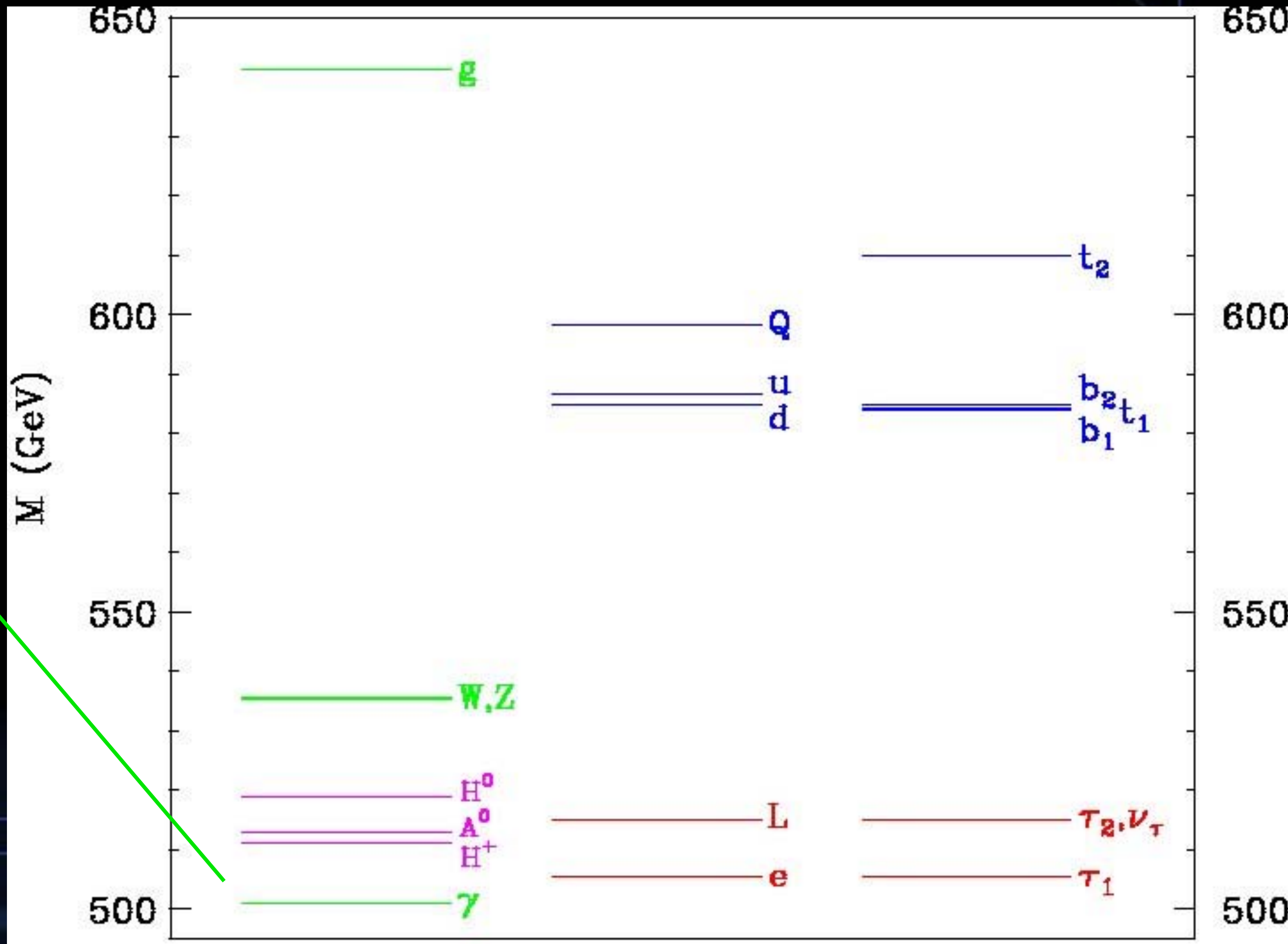
Lightest and stable mass state by KK parity conservation $(-1)^n$:

$\gamma \approx B^{(1)}$

Dark Matter candidate KK state of the hypercharge gauge boson

The LKP (Lightest KK Particle)

SM particles production just by self-annihilation



R^{-1} = 500 GeV, m_h = 120 GeV, $\Lambda = 20\ R^{-1}$

Dark Matter,

Phenomenological model UED

UED specific model : in the spectrum mass development, all boundary kinetic terms are assumed to vanish at a cut-off scale $\Lambda > R^{-1}$

➔ Basis of the minimal UED model (MUED), virtually common used in the litterature

➔ The most predictive model with only three free parameters :

R, Δ, and SM Higgs mass m_h

Dark Matter,

Phenomenological model UED

First Constraints:

- Branching ratios with weak dependence to the degeneration of the mass spectrum

Neutrinos:
Direct and indirect productions

États initials	États finals	Rapports de branchement
$B^{(1)}B^{(1)}$	$\nu_e\overline{\nu_e}$, $\nu_\mu\overline{\nu_\mu}$, $\nu_\tau\overline{\nu_\tau}$	0.014
	e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$	0.23
	$u\overline{u}$, $c\overline{c}$, $t\overline{t}$	0.077
	$d\overline{d}$, $s\overline{s}$, $b\overline{b}$	0.005
	$\phi\phi^\star$	0.027

Direct production of muons, but quickly absorbed in the propagation medium

great interest for the neutrino telescopes, direct production
➔ Direct link to the LKP mass at E_ν

- $R^{-1} \geqq 350$ GeV (LEP II constraints) - $\Omega_{CDM}h^2 = 0.11 \pm 0.006$ (WMAP, 5 yrs)

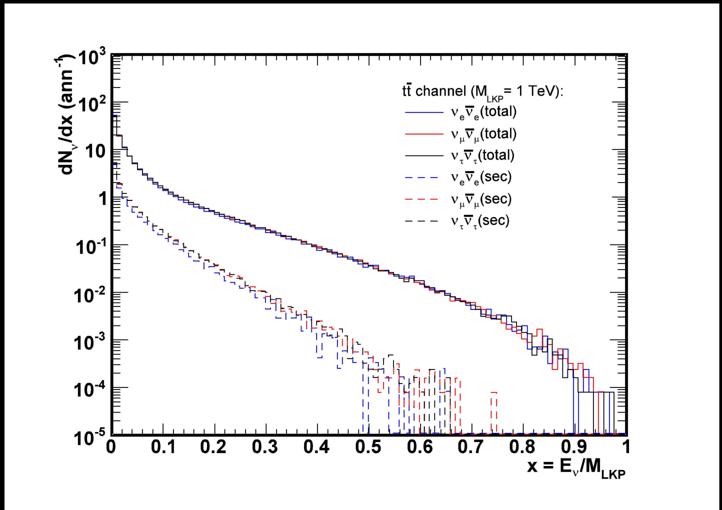
- Coannihilations or not LKP–NextLKP ⇨ $\Delta \equiv (m_{NLKP} - m_{LKP}) / m_{NLKP}$, model-dependent
MUED ➔ $\Delta = 0.14$

Dark Matter,

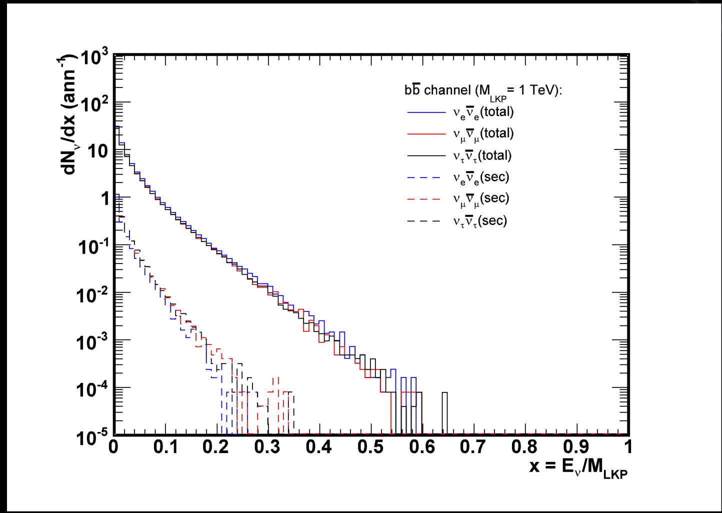
Neutrinos at the surface of the Earth

$M_{WIMP} = 1$ TeV

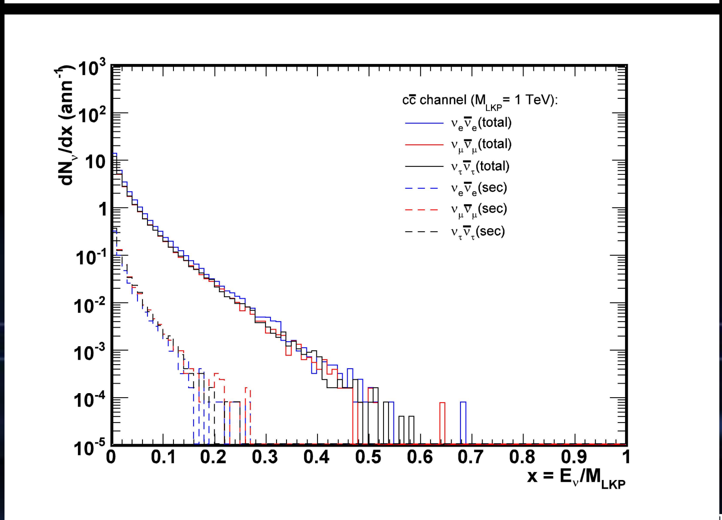
Canal top



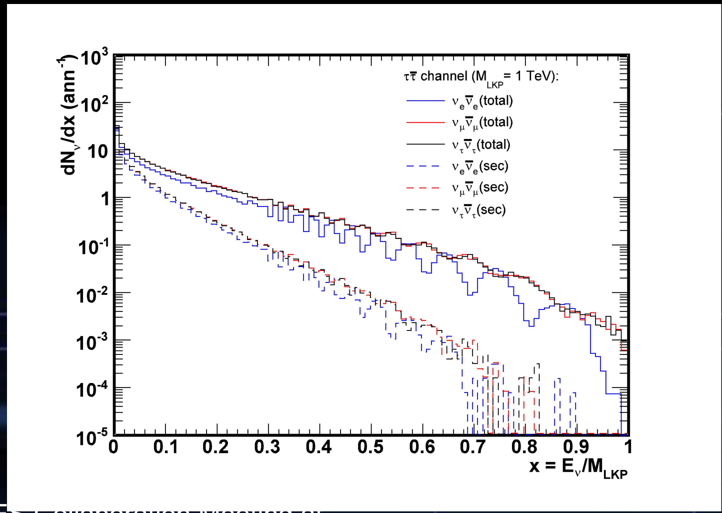
Canal b



Canal c



Canal τ

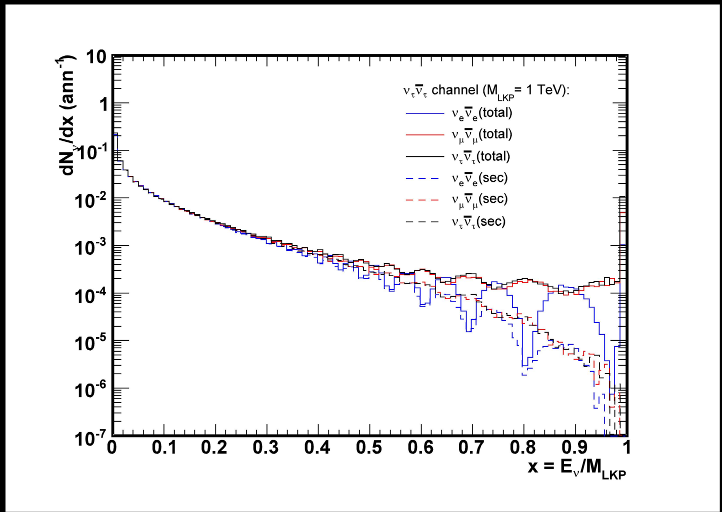


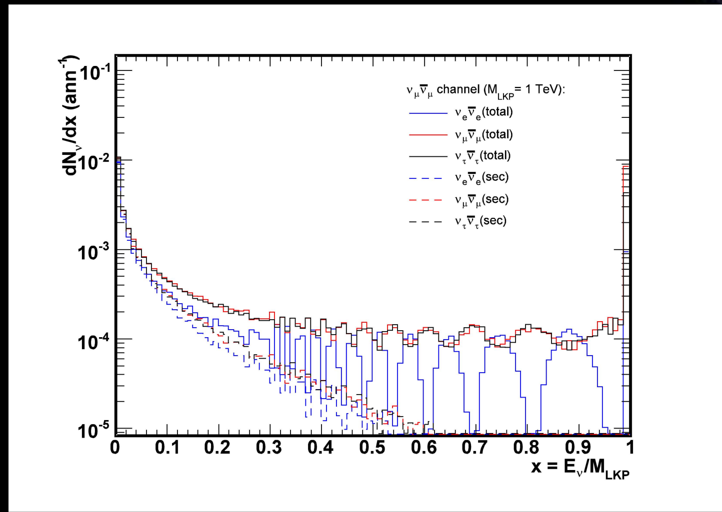
Dark Matter,

Neutrinos at the surface of the Earth

$M_{WIMP} = 1$ TeV

ν_τ





ν_μ

Main secondary production from τ and top channels, and primary production from ν_τ and ν_μ direct channels

+ constraints of MUED dark matter on :

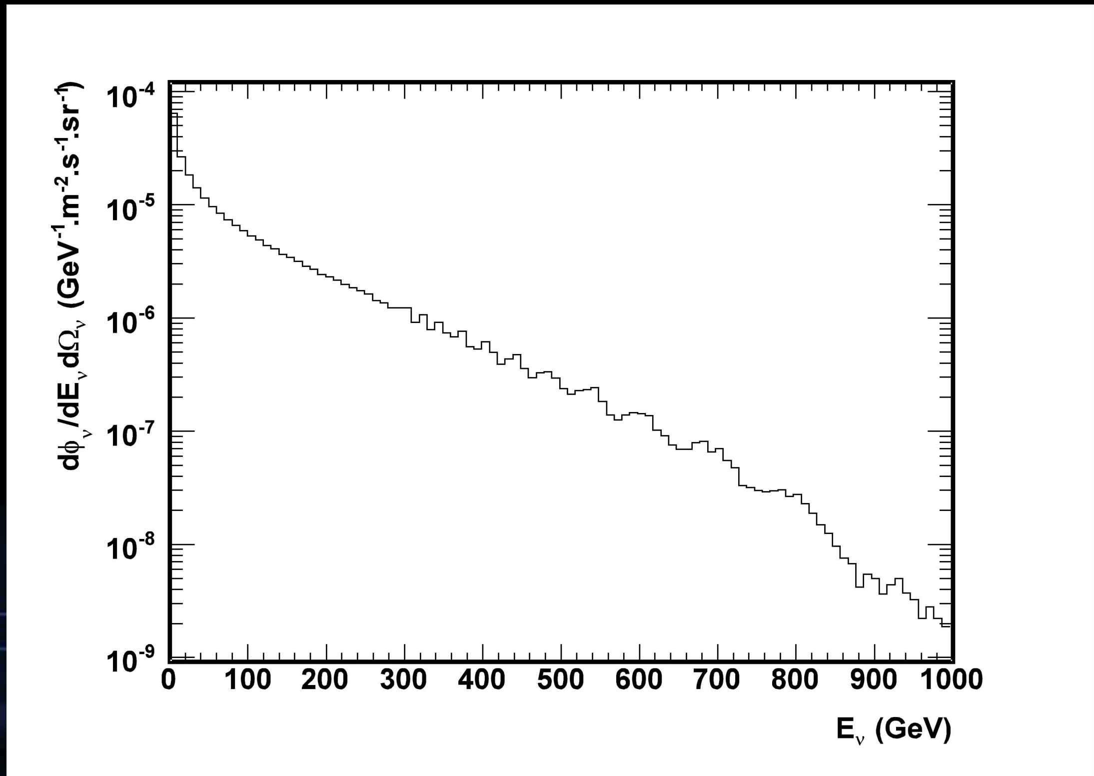
- ✓ Self-annihilation rate $\Gamma \propto \sigma_{MUED,SD}$ (spin-dependent cross section)
- ✓ Branching ratios

Dark Matter,

Simulation

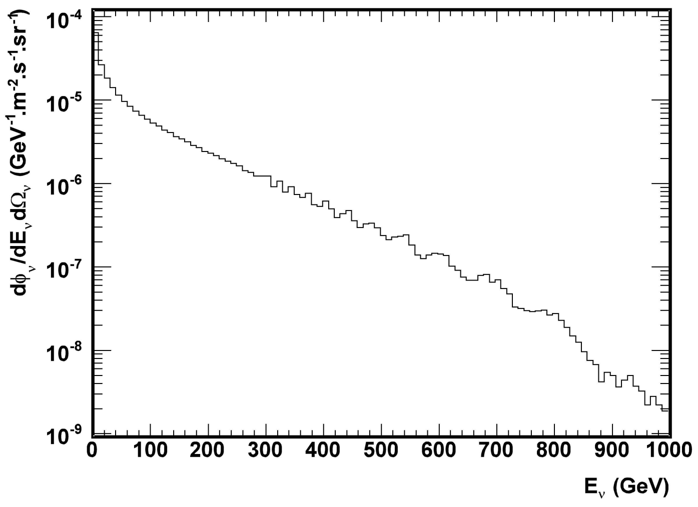
Global flux at Earth :

$$\frac{\quad}{dE\,d\Omega} = \frac{\quad}{4\pi d^2}\sum_i B_i \frac{\quad}{dE_i}$$

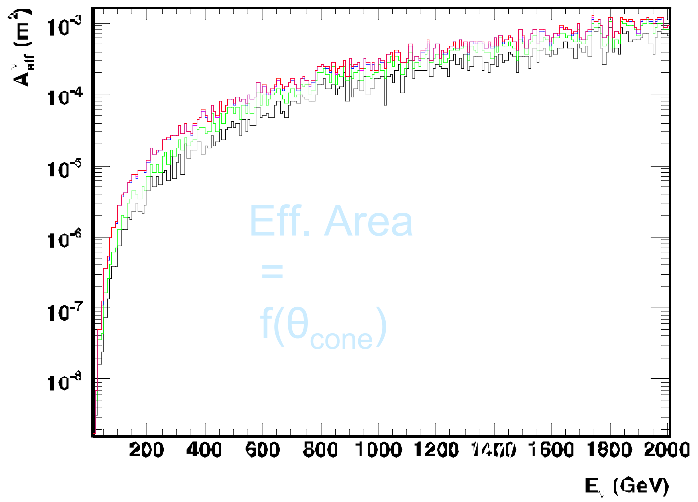


Dark Matter,

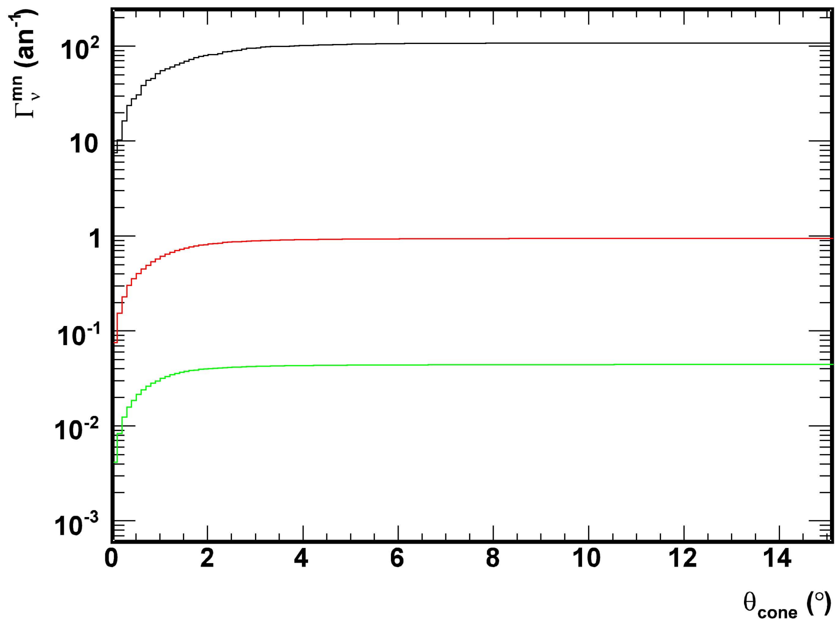
Expected Rates



Convolutio



Neutrinos rate = $f(\theta_{cone}, M_{LKP})$

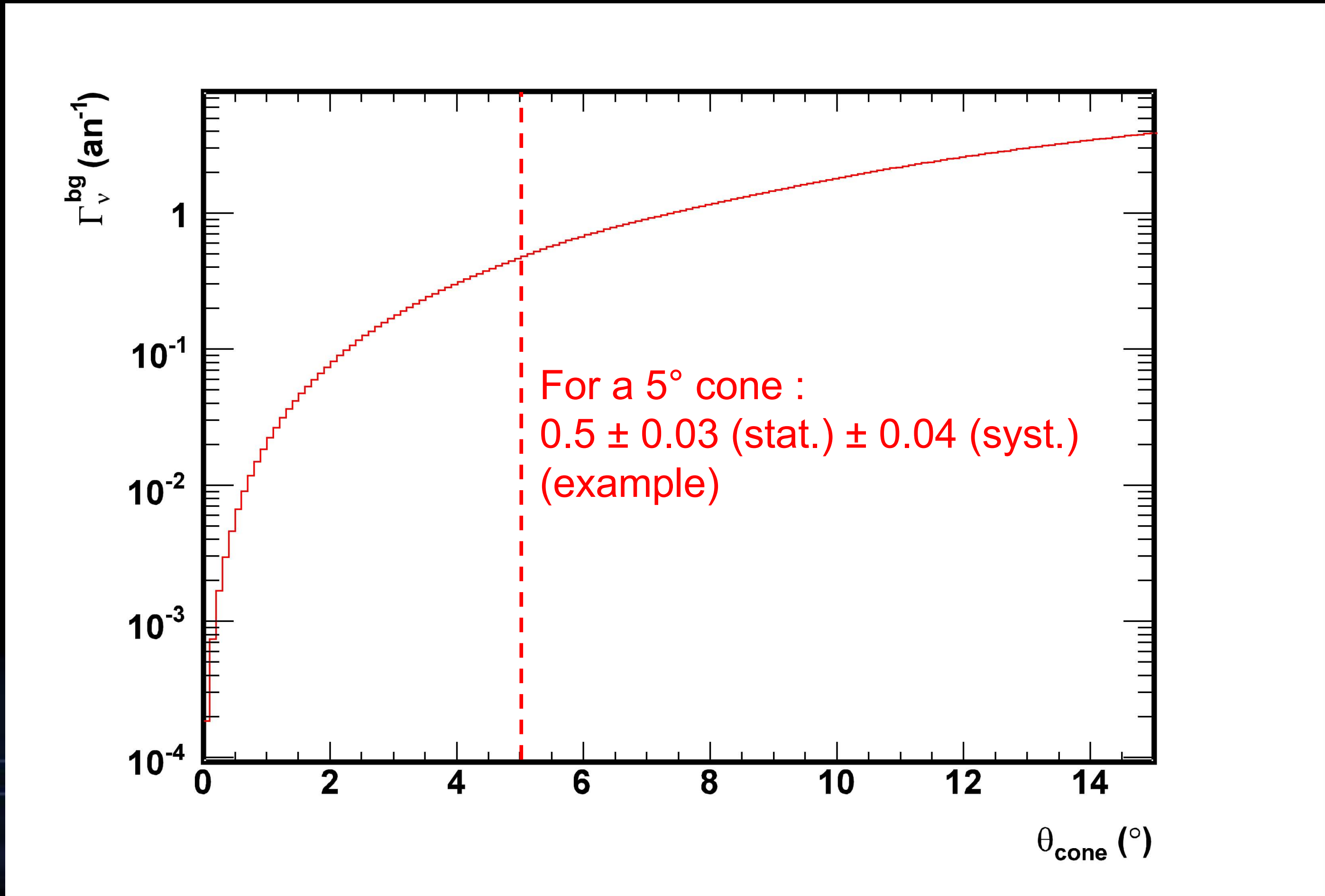


Eff. Area from background study, similar to Gordon's MSSM study with Aart's strategy (linear prefit, $\cos\theta > 0.1$, $\Lambda > -5.0$)

Background rate VS

Dark Matter signal

Atmospheric neutrinos and muons



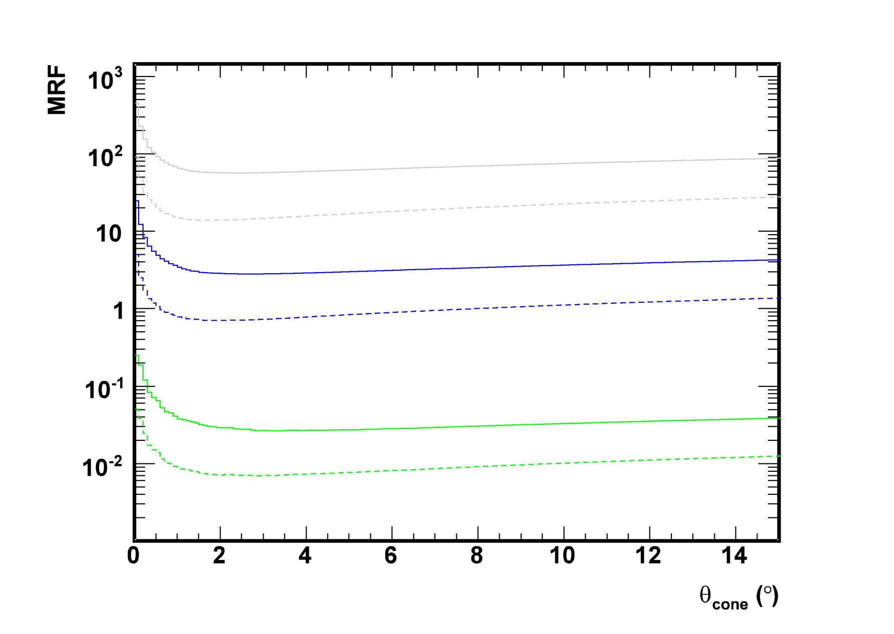
Background rate VS

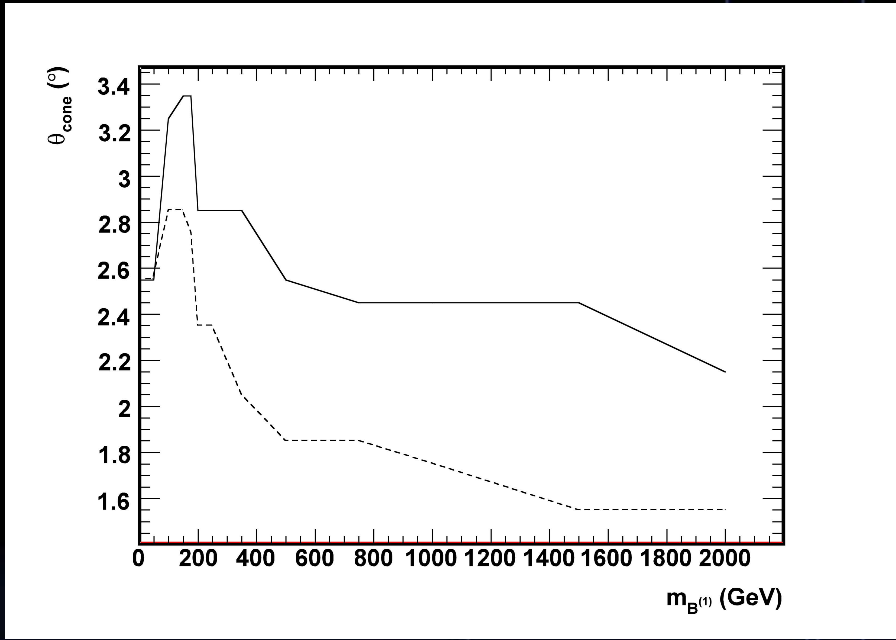
Dark Matter signal

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

Averaged Upper Limit on the background (Feldman-Cousins: assumption – no signal)

Half-cone angle VS M_{LKP}





LKP search with M_{LKP} E [10;2000] GeV

More the LKP is heavy, more the signal is weak ➔ reduction of the half-cone angle to reduce the background amount

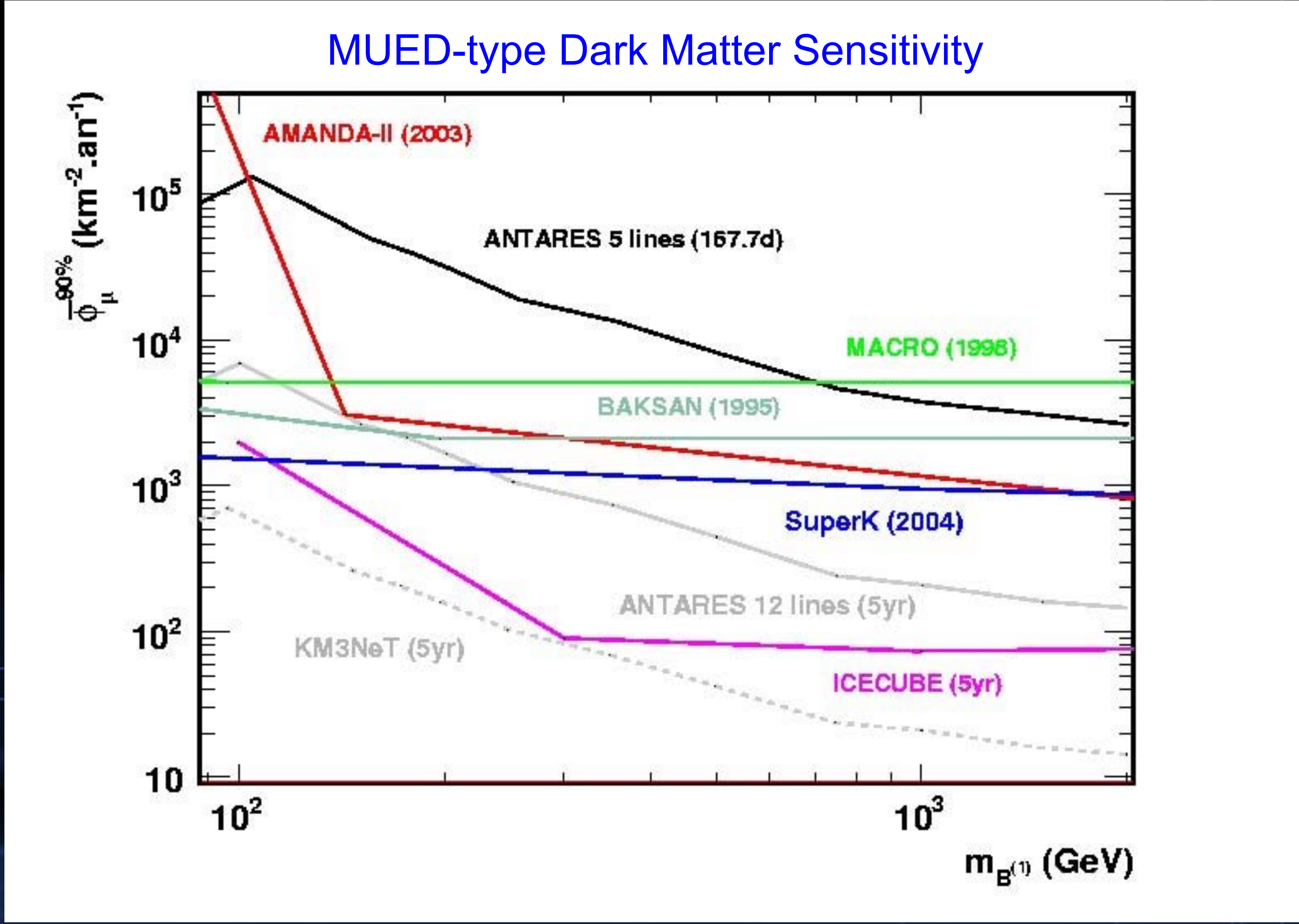
Background VS Dark Matter Signal

ANTARES sensitivity for the MUED-type Dark Matter

Flux from the dark matter simulation

$$\bar{\phi}_{\mu}^{90} = \phi_{\mu} \times MRF$$

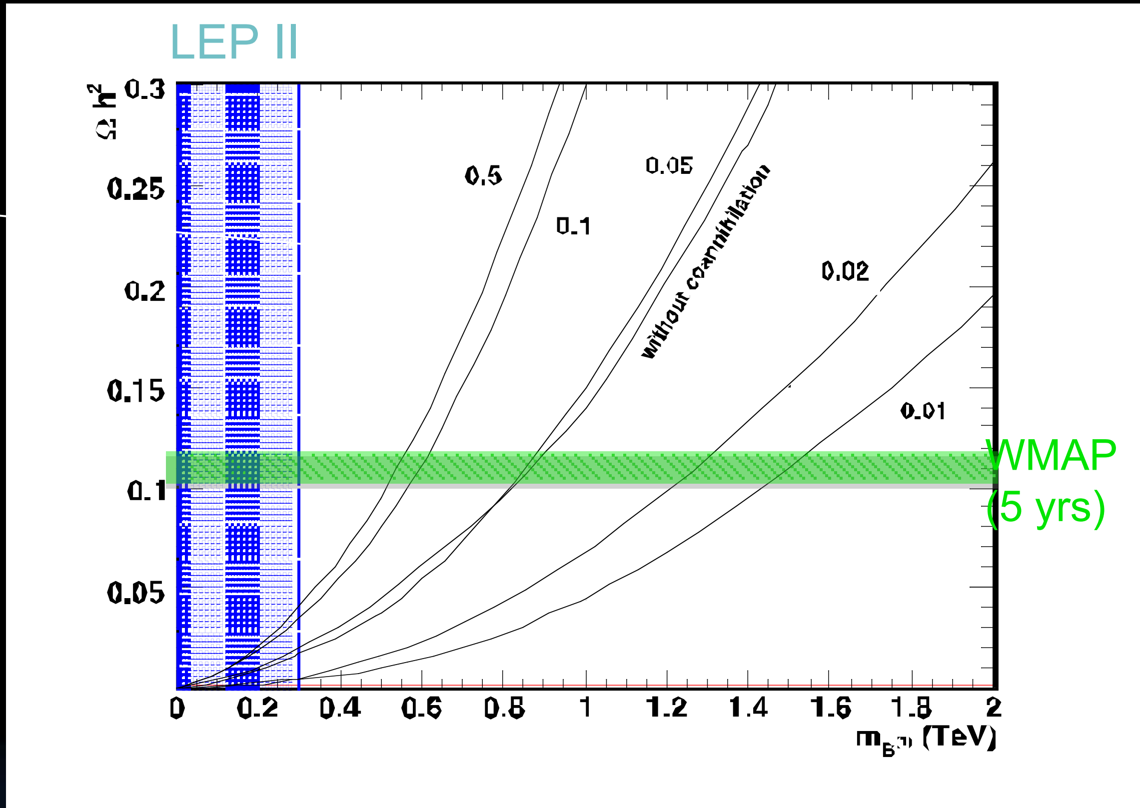
Sensitivity computed for t =167.7 days (integrated time for all of the 5-line silver runs)



Mass spectrum, relic density and LKP mass range

$m_{B(1)}$-dependence of $\Omega_{CDM}h^2$ with coannihilations or not

Δ > 0.5, NLKPs contribution degeneration



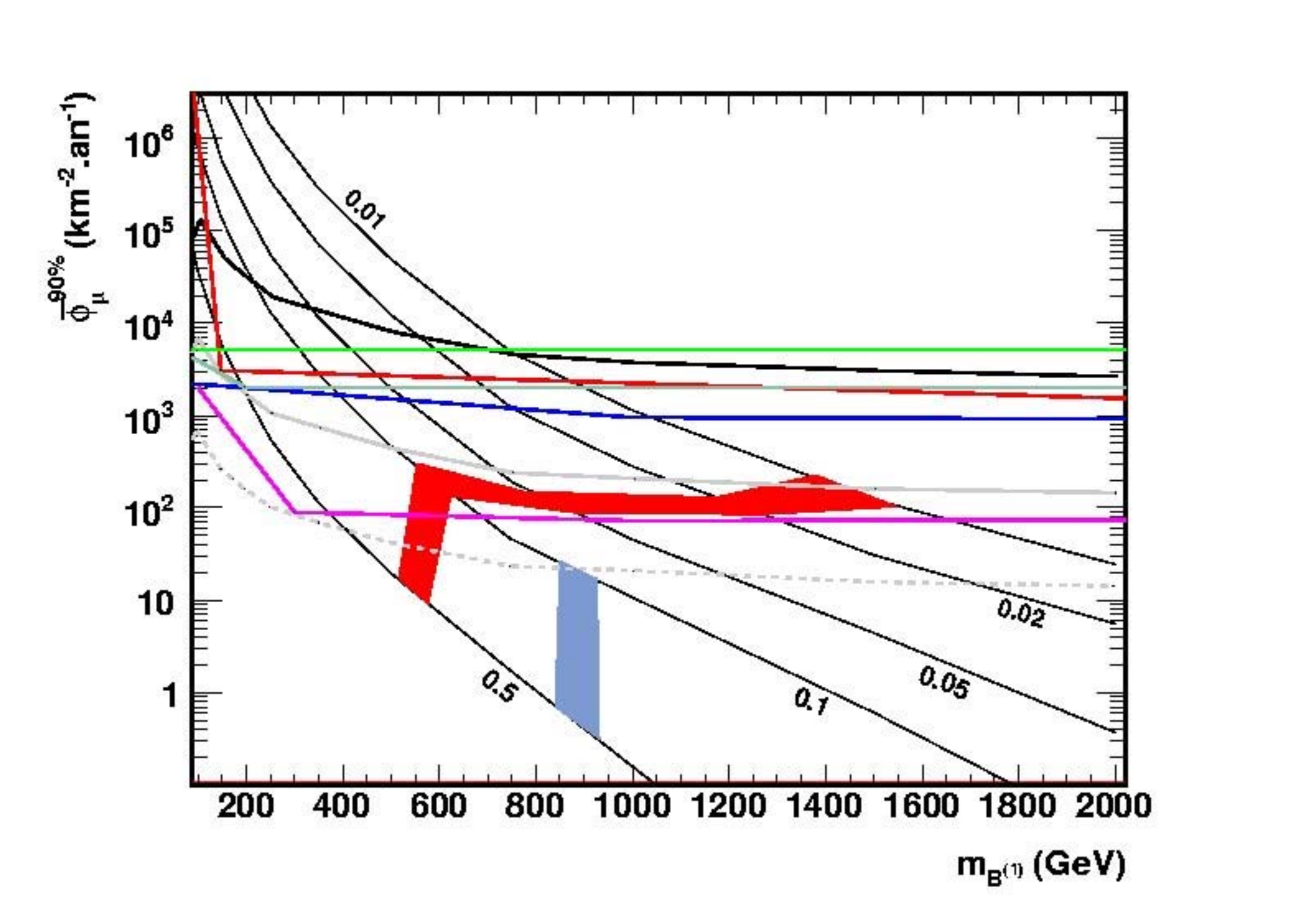
Cold Dark Matter relic density constraints by LEP II & WMAP

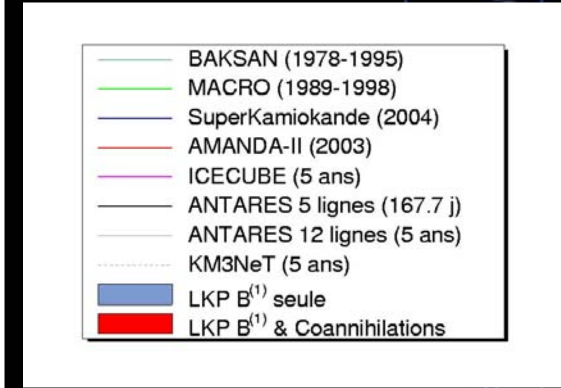
Δ values constrains the relic density at *freeze out*

Dark Matter sensitivity

Phenomenological constraints

$$\bar{\phi}_\mu^{90} = \phi_\mu \times MRF$$





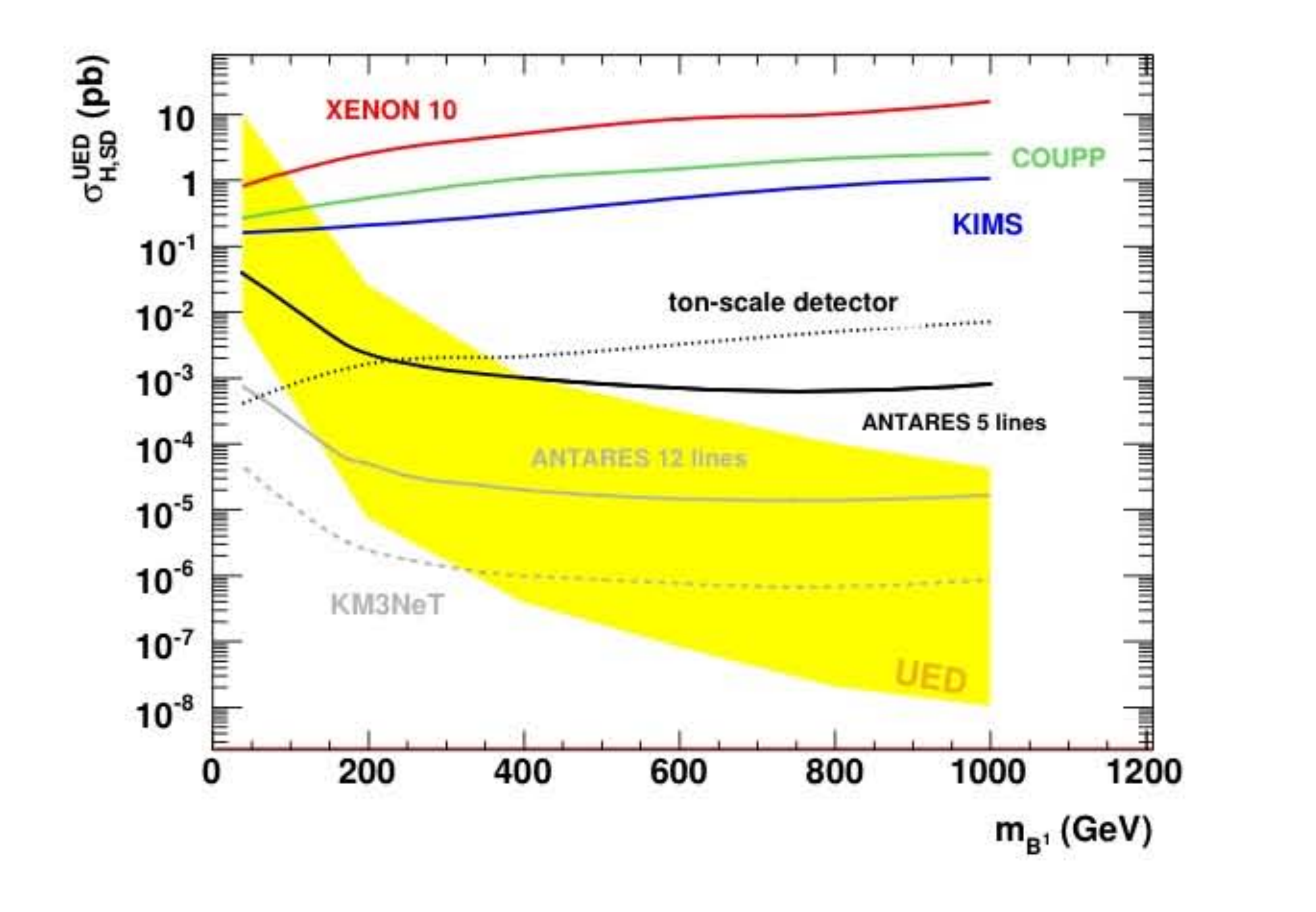
From 5-line constraints (Δ,m_{LKP})

From 12-line (5 years)
Close to the WMAP constraints

With Icecube, and KM3NeT (5 years)
Strong constraints expected

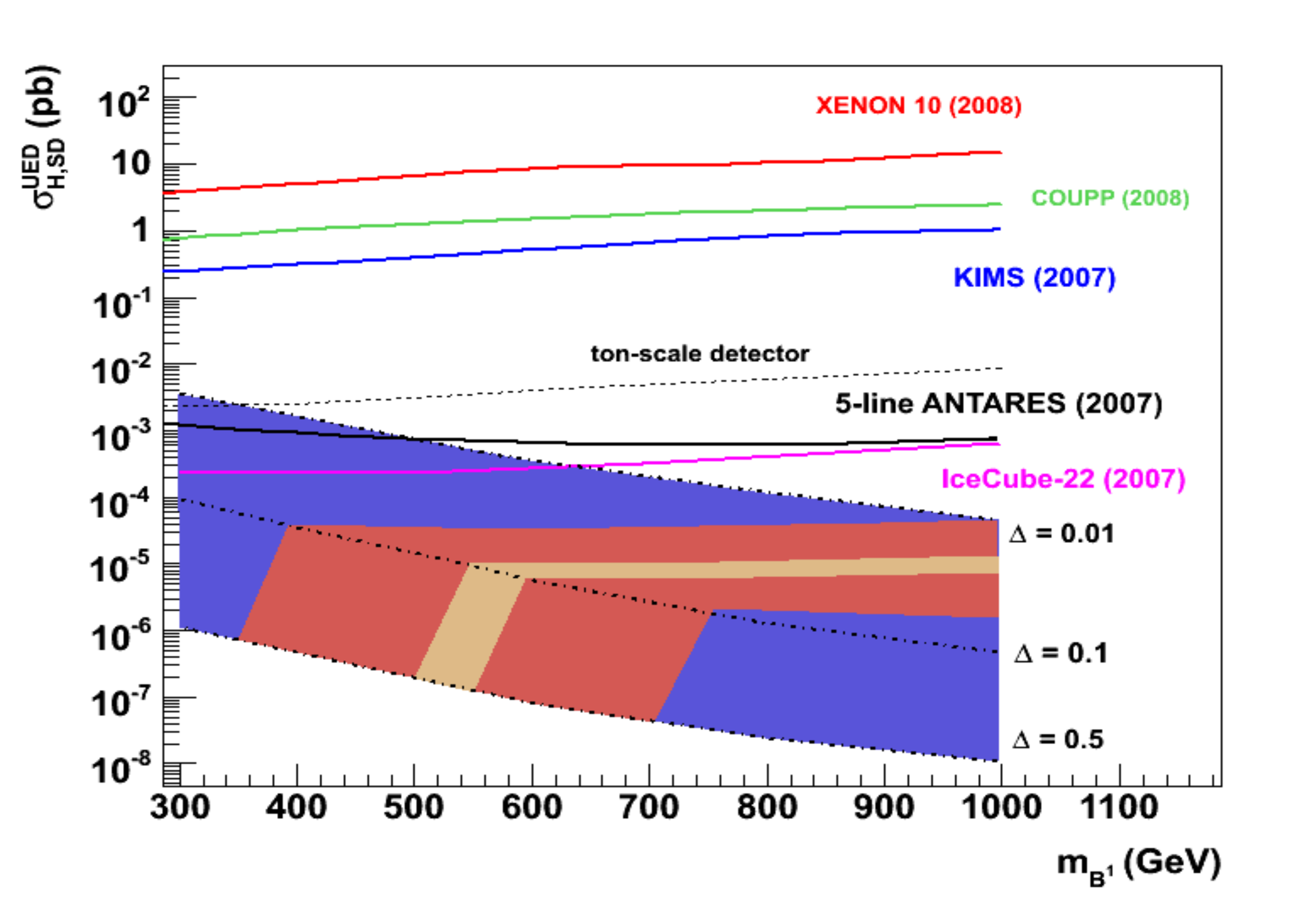
Dark Matter sensitivity

Phenomenological constraints

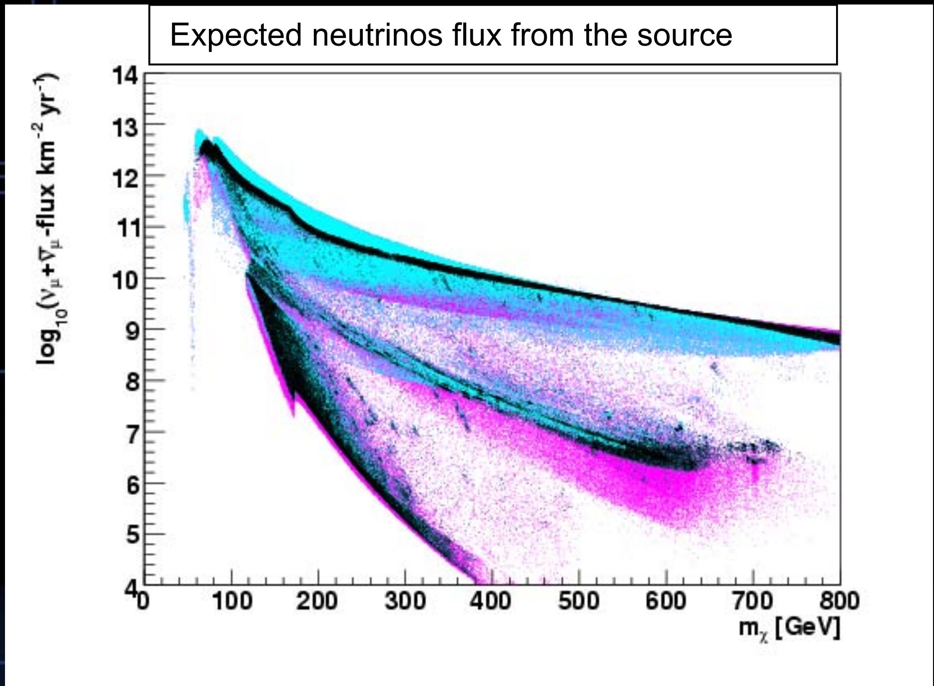


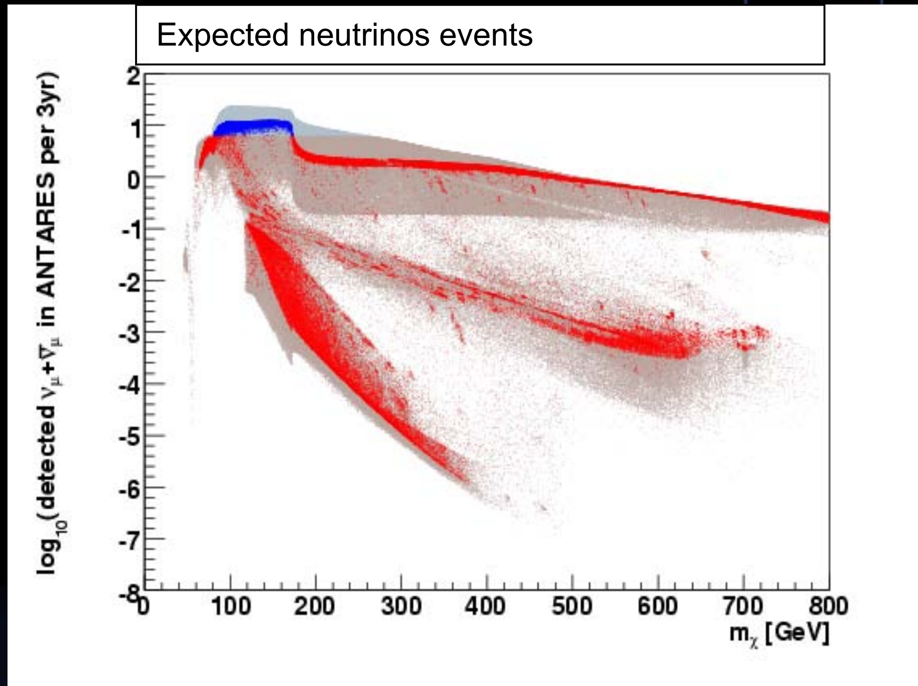
Dark Matter sensitivity

Phenomenological constraints



Expected neutrino flux from the Sun





All models studied

0,094 < Ωh² < 0,129 (WMAP 3yr constraint)

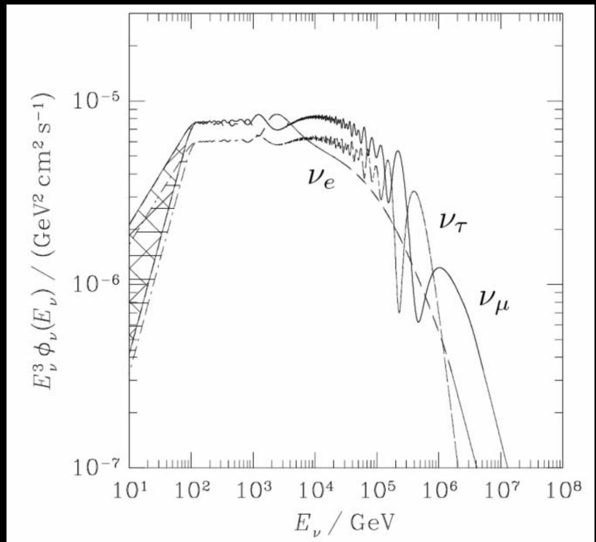
Ω h² < 0,094

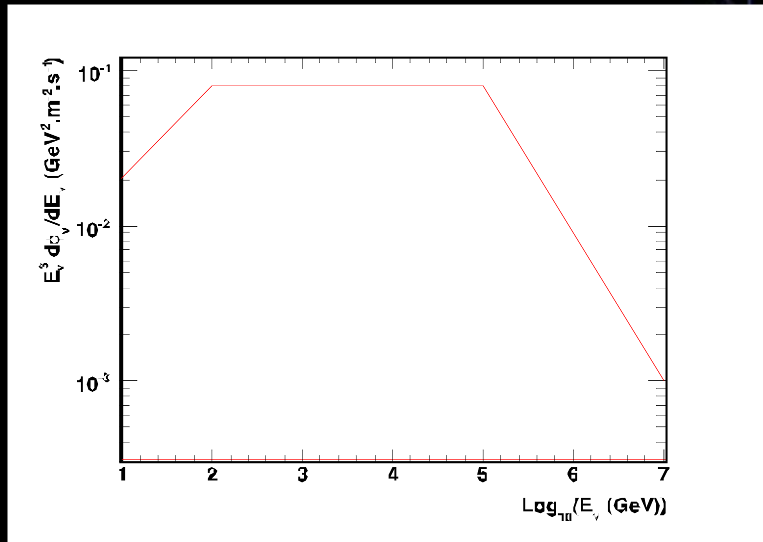
All models studied

0,094 < Ωh² < 0,129 (WMAP 3yr constraint)

Average upper limit signal

Solar Background
(interactions CRs – Solar atmosphere)





De C. Hettlage, K. Mannheim, J. G. Learned, Astropart.Phys. 13 (2000) 45-50 ; arXiv :astro-ph/9910208

Simplified parameterization
Averaged on the oscillations