The Ohio State University's Center for Cosmology and AstroParticle Physics

DARK MATTER SEARCHES WITH NEUTRINO TELESCOPES

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The Ohio State University

Focus Week on Indirect Dark Matter Search
Dec 7 – 11, 2009

Overview

- Motivation
- Neutrino Telescopes Overview
- Selected Analyses
  - Solar WIMPs
  - Halo WIMPs
- Deep Core Capabilities
- Conclusions

Motivation

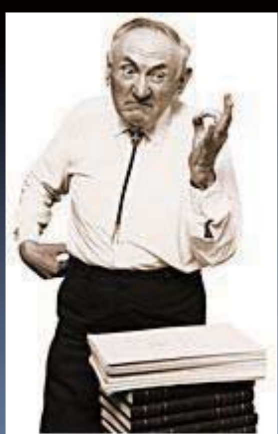
Dark Matter Understanding

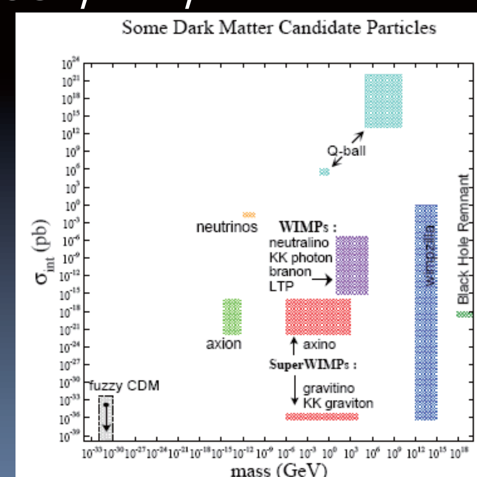
- Observational Evidence
  - Non-baryonic
  - Cold massive
  - Not strongly interacting
  - Stable (long lived)

WIMP

- Particle Nature
  - Mass ?
  - Cross-sections ?
    - Self-annihilation $<\sigma_A v>$
    - Interaction with matter
  - Theoretical Model
    - SUSY, LED, ...

Measure





Strategies for WIMP Detection

- Direct Detection
  - Recoil effects - WIMP scattering of nucleons
- Indirect Detection
  - Neutrinos – annihilation signals from WIMPs accumulated in the Sun or Earth
  - Photons, Neutrinos – Milky Way Halo, Cosmic Flux, …
  - Anti-matter (e+,D,pbar) – local neighborhood (few kpc)
- Production
  - Tevatron, LHC, ILC, …

This talk

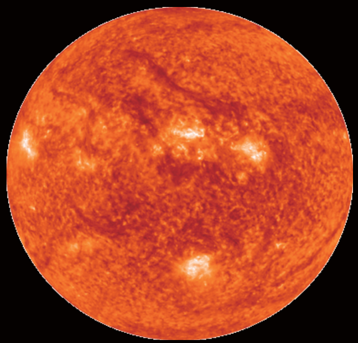
WIMP-Nucleon Scattering cross-section

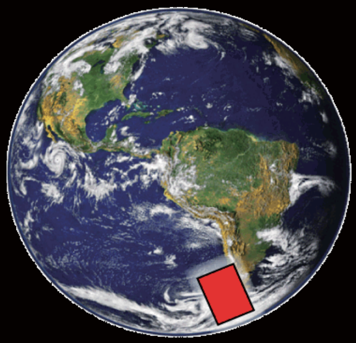
WIMP Self-annihilation cross-section

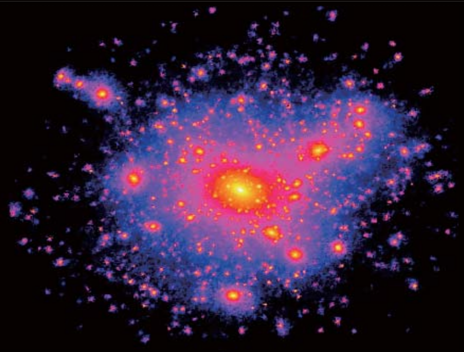
Neutrino Dark Matter Searches

Solar/Earth WIMPs probe WIMP-nucleon scattering cross-section (compare to direct detection experiments)

Halo WIMPs compare to γ-ray indirect detection experiments



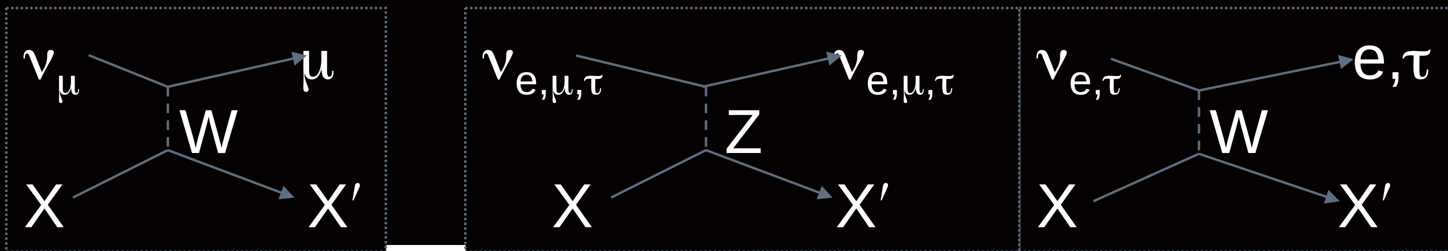


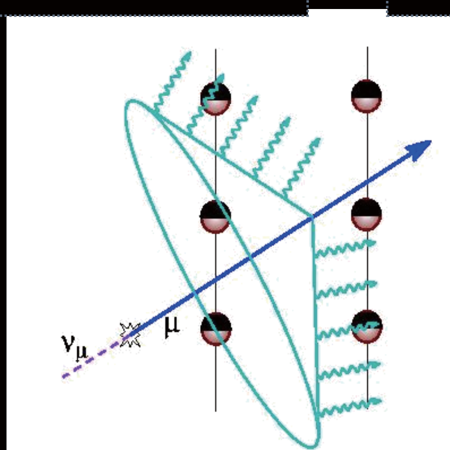


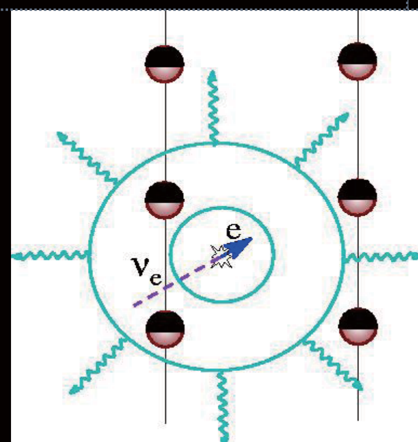
Solar	Earth	Halo
Neutrino Flux, **Scattering cross-section**	Neutrino Flux, **(Scattering cross-sections)**	Neutrino Flux**, Self-annihilation cross-section**
Muon neutrinos	Muon neutrinos	Muon neutrinos, **Cascades**
Background off-source on-source	Background simulations	Background off-source on-source, simulations
M_{WIMP}~<TeV	M_{WIMP}~<100GeV	All M_{WIMP}

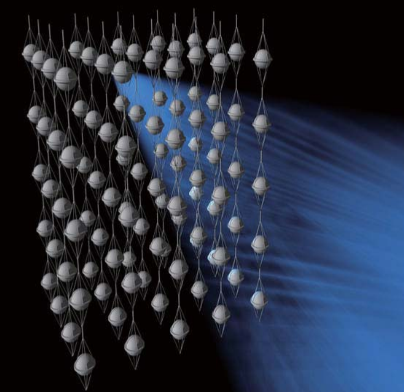
Neutrino Telescopes Overview

Neutrino Telescopes – Detection Principle









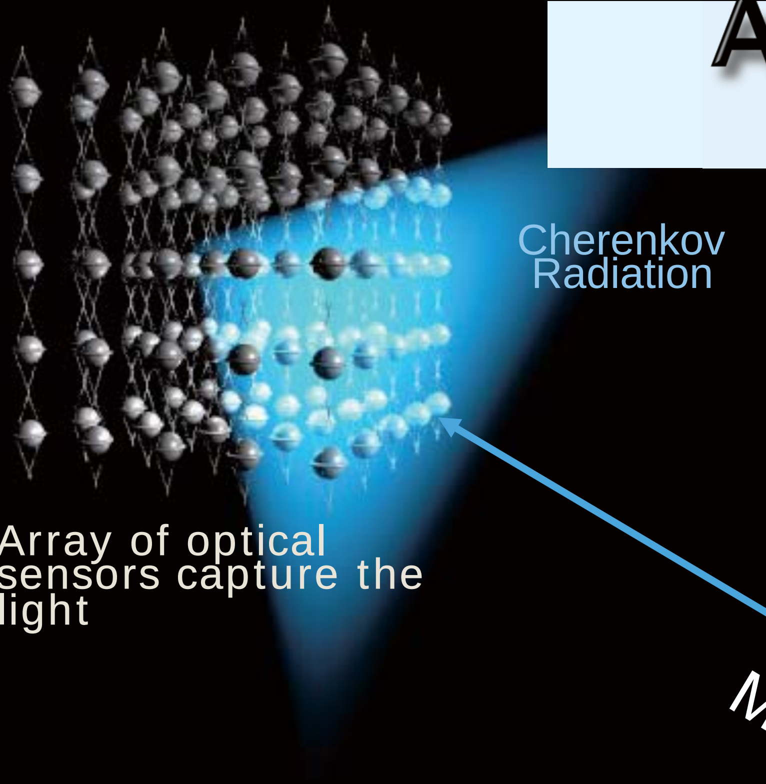
- Muon neutrino interacts in water/rock/ice near/in the detector
- Relativistic muon produces Cherenkov light and suffers radiative losses (track)

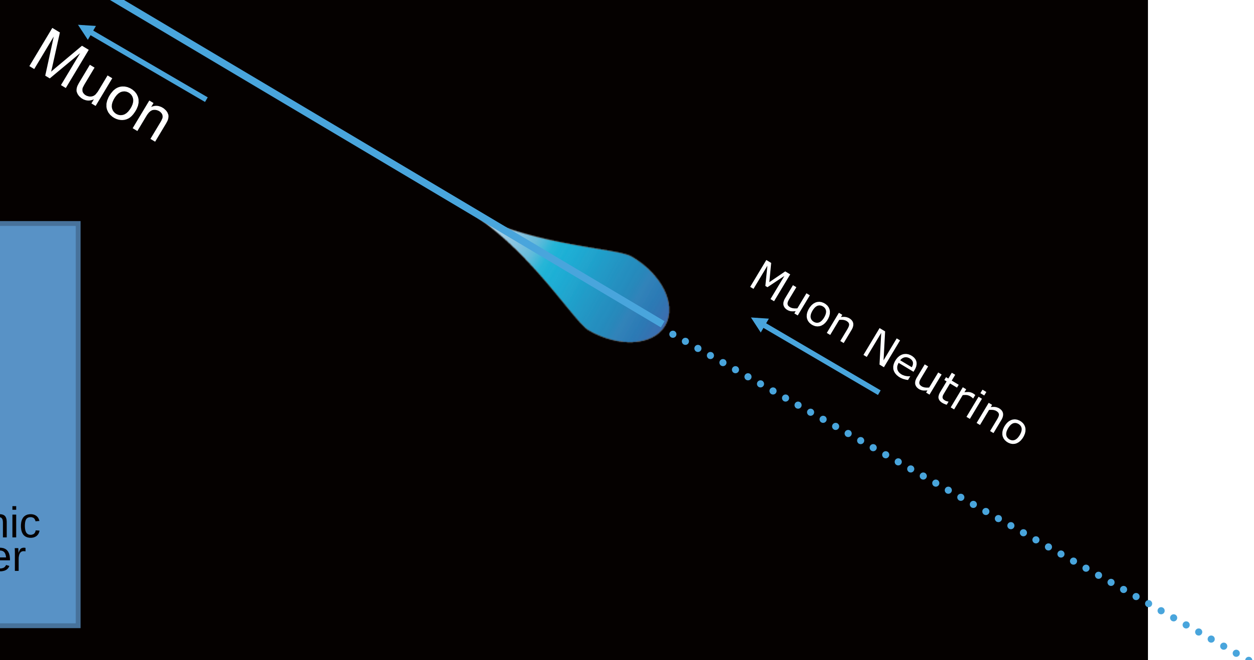
- Electron / tau neutrinos interacts in the detector
- Rapid radiative loss (shower)

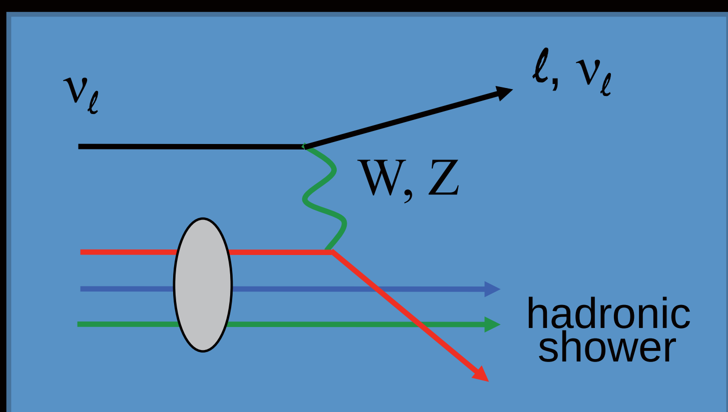
- Optical sensors detect radiation
- Based on number of photons and arrival time the event can be reconstructed

An Optical Neutrino Telescope

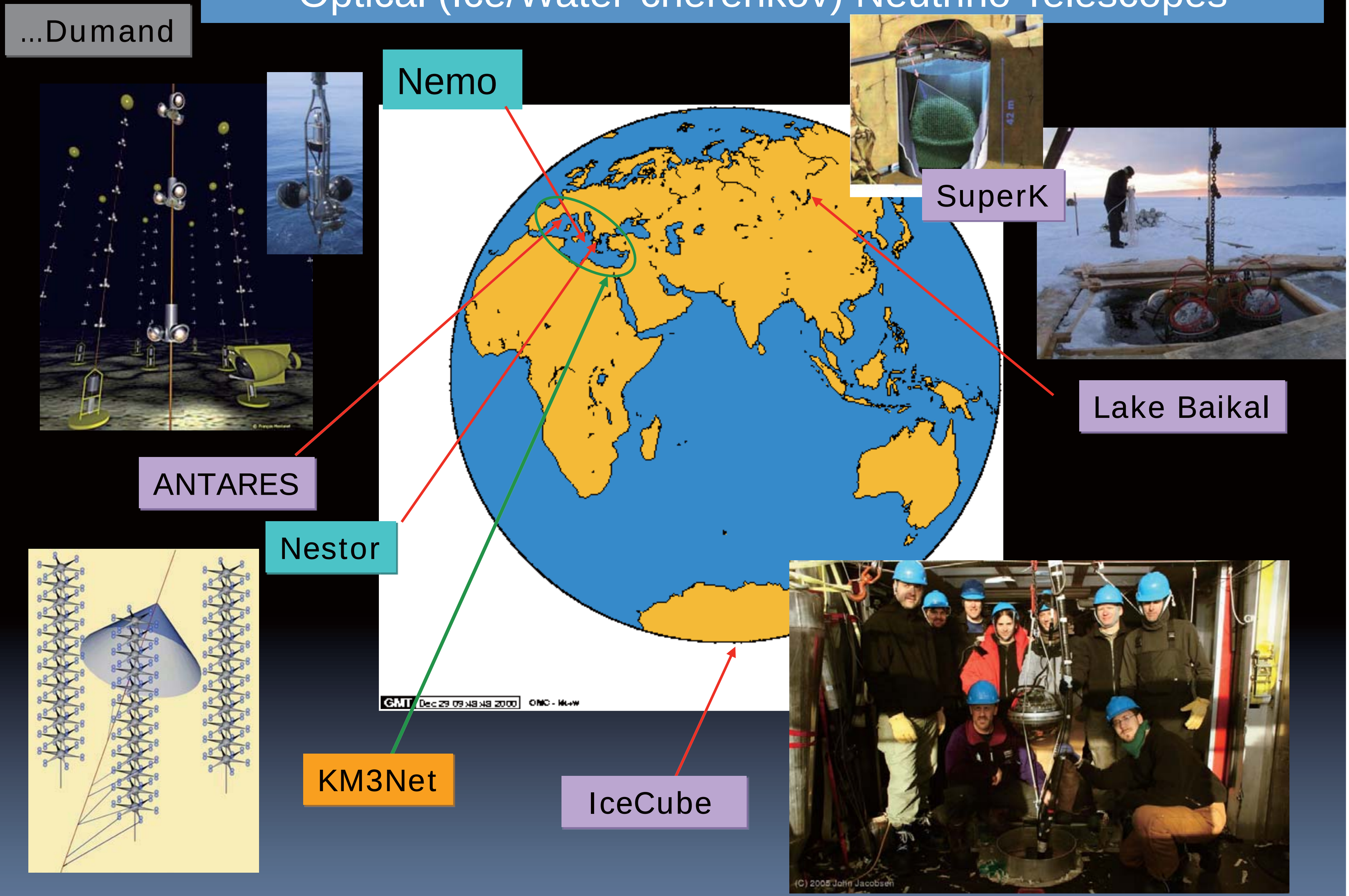
- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
- ***O*** (km) muons from ν_μ
- ***O*** (10m) cascades from ν_e, ν_τ, NC

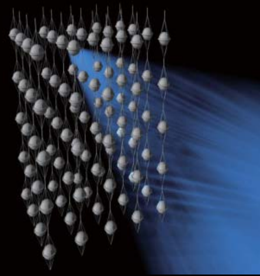






Optical (Ice/Water-cherenkov) Neutrino Telescopes



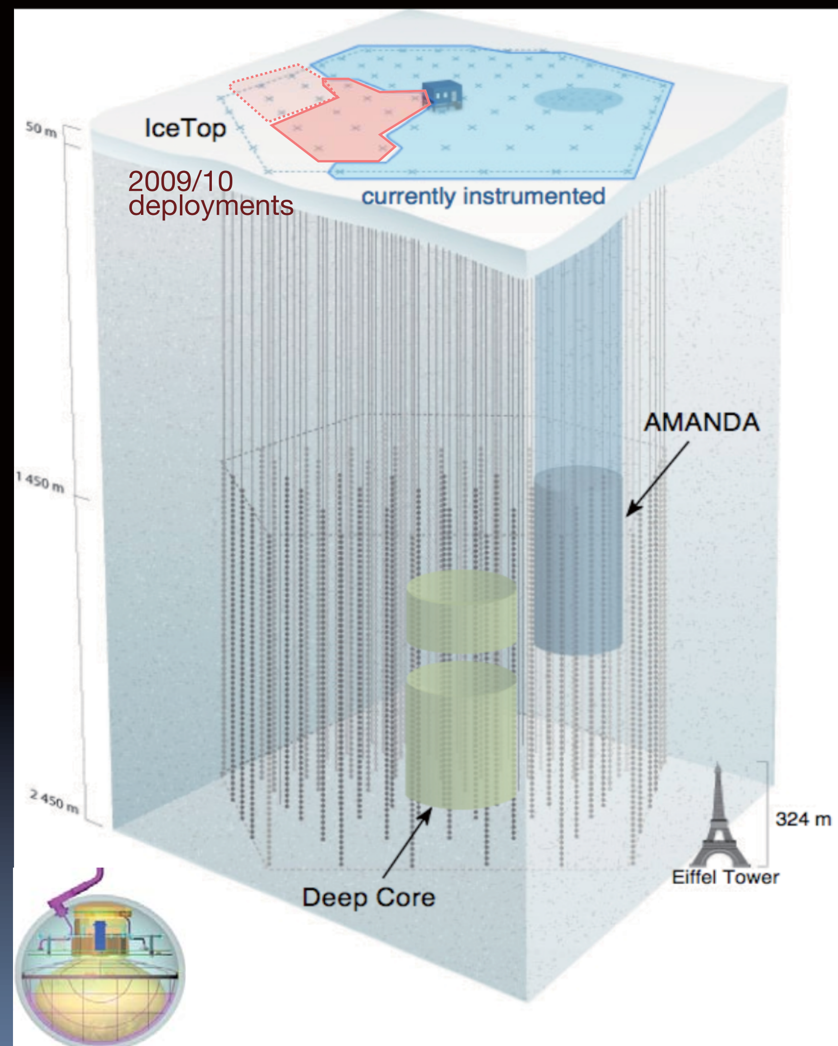


	IceCube	Deep Core	ANTARES	Super K
Location	South Pole (1500m)	South Pole (2000m)	Mediterranean (2100m)	Kamiokande (1000m)
Volume	~1GT by 2011	~14MT by 2010	~10 MT	~22.5 KT
Accessibility	Northern Sky	All Sky (using IceCube as veto)	Southern Sky + large part of Northern Sky	Southern Sky + large part of Northern
Advantages	Large volume	“Shielded” from atm. muon backgrounds	Good angular resolution	Large dataset, excellent flavor id, well understood detector, …
Energy	100GeV-…	10-100GeV	100GeV- …	GeV-range

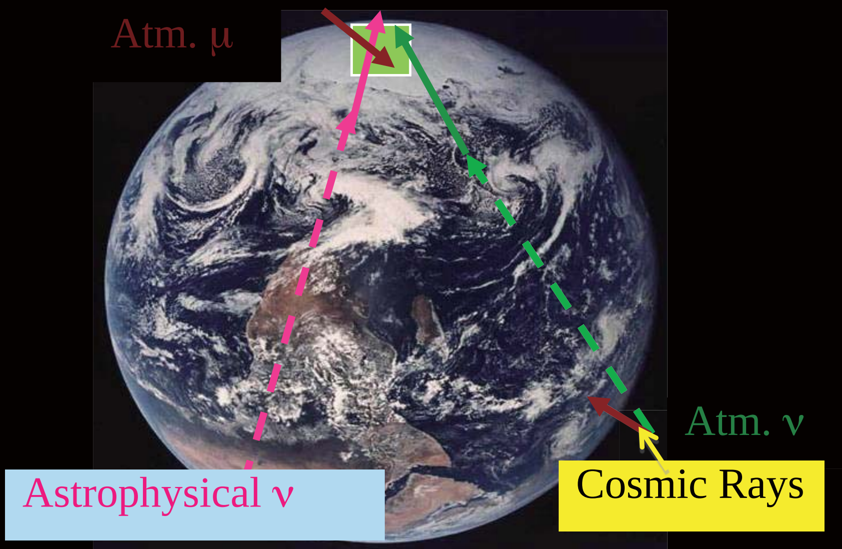
The IceCube Neutrino Telescope

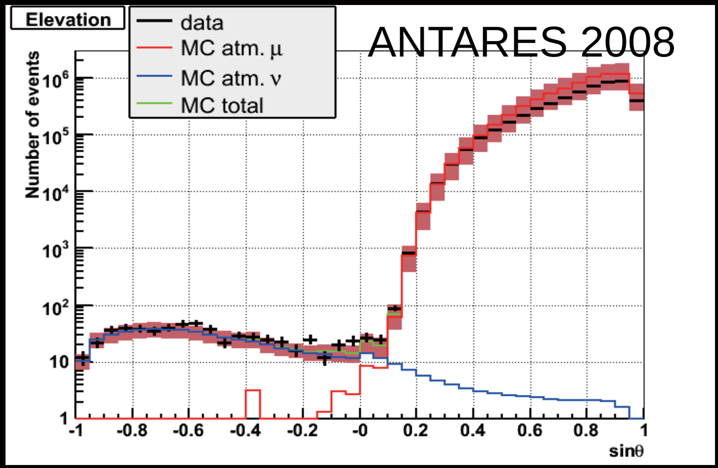
- **IceTop**
  - 80 Stations (2 tanks each)
  - Surface air shower array
  - 300TeV threshold
- **IceCube (InIce)**
  - 80 Strings with 60 DOMs each
  - Hexagonal pattern with an interstring distance of 125 m
  - Vertical DOM spacing of 17 m
  - Optimized for TeV range
- **AMANDA (switched off since May 11th ,2009)**
  - 19 strings with 677 modules total
  - 10-20 m vertical spacing
  - 40-50 m horizontal spacing
- **Deep Core**
  - 6 additional strings with 60 High Quantum Efficiency DOMs (vert. spacing 7 m)
  - "Low Energy extension"

IceCube will instrument a volume of one cubic kilometer of Antarctic ice by 2011



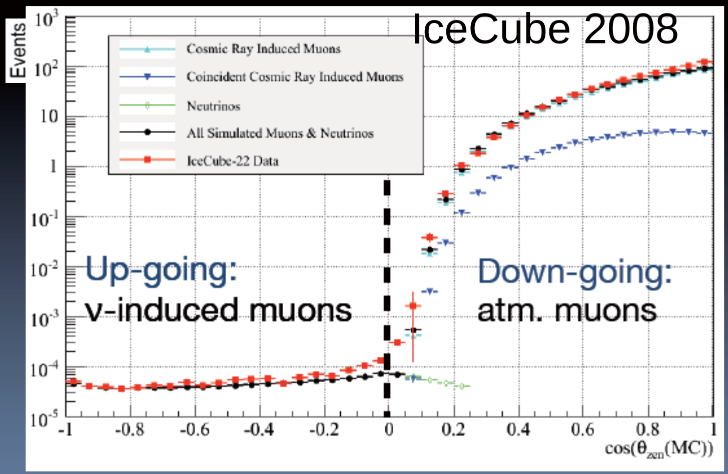
Down-going muons are dominant background to atmospheric neutrino signals



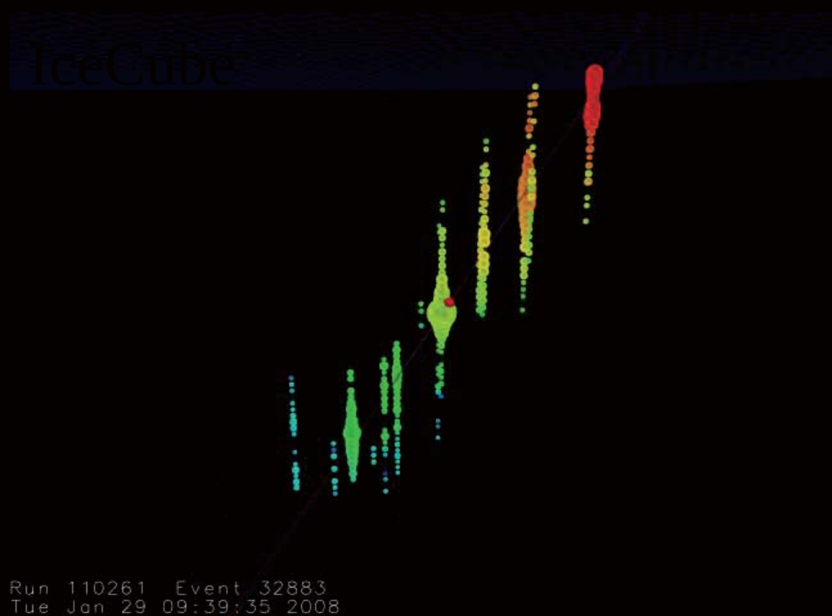


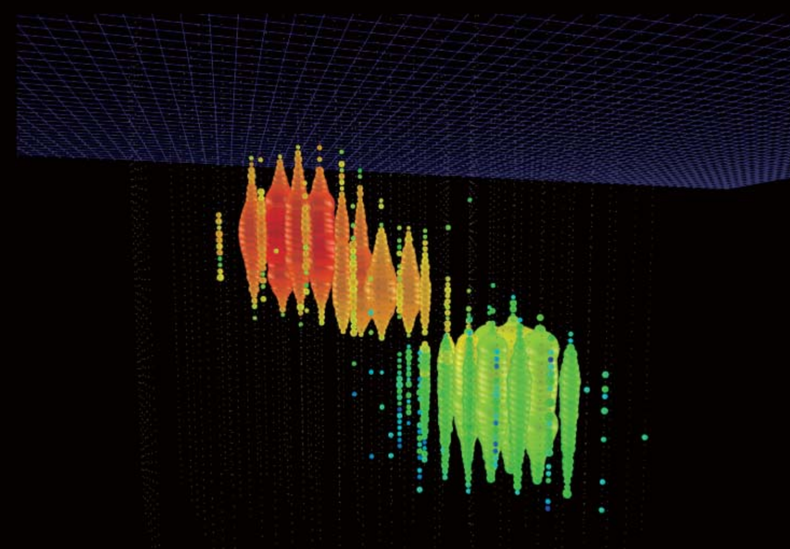
IceCube

Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1500 Hz	160 / day
IC86*	2011	~365 days	1650 Hz	220 / day



Neutrino Event Identification





16 PeV ν_τ simulation

Track-Like	IceCube	AMANDA
Time Resolution	2 ns	5-7 ns
Energy Resolution ($\log_{10}E$)	0.3 – 0.4	0.3 – 0.4
Field of View	2π	2π
Noise Rate	low	
Angular resolution	$<1^{o}$	~1.5-2.5^{o}

Cascade-Like	IceCube	AMANDA
Time Resolution	2 ns	5-7 ns
Energy Resolution ($\log_{10}E$)	0.18	0.18
Field of View	4π	4π
Noise Rate	low	
Angular resolution	30^{o}	~30-40^{o}

Cascade reconstruction

- Make use of the full waveform information in IceCube
- Take inhomogeneity of the ice into account
  - Photonics package is used to construct "tabulated delay time distributions"
  - Maximum log reconstruction

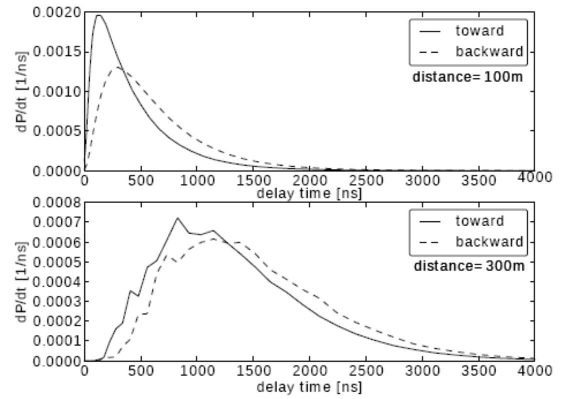
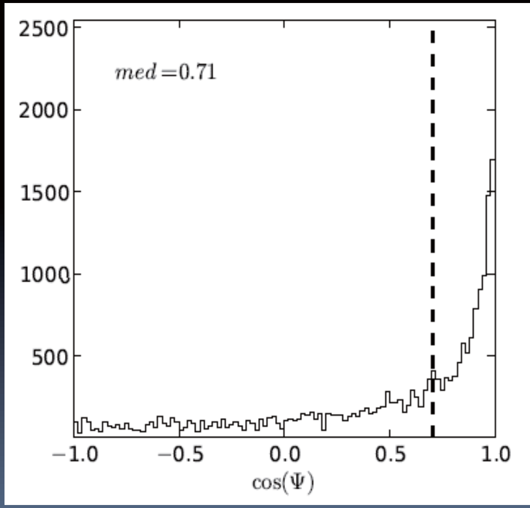
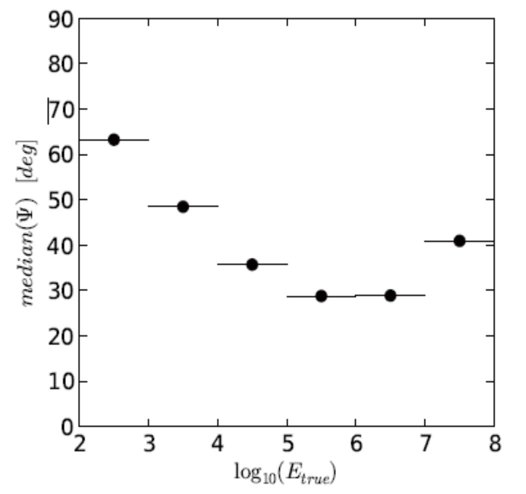


Fig. 1. Tabulated delay time distributions for a DOM at 100m and 300m distance to the cascade. The distributions are shown for two orientations of the cascade, pointing either toward or away from the DOM. Photons are increasingly delayed if they either travel larger distances or have to be backscattered to reach the DOM.



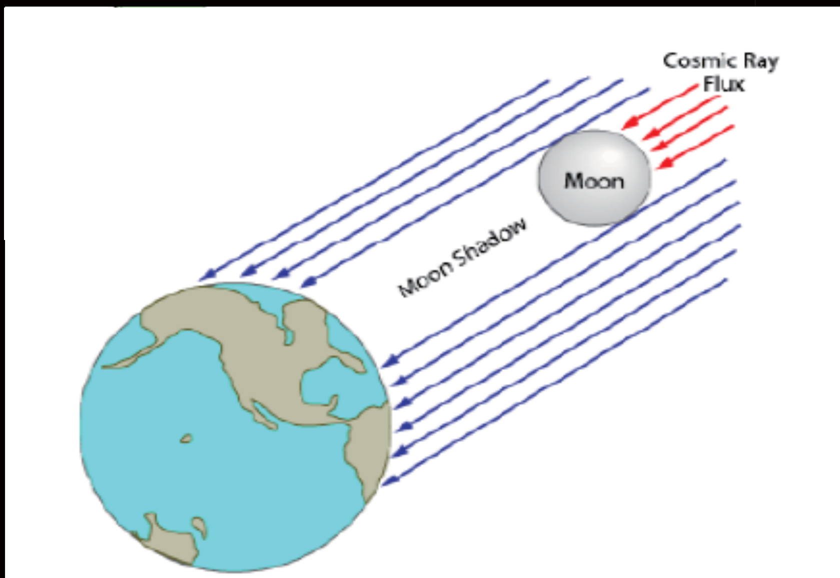


~30deg 100TeV – 10PeV
~65deg 10-100GeV

For 40 string detector study case

E.Middell, J. McCartin, M.D'Agostino [IceCube], ICRC 2009

IceCube-40 - Moon Shadow

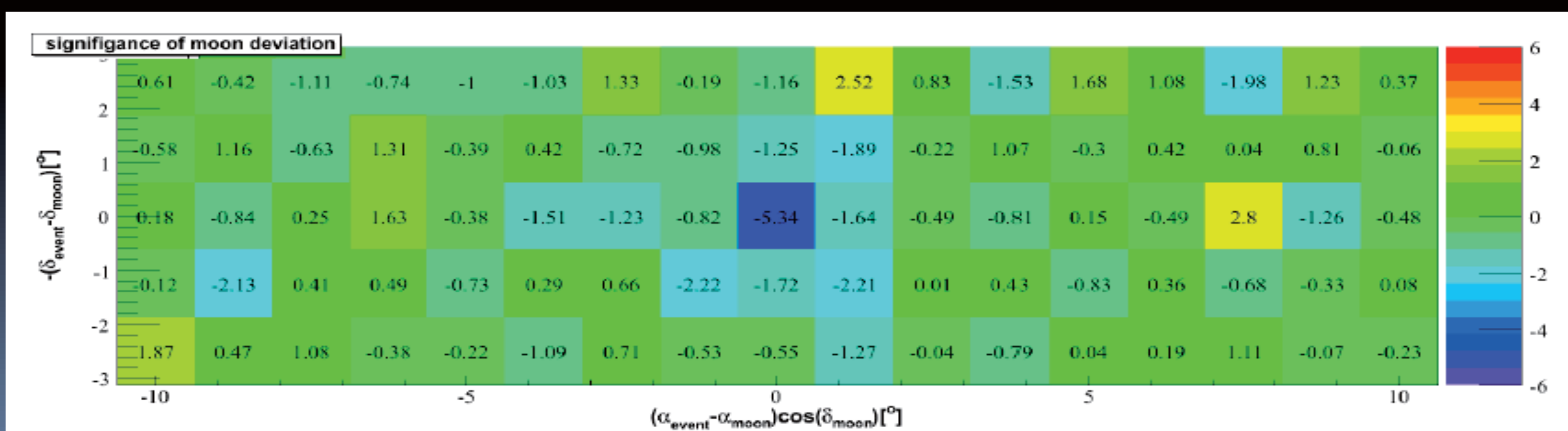


Cosmic rays blocked by the moon lead to a point-like deficit in the distribution of down-going muons in the detector

Moon shadow observed in 8 months of IC40 data

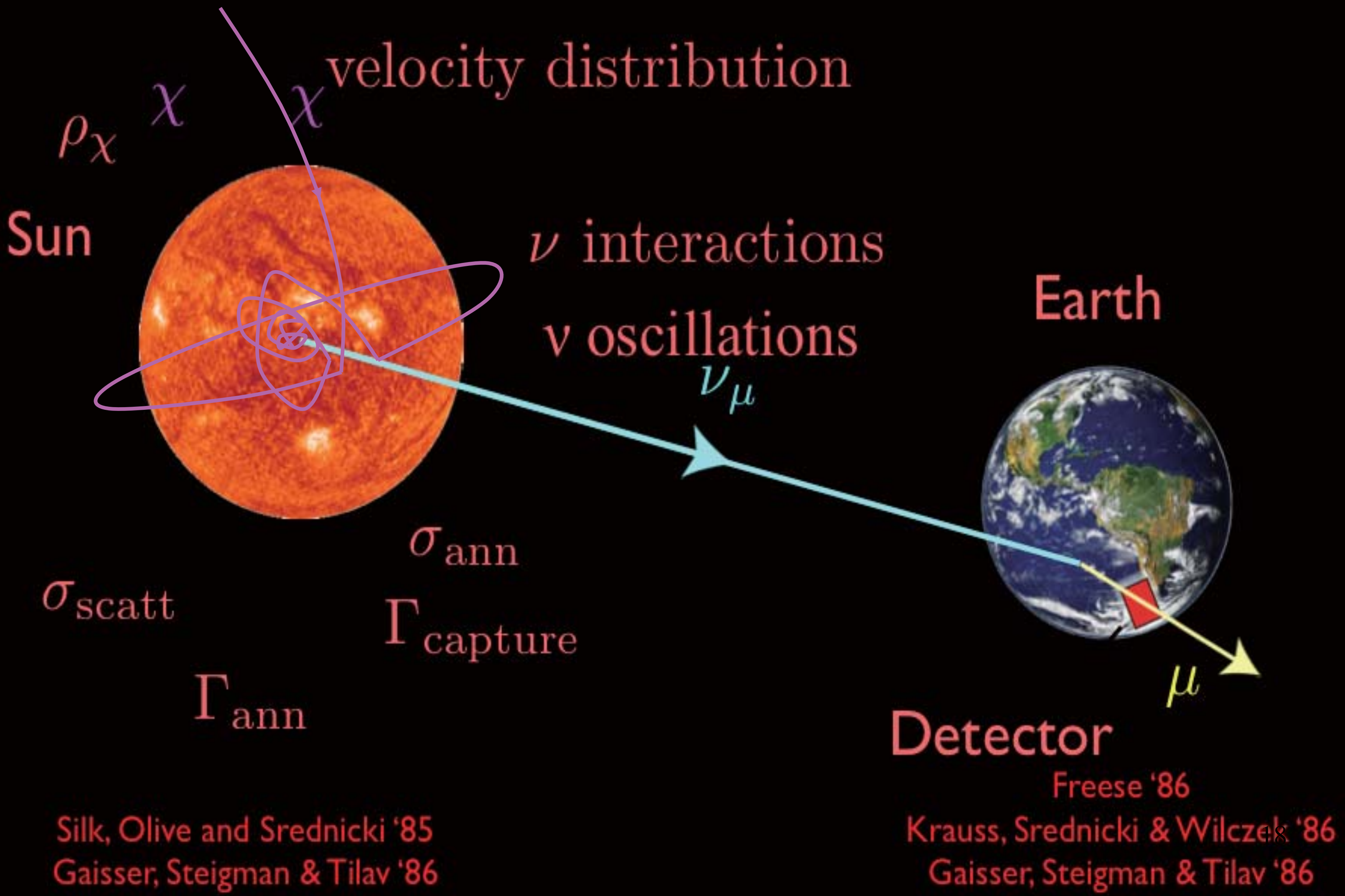
- Validates pointing capabilities: Angular resolution:
  - – IceCube 22 < 1.5°
  - – IceCube 80 < 1°

- Used to verify detector angular resolution



Dark Matter nucleon scattering cross -section

Indirect detection principle: Neutrinos from the sun



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

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

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

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

$t = t^{\odot} \sim 4.5 \cdot 10^9$ 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 → **σ SD, SI**

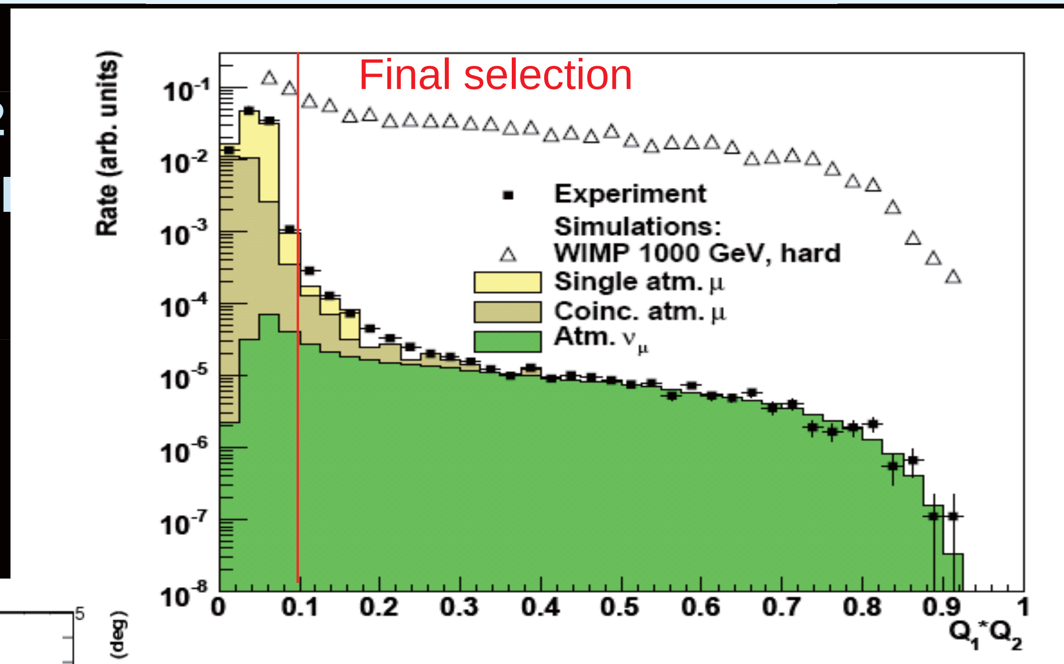
$\sigma^{SI} = \kappa_f^{SI}(m_\chi)\Phi_\mu^f$ $\sigma^{SD} = 0$

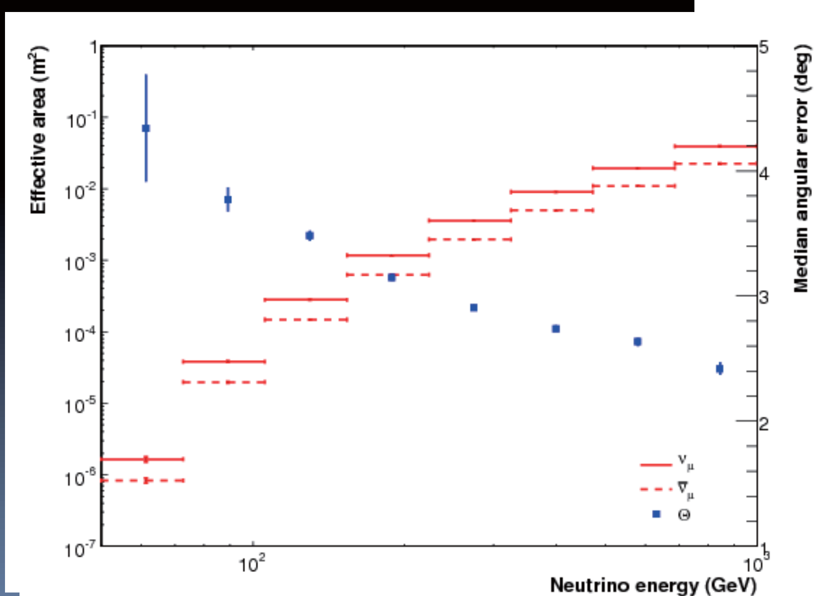
$\sigma^{SD} = \kappa_f^{SD}(m_\chi)\Phi_\mu^f$ $\sigma^{SI} = 0$

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).

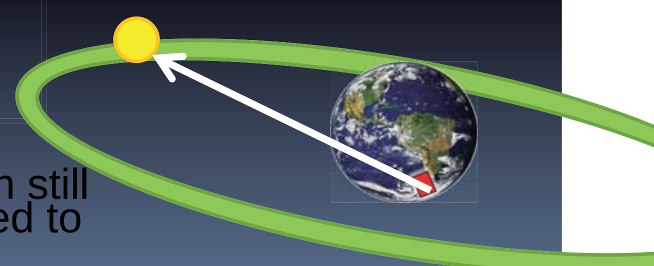
Solar WIMPs

- Product of two SVMs Q1*Q2 was used to remove background at final cut level
- Data and simulation agree well





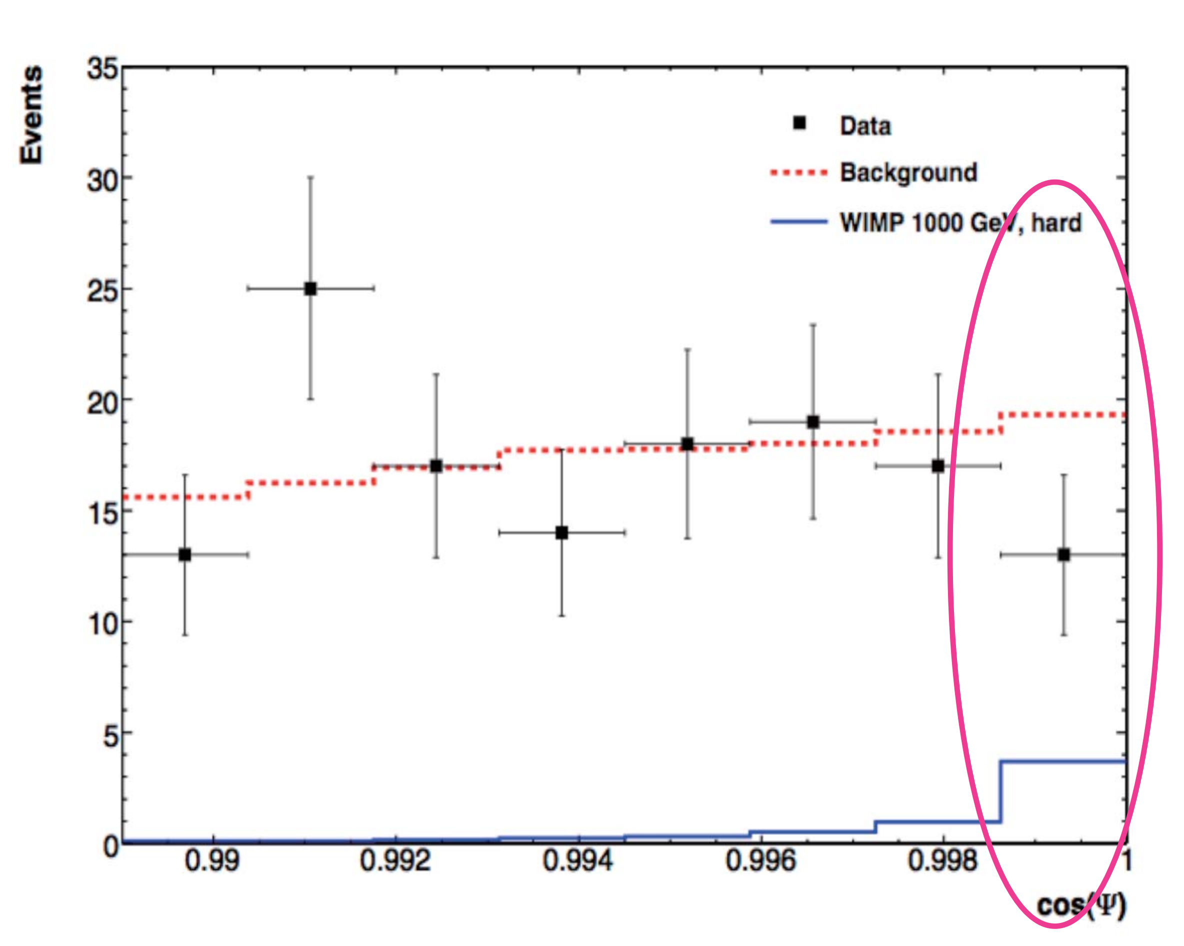
At the final cut level, atm. neutrinos form biggest background

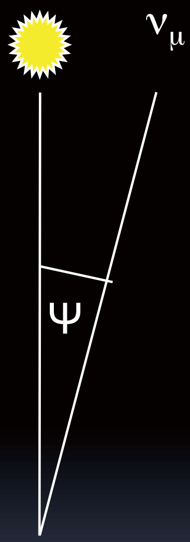


Direction of the sun still remained scrambled to this point

IceCube Search
Neutralino Searches

Muon flux from the sun



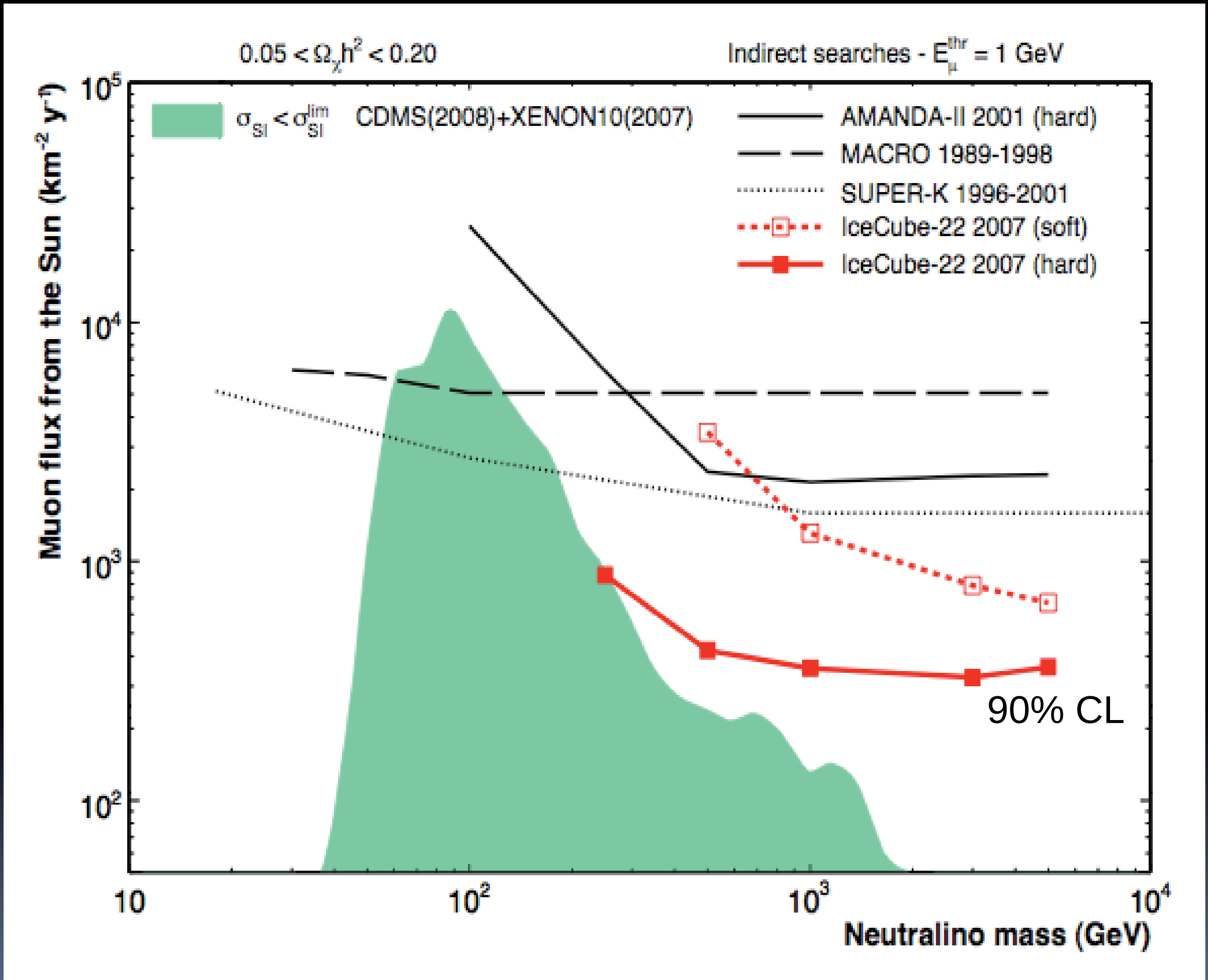


Observation consistent with expectations from atmospheric neutrinos ⇒upper limit

Abbasi et al., PRL, 2009

Neutralino Searches

Muon flux from the sun

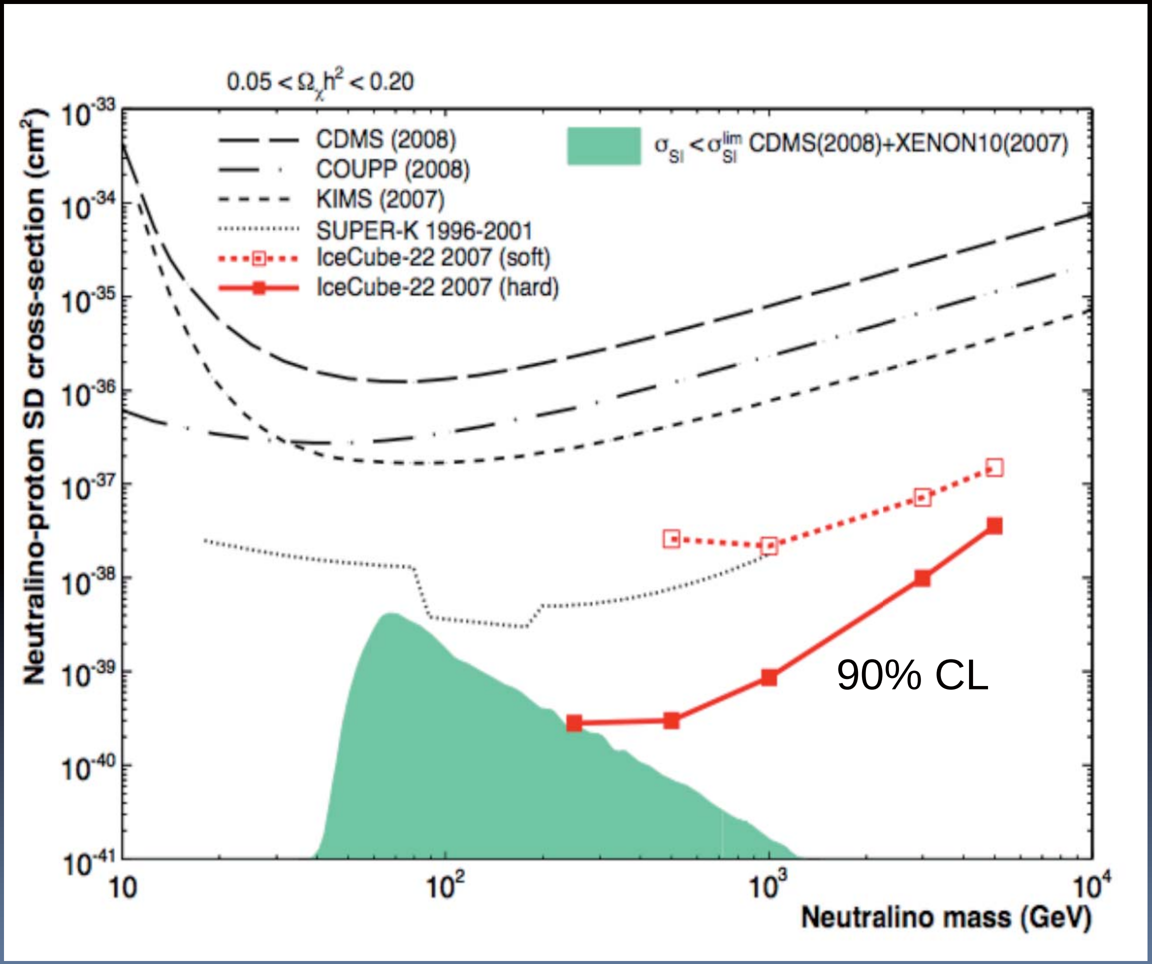


Abbasi et al., PRL, 2009

Neutralino Searches

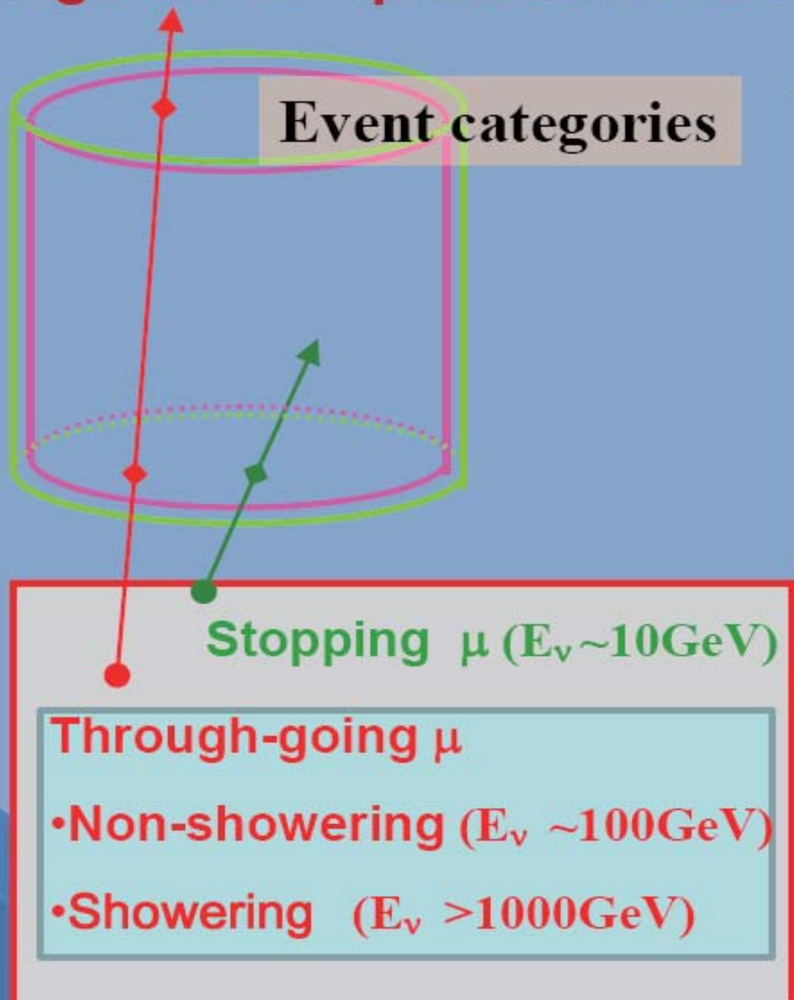
Spin dependent cross-section

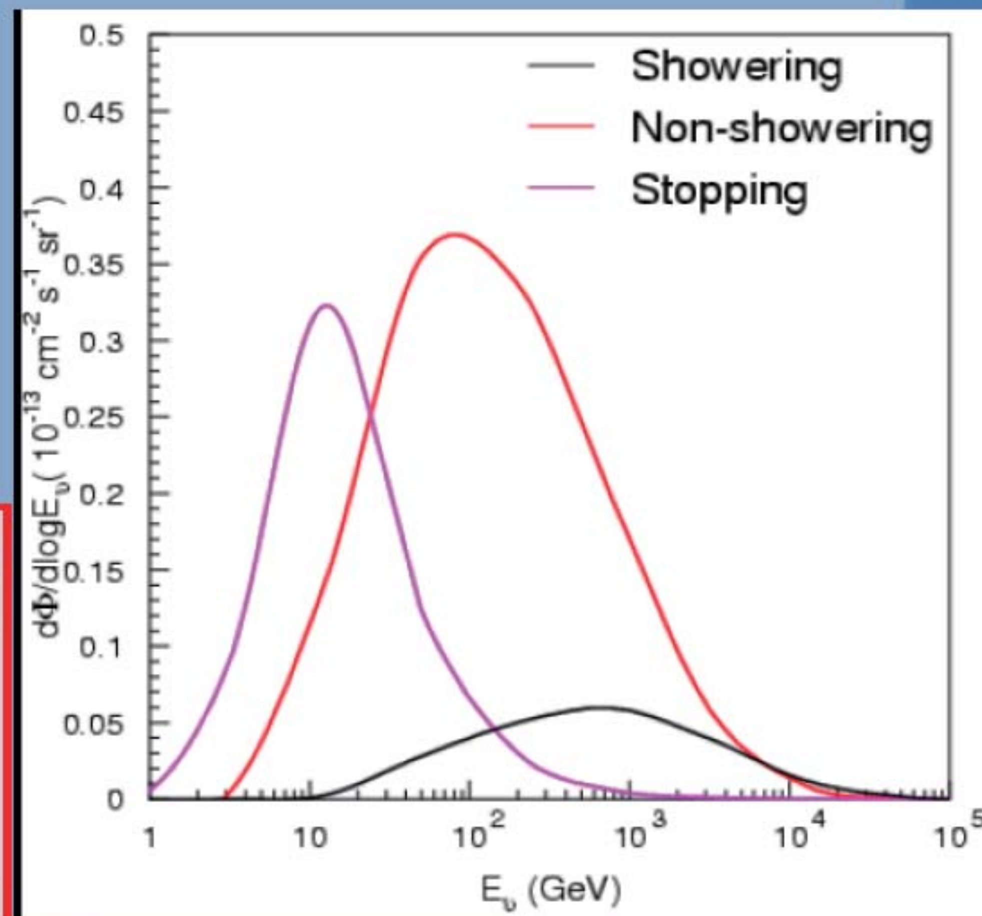
From flux to cross-sections:
(assuming capture rate C_C in equilibrium)



Upward going muon(upmu) event in SK

Upmu event was used for WIMP analysis. There are 3 categories of upmu event in SK.(Effective area ~ 1200 m^2)



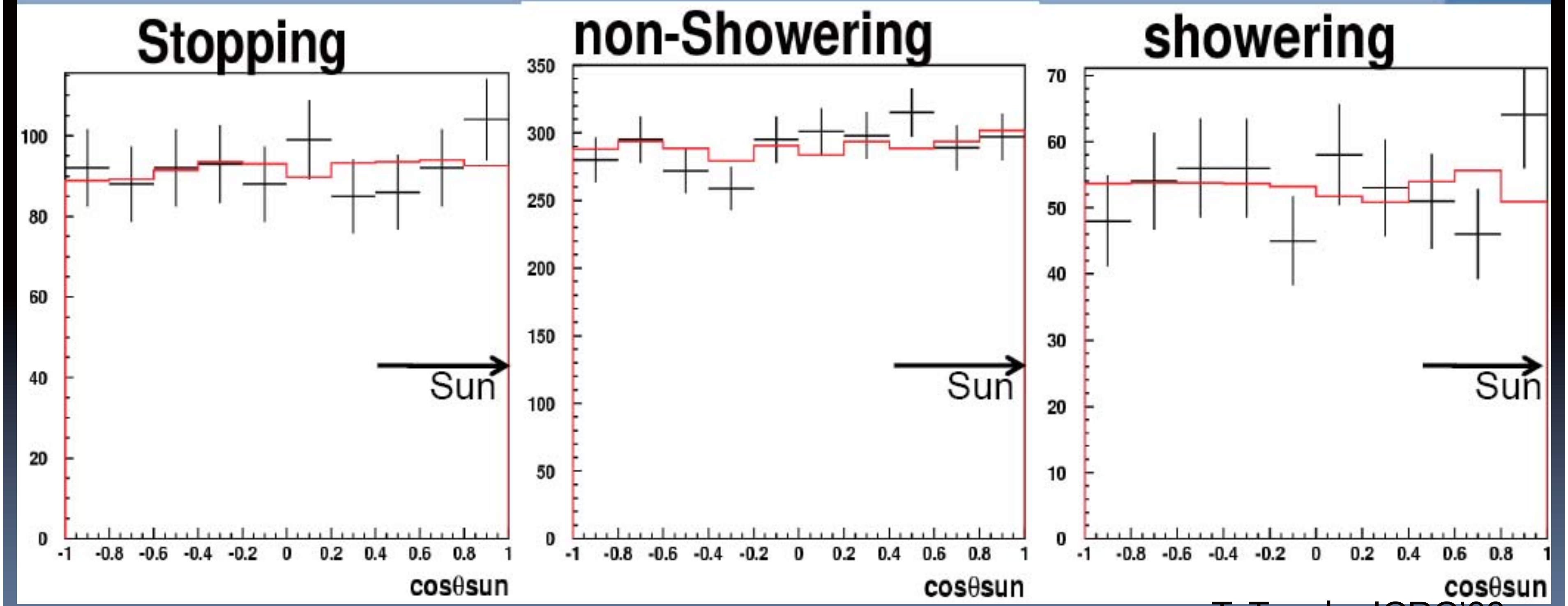


T. Tanaka ICRC'09

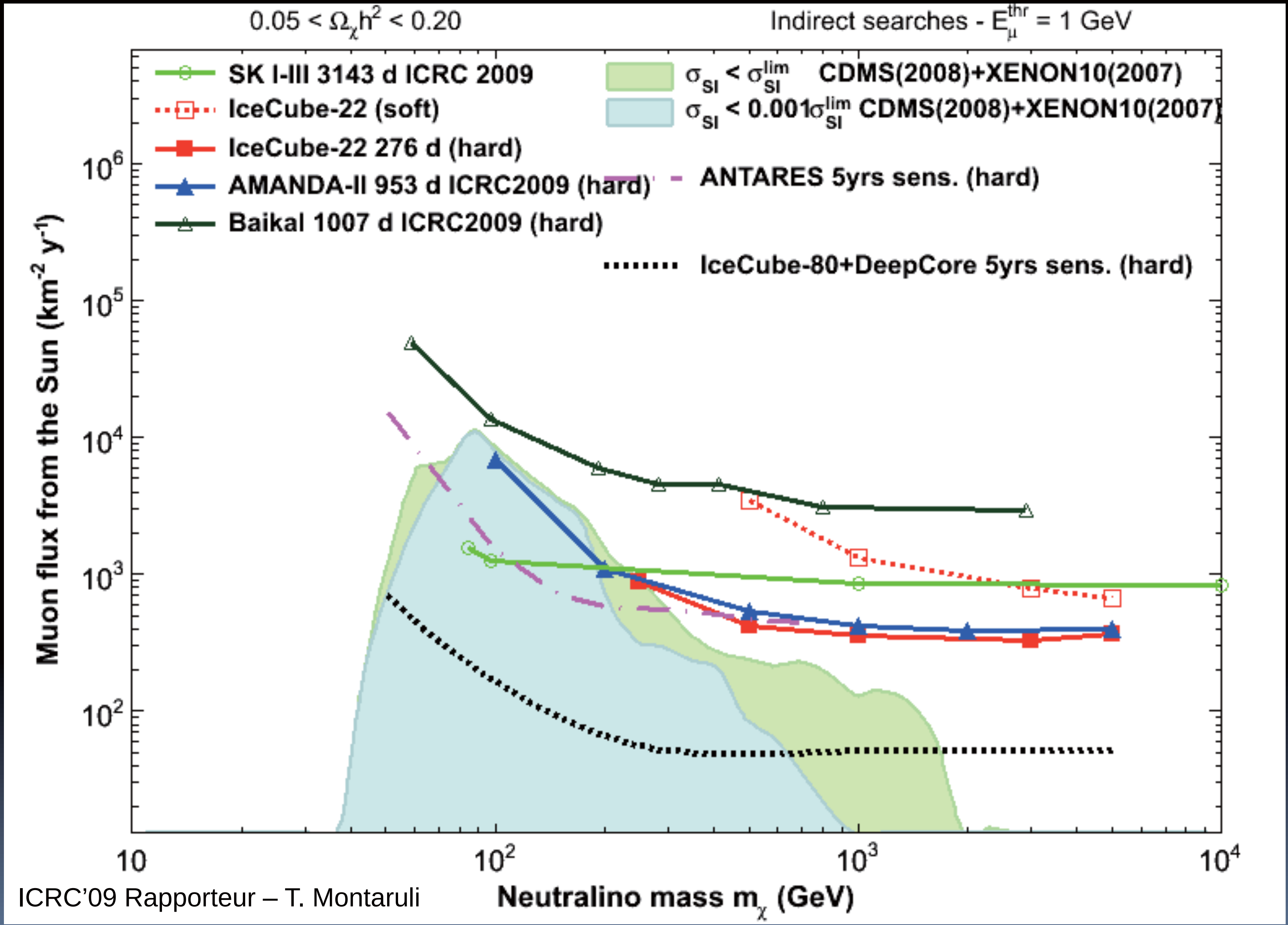
- SKI~III upmu samples (3149.2 days)
- Cos θ_{Sun} = 1 means the direction of the Sun

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



T. Tanaka ICRC'09



0.05 < Ωχh2 < 0.20
Indirect searches - Eμthr = 1 GeV
SK I-III 3143 d ICRC 2009
IceCube-22 (soft)
IceCube-22 276 d (hard)
AMANDA-II 953 d ICRC2009 (hard)
Baikal 1007 d ICRC2009 (hard)
σSI < σSIlim CDMS(2008)+XENON10(2007)
σSI < 0.001σSIlim CDMS(2008)+XENON10(2007)
ANTARES 5yrs sens. (hard)
IceCube-80+DeepCore 5yrs sens. (hard)
Muon flux from the Sun (km-2 y-1)
Neutralino mass mχ (GeV)
ICRC'09 Rapporteur – T. Montaruli

Kaluza Klein Dark Matter

From Universal Extra Dimension theories

- 2 free parameters, R and cutoff scale L.
- finite space dimension → momentum is quantized
- p = *n*/R which can be interpreted as mass = *n*/R

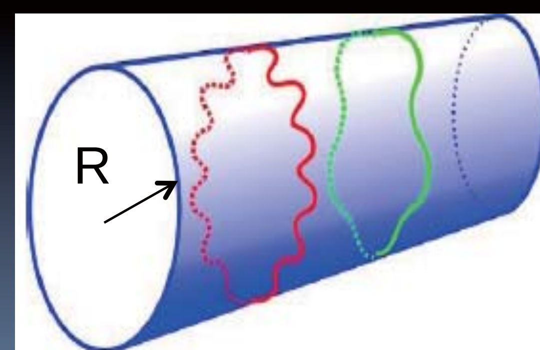
→ tower of mass eigenstates.

The lightest is stable → candidate for dark matter

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

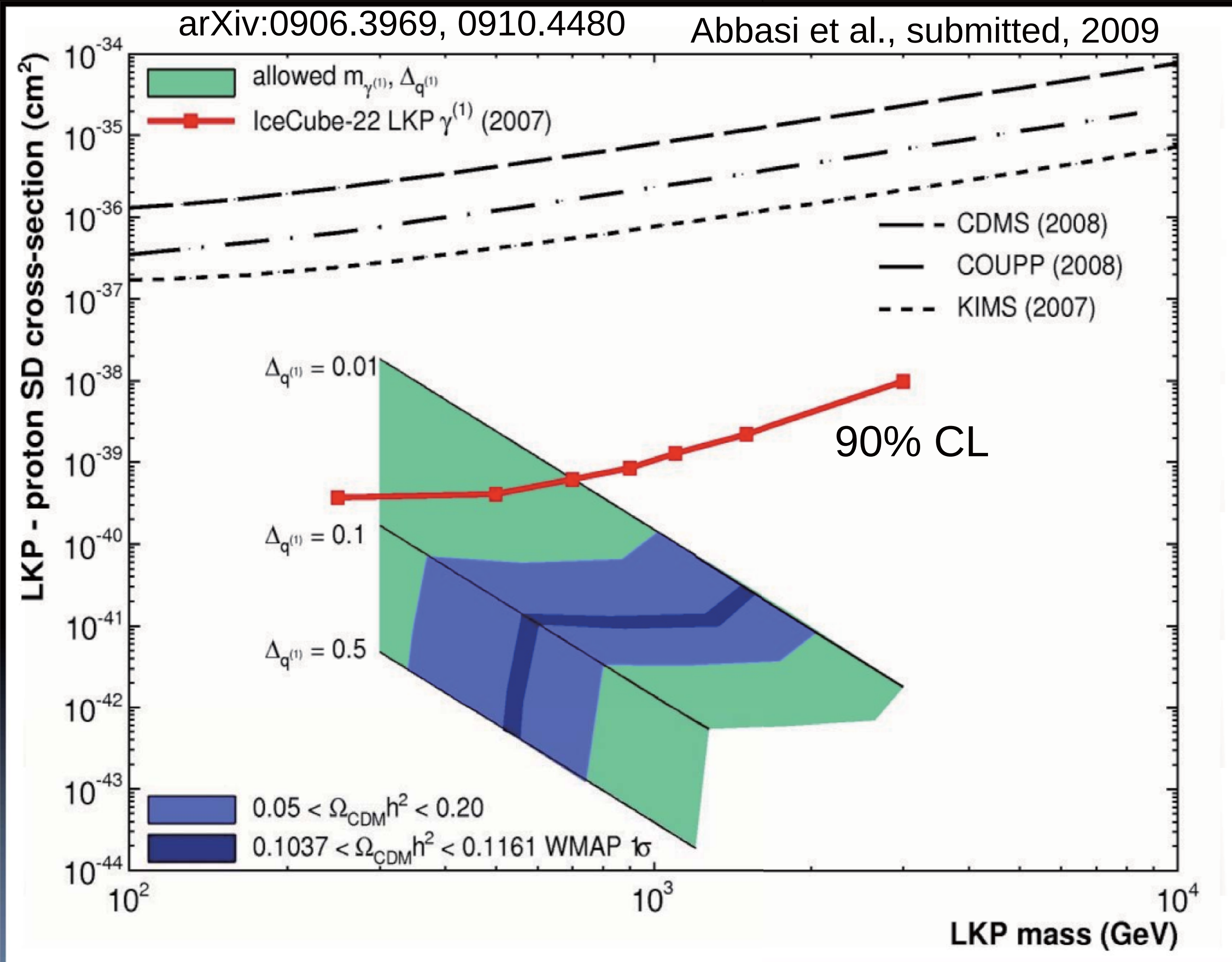
TABLE I
POSSIBLE CHANNELS FOR THE PAIR ANNIHILATION OF $B^{(1)}B^{(1)}$ AND BRANCHING RATIOS OF THE FINAL STATES. FIGURES TAKEN FROM [20].

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



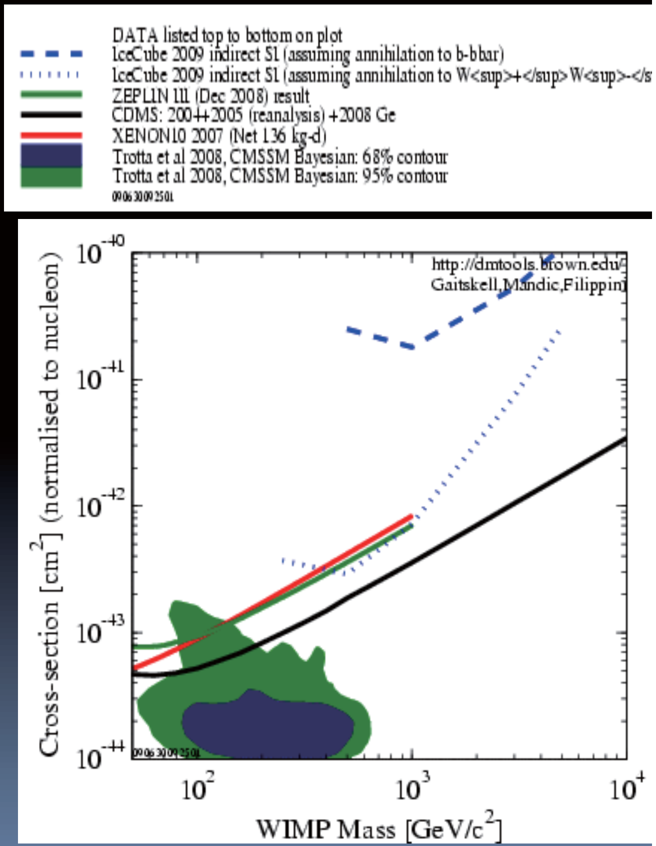
See D.Hooper and S.Profumo, Phys. Rep. 453, 29, (2007)
See talk from Seong Chan Park

Kaluza Klein Dark Matter



Summary Solar WIMPs

- Neutrino Telescopes can provide stringent limits on the WIMP-nucleon scattering cross-section
  - Extremely competitive for spin-dependent cases
  - Spin-independent constraints not too bad (and we get them for free)



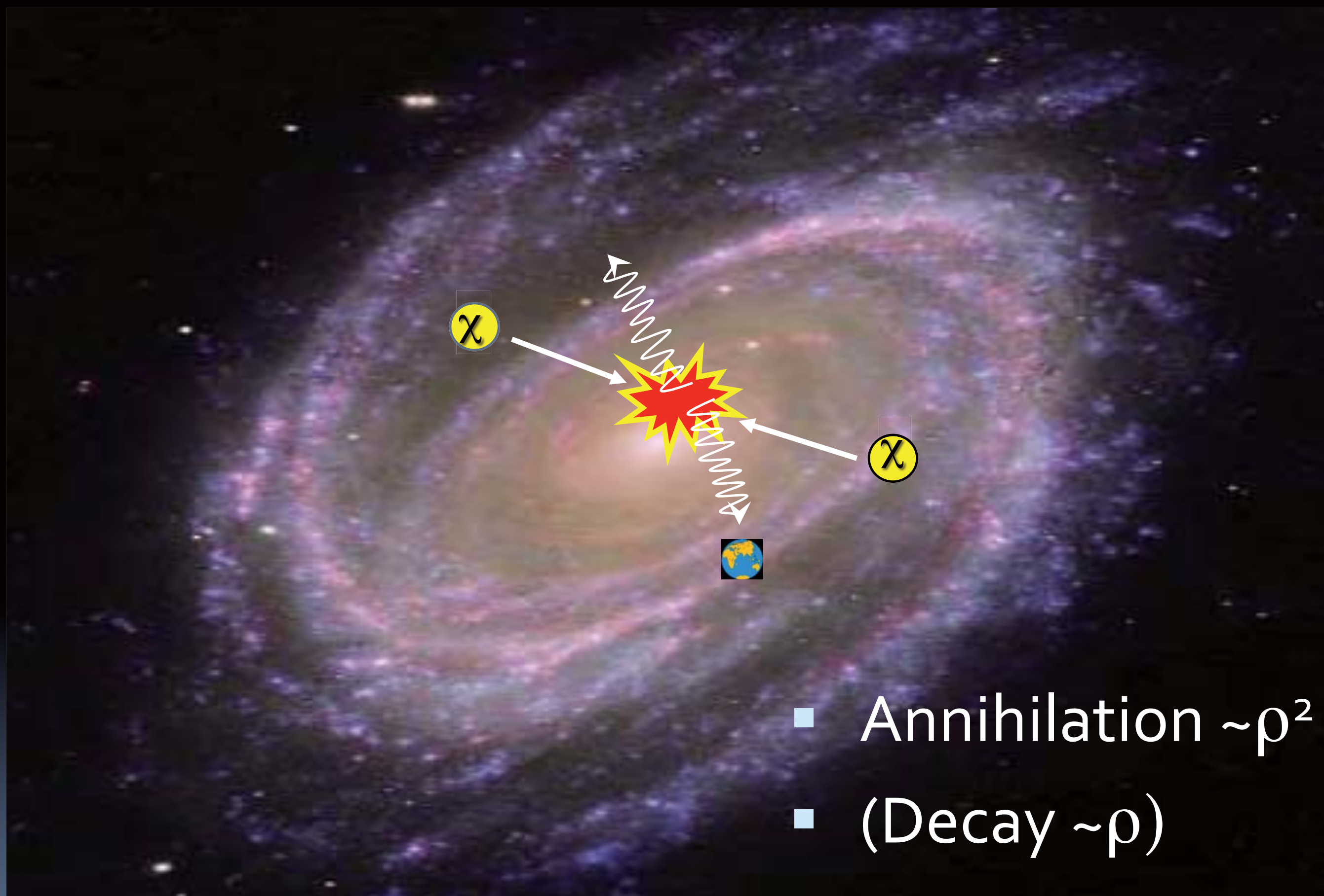
Dark Matter Self -annihilation cross -section

Searches Strategies

- Galactic Center
  - Large halo profile uncertainty
  - Other sources ?
  - *Bengtsson et al.'90, Berezinsky et al. '94, …*
- Dwarf Satellite Galaxies
  - High M/L, many within 100kpc
  - *Bergstrom '06, Profumo '06, Sandick et al.'09, …*
- Milky Way Halo
  - Large scale anisotropy
  - Less profile dependence
  - *Yuksel et al. '08, (see Poster from Surav Mandal)*

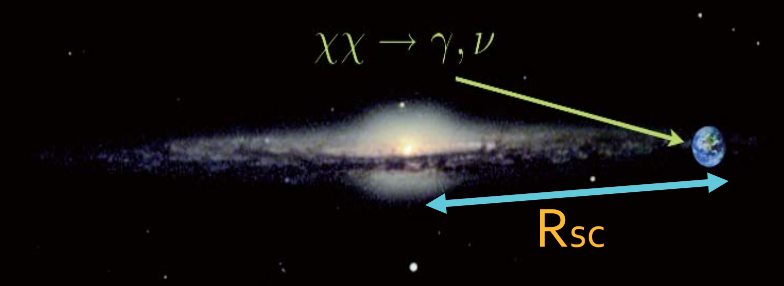
…

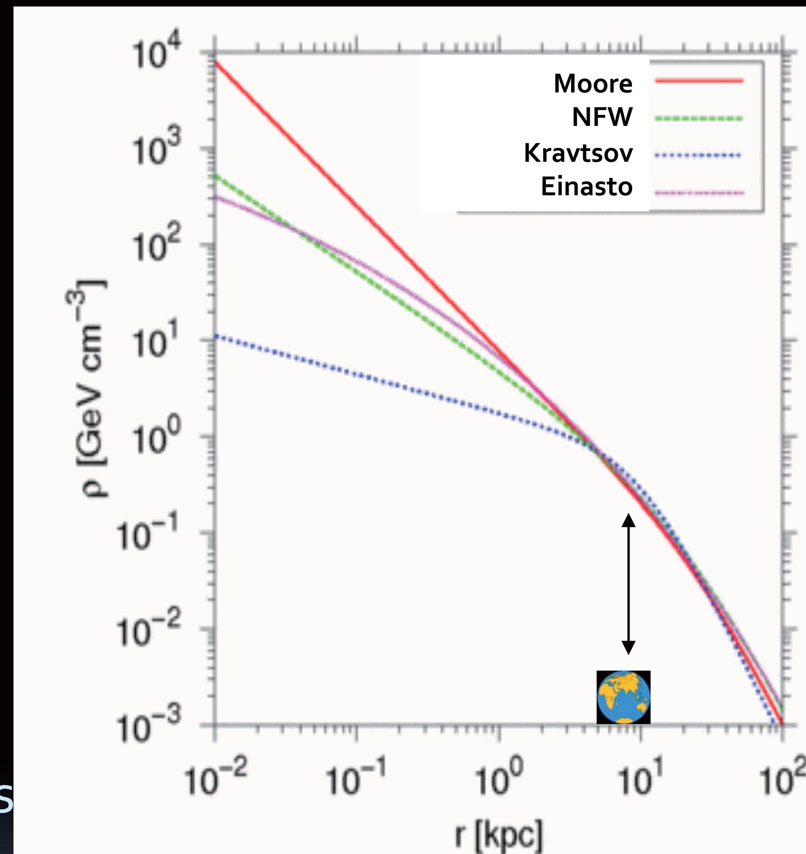
Milky Way Halo - IceCube Sensitivity



- Annihilation ~ρ^2
- (Decay ~ρ)

Halo Profiles





Moore, NFW, Kravtsov

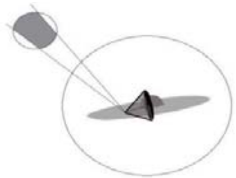
$$\rho(r) = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

γ - cusp
r_s - scale radius
R_{sc} - 8.5kpc

	α	β	γ	r_s	$\rho(R_{sc})$
Moore	1.5	3	1.5	28	0.27
NFW	1	3	1	20	0.3
Kravtsov	2	3	0.4	10	0.37

Einasto

$$\rho(r) = \rho_{-2} exp\left(\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]\right)$$



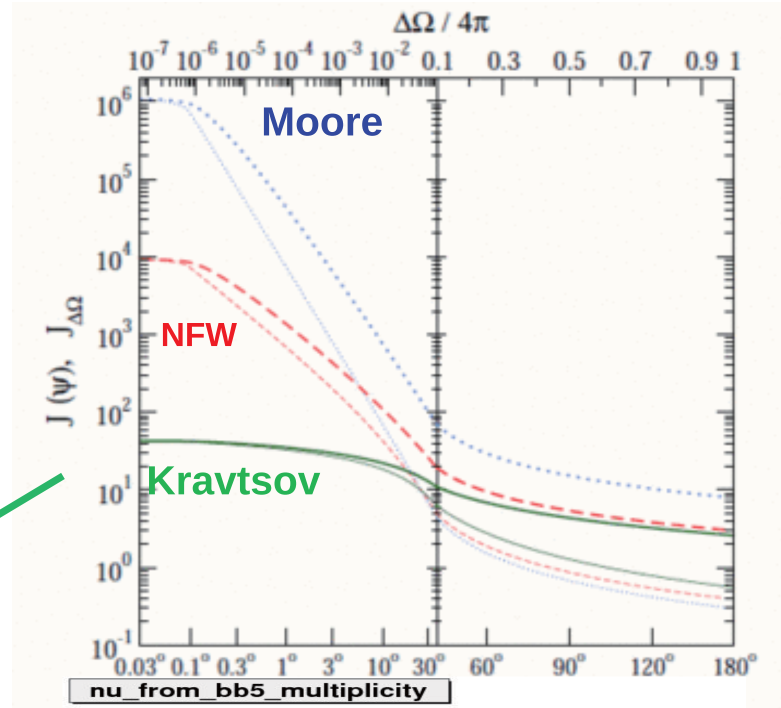
Halo WIMPs

Line of sight integral:

$$\ell_{max} = \sqrt{(R_{MW}^2 - \sin^2\psi R_{sc}^2)} + R_{sc}\cos\psi$$

$$\mathcal{J}(\psi) = \frac{1}{R_{sc}\rho_{sc}^2}\int_0^{\ell_{max}} \rho^2\left(\sqrt{R_{sc}^2 - 2\,l\,R_{sc}\cos\psi + l^2}\right) d\ell$$

$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\cos\psi}^{1} \mathcal{J}(\psi')\,2\pi\,d(\cos\psi')$$



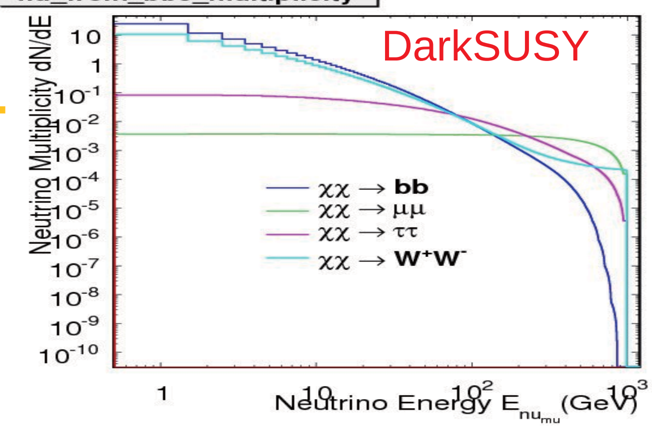
Expected differential neutrino Flux:

$$\frac{d\Phi}{dE} = \frac{<\sigma_A v>}{2} J(\psi)\frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2}\frac{dN}{dE}$$

?

Measure integrated flux

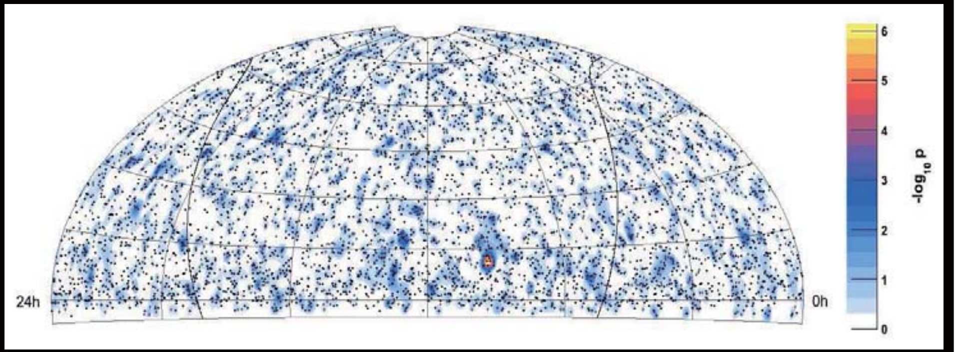
Isotropic emission



Carsten Rott

Event selection / dataset

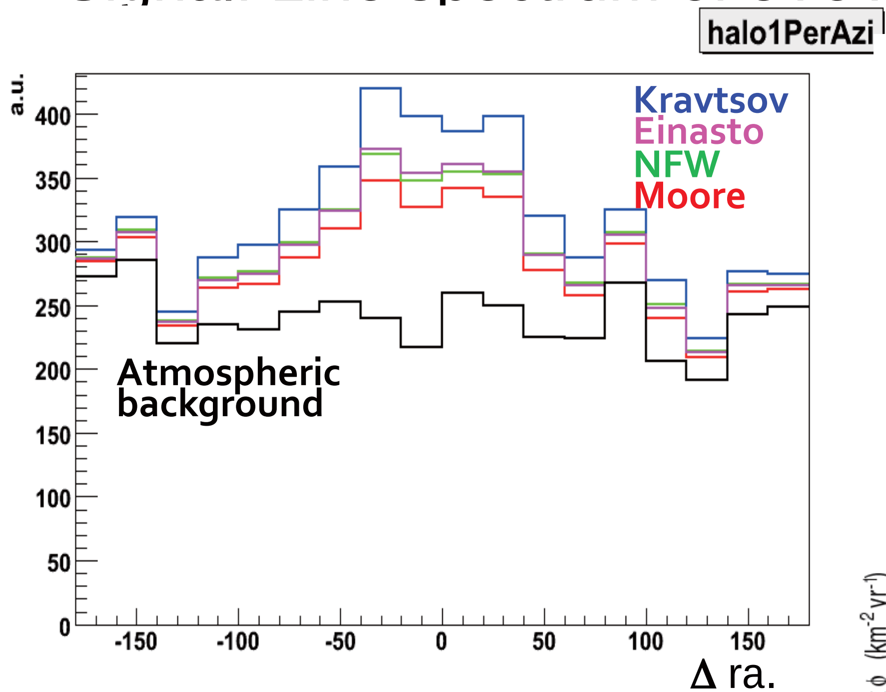
- 275.7 days of livetime collected with IceCube operating in the 22-string configuration (2007-2008)
- 5114 Events after selection from -5° to +85° declination
- Track selection criteria have been well established for the IceCube point source search, for simplicity and minimization of systematic effect we apply the same selection criteria (**Astrophys.J.701:L47-L51,2009**.)

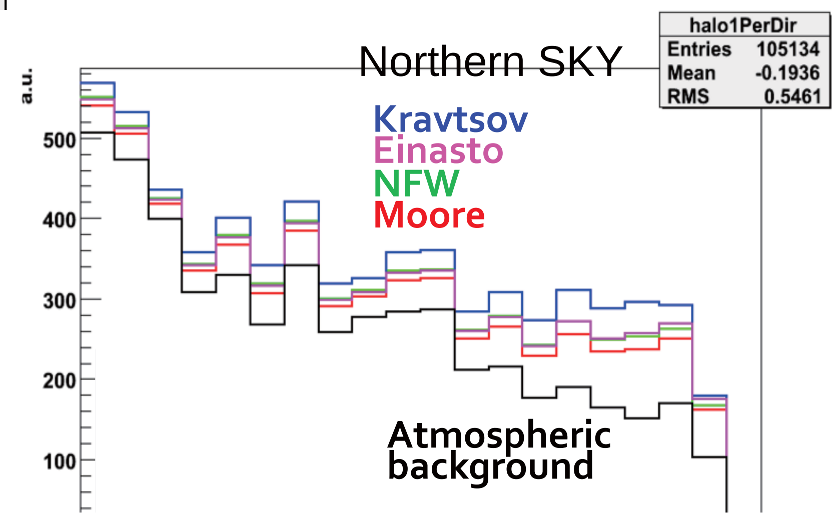


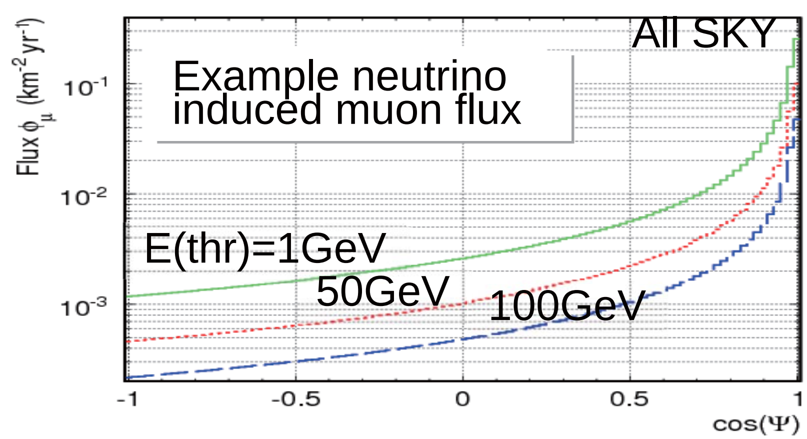
- No energy weighting factors have been applied
- The following slides are for simulation, matching the IC22 dataset.
- We compute the sensitivity based on this dataset

Halo Profile Dependence

- Background MC scaled 5114 events
- Signal: Line spectrum of 5TeV WIMP



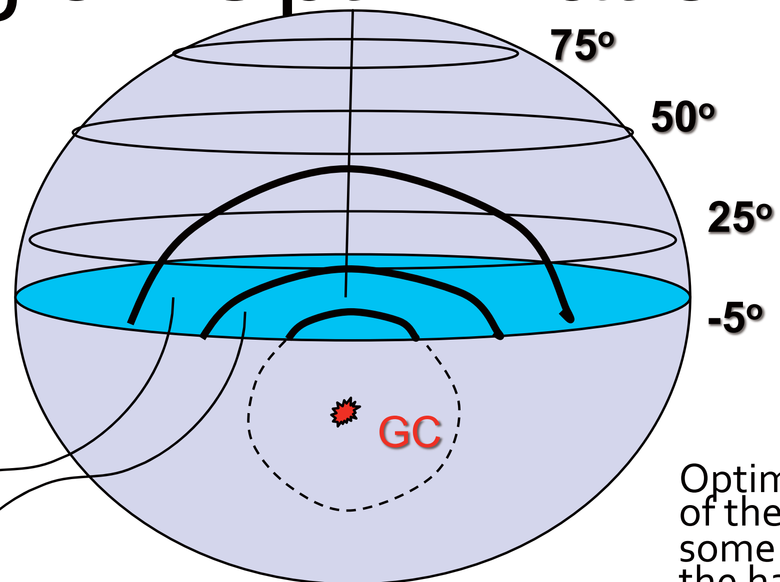


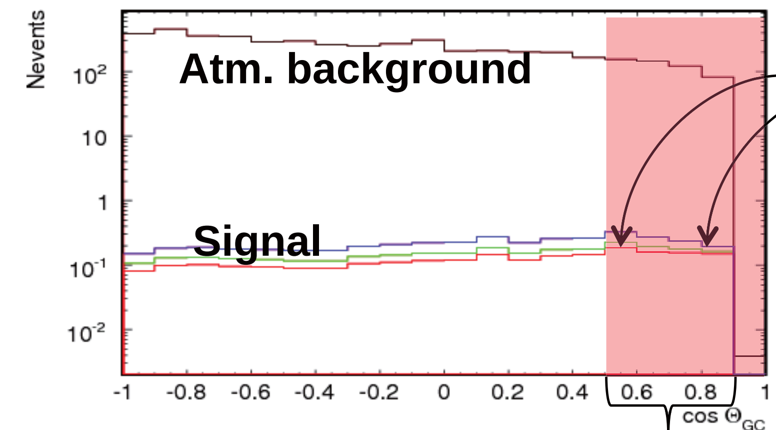


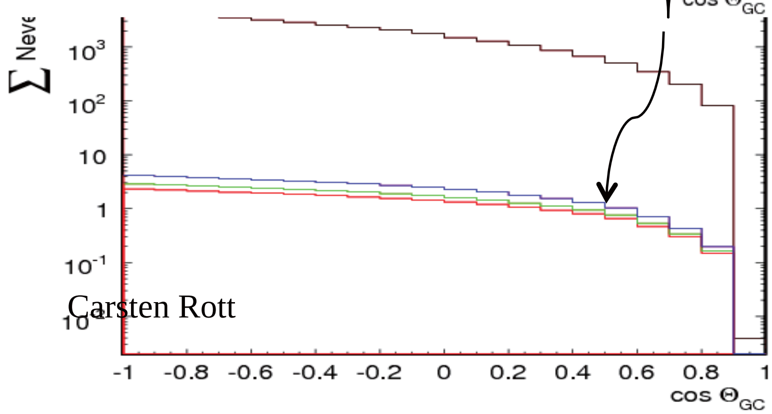
Signal has varying intensity, while background is essentially "flat"

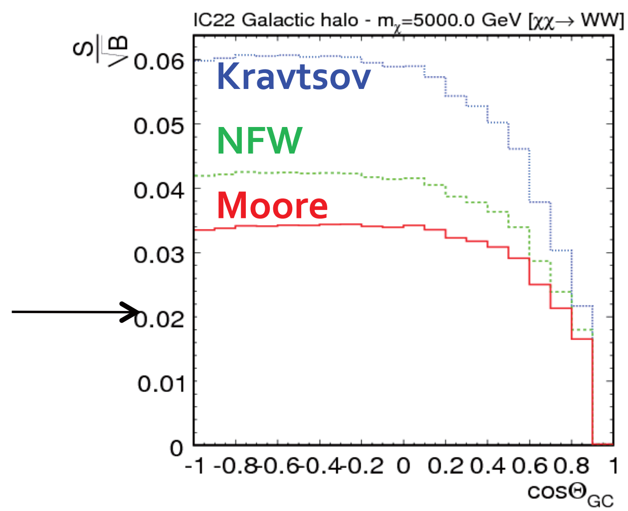
Signal Region Optimization

- Calculate flux signal flux as function of the distance to the GC on Northern Hemisphere (-5° – 85°)
- Optimize $S/\sqrt{(B)}$









Optimal signal extend of the region shows some dependence on the halo model, annihilation channel and WIMP mass.

Their overall behavior is however very similar:

Larger regions are better and S/sqrt(B) flattens out or declines beginning with $\Delta\theta_{GC}$~80°

Analysis Strategy

- Three regions:
  - on-source
    - "signal region"
  - transition
    - "control region"
  - off-source
    - "background estimate"
- Symmetric on/off source region
  - simplistic approach
  - minimize systematic uncertainties

- Muon neutrinos on Northern Hemisphere
- Less dependent on halo profile
- Look for an excess of events in the on-source region with respect to the off-source
- Set limit on the self-annihilation cross section

$$\frac{d\Phi}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

Measure

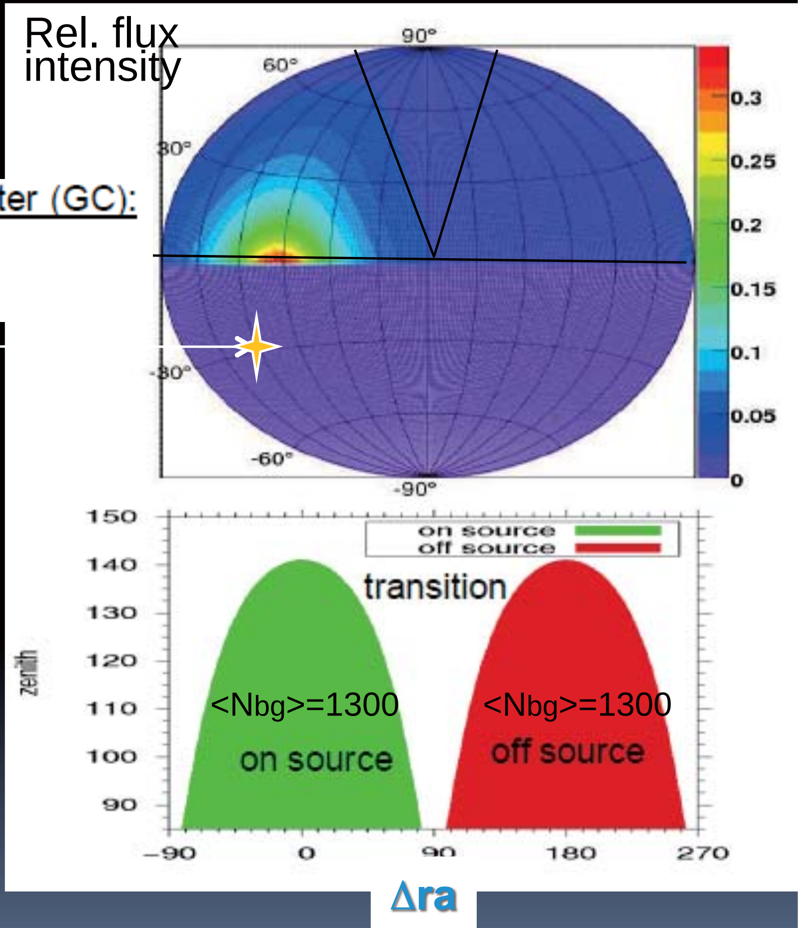
Halo Model

Theory

Galactic Center (GC):

R.A.=277°

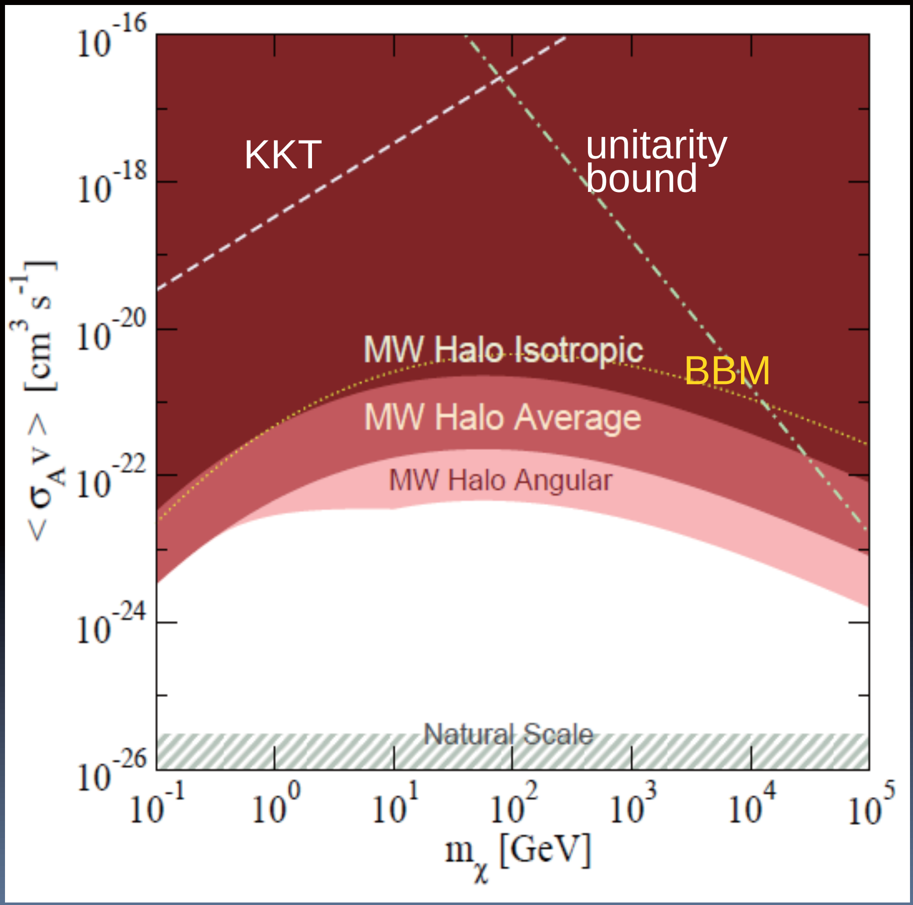
Θ = -28°



Rott , CCAPP Symposium 09

How large can the self-annihilation cross-section $\langle\sigma_A v\rangle$ be ?

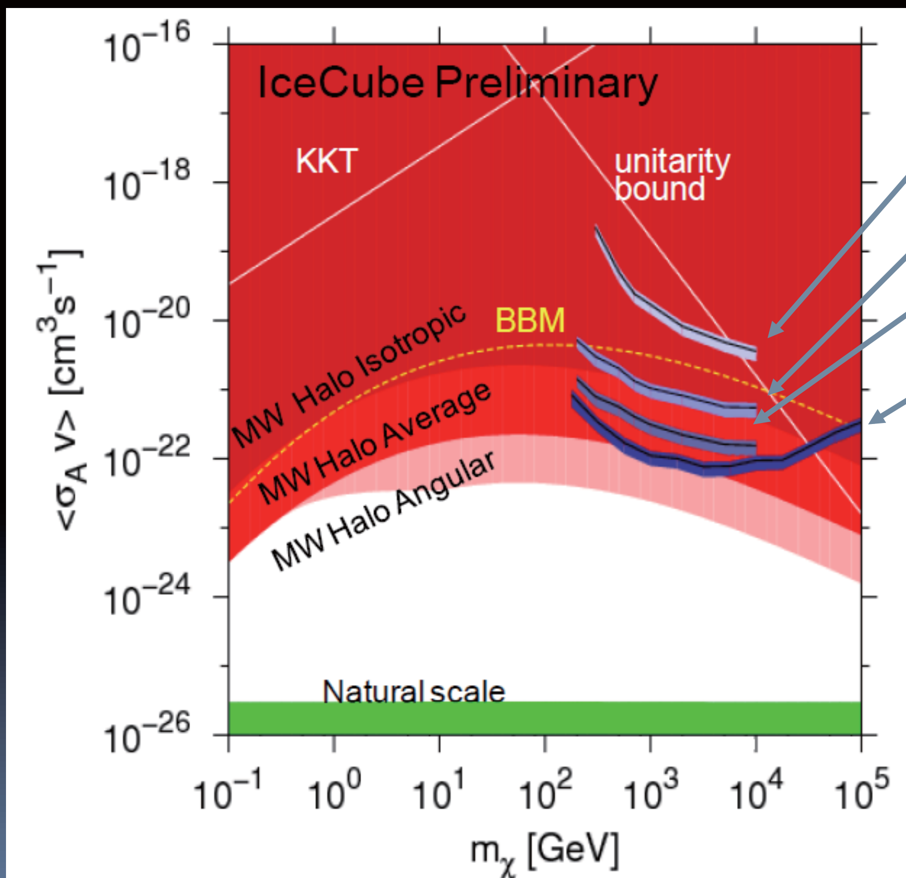
Yuksel, Horiuchi, Beacom, Ando (2007)



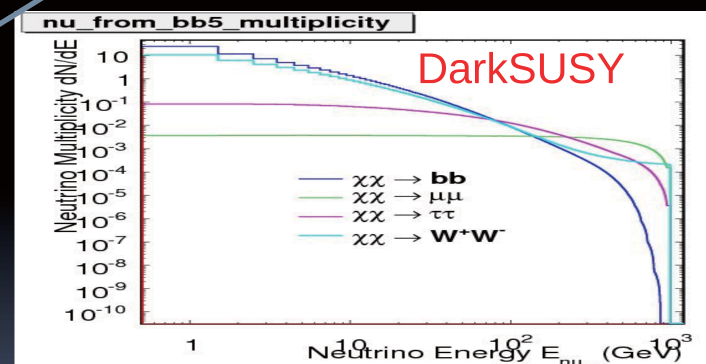
- Theoretical/cosmological constraints:
  - KKT - Kaplinghat, Knox, Turner (2000)
    - "DM annihilation flattens cusp"
  - Unitarity bound
    - Unitarity of the scattering matrix
  - Natural scale
    - DM is thermal relic of early universe
- Derived limits/sensitivity:
  - BBM - Beacom, Bell, Mack (2008)
    - Cosmic time-integrated annihilation
  - MW Halo Isotropic
    - $J(\psi=\pi)$(immediate neighborhood)
  - MW Halo Average
    - Average flux from halo
  - MW Halo Angular
    - 30° cone around GC

IceCube 22-string Sensitivity

- Average upper limit at 90%C.L.
  - ΔN_{90} = 65.2 events (This is a limit on the difference between on and off-source)



soft(bb)
hard(WW)
hard(μμ)
line (νν)



Line width:
– Uncertainty due to halo profile
Central line:
- Einasto

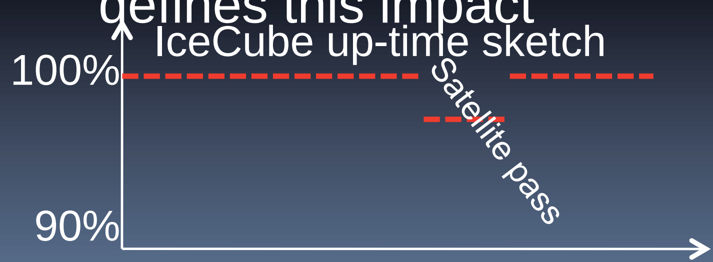
Systematic uncertainties

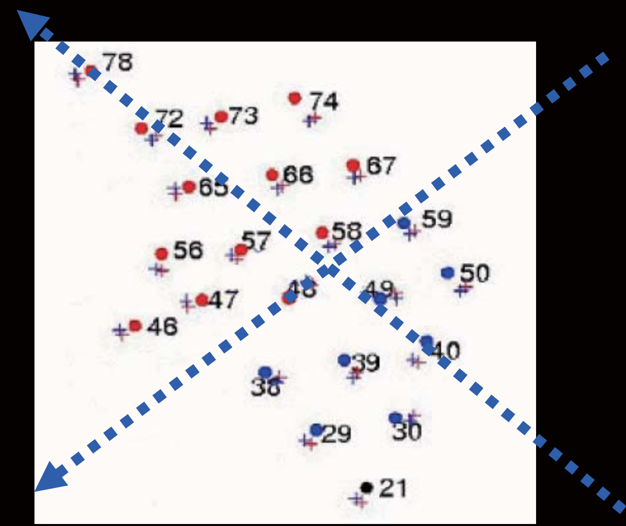
- Signal acceptance:
  - Uneven "exposure" (negligible)
  - Ice properties / DOM efficiency (~20%)
  - MC/data disagreement (horizontal events)

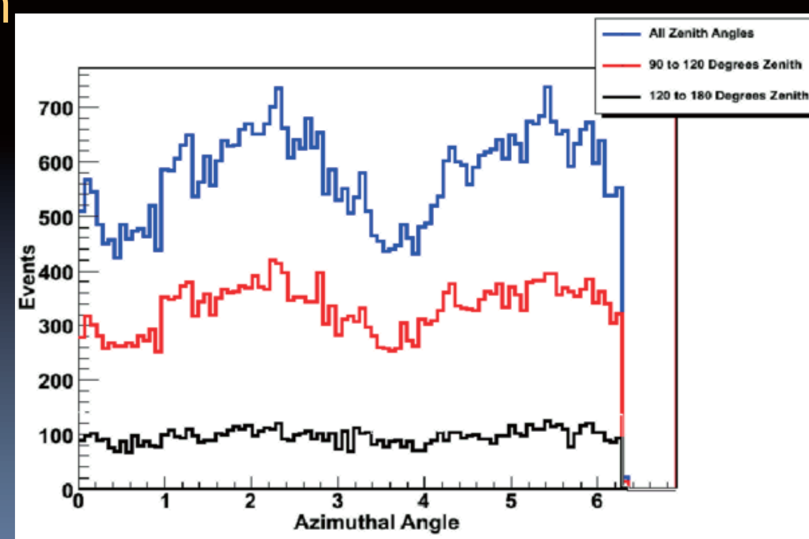
- Background:
  - Majority of systematics cancel out (as we use the data itself)
  - "existing" large scale anisotropy
    - - Uneven "exposure"
    - - Neutrino anisotropy caused by cosmic ray anisotropy

Uneven Exposure

- Track reconstruction efficiency varies in detector coordinates
- In equatorial coordinates this reconstruction efficiency is smeared out (as the detector rotates)
- Uneven detector up-time can however reduce this smearing effect
- Detector down-time correlates with satellite visibility (maintenance mode)
- Detector uptime in sidereal days defines this impact

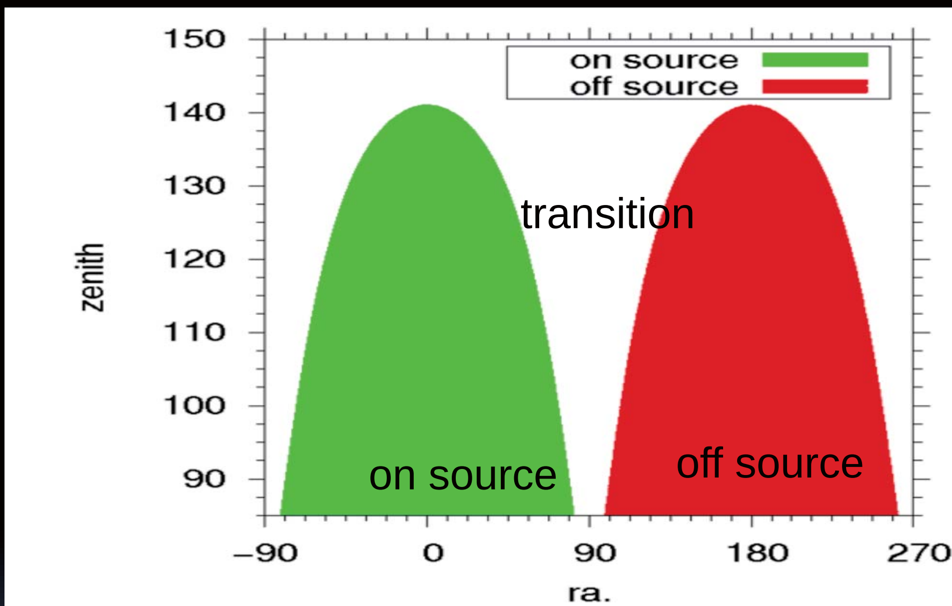


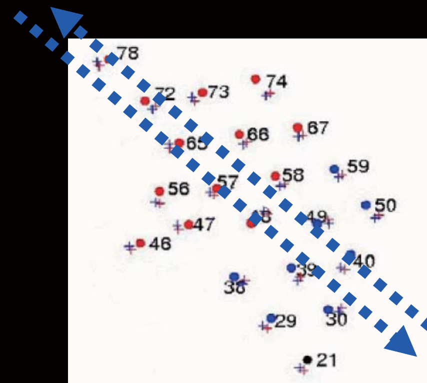


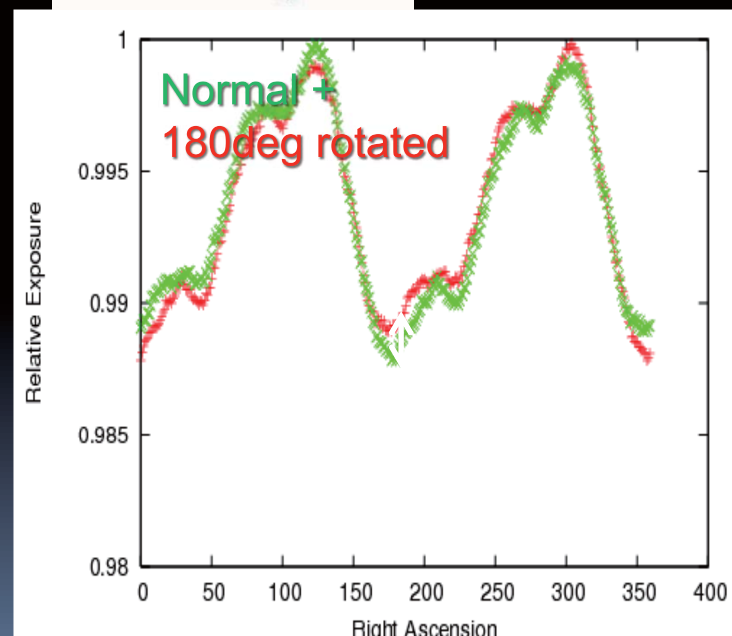


Uneven Exposure

- Track reconstruction efficiency shows “mirror symmetry”

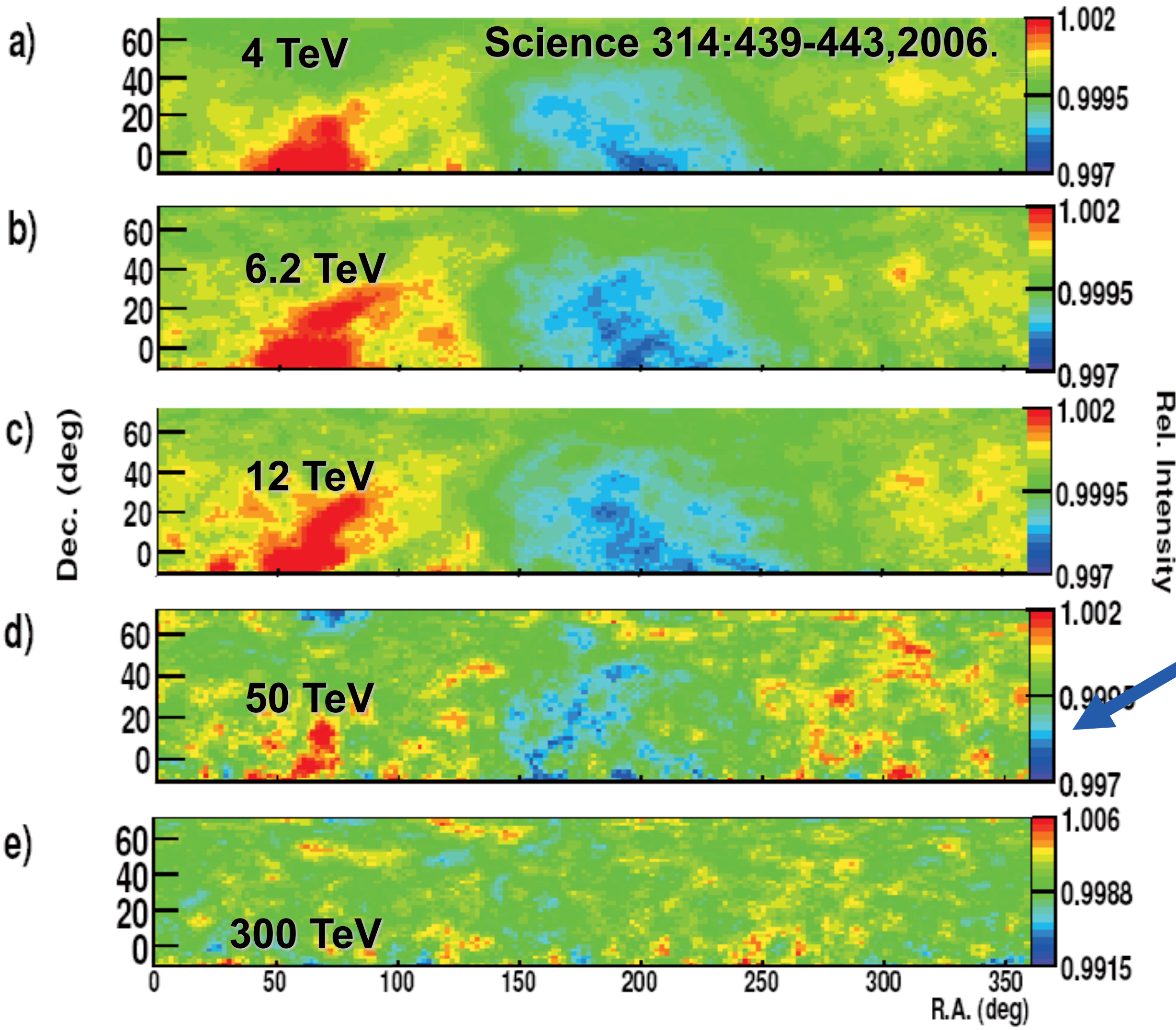






- Uneven exposure systematic uncertainty is on the order of the difference between the two graphs ~0.1%
- **Total systematic effect ~ 3%**

Celestial Cosmic Ray intensity map at different energies (TIBET)



Neutrino energy is roughly 1/10-1/30 of the shower energy (cosmic ray primary)

most relevant energy region

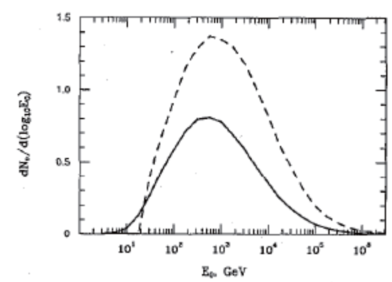


FIG. 1. Primary cosmic-ray nucleon energy contribution to the upward-going neutrino induced muon flux (E_μ >1 GeV). The solid line is for $\cos(\theta)=-1$ and the dashed is for $\cos(\theta)=-0.15$.

Phys.Rev.D53:1314-1323,1996.

See also Abbasi et al ICRC'09

Cosmic Ray Anisotropy

- Cosmic ray anisotropy could also cause anisotropy in atmospheric neutrinos
- At relevant energies the anisotropy of cosmic rays is a fraction of a percent
- On/off-source region has a background expectation of 1300 neutrino candidate events
- For an anisotropy of 0.2%, a maximum effect of 2.6events -> 4% syst. uncertainty can be expected

IceCube Halo Summary

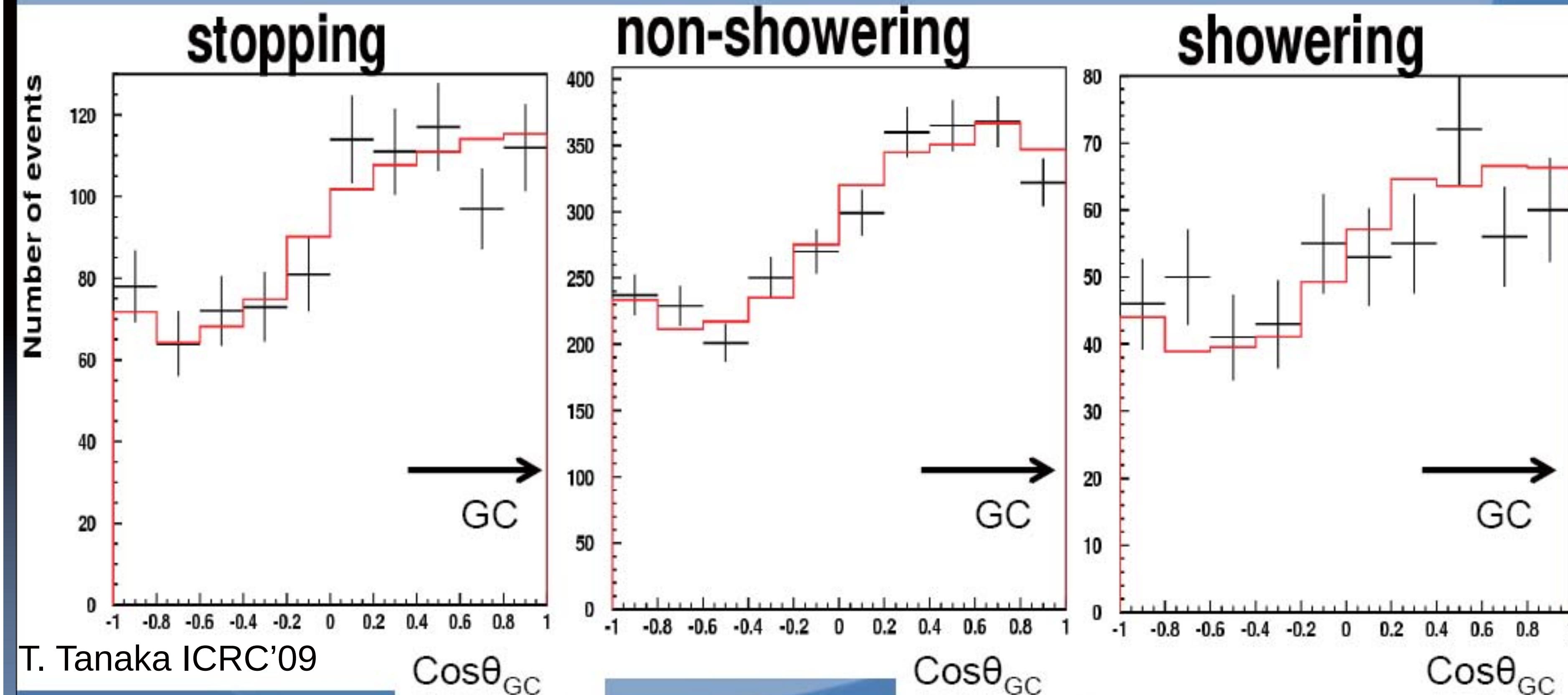
- Neutrino Telescopes can probe Dark Matter self-annihilation cross-section
- Computed IceCube's sensitivity to Galactic halo WIMPs, using the IC22 string up-going neutrino sample
- IceCube will be able to set very completive constraints on the Dark Matter self-annihilation cross-section $\langle\sigma_A v\rangle$
- Preliminary study of systematics shows they are well under control
- DeepCore and the larger IceCube detector will have significantly improved sensitivities

Cos θ_{GC} distribution (using upmu samples) SKI+II+III (3149.2 days)

Here, Cosθ_{GC}=1 is the direction of the GC

No significant excess of data was seen...

Red:Atmospheric ν MC
(with oscillation)
$\sin^2 2\theta=1$, $\Delta m2=2.5\times10^{-3}$ eV
Cross: data



T. Tanaka ICRC'09

Searches in neutrino telescopes: SuperK

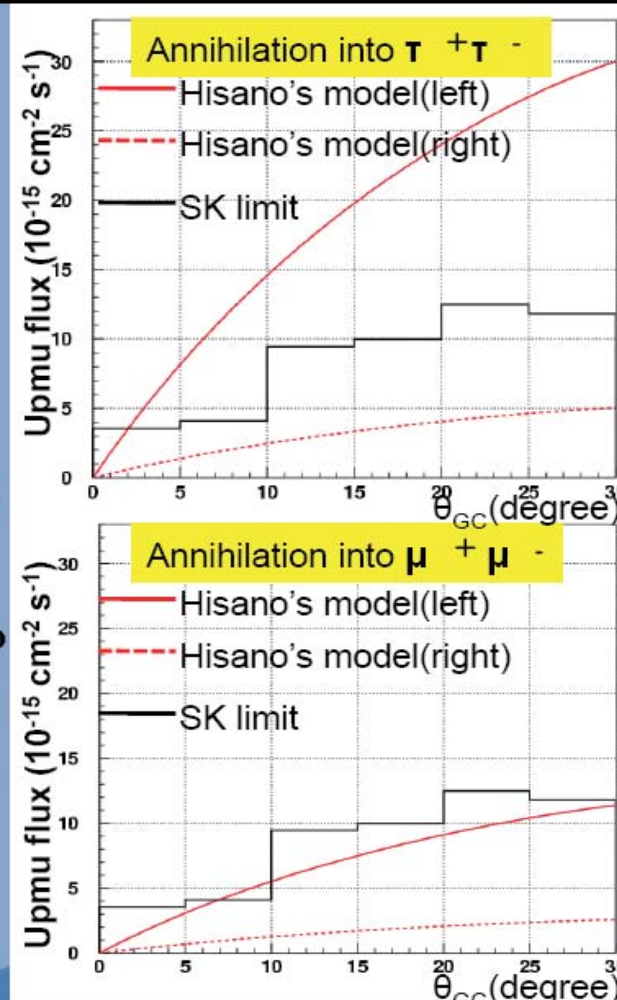
Upmu flux limit from GC and comparing with Hisano's model

θ_{GC}	Upmu flux limit ($\times 10^{-15}$ cm^{-2} sec^{-1})
10°	4.11
20°	9.99
30°	11.81

This SK upmu flux limit is compared with the expected upmu flux limit from the Hisano's model.
The WIMP mass and annihilation rate(into lepton pair) which can explain PAMELA excess are estimated in this model.

Hisano et.al. Phys.Rev.D79(2009)043516

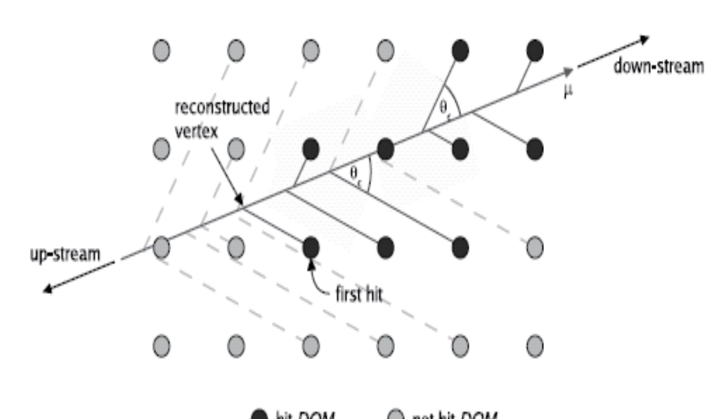
Some scenario of Hisano's model such as annihilation into left handed $\tau^+\tau^-$ can be excluded by SK upmu



Tanaka ICRC'09

Halo Summary Outlook

- SuperK can already rule out DM model motivated by lepton excess
- IceCube 22 string sensitivity for galactic halo WIMPs has been evaluated
- Data is available and analysis is getting finalized
- Beginning with the IceCube 40 string configuration, a starting track filter has been active
  - This allows to probe the Galactic Center directly
    - Halo WIMP sensitivity is expected to be significantly larger
    - Larger uncertainty due to halo models



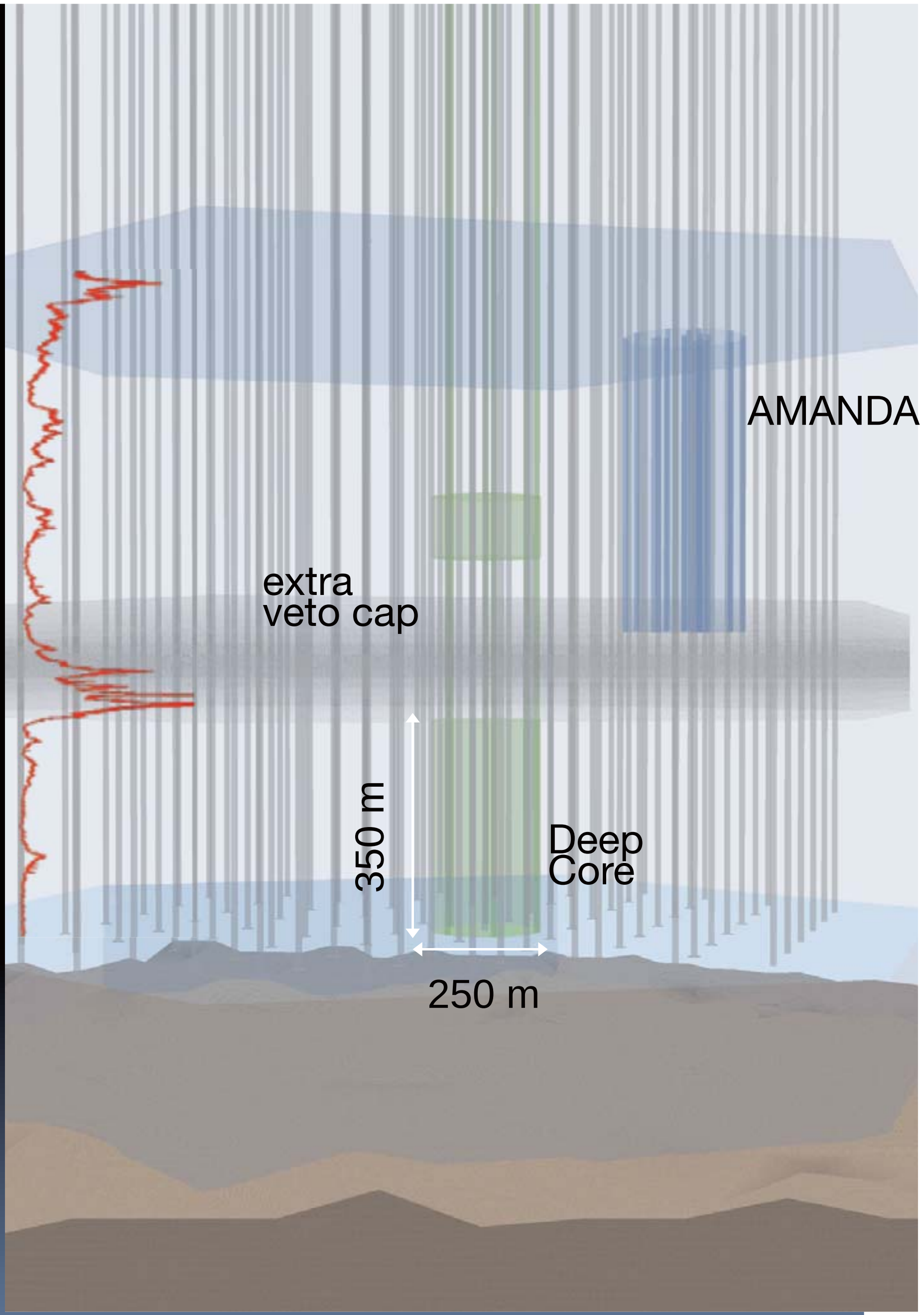
Principle of veto reconstruction
(Schulz, Euler, Grant, ICRC 2009)

Deep Core

Deep Core

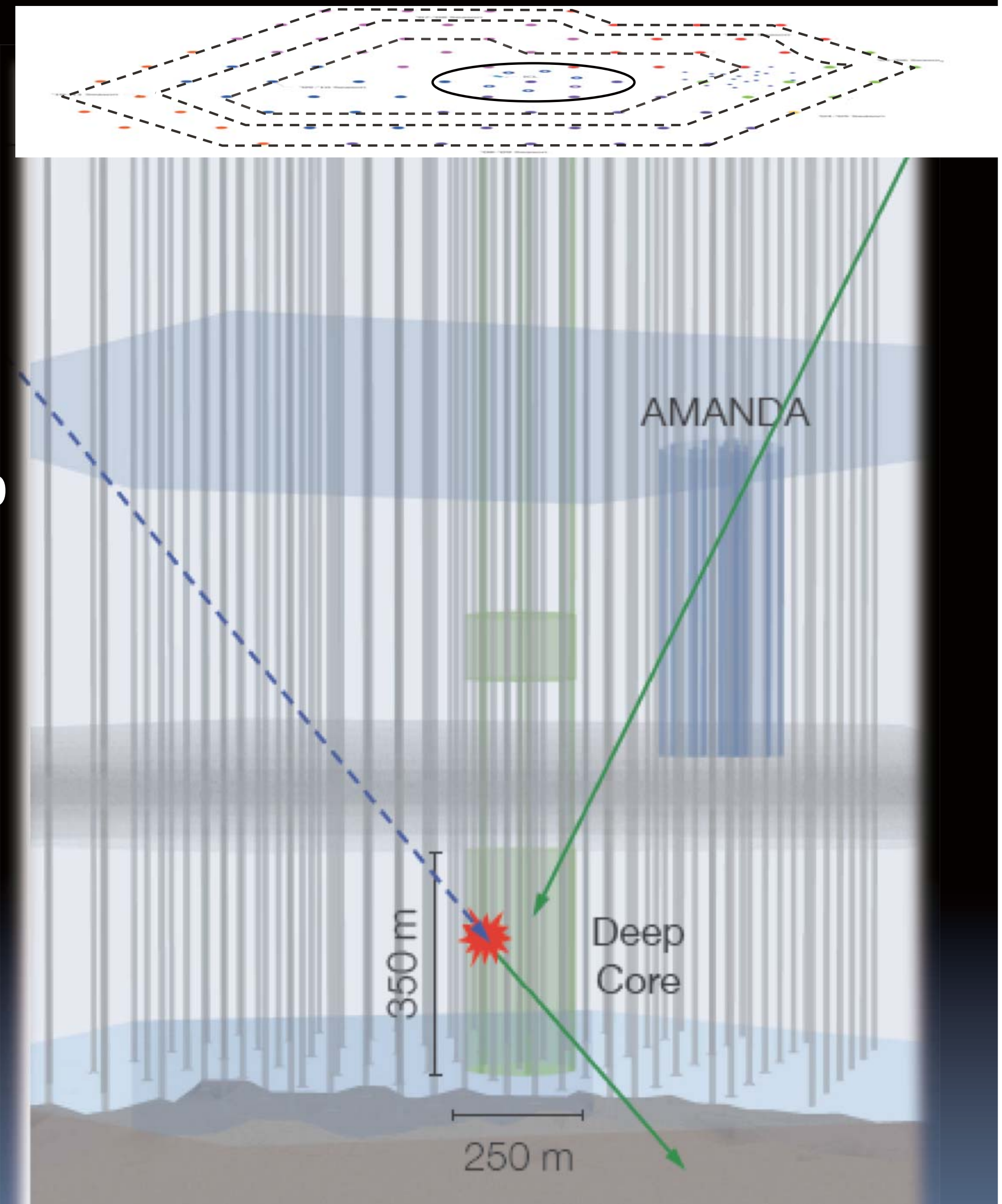
- Six special strings plus 7 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing on string
  - High Q.E. PMTs (40% better)
  - ~10x higher eff. photocathode density

  - Deep Core is currently being constructed and will become operational in spring 2010
- Clearest ice below 2100 m
  - $\lambda_{atten} \approx$ 40-45 m



Veto

- Top and outer layers of IceCube can be used to veto down-going muons
  - By 2011 there will be 3 veto string layers surrounding Deep Core
- Look for starting events in Deep Core
- Veto rejection power:
  - ~10^4 demonstrated with 98% signal eff.
  - ~10^5-10^6 likely

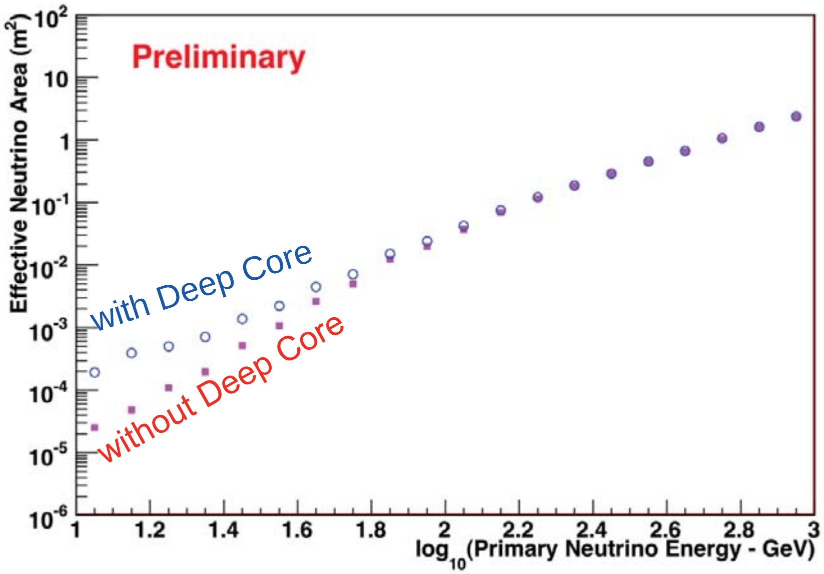


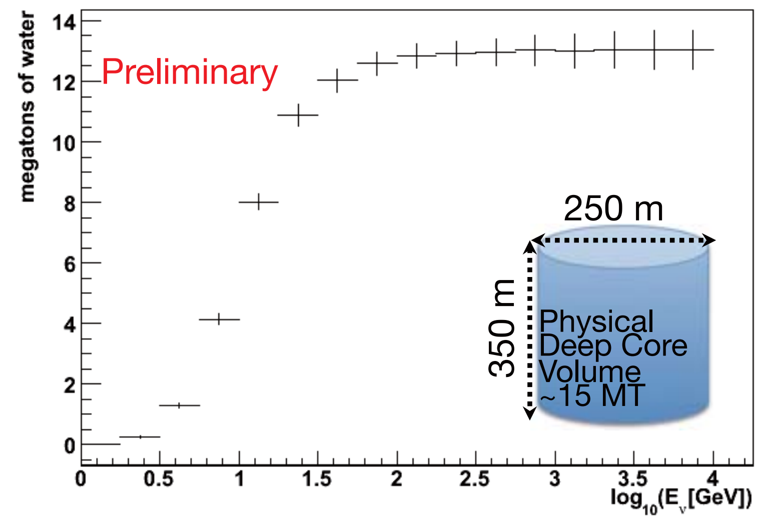
C.Wiebusch [IceCube] ICRC'09

Deep Core Effective Area & Effective Volume

Effective area for up-going ν_μ at trigger level

Reconstruction efficiencies not included yet – relative improvement likely to increase





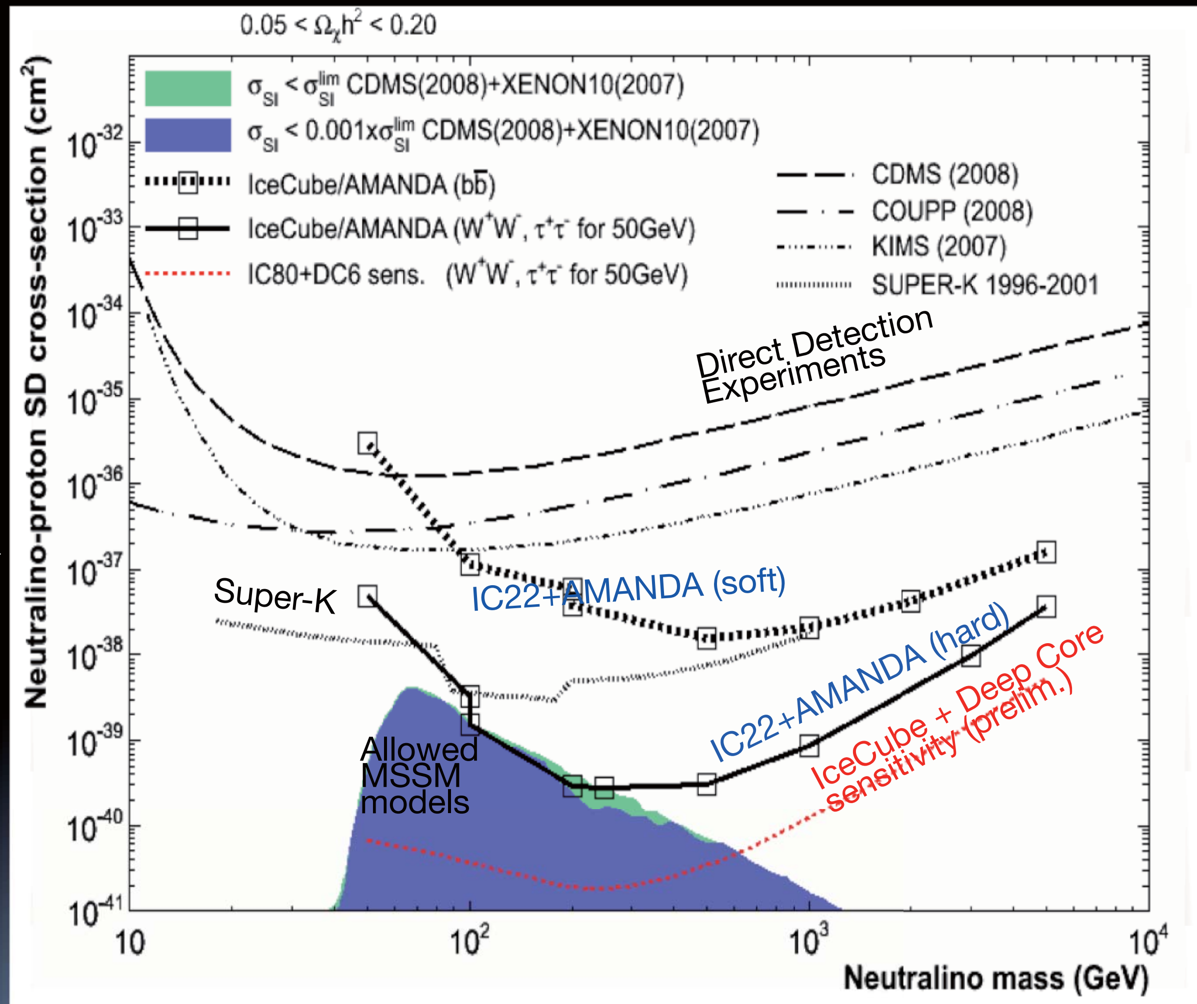
Effective volume for down-going ν_μ interacting in Deep Core

Trigger level, reconstruction efficiencies not included yet

T.DeYoung [IceCube], NDM 2009

Spin dependent cross-section limits

- IceCube with Deep Core will probe large regions of allowed phase space
- DeepCore:
  - All year Sun visibility



D. de los Heros [IceCube], CosmoOLE 2009

Conclusions

- Neutrino Telescopes can probe Dark Matter self-annihilation cross -section
  - Solar/Earth WIMPs probe WIMP-nucleon scattering cross-section (compare to direct detection experiments)
    - Very competitive constraints on SD WIMP nucleon scattering cross-section
  - Halo WIMPs compare to γ-ray indirect detection experiments
    - Constrains can be obtained from galactic center but also large scale anisotropy provides a good discovery channel
- Observations in lepton channels (if interpreted as DM signals) favor models with high-mass leptophilic WIMPs
  - Neutrinos are powerful to test these models
- Neutrinos have a crucial part in obtaining a more complete DM picture