Galactic Halo Analyses

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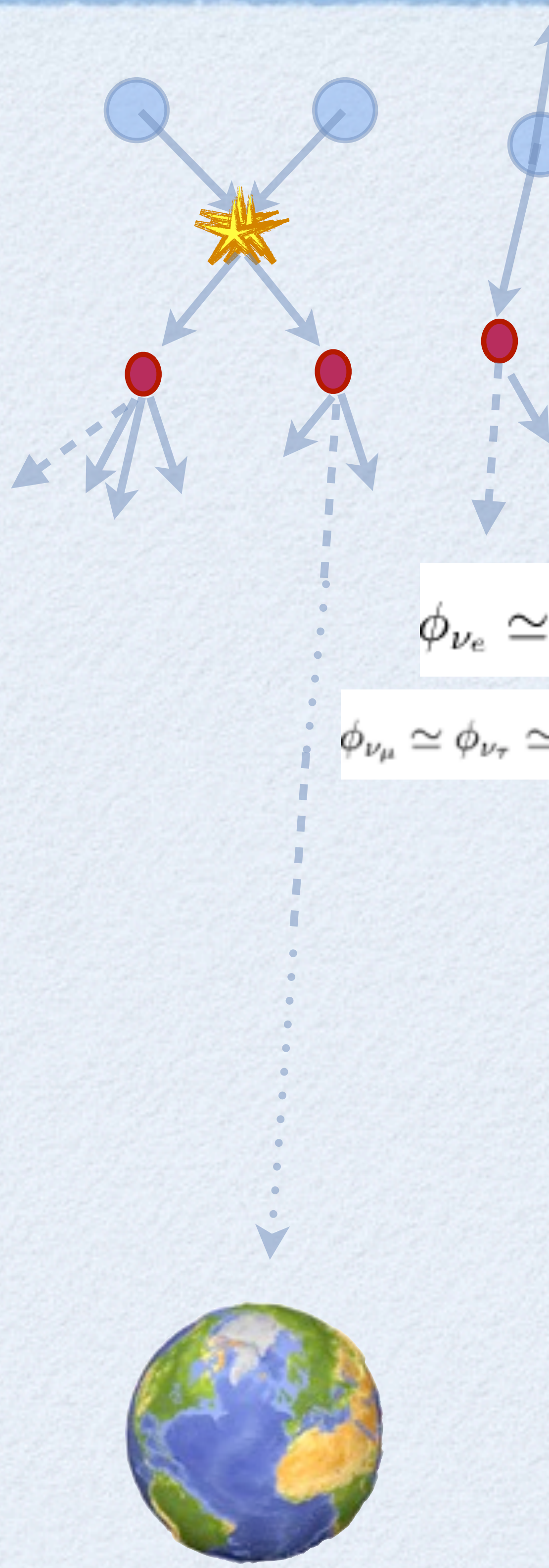
Motivation

- Signal from the Galactic Halo can be used to test the dark matter self-annililation cross section
- Neutrinos search can be used to cover entire WIMP mass spectrum
- Result are (completely) model independent

Expected Signal

- Dark Matter Self-annihilation
  - $N \sim \varrho^2$
- Dark Matter Decays
  - $N \sim \varrho$



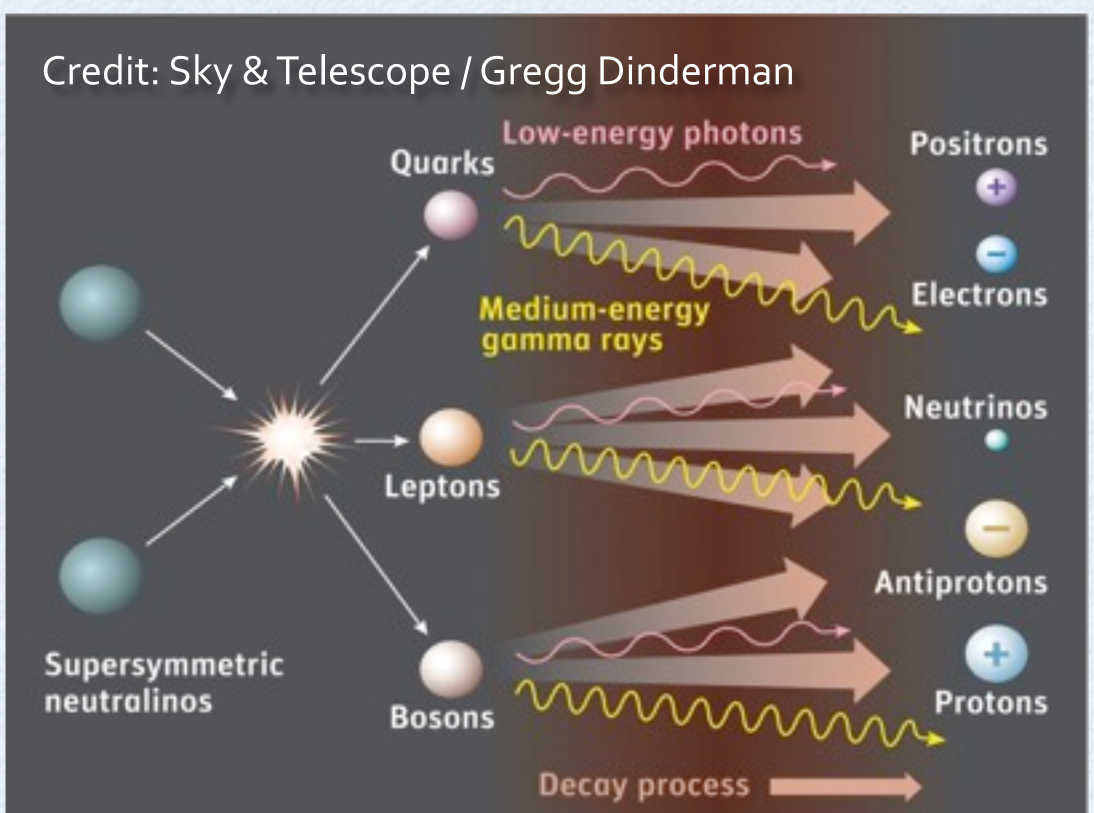
$\chi\chi \rightarrow \{\mu\mu, \tau\tau, WW, bb, ...\} \rightarrow \nu\nu$

Neutrino oscillations in the long-baseline limit

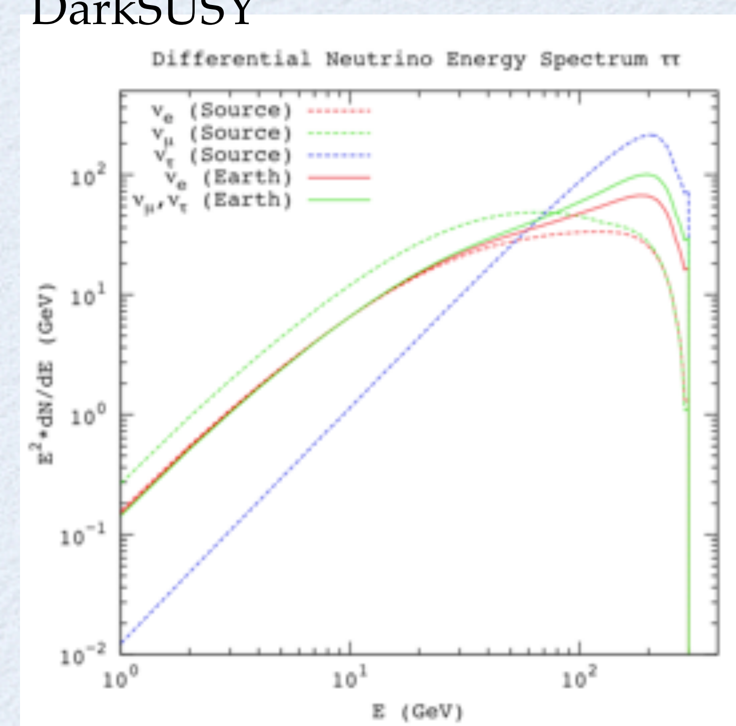
$$\phi_{\nu_e} \simeq \phi^0_{\nu_e} - \frac{1}{4} sin^2 2\Theta_{12}(2\phi^0_{\nu_e} - \phi^0_{\nu_\mu} - \phi^0_{\nu_\tau})$$

$$\phi_{\nu_\mu} \simeq \phi_{\nu_\tau} \simeq \frac{1}{2}(\phi^0_{\nu_\mu} + \phi^0_{\nu_\tau}) + \frac{1}{8} sin^2 2\Theta_{12}(2\phi^0_{\nu_e} - \phi^0_{\nu_\mu} - \phi^0_{\nu_\tau})$$

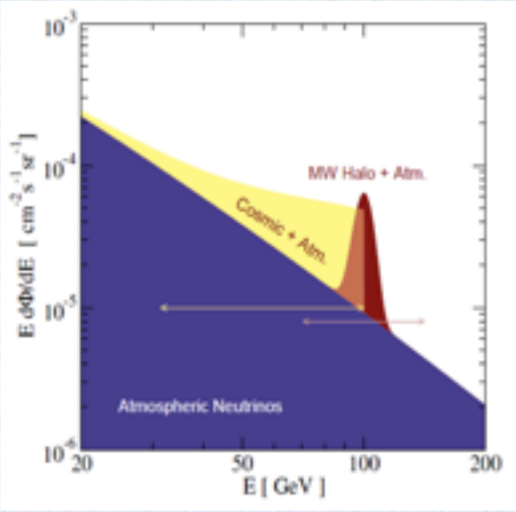
Phys. Rev. D 67, 073024 (2003)



DarkSUSY



overview



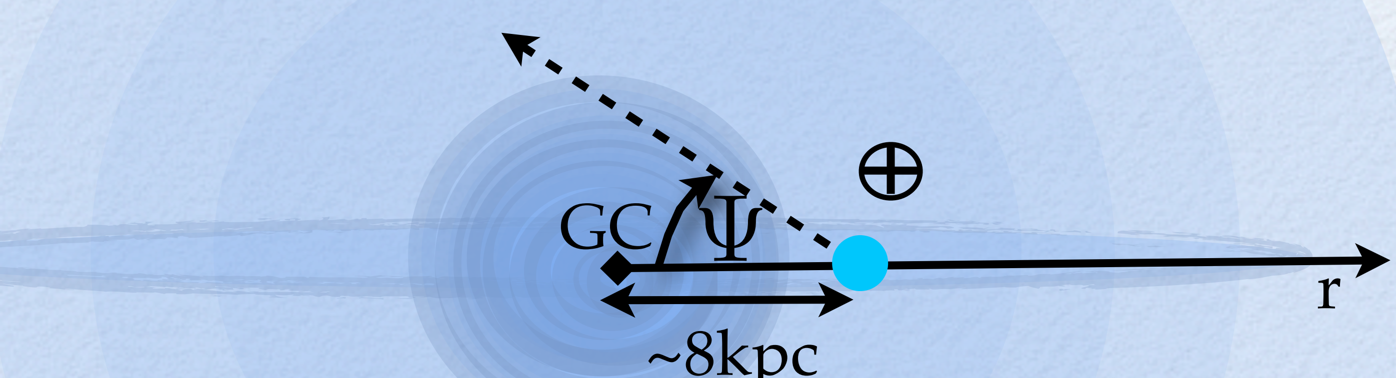
- Extragalactic
  - **Beacom et al., Phys. Rev. Lett. 99, 231301 (2007)**
- Milky Way Halo
  - **Yuksel et al., Phys. Rev. D 76, 123506 (2007)**
- Galactic Center
  - **Yuksel et al., Phys. Rev. D 76, 123506 (2007)**
  - **Mandal et al., Phys. Rev. D81, 043508 (2010)**
- Dwarf Spheriodal Galaxies

✓ IceCube 22-strings
  - **Phys.Rev.D84:022004,2011**

✓ IceCube 40-strings
  - **J-P Huelss, PhD Thesis 2010**
  - **Bissok, Boersma, Huelss, Rott ICRC 2011**
- IceCube 59-strings
  - **Luenemann, Rott ICRC 2011**

Dark Matter in the Milky Way

- N-body simulations of Milky Way like galaxies yield halo profiles
- Outer halo relatively well understood
- Inner halo still subject of debates (cusp-core problem)



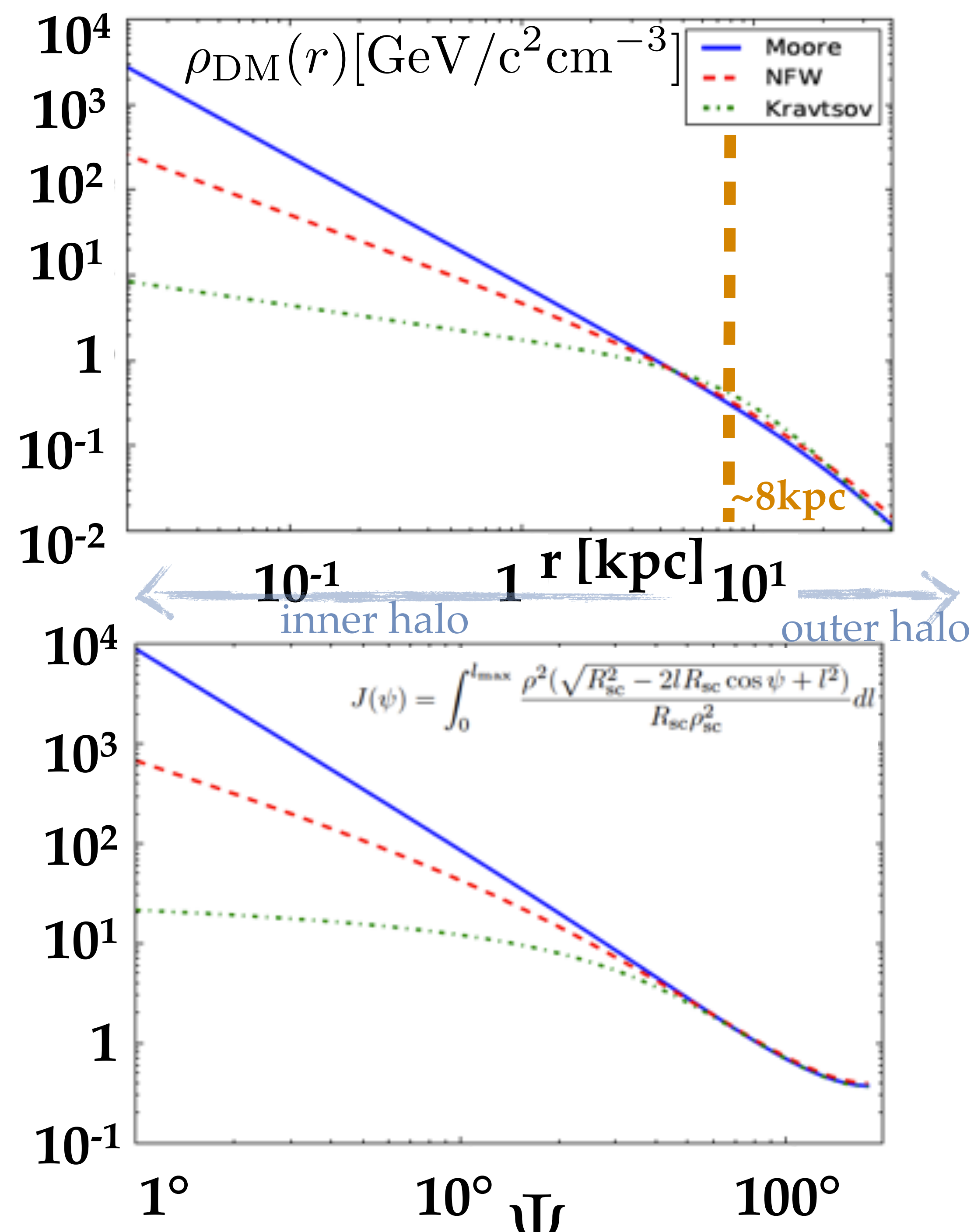


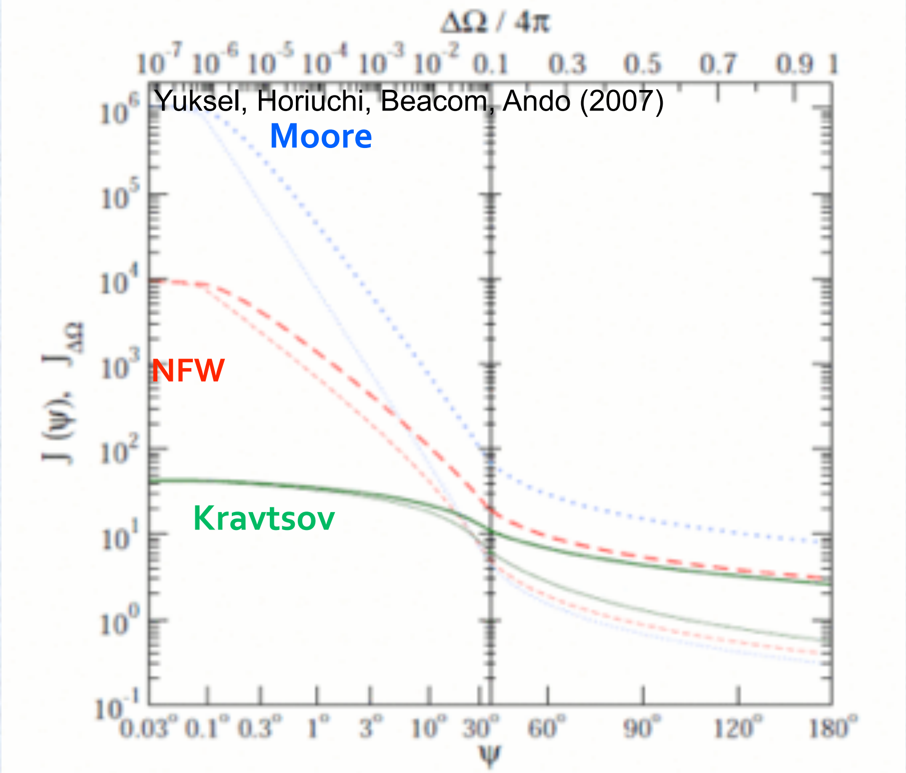
Figure 2: $J(\Psi)$ is shown for the NFW, Moore, and Kravtsov profile.

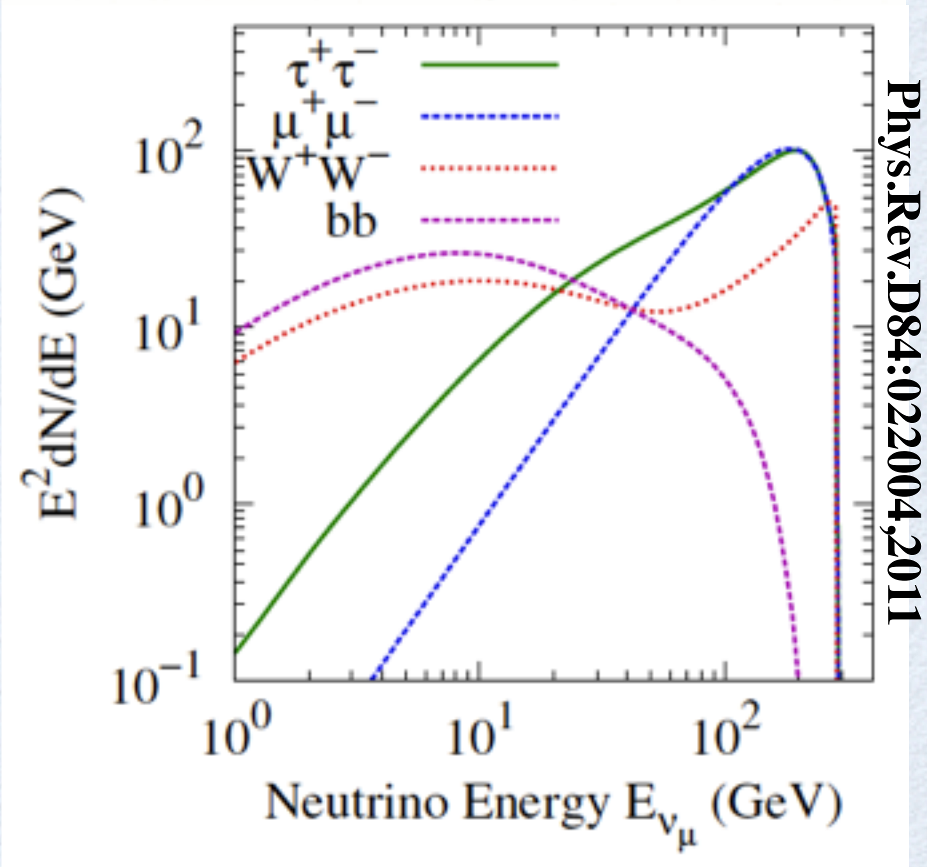
J. Einasto, Trudy Inst. Astroz. Alma-Ata 5, 87 (1965), Navarro, Frenk, White, *Astrophys. J.* ***490, 493–508 (1997)***, Moore, et al. Mon. Not. Roy. Astron. Soc. 310, 1147 (1999) [arXiv:astro-ph/9903164], Kravtsov et al. Astrophys. J. 502, 48 (1998) [arXiv:astro-ph/9708176].

Expected Signal

$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

- Under assumption of a dark matter distribution and annihilation channel, the dark matter self-annihilation cross section can be tested

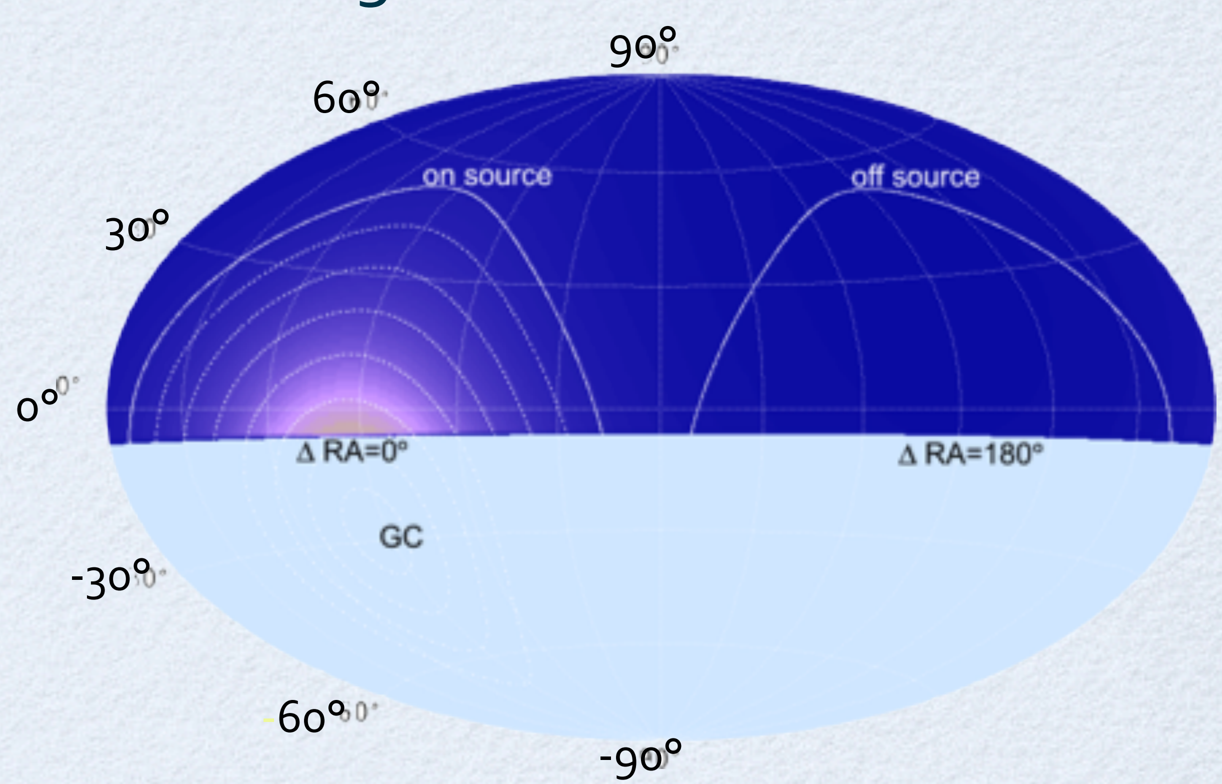




IC22 Data Sample

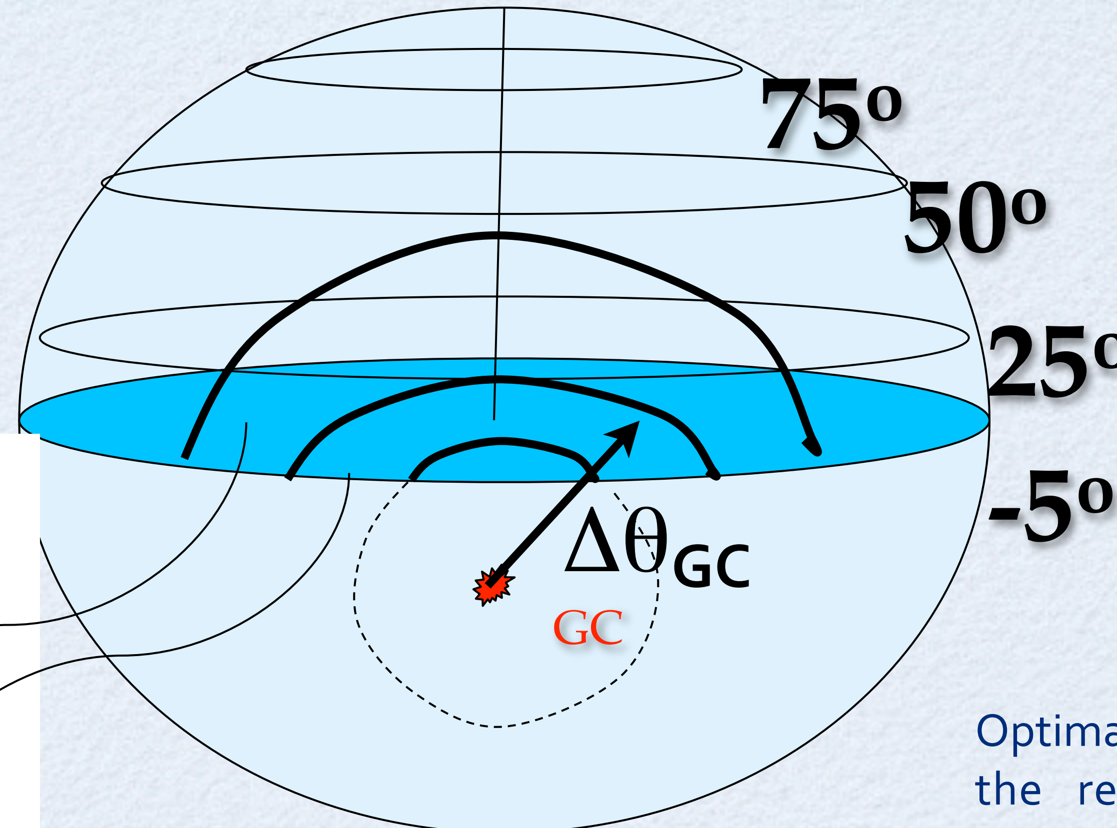
- 275.7 days of livetime collected with IceCube operating in the 22-string configuration (2007-2008)
- Track selection criteria have been well established for the IceCube point source search, for simplicity and minimization of systematic effect we apply the same selection criteria (**Astrophys.J.701:L47-L51,2009**.)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

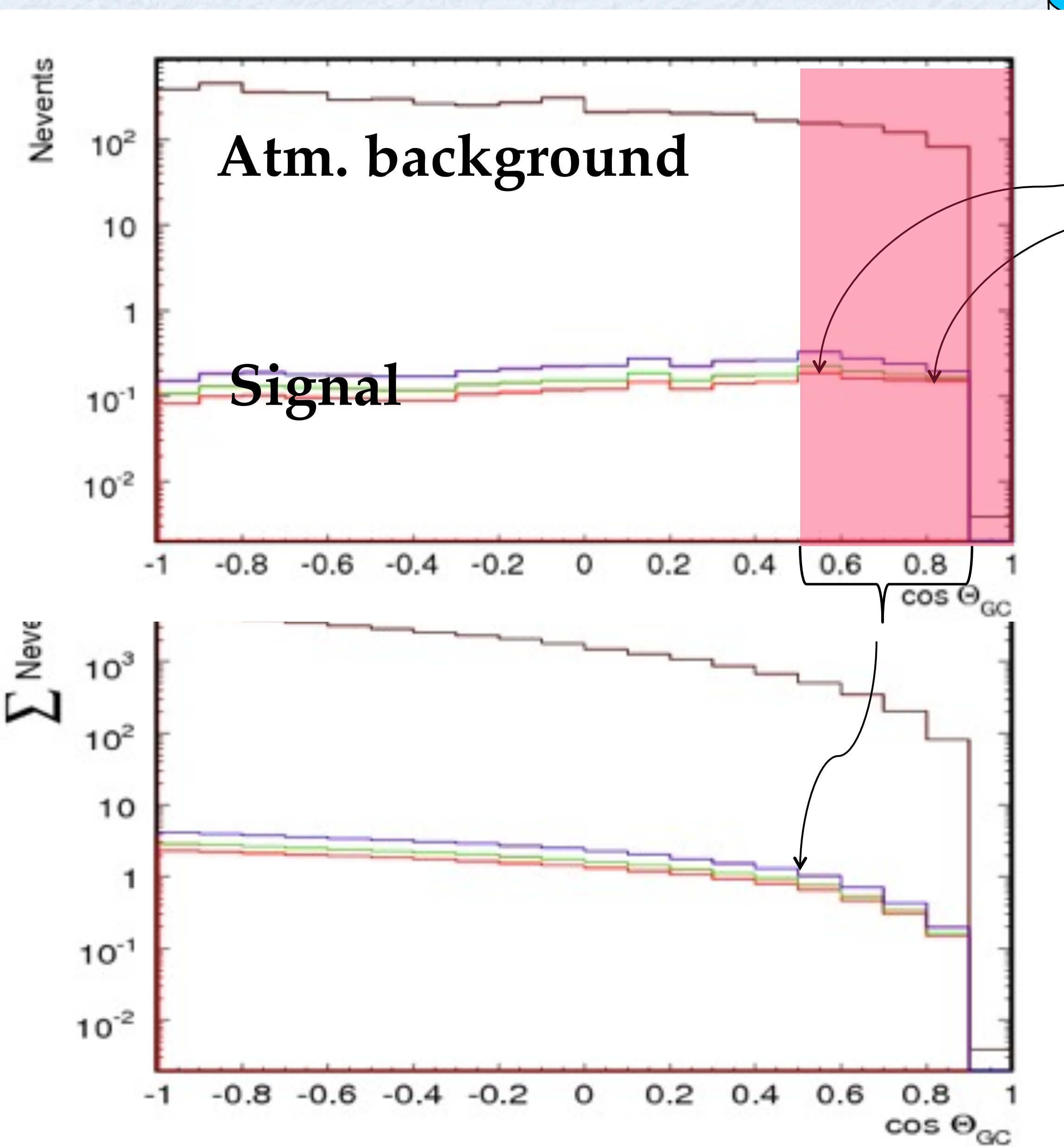
- Use an on and off-source region
  - Set it up so that they are symmetric and shifted by 180° in RA → minimize systematic uncertainty on background estimate



IC22 OPTIMIZATION

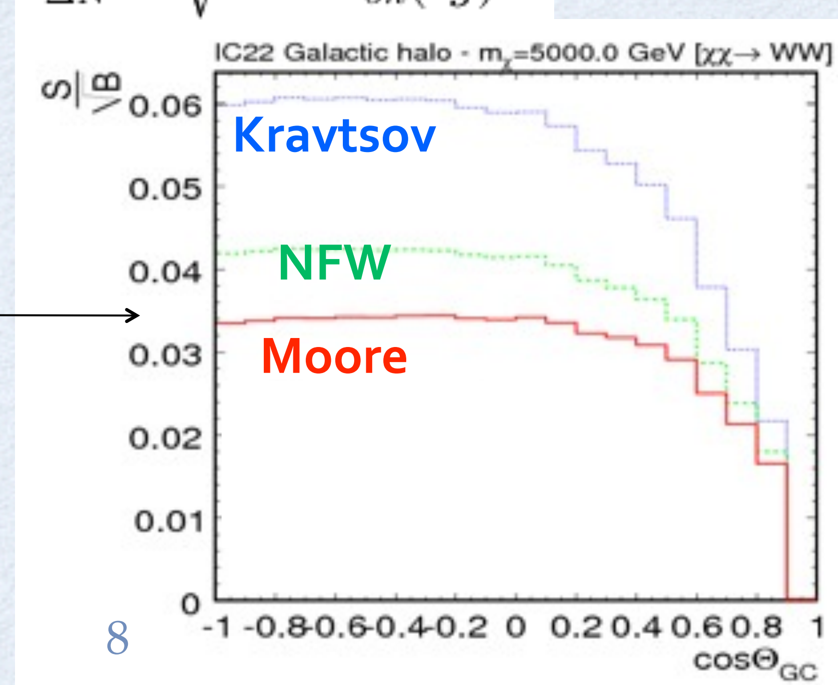
- Optimize as function of distance from GC on Northern Hemisphere
- Optimize --- S/sqrt(B)





$$<\Delta N(bg)> = <Non(bg)> - <Noff(bg) = 0$$

$$\sigma_{\Delta N} = \sqrt{2 < N_{on}(bg) >}$$



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

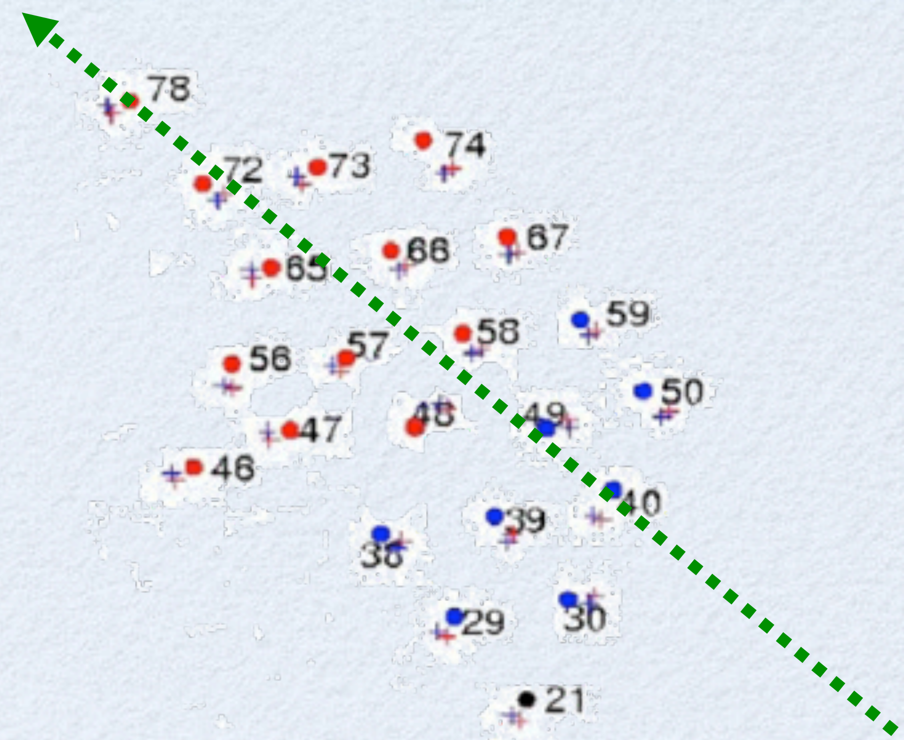
Their overall behavior is however very similar:

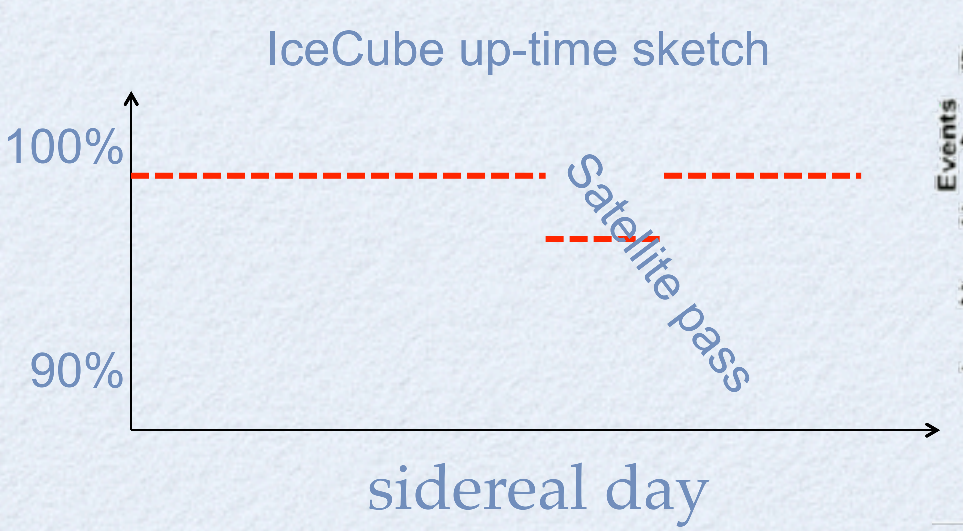
Larger regions are better and S/sqrt(B) flattens out or declines beginning with

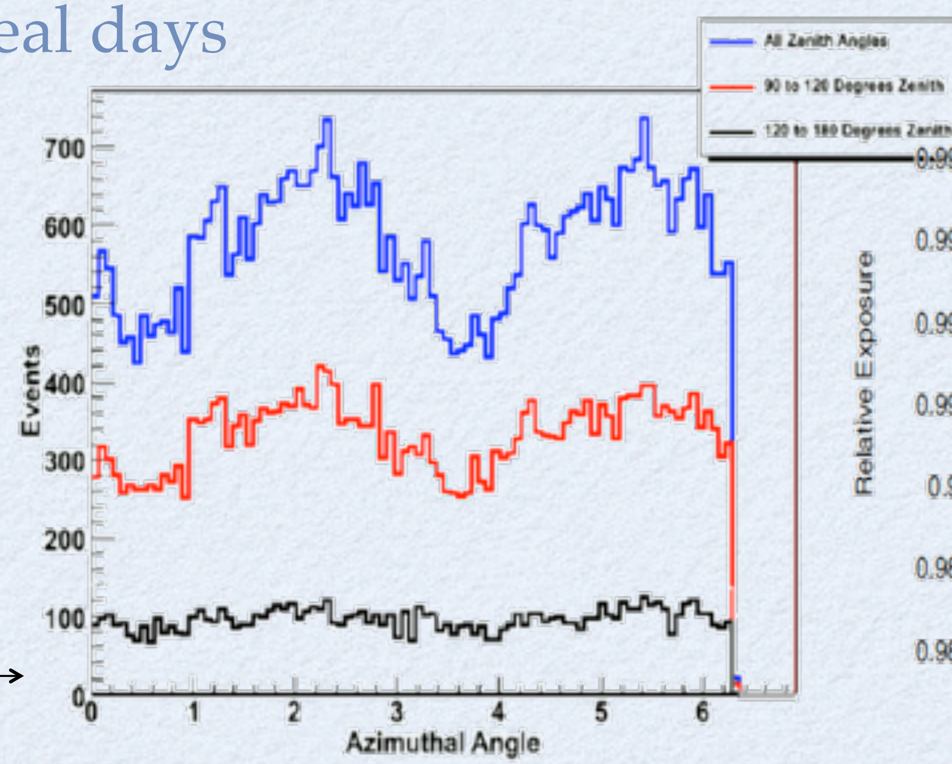
$\Delta\theta_{GC} \sim 80^{o}$

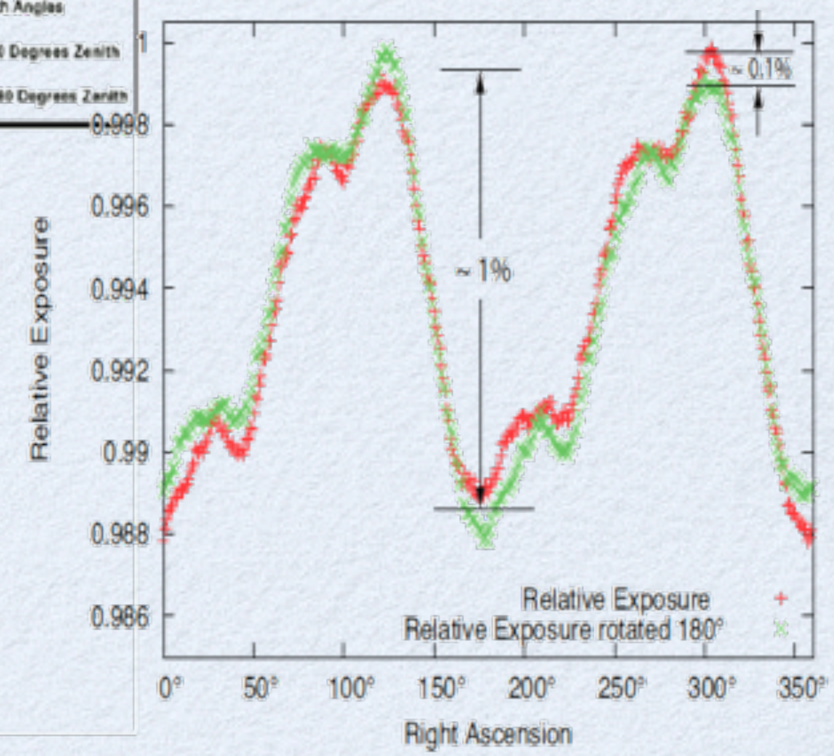
IC22 Uneven Exposure

- 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









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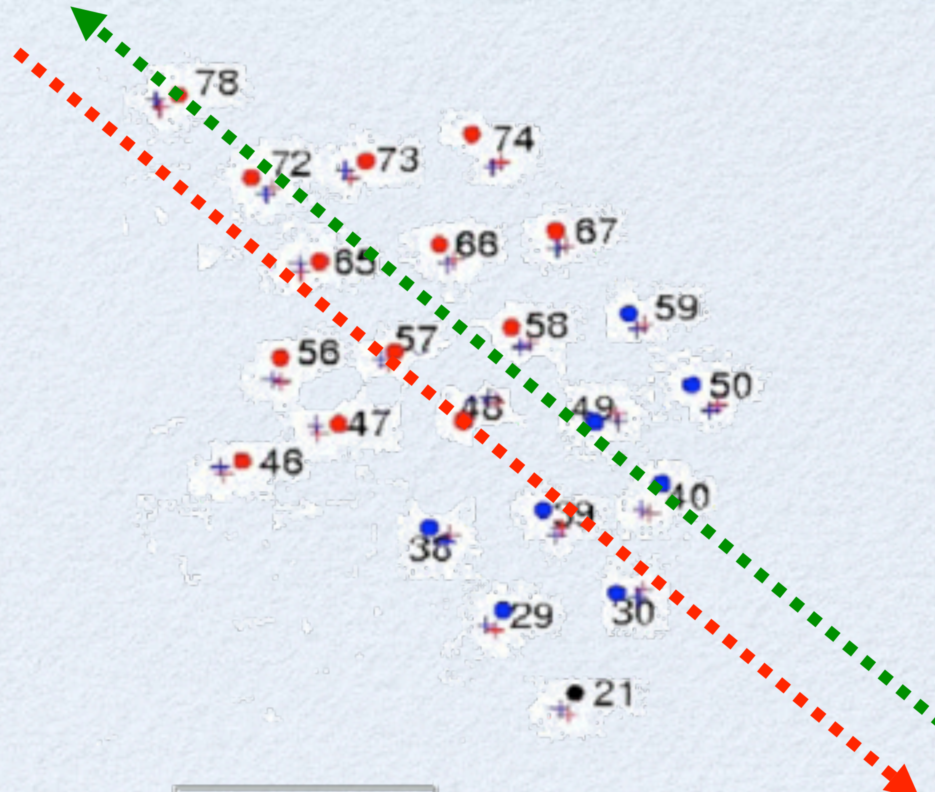

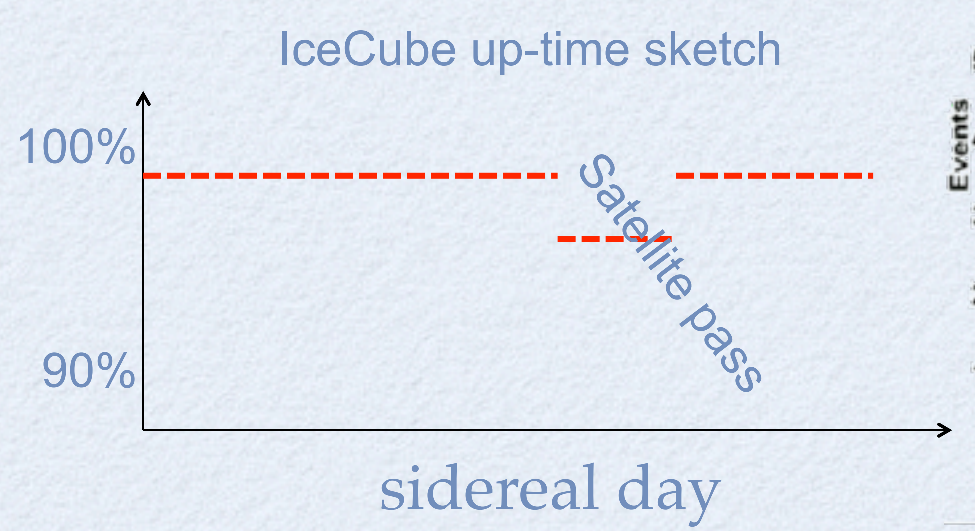

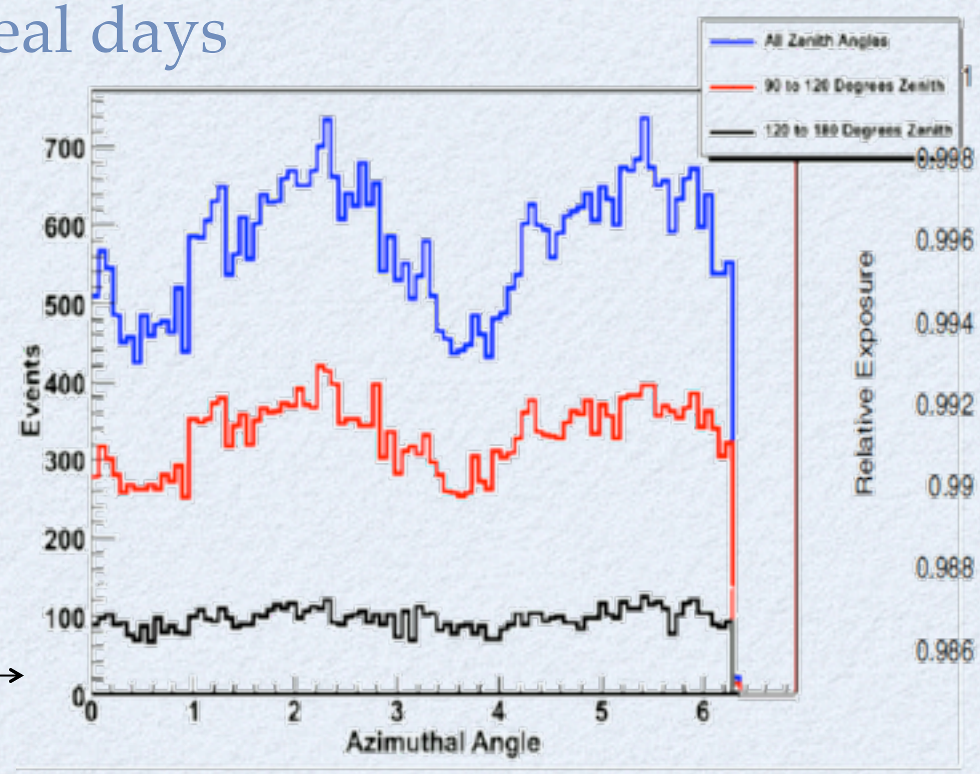

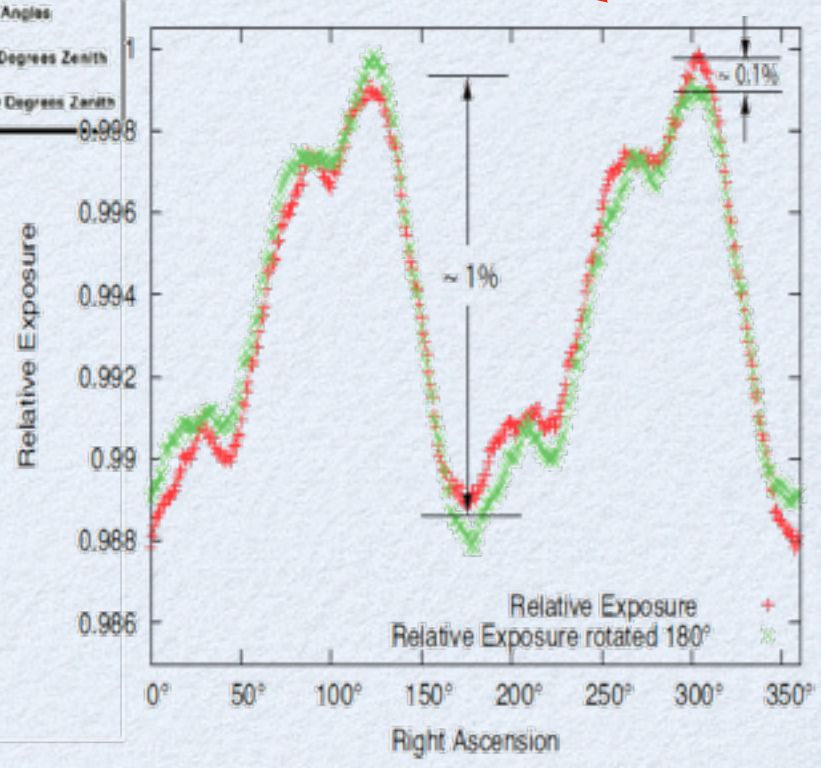

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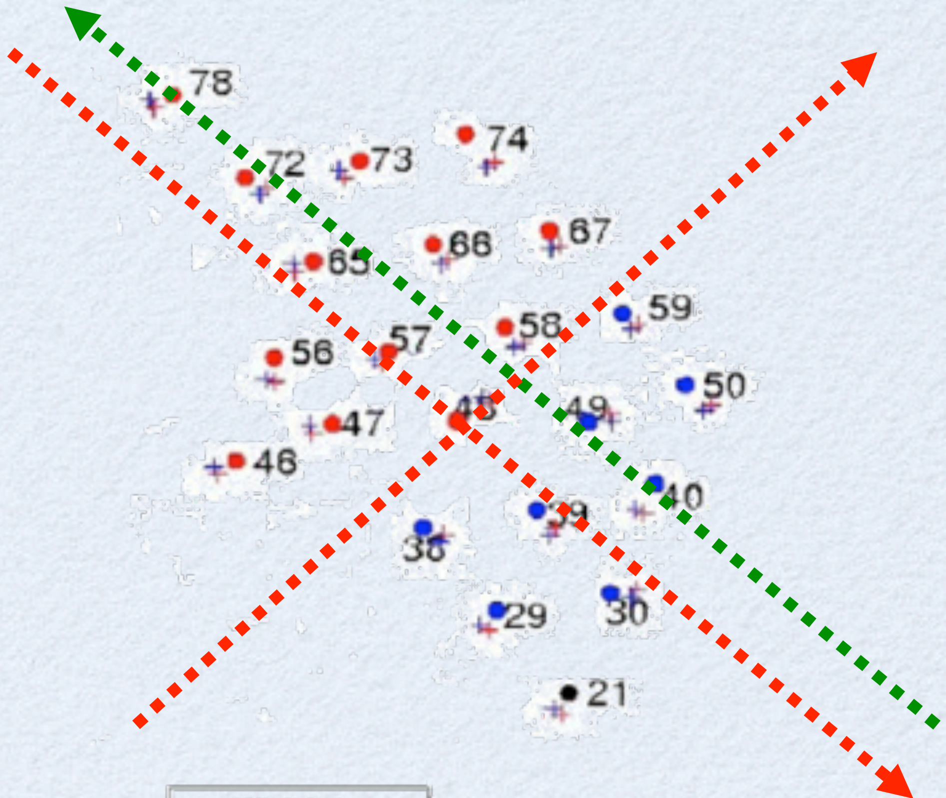
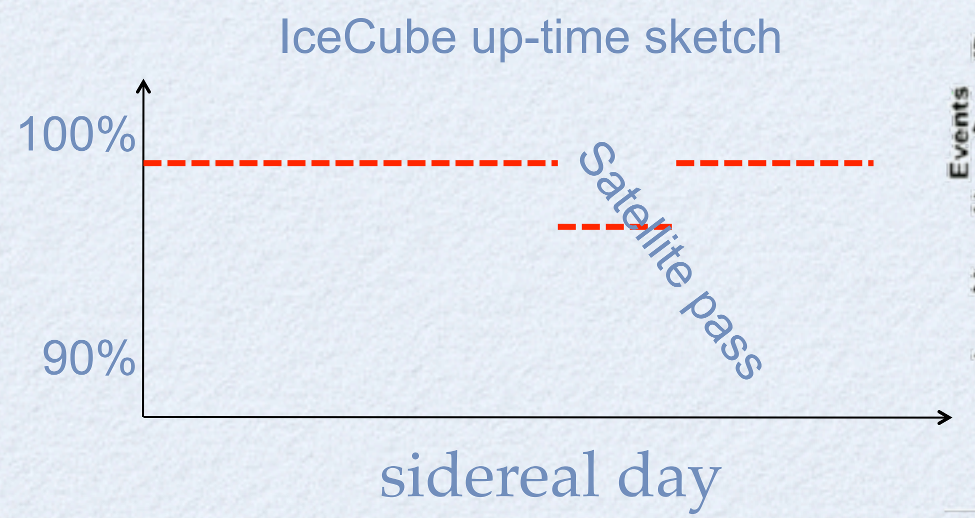
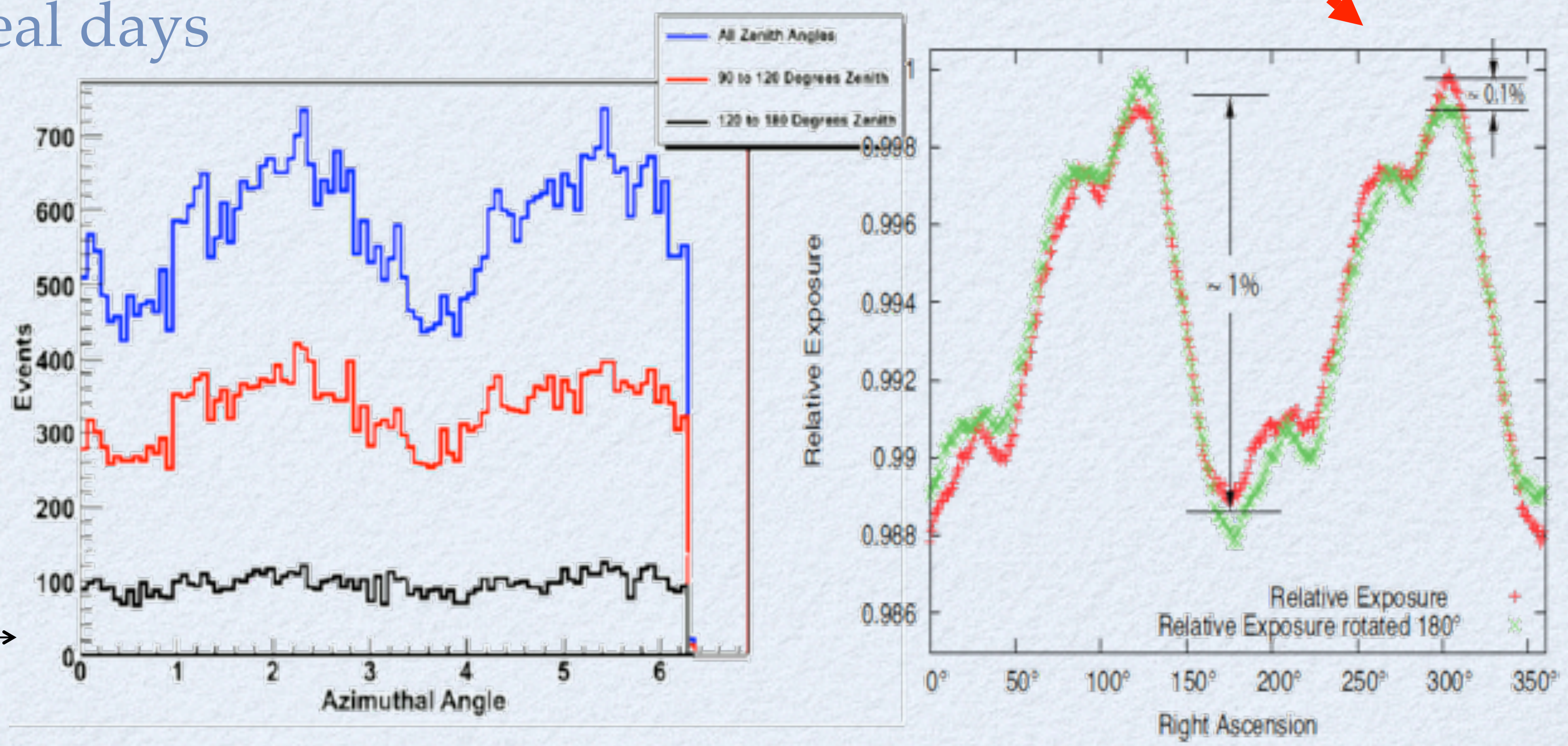
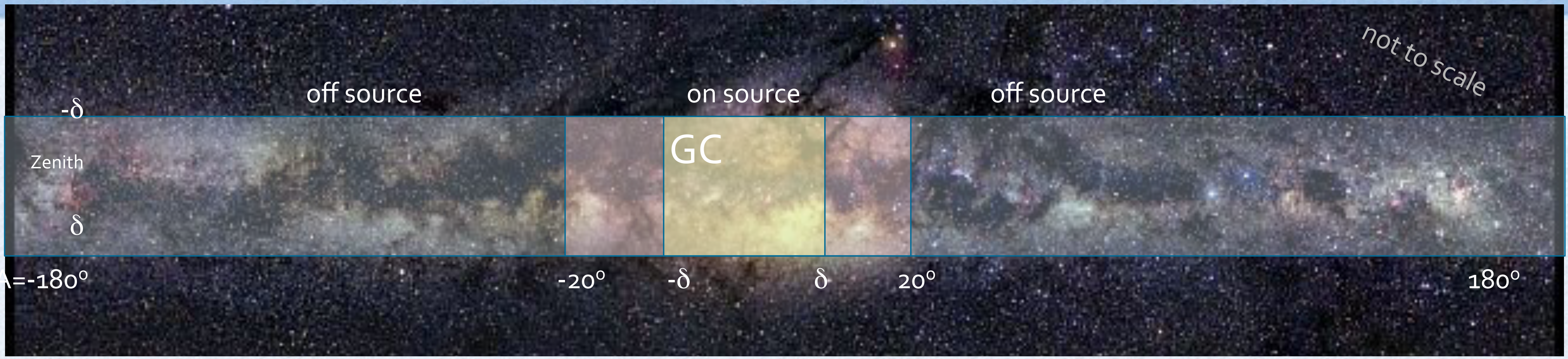


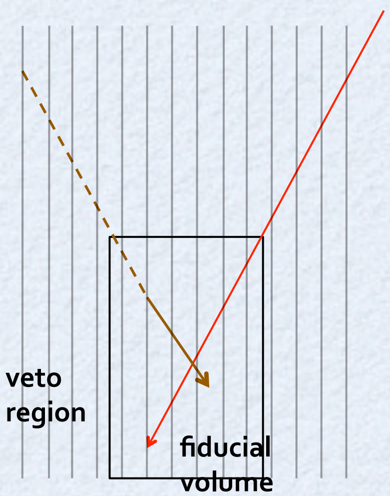


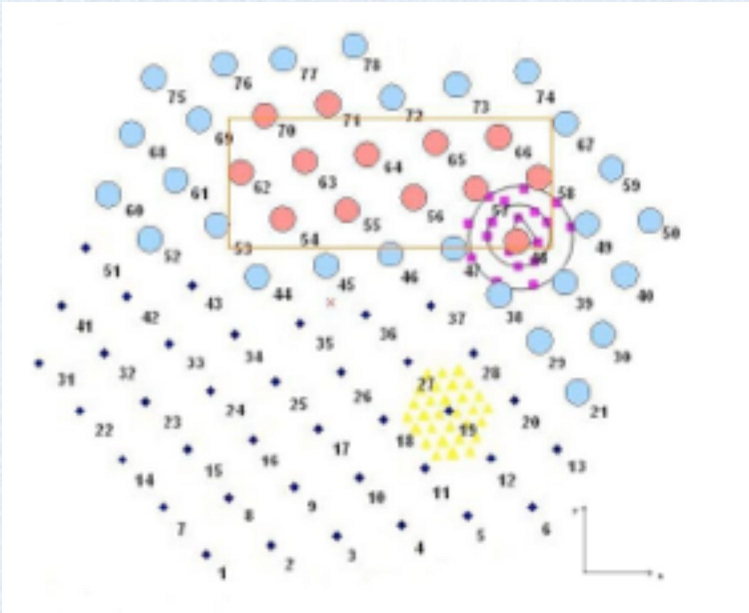


Galactic Center IC40



- Galactic Center is above the horizon → events are down-going in IceCube
  - Use starting events to reduce atmospheric muon background





- Dark Matter profiles are peaked at the Galactic Center
- Optimize the size of the on-source region
  - → $\delta = 8^{o}$
- Compare the amount of events in the on- and off-source region

Milky Way Halo Analyses

Analysis	Galactic Halo	Galactic Center
Detector configuration	22-strings	40-strings
Dataset	275days (June 2007 - March 2008)	367days (April 2008 - May 2009)
Signal	up-going muon neutrino candidate events (-5° - 85° in declination)	down-going muon neutrino candidate events centered around -30° in declination
Neutrino events	through-going	vertex contained
Background estimate	**1389** (dominated by atm. neutrinos)	**798842** (dominated by atm. muons)
Observed	**1367**	**798819**

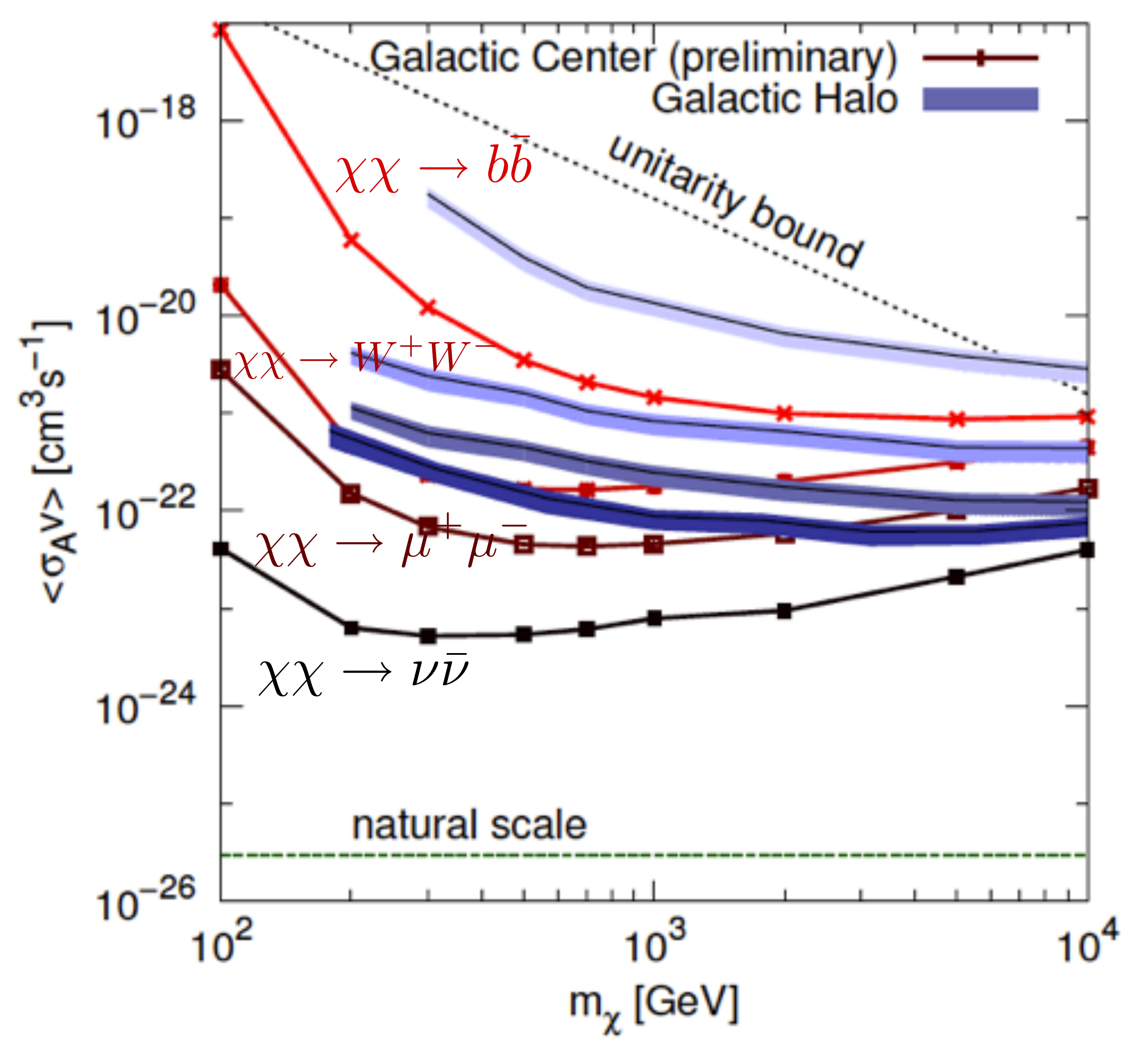
- Observations in both analyses were consistent with background only expectations → constrain the self- annihilation cross section

Results

- Limits computed at 90% C.L. as function of WIMP mass and for various annihilation channels assuming branching fractions of 100%

$$\langle\sigma_A v\rangle_{90} = \Delta N_{90} \times \frac{\langle\sigma_A v\rangle_0}{\Delta N^{\mathrm{sig}}(\langle\sigma_A v\rangle_0)}$$

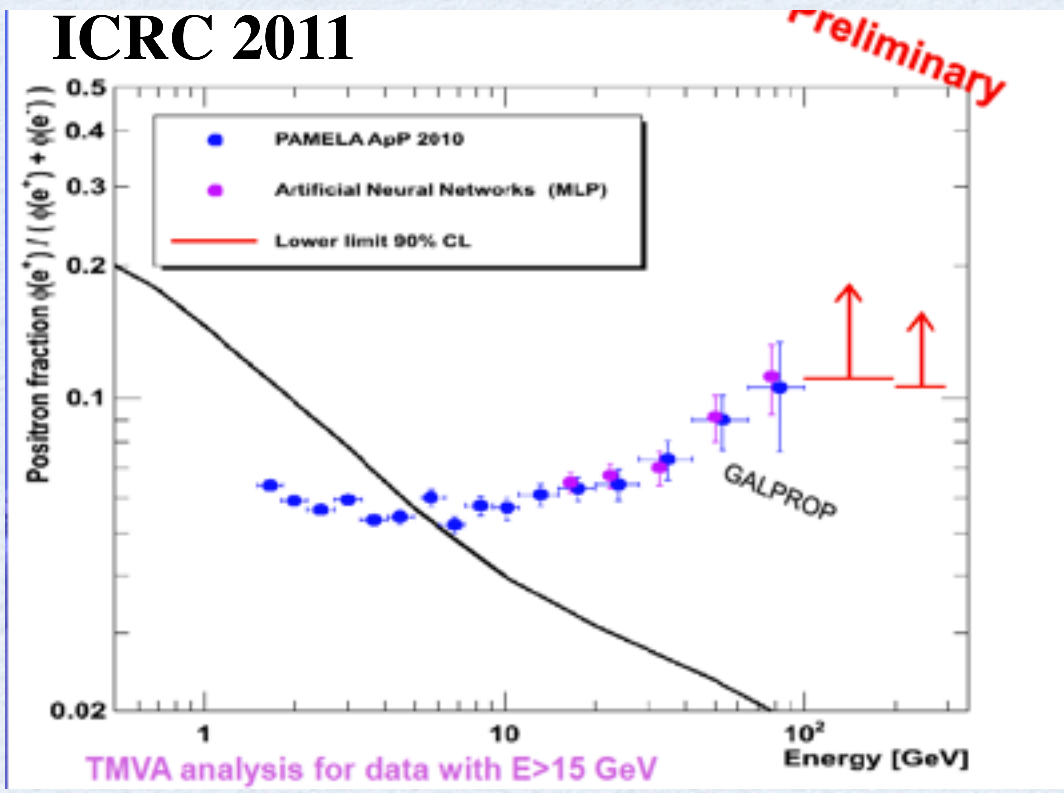
- Bands show uncertainty due to the choice of halo model

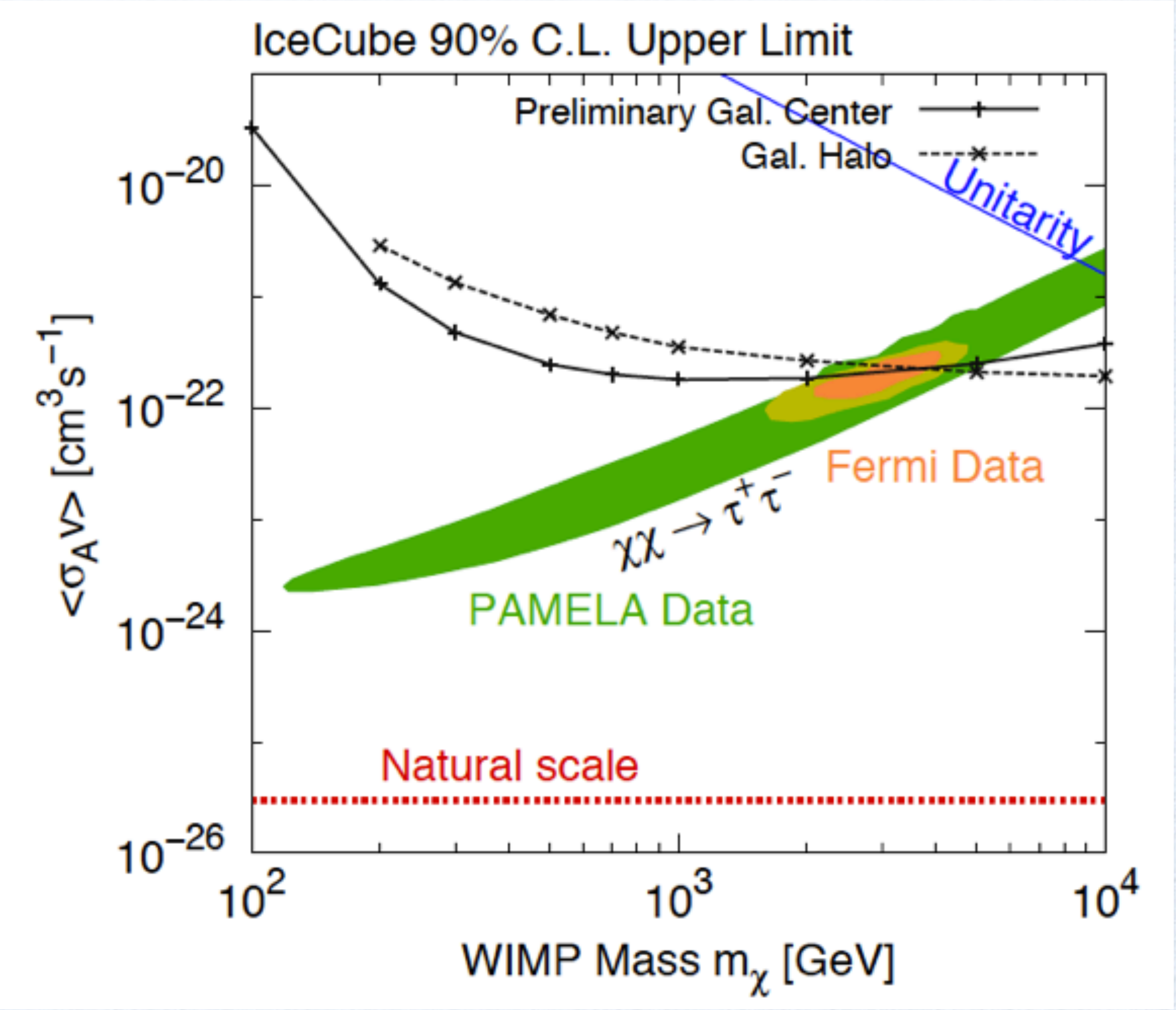


Phys.Rev.D84:022004,2011

Relevance

- Test dark matter models motivated by PAMELA, Fermi, H.E.S.S. data (e.g. Meade et al. 2008)





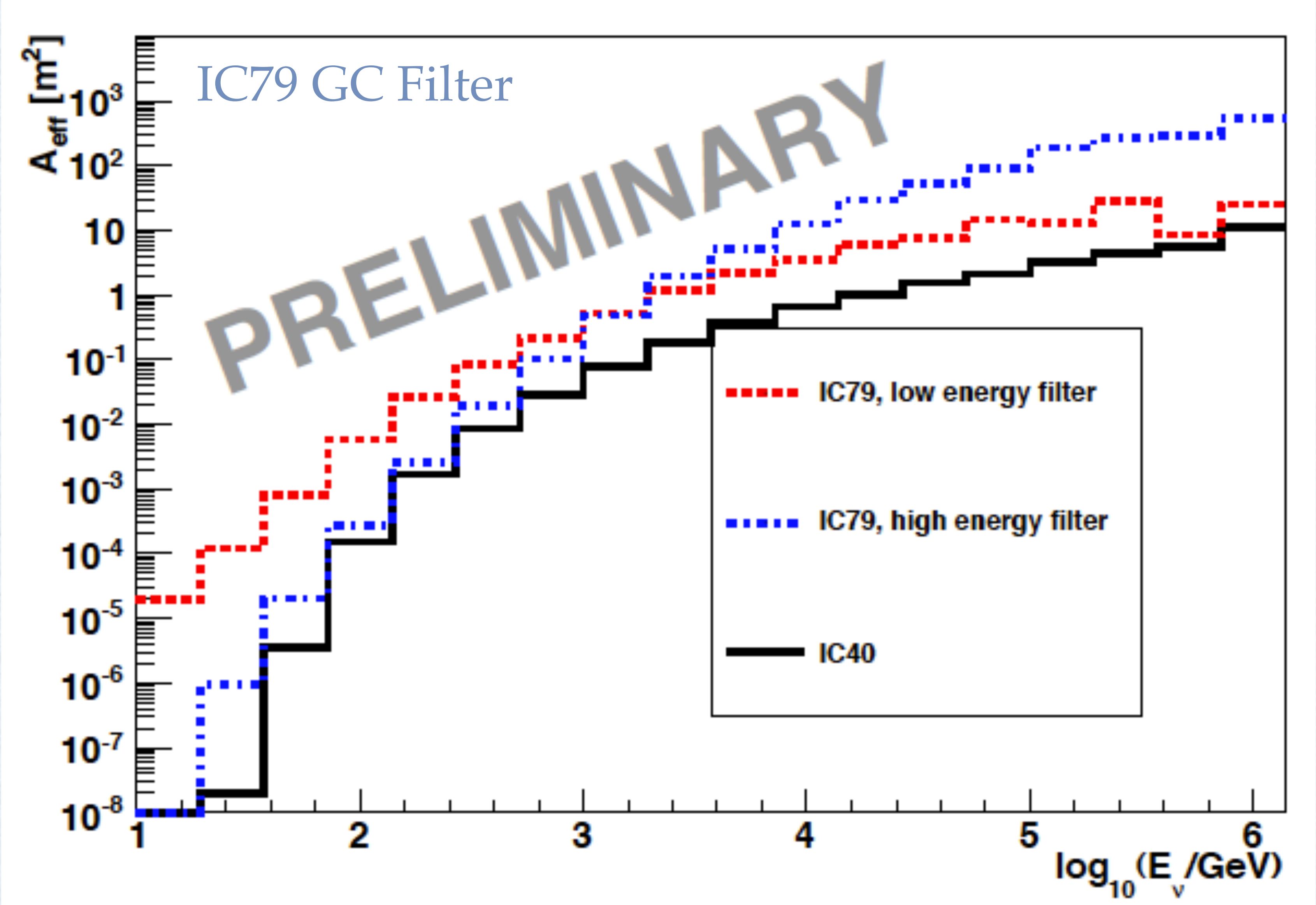
Systematic Uncertainties

- Systematic uncertainties for the halo analysis have been finalized (see Phys.Rev.D84:022004,2011), studies for the Galactic Center analysis are on-going
  - Background
    - Can be estimated from data itself (off-source), no direct dependence on simulations
    - 0.3% due to pre-existing anisotropy in data (Cosmic Ray, exposure)
  - Signal acceptance
    - ~30% limitations on the simulation of photon propagation through the ice
    - minor effects: νN-cross sections, exposure, ...

Whats next ?

- Dedicated Galactic Center filter for full IceCube detectors
- Optimized for two different energy regimes:

Filter	low-energy	high energy
Acceptance around GC	ΔDEC ±15° ΔRA ±20°	ΔDEC ±10° ΔRA ±40°
Pre-scale	3 (for off-source)	no
Veto	top 5 DOMs & outer strings	no
Track selection	all	zenith-dependent brightness threshold



$$N_{\text{Events}} = \int dt \int dE\, A_{\text{eff}}(E) \cdot \Phi_{\nu_\mu + \bar{\nu}_\mu}(E)$$

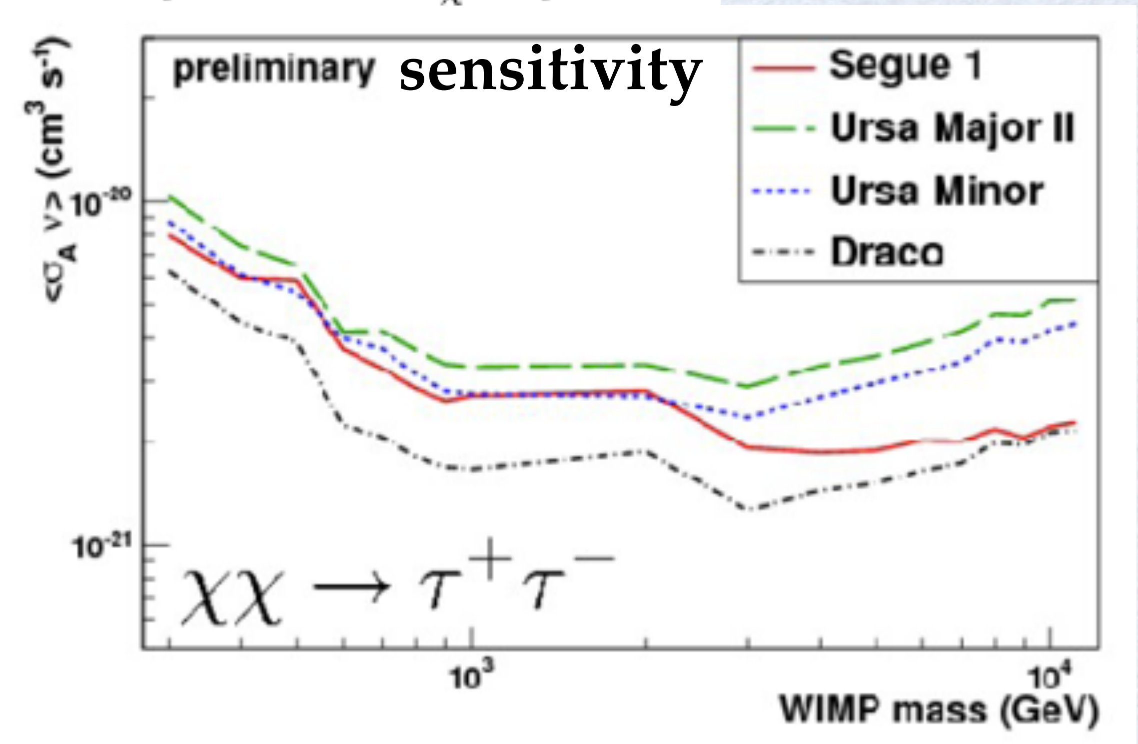
Dwarf Spheriodals

- Well defined targets
- can be regarded as point sources
- Northern hemisphere well covered
- Dominated by few close objects

Source	Distance (kpc)	Mass (10^7 M_{Sun})	Right asc.	Dec.
Segue 1	25	1.58	10 07′ 04″	+16 04′55″
Ursa Major II	32	1.09	08 51′ 30″	+63 07′48″
Willman 1	38	0.77	10 49′ 22″	+51 03′04″
Coma Berenices	44	0.72	12 26′ 59″	+23 55′09″
Ursa Minor	66	1.79	15 09′ 09″	+67 13′21″
Draco	80	1.87	17 20′ 12″	+57 54′55″
…	…	…	..	…

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(s) ds.$$

$$\frac{d\Phi_j(\Delta\Omega, E_j)}{dE_j} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_j}{dE_j} J(\Delta\Omega)$$



Neutrino detectors continuously operating, but large effort for IACTs

Neutrino Telescopes are competitive for high-mass WIMPs

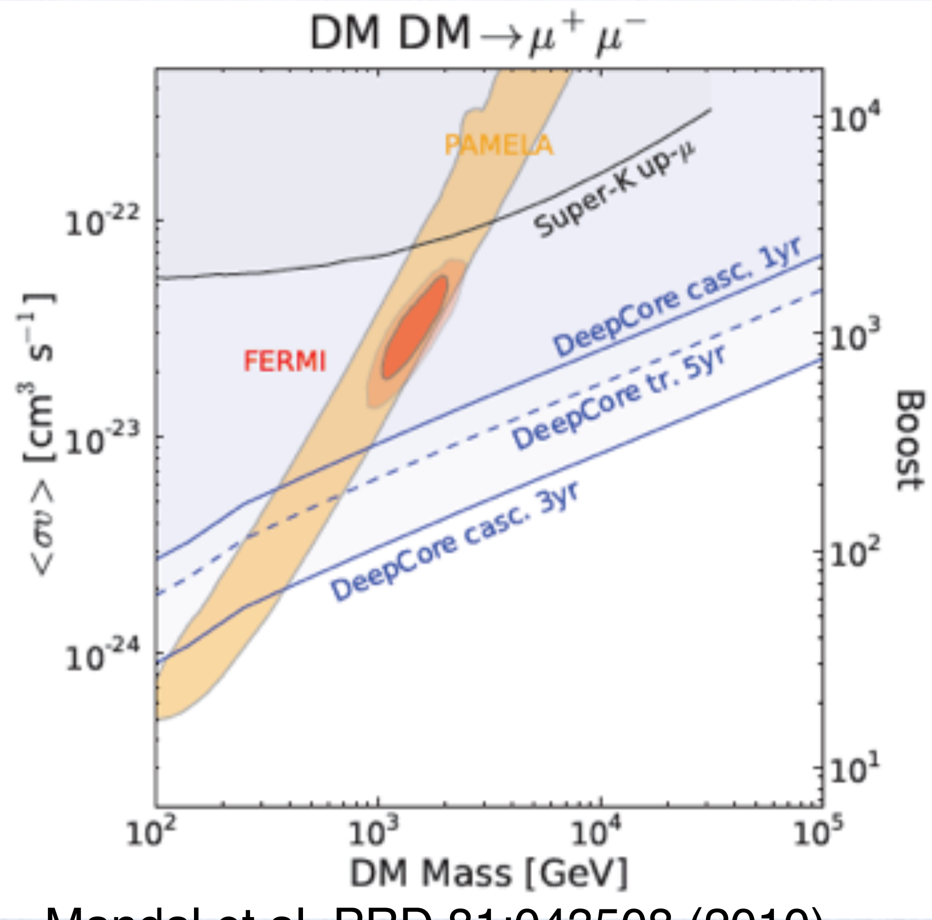
Dark Matter with Cascades

For neutrino energies where the average muon track length approaches the detector diameter:

- ν_μ ν_e signal rates similar
- but $R(\nu_\mu^{atm}) >> R(\nu_e^{atm})$

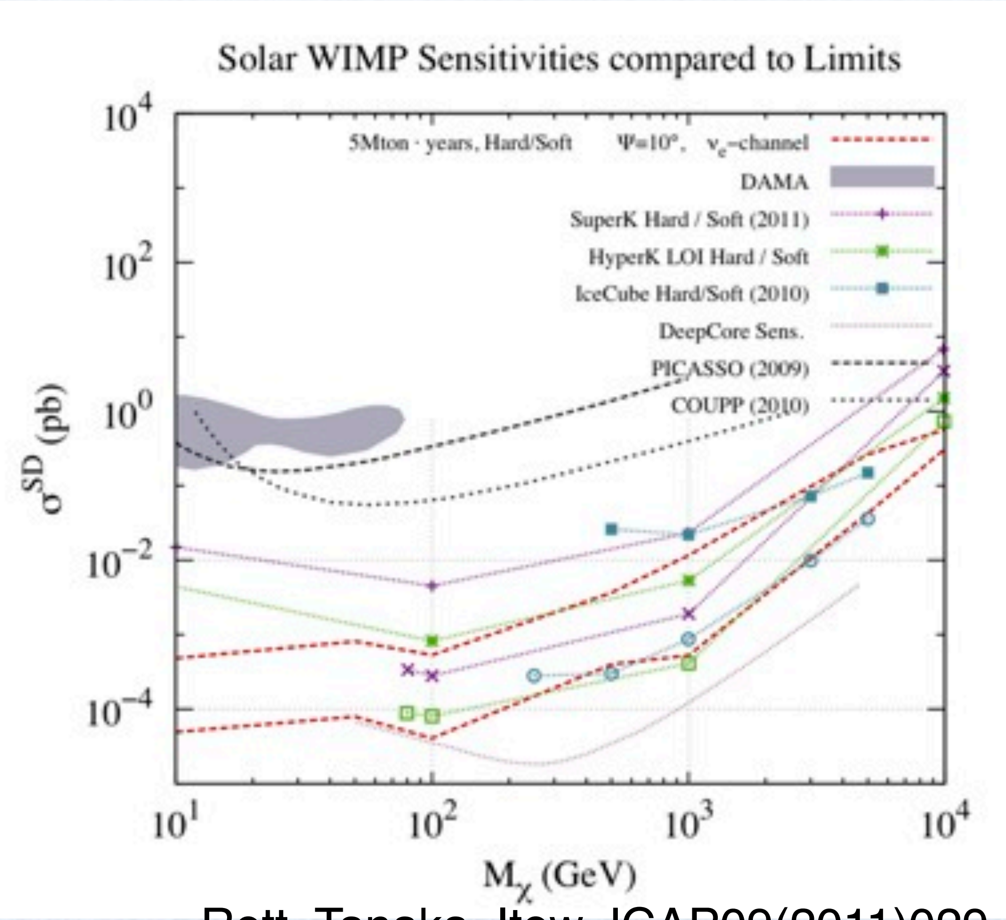
- Benefit from better energy resolution
- Lower atmospheric neutrino background
- Despite limited angular resolution competitive sensitivities can be obtained

Galactic Center



Mandal et al. PRD 81:043508 (2010)

Solar WIMPs



Rott, Tanaka, Itow JCAP09(2011)029

Conclusions

- IceCube Data from May 2007 - April 2009 has been searched for neutrino signals from dark matter annihilations in the Galactic Center and halo
- Limits on the dark matter self-annihilation cross section at the level of $10^{-22} cm^3 s^{-1}$ to $10^{-23} cm^3 s^{-1}$ are achieved depending on WIMP mass and annihilation channel
- On-going analyses for Galactic Center, Milky Way Halo, and Dwarf Spheriodal Galaxies
- First analyses using the cascade channel (ν_e ,ν_τ) in DeepCore have started

BONUS SLIDES

Comparison of Tracks and Cascades

- Fully contained events allow for better energy resolution
- For neutrino energies where the average muon track length approaches the detector diameter:
  - ν_μ ν_e signal rates similar
  - but $R(\nu_\mu^{atm}) >> R(\nu_e^{atm})$
- ν_τ and NC events also contribute to signal cascade rates