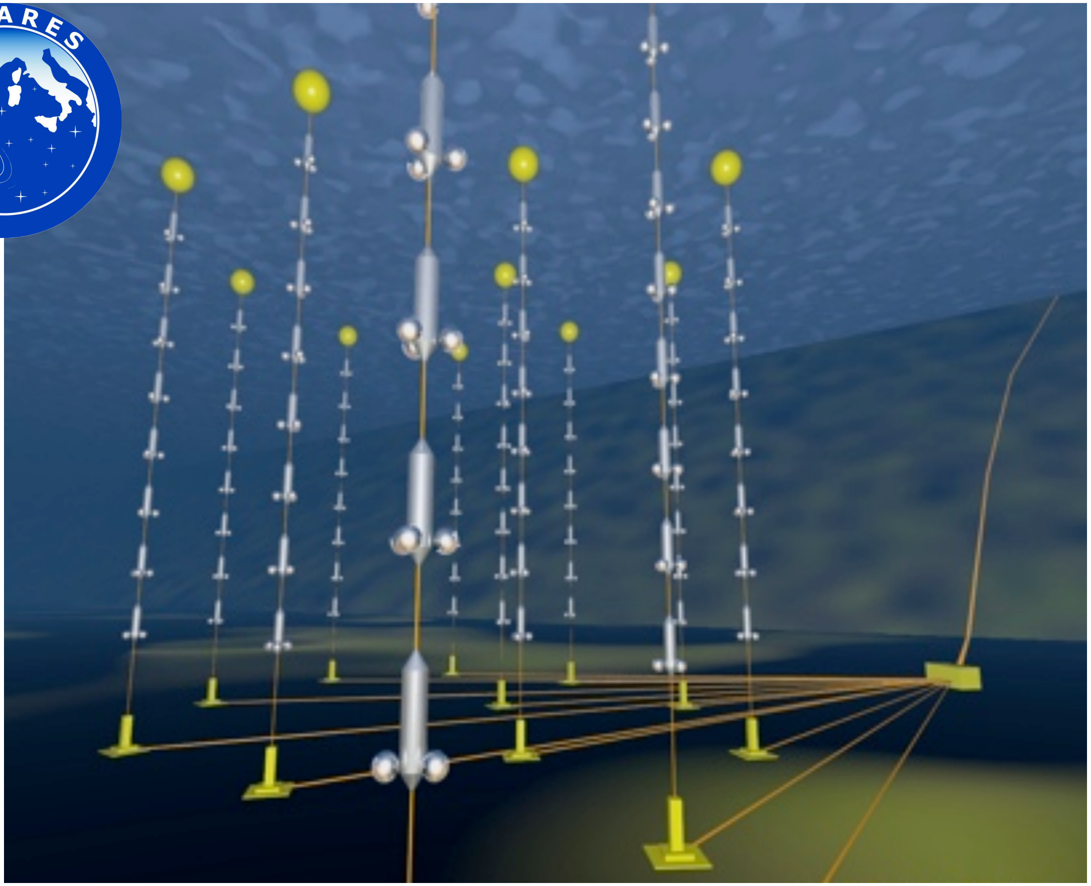
ANTARES Neutrino Telescope
Recents results



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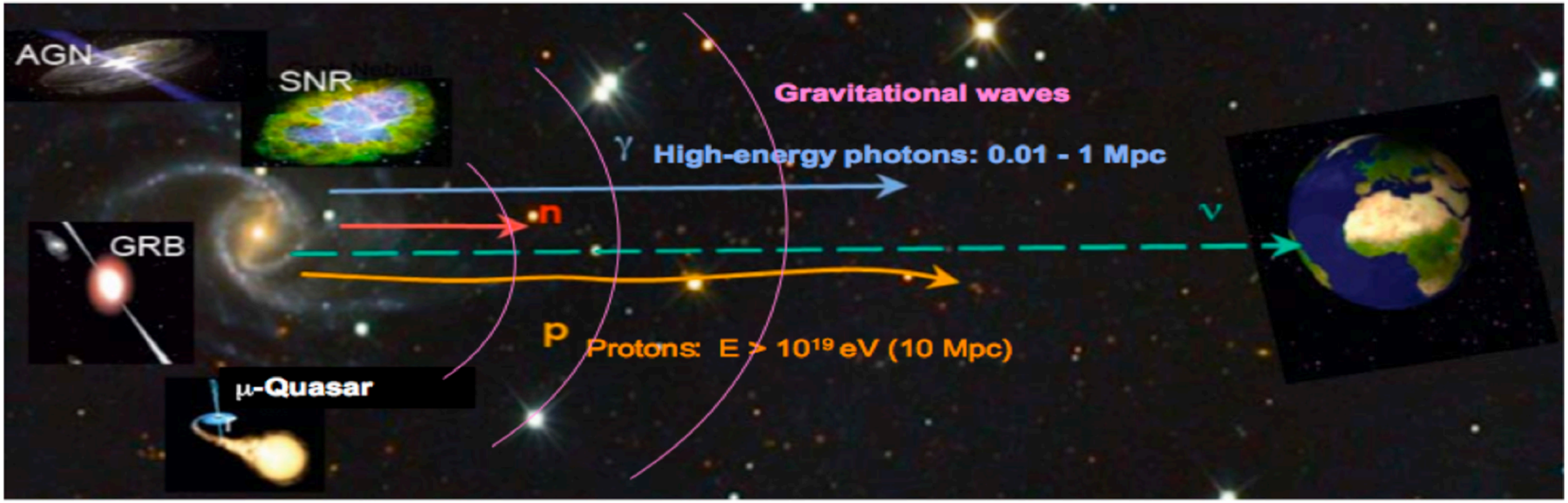
Introduction

1. ANTARES telescope
2. Relativistic magnetic monopoles
3. Neutrino oscillations
4. Dark matter
5. Outlook

Multi messager astronomy



Why neutrino astronomy

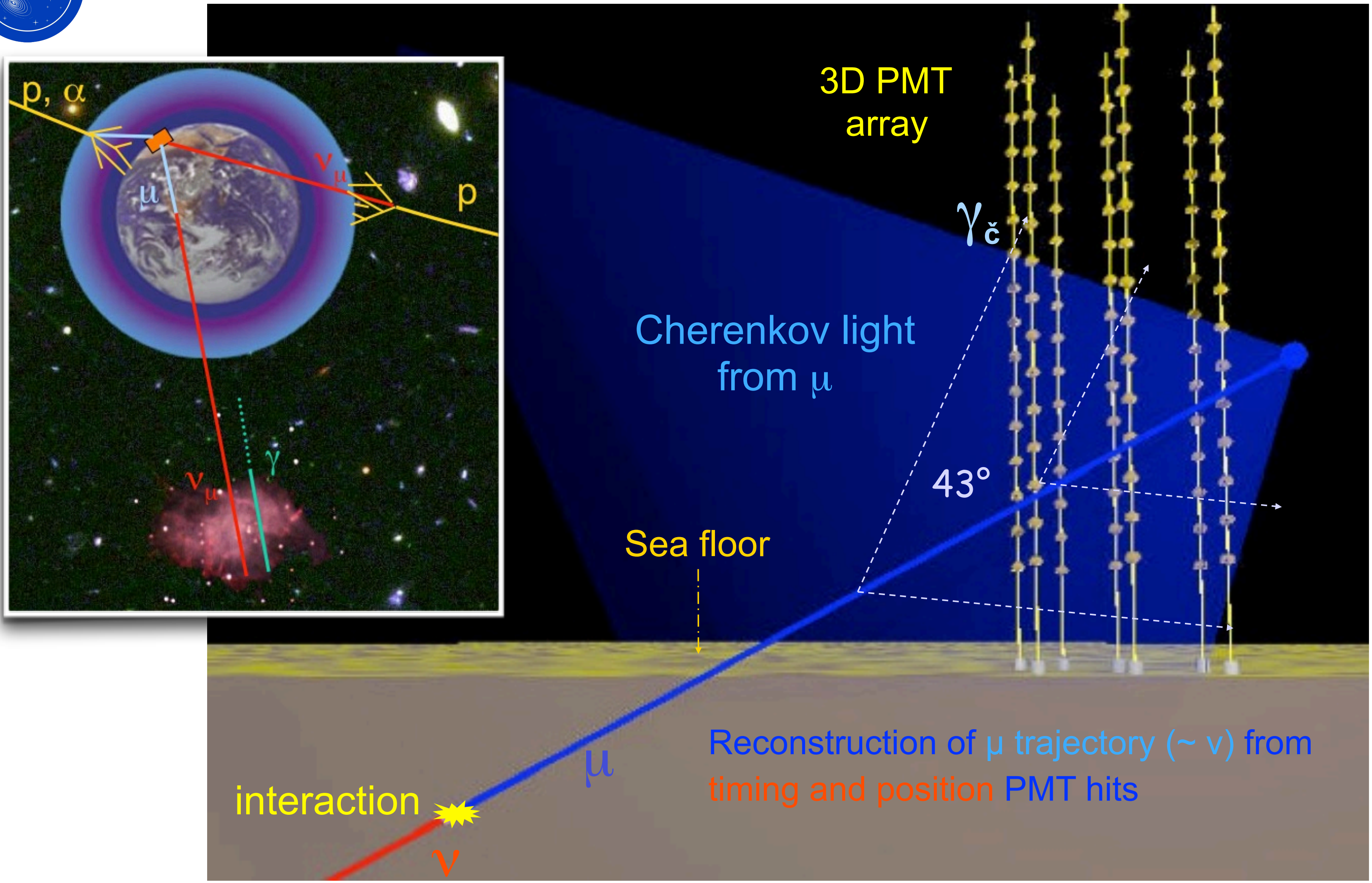
- neutrinos point back to the source
- neutrinos travel cosmological distances
- neutrinos escape optically thick sources
- neutrinos are a clear sign of hadron acceleration

⇒ complementary to gamma and cosmic rays

Some source candidates

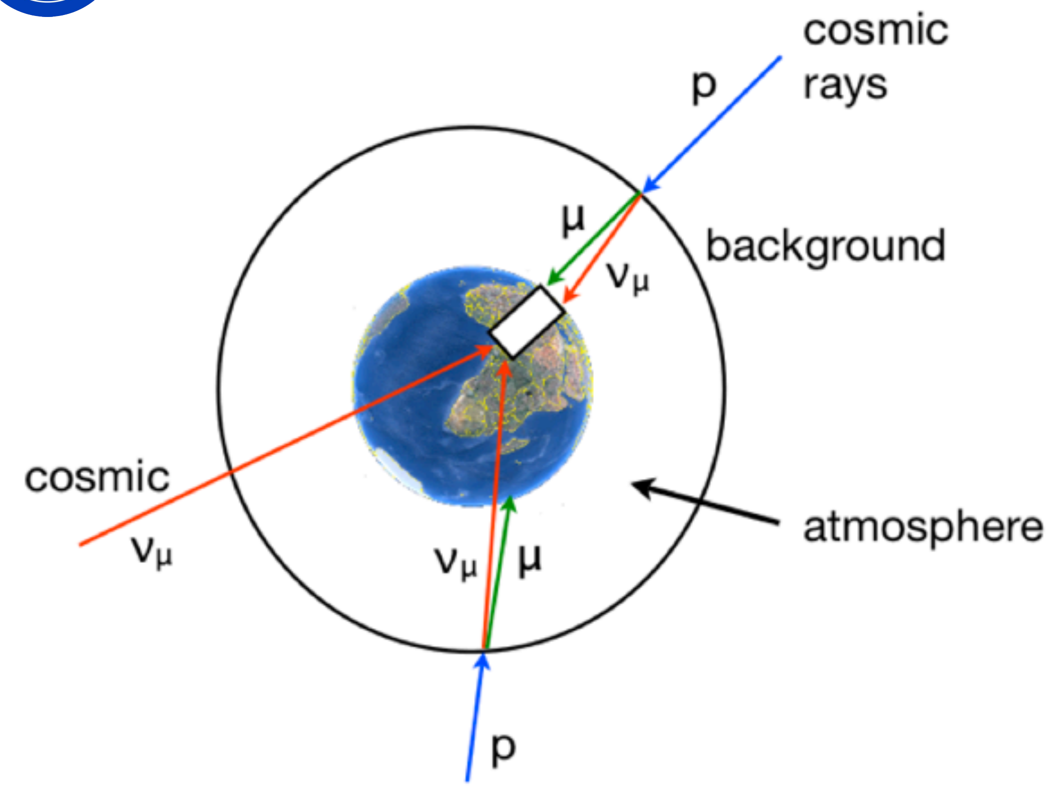
- Galactic sources: supernova remnants, microquasars
- Extra-galactic sources: active galactic nuclei, gamma ray bursts
- Dark matter

Neutrino telescope : detection principle



Reconstruction of μ trajectory (~ ν) from timing and position PMT hits

Background rates

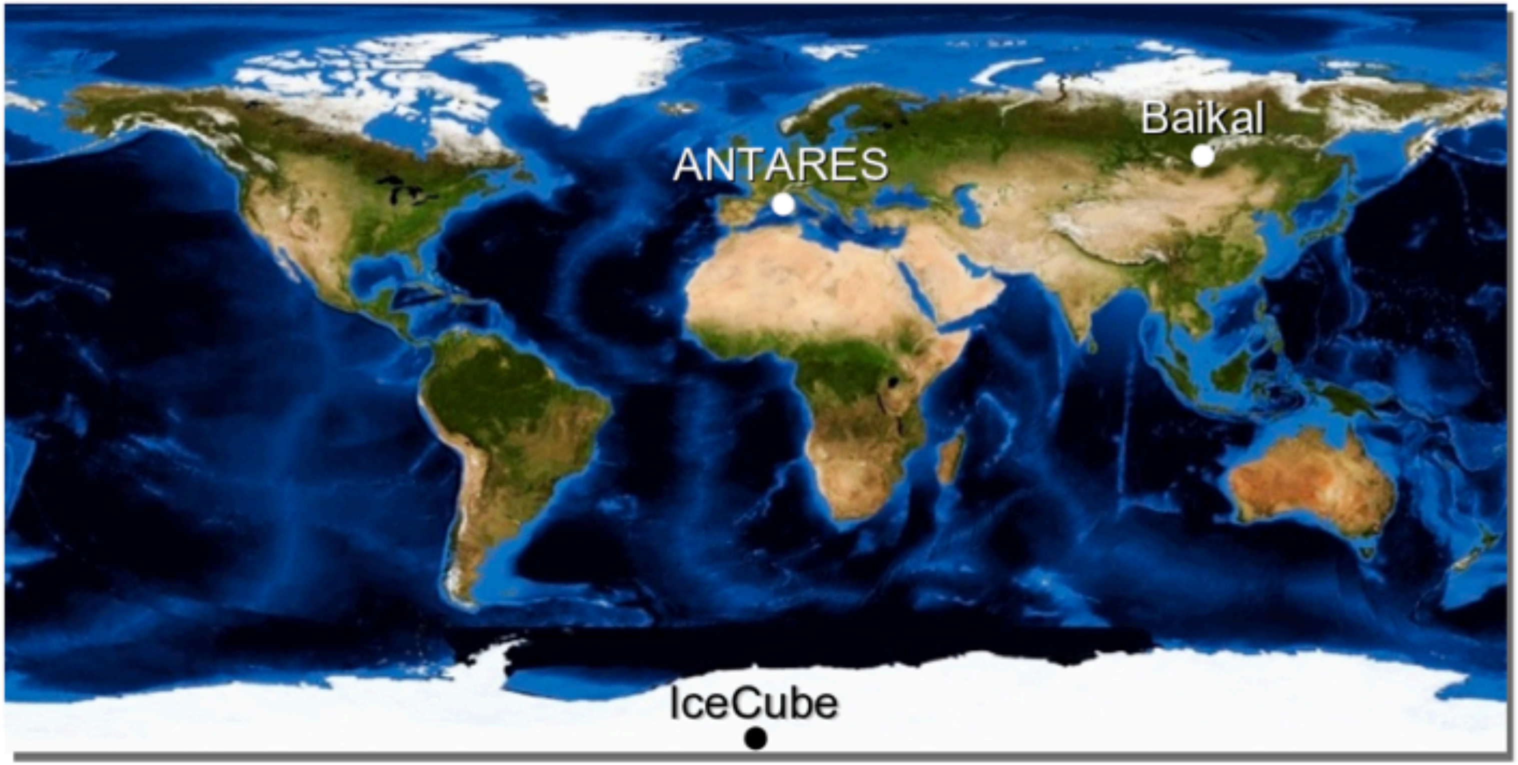


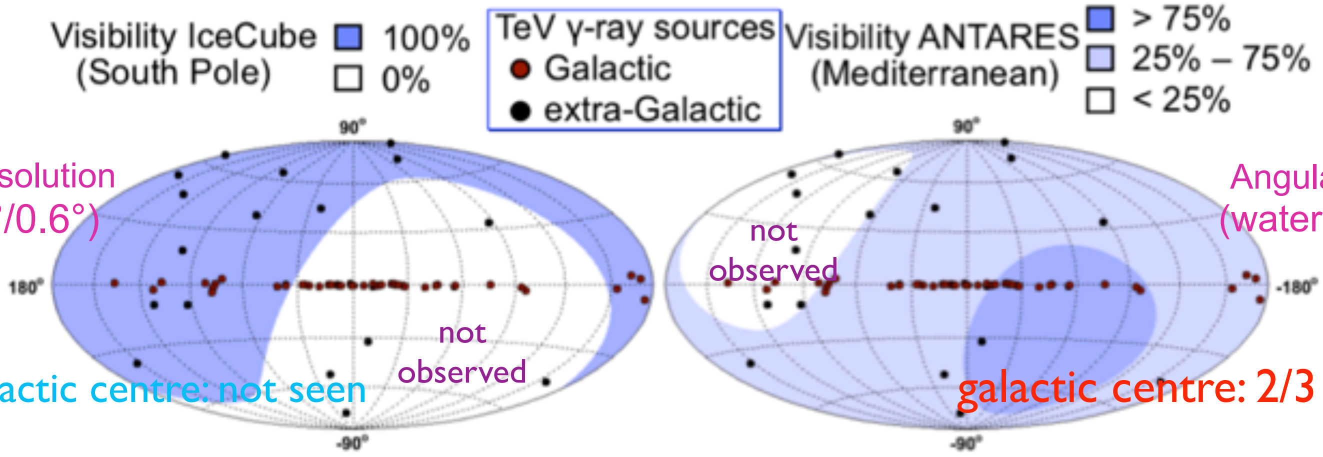
Event rates:

- $\sim 10^6$ atmospheric muons per day
- ~ 5 atmospheric neutrinos per day
- ??? cosmic neutrinos

⇒ Selecting only well reconstructed upgoing particles

Neutrino telescopes





Angular resolution
(Ice: ~2°/0.6°)

not observed

Galactic centre: not seen

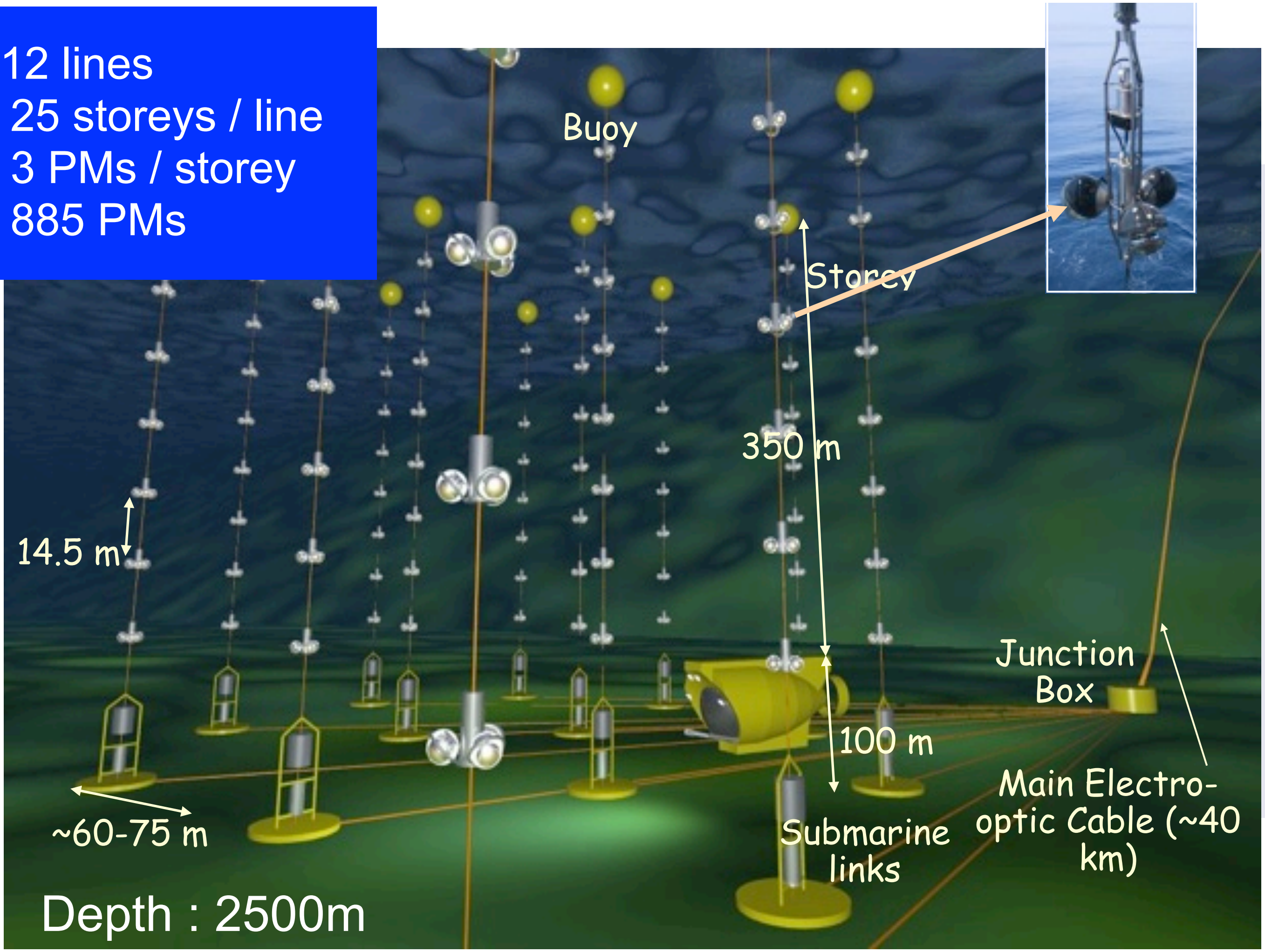
not observed

Angular resolution
(water: ~0.2°/0.1°)

galactic centre: 2/3 of the time

ANTARES Detector

- 12 lines
- 25 storeys / line
- 3 PMs / storey
- 885 PMs



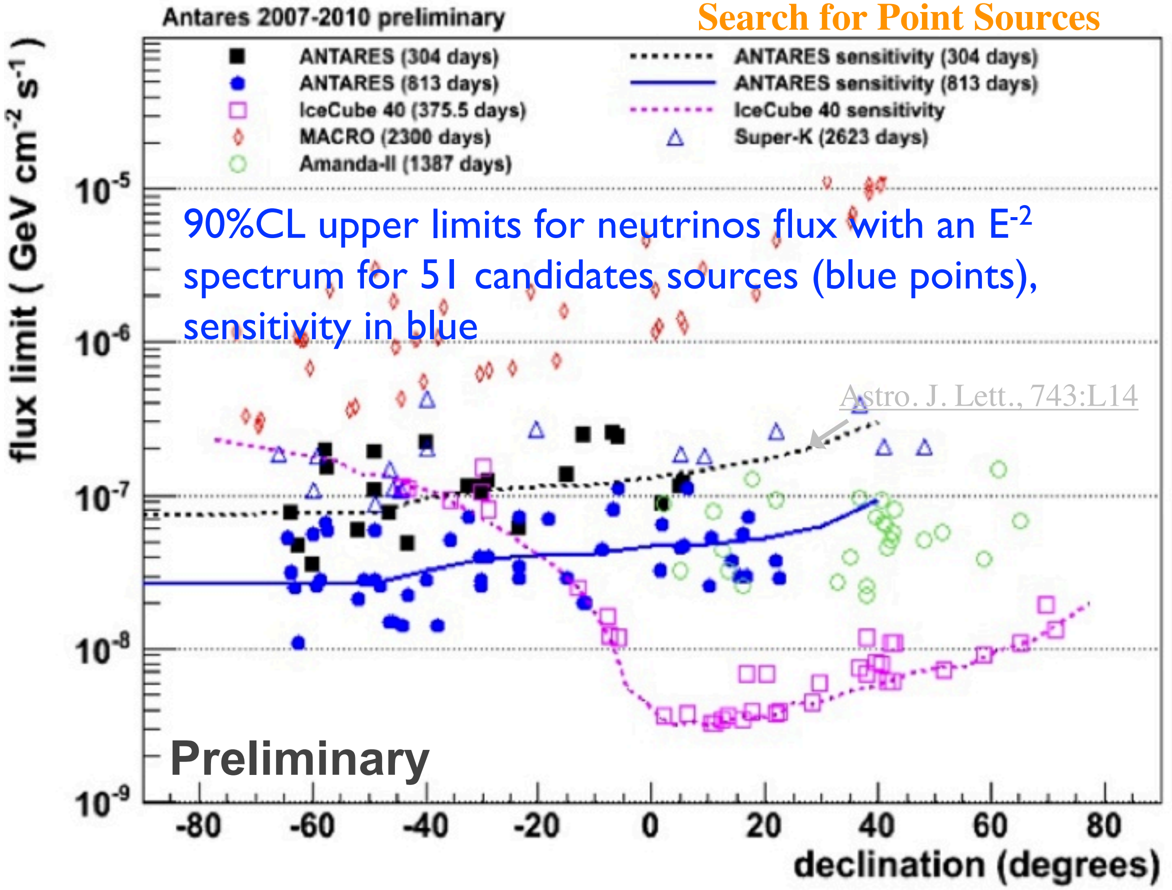
- deployment finished: 2008
- detection lines: 12
- horizontal spacing between lines: ∼ 70 m
- storeys per line: 25
- vertical spacing between storeys: 14.5 m
- optical modules per storey: 3
- total optical modules: 885

Some analysis topics

Cosmic neutrinos

- Steady sources
  - full sky search
  - candidate list
- Transient sources – multi-messenger
  - flare analysis (GRBs, microquasars, etc.)
  - triggered search, optical follow-up
  - gravitational waves
- Diffuse flux

Search for Point Sources



90%CL upper limits for neutrinos flux with an E^{-2} spectrum for 51 candidates sources (blue points), sensitivity in blue

Astro. J. Lett., 743:L14

Particle physics and exotic phenomena

super-heavy particles
neutrino oscillations
indirect search of dark matter

Environmental and marine science

seismology
marine biology
in situ oxygen comsumption

Relativistic Magnetic Monopoles

Magnetic monopoles

required in many models via SSB [‘t Hooft, Polyakov]

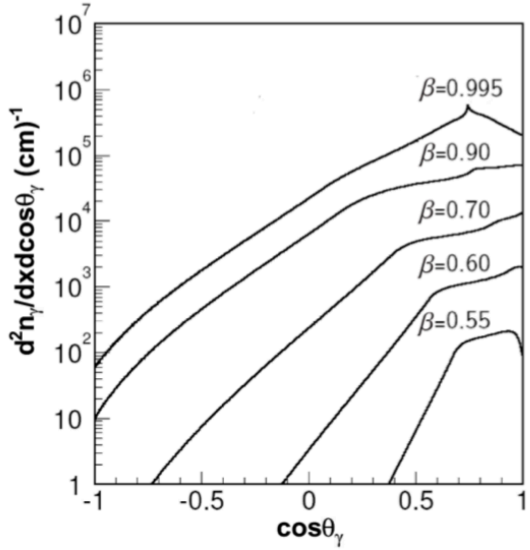
$$g_{MM} = k\frac{e}{2\alpha}$$

light yield

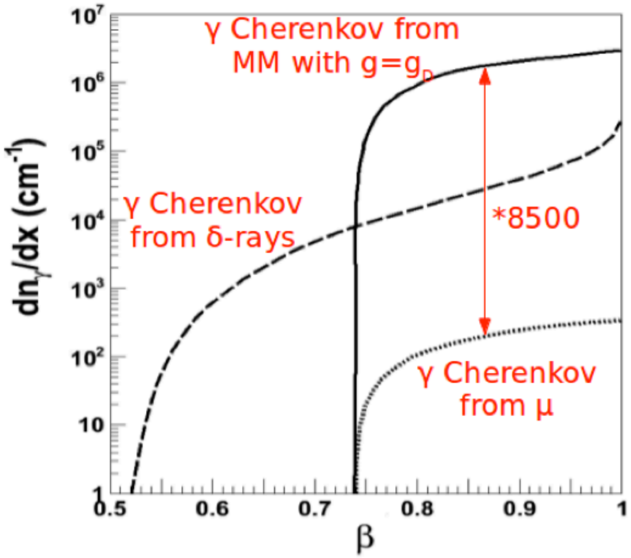
Cerenkov regime $\beta > \beta_{th} = 0.75$

via δ-rays $0.5 < \beta < 0.75$

knock off electrons (δ–rays) produced along its path



Photons angular distribution



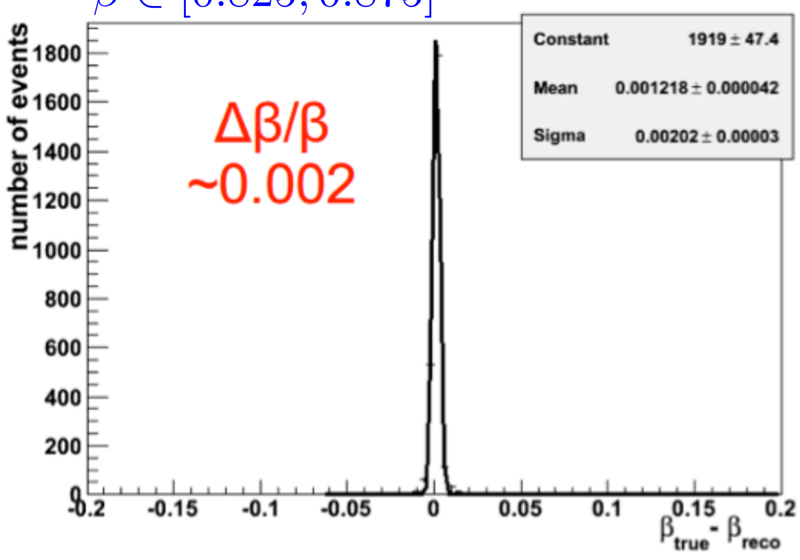
Monopole light yield

Relativistic Magnetic Monopoles

standard track
reconstruction β=1

Reconstruction algorithm developped for magnetic monopole, also below Cerenkov threshold,
β free parameter

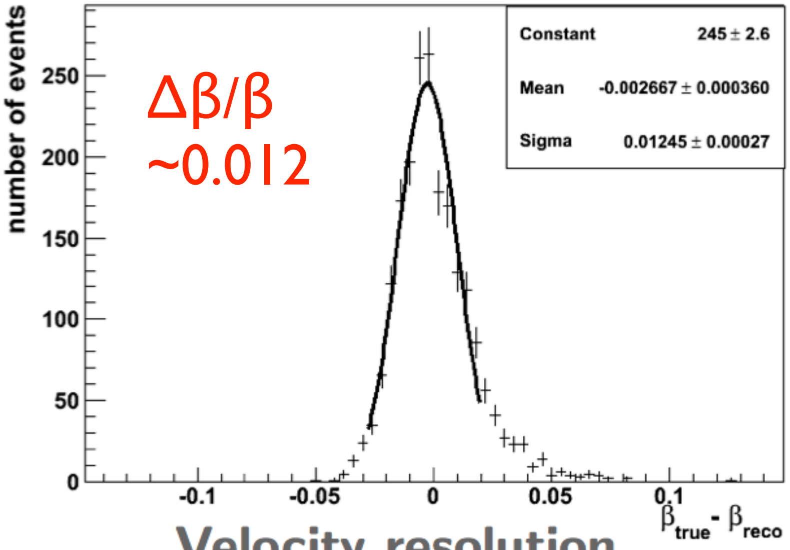
$\beta \in [0.825, 0.875]$



Δβ/β
~0.002

Velocity resolution

$\beta \in [0.625, 0.675]$



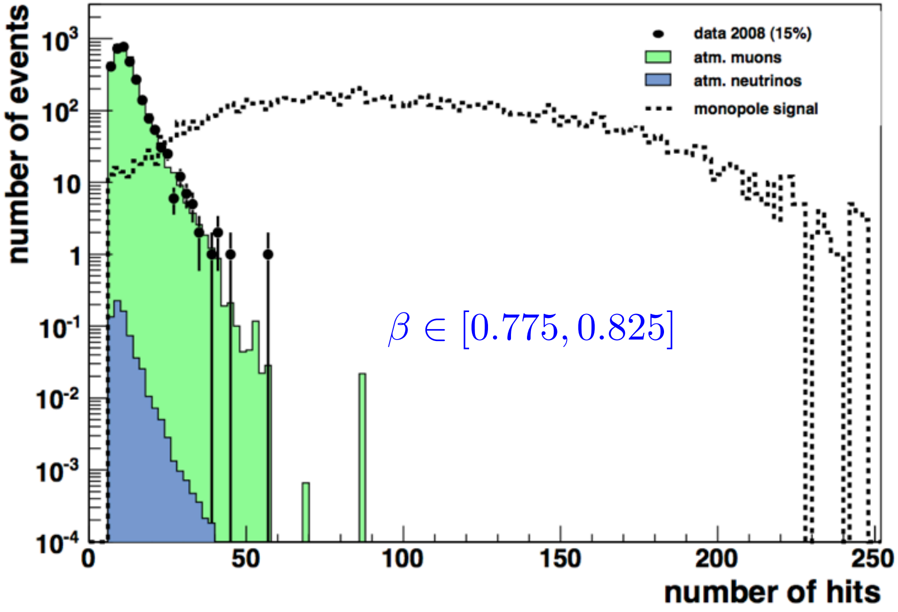
Δβ/β
~0.012

Velocity resolution

Relativistic Magnetic Monopoles

Discriminante variables

- cut on numbers of hits
- cut on the ratio of reconstruction qualities λ

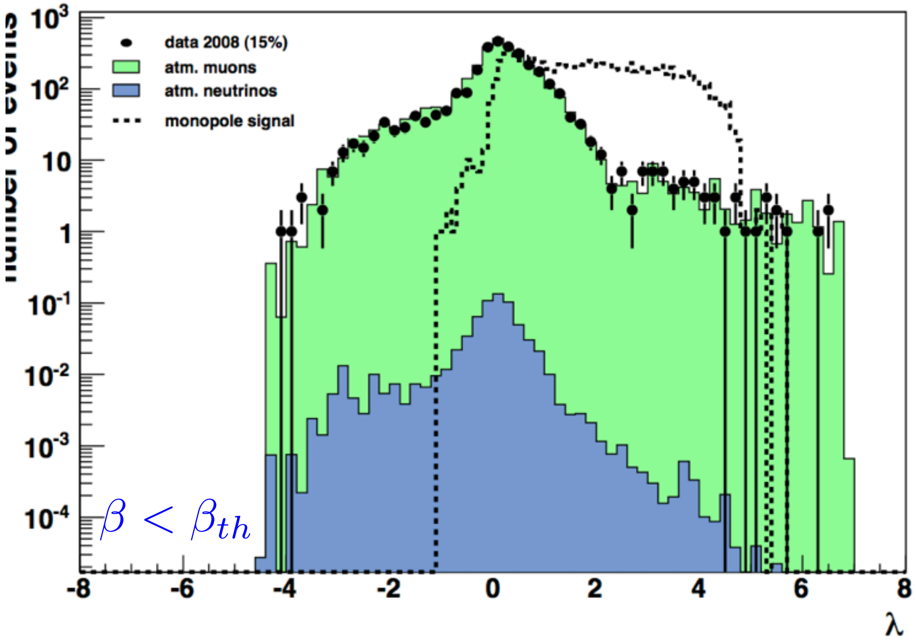


$\beta \in [0.775, 0.825]$

15% of data used here

$$\lambda = log[\frac{Q_{\beta=1}}{Q_{\beta=free}}]$$

λ>0 expected for monopole events



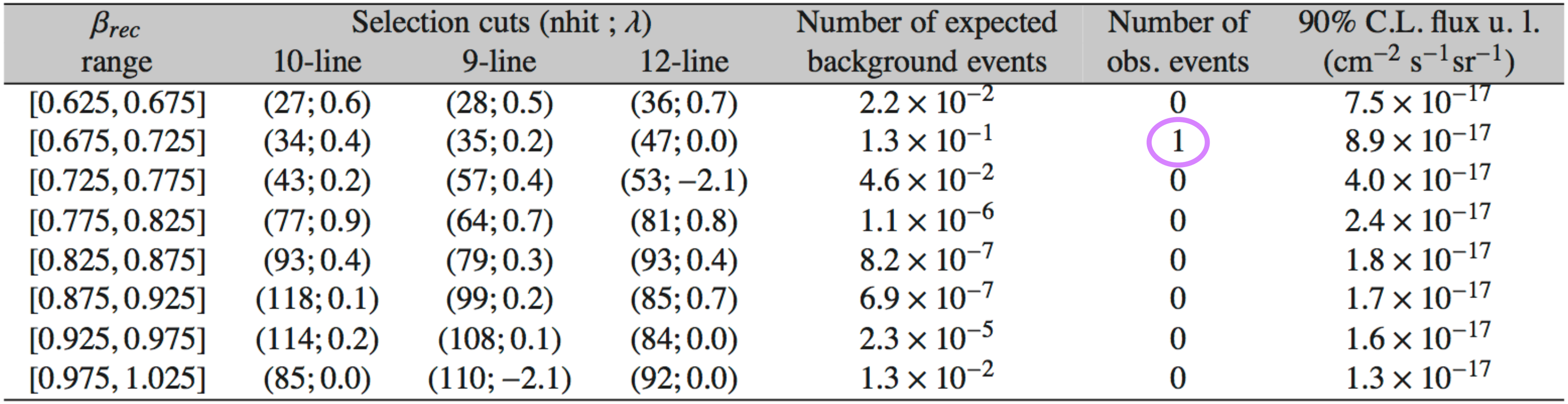
$\beta < \beta_{th}$

Relativistic Magnetic Monopoles

2007-2008

116 days

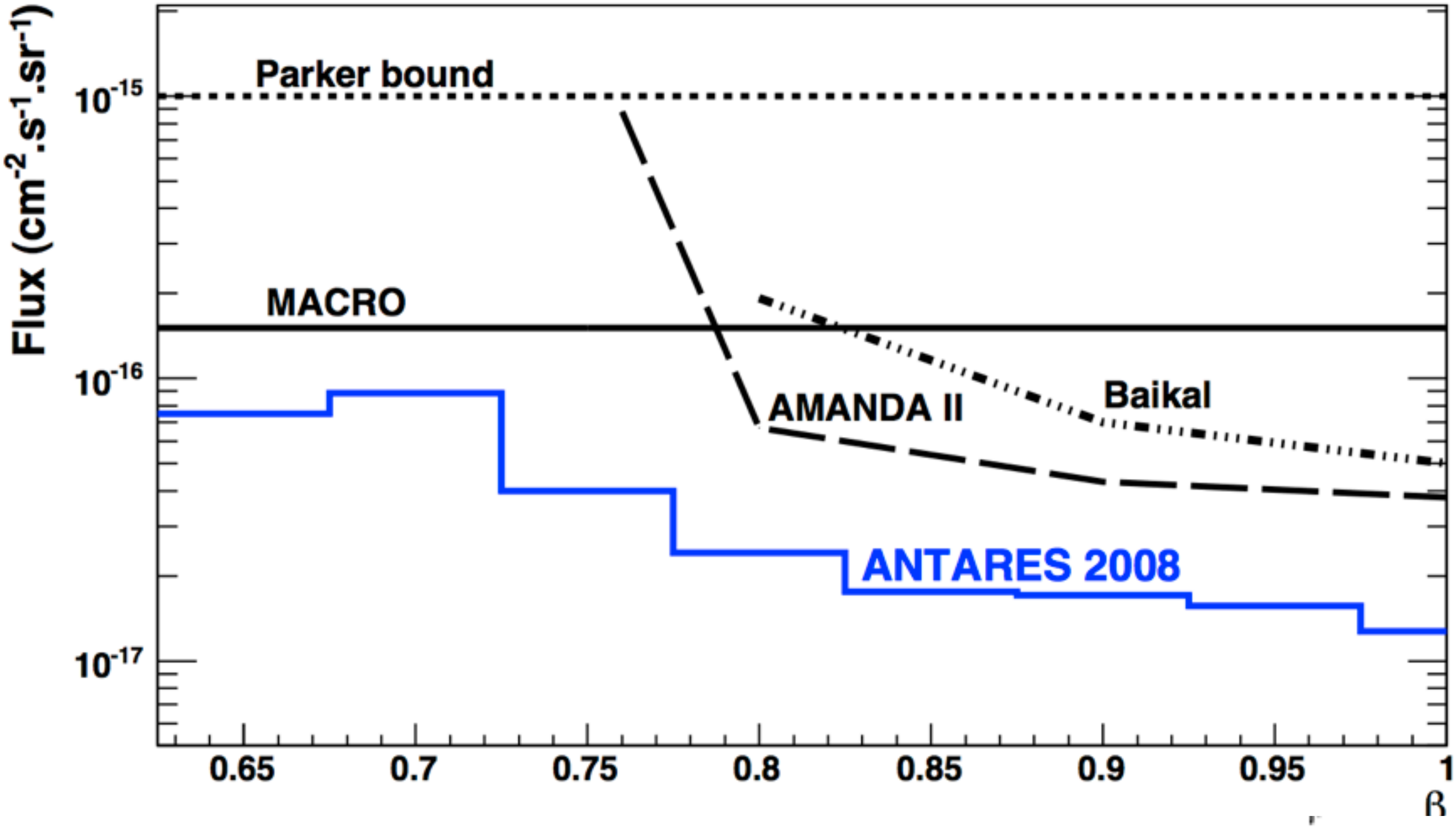
cuts backg observed



β_{rec} range	Selection cuts (nhit ; λ) 10-line	9-line	12-line	Number of expected background events	Number of obs. events	90% C.L. flux u. l. ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}$)
[0.625, 0.675]	(27; 0.6)	(28; 0.5)	(36; 0.7)	2.2×10^{-2}	0	7.5×10^{-17}
[0.675, 0.725]	(34; 0.4)	(35; 0.2)	(47; 0.0)	1.3×10^{-1}	1	8.9×10^{-17}
[0.725, 0.775]	(43; 0.2)	(57; 0.4)	(53; −2.1)	4.6×10^{-2}	0	4.0×10^{-17}
[0.775, 0.825]	(77; 0.9)	(64; 0.7)	(81; 0.8)	1.1×10^{-6}	0	2.4×10^{-17}
[0.825, 0.875]	(93; 0.4)	(79; 0.3)	(93; 0.4)	8.2×10^{-7}	0	1.8×10^{-17}
[0.875, 0.925]	(118; 0.1)	(99; 0.2)	(85; 0.7)	6.9×10^{-7}	0	1.7×10^{-17}
[0.925, 0.975]	(114; 0.2)	(108; 0.1)	(84; 0.0)	2.3×10^{-5}	0	1.6×10^{-17}
[0.975, 1.025]	(85; 0.0)	(110; −2.1)	(92; 0.0)	1.3×10^{-2}	0	1.3×10^{-17}

Relativistic Magnetic Monopoles

Limits



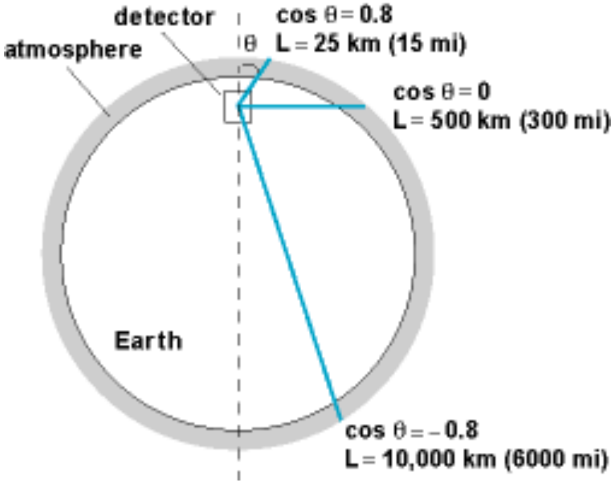
90% confidence level limit on upgoing magnetic monopole flux, ANTARES 2008 (116 days)

Astroparticle Physics 35 (2012) 634–640 [arXiv:1110.2656]

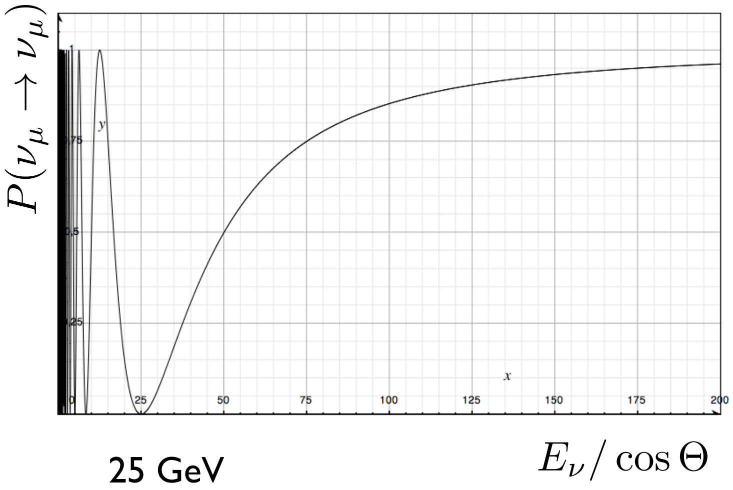
Neutrino oscillations

oscillations w/ atmospheric neutrinos

- $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2(\frac{1.27 \Delta m^2_{32} L}{E_\nu})$
  where $L = D_{Earth} \cdot \cos\Theta$
- $\Rightarrow P(\nu_\mu \to \nu_\mu)$ function of $E_\nu / \cos\Theta$



$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2(\frac{16200 \Delta m^2_{32} \cos\Theta}{E_\nu})$$



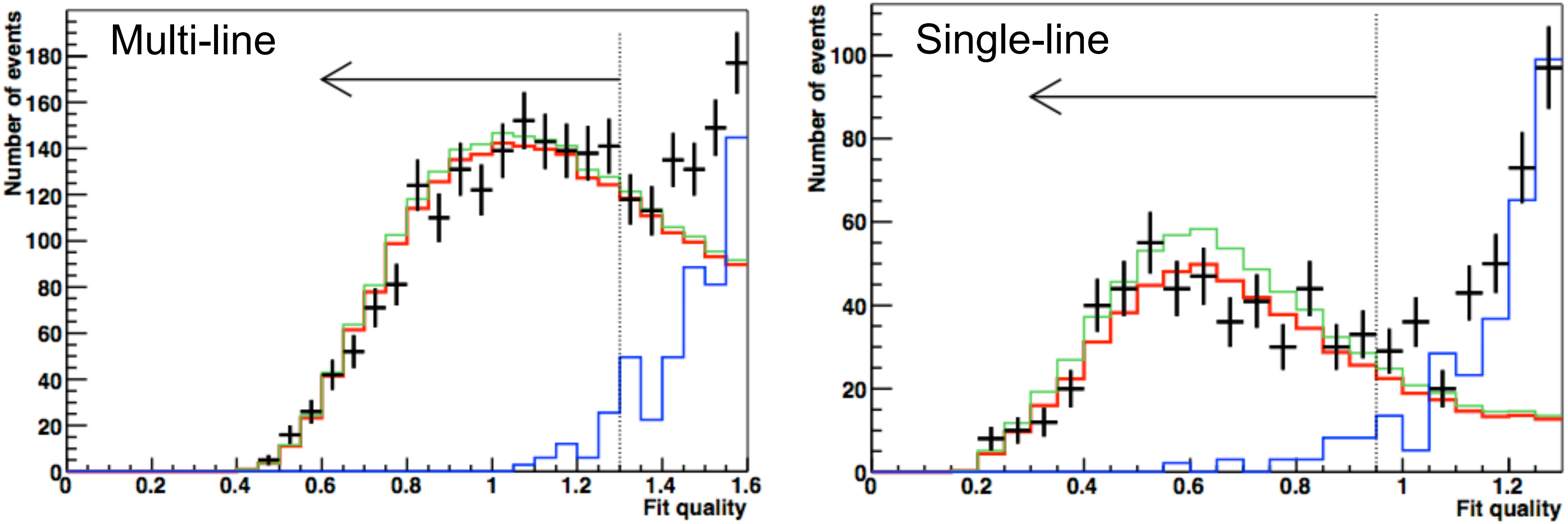
vertical ↑ ν_μ expected to be completely suppressed at $E_\nu = 25$ GeV
(muon range~120m)

Larger effect on single-line events (low energy) than multi-line events (higher energy)

Neutrino oscillations

track selection

Special low energy fit for single-line events (>7storeys, do not fit azimuth)



Red: atm. neutrino w/ oscill.
green : w/o oscill.
blue : atmo. muons

Select pure sample of atmospheric neutrinos (<5% muon contamination)

zenith angle resolution

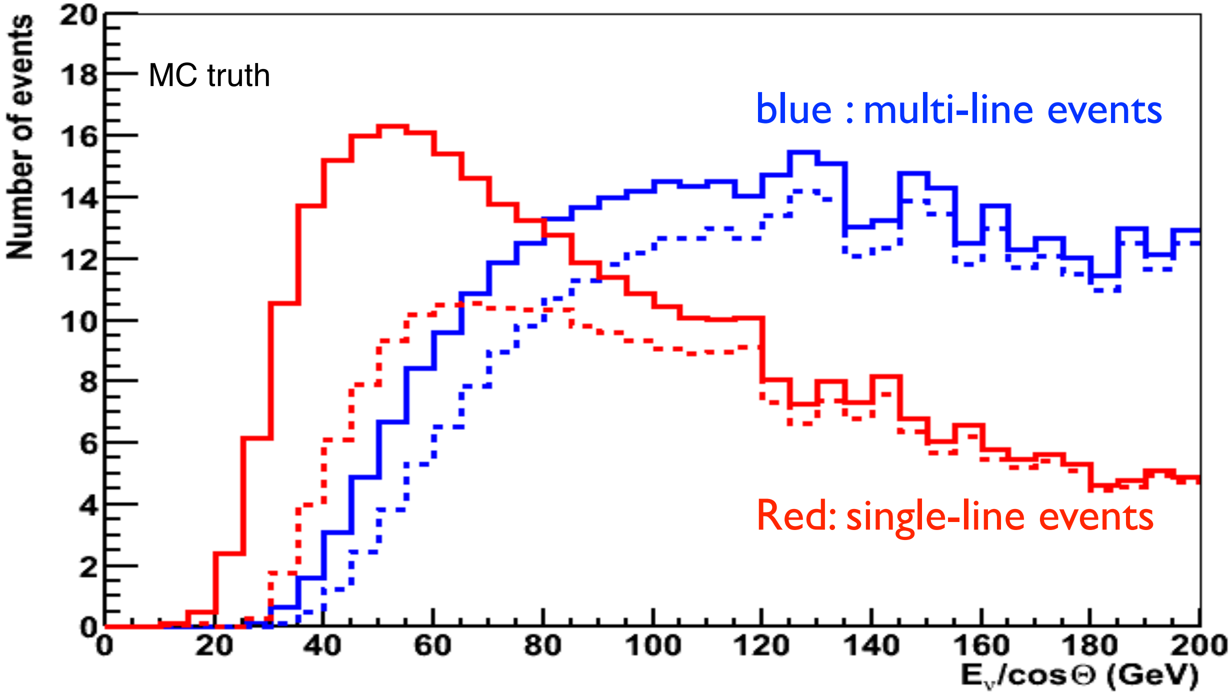
0.8° for multi-line events
3° for single-line events

Neutrino oscillations

Analysis, low energy not easy!

$E_\nu > 50$ GeV : multi-lines (65 m between lines)

$E_\nu \geq 20$ GeV : single-line



Solid line : no oscill.
dashed line : w/ oscill.

Neutrino oscillations

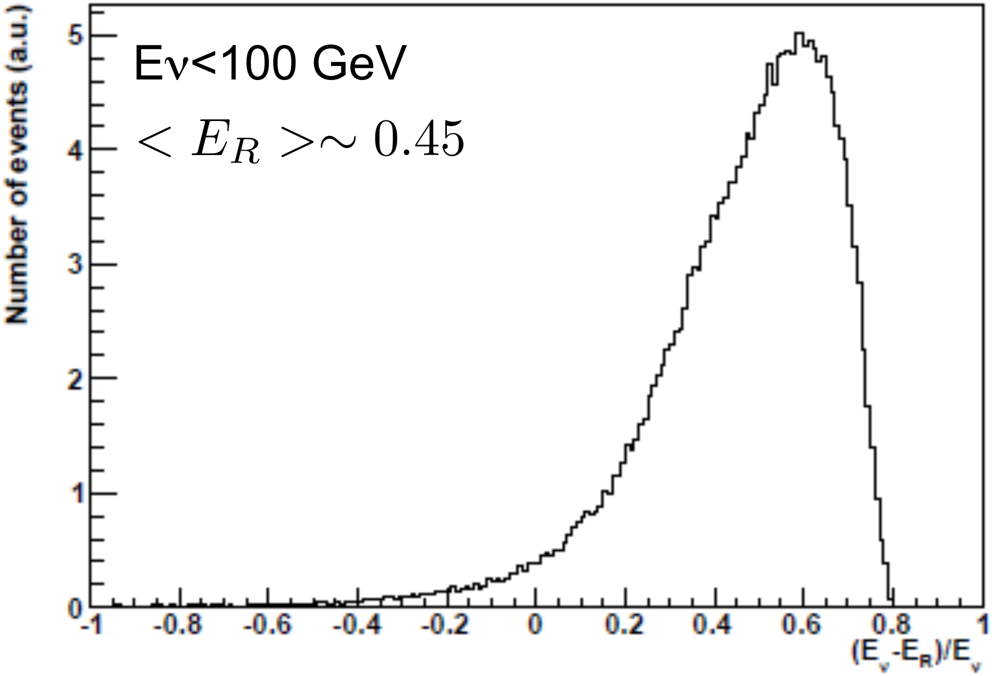
Observable $E_\nu / \cos\Theta$

Energy estimator using approximate μ range $S = (z_{max} - z_{min})/\cos\Theta_R$

$$E_R = 0.2(z_{max} - z_{min})/\cos\Theta_R$$

ionisation energy loss 0.2GeV/m for μ
@ mip in sea water

E_ν from muon range →



Neutrino oscillations

Test the distribution of $E_R/\cos\Theta_R$

Absolute normalisation free

(absorbs dominant uncertainties)

2008-2010 data (863 days):

No oscillation: χ^2/NDF = 40/24 (2.1%)

Best fit: χ^2/NDF = 17.1/21

$\Delta m^2 = 3.1\ 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta = 1.00$

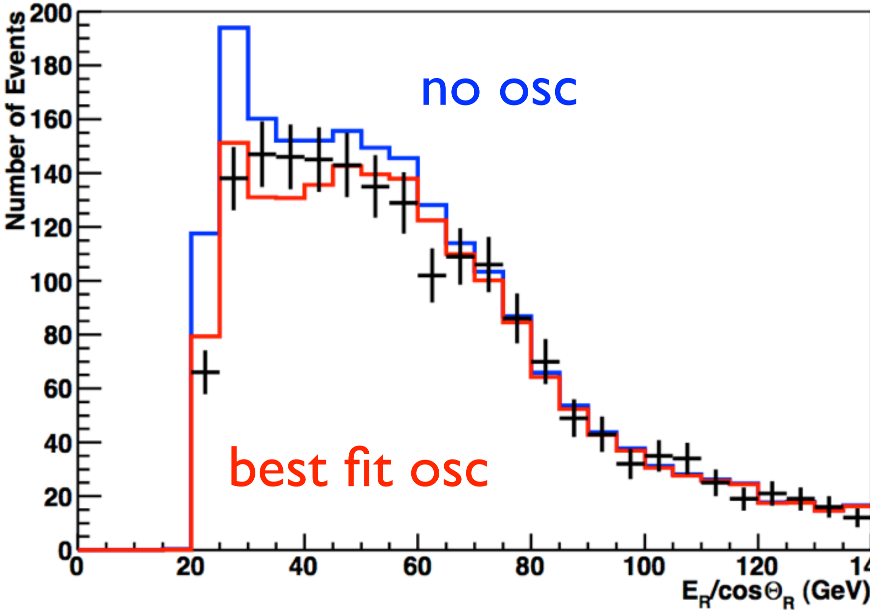
Systematics:

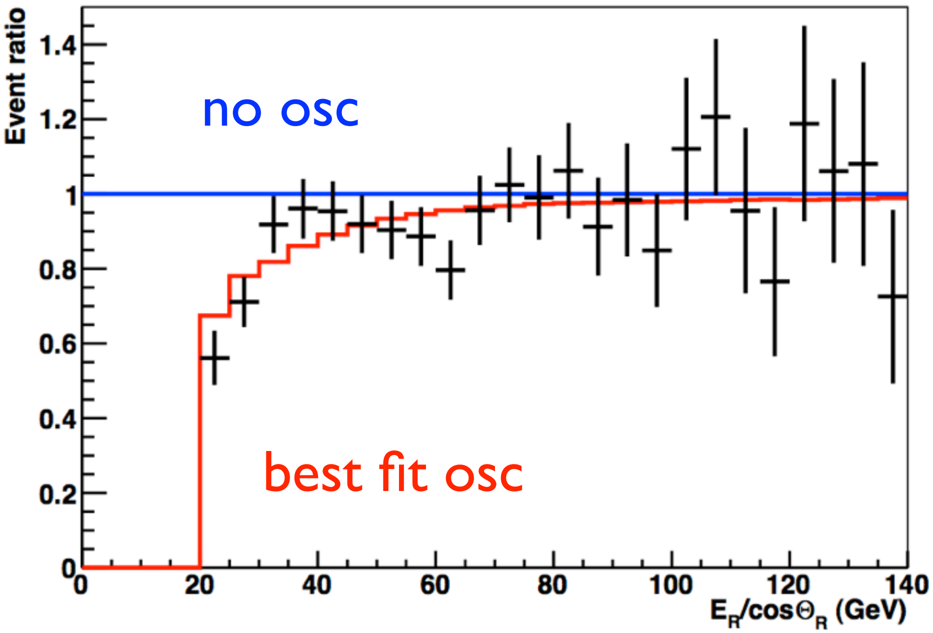
(Absolute normalisation free)

Absorption length: ±10%

Detector efficiency: ±10%

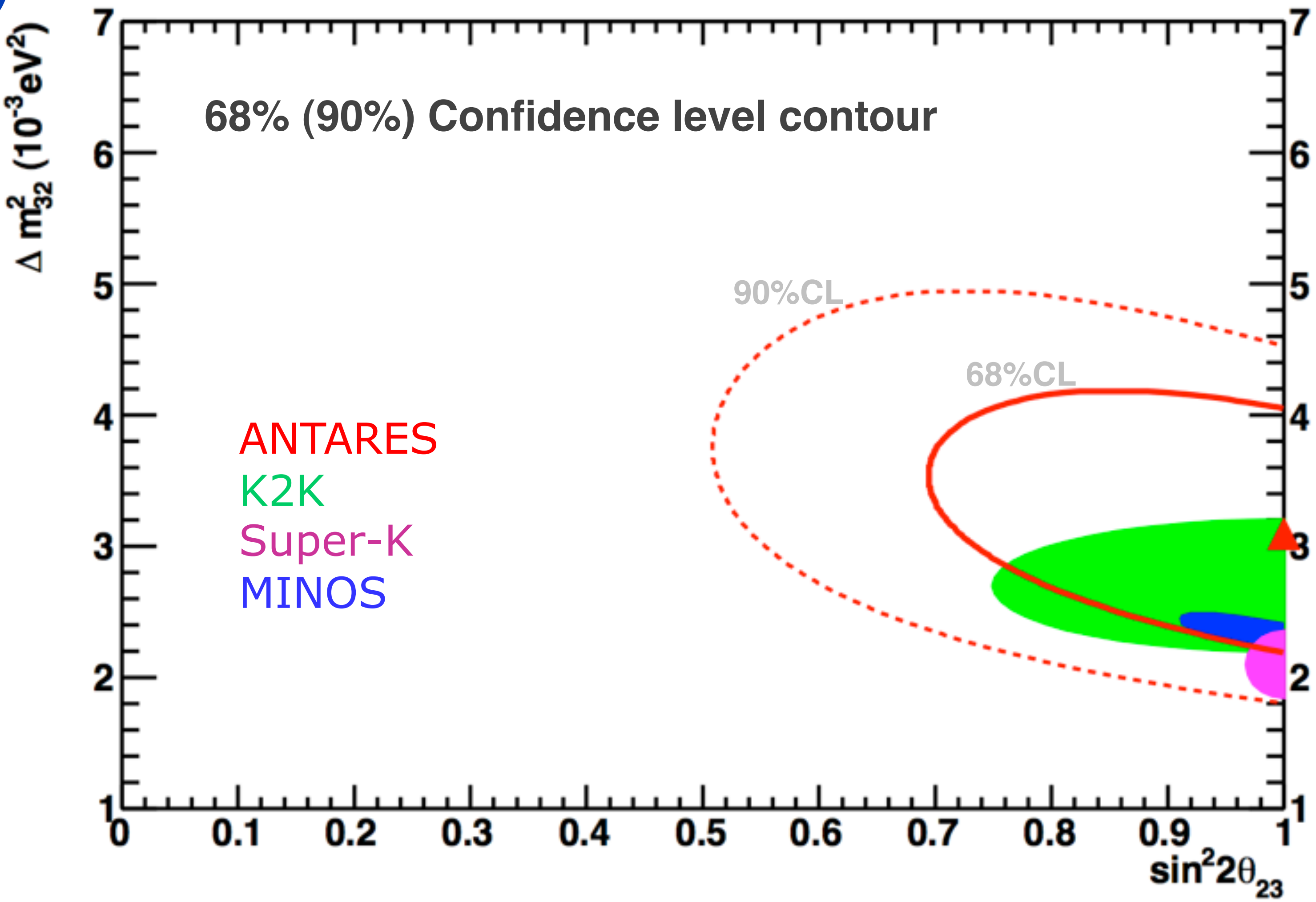
Spectral index of ν flux: ±0.03





Red: best fit w/ oscill. blue : atm.neutrinos w/o oscill. + atm. muons

Neutrino oscillations



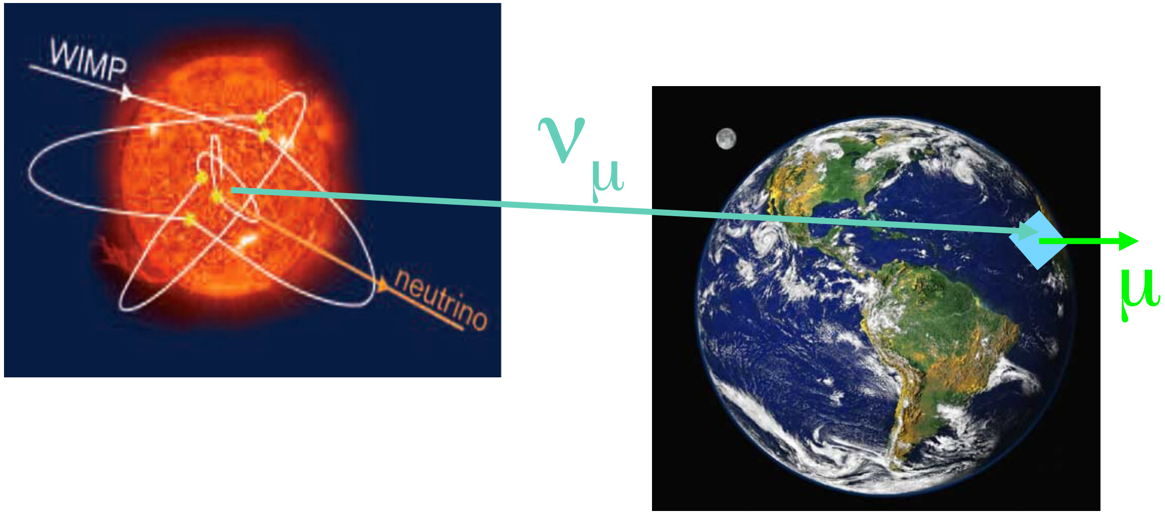
best fit point

Assuming maximal mixing: $\Delta m^2=(3.1\pm0.9)\ 10^{-3}\ \text{eV}^2$

Phys. Lett. B 714 (2012) 224 [arXiv:1206.0645v2]

Search for Dark Matter in the Sun

- WIMPs (neutralinos, Kuluza Klein particles) are among the most popular explanations for Dark Matter
- They would accumulate in massive objects like the Sun, the Galactic Center, dwarf galaxies…



- The products of such annihilations 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 Galactic Centre, for instance)

Neutralino annihilations in the Sun in CMSSM

Study of **neutralino DM** sensitivity within SUSY CMSSM framework

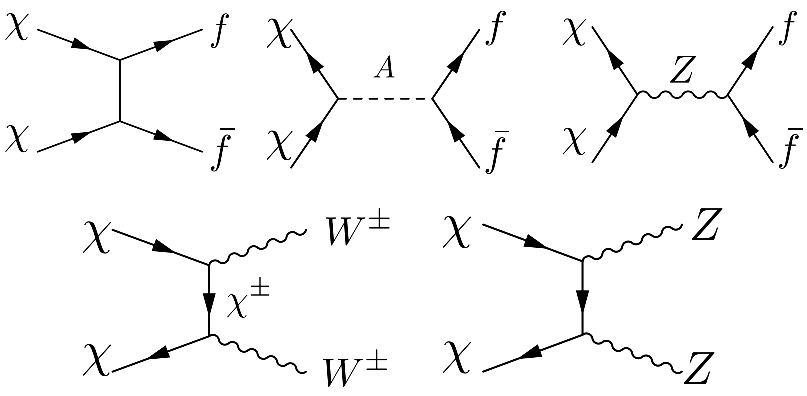
Random scan within CMSSM parameter space

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

$0 < m_0 < 8000$ GeV

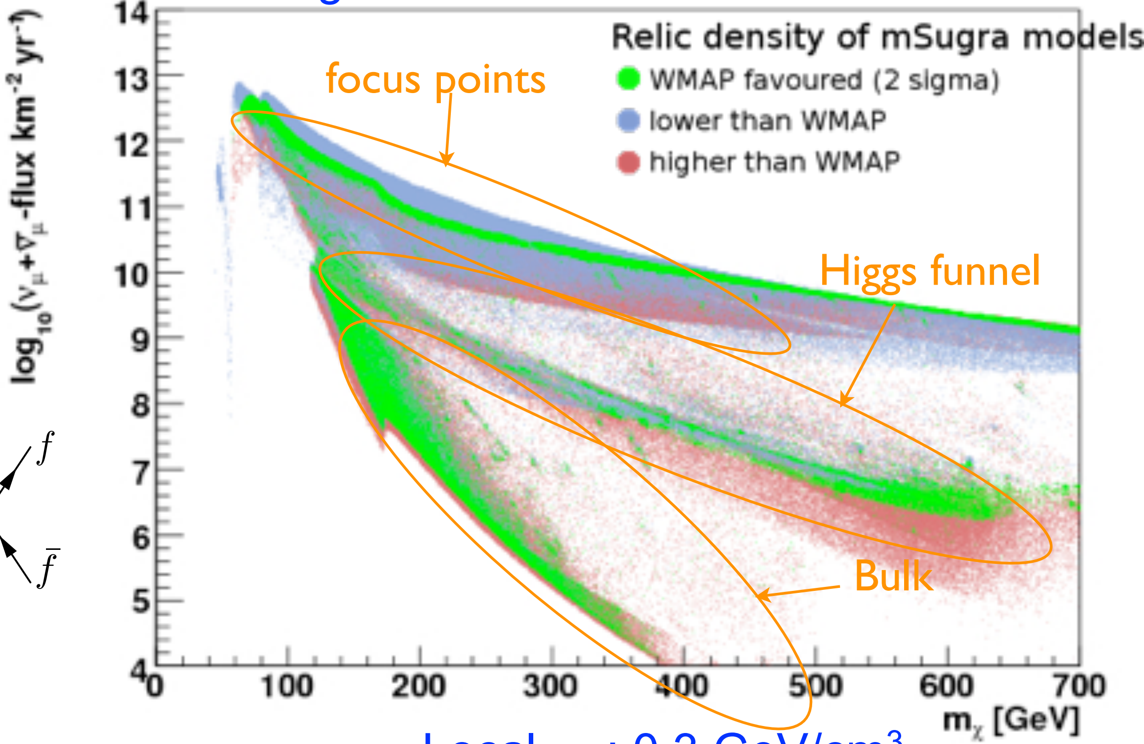
$0 < \tan\beta < 60$

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



DarkSUSY & ISASUGRA (RGE code)
w/ $m_{top} = 172.5\ \mathrm{GeV/c^2}$
Including ν oscillation effects in the Sun and in vacuum

Integrated neutrino flux for Eν > 10 GeV



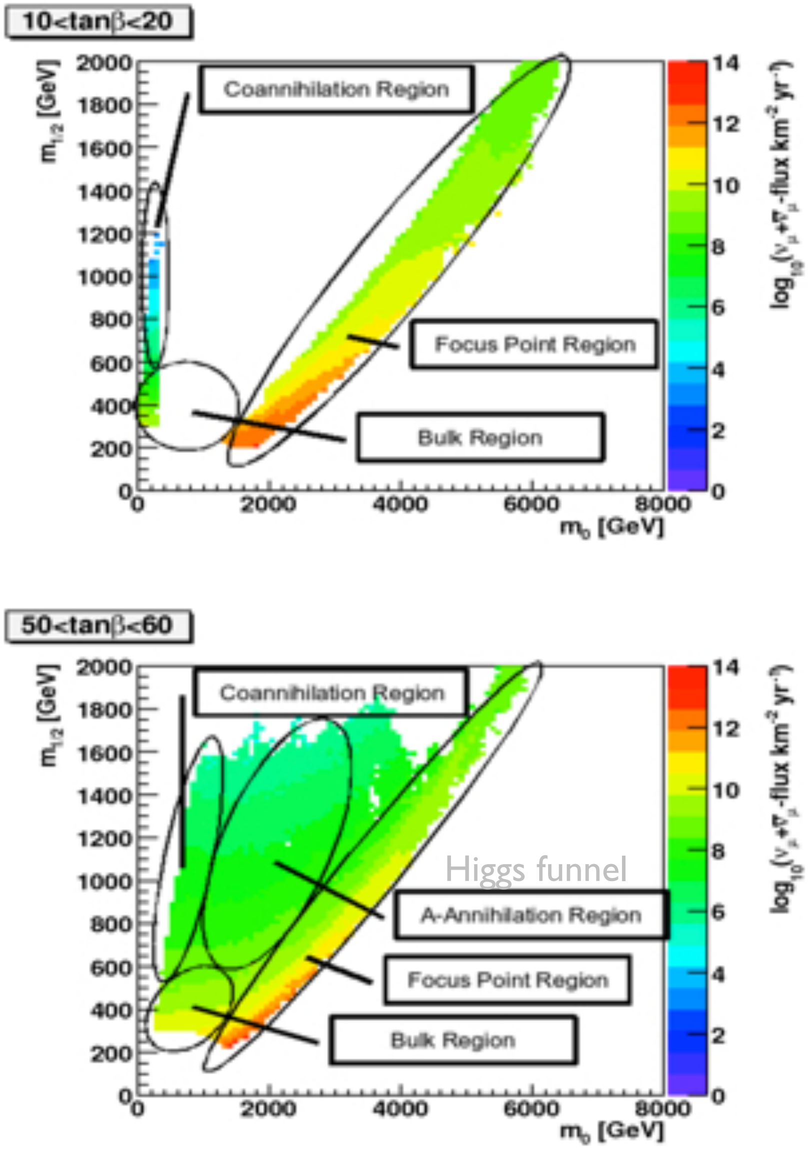
Local ρ_χ : 0.3 GeV/cm^3

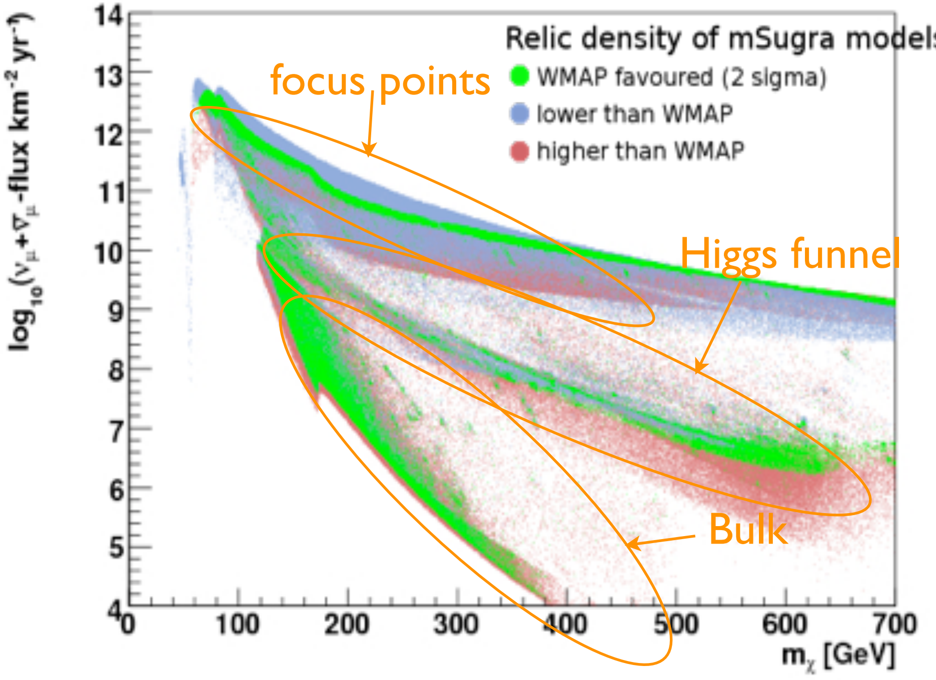
$\langle v_\chi \rangle = 220$ km/s

V. Bertin E. Nazri J. Orloff

Bulk low m_0 and $m_{1/2}$

Neutralino annihilations in the Sun in CMSSM





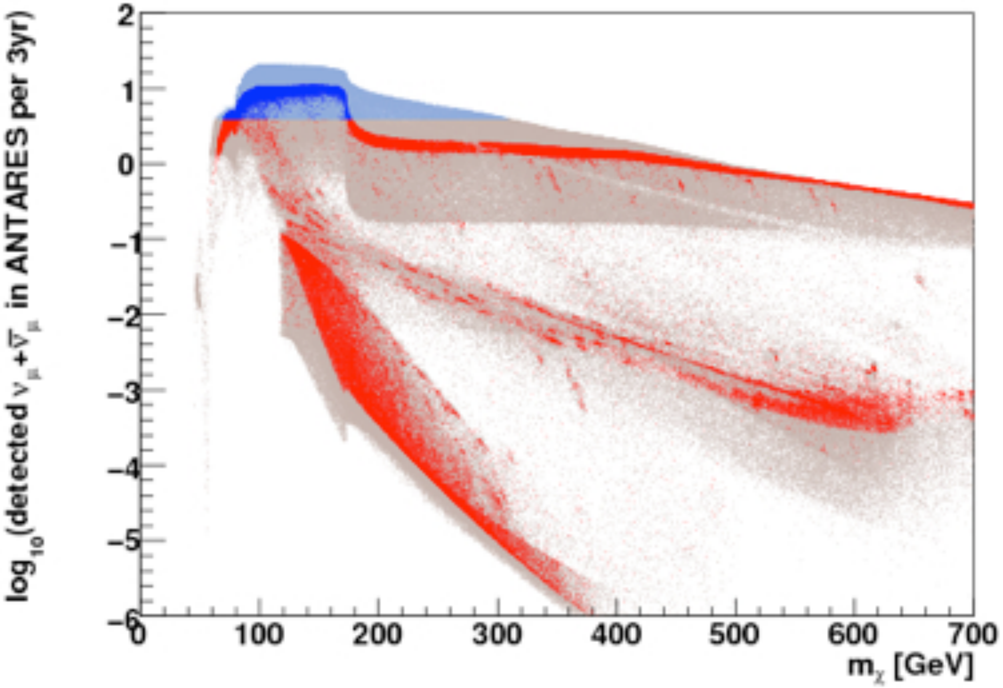
Neutralino annihilations in the Sun in CMSSM

Detection rate with ANTARES in 3 years

Detection rate (t) =
$\nu_\mu + \bar{\nu}_\mu$ flux (E_ν, θ_ν, t) ·
Effective Area (E_ν, θ_ν) ·
Sun's θ_ν distribution

Sensitivity calculated for 3 years of data taking

"Excludable" =
Signal is distinguishable from the background at 90% C.L. (Feldman-Cousins scheme)



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

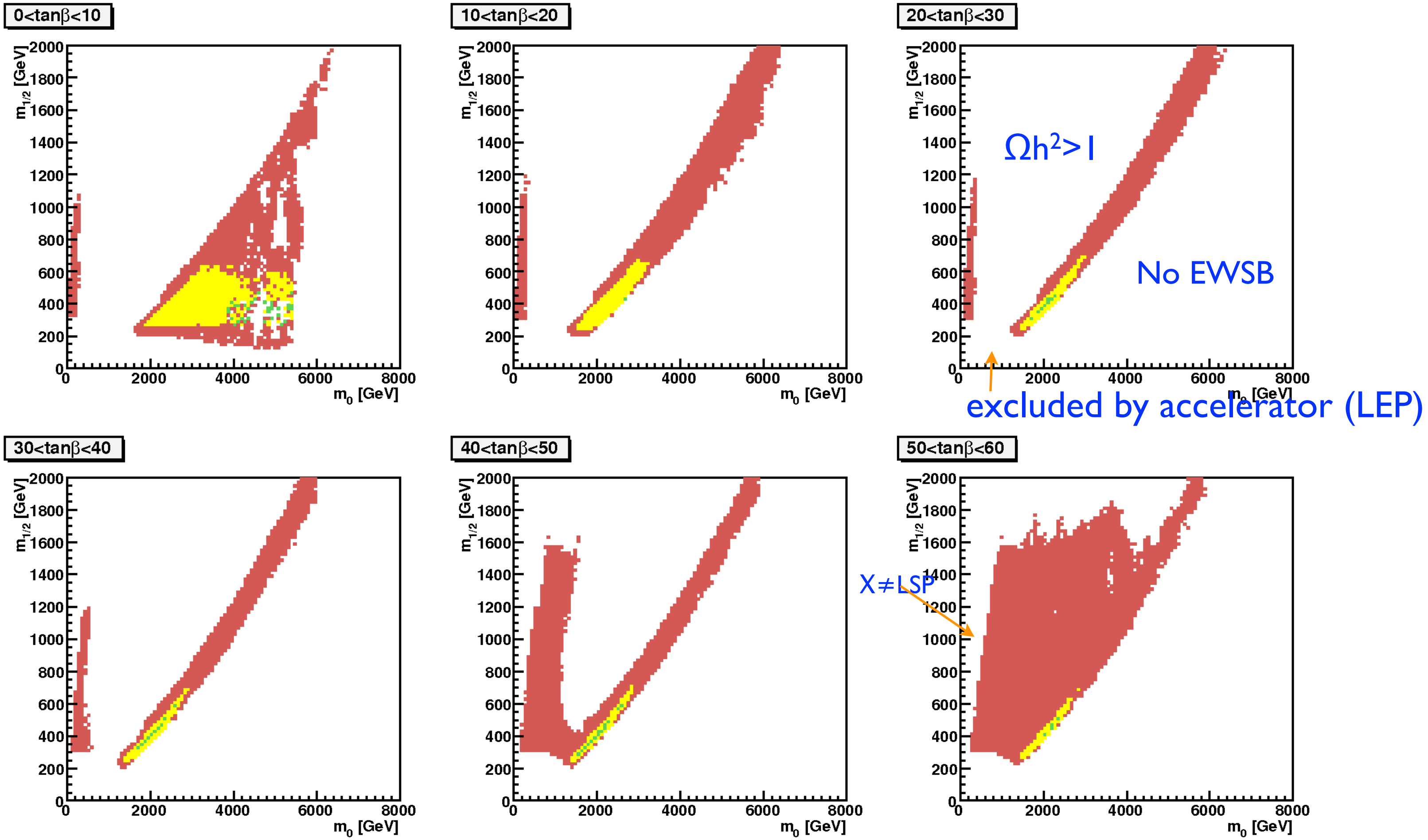
mSugra models disfavoured by WMAP
- ● 90% CL excludable by ANTARES
- ● not excludable

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

Model with relic density **within 2σ** of WMAP constraint are **highlighted** ($0.094 < \Omega_\chi h^2 < 0.129$)

Search for neutralino annihilations in the Sun

Exclusion capabilities of ANTARES for the CMSSM parameter space :
mainly Focus Point region (good complementarity to direct search at LHC)



$\Omega h^2 > 1$

No EWSB

excluded by accelerator (LEP)

X≠LSP

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)

neutrino signal from WIMP annihilation

Signal energy spectrum derived from **WIMPSIM** simulation package for different **WIMP masses**

- 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.)

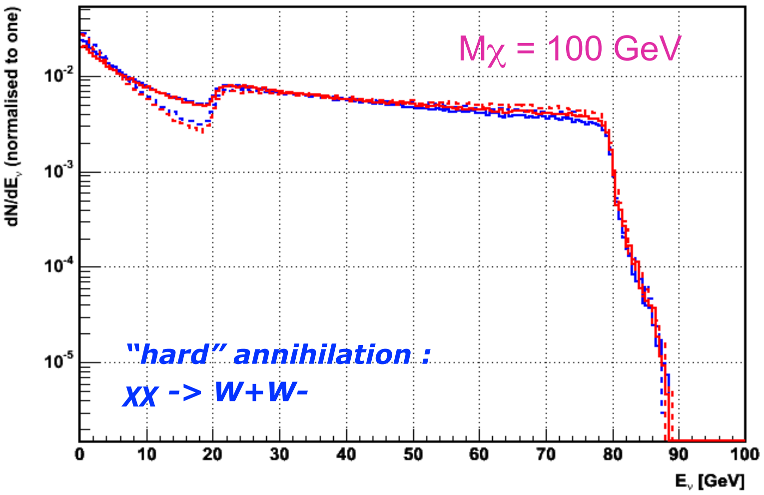
- Available parameters: WIMPs mass, oscillations parameters...

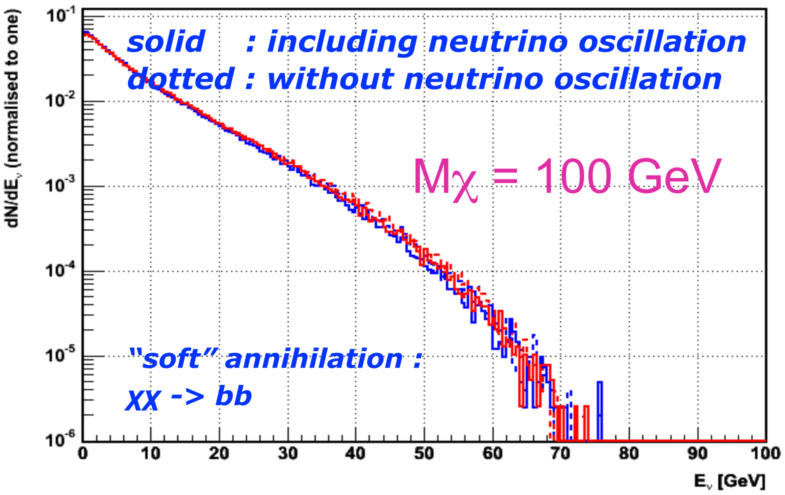
Neutrino spectra from neutralino annihilations

“hard” annihilation : $\chi\chi$ -> W+W-

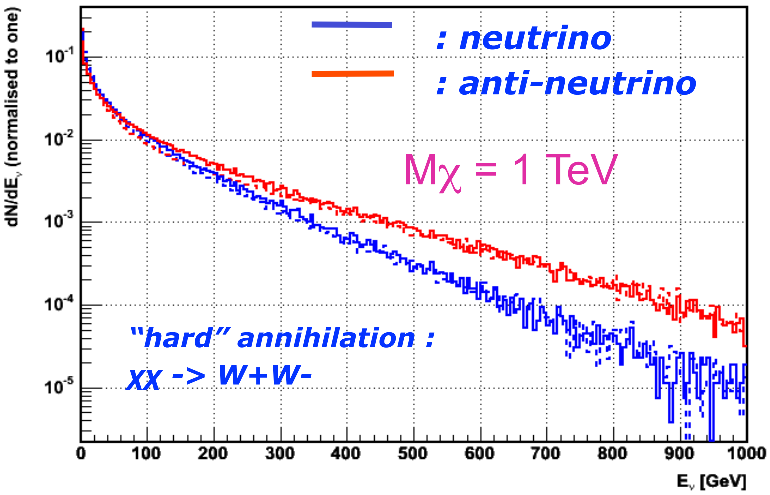
“soft” annihilation : $\chi\chi$ -> bb

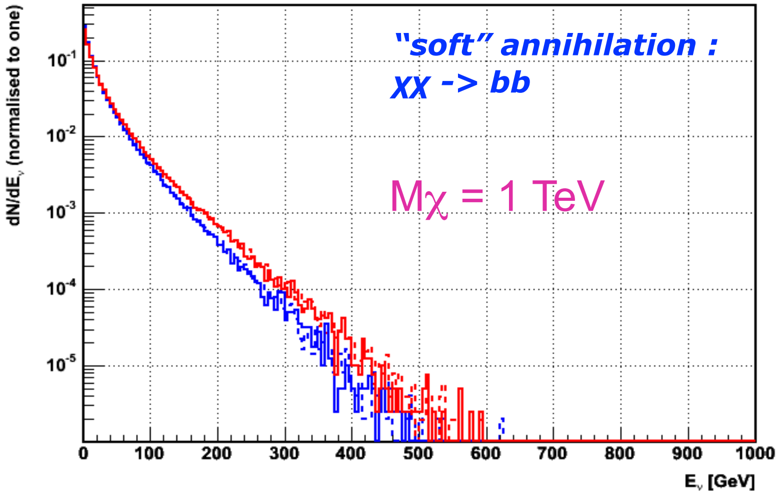
$M\chi$ = 100 GeV





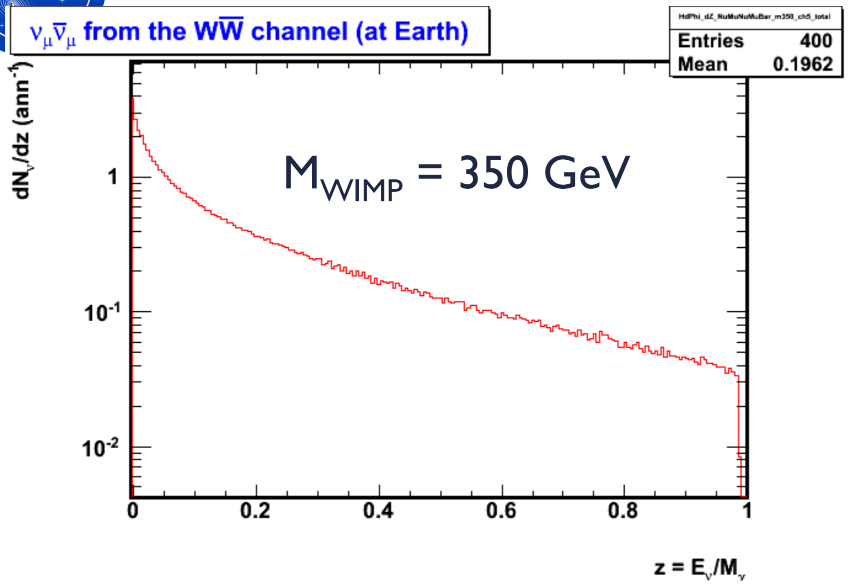
$M\chi$ = 1 TeV



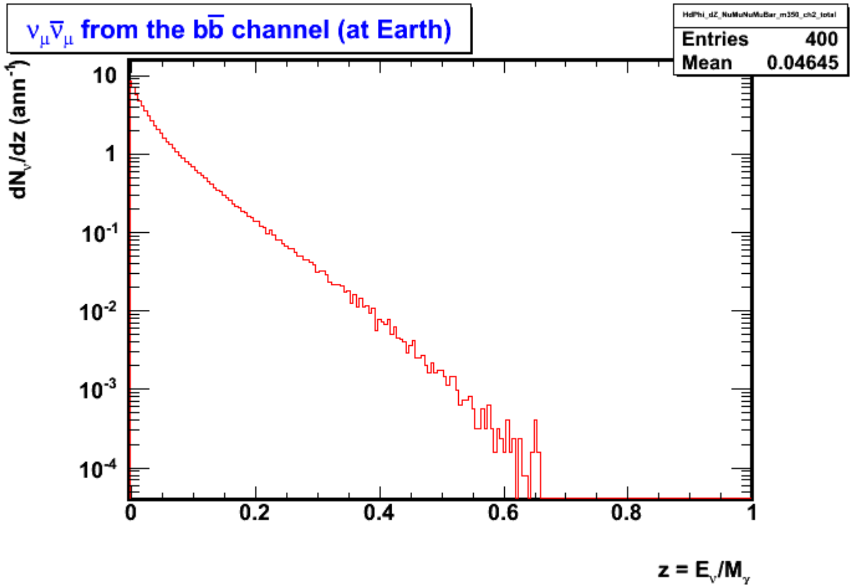


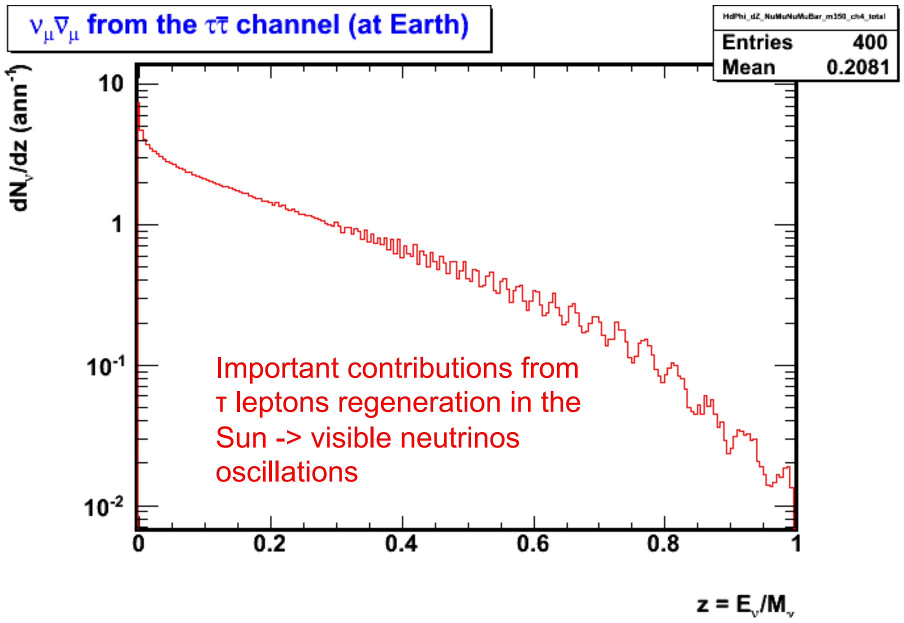
Neutrinos from $\chi\chi \rightarrow$ WW (hard spectrum) are more energetic and easier to detect

Main annihilation channels

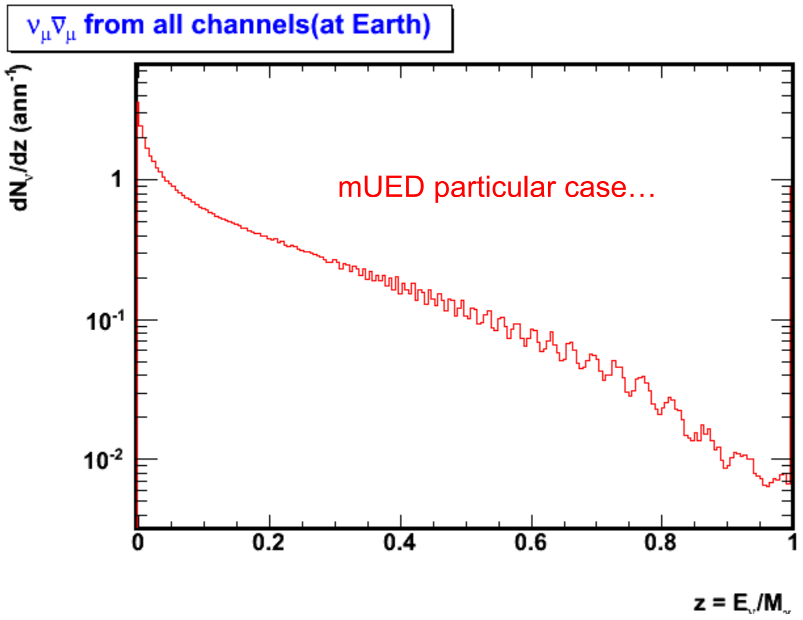

$\nu_\mu\bar{\nu}_\mu$ from the $W\bar{W}$ channel (at Earth)

M_{WIMP} = 350 GeV


$\nu_\mu\bar{\nu}_\mu$ from the $b\bar{b}$ channel (at Earth)


$\nu_\mu\bar{\nu}_\mu$ from the $\tau\bar{\tau}$ channel (at Earth)

Important contributions from τ leptons regeneration in the Sun -> visible neutrinos oscillations


$\nu_\mu\bar{\nu}_\mu$ from all channels(at Earth)

mUED particular case…

Dark Matter Sun analysis

New results with Sun analysis, 200-2008 data,
~ 295 days

2007-2011 analysis ongoing, ~400 effective days

Search strategy

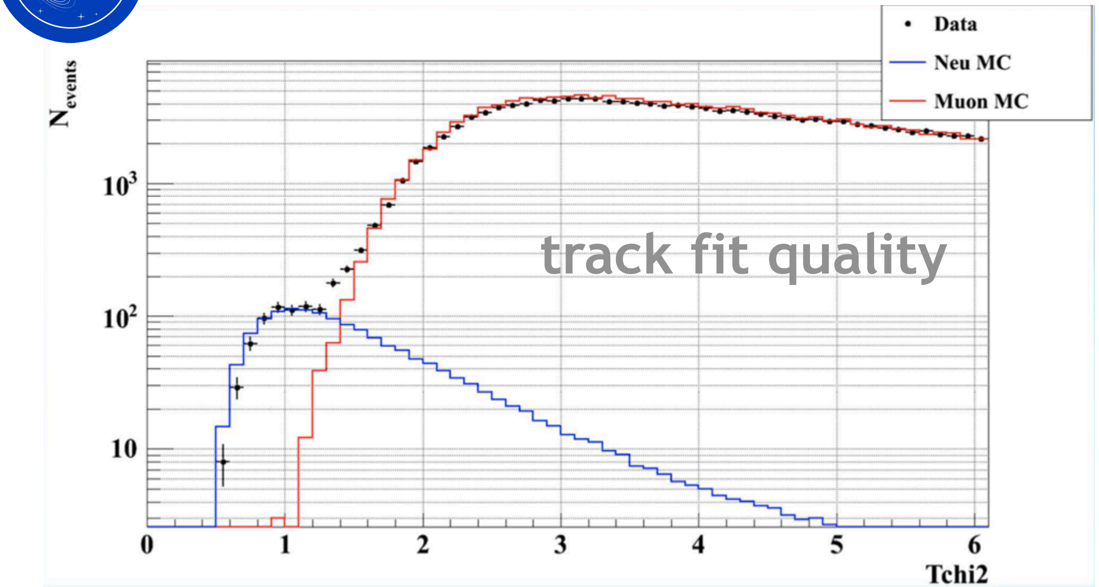
Binned search towards the direction of the **Sun** (visibility below horizon)

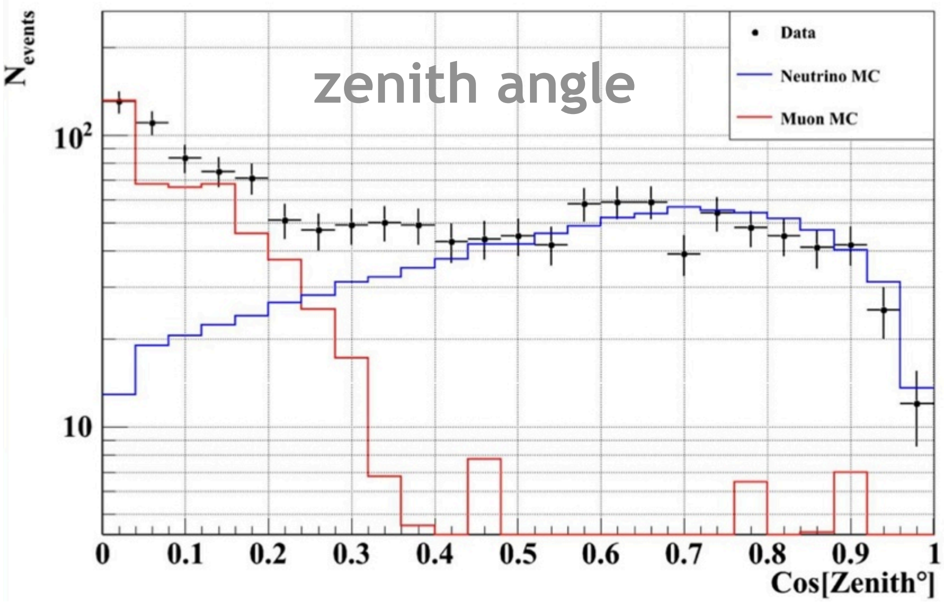
Background from atm. neutrinos and muons estimated from MC simulation and **scrambled data**

Signal energy spectrum from **WIMPSIM**

Sensitivity optimised using Feldman-cousins method, scanning track quality cut and cone opening angle

Dark Matter Sun analysis





Event selection

Quality parameter of the track reconstruction for upgoing events

- very good agreement data vs. Monte Carlo events
- good separation between neutrino and muon events

Zenith distribution of selected events (Tchi2 < 1.6)

strong reduction of the atmospheric muon background

Signal and cut optimization

Neutrino flux at the earth, from the Dark Matter coannihilation, are convoluated with the efficiency of the detector for a cuts parameter space (track fit quality cut,cone)

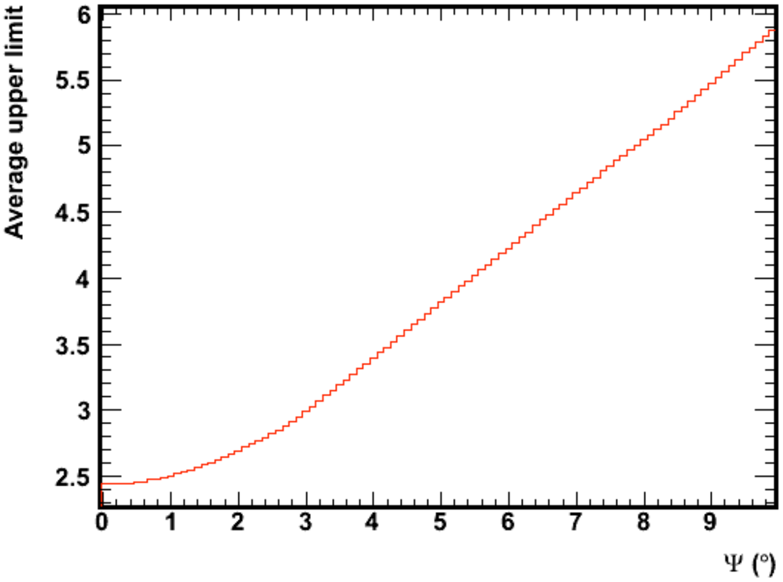
Neutrino background from the scrambled data in the Sun direction is evaluated in the same space

Minimize this quantity: $$\bar{\Phi}_{\nu}^{90\%} = \frac{\bar{\mu}_{90}}{A_{eff}(M_{WIMP})\,T_{eff}}$$

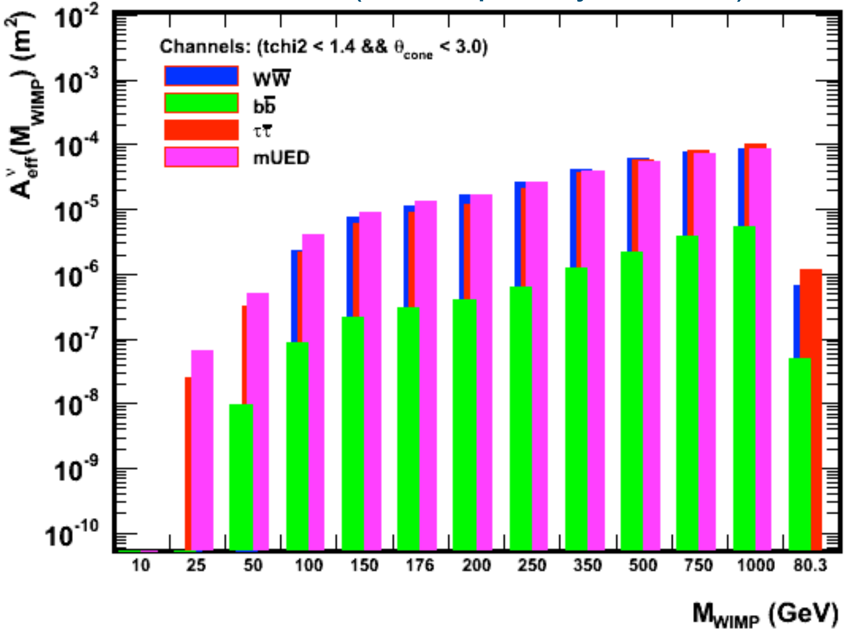
T_{eff} active time

A_{eff} effective area

Average upper limit (Feldman-Cousins)

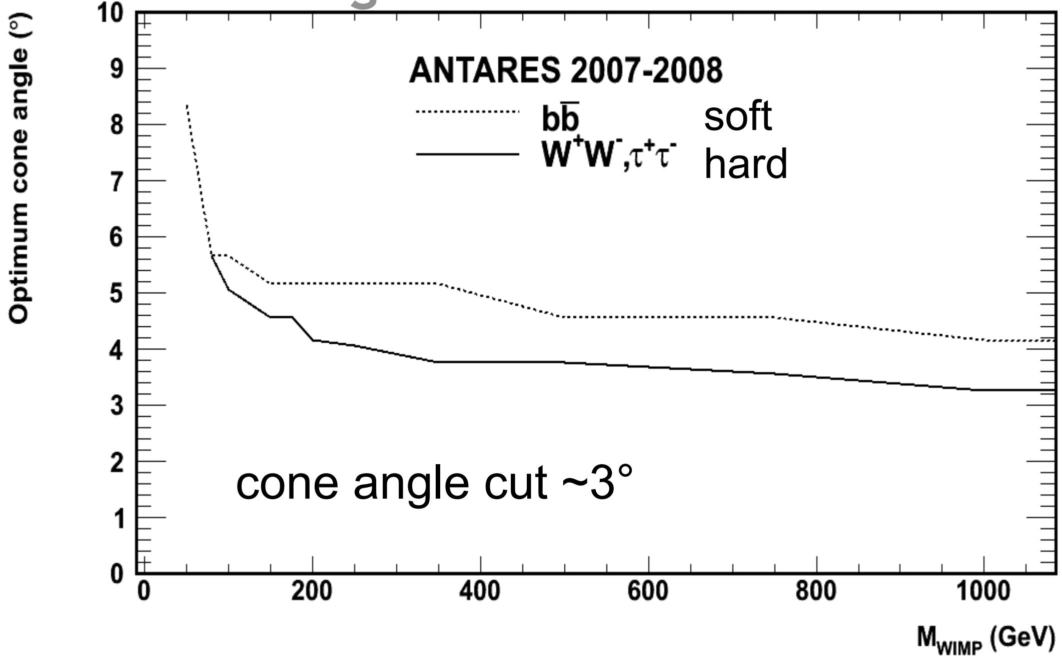


Acceptance to be estimated for different sets (Track quaktity fit ,cone)



Dark Matter Sun analysis

cone angle



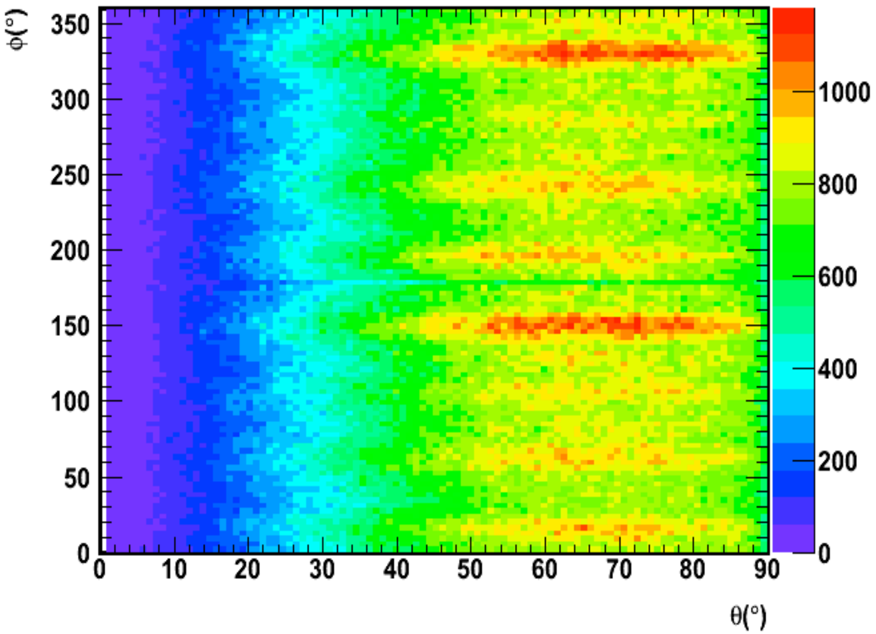
comparaison of the number of events observed in a cone around the Sun direction with the excepted background

background in the sun direction

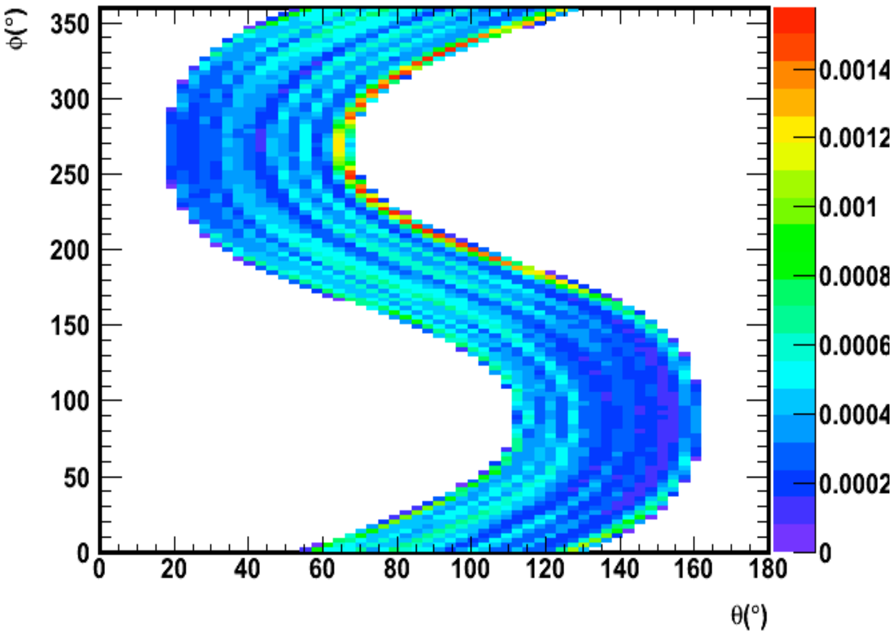
- Background estimated from data scrambled in time and (θ,Φ) using the Sun visibility at the ANTARES location
- 2007-2008 period, ~295 days
- Fast algorithm for muon track reconstruction (Astro. Phys. 34 (2011) 652-662)

- Background from CR interactions in the Sun corona much lower (<1% of atmospheric neutrinos)

All upward-going events from 2007-2008 data



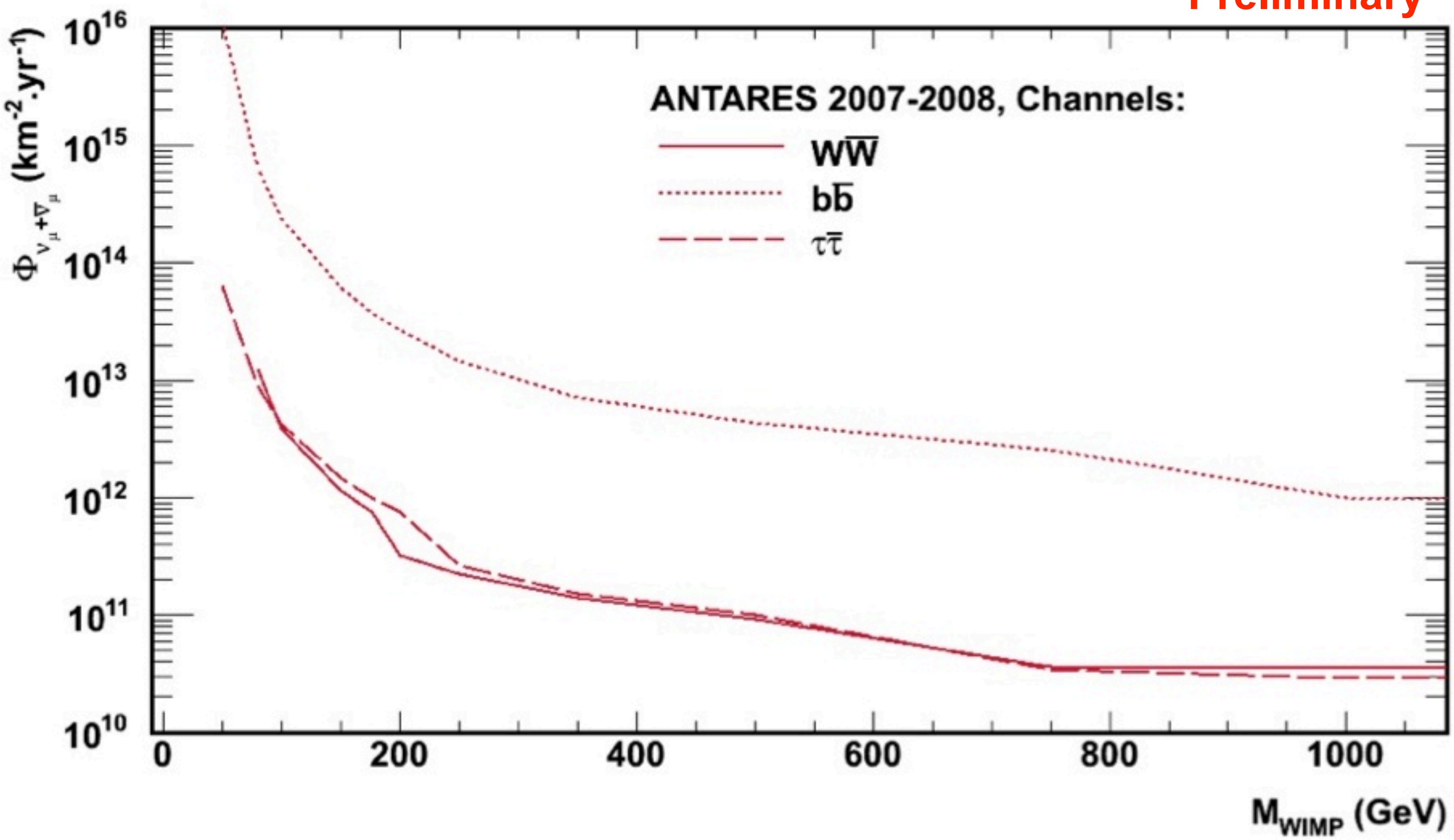
Example of Sun tracking in horizontal coordinates



Neutrino flux sensitivity

Neutrino flux sensitivity @ 90% CL for 2007-2008 data

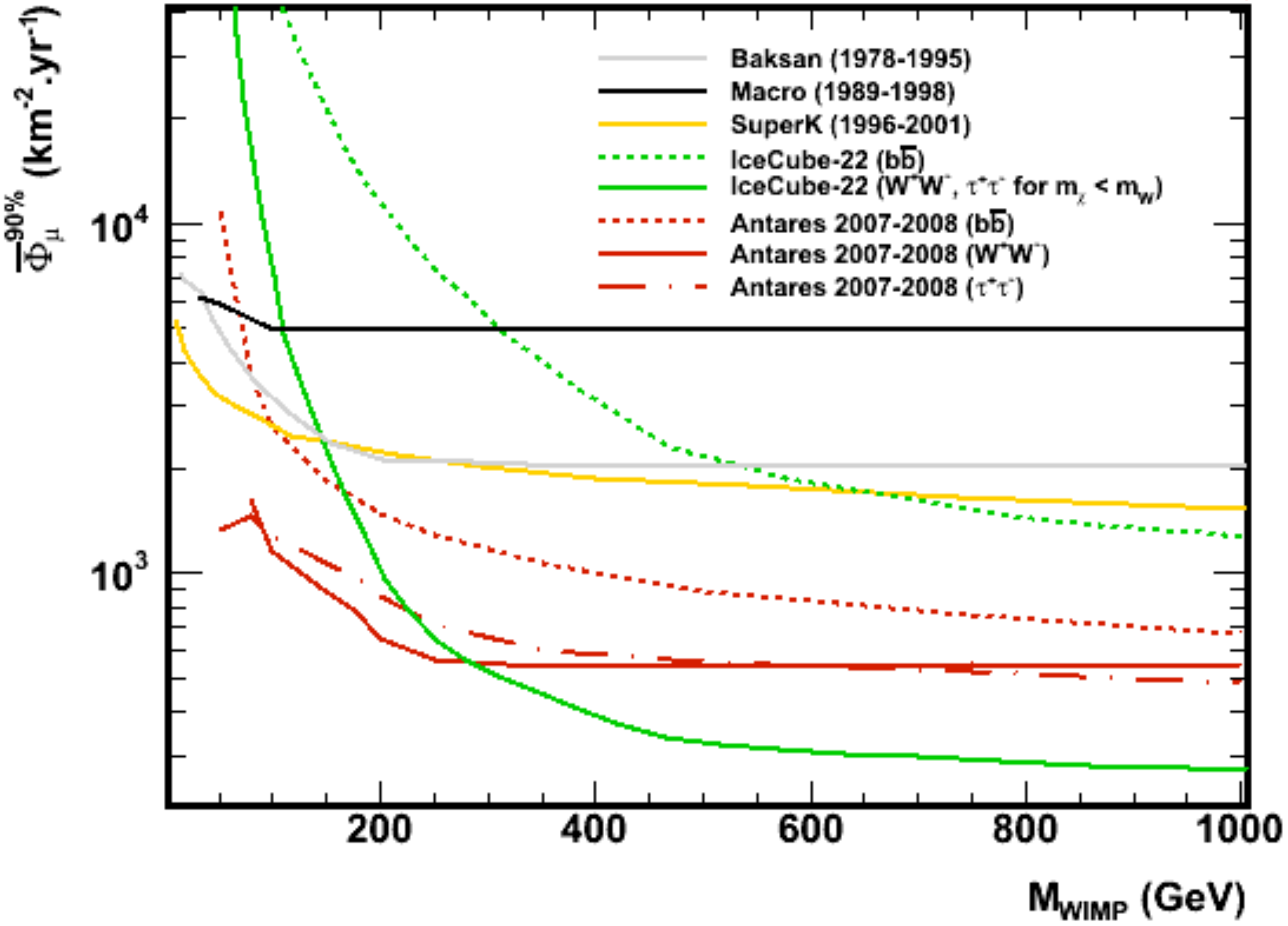
Preliminary



Muon flux sensitivity

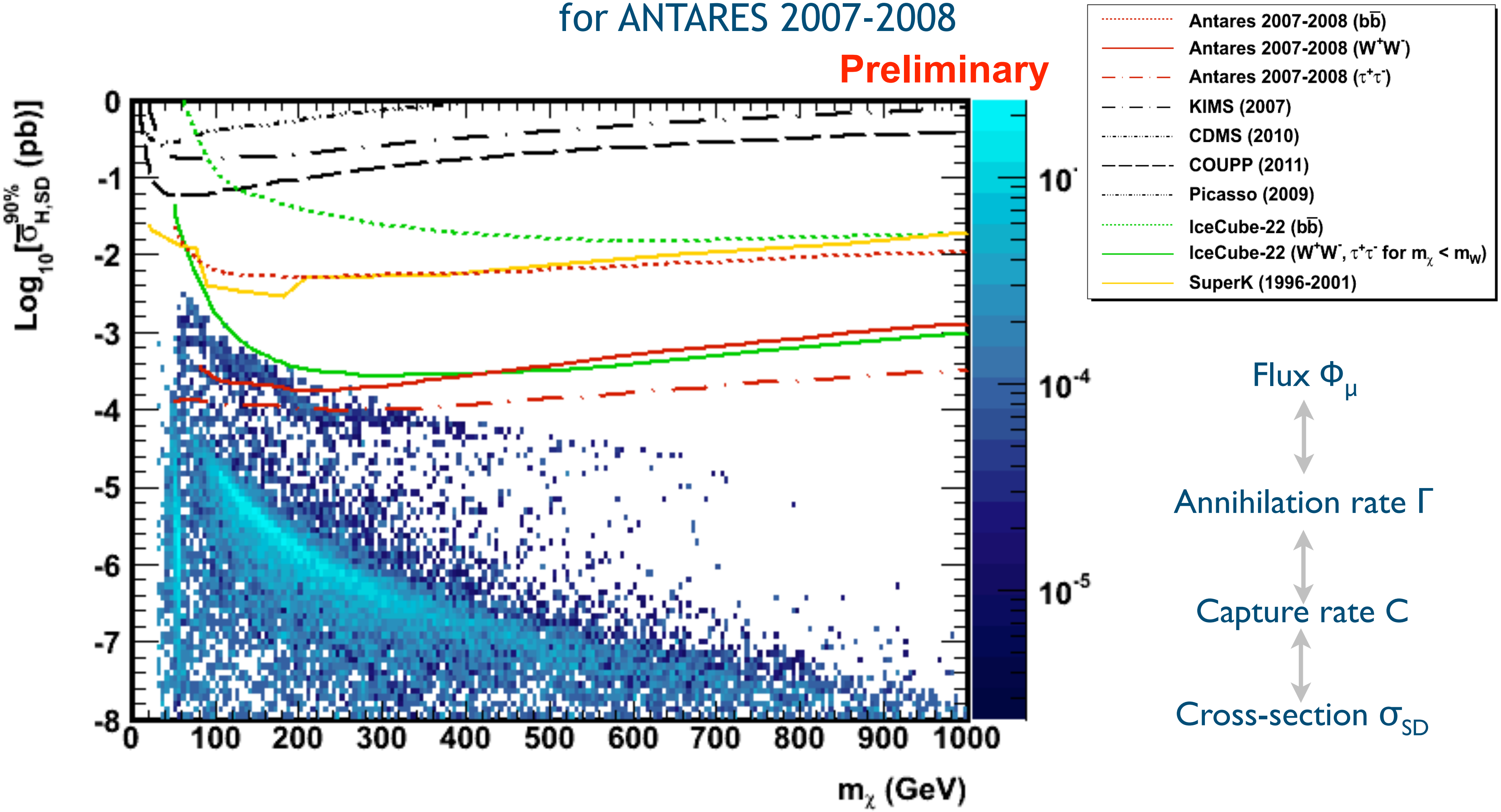
Muon flux sensitivity @ 90% CL for ANTARES 2007-2008

Preliminary



CMSSM cross-section sensitivity

Spin-dependent cross-section flux sensitivity @ 90% CL
for ANTARES 2007-2008



Flux Φ_μ

↕

Annihilation rate Γ

↕

Capture rate C

↕

Cross-section σ_{SD}

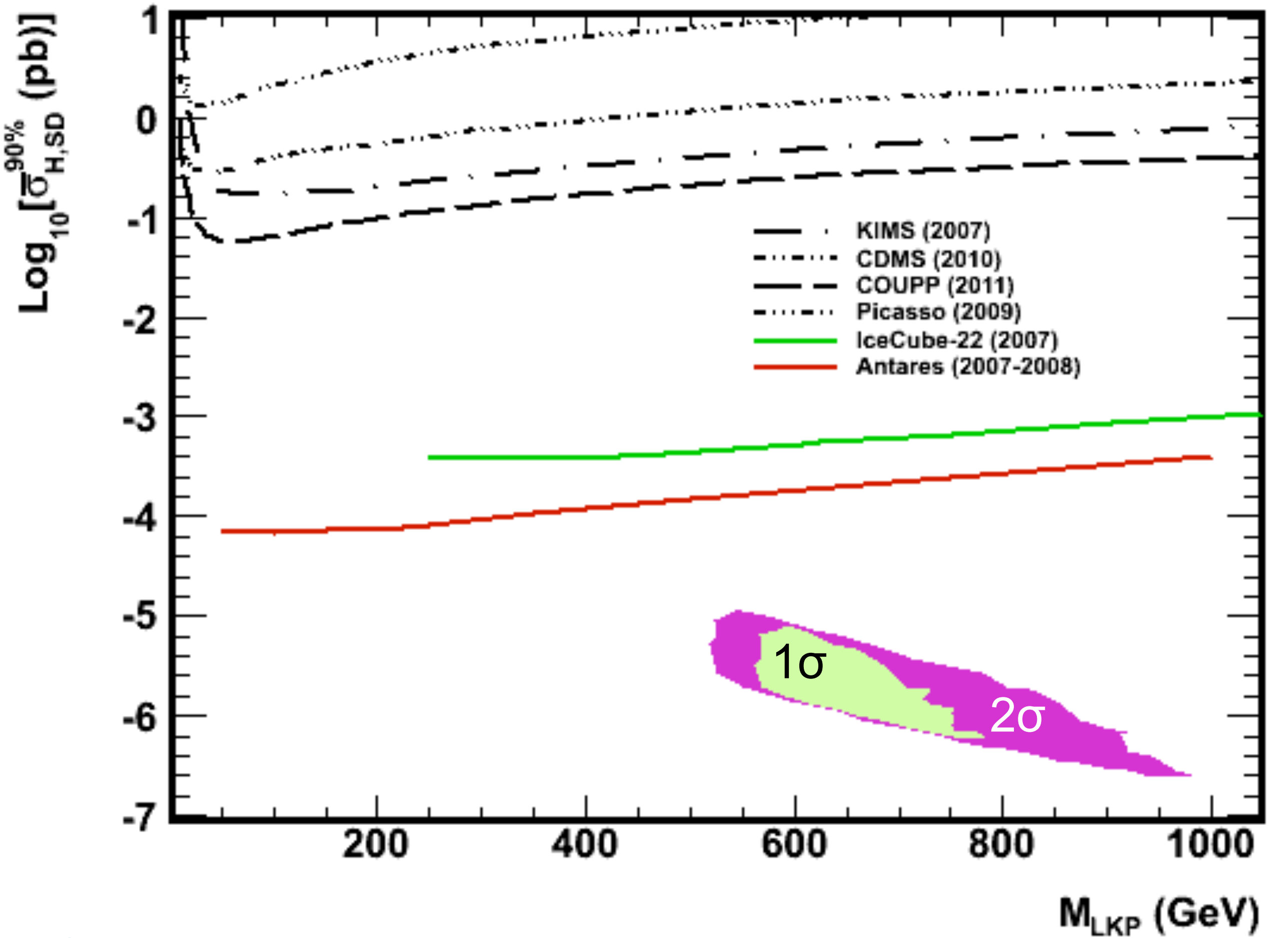
Compare SUSY predictions to observables as sparticles masses, collider observables, dark matter relic density, direct detection cross-sections, …

SuperBayes
(arXiv:1101.3296)

mUED cross-section sensitivity

Spin-dependent cross-section flux sensitivity @ 90% CL for ANTARES 2007-2008

Preliminary



Cross- section

σ_{SD}

⇳

Capture rate C

⇳

Annihilation rate Γ

⇳

Flux Φ_μ

⇳

Flux Φ_ν

SuperBayes
modified version
Physical Review D 83, 036008 (2011)

Compare mUED predictions to observables as KK masses, collider observables, relic density, direct detection cross-sections, …

Summary

ANTARES complete and running since 2008

Physics analysis ongoing
take advantage of
- low energy threshold
- low diffusion of deep sea water

Exotic massive particles
- as magnetic monopoles, stringent limits
- also below Cerenkov threshold

Oscillation analysis
- 2007-2010 data analysed
- measurement compatible with world data
- low energy is reliable and systematics under control

Dark matter
- 2007-2008 data analysis completed
- 2007-2011 analysis on track