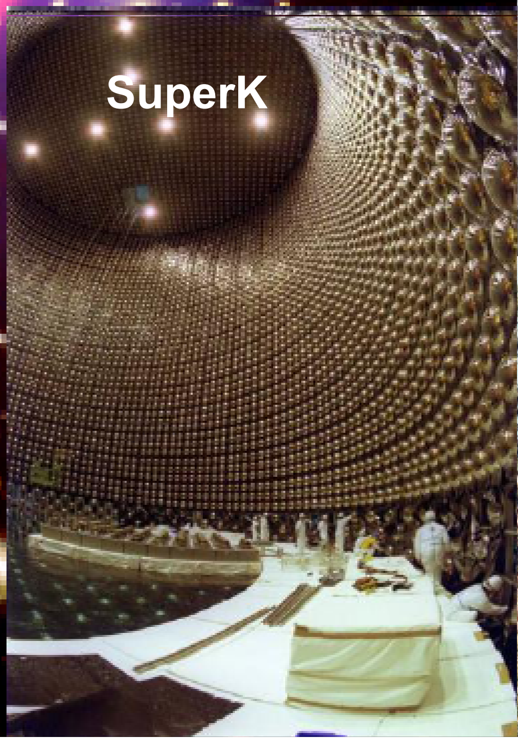
Loucatos,
U, CEA-Saclay
nce

Indirect dark matter searches with neutrino telescopes

NDM09
Madison, September 09

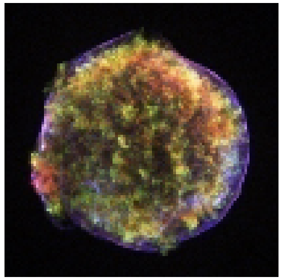


Potential sources of ν's

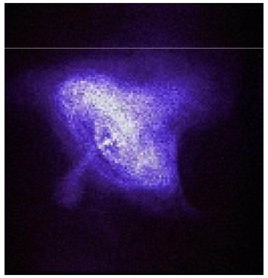
GALACTIC

EXTRAGALACTIC

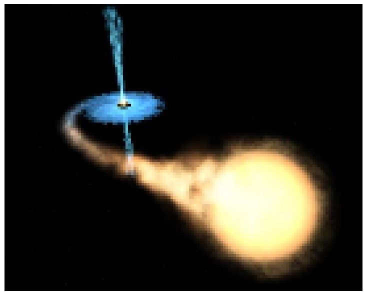
Indirect dark matter signal



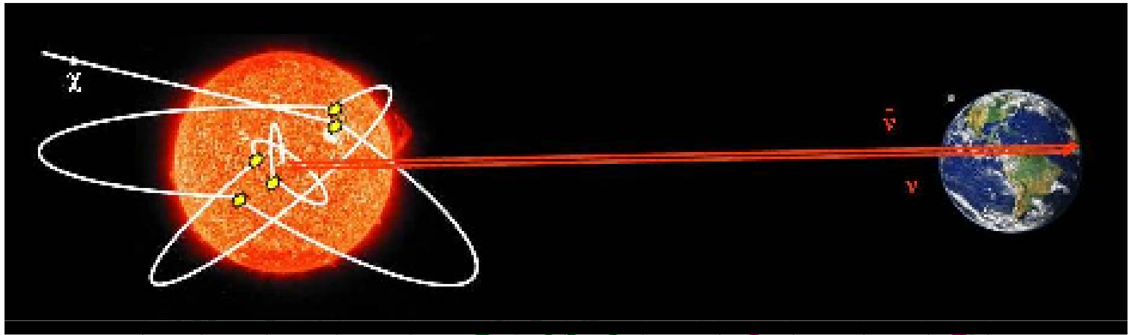
Supernova remnants



Pulsars



Microquasars



Relic WIMPs captured in celestial bodies

χχ self-annihilations into

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

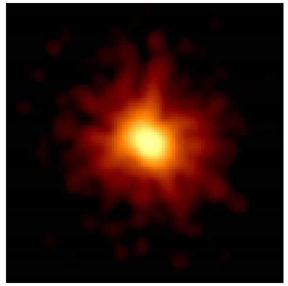
(prompt)

→ significant

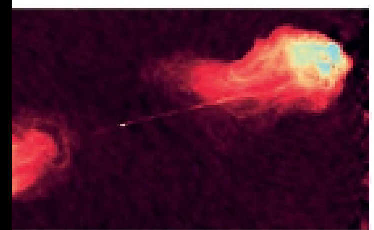
high-energy ν flux

Potential χχ→ν sources :

Sun, Earth, Galactic Centre



GRBs



AGNs

Other DM candidates

Ed Witten,
Physics landscape
away from the HE frontier,
CERN 09.

- Axions, axinos
- Primordial BH > or < $m_{\odot}$
- Particles with m_{Pl} or m_{GUT} in cosmic rays
- Gravitinos
- KK particles ($\rightarrow \nu$)

See also
D. Cline,
this conference

Parameter space scans (Darksusy)

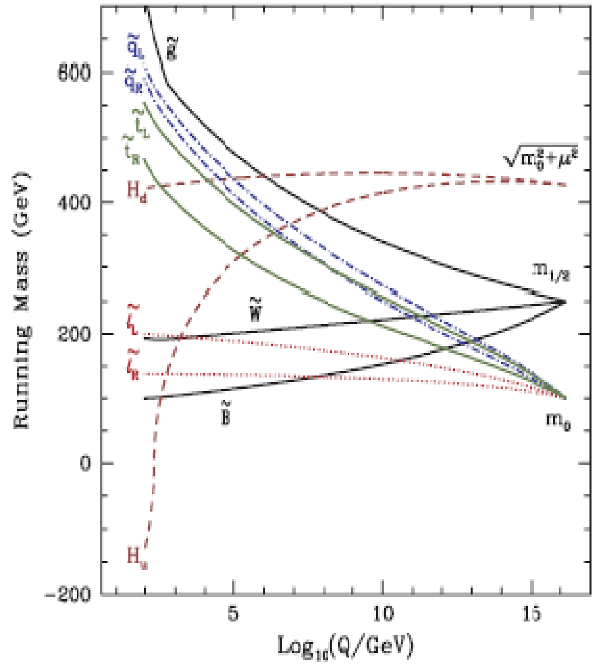
- Neutralino: natural WIMP dark matter candidate in SUSY models, like the MSSM.
- Extensive scans of the MSSM model parameters both in mSUGRA models and low-energy phenomenological MSSM-7 and MSSM-9 models (in these models, one specifies the supersymmetric parameters at the electroweak scale instead of at the GUT scale as in mSUGRA

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

ANTARES: neutralino annihilations in the Sun

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

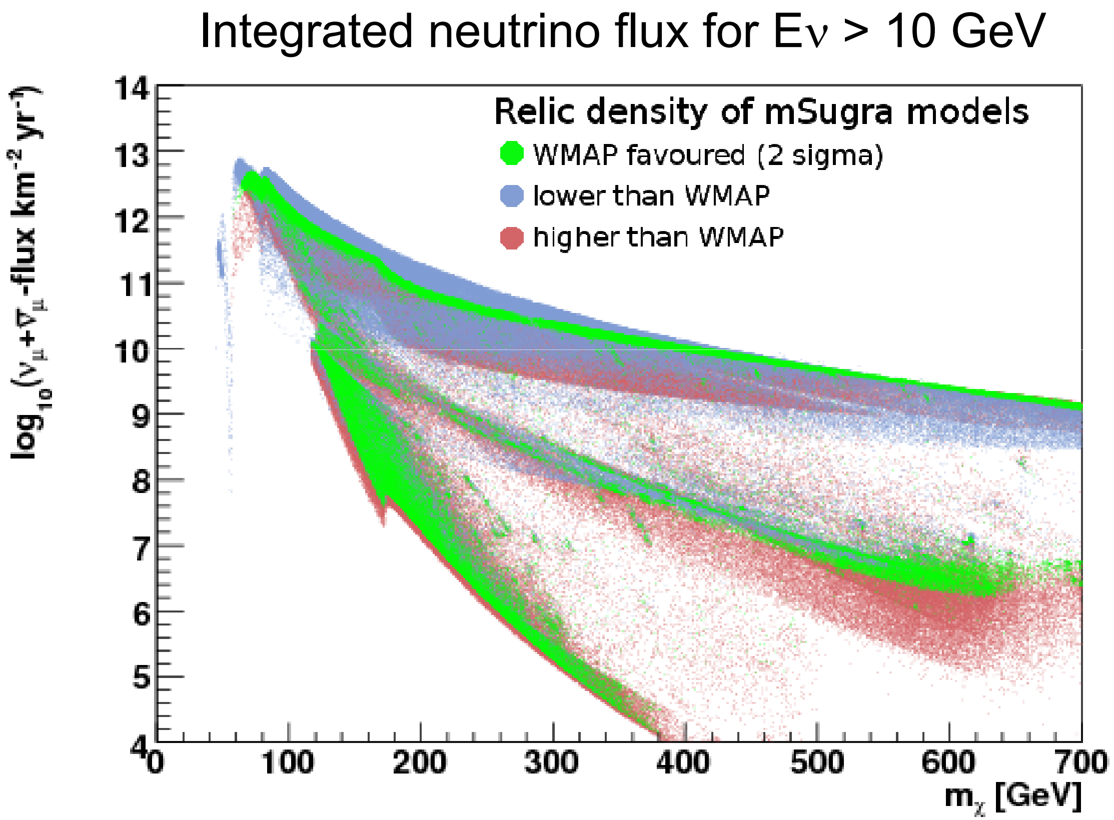
Random walk scan within mSUGRA parameter space :

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

Capture and annihilation

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

capture (C_C), annihilation (C_A), and evaporation (C_E) (negligible)

Annihilation rate: $\Gamma_A \equiv \frac{1}{2} C_A N^2 = \frac{1}{2} C_C \tanh^2(t/\tau)$

$$\tau \equiv 1/\sqrt{C_C C_A},$$

$t = t^{\odot} \simeq 4.5 \cdot 10^9$ years Equilibrium for: $t^{\odot}/\tau \gg 1$

=> dN/dt = 0 , $\Gamma_A = \frac{1}{2} C_C.$ Depends only on scattering

From a (non)observed μ flux → $\sigma^{SD, SI}$

$$\sigma^{\rm SI} = \kappa_f^{\rm SI}(m_\chi)\Phi_\mu^f \qquad \sigma^{SD} = 0$$

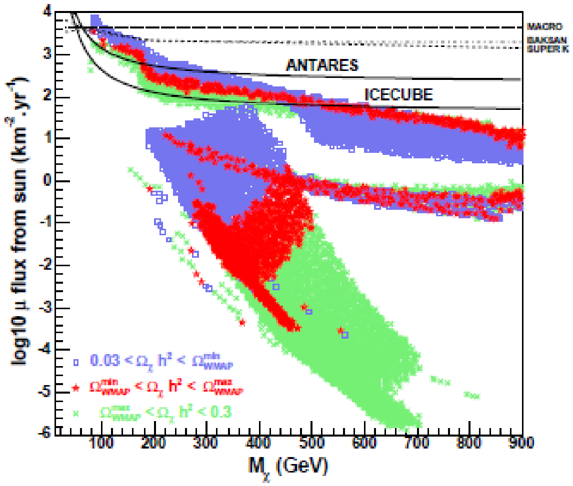
$$\sigma^{\rm SD} = \kappa_f^{\rm SD}(m_\chi)\Phi_\mu^f \qquad \sigma^{SI} = 0$$

A. Gould, Astrophys. J. 321 (1987) 571
G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267 (1996) 195
G. Wikstrom and J. Edsjo, JCAP 04, 009 (2009).

Predicted fluxes

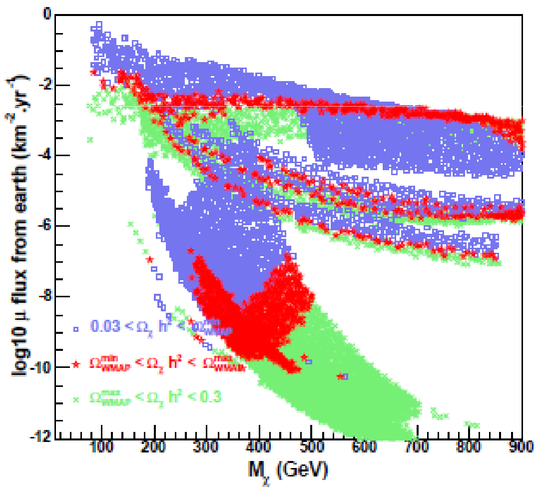
$F_{Sun} > F_{Earth}, F_{GC}$

MSSM:

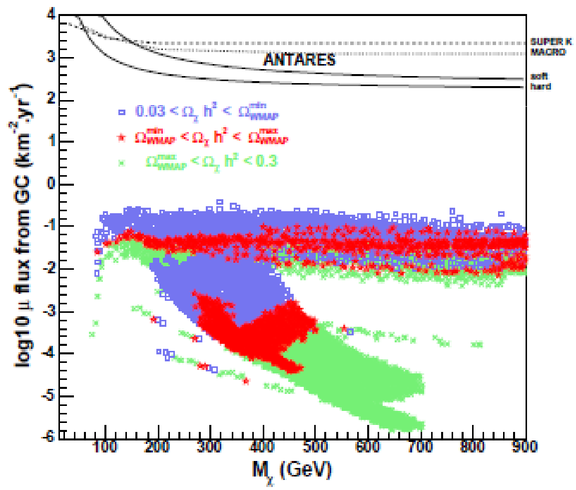


SUN

Bertin, E.N, Orloff 02



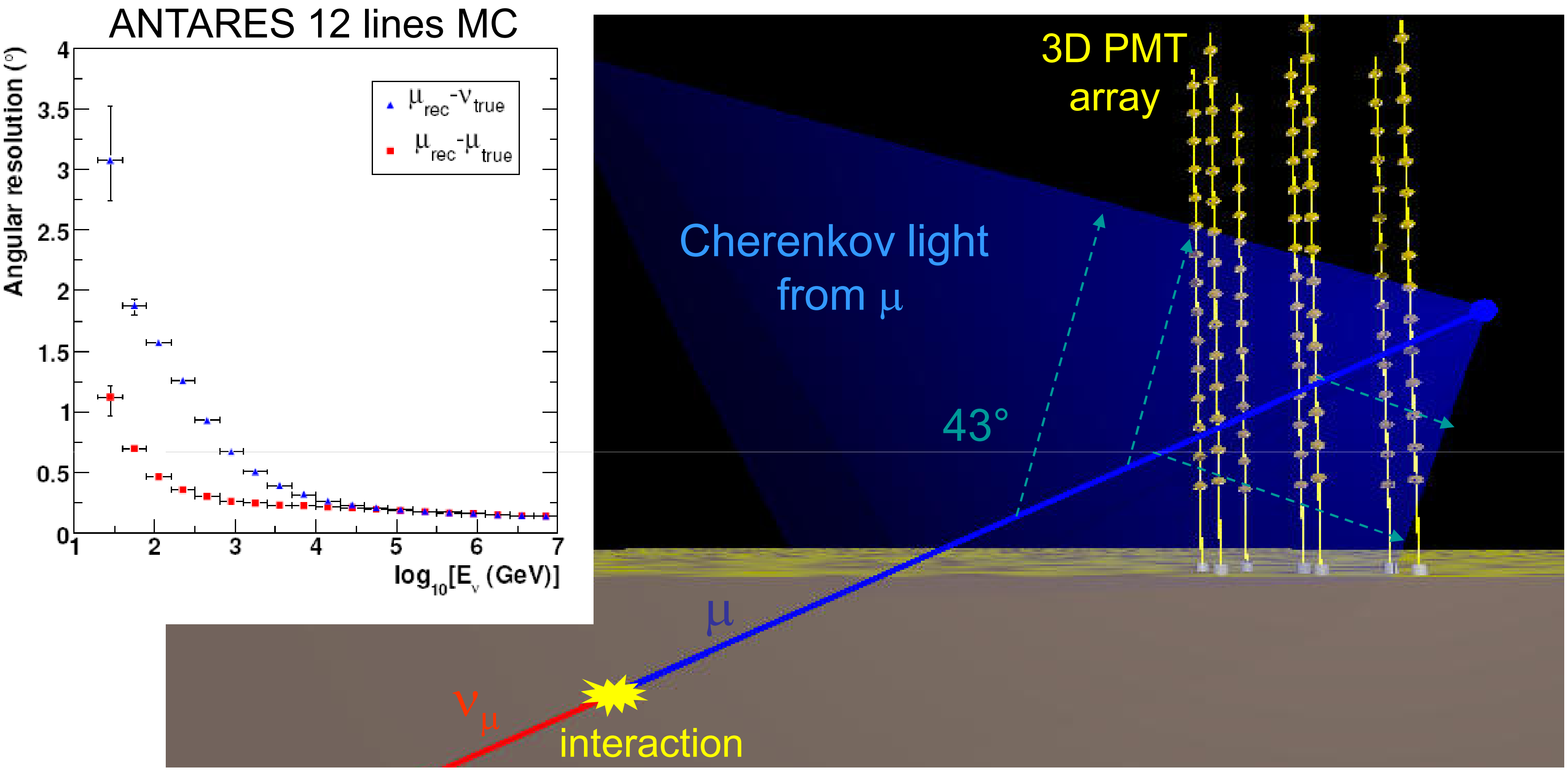
EARTH



GALACTIC CENTER (NFW)

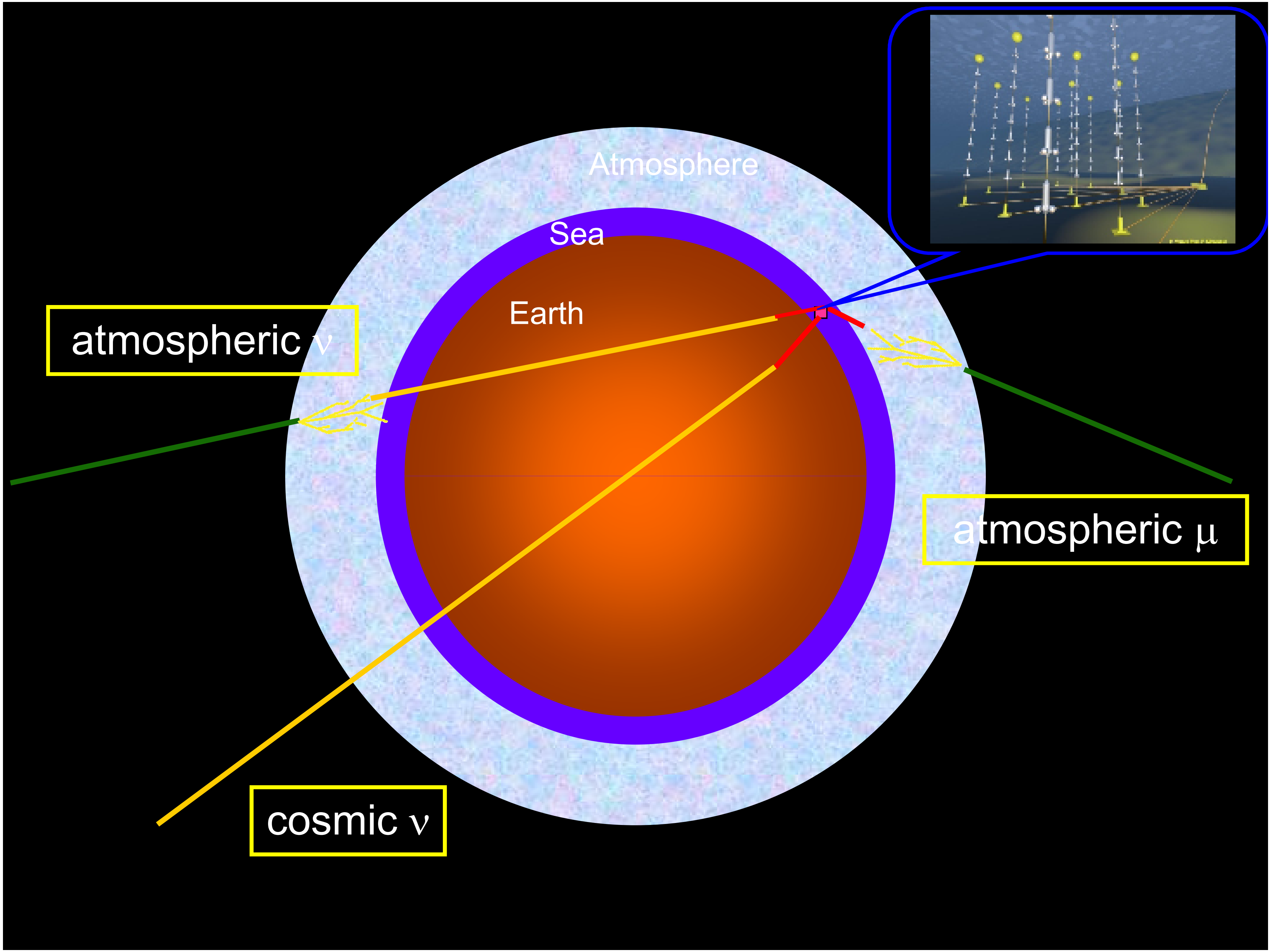
Bertone, E.N, Orloff, Silk 04

Detection principle

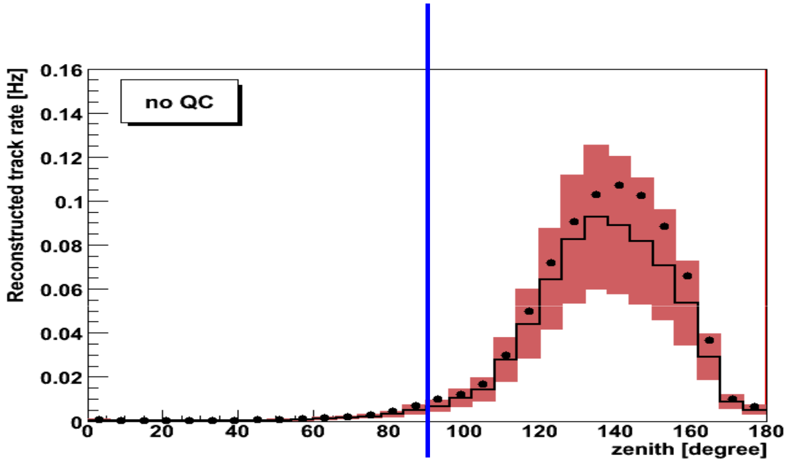


Main detection channel: charged ν_μ interaction giving an ultrarelativistic μ

Energy threshold: 10 GeV


Atmosphere
Sea
Earth
atmospheric ν
atmospheric μ
cosmic ν

Selection of neutrino events

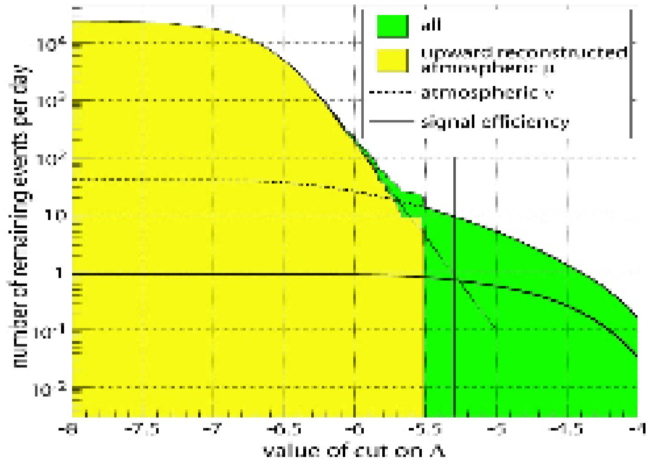


Upgoing events Downgoing events

Upgoing events dominated by the tail of badly reconstructed atmospheric muons

Λ: maximum likelihood of the track fit

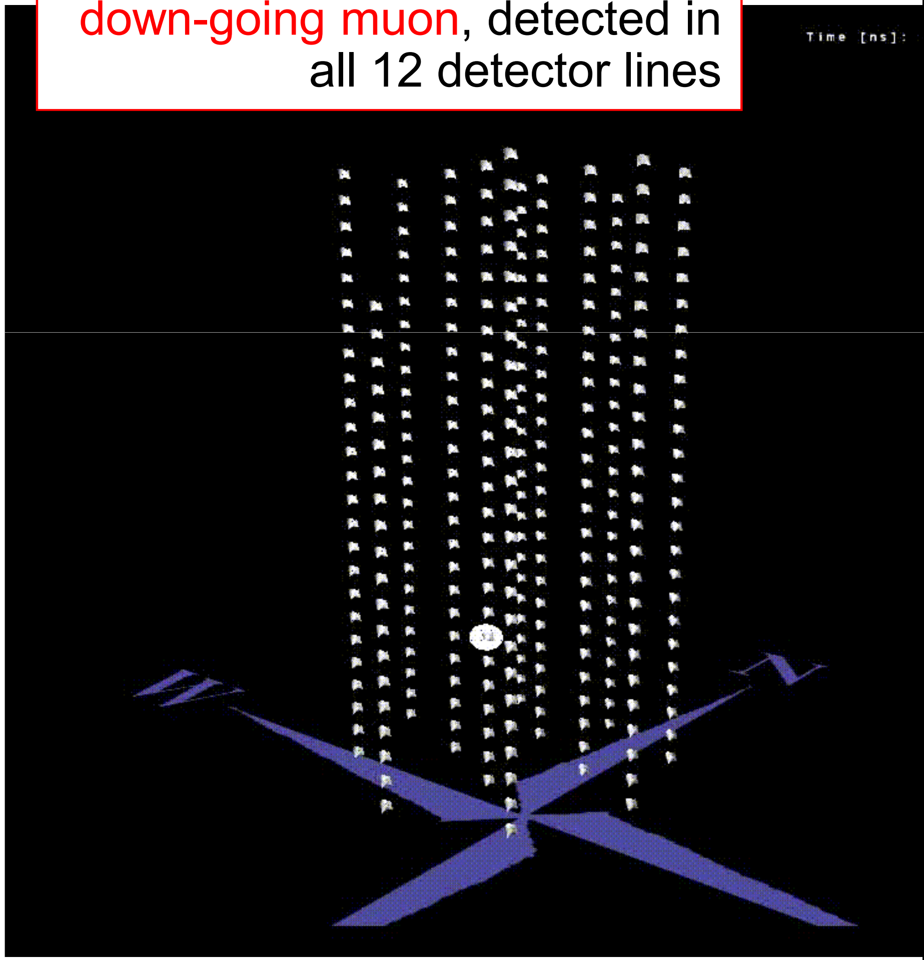
MC



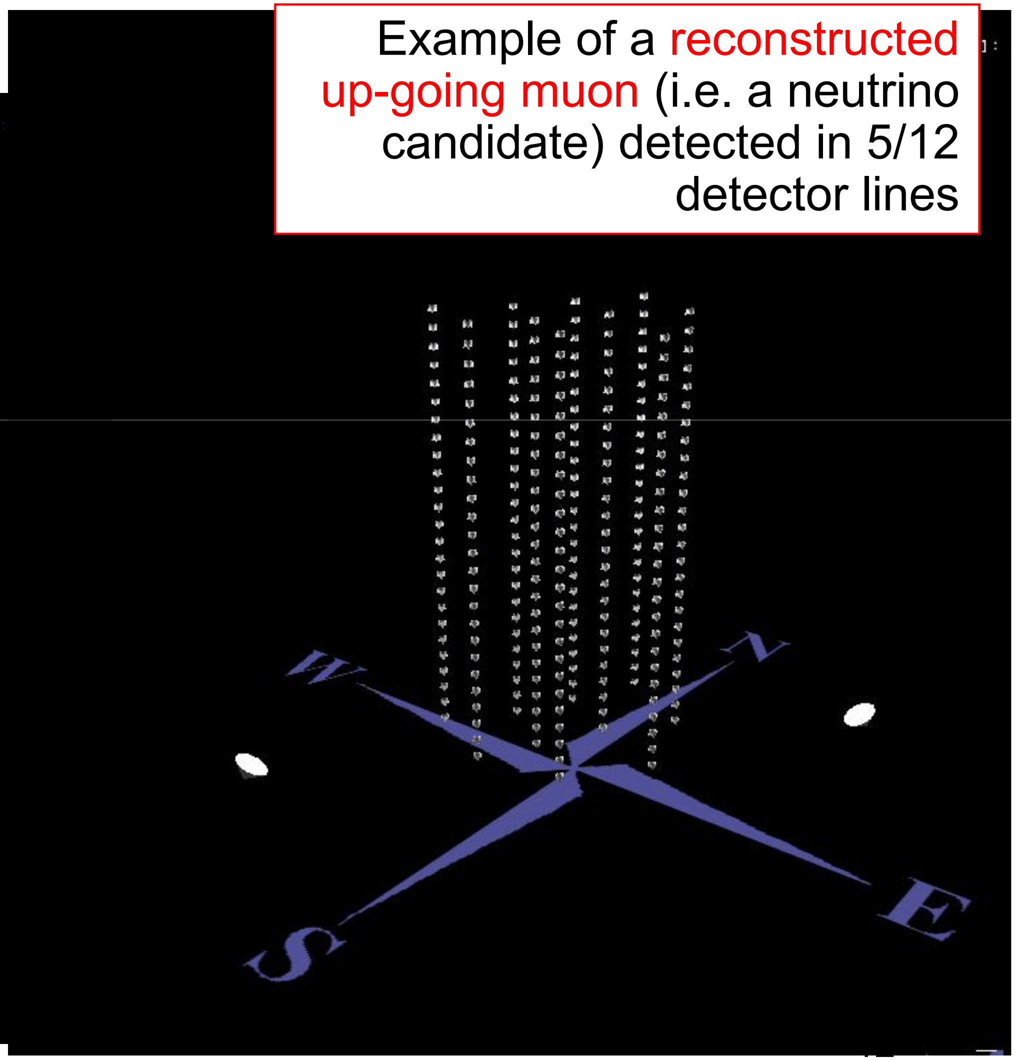
S. Loucatos IRFU, CEA-Saclay

Atmospheric muons and neutrino-induced muons

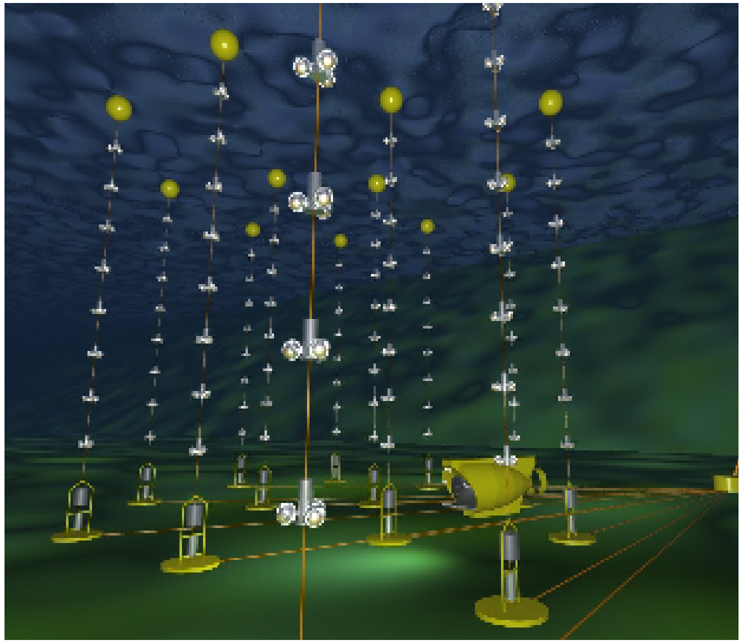
Example of a reconstructed down-going muon, detected in all 12 detector lines

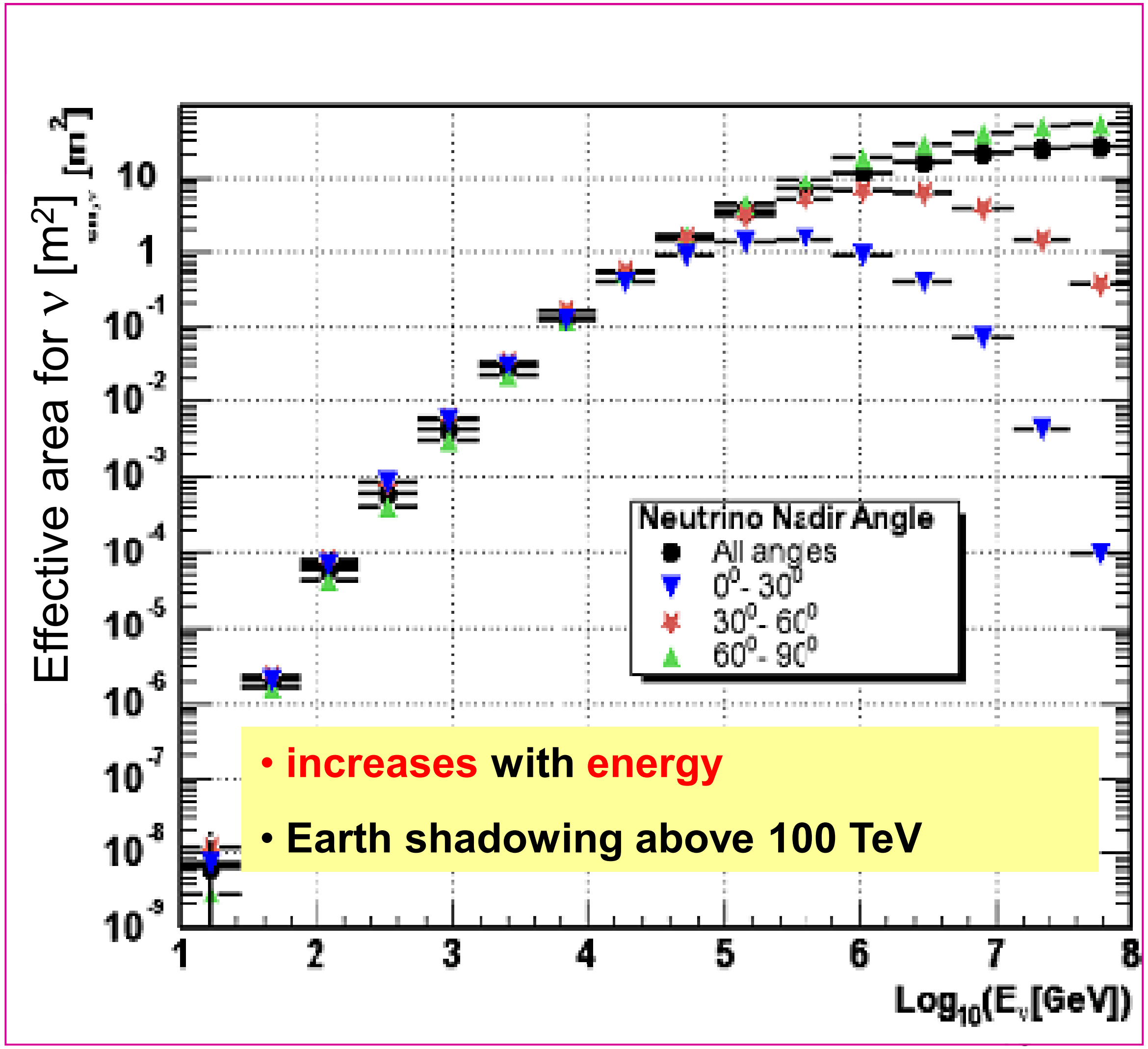


Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 5/12 detector lines

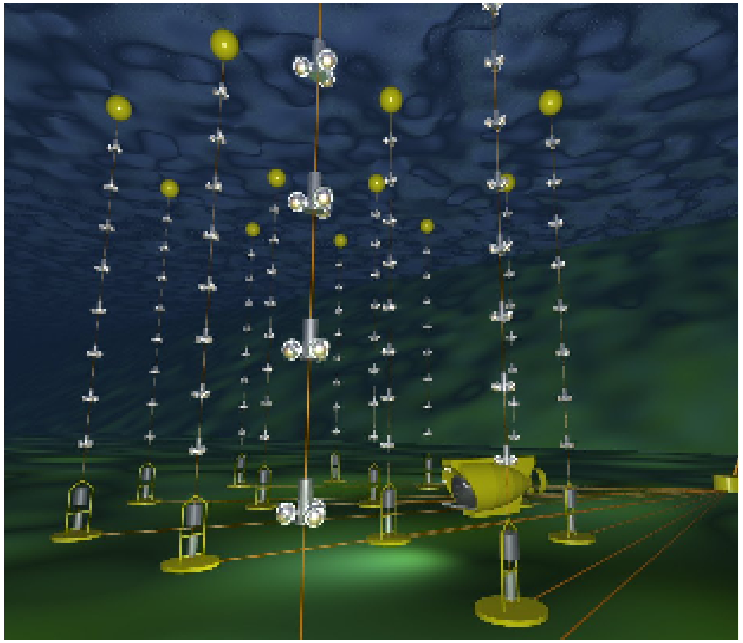


Effective area of the detector





Low-energy performance

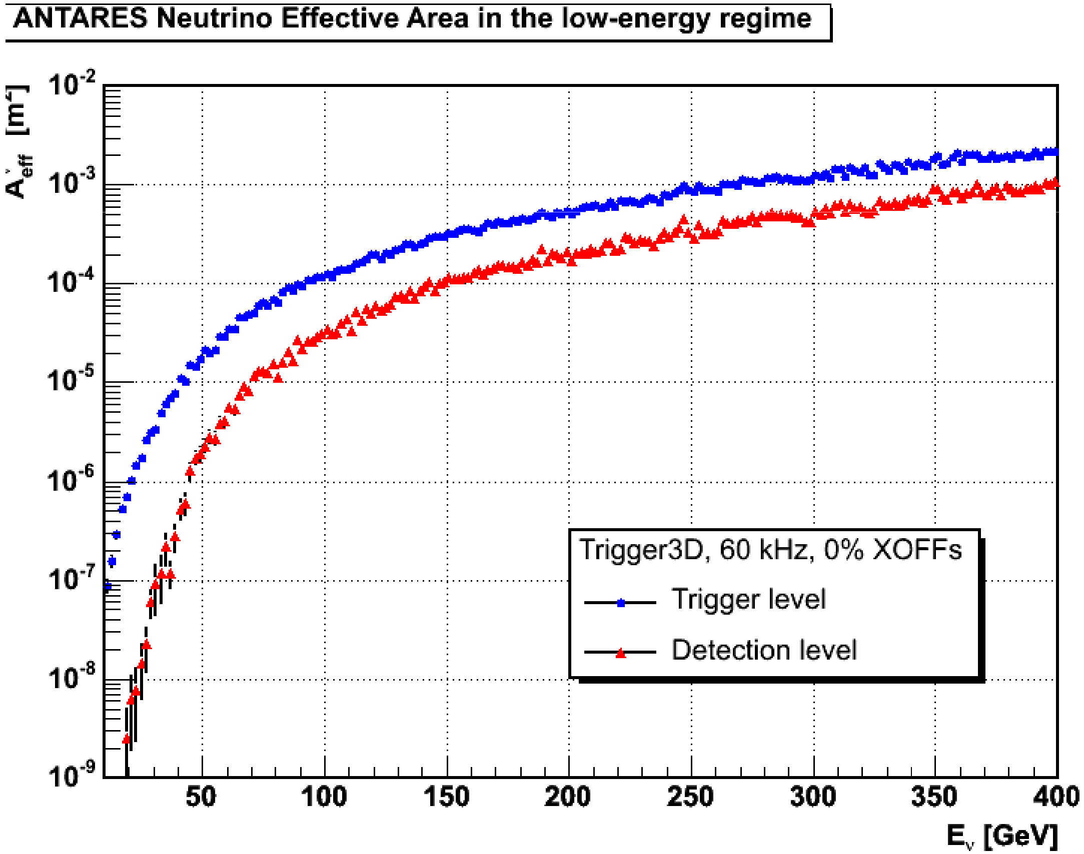


Trigger : Events with hits on at least 5 storeys in whole detector

Detection : Selected after 3D reconstruction with quality cuts

ANTARES Low-Energy Effective Area

Assume 60 kHz of optical background mean rate



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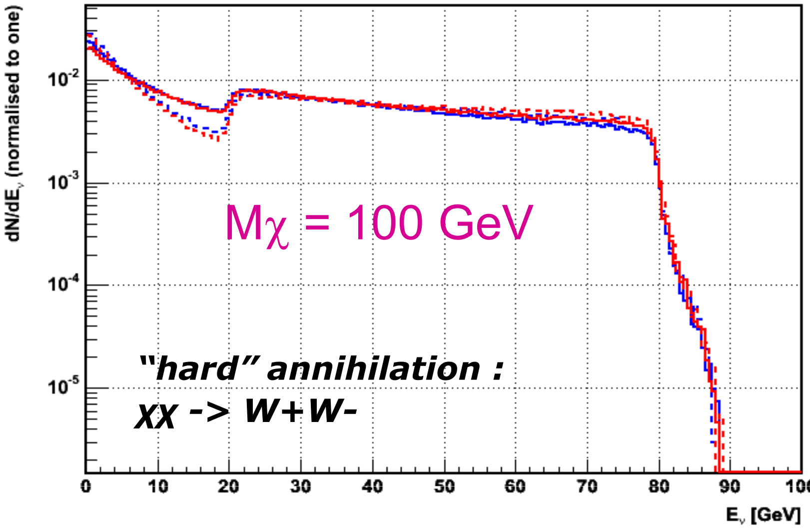
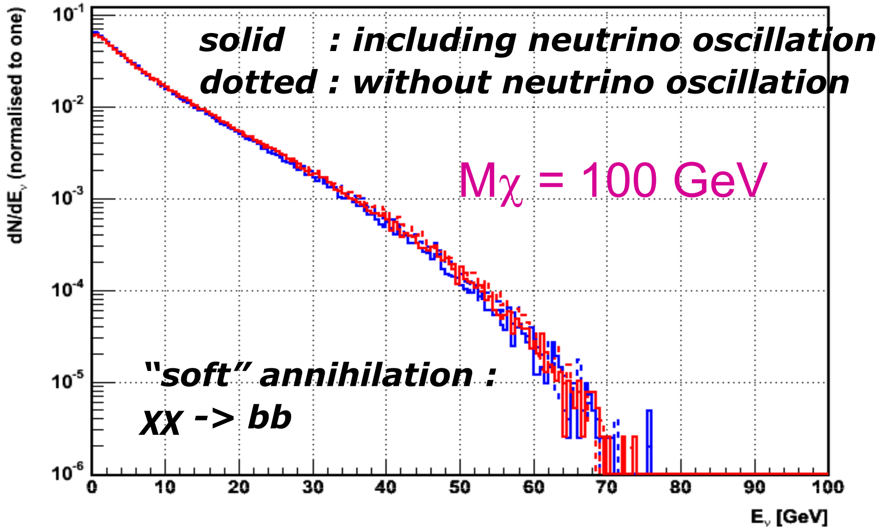
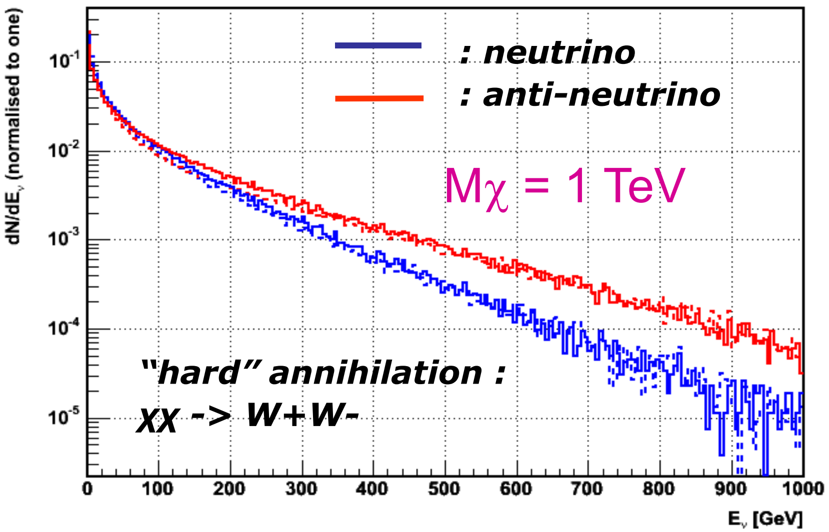
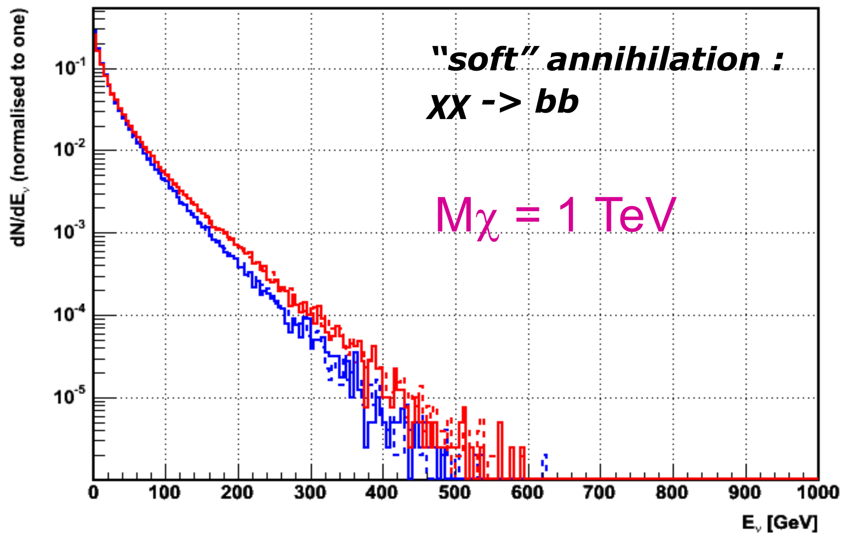
Neutrino spectra from neutralino annihilations





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

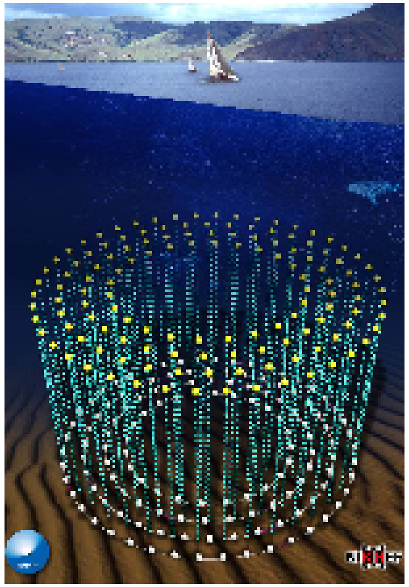




Neutralino annihilations in the Sun in mSUGRA

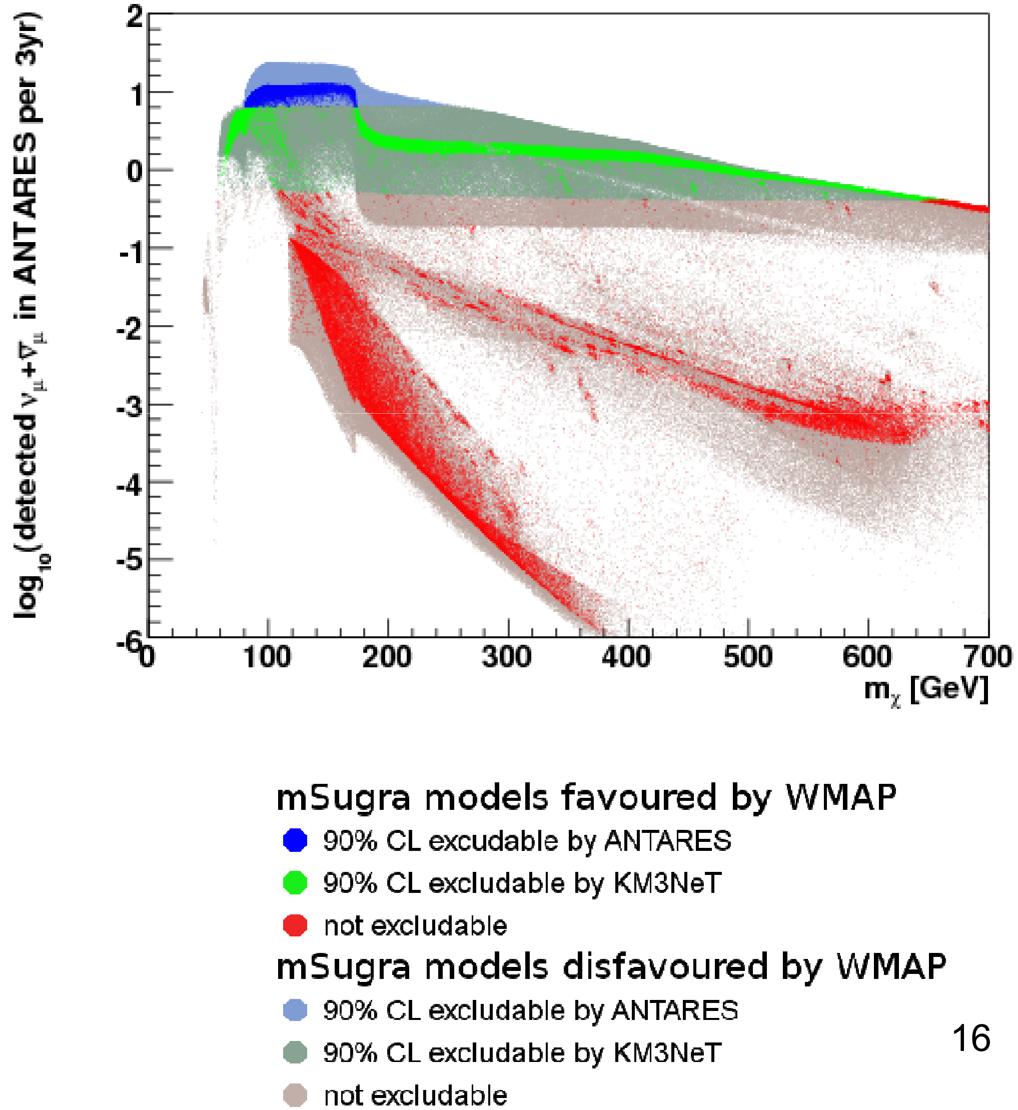
Sensitivity calculated for 3 years of data taking

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



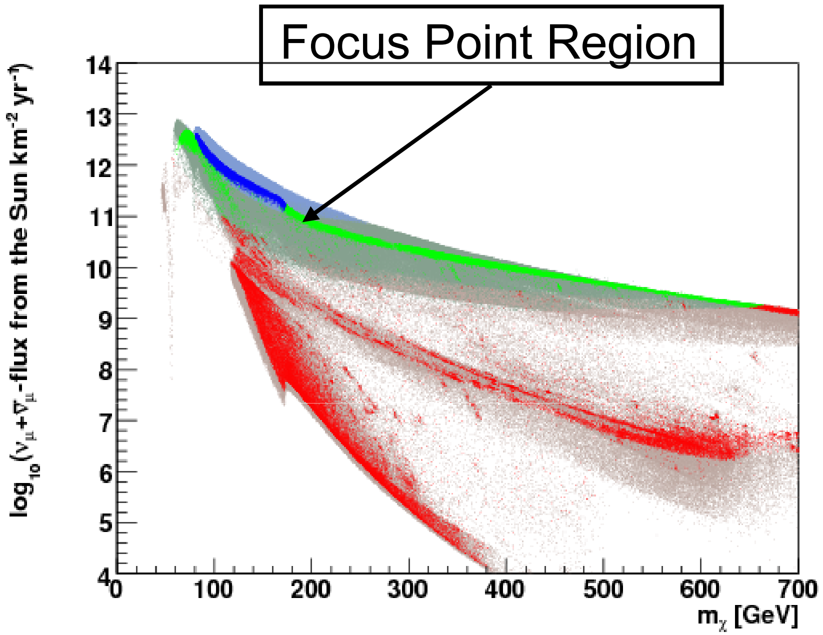
KM3NeT detector

Detection rate with ANTARES and KM3NeT detectors



Neutralino annihilations in the Sun in mSUGRA

mSugra Parameter Space



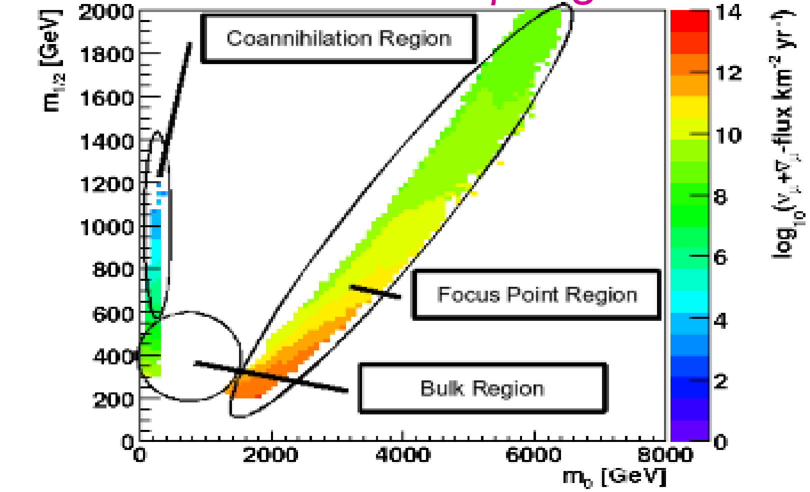
mSugra models favoured by WMAP

- 90% CL excudable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

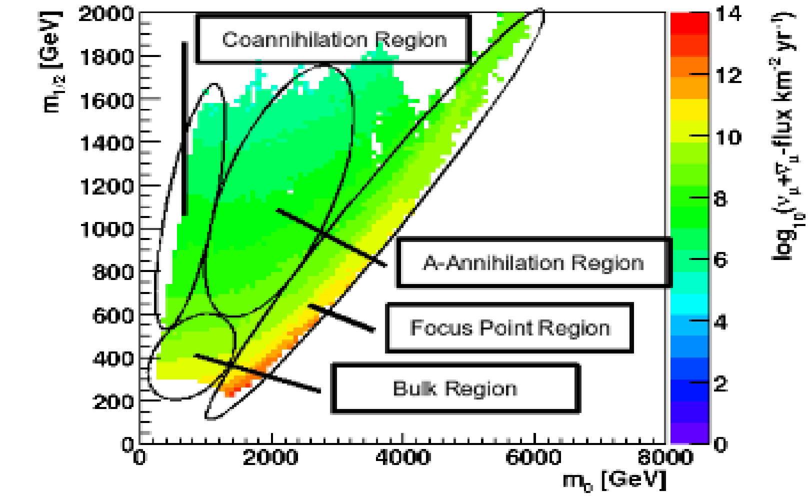
mSugra models disfavoured by WMAP

- 90% CL excludable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

10<tanβ<20 Medium tanβ regime



50<tanβ<60 High tanβ regime



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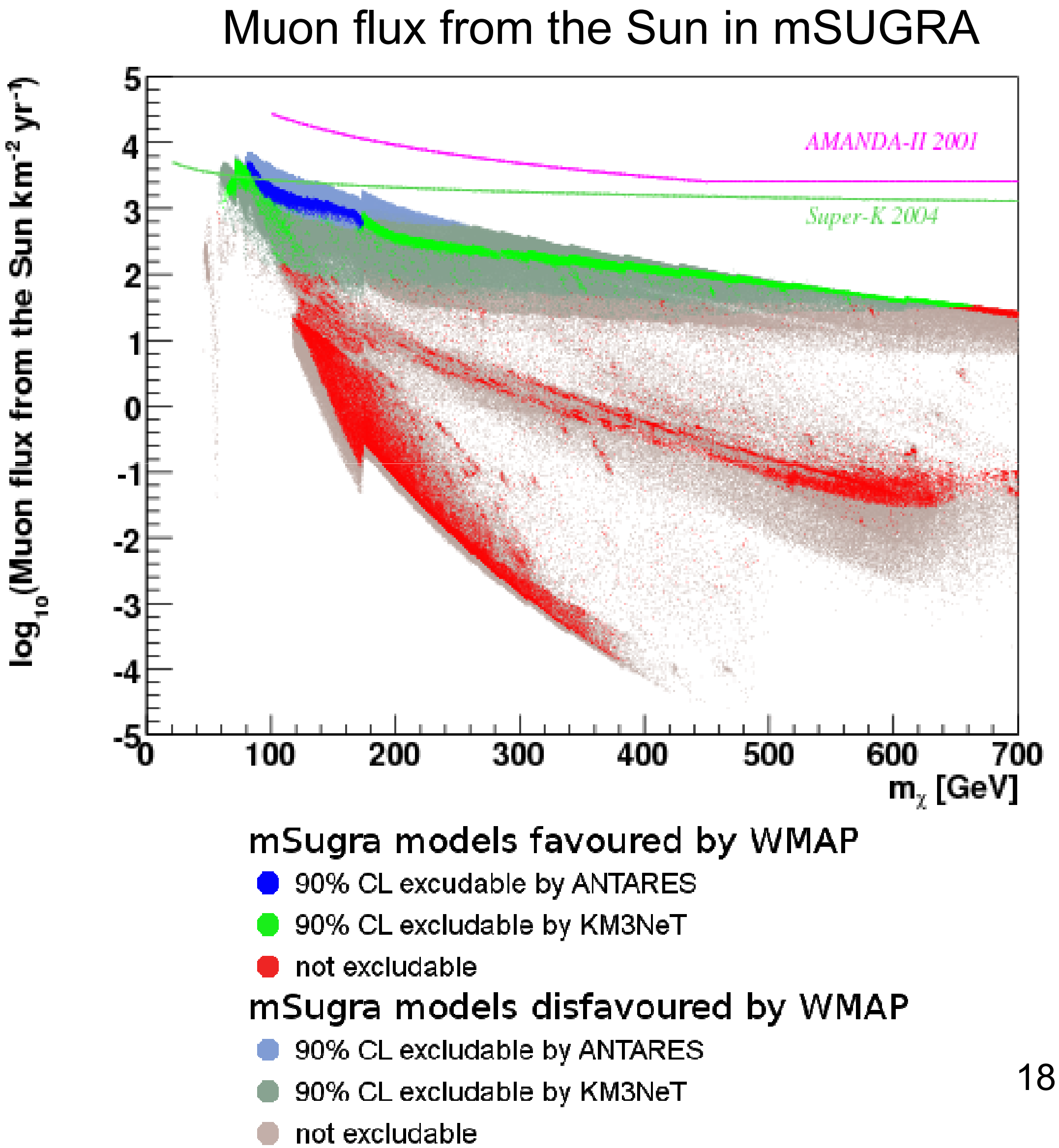
Muon flux from neutralino annihilations in the Sun

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

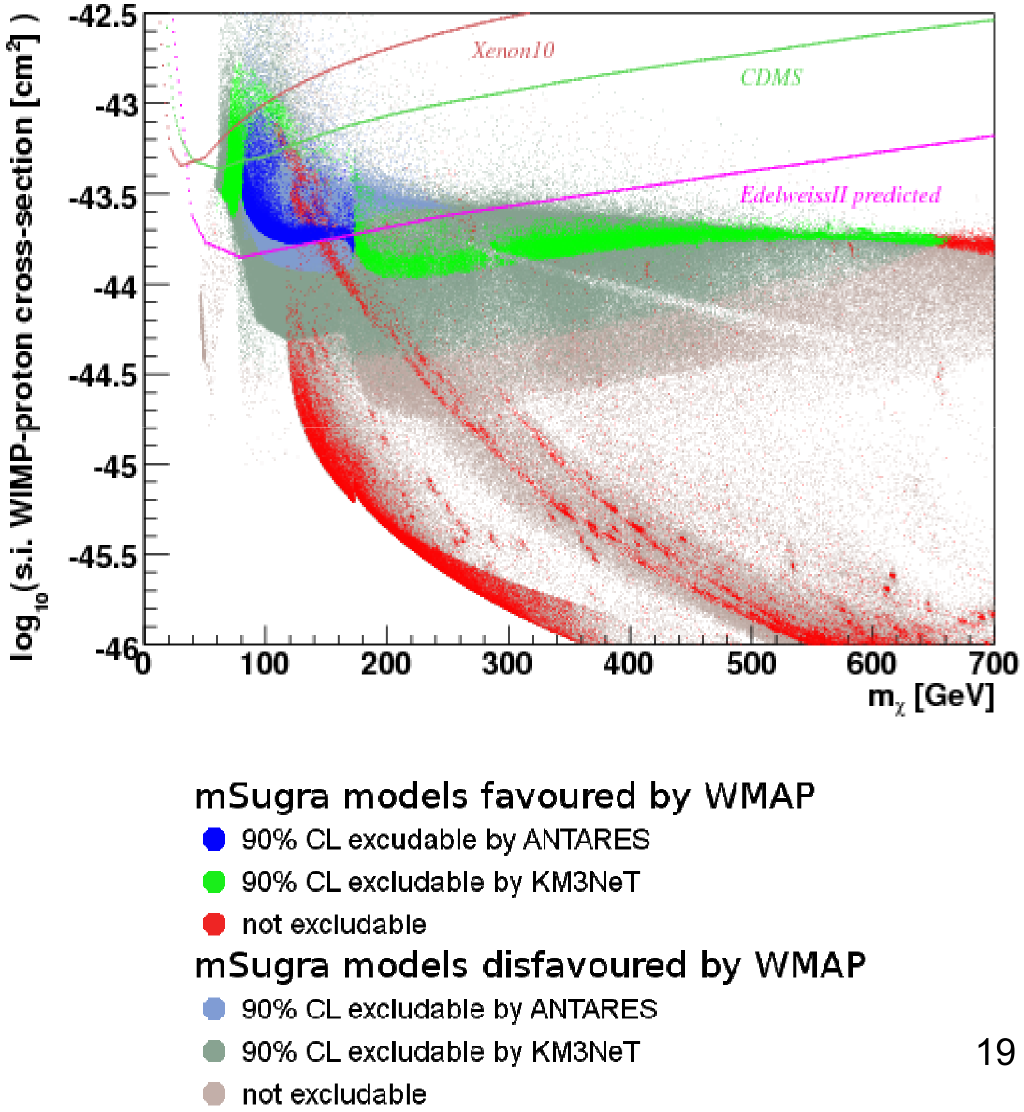


Comparison to Direct Detection sensitivity

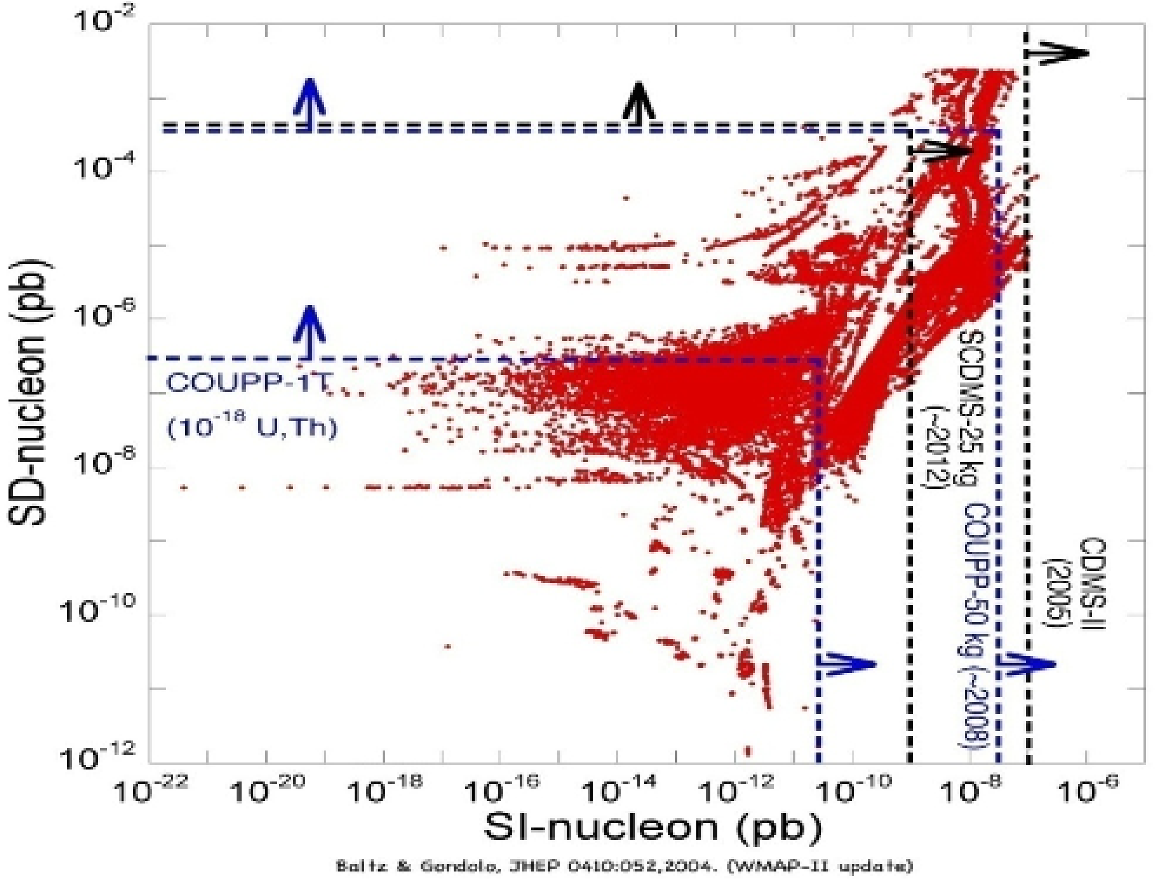
Comparison to direct detection experiments sensitive to spin independent WIMP-nucleon cross section

(10^{-7}pb = 10^{-43} cm^2 ⇔ .1 ev/kg/day)

Spin dependent scattering limits (direct search) not yet low enough to put constraints on mSUGRA Dark Matter => more interesting !



Prediction: $\sigma^{SD} > \sigma^{SI}$



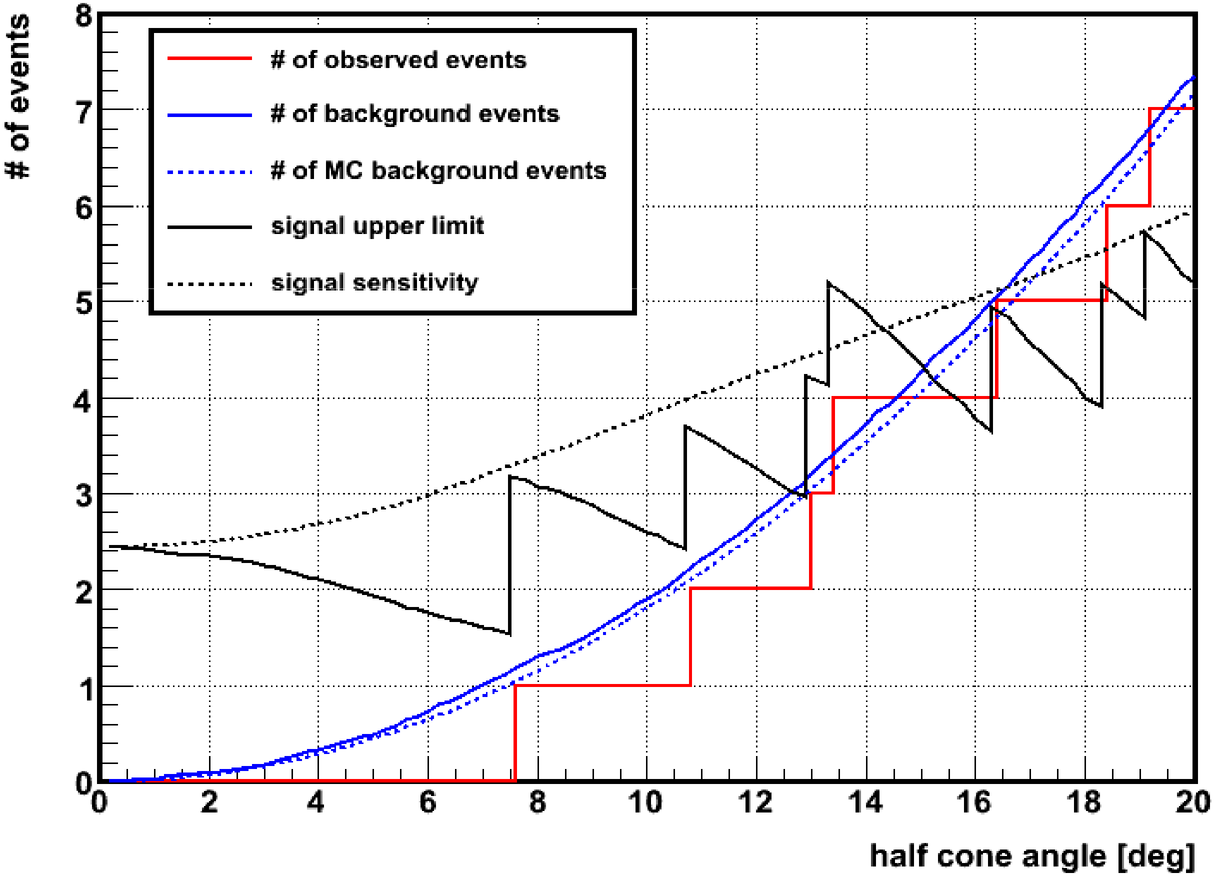
See M.Szydagis, this conference

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 Mχ and
hard/soft spectrum



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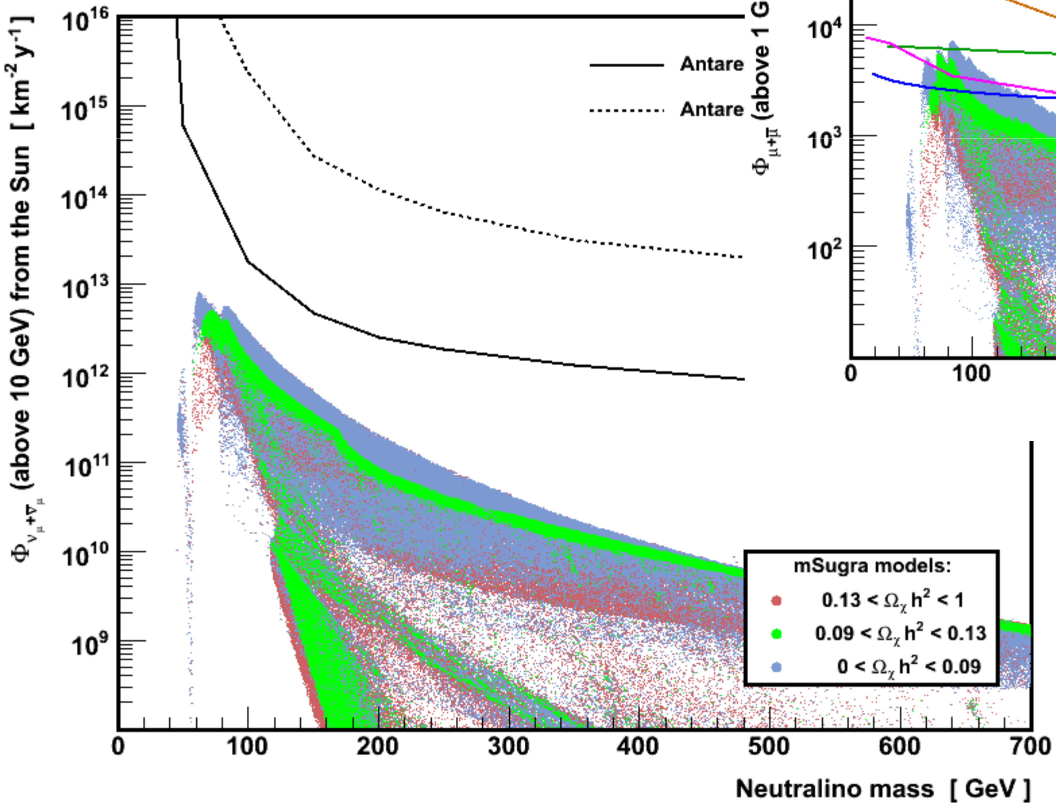
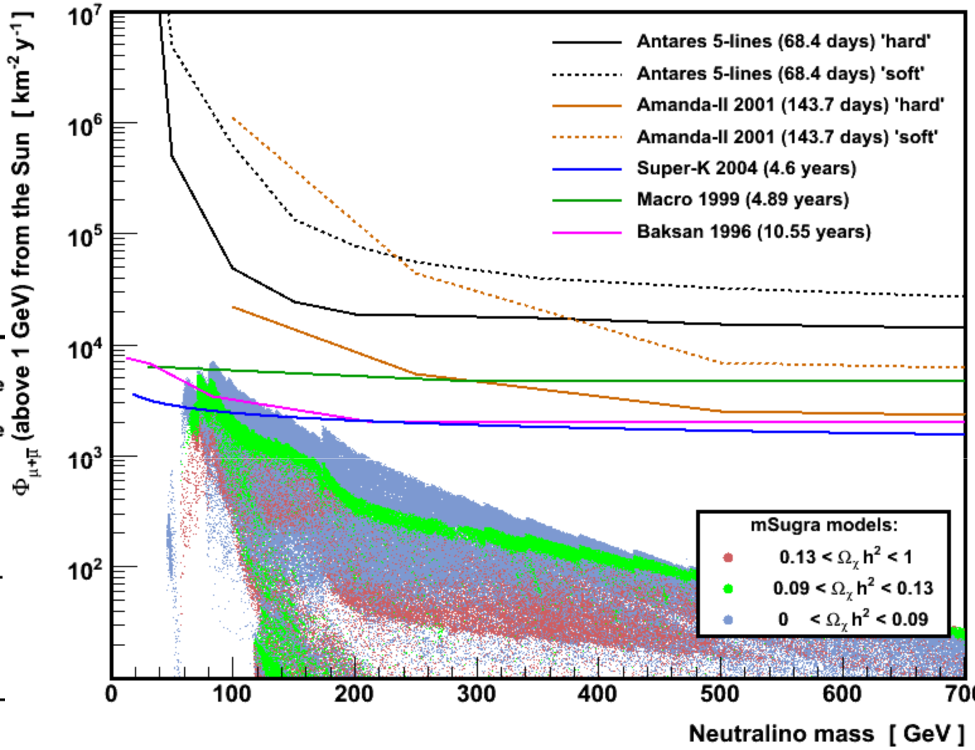
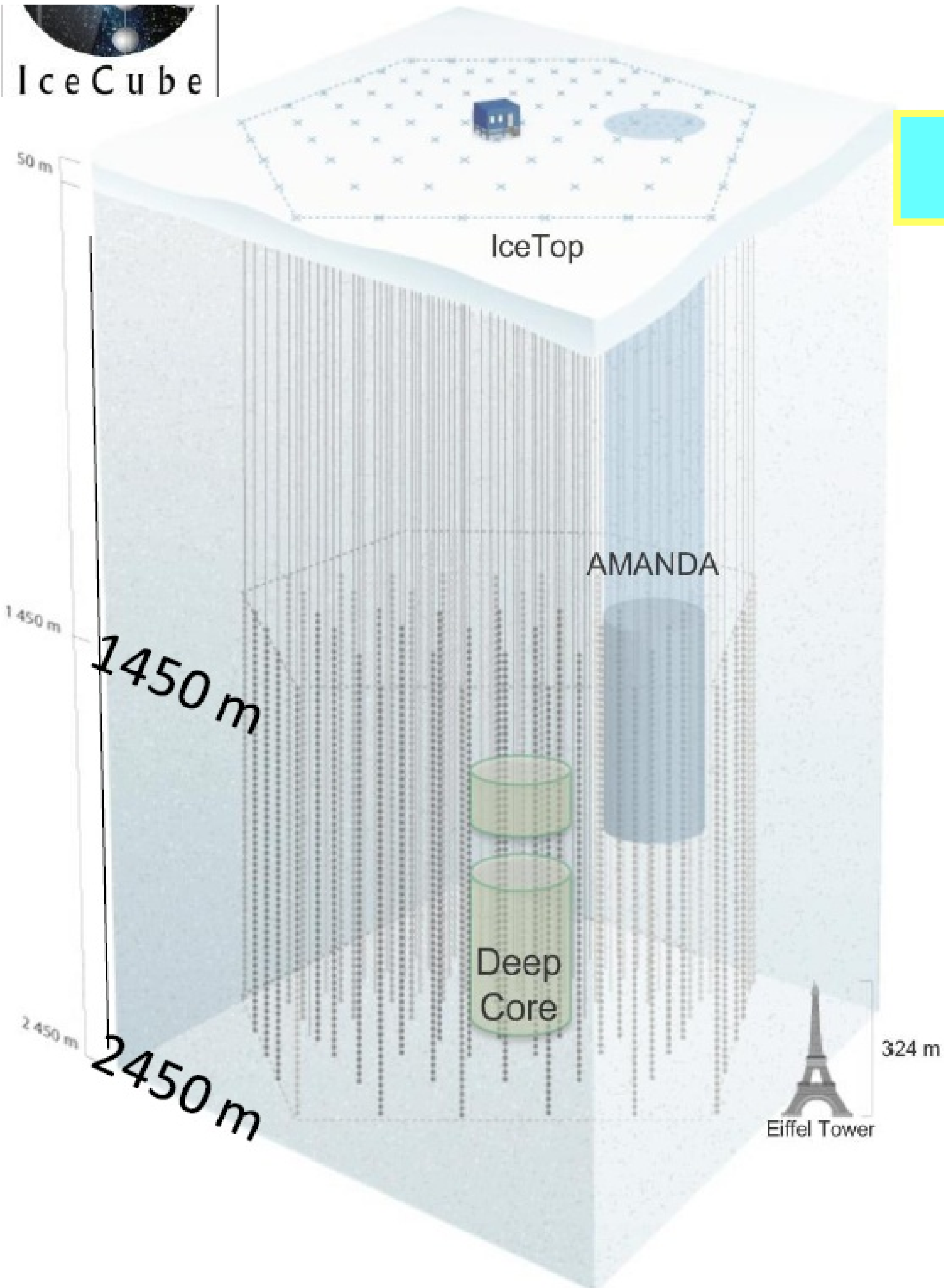
First ANTARES limit on ν/μ flux from the Sun

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





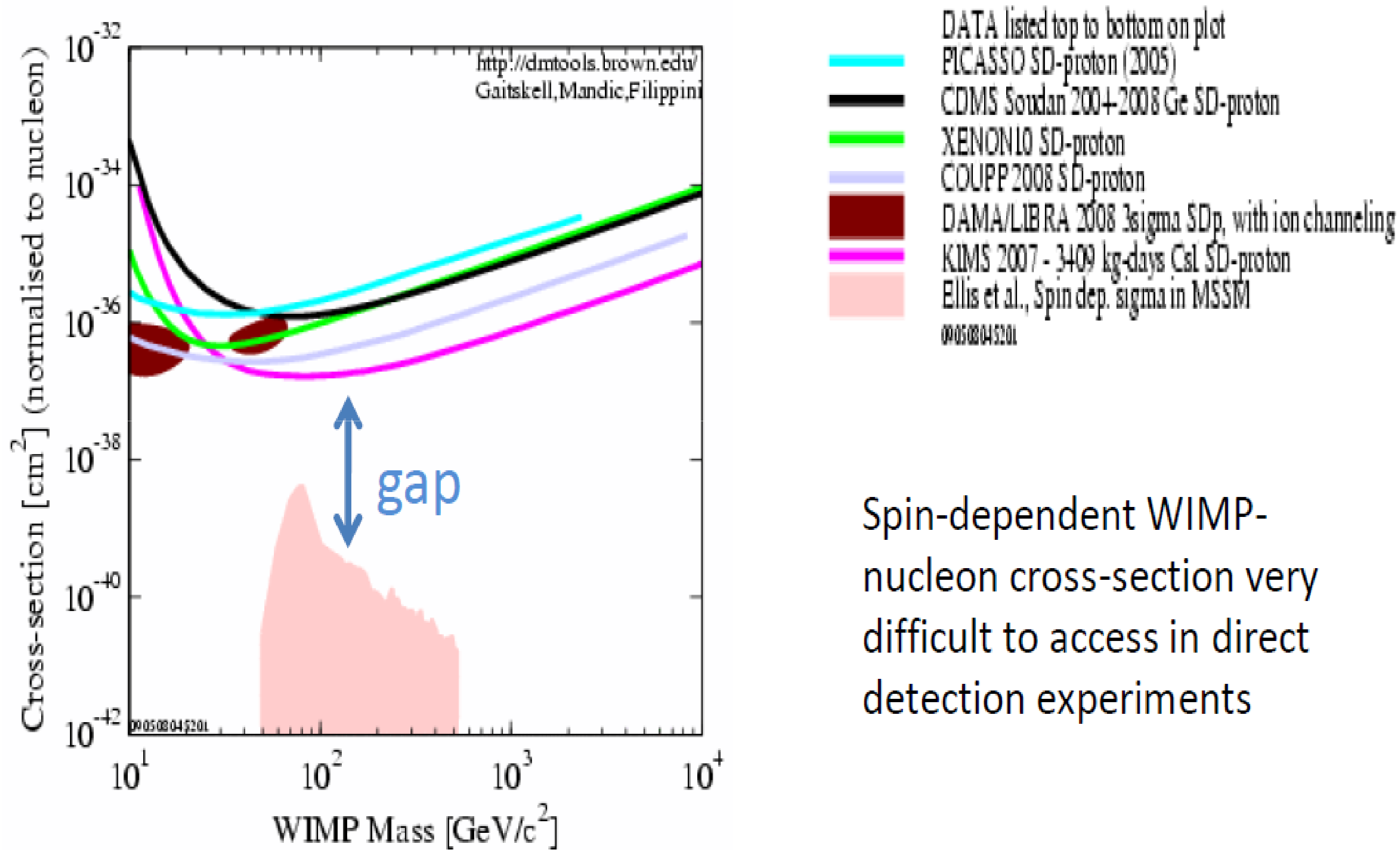
Limit with b-quark (soft) or W-boson (hard) annihilation channel



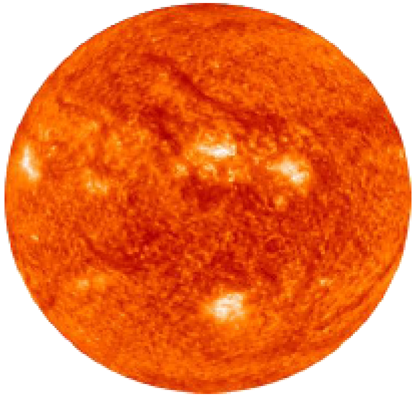
Icecube, Amanda

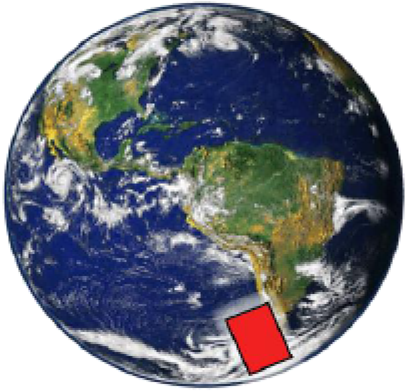
Phys.Rev.Lett.102:201302,2009,
C. Rott, ICRC 09

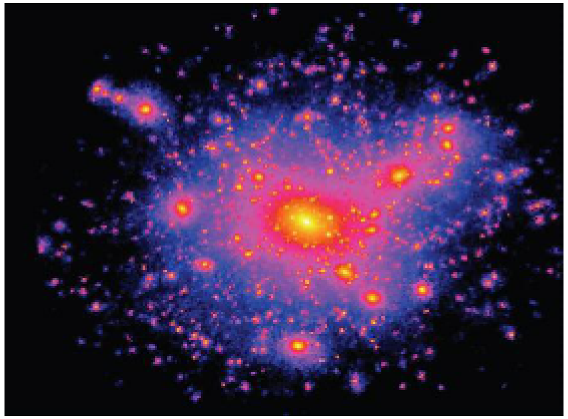
Spin-dependent WIMP-proton cross-section



Spin-dependent WIMP-nucleon cross-section very difficult to access in direct detection experiments







Solar	Earth	Halo
Neutrino Flux, **Scattering cross-section**	Neutrino Flux, **?**	Neutrino Flux**, Self-annihilation cross-section**
Muon neutrinos	Muon neutrinos	Muon neutrinos, **Cascades**
Background off-source on-source	Background simulations	Background off-source on-source
Excess	Excess	Anisotropy
IceCube (+ Deep Core)	**IceCube** (+ Deep Core)	**DeepCore** (+ IceCube)

IC track selection

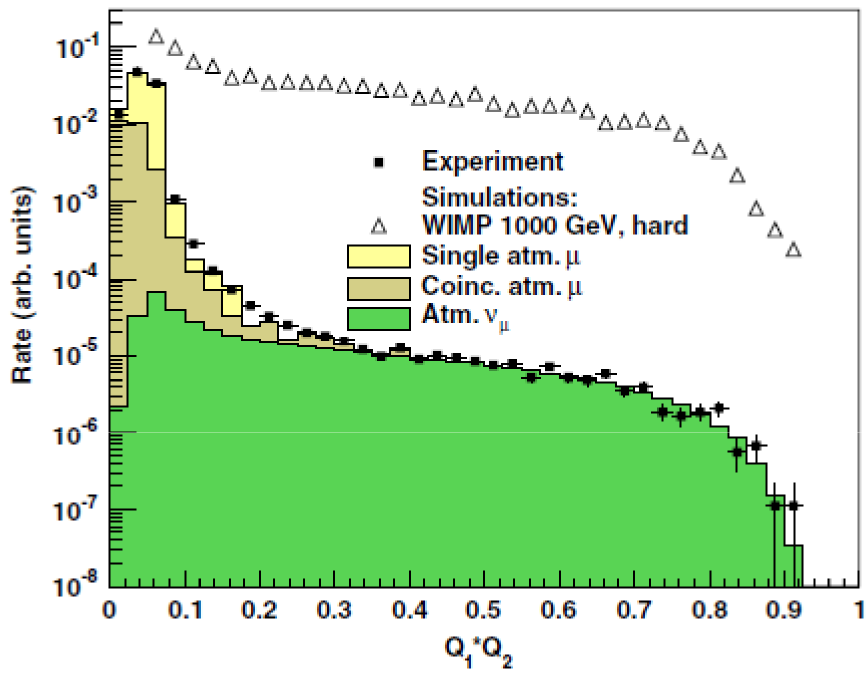
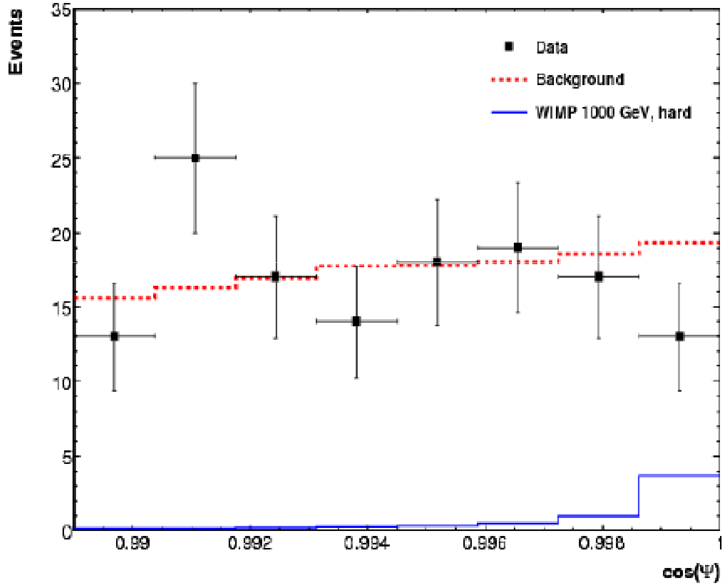


FIG. 1 (color online). The product $Q_1 \times Q_2$ of the output values of the two SVMs for the experimental data, a simulated signal ($m_{\tilde{\chi}_1^0} = 1000$ GeV, hard spectrum) and the background. The background has been scaled to match the data rate and it is shown divided into three components: atmospheric neutrinos and single and coincident atmospheric muons.

Search for an excess from the sun

Search for an excess neutrino flux from the direction of the sun

Analysis performed with the IceCube 22 string detector and 104 days of livetime (when the sun below the horizon)



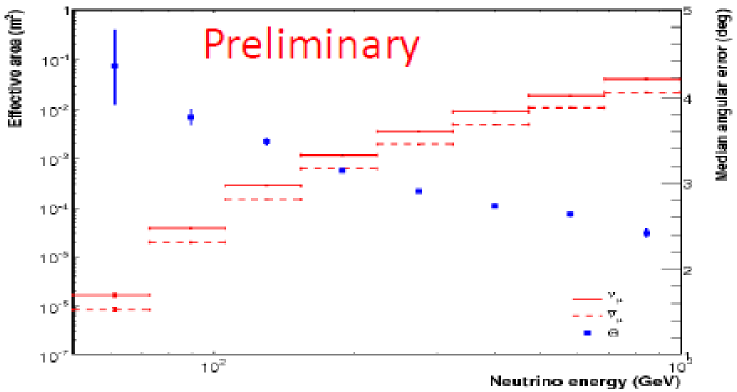
Cold Dark Matter candidate particle is assumed to be the LSP (neutralino) in MSSM, R-parity conserving scenario

Neutralino is a Majorana particle and self-annihilates

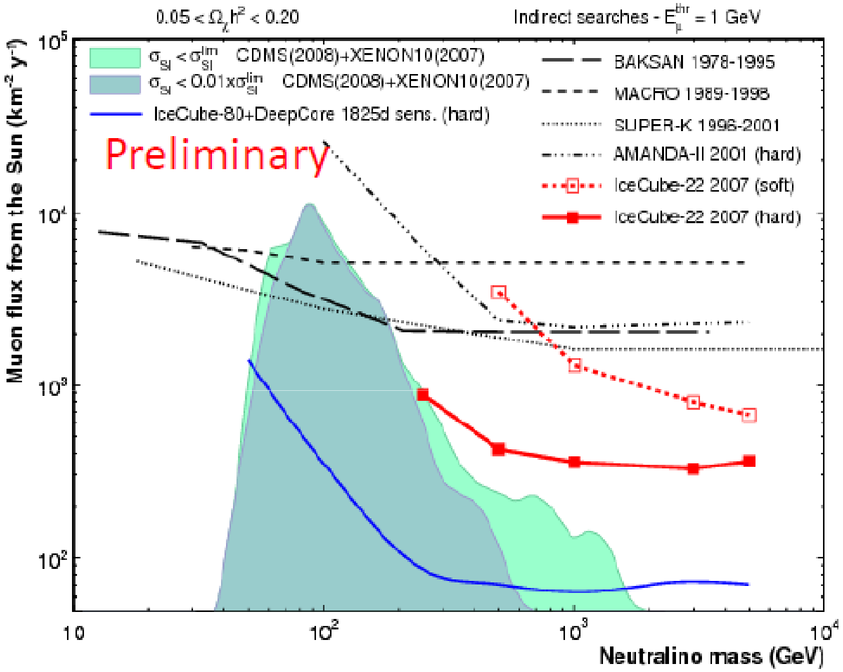
Consider two annihilation channels:

- **Hard:** $\chi\chi \rightarrow W^+W^- \rightarrow \nu\,\nu$
- **Soft:** $\chi\chi \rightarrow bb \rightarrow \nu\,\nu$

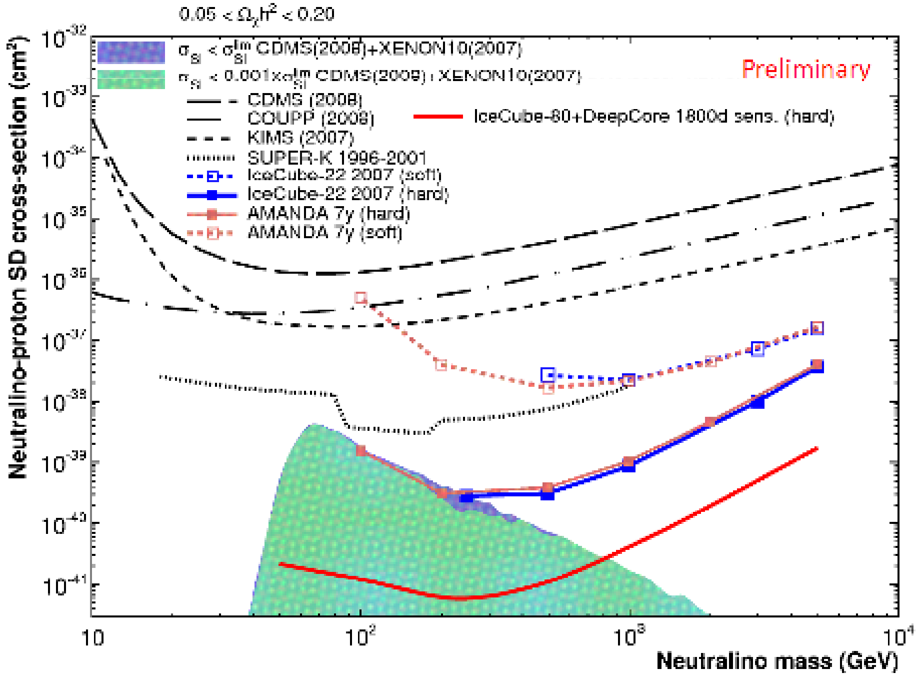
Consider 7 neutralino masses from 50 GeV to 5 TeV



Solar wimp limits



- Look for an excess of (muon) neutrinos in the direction of the sun
- No evidence for a signal observed
- Upper limits on muon flux from neutralino annihilations in the Sun

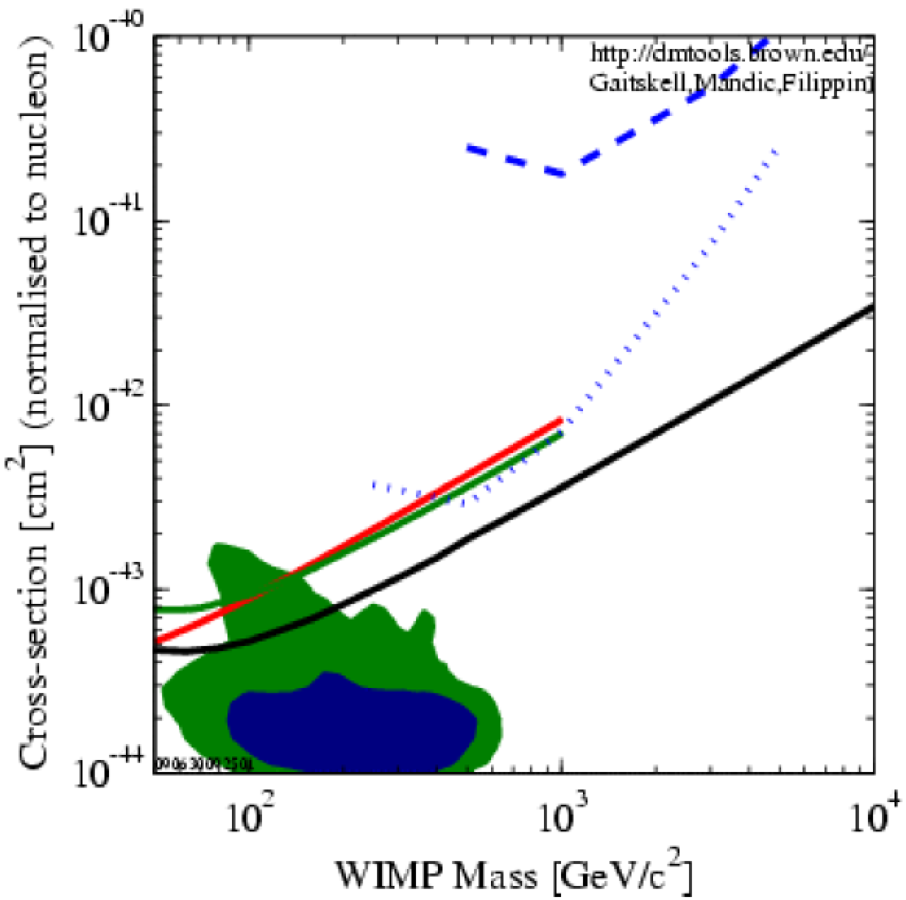


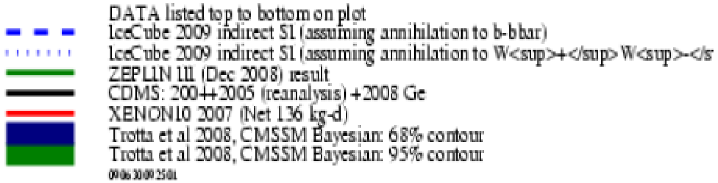
arXiv: 0902.2460 (PRL 102, 201302)

- Under the assumption of equilibrium condition in the Sun, a limit on the WIMP-Nucleon cross-section can be obtained
- For spin-dependent couplings, IceCube's sensitivity is about 2-orders of magnitude better than direct searches

S. Loucatos IRFU, CEA-Saclay

σ ^{SD} limit

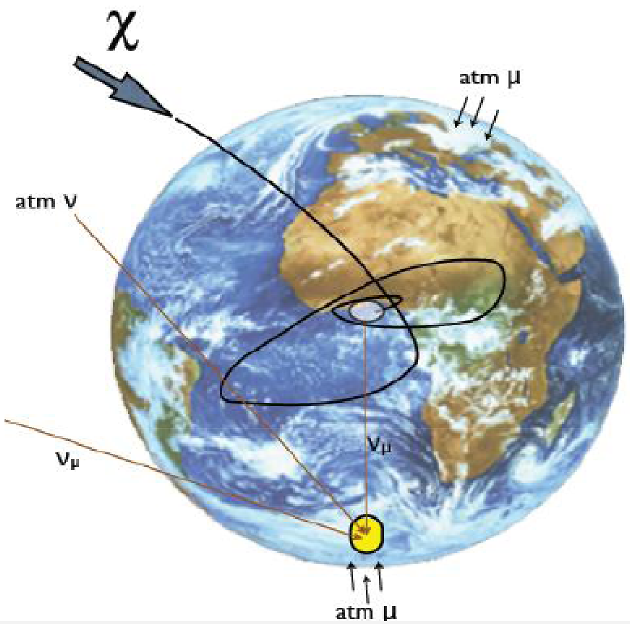




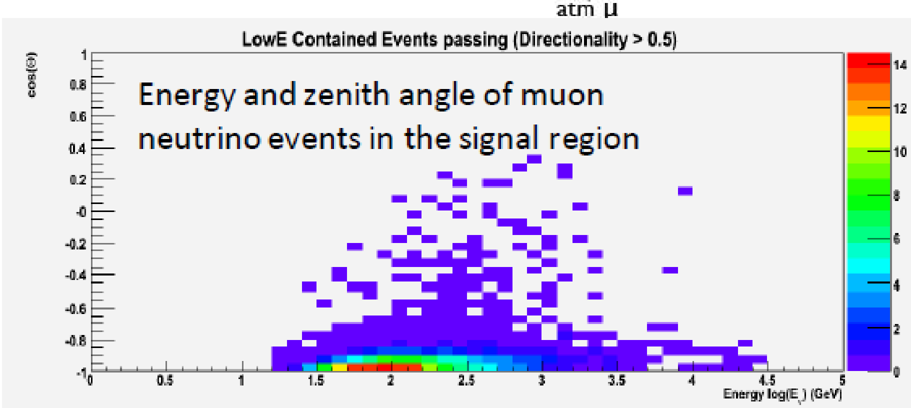
- Under the assumption of equilibrium condition in the Sun (and the assumption that capture is dominated by spin-independent cross-section), a limit on the WIMP-Nucleon cross-section can be obtained
- IceCube limits are competitive with direct detection experiments at WIMP masses, where IceCube is sensitive

Earth wimps

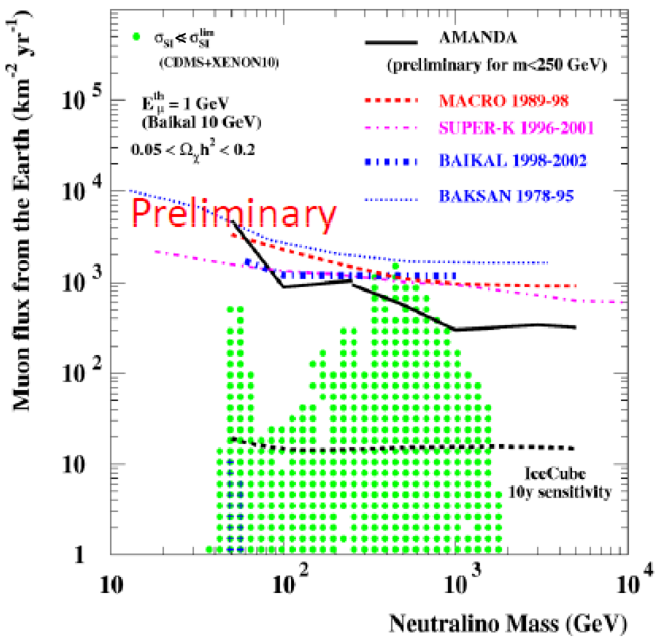
- Dark Matter could be clustered in the centre of the Earth
  - Annihilation signal might be observable in vertically up-going events



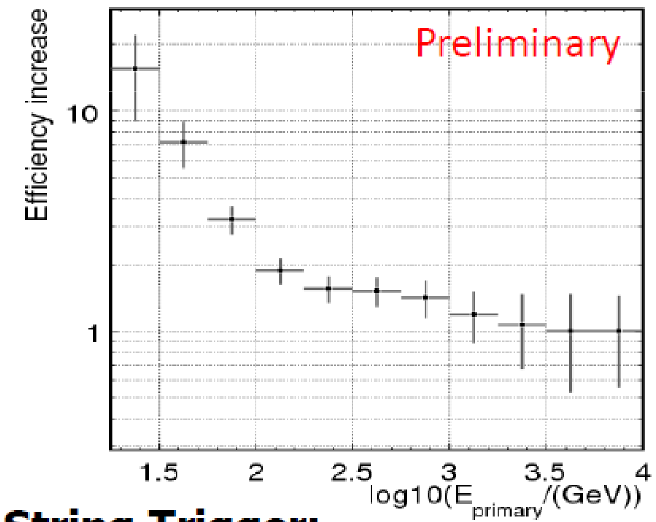
- AMANDA analysis on-going
- IceCube analysis on-going
  - Understanding of low energy vertical tracks extremely important

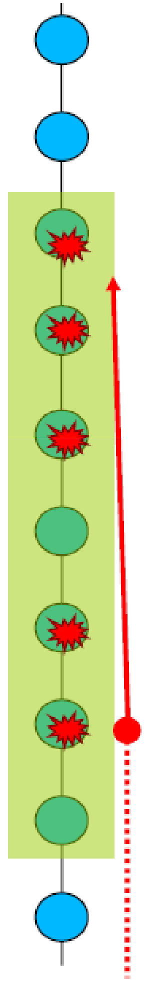


Earth wimps limit



Beginning with 40 string data, IceCube lowered the multiplicity 8 trigger threshold to 5 applying a string trigger



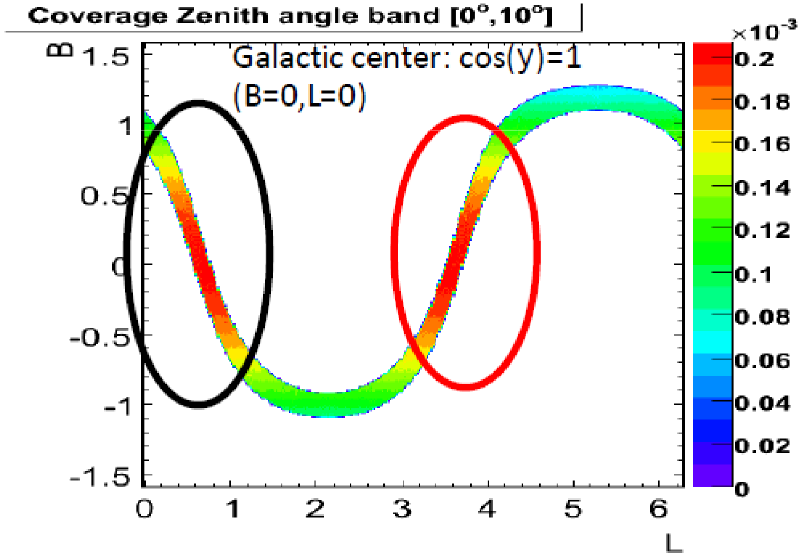


String Trigger:
5 DOMs hit within a series of 7 DOMs within a time window of 1500ns

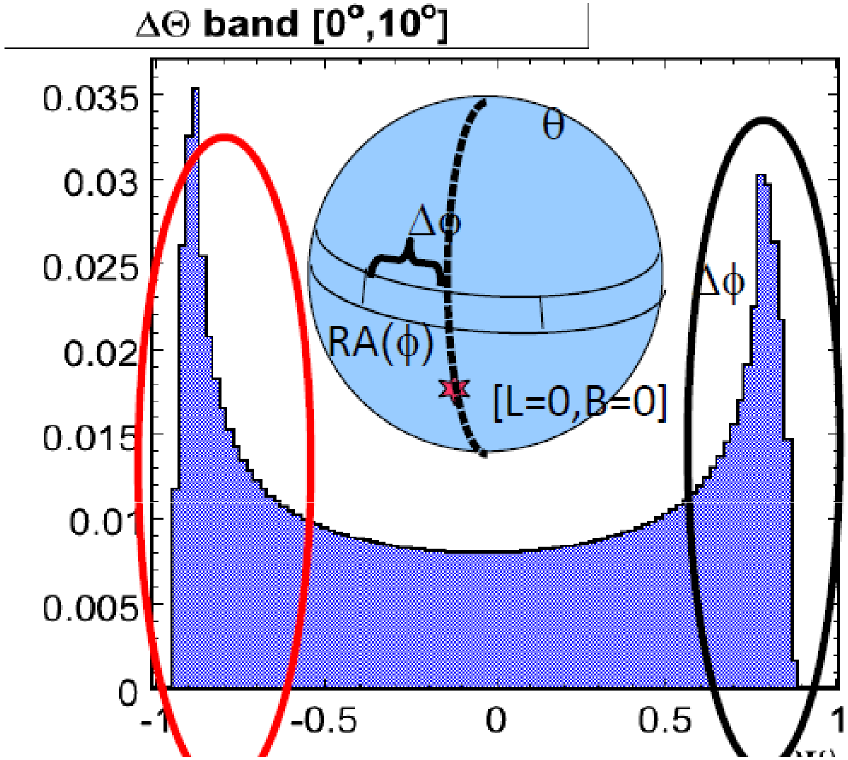
Halo wimps

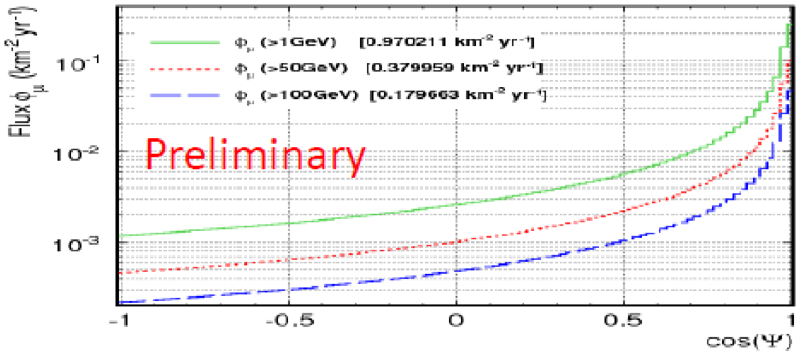
A neutrino flux from annihilations in the Milky way halo might be observable as neutrino flux anisotropy.

Use up-going tracks (from the Northern hemisphere) to have access to TeV range neutrinos.



Example: 10 degree zenith angle band mapped in galactic coordinates



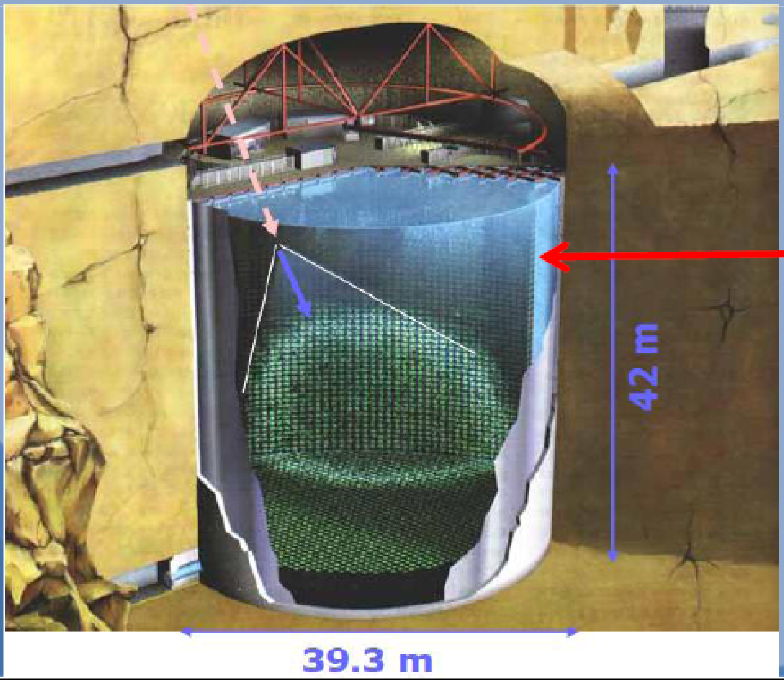


Super-Kamiokande detector

- Large water Cherenkov detector located Kamioka-mine, Japan (1000m under ground).

T. Tanaka, ICRC 09.

- 50kt water inside the tank(22.5 kt fiducial)
- 42m height, 39.3m diameter
- 2m outside detector(OD) for cosmic muon veto

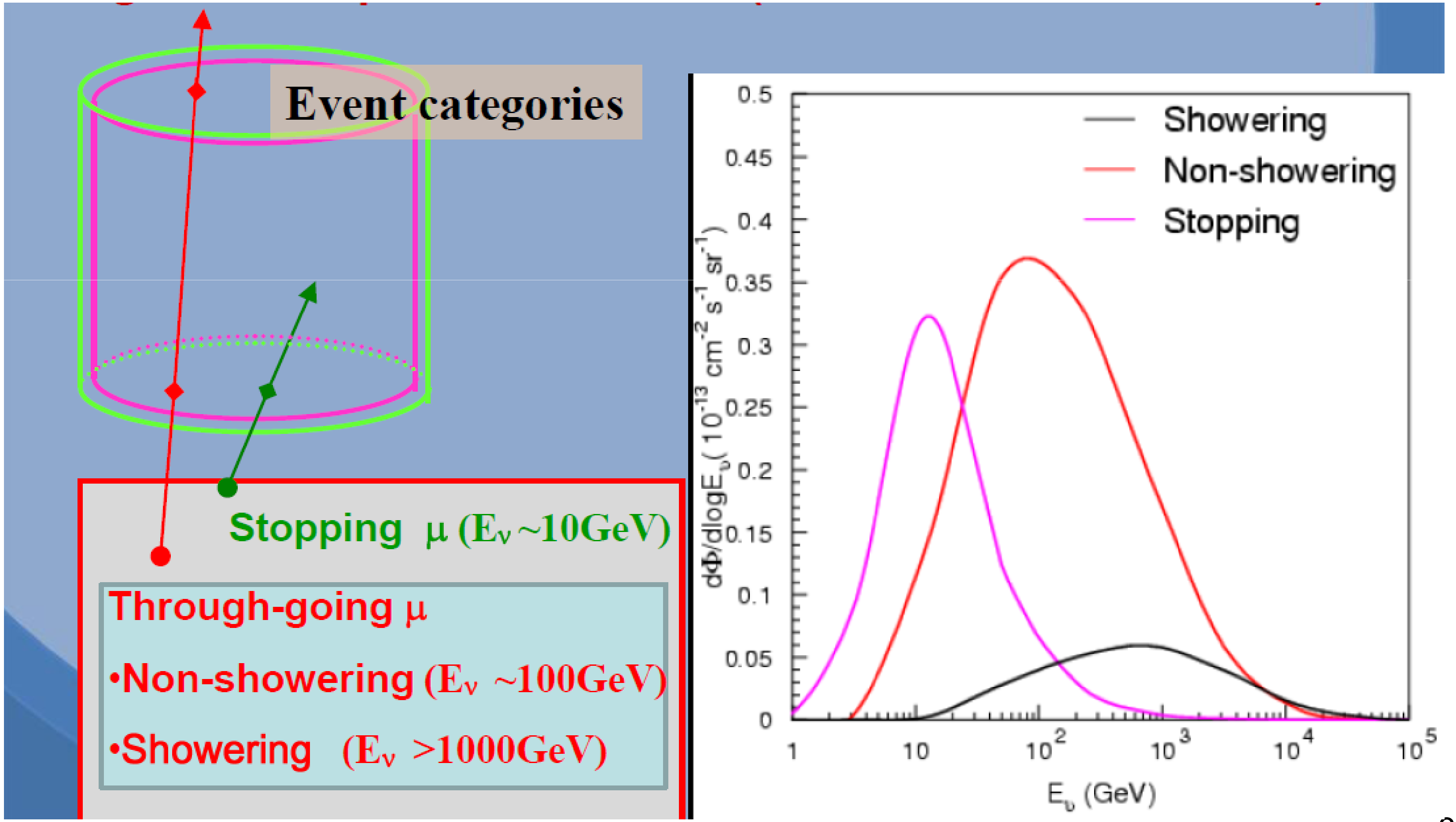


20″ PMT with acrylic cover

~11000 PMT(ID)

Upward muons

A_{eff} (μ)= 1200 m^2



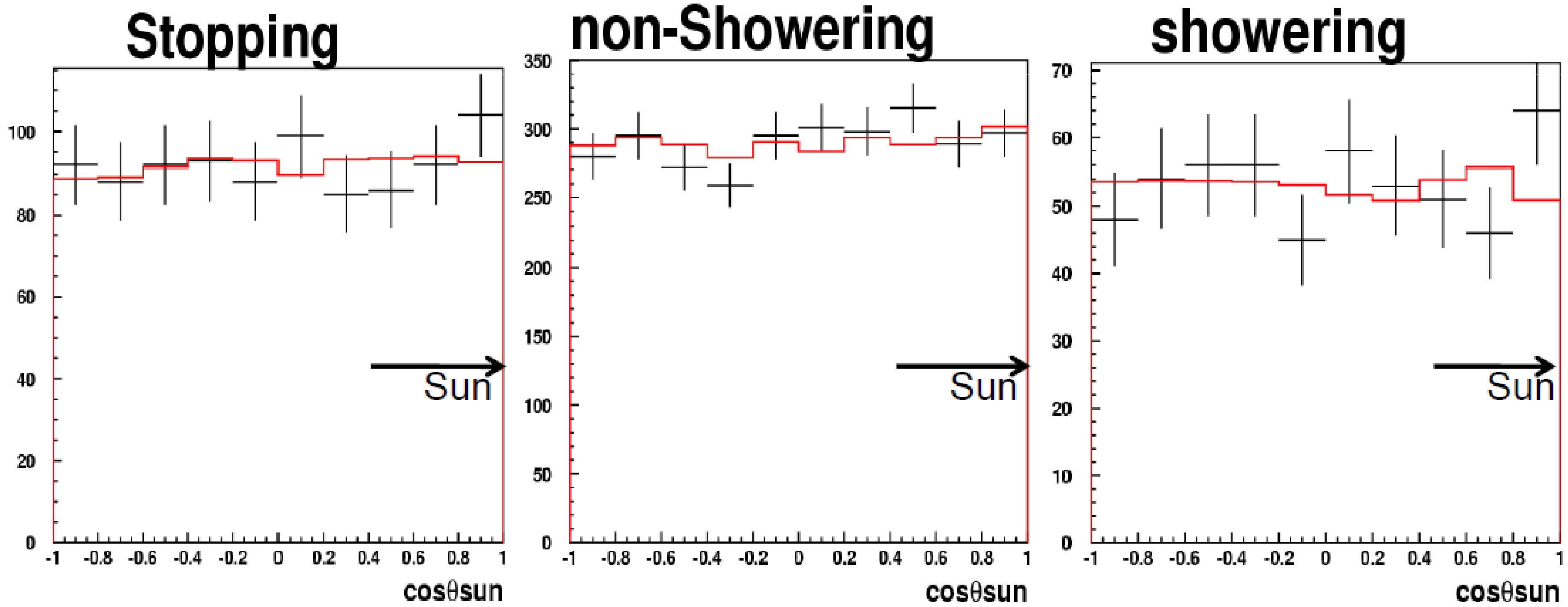
S. Loucatos IRFU, CEA-Saclay

•SKI~III upmu samples (3149.2 days)

•Cos θ_{Sun} = 1 means the direction of the Sun

Data and MC are consistent.

Red:Atmospheric ν MC (with oscillation)
$\sin^2 2\theta = 1$,
$\Delta m^2 = 2.5 \times 10^{-3}$ eV
Cross: data



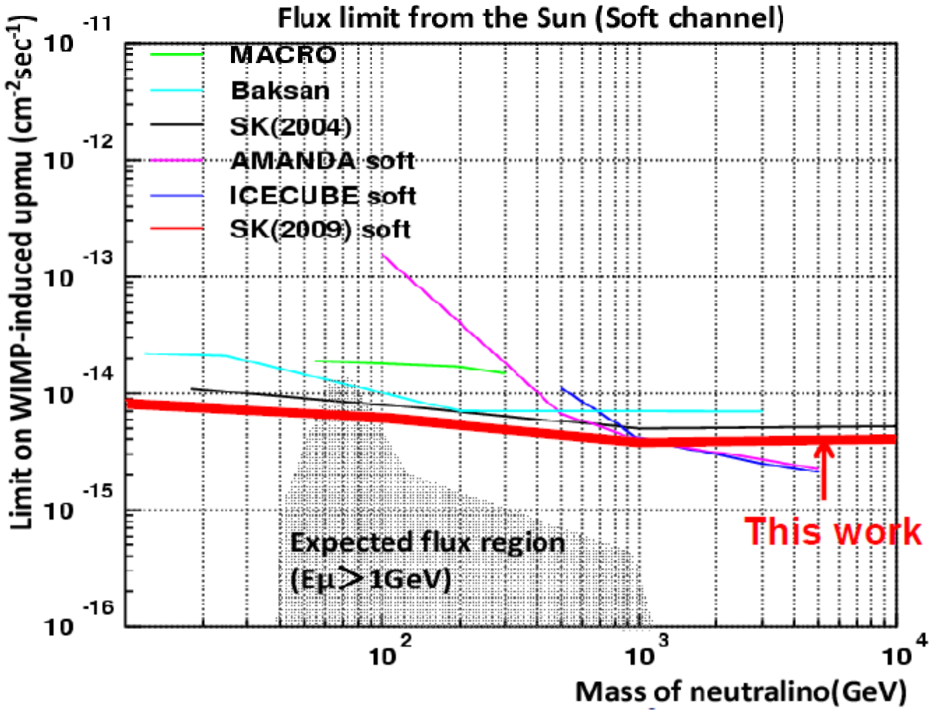
WIMP mass (GeV)	θ_{Sun} (deg.)
10	30
100	10
1000	6
10000	5

For each M_χ a cone for 90% signal containment is defined.

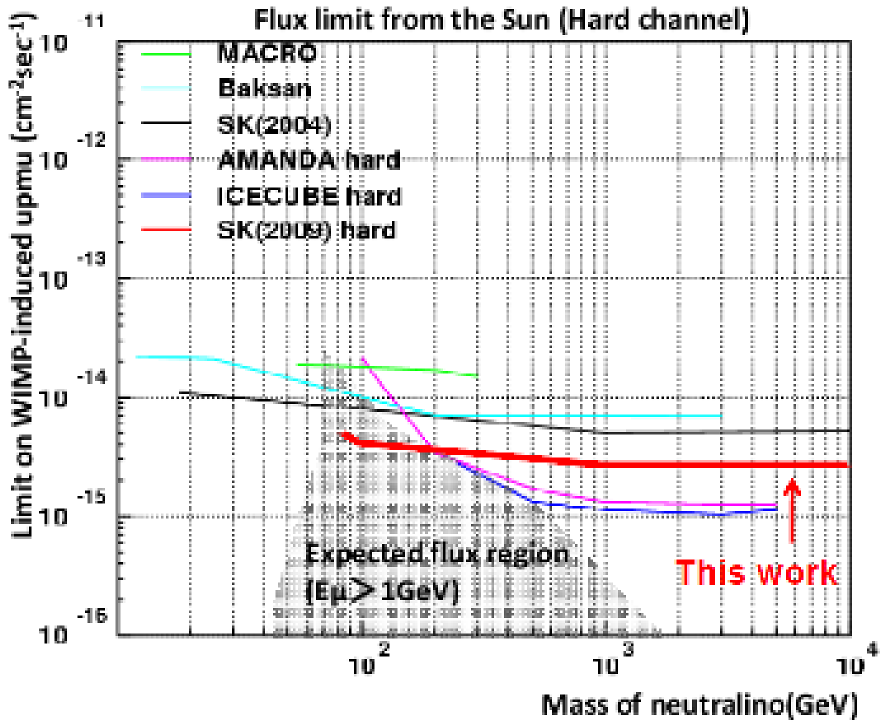
No excess → 90% limit

$$\mathrm{cm}^{-2}\,\mathrm{sec}^{-1} = 10^{10}\,\mathrm{km}^{-2}\;\pi\,10^{7}\,\mathrm{y}^{-1} = \pi\,10^{17}\,\mathrm{km}^{-2}\,\mathrm{y}^{-1}$$

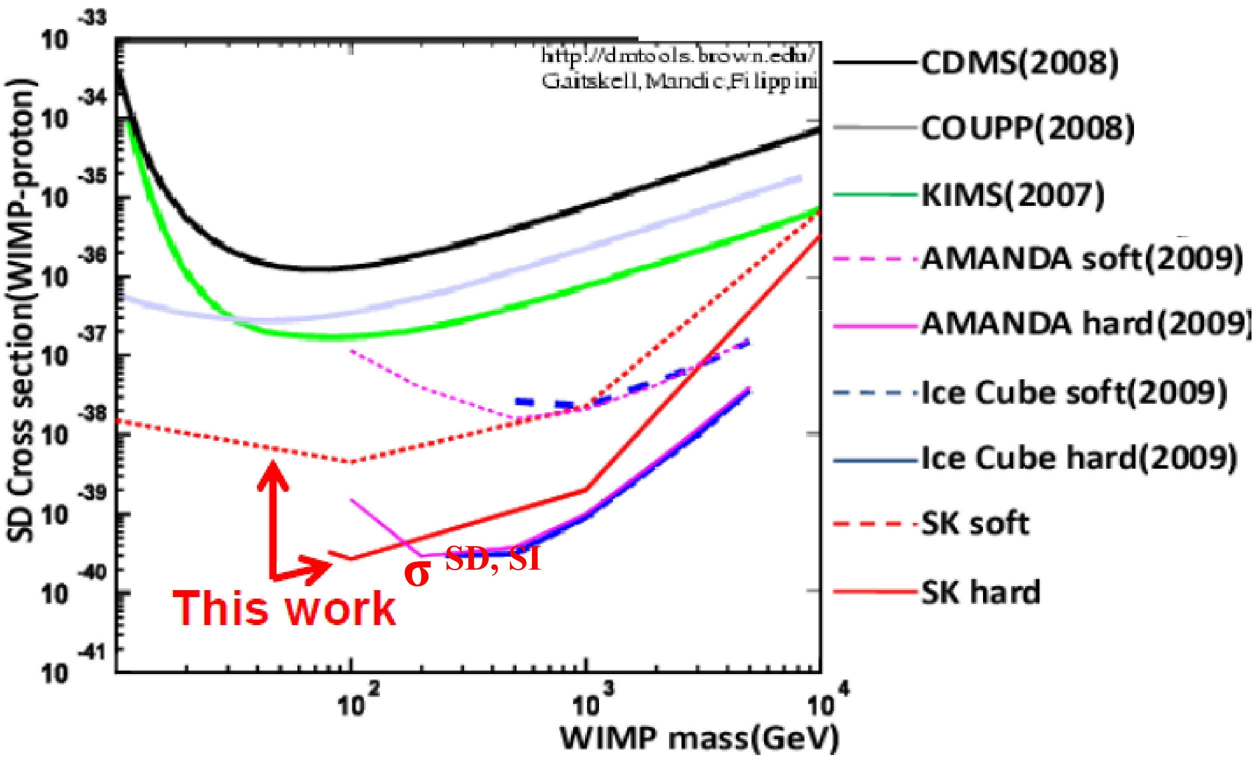
Soft channel



Hard channel



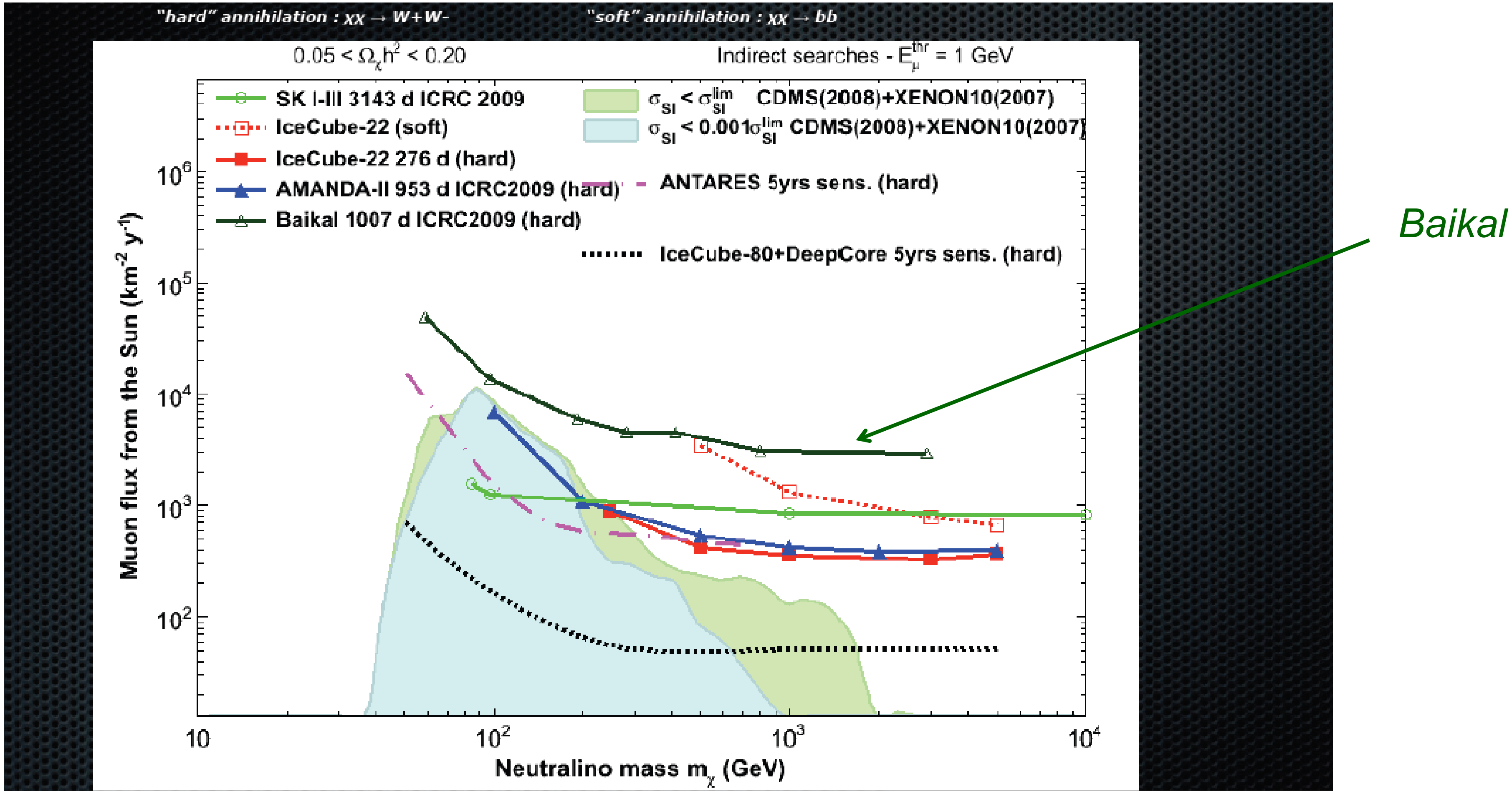
SK σ^{SD} result



S. Loucatos IRFU, CEA-Saclay

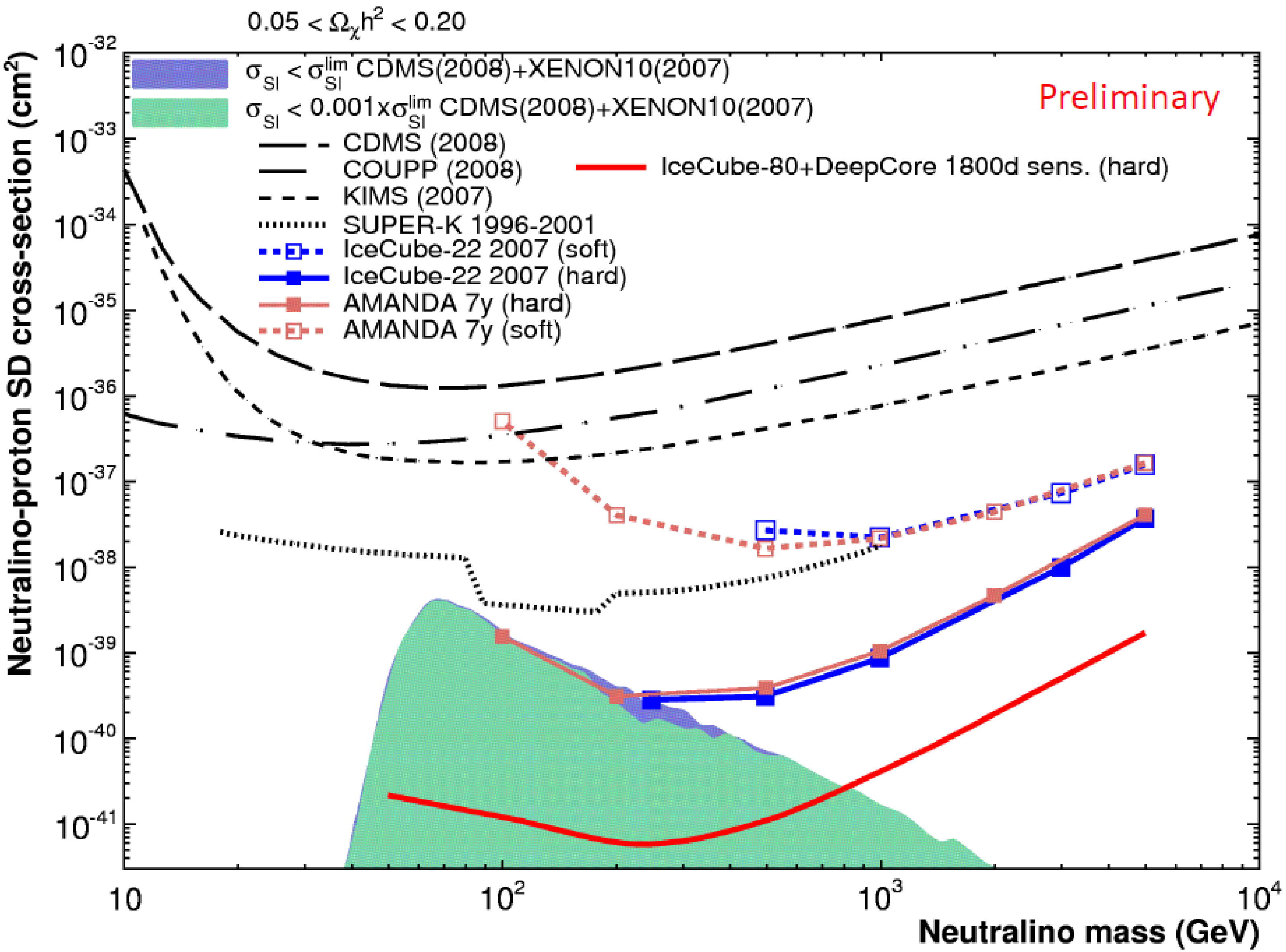
Compilation

T. Montaruli, ICRC 09.



IceCube 22 strings 6946, livetime 276 d (effective 104 d) PRL 102 (2009)
HE2.3 0834, 0505, 1356 for KK
Deep core vetoed by IceCube: 4-6 orders of magnitude of background rejection (OG 2.5 1237)

SD cross section



S

UED – Kaluza Klein

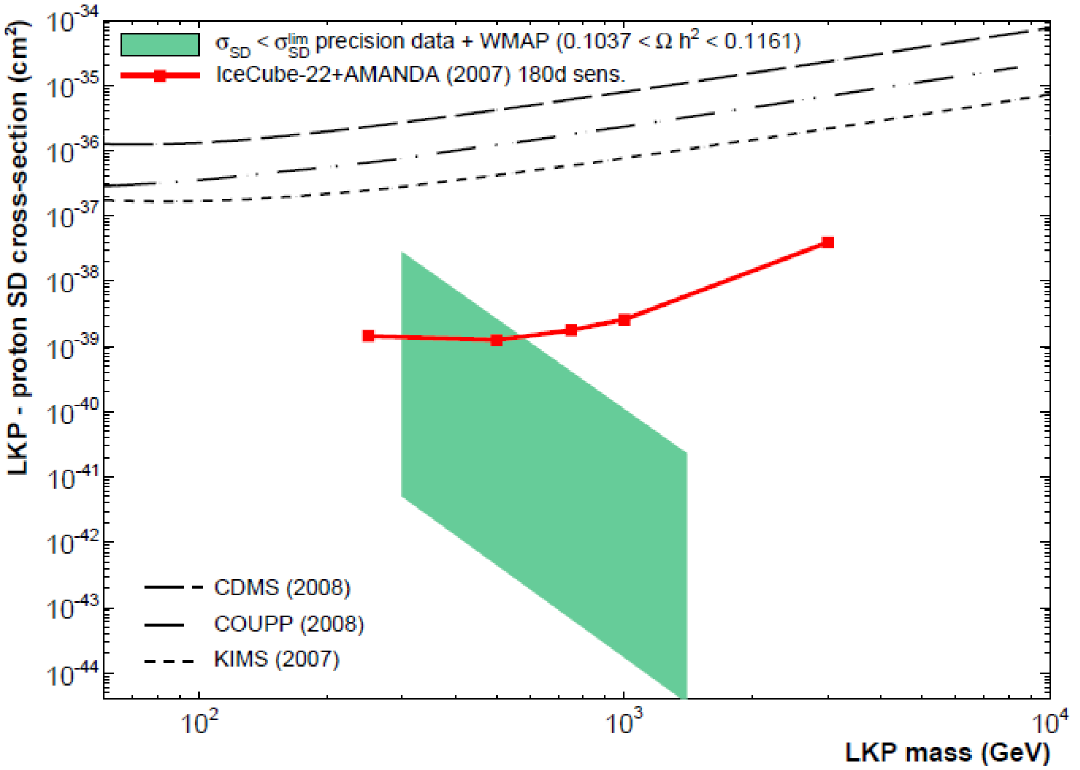
K. Han, ICRC 09.

LKP = $B^{(1)}$ 1st excitation of the KK photon

TABLE I

POSSIBLE CHANNELS FOR THE PAIR ANNIHILATION OF $B^{(1)}B^{(1)}$ AND BRANCHING RATIOS OF THE FINAL STATES. FIGURES TAKEN FROM [20].

Annihilation Process			Branching ratio
$B^{(1)}B^{(1)}$	$\rightarrow$	$\nu_e\overline{\nu}_e$, $\nu_\mu\overline{\nu}_\mu$, $\nu_\tau\overline{\nu}_\tau$	0.012
	$\rightarrow$	e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$	0.20
	$\rightarrow$	$u\overline{u}$, $c\overline{c}$, $t\overline{t}$	0.11
	$\rightarrow$	$d\overline{d}$, $s\overline{s}$, $b\overline{b}$	0.07



S. Loucatos IRFU, CEA-Saclay

Inert Doublet Model

(Barbieri et al 2006, Ma 2006)

E. Nezri, 2009

- ⋆ *ad hoc* model and does not address any deep issue (hierarchy problem).
- ⋆ a very simple extension of the Standard Model and rich phenomenology.
- ⋆ H_0 dark matter phenomenology intertwined with that of the Higgs particle.
- ⋆ few parameters (7), effective model

Standard Model + 2 Higgs doublets : H_1 and H_2

A Z_2 symmetry (to avoid FCNC) : $H_1 \to H_1$ and $H_2 \to -H_2$.

Standard Model fields are even under Z_2.

Assume Z_2 is not broken, *i.e.* H_2 does not develop a vev : $\langle H_2 \rangle = 0$

Potential: $$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

$SU(2) \times U(1)$ symmetry broken by $\langle H_1 \rangle = \frac{v}{\sqrt{2}}$

Higgs mass $M_h^2 = -2\mu_1^2 \equiv 2\lambda_1 v^2$

$\to$ 3 new scalar particles : H^+ charged : $M_{H^+}^2 = \mu_2^2 + \lambda_3 v^2/2$

A_0 neutral pseudo : $M_{A_0}^2 = \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2/2$

H_0 neutral : $M_{H_0}^2 = \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2/2$

$H_0 \equiv$ scalar WIMP dark matter candidate

Summary and Outlook

- Search for neutrino signals from Dark Matter annihilation in the Sun performed by all telescopes
- SUSY Dark Matter can produce interesting signals :
  - Stringent limits for Spin-Dependent χ-p cross section (Amanda-IC, SK)
  - mSUGRA parameter space reachable. Promising sensitivities of KM3,IC
  - Complementarity of neutrino telescopes with direct detection and LHC
- Sensitivity to other SUSY models (pMSSM, AMSB,…) or Dark Matter candidates is being studied (KK excitations,…)
- First limit on Earth signal from Amanda
- Search towards Galactic Centre in progress