2010 Snowbird Workshop on Particle Astrophysics, Astronomy & Cosmology (SNOWPAC)

Dark Matter Searches with IceCube

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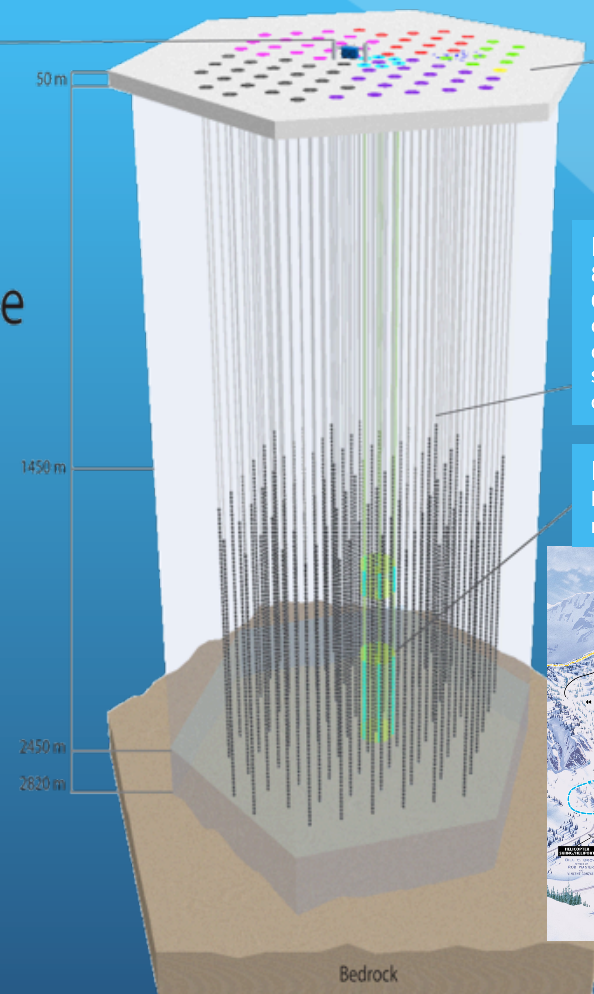
Overview

- Motivation
- The IceCube Neutrino Telescope
- Probing for Dark Matter
  - WIMP-Nucleon Scattering cross section
    - Sun
  - Self-annihilation cross section
    - Galactic Halo and Center
- Future Outlook and DeepCore
- Conclusions

IceCube

IceCube Lab



IceTop
80 stations each with 2 Cherenkov detector tanks

InIce Array
86 strings with 60 DOMs. Currently 79 strings deployed. 59 string taking data. Transition to 79 string detector configuration in April

Deep Core
Extension for 10-100GeV neutrino detection

Motivation

Overwhelming Observational Evidence

- Dark Matter already gravitationally “observed”, but …
  - What is it ?
  - What are it’s properties ?

Dark Matter Understanding

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

WIMP

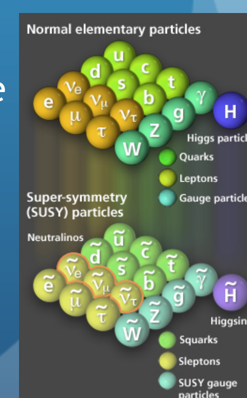
X

- WIMP - Particle Nature
  - Mass
  - Cross sections
    - Self annihilation $\langle \sigma_A v \rangle$
    - Interaction with matter

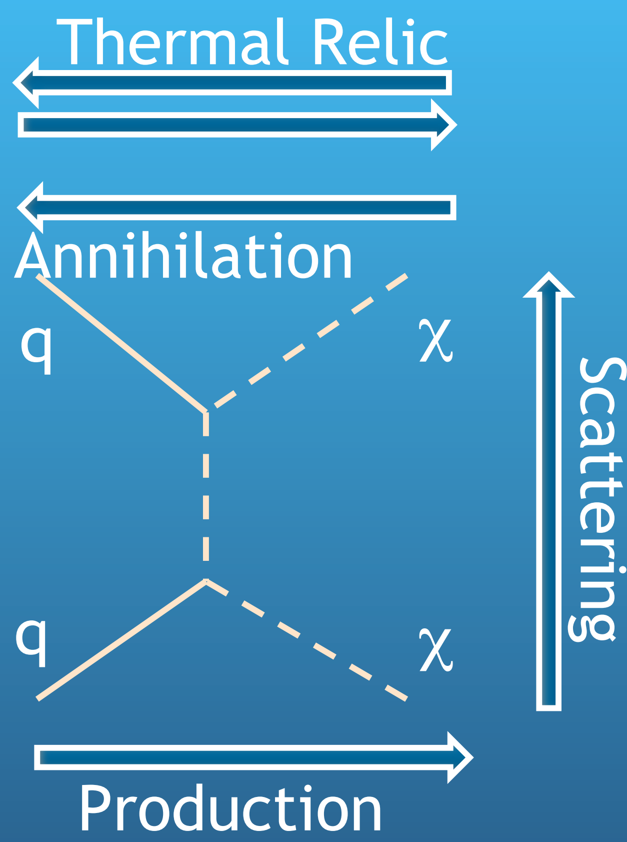
Measure

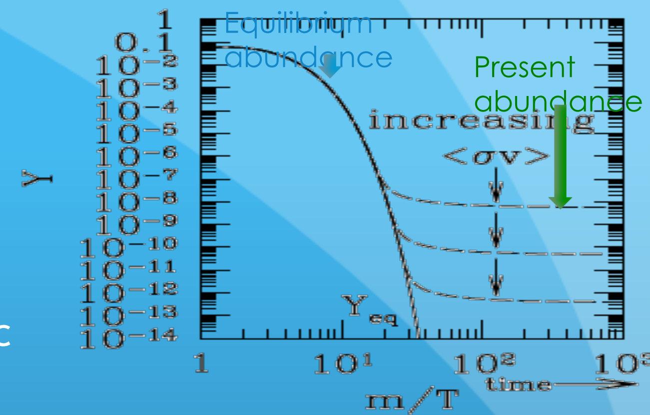
- A Weakly Interacting Massive Particle (WIMP) is generic Dark Matter particle candidate that “fits” the Dark Matter picture

- WIMPs are prominent Dark Matter candidates:
  - Arise naturally in various well-motivated theories (SUSY, Extra Dimensions, …)
  - Produced naturally with the correct thermal relic density “WIMP miracle”
  - Predict signals that might be observable in current and near future experiments



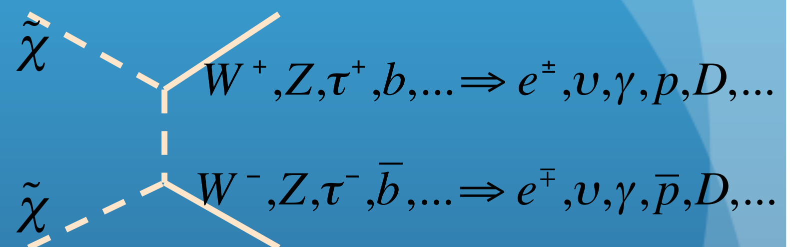
Ways to Study WIMPs

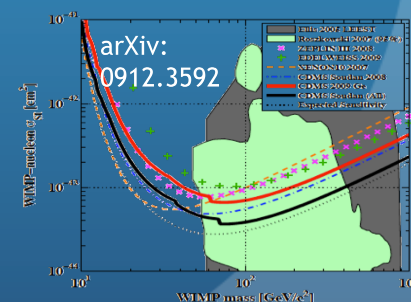


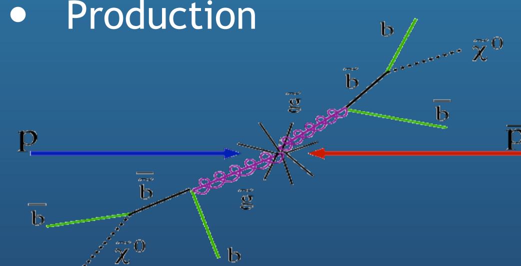


[Jungman, Kamionkowski, Griest, 1996]

- Thermal relic
- Indirect Detection
- Nuclear Recoils
- Production



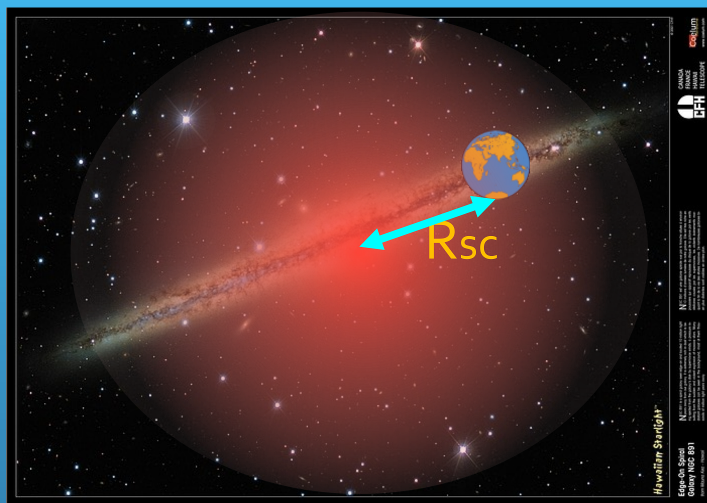


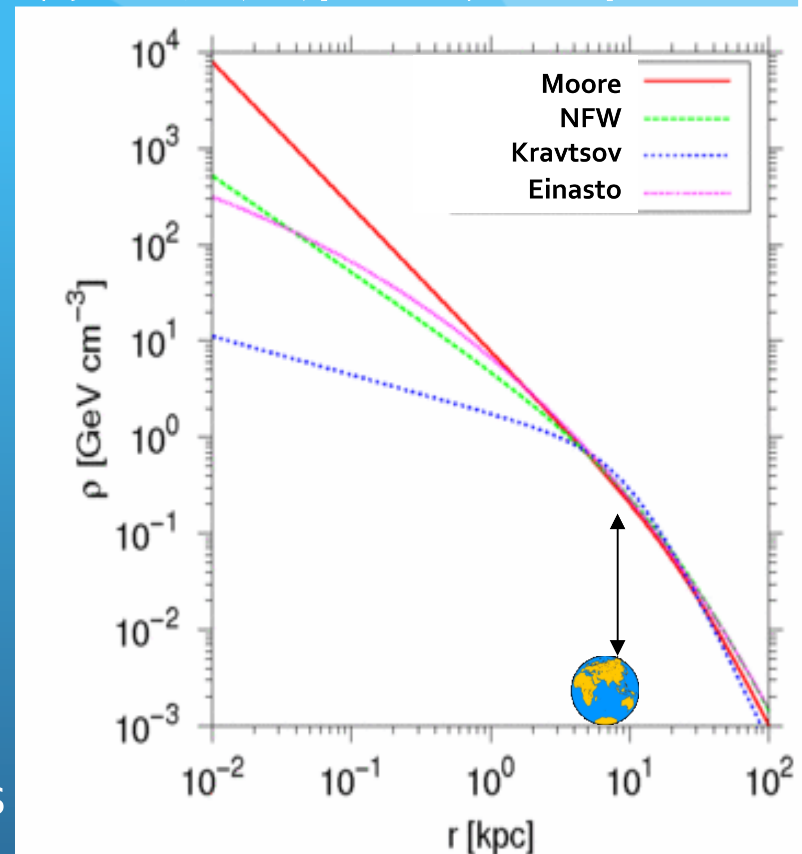


Indirect Detection with Neutrinos

J. Einasto, Trudy Inst. Astroz. Alma-Ata 5, 87 (1965),
Navarro, Frenk, White, *Astrophys. J.* ***490, 493-508 (1997)***,
Moore, et al. Mon. Not. Roy. Astron. Soc. 310, 1147 (1999) [arXiv:astro-ph/9903164],
Kravtsov et al. Astrophys. J. 502, 48 (1998) [arXiv:astro-ph/9708176].

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
rs - scale radius
Rsc - 8.5kpc

Profile	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

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

Messengers from Dark Matter Annihilations

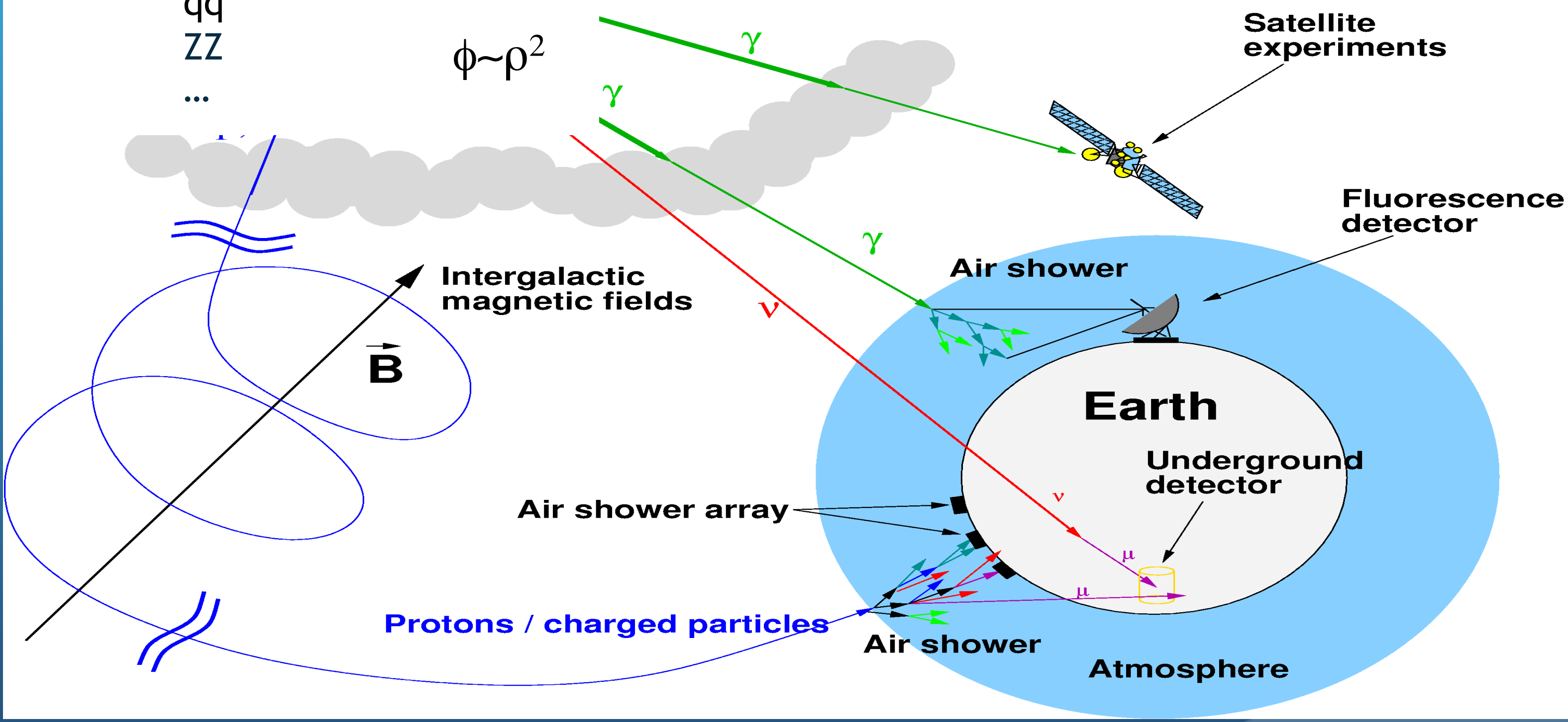
$\chi + \chi \rightarrow WW \rightarrow e + \nu\text{'s} + \ldots$

$b\bar{b} \rightarrow \nu + \gamma + \ldots$

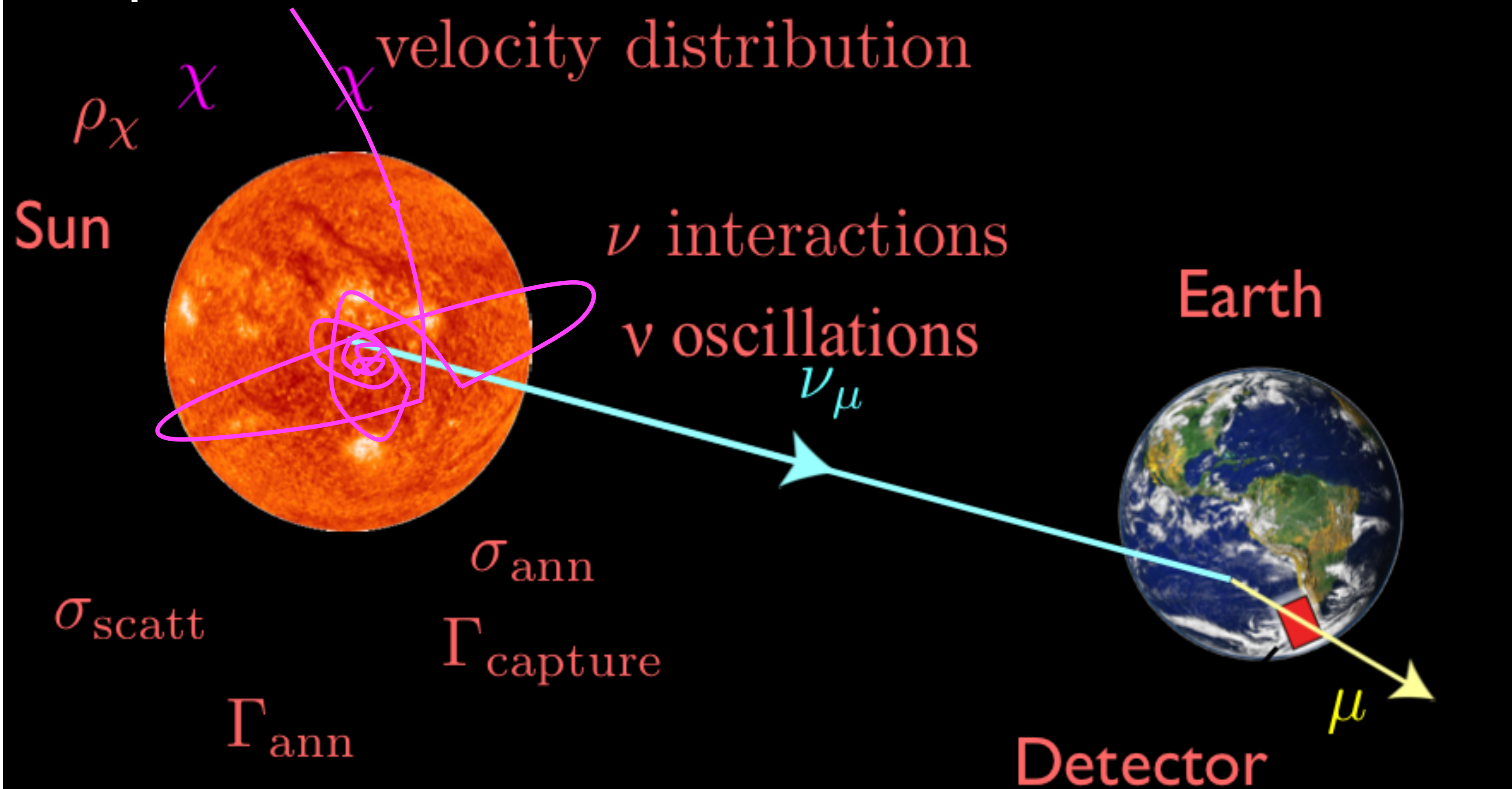
qq

ZZ

...



Neutrinos from annihilating Dark Matter captured in the Sun



Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Annhilation Rate ←→ Cross section

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

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 → $\sigma^{\text{SD, SI}}$

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

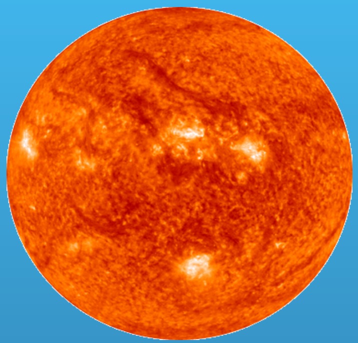
$\sigma^{\text{SD}} = \kappa_f^{\text{SD}}(m_\chi)\Phi_\mu^f$ $\sigma^{\text{SI}} = 0$

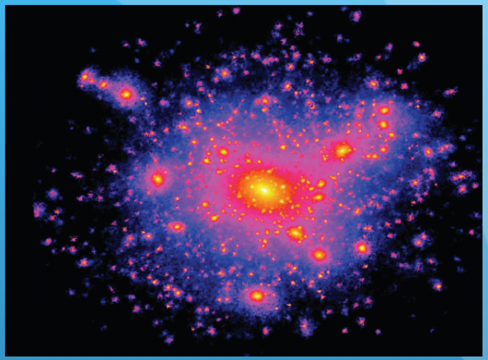
A. Gould, Astrophys. J. 321 (1987) 571
G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267 (1996) 195
G. Wikstrom and J. Edsjo, JCAP 04, 009 (2009).

Why Neutrinos

- Neutrinos are unique messengers, which allow to probe both
  - WIMP-Nucleon scattering cross section
    - Complementary to direct detection experiments
  - Self-annihilation cross section / Lifetime
    - Complimentary searches to gamma-ray searches

Neutrino Dark Matter Searches

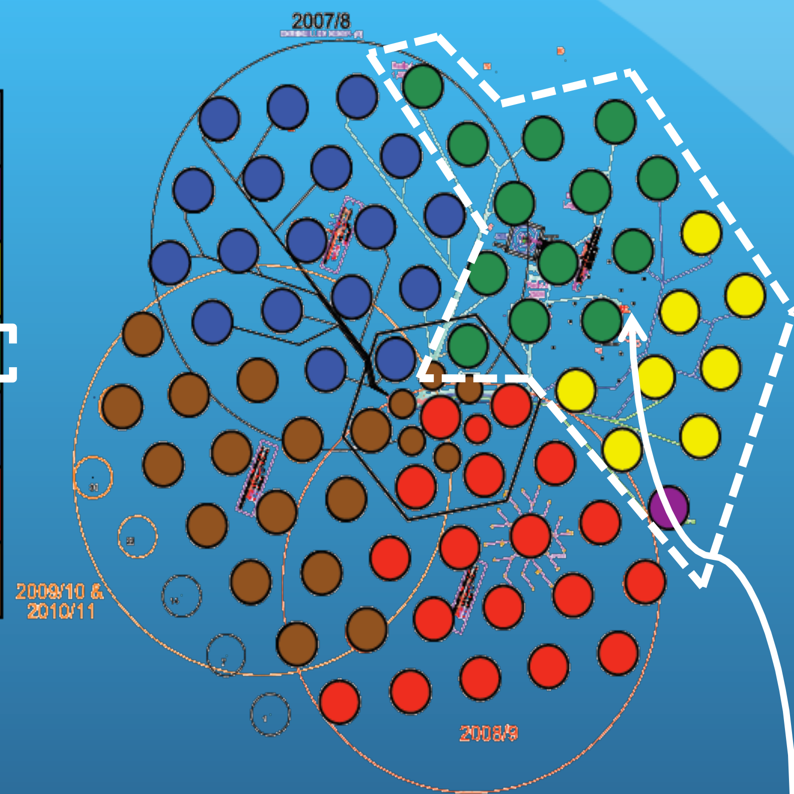




Solar	Earth	Halo
Neutrino Flux, **Scattering cross-section**	Neutrino Flux, **(Scattering cross-sections)**	Neutrino Flux**, Self-annihilation cross-section**
Muon neutrinos	Muon neutrinos	Muon neutrinos, **Cascades**
Background off-source on-source	Background simulations	Background off-source on-source,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

IceCube

Year	Deploy	Total
2004/5	1	1
2005/6	8	9
2006/7	13	22
2007/8	18	40
2008/9	18+1	58+1
2009/10	15+5	73+6



- The Searches covered in this talk use primarily the IceCube 22 string configuration, active 2007-2008

IceCube

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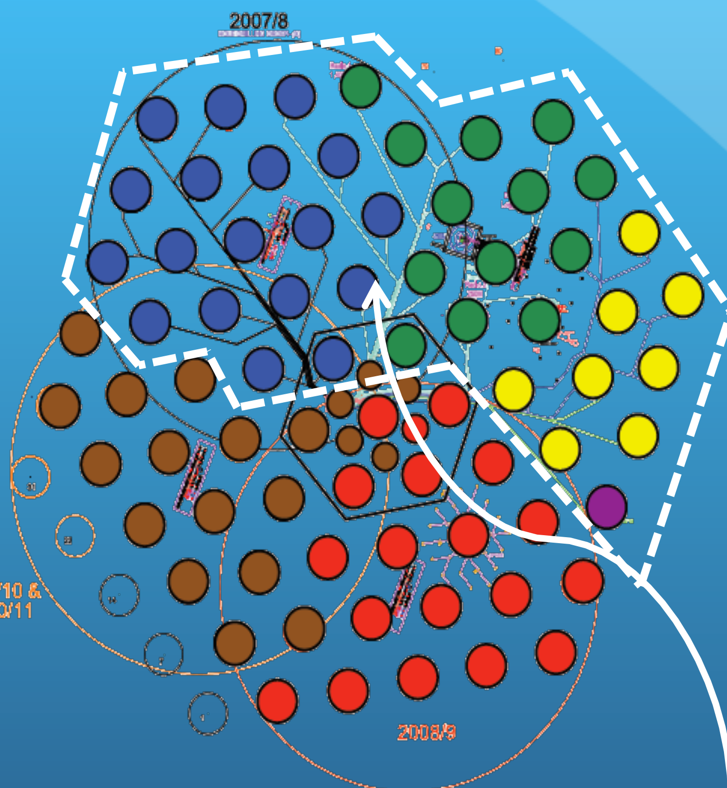
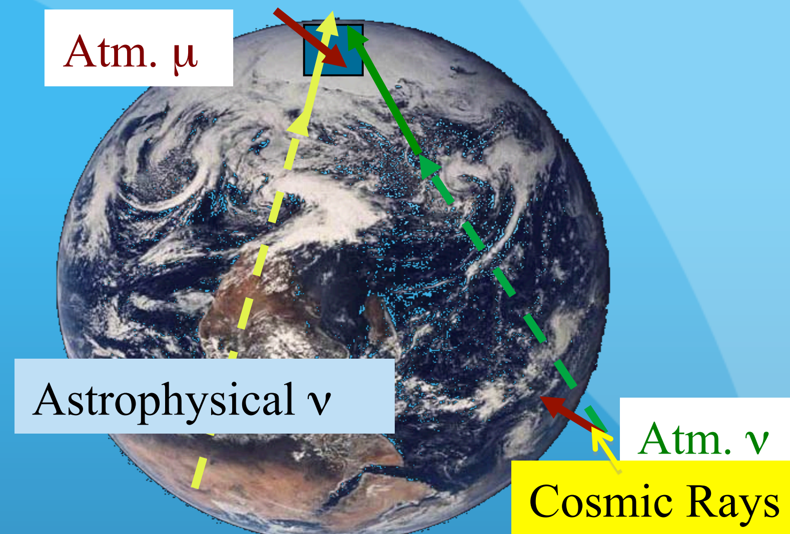
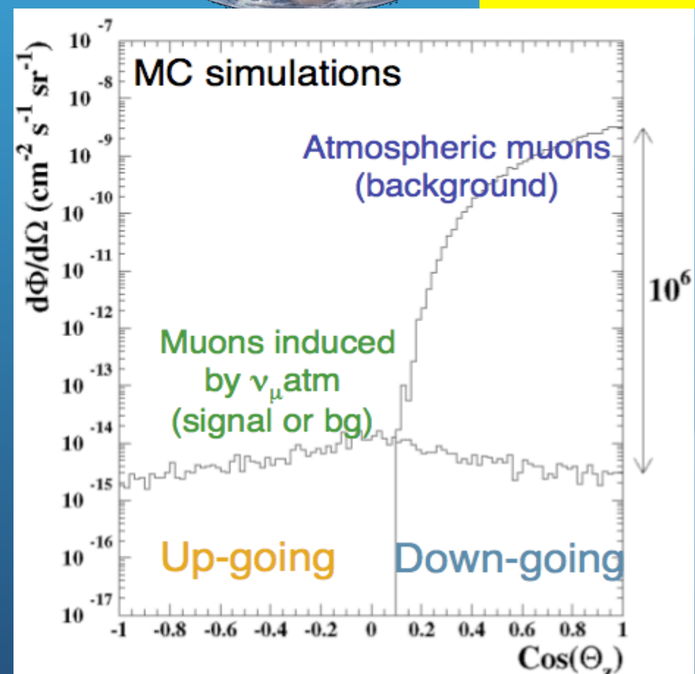


- Some of them use the IceCube 40 string configuration, active 2008-2009
- IceCube just completed a very successful deployment season 2009/2010 and now has 79 strings installed and the low-energy extension Deep Core completed

Backgrounds

- High energy muons created in airshowers produce continuous stream of background
  - $p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons
    - $\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$
- Up-going events can be used to obtain "clean" neutrino sample
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

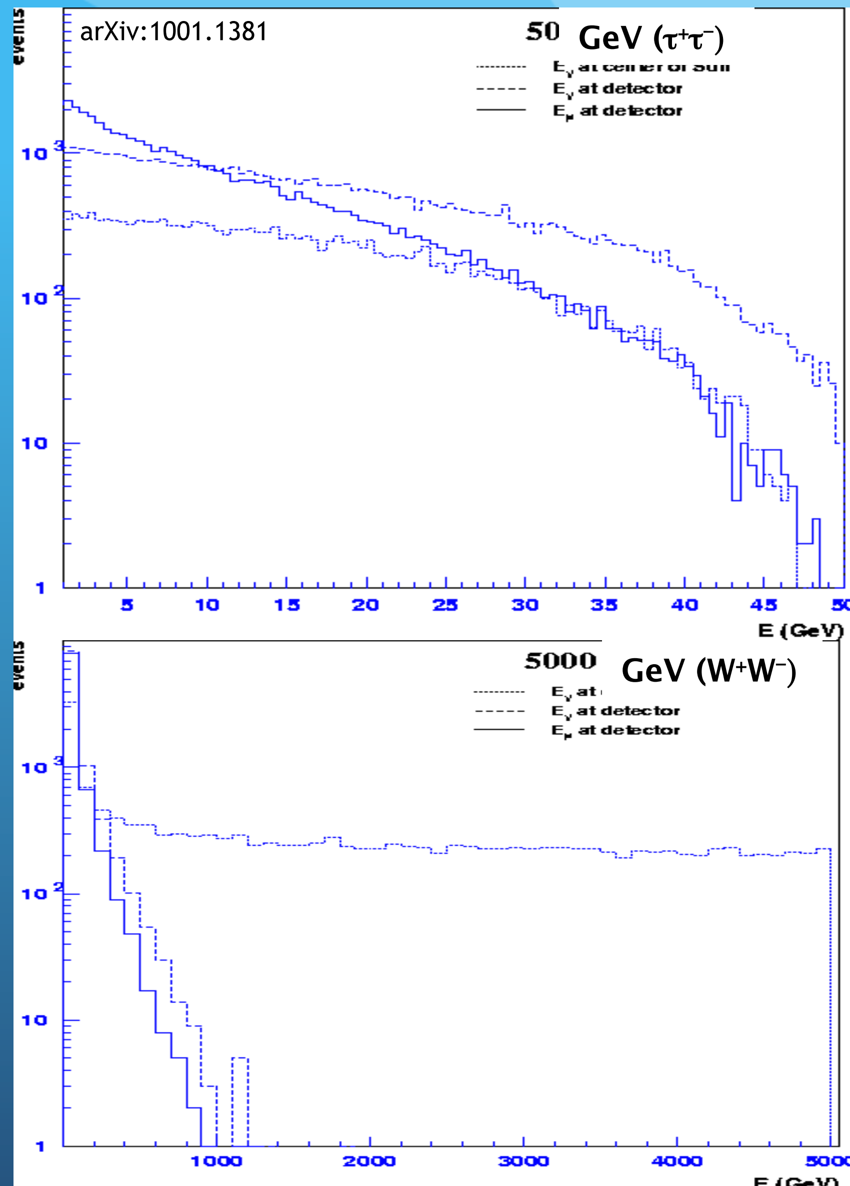




Solar WIMPs

Solar WIMPs

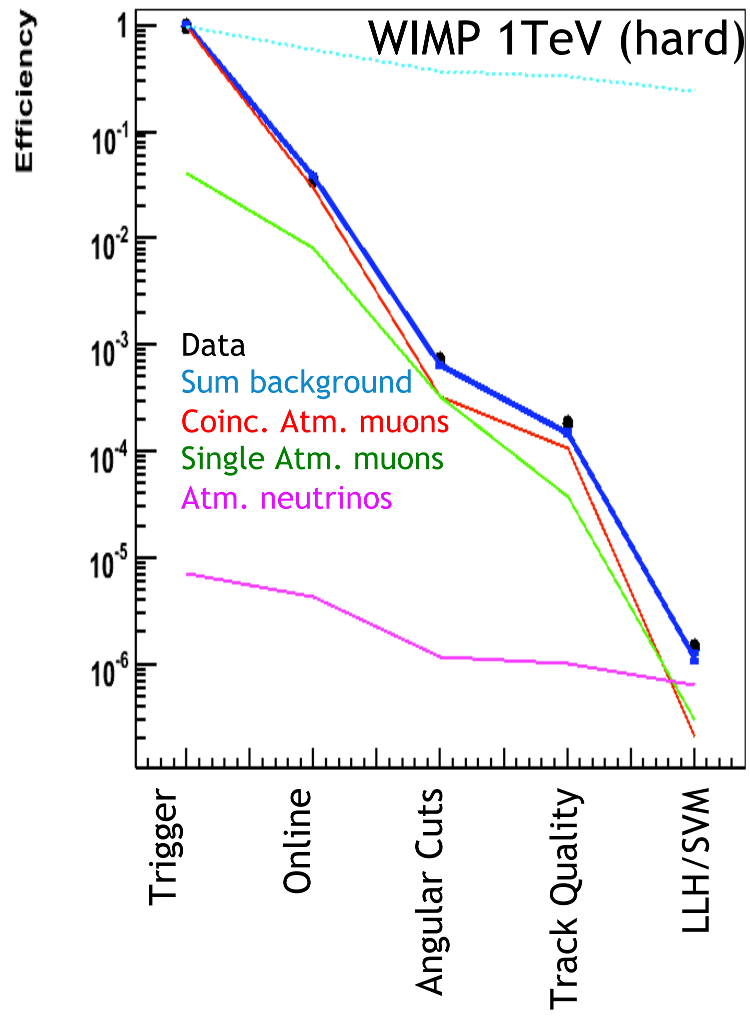
- High energy neutrinos (1TeV) do not escape the Sun → Indirect dark matter searches from the **Sun** are "low-energy" analysis in neutrino telescopes.
- Utilize data when the Sun is below the horizon to reduce atmospheric muon background
- Consider different annihilation channels
  - hard $\tau\tau$, W^+W^-
  - soft $b\bar{b}$
- Off-source region can be used to estimate background from data itself



Solar WIMP

- Event Selection
  - Sun is below the horizon at South Pole (March – September) – (IceCube livetime = 104.3 days)
  - Event pre-selection at South Pole for Satellite transmission (filter)
  - Angular selections
  - Track reconstruction track quality criteria
  - Final selection via LogLikelihood and advanced analysis tools (SVM – support vector machine)
- Signal efficiency >20%
- Background rejection ~10^6

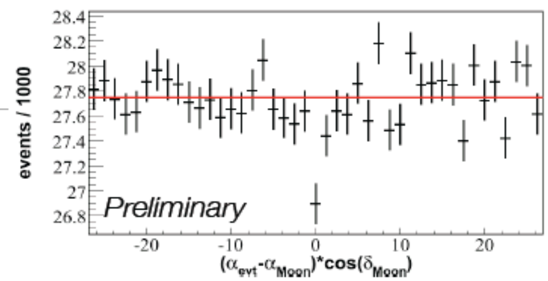
IceCube-22 string analysis

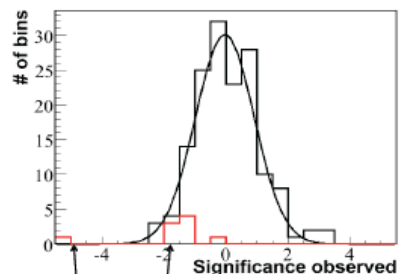


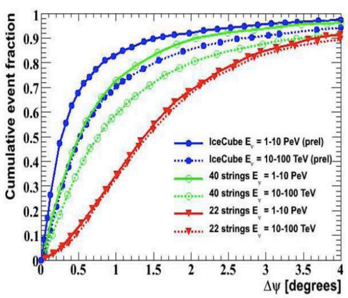
Experimentally verify that neutrinos are reconstructed correctly and test pointing resolution

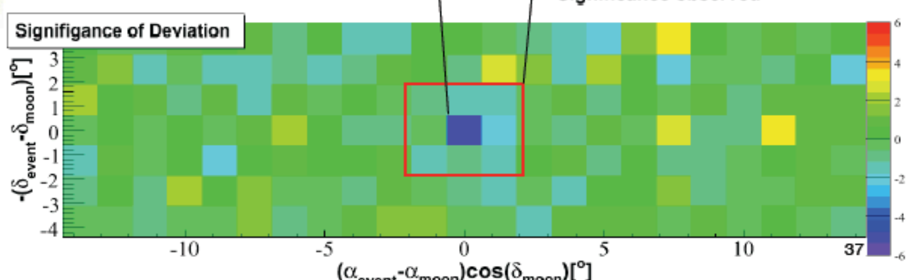
IceCube
Moon shadow

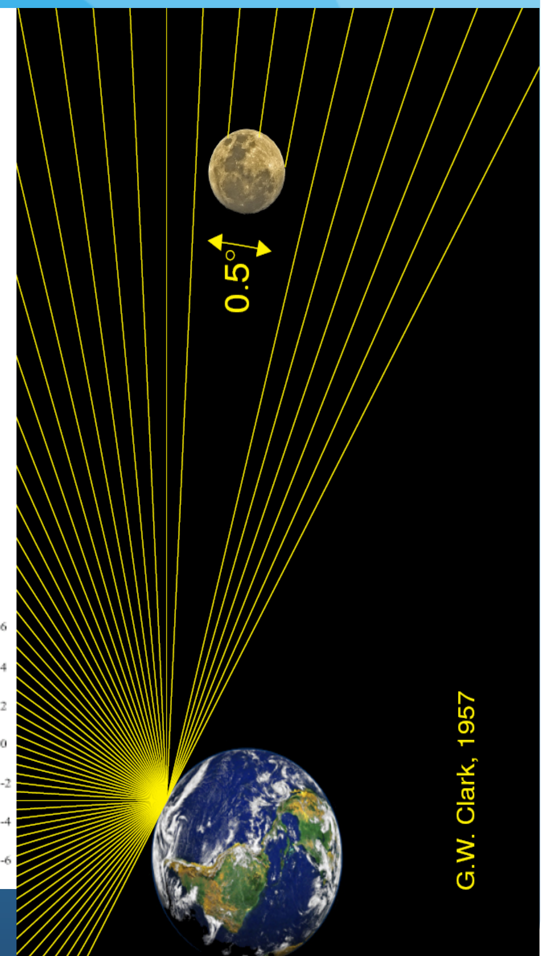
- 5 months of IC40
- Moon max. altitude at the South Pole (2008): 28°
- Median primary cosmic ray energy: 30TeV
- Deficit: 5 σ (~900 events of ~28000) - consistent with expectation.
- Verification of angular resolution and absolute pointing.
- More statistics will allow study of angular response function





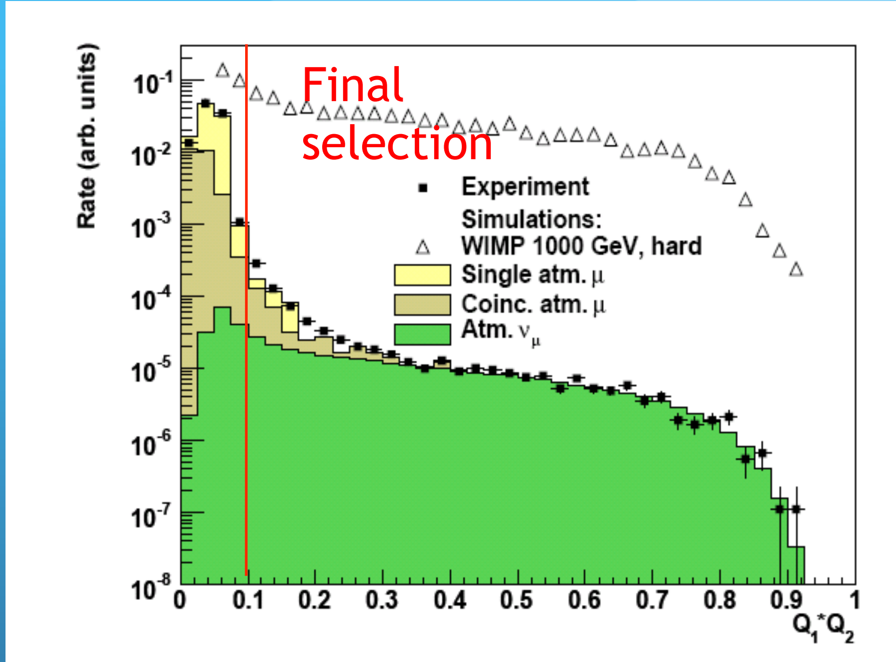


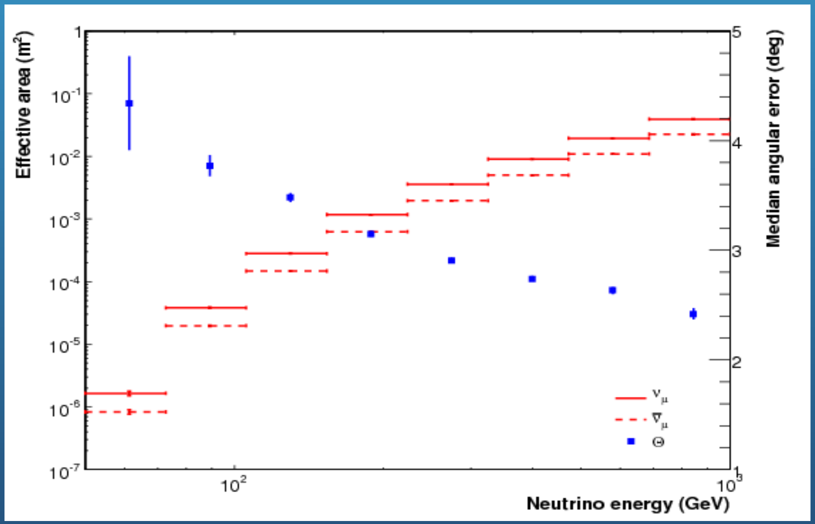




IceCube 22-strings Solar WIMP Search

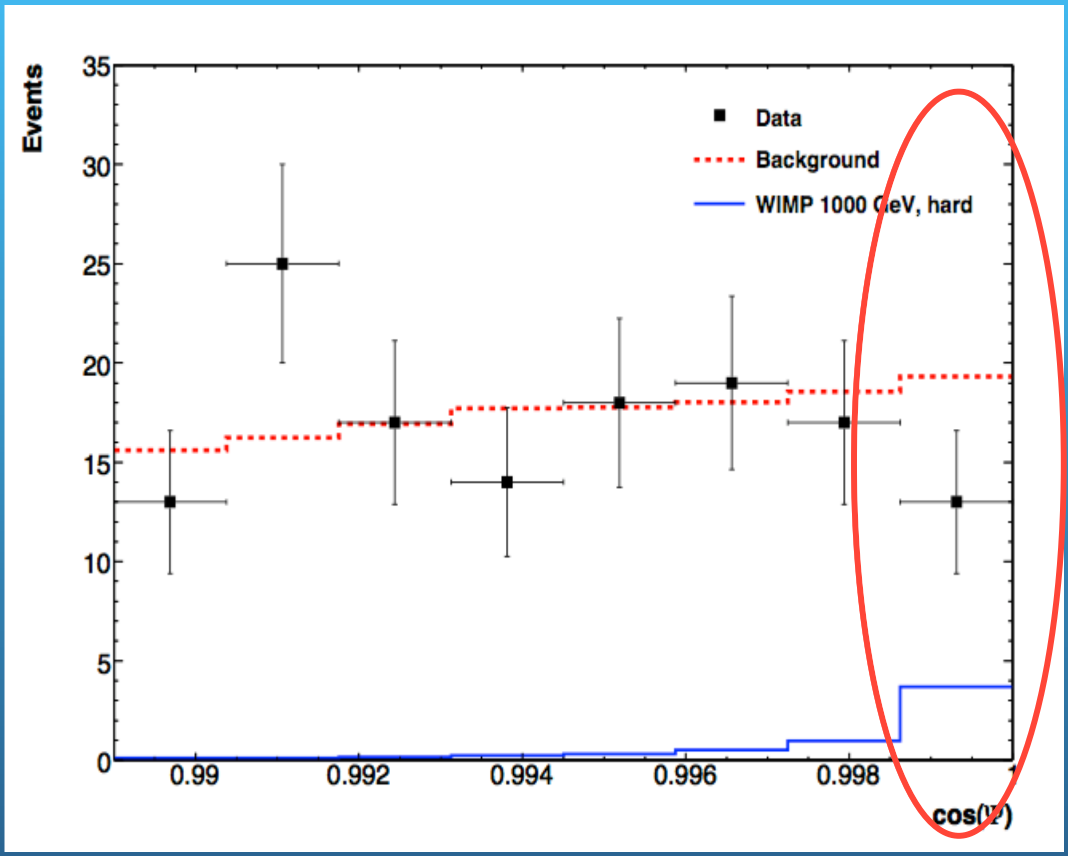
- Several levels of filtering are applied to remove atmospheric muon backgrounds and utilize a Support Vector Machine SVMs Q1*Q2 to define final cut level
- Data and simulation agree well

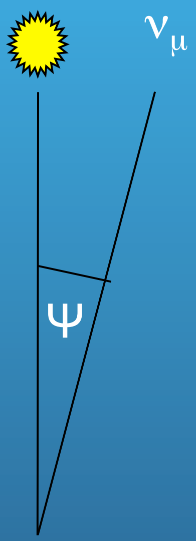




- At the final cut level, atm. neutrinos form biggest background (~56%)
- Signal efficiency is of order 20% depending on the WIMP mass
- Direction of the sun still remained scrambled to this point

IceCube 22-strings Solar WIMP Search





Muon flux in direction of the sun

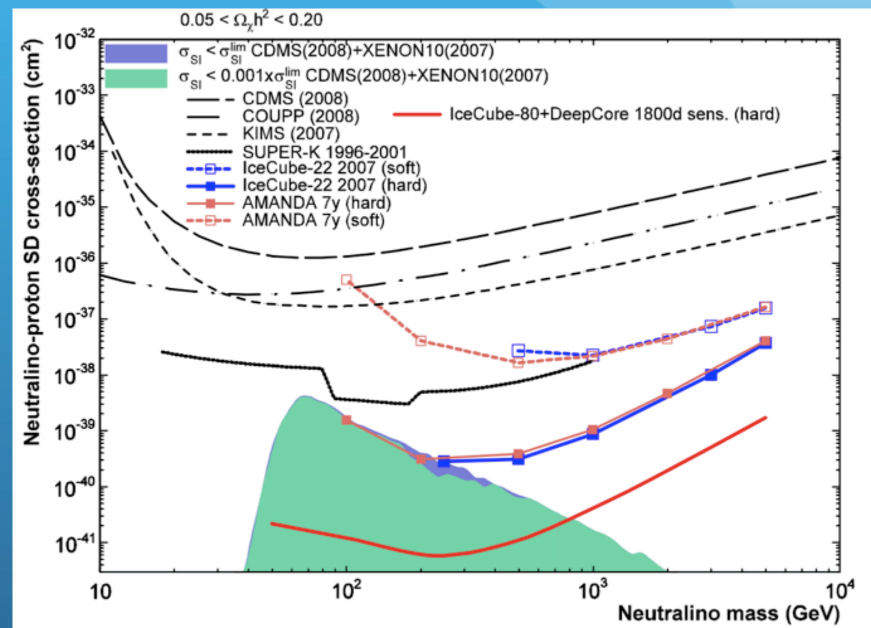
Examine angular distribution Ψ for Sun and muon tracks.

Angular resolution: IceCube-22 (>500 GeV) 3 degrees

Observation consistent with expectations from atmospheric neutrinos ⇒upper limit

Solar WIMPs – Spin dependent cross section limit

- Obtain limit on the muon flux in direction of the Sun
- Constraints are computed in terms of annihilation modes (hard, soft)
- Assume equilibrium condition and standard halo parameters to obtain constrain on the WIMP-proton scattering cross-section
    - Spin independent cross section tightly constrained in direct detection experiments
    - Sun ideal to test spin dependent WIMP nucleon scattering cross section



Phys. Rev. Lett. ***102*****, 201302 (2009)**
arXiv:0902.2460

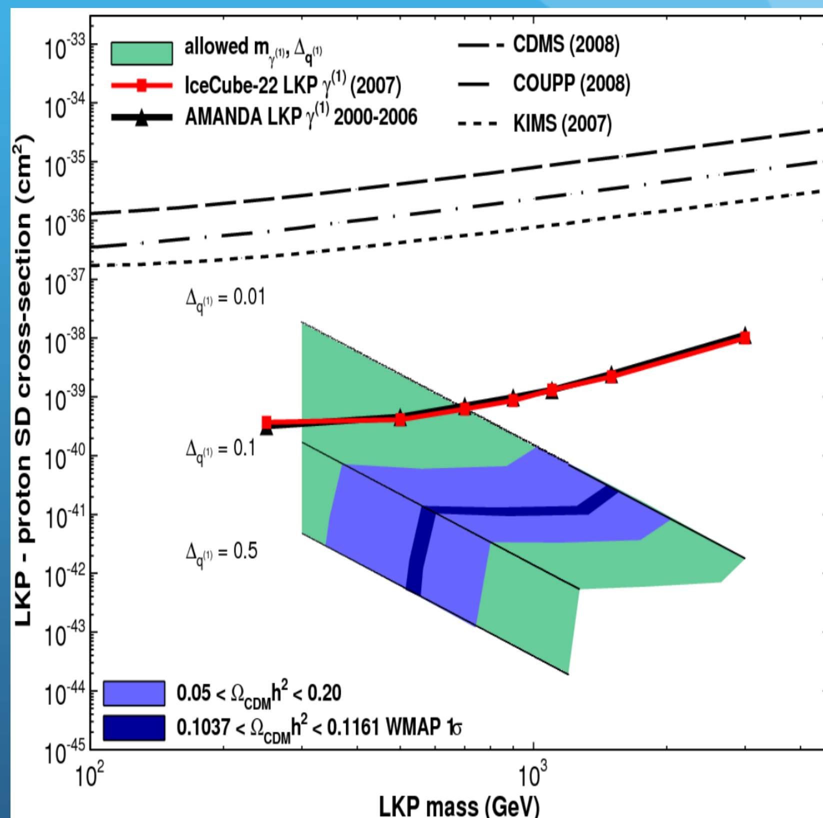
Solar WIMPs - Kaluza Klein Dark Matter Limit

- UED in 5 extra dimensions
- WIMP is LKP (KK photon)
- Model described by two parameters: Δ_q and M_{LKP}
- Limits on SD WIMP-proton cross section IceCube 22-string and AMANDA 6-year

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

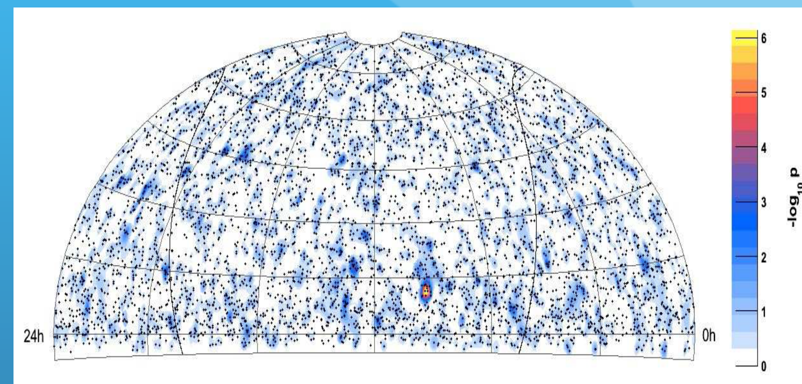


arXiv:0910.4480
(accepted PRD)

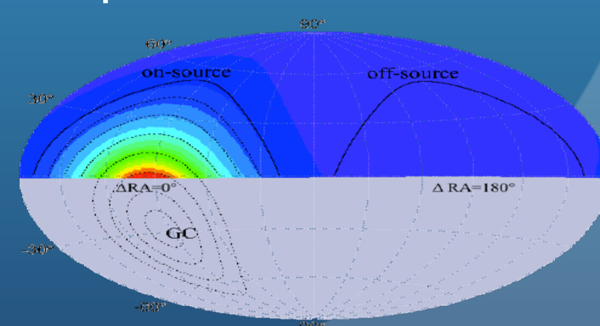
Galactic Halo WIMPs

Sky map IceCube (22strings)

- 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**.)
- Theoretical motivation see:
  - Yuksel, Horiuchi, Beacom, Ando (2007)



- Do we see any effects on Dark Matter in our neutrino sample ?

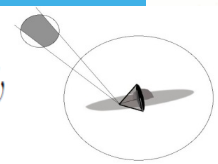


Neutrino Flux from annihilations

Yuksel, Horiuchi, Beacom, Ando (2007)

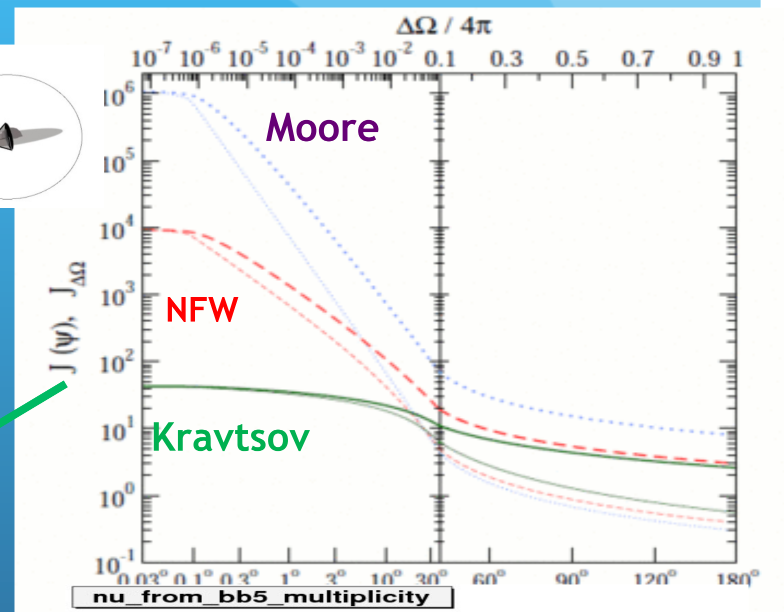
Line of sight integral:

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



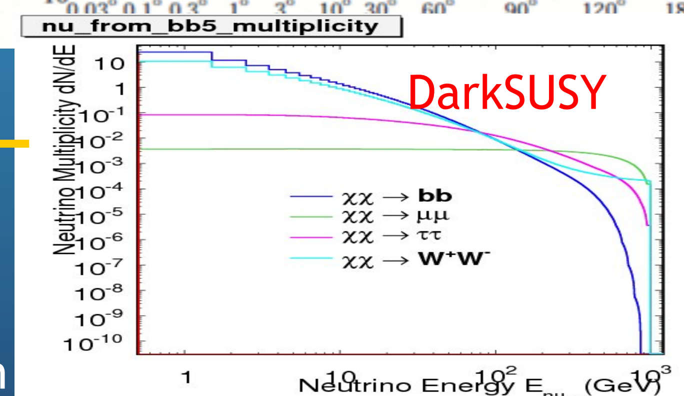
$$\mathcal{J}(\psi) = \frac{1}{R_{sc}\rho_{sc}^2} \int_0^{\ell_{max}} \rho^2\left(\sqrt{R_{sc}^2 - 2\,l\,R_{sc}\cos\psi + l^2}\right) d\ell$$

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



Expected differential neutrino Flux:

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

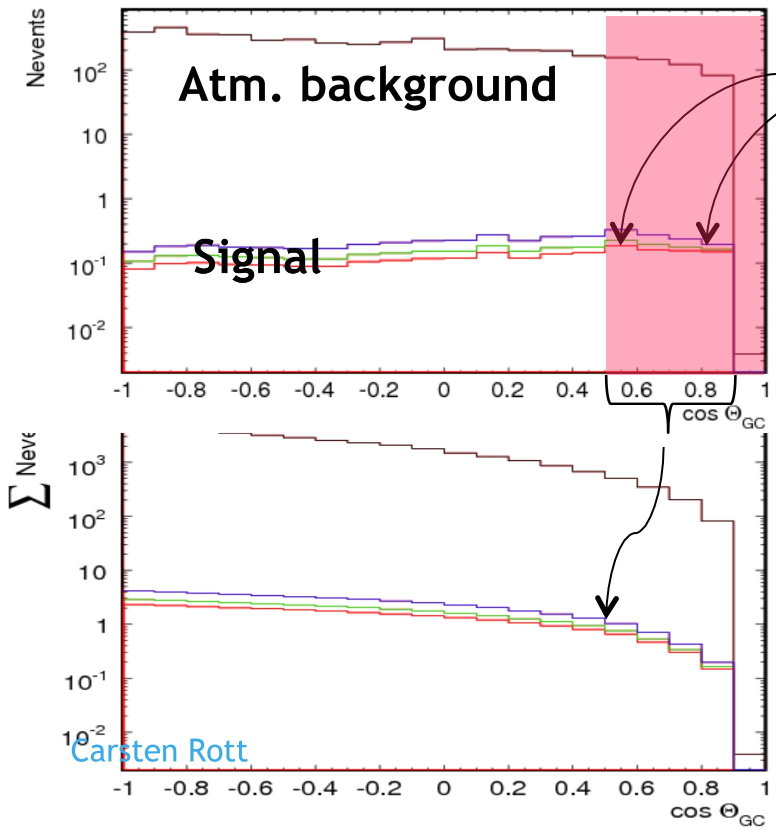


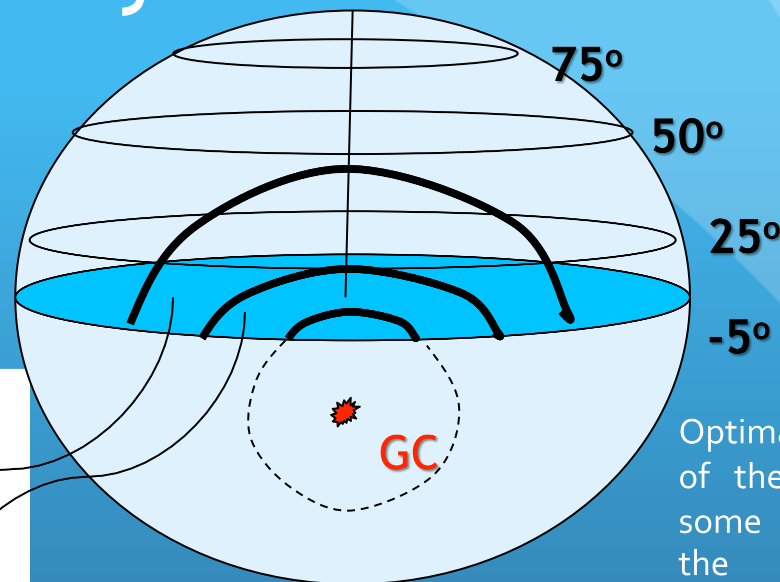
Measure integrated flux

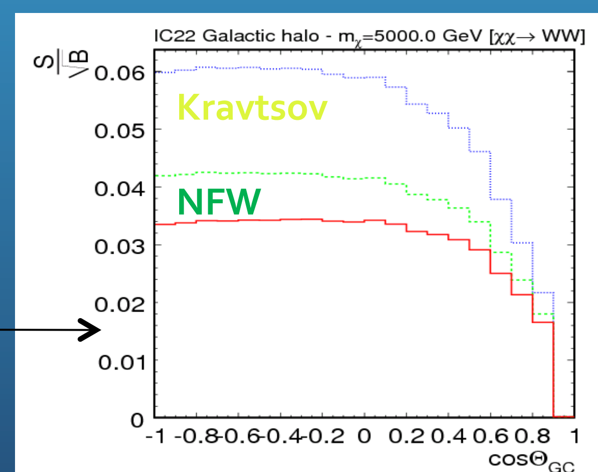
Isotropic emission

Galactic Halo Analysis - IceCube

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







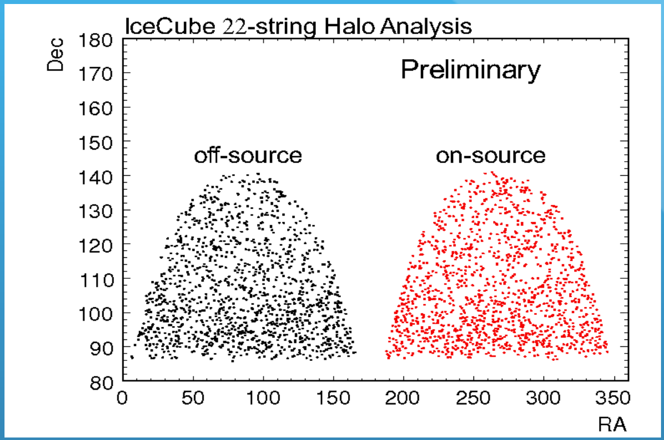
Optimal signal extend of the region shows some dependence on the halo model, annihilation channel and WIMP mass.

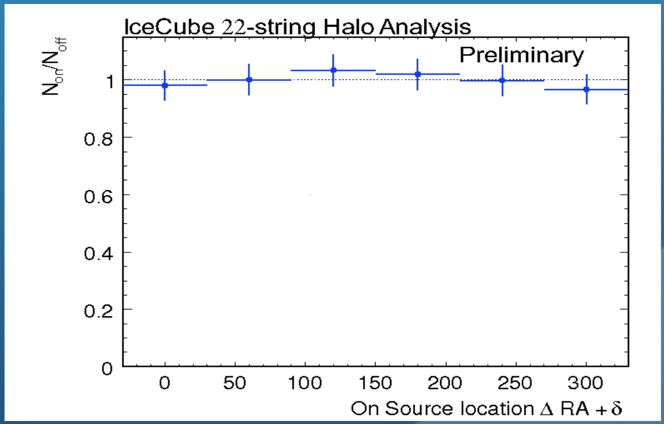
Their overall behavior is however very similar:

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

Galactic Halo IceCube 22

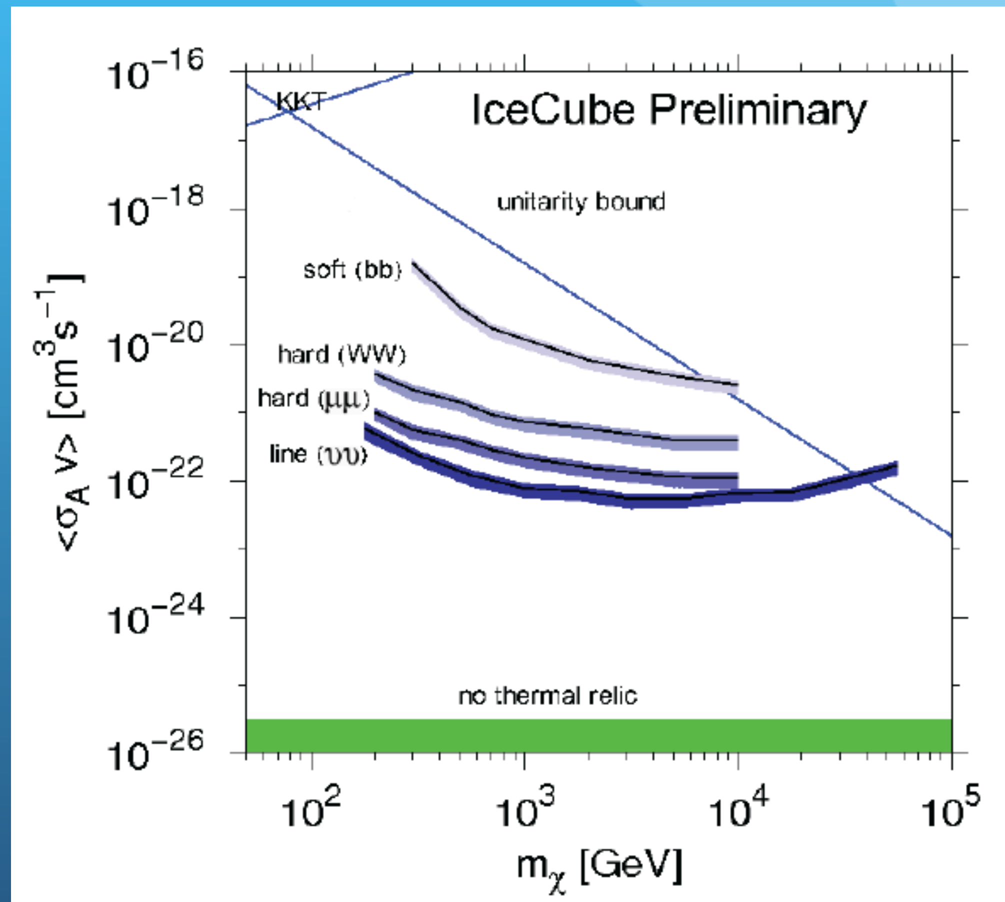
- Compare regions of equal "size" (on vs. off-source)
- No excess flux in the region, closer to the galactic center
- Rotate regions in 60^o steps as systematic cross check
  - Distribution is flat





Galactic Halo Analysis - IceCube

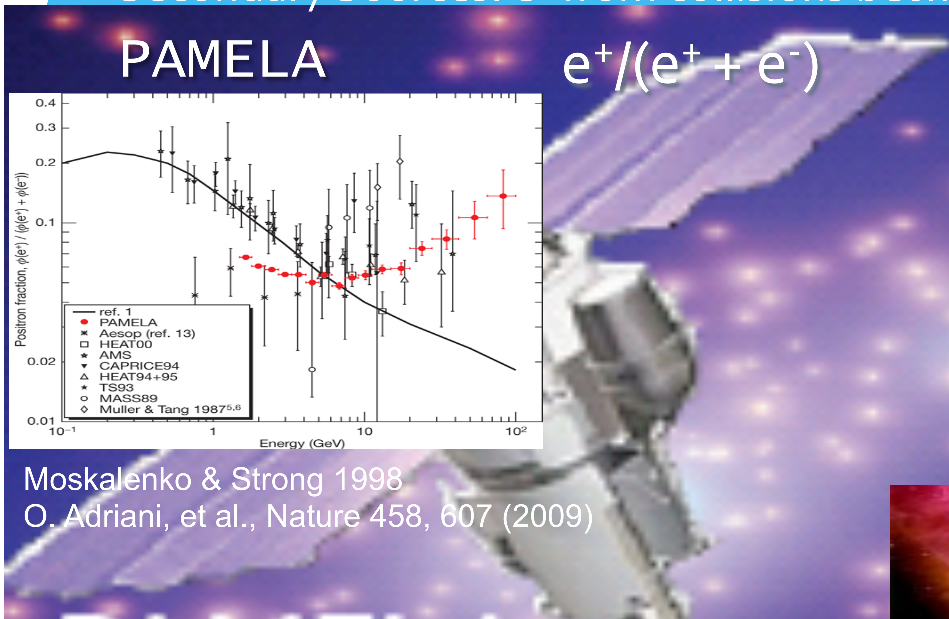
- No anisotropy was observed in IceCube data – constrain the dark matter self-annihilation cross-section
- Limits are at 90% C.L.
- As we probe the outer halo, there is only a small dependence on halo profiles
- Annihilation into $\nu\nu$ could also be interpreted as upper limit on total dark matter annihilation cross section (Beacom, Bell, Mack 2008)



arXiv0912.5183

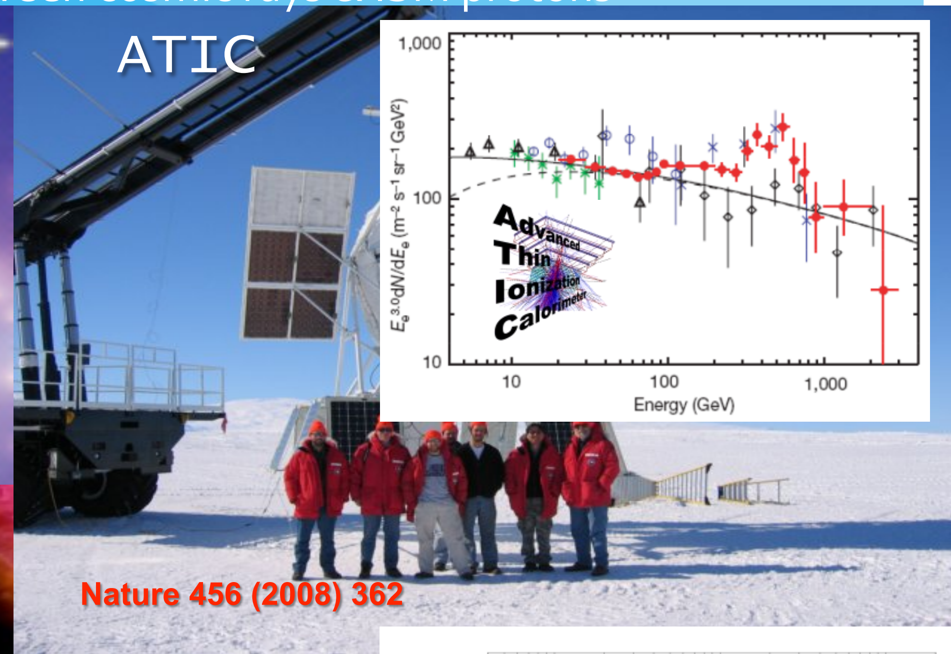
Primary Sources: e− accelerated in supernova remnants
Secondary Sources: e± from collisions between cosmic rays & ISM protons

PAMELA



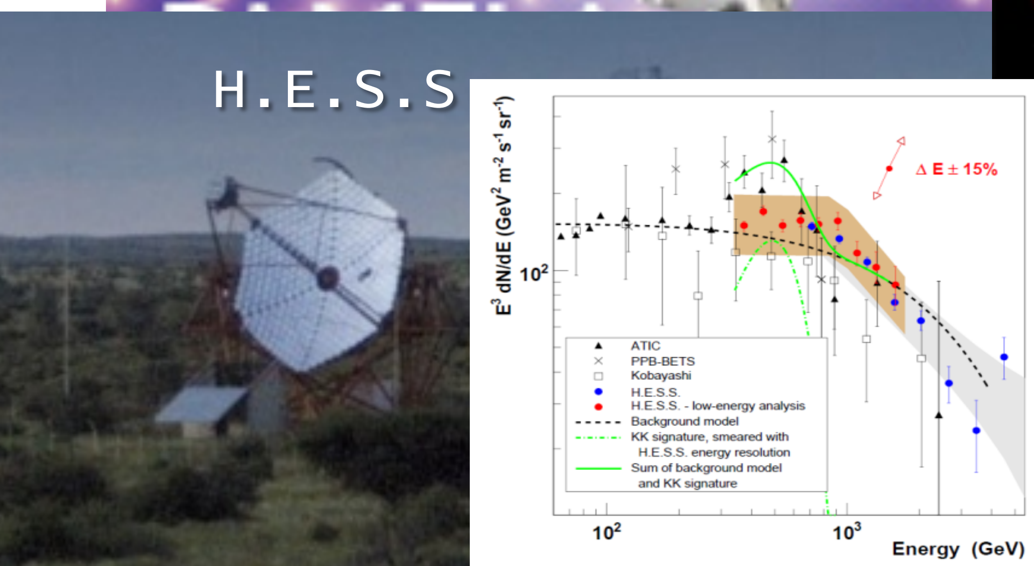
Moskalenko & Strong 1998
O. Adriani, et al., Nature 458, 607 (2009)

ATIC



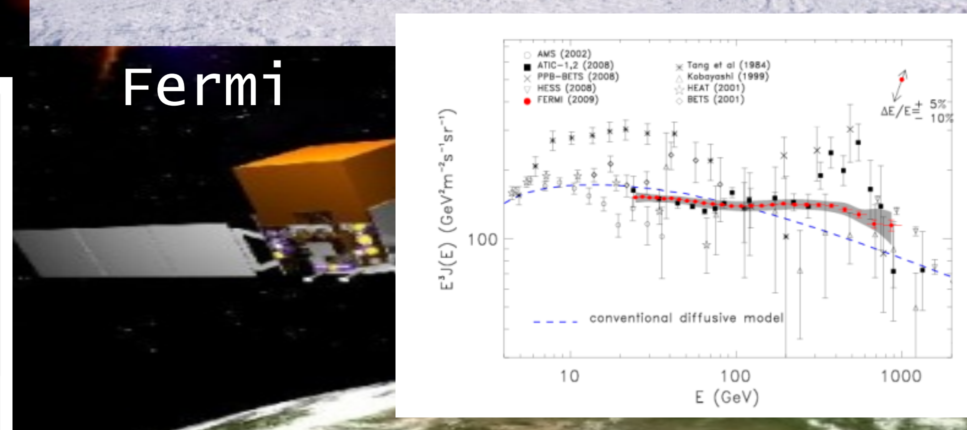
Nature 456 (2008) 362

H.E.S.S



Carsten Rott
F. Aharonian et al., Phys. Rev. Lett. 101, 261104 (2008).
F. Aharonian et al., arXiv:0905.0105.

Fermi

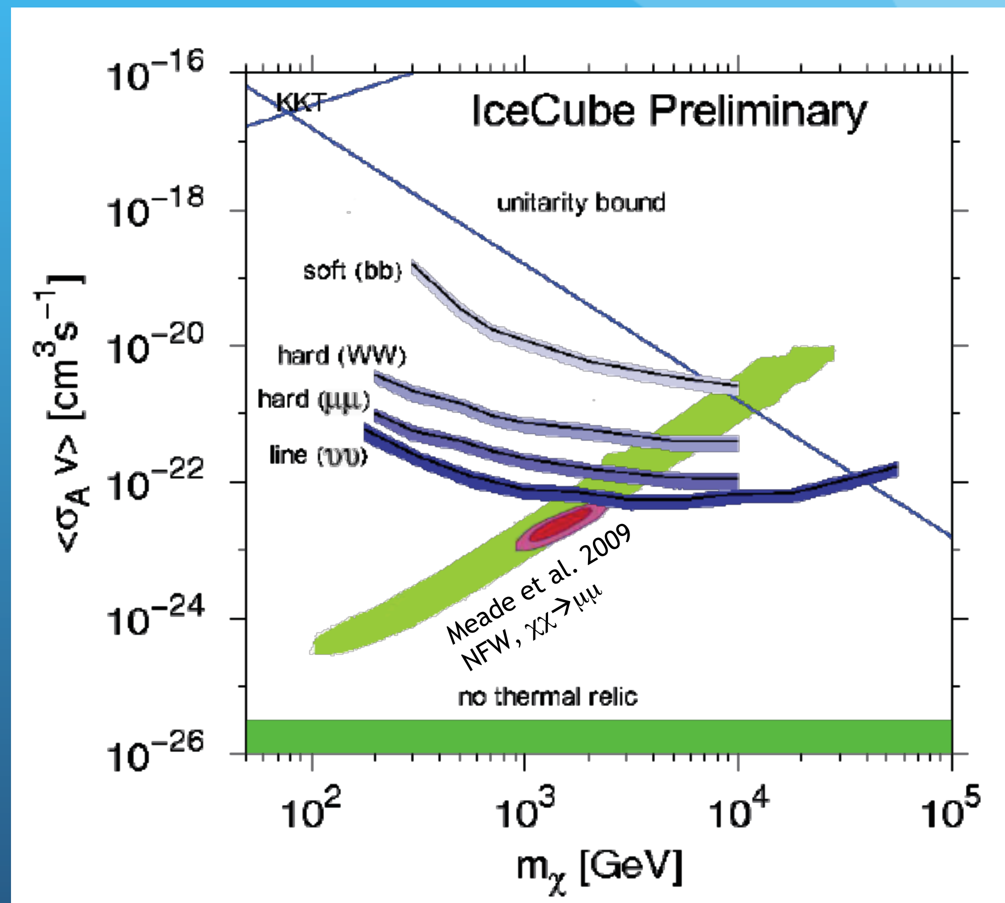


Fermi Collaboration, arXiv:0905.0025

M. Ackermann, "Observation of the extragalactic diffuse continuum gamma-ray emission with Fermi LAT," talk at TeV Particle Astrophysics 2009, http://www-conf.slac.stanford.edu/tevpa09/

Galactic Halo Analysis - IceCube

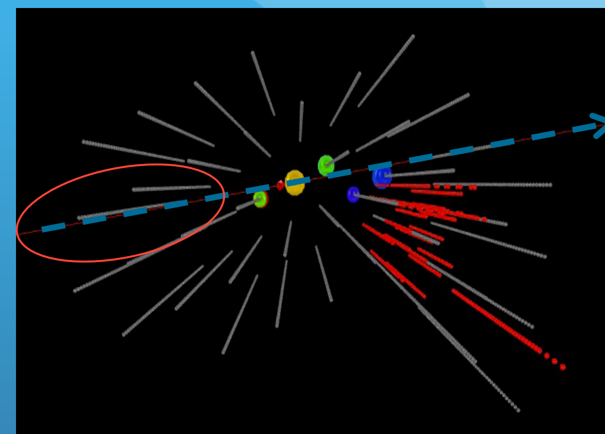
- Preliminary IceCube constraints using 275 days of data and the 22 string dataset can probe already some of the preferred parameter space
- Significantly more data has been collected already

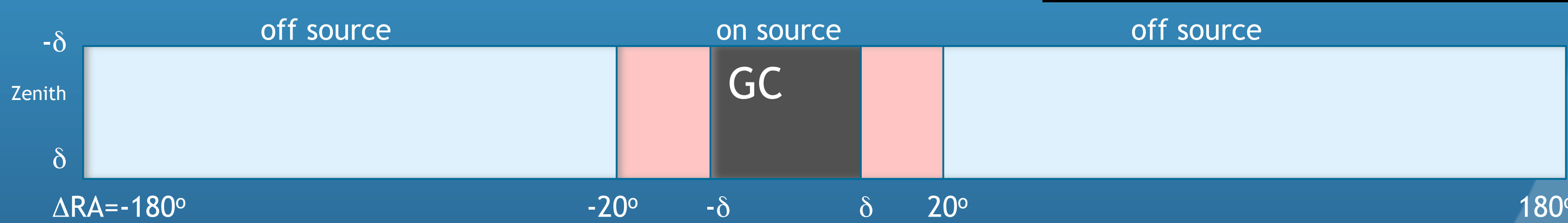


arXiv0912.5183

Galactic Center IceCube – 40 strings

- Dark Matter profiles are peaked at the galactic center
- As the galactic center (GC) is above the horizon these events are down-going in IceCube
  - Use down-going starting events to reduce atmospheric muon background

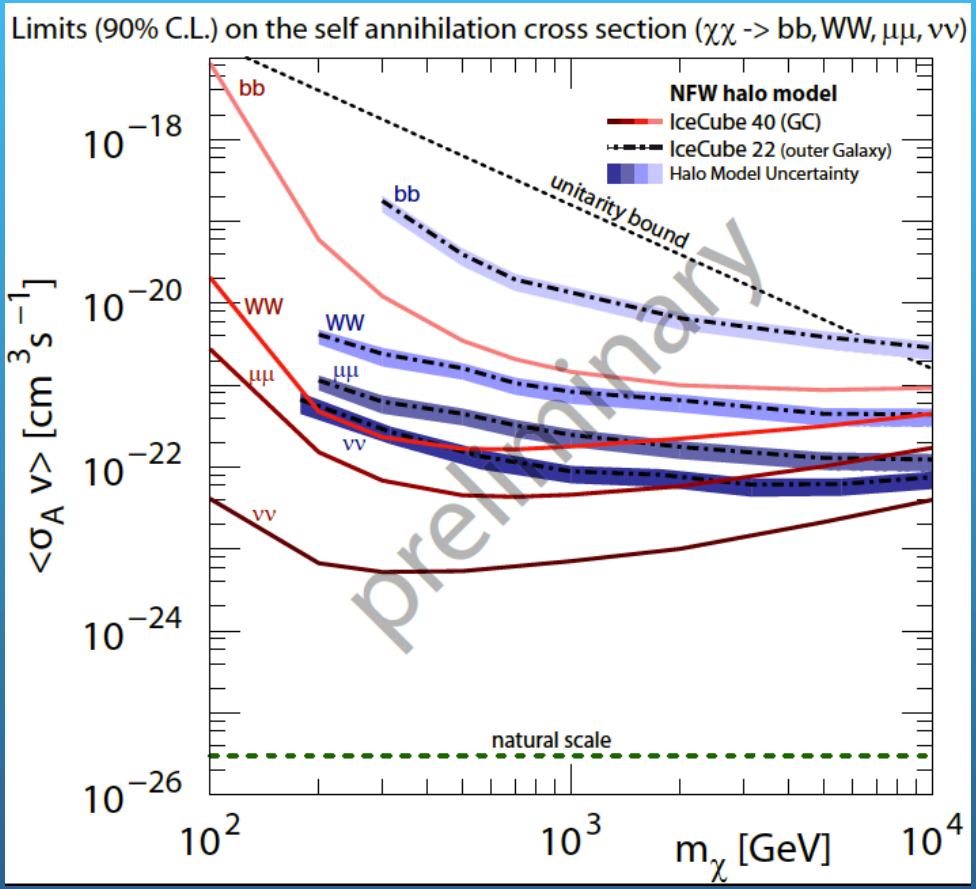




Optimize the size of the on-source region

- $\delta = 8^{o}$
- compare the amount of events in the on- and off-source region

Galactic Center



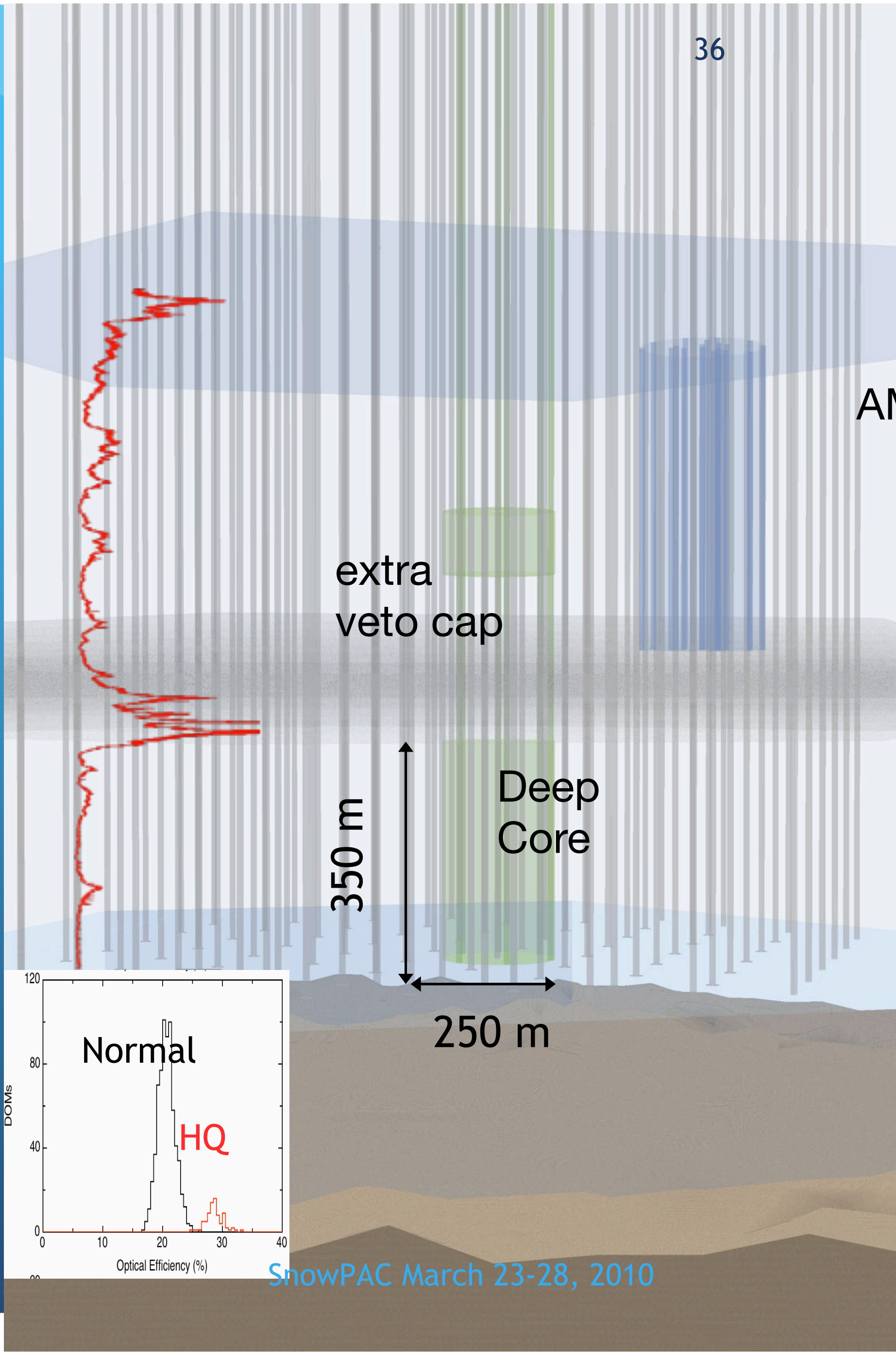
Arxiv:0912.5183
See also J.Huelss DPG

- Neutrino constraints from IceCube are very competitive and start to probe preferred regions from the PAMELA positron excess and Fermi
- The Deep Core subdetector is designed to obtain a clean neutrino sample of starting events, which will substantially improve our sensitivity for WIMPs in the 100 GeV range

Deep Core

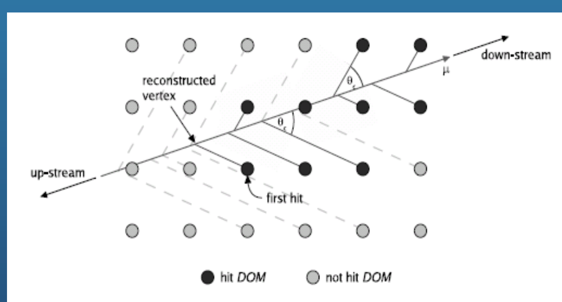
Deep Core

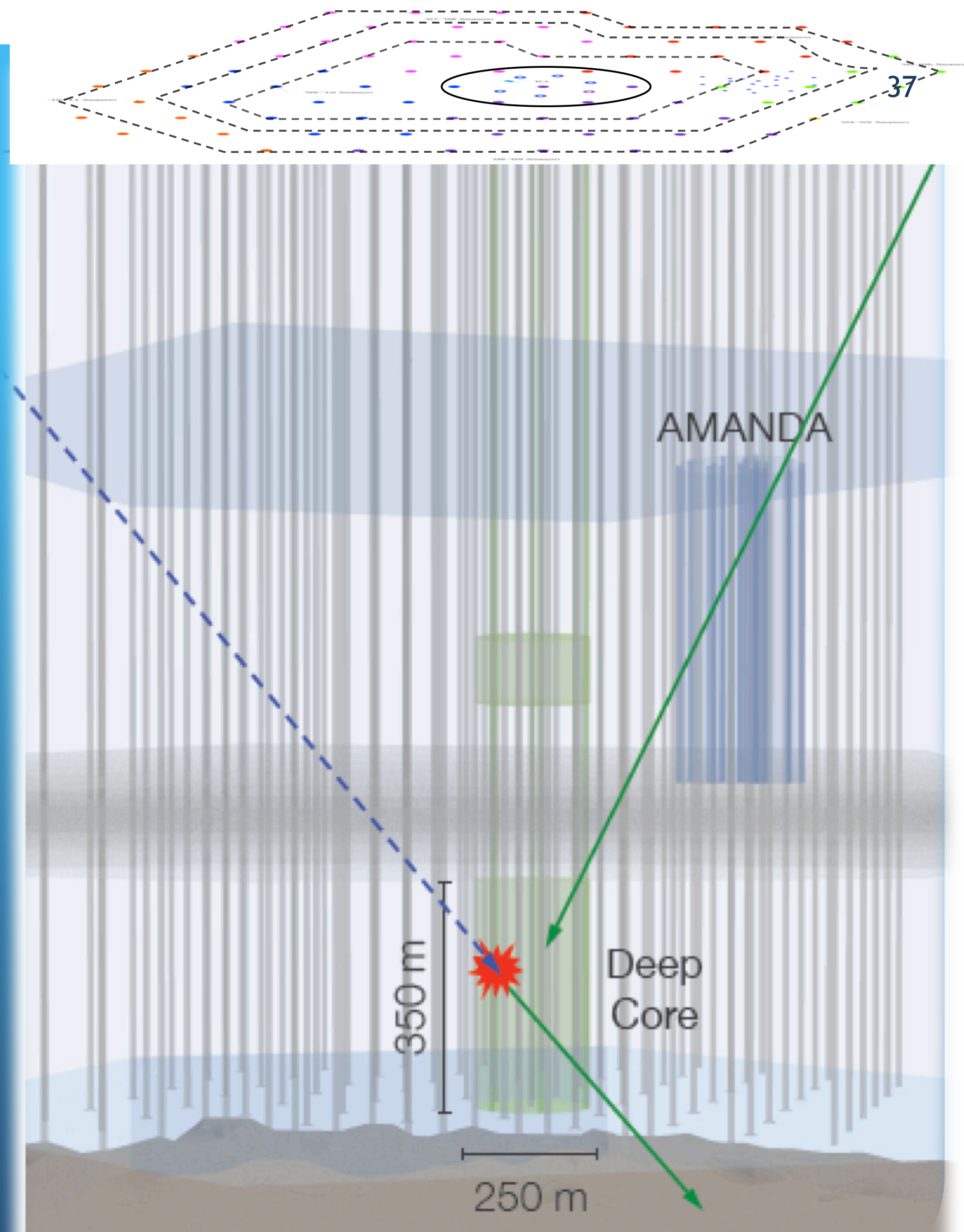
- The Deep Core subdetector has recently been completed and will become operational in spring 2010
- It consists of six special strings plus 7 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing on string
- High Q.E. PMTs (~40% better)
  - ~5x higher eff. photocathode density
- 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
  - Three 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





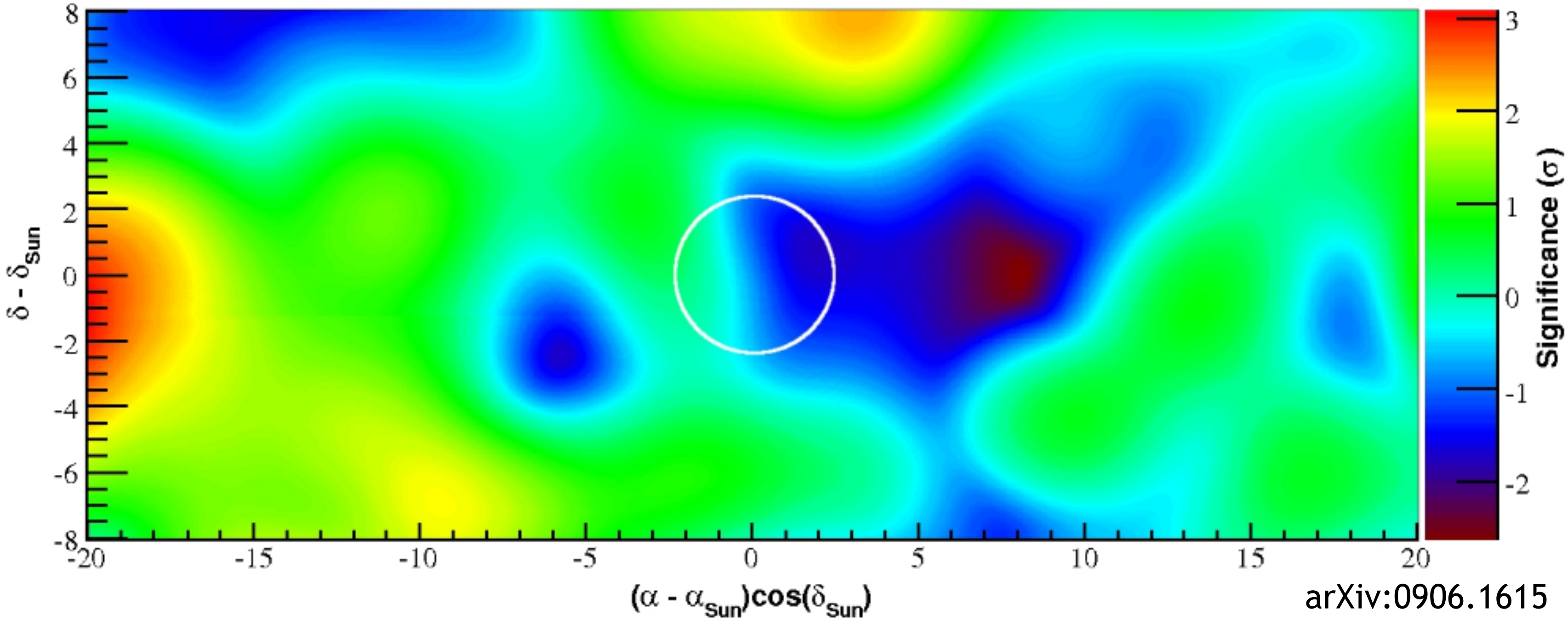
Conclusions

- Neutrino Searches can be used to constrain both the WIMP-proton scattering cross section (Solar WIMPs) and the self-annihilation cross section (Galactic Halo)
- IceCube currently provides the worlds best constrain on the Spin dependent WIMP-proton cross section for WIMPs in the 100GeV-TeV range
- Galactic halo searches can constrain the WIMP self-annihilation cross section significantly
- Using the Galactic center we can tightly constrain the WIMP-self annihilation cross section
- Deep Core has been deployed and has been performing well during its commissioning, it will be fully integrated in IceCube physics data taking in April
- Deep Core will significantly increase IceCube sensitivity to WIMP masses around and below 100GeV

Backup Slides

Sun-Centered Skymap – AMANDA II

AMANDA-II
953 days livetime
4665 total events

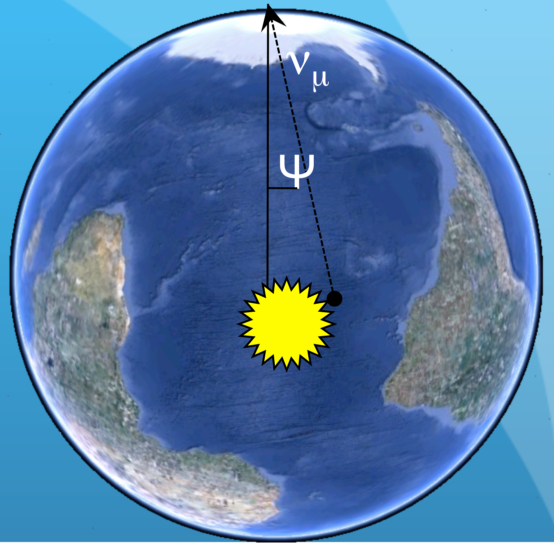


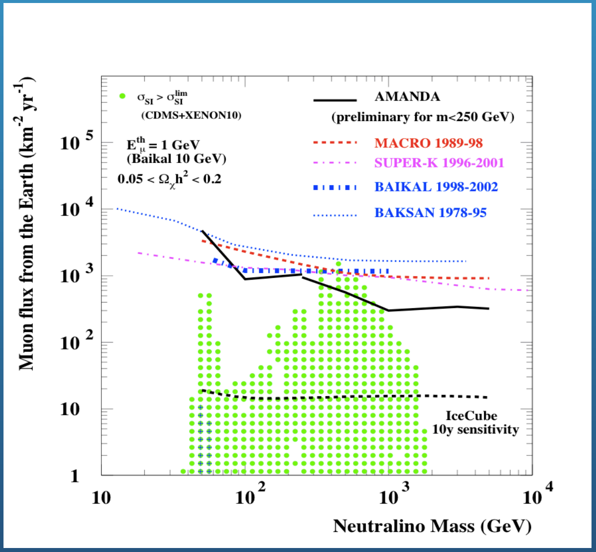
arXiv:0906.1615

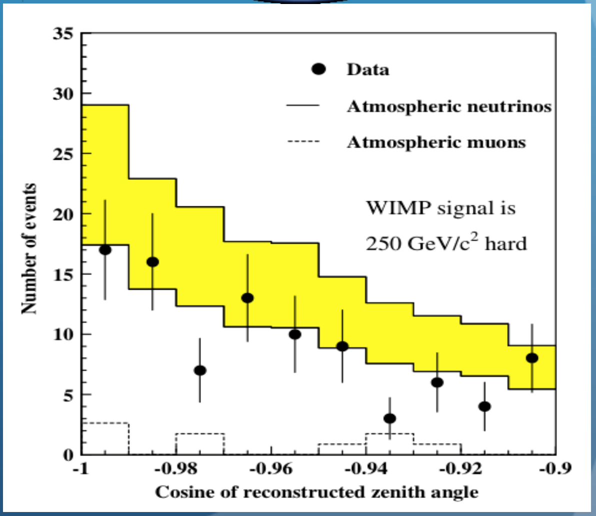
Maximum likelihood search reveals 0.8σ downward fluctuation

WIMPs in the Earth

- WIMP annihilation in the Earth
- Muon neutrinos provide good pointing resolution



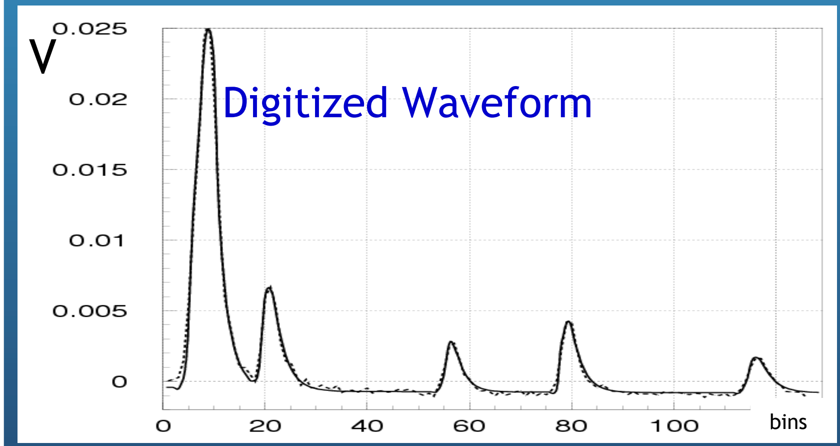




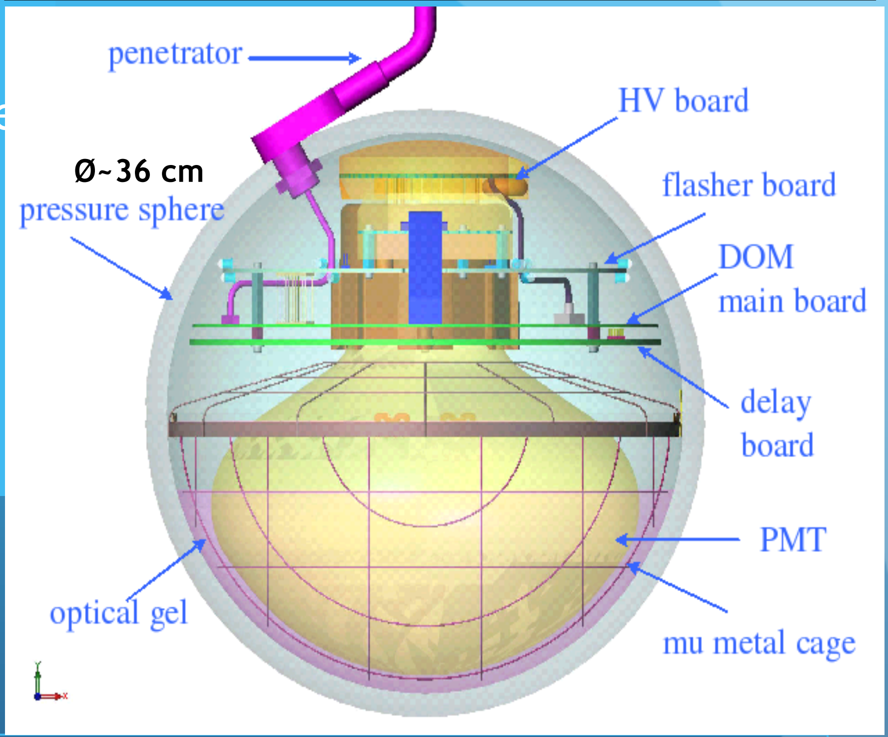
Digital Optical Module (DOM)

Measure individual photon arrival time:

- 2 ping-ponged four-channel ATWDs:
  - Analog Transient Waveform Digitize
  - 200-700 Megasamples/s
  - 400 ns range
  - 400 pe / 15 ns
- fADC (fast 'ADC'):
  - 40 Megasamples/s
  - 6.4 μs range



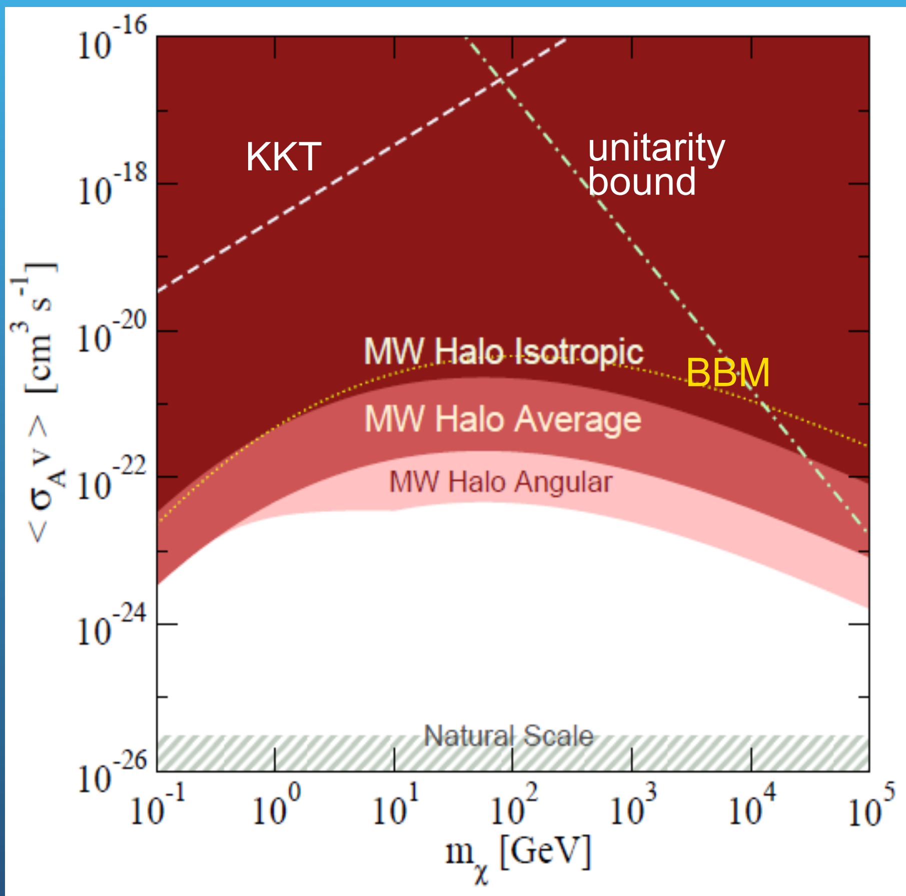
10 inch Hamamatsu PMT (R-7081-02)



- Dark Noise rate ~ 350 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2 ns

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

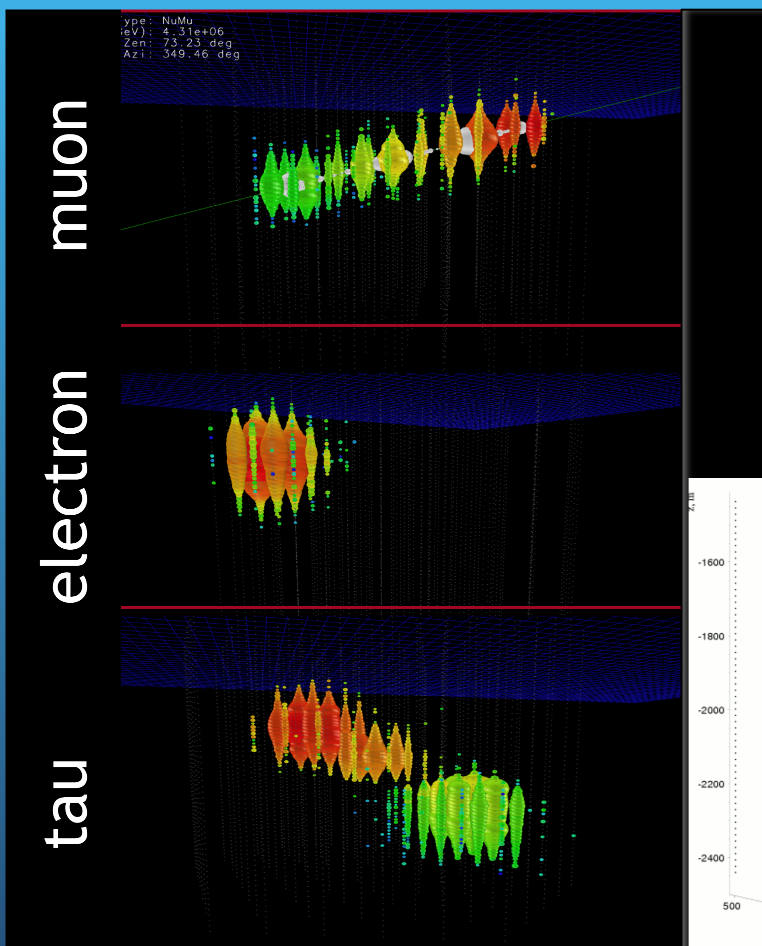
Yuksel, Horiuchi, Beacom, Ando (2007)



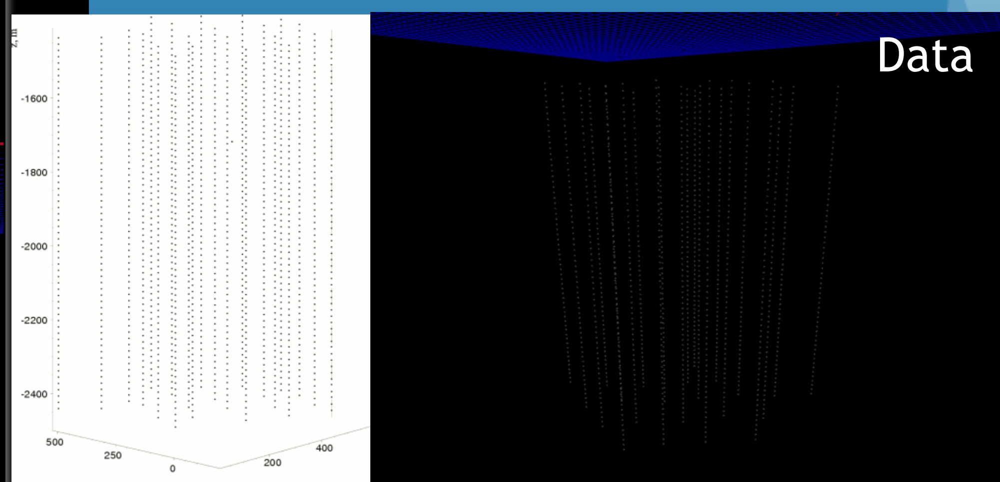
- Theoretical/cosmological constraints:
  - KKT - Kaplinghat, Knox, Turner (2000)
    - "DM annihilation flattens cusp"
  - Unitarity bound
    - Unitarity of the scattering matrix
  - Natural scale
    - DM is thermal relic of early universe
- Derived limits/sensitivity:
  - BBM - Beacom, Bell, Mack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

Neutrino Detection - Examples

Simulation



- ν_μ produce long μ tracks
  - Angular resolution ~ 1^0
- ν_e CC, ν_x NC cause showers
  - ~ point sources ->'cascades'
    - Good energy resolution
- ν_τ 'double bang events
  - Other ν_τ topologies under study



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

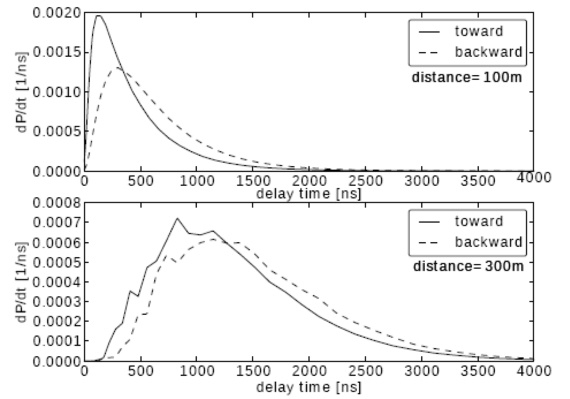
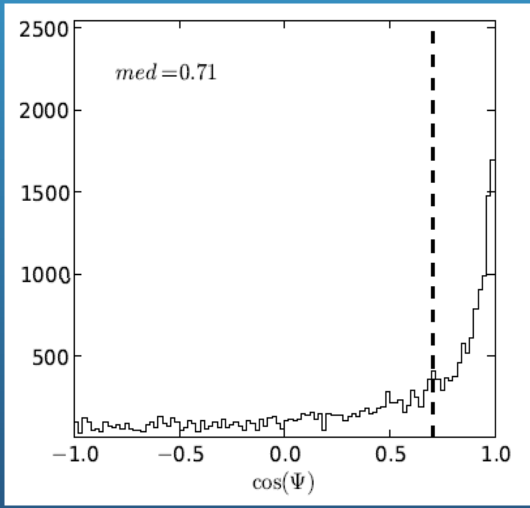
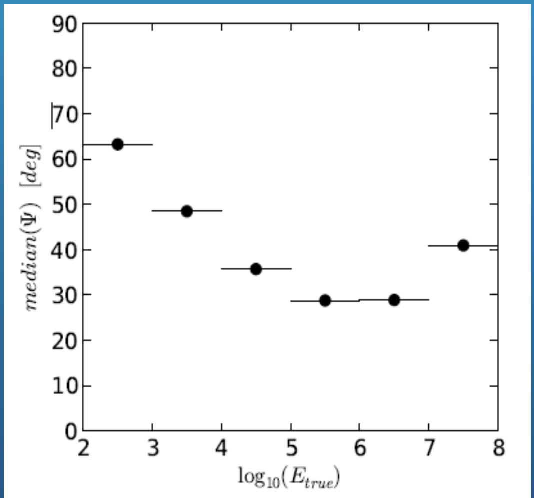


Fig. 1. Tabulated delay time distributions for a DOM at 100 m and 300 m distance to the cascade. The distributions are shown for two orientations of the cascade, pointing either toward or away from the DOM. Photons are increasingly delayed if they either travel larger distances or have to be backscattered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





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

For 40 string detector study case

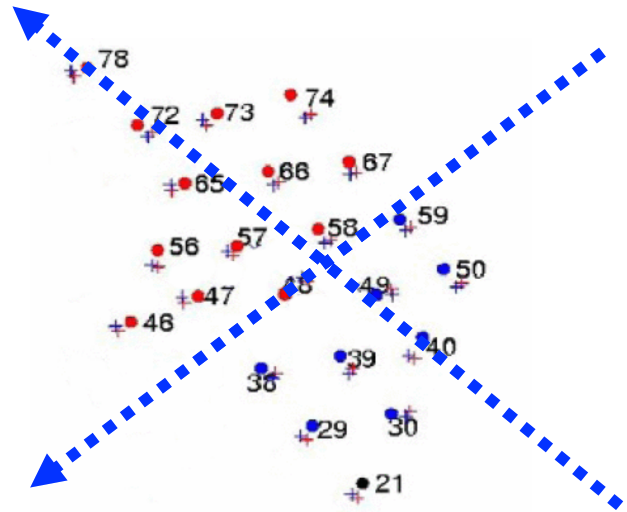
E.Middell, J. McCartin, M.D'Agostino [IceCube], ICRC 2009

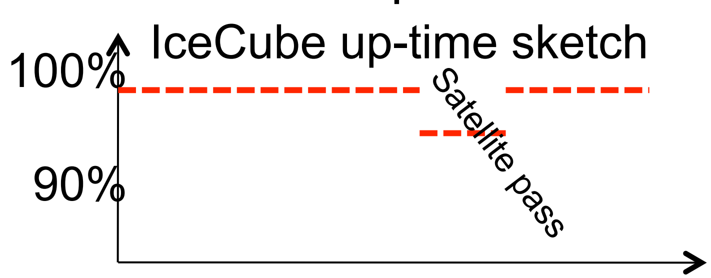
Systematic uncertainties Halo Analysis

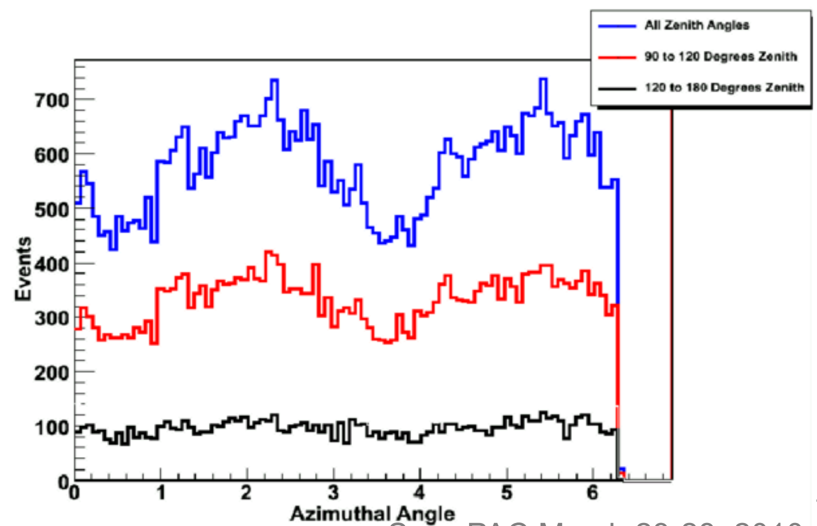
- Signal acceptance:
  - Uneven “exposure” (negligible)
  - Ice properties / DOM efficiency (~20%)
  - MC/data disagreement (horizontal events)
- Background:
  - Majority of systematics cancel out (as we use the data itself)
  - “existing” large scale anisotropy
    - - Uneven “exposure”
    - - Neutrino anisotropy caused by cosmic ray anisotropy

Systematics 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

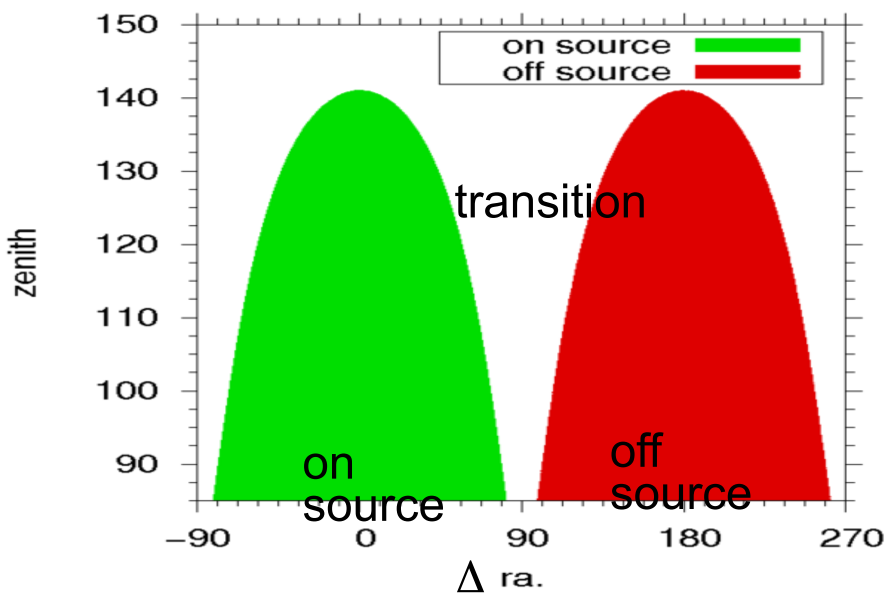


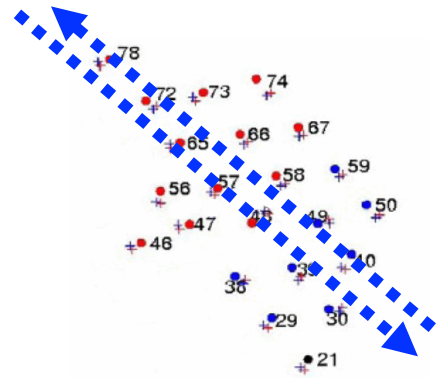


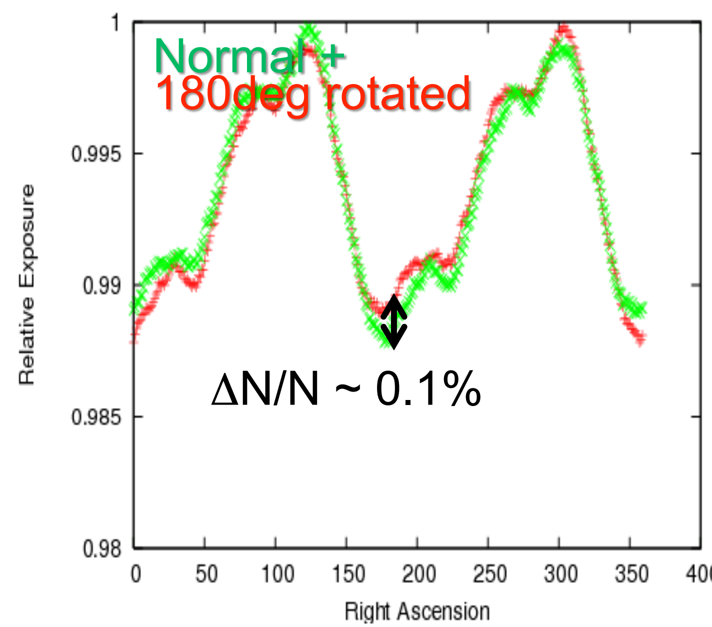


Systematics Uneven exposure

- Track reconstruction efficiency shows “mirror symmetry”

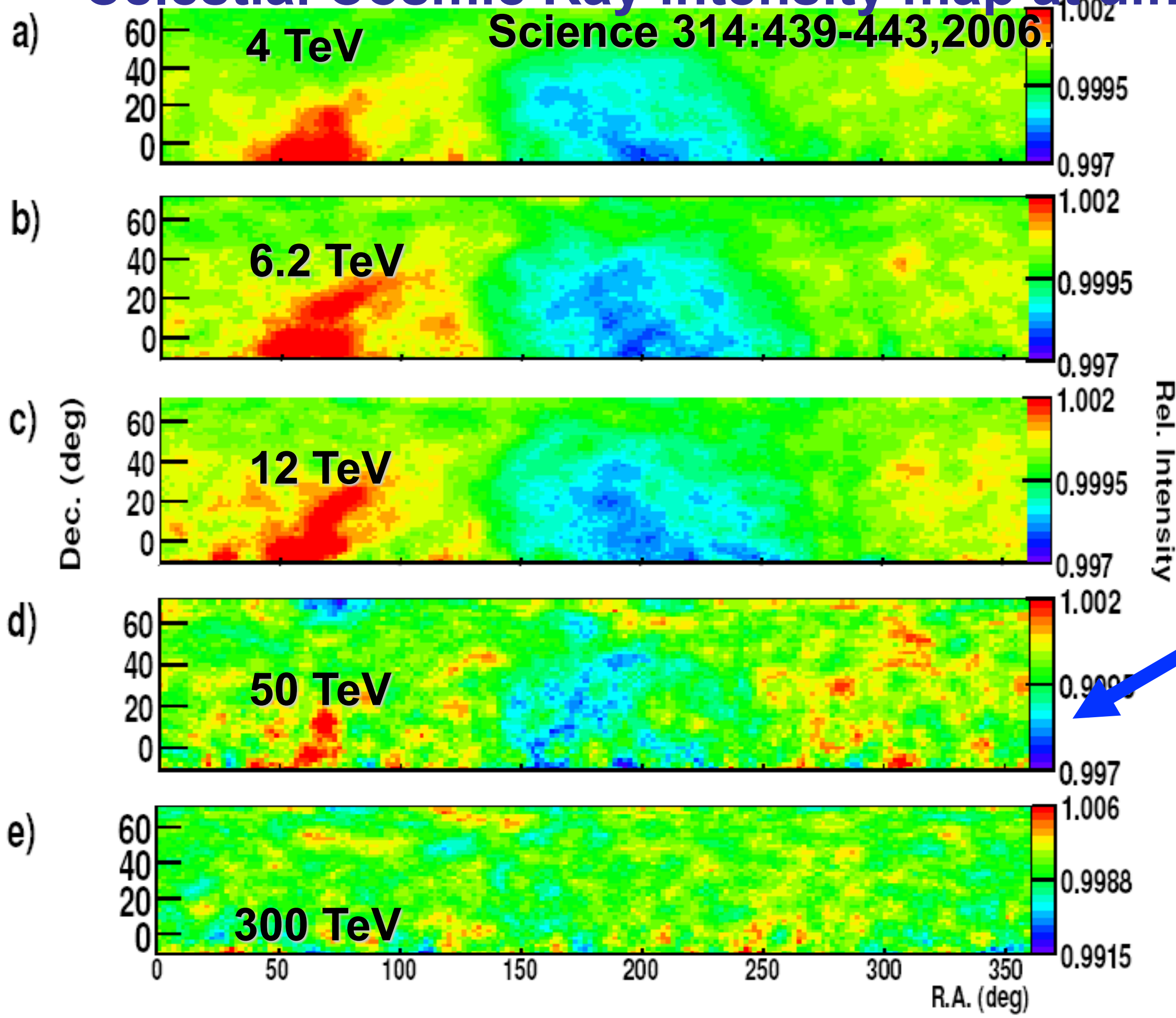






- Uneven exposure systematic uncertainty is on the order of the difference between the two graphs ~0.1%
- **Total systematic effect ~ 3%**

Systemtaics Halo Analysis
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

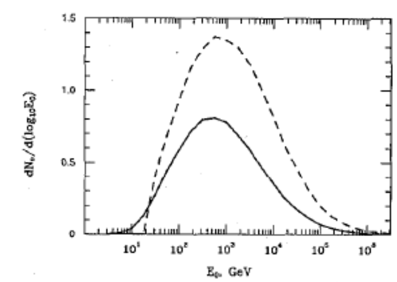


FIG. 1. Primary cosmic-ray nucleon energy contribution to the upward-going neutrino induced muon flux (E_μ >1 GeV). The solid line is for cos(θ)=−1 and the dashed is for cos(θ)=−0.15.

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

See also Abbasi et al ICRC'09

Systematics Halo Analysis - 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