# Upward Showering muons in Super-Kamiokande

From SK's Highest Energy $\nu$'s

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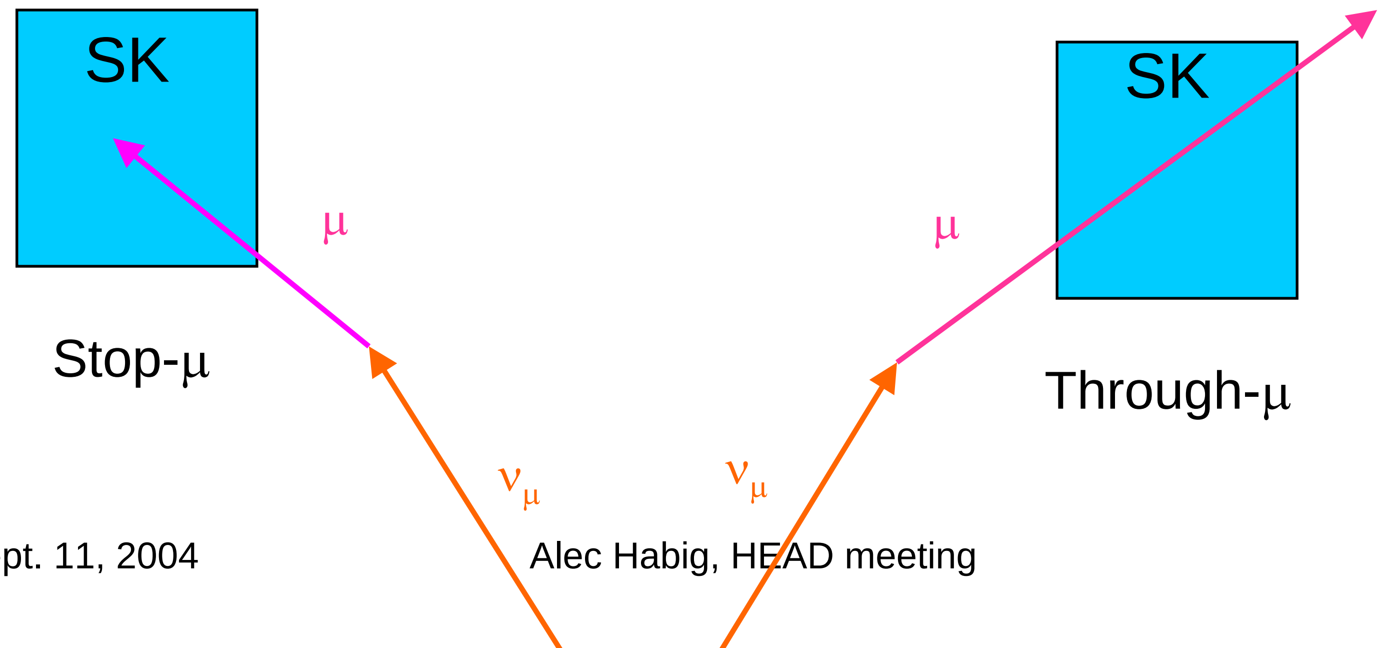
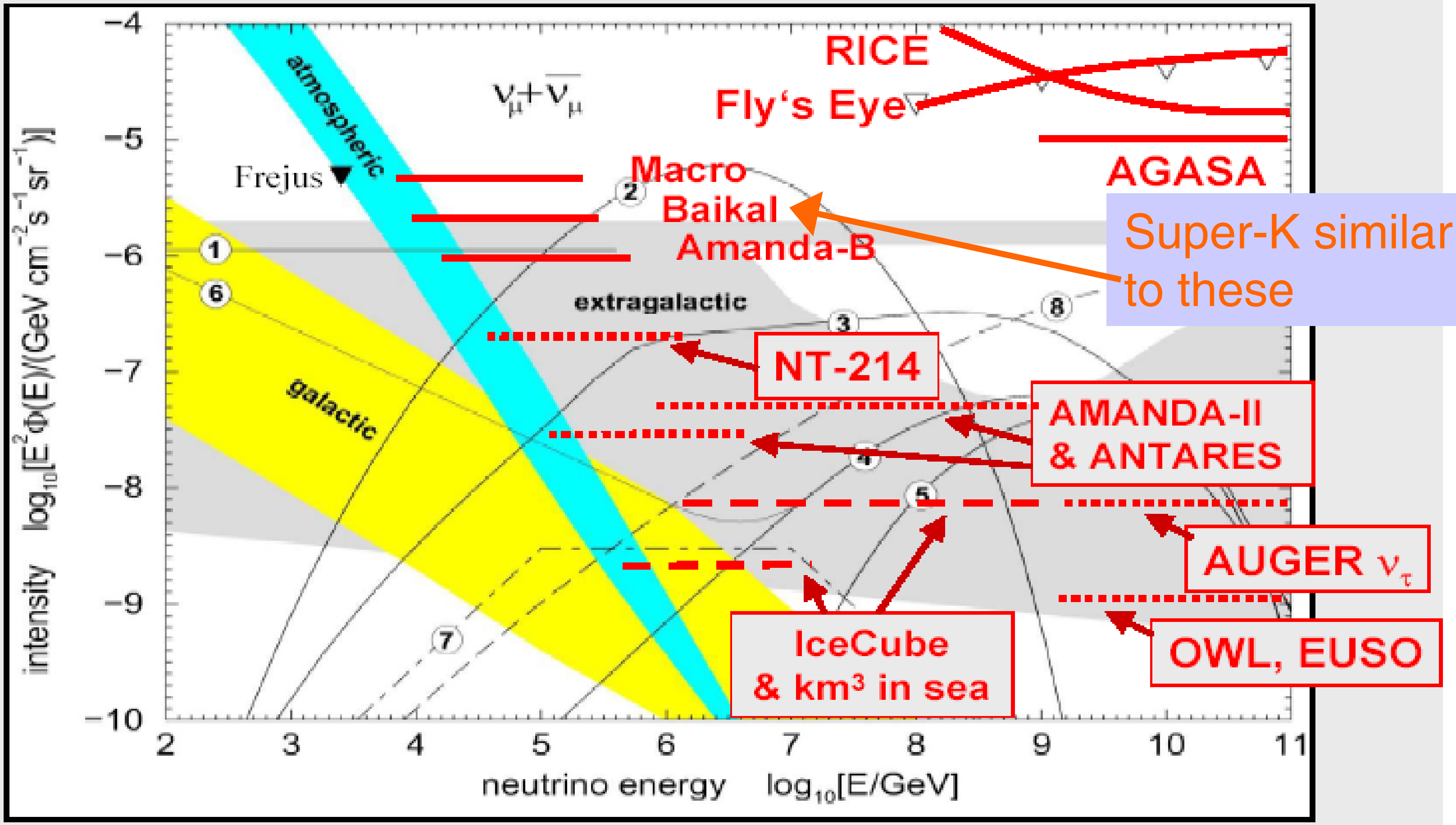
(*and Shantanu Desai in particular*)

# Upward-going μ

- High energy $\nu_\mu$ can interact in rock some distance away and still produce a μ seen by detector
  - Higher energy particles, more range, more effective volume!
  - Increasing target mass at high E offsets falling $\nu_\mu$ spectra
- Down-going entering cosmic ray muons restrict this technique to upward-going entering muons



# Highest Energies best for ν-astronomy




Courtesy: Learned & Mannheim; Spiering

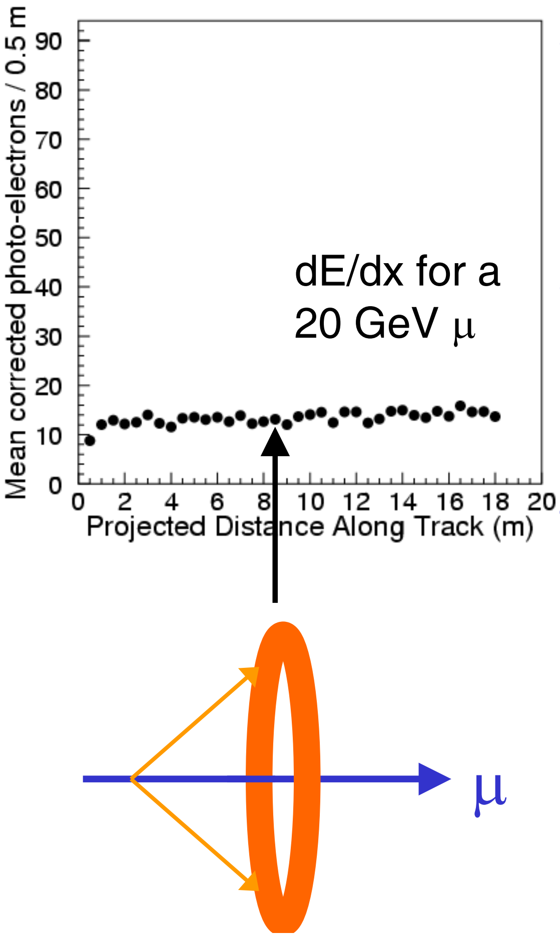


From Doug Cowen's ν2002 talk

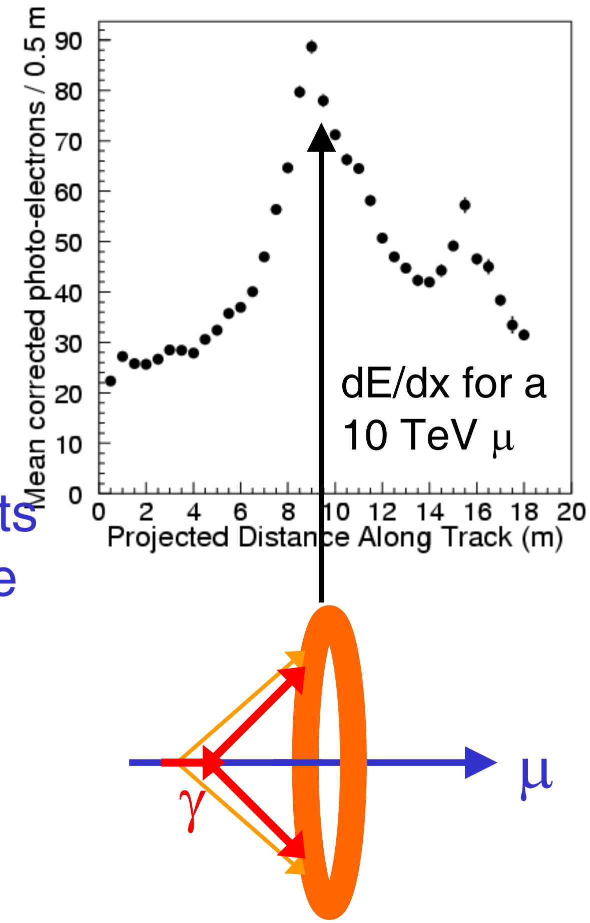
# Astrophysical ν

- Astrophysical sources we could surely see:
  - Solar (~MeV)
  - Supernovae (~10 MeV) (*including relic SN ν*)
- Sources which are likely fainter than the atmospheric ν background at SK's optimal energy:
  - UHE ν sources such as AGNs, GZK CR's, etc.
  - WIMP annihilation (well, some fraction of parameter space)
  - MeV to ~GeV ν from GRB's, SN shock breakout etc.
  - "Atmospheric" ν from CR interactions in the ISM (~GeV & up)
- Of course, except for solar ν and SN1987A, nothing seen
  - Upper limits set
- But there should be better S/N at higher energies!

# Selecting Highest Energy μ in SK




- Higher energy μ lose more energy per dx
  - Radiative processes
- "Critical point"
  - $dE/dx_{(rad)} > dE/dx_{(ion)}$ @ ~1 TeV
- So select high dE/dx events to get high energy μ (made by higher energy ν)




Ionization energy loss only, Cherenkov light seen from μ only

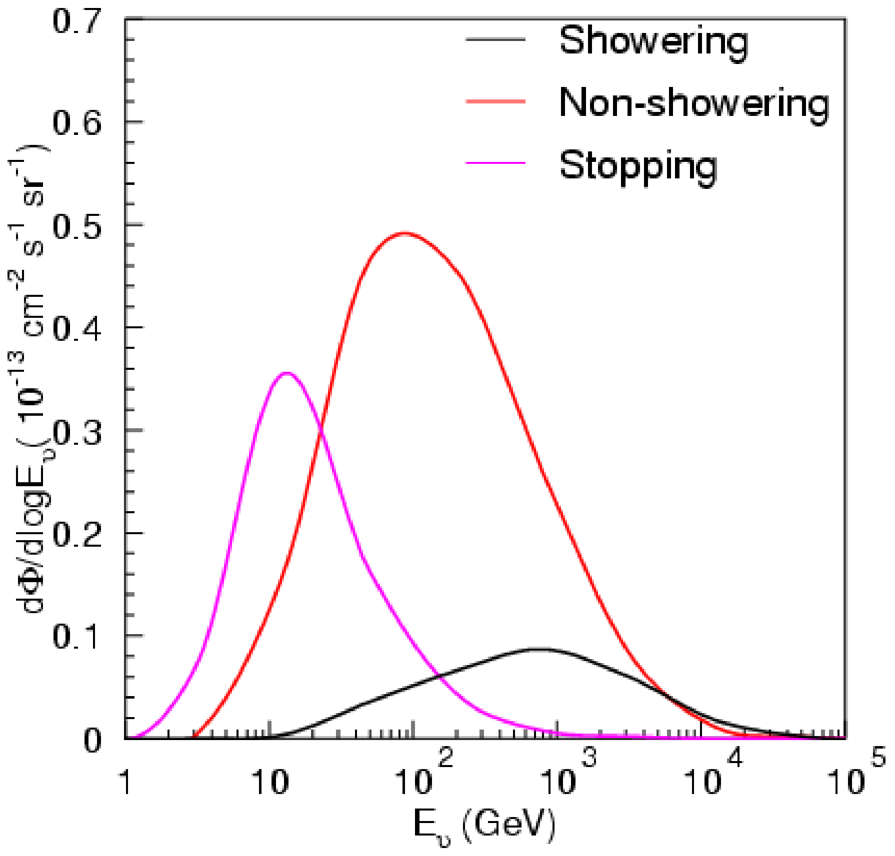
Bremsstrahlung happens, Cherenkov light from EM shower also contributes

# Data Selection

- Form a $\chi^2$ between dE/dx histogram for each up-going $\mu$ and the expected, minimum ionizing dE/dx
  - Corrected for geometry, absorption, scattering, and trapping on bad fits, stopping $\mu$
  - $\Delta E/\Delta x > 2.85$ MeV/cm is considered "showering"
- Call events with bursts of light "showering" $\mu$
  - From monte carlo studies, 95% purity, 75% efficiency in selecting $\mu$ having radiative processes
- For "SK-I" (4/96 to 7/01) **332** showering up-$\mu$ (*of 1892 total thru-$\mu$*) seen

# SK Up-μ ν Spectra

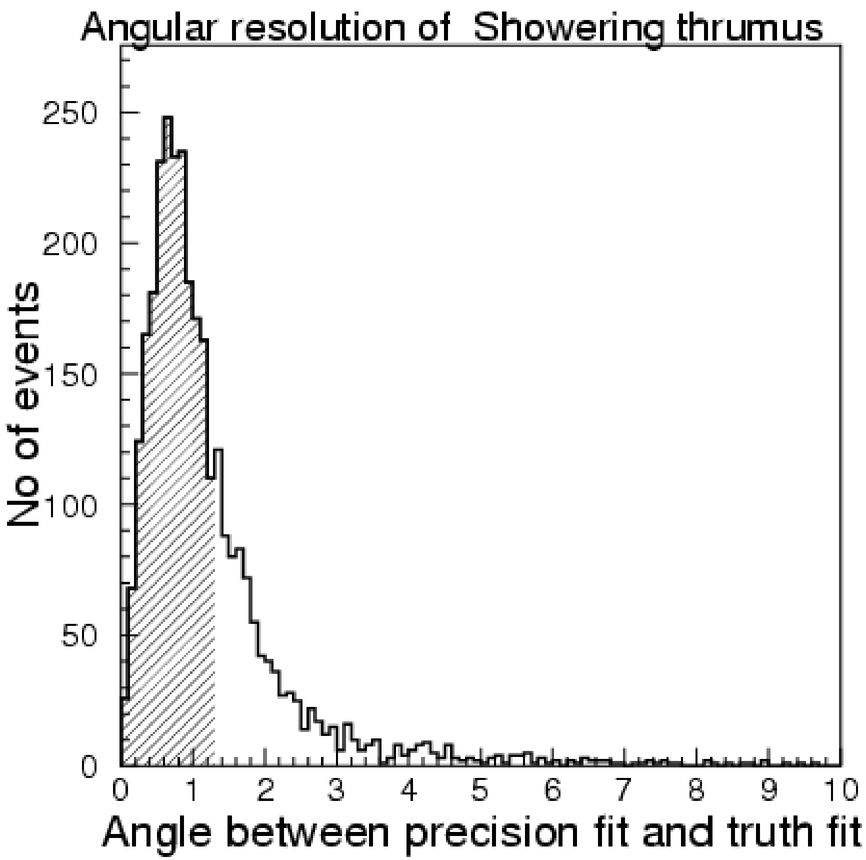
- Three classes of UGM:
  - Stopping μ: $E_\nu$ ~10 GeV
  - Through-going μ: $E_\nu$ ~100 GeV
  - Showering μ: $E_\nu$ ~ 1 TeV
    - Selected by high dE/dx
  - (*energies from atm. ν spectra*)
- Also available:
  - Extremely high energy μ's (saturate all PMTs)
  - Collected, but not yet understood well enough to publish diffuse flux limit (*e.g.* AMANDA, MACRO)



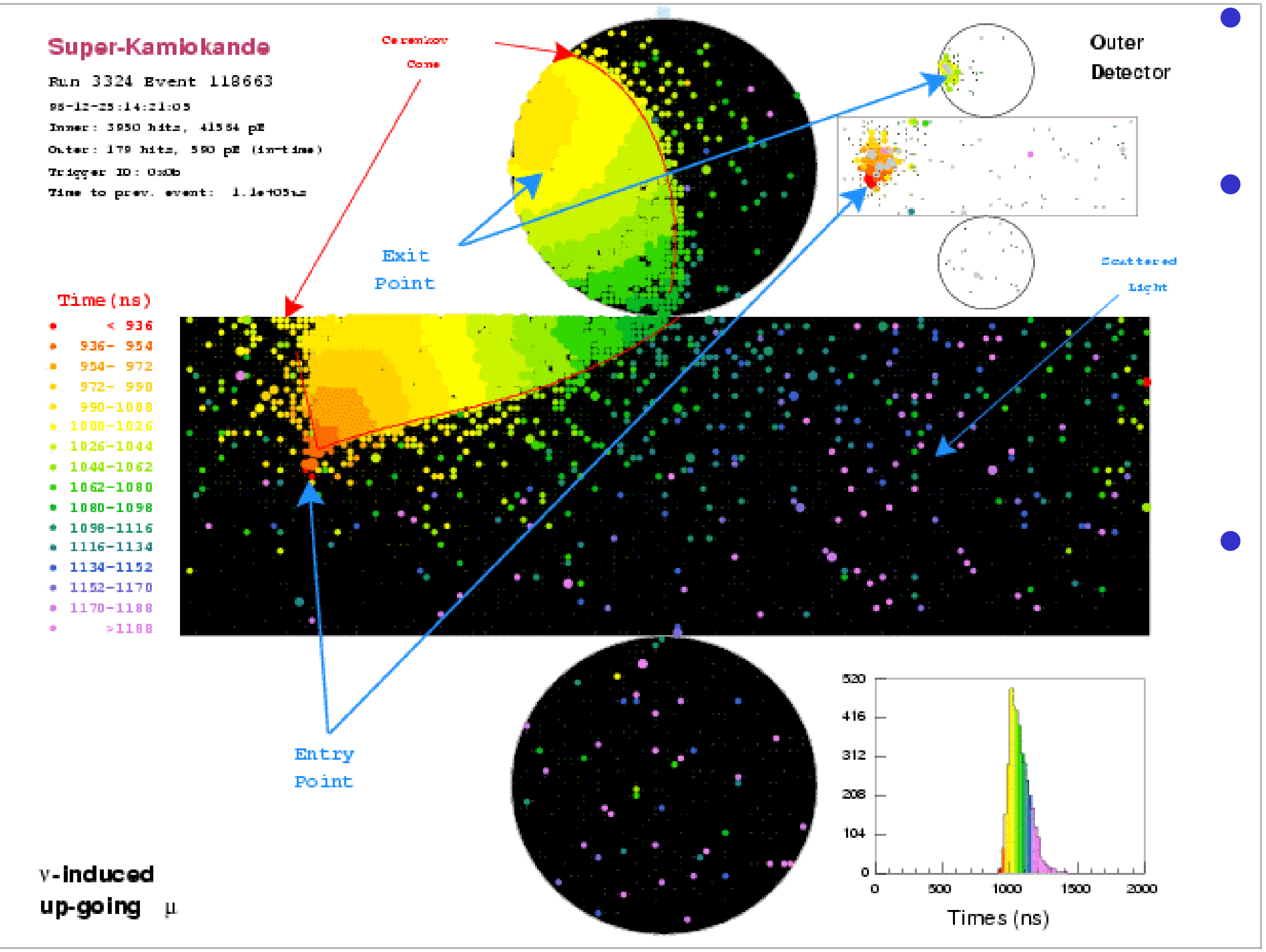

Spectra of parent ν Producing SK's up-μ

# Angular Resolution

- Good angular resolution
  - 1.25° for the showering sample
  - 1.4° for the through-going sample
  - Higher energies mean tighter $\nu \to \mu$ following angle



# Up-μ's in Super-K



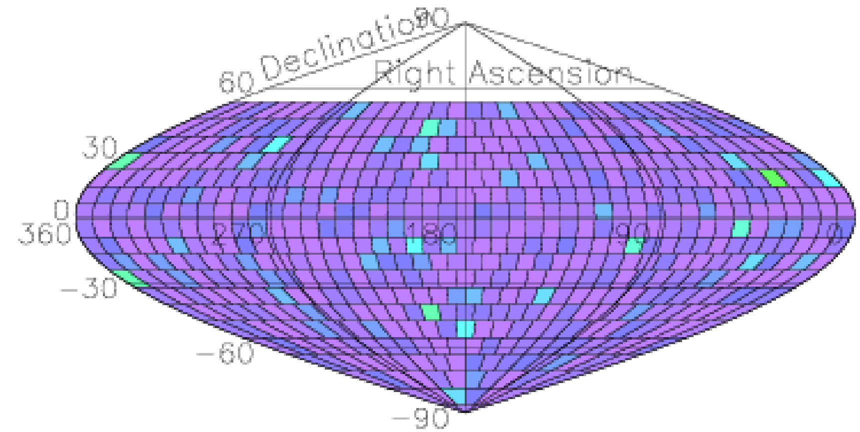

- For "SK-I"
  - 4/96 to 7/01
- 1680 live-days
  - More than other SK analyses, this is insensitive to poor detector conditions
- For >7m path (>1.6 GeV):
  - 1892 thru-μ
    - <1.4° tracking res.
    - 332 are showering
  - 467 stop-μ

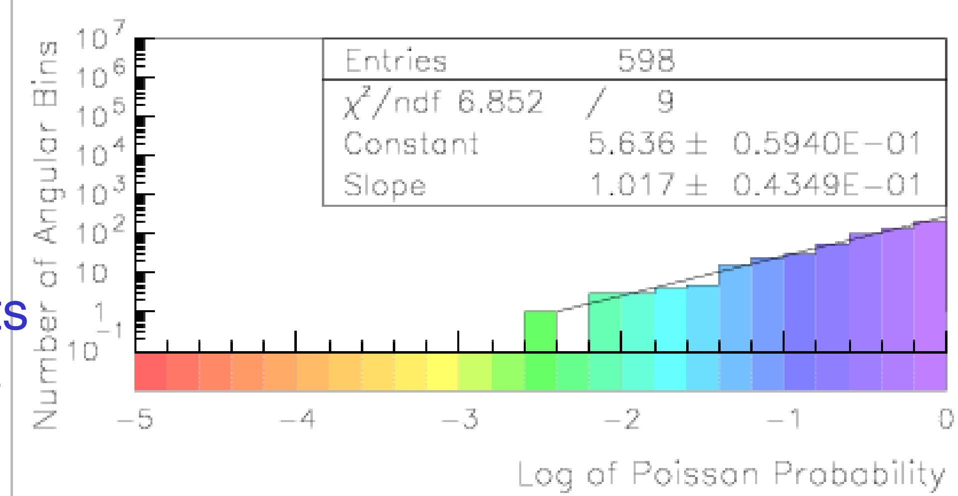
# All-sky survey

- Do we see anything anywhere sticking out over background?
  - This is the first astronomical thing one does in a new area of the spectrum
- The simplest thing:
  - break the data into spatial bins on the sky, sizes chosen for good S/N
  - Calculate the expected atm. $\nu$ background in bins
  - Apply Poisson statistics, discover things or set limits

# Bins

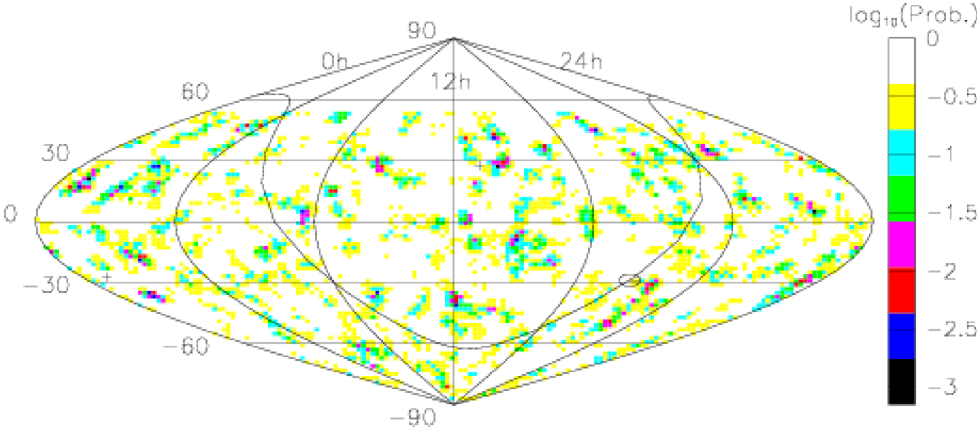
- Being a spherical sky, an igloo pixelization works better than the alternatives
  - Although size is hard to optimize
- Problem: a source on a bin boundary would be unnoticed
  - Doing multiple offset surveys solves this but hurts sensitivity with trials factors

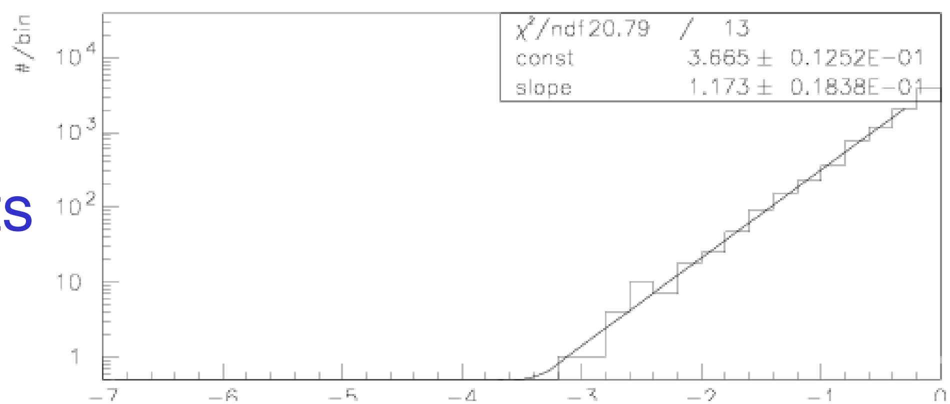


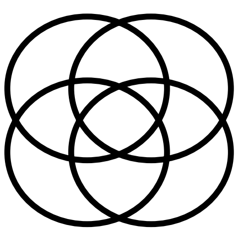



# Cones

- Another approach: overlapping cones
  - Any point in the sky is near center of at least one cone
  - Fewer bin-edge problems, but must account for oversampling effects



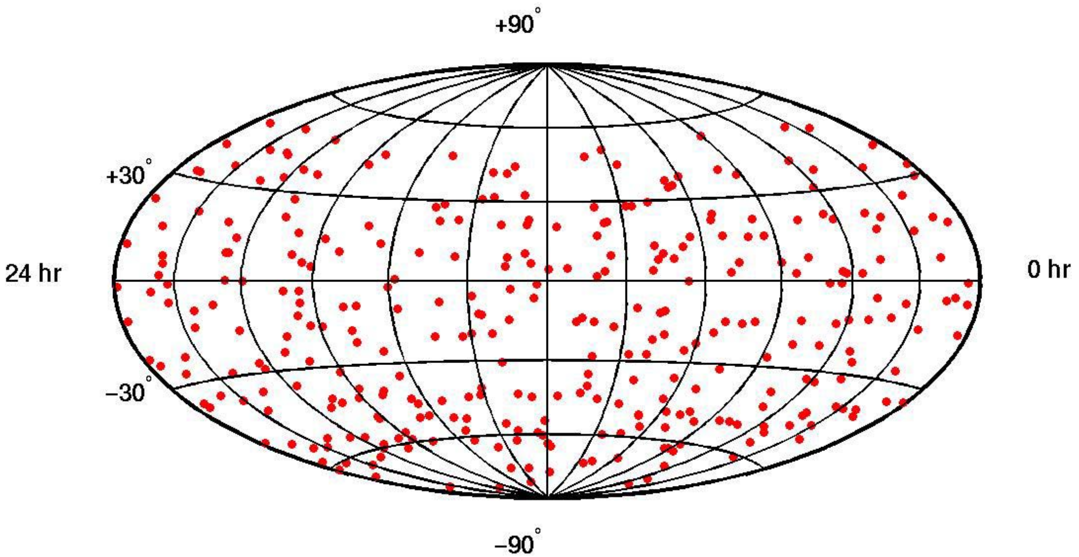



(Unbinned searches also turn nothing up)

Either way, ν spatial distribution consistent with random – no sources seen

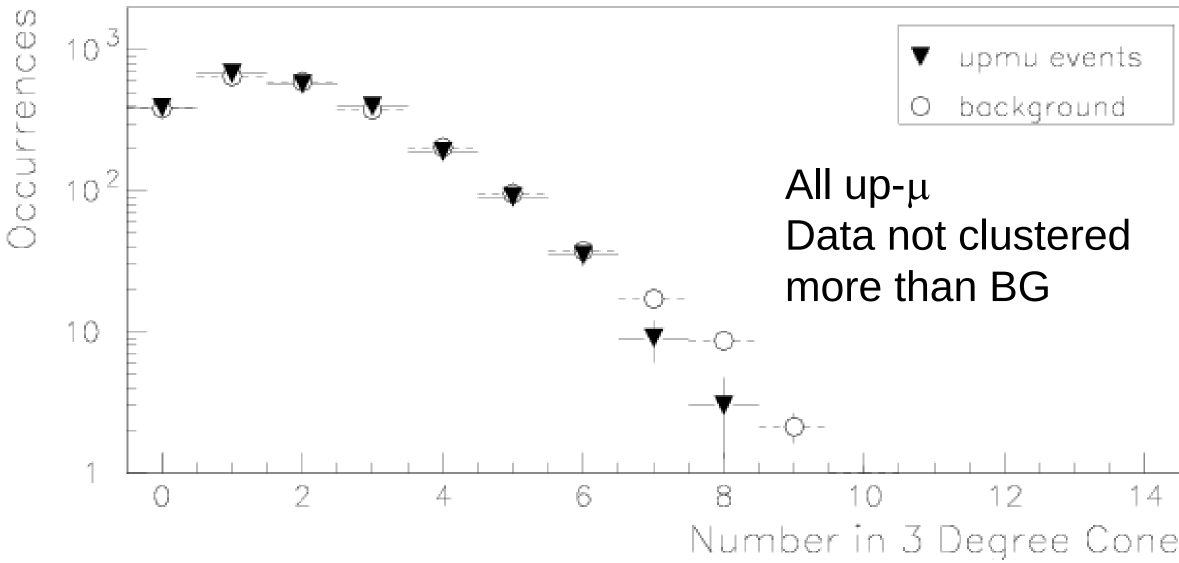
# Showering up-μ Sky

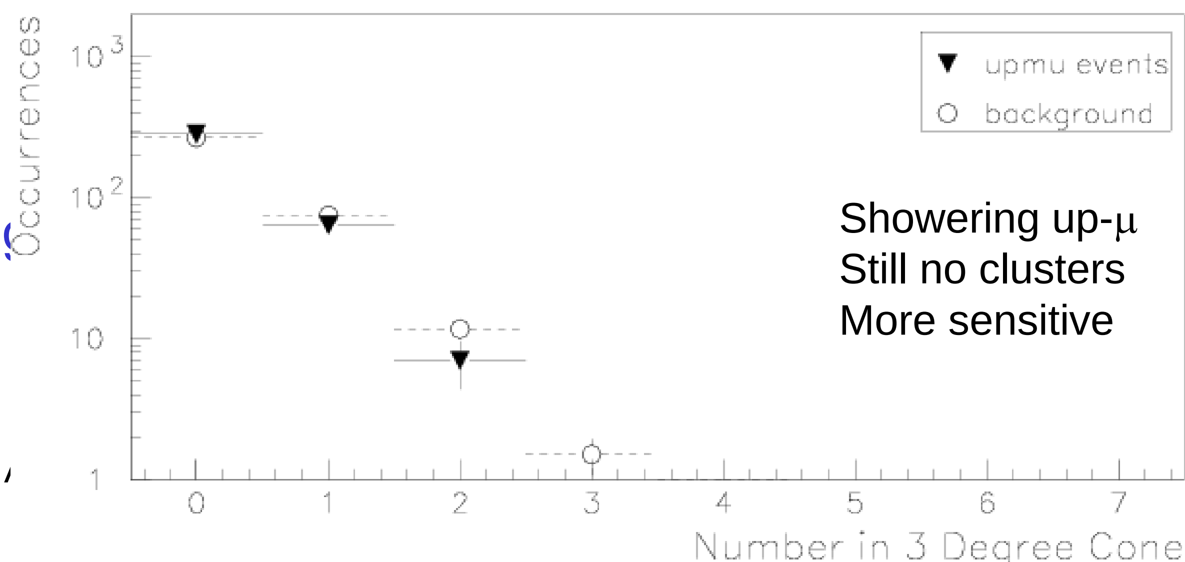
- The sky seen in showering up-μ is below
  - Should be better S/N at these higher energies, where Signal is AGN's etc and Noise is atmospheric ν
  - No statistically significant clusters seen



# Unbinned Clustering

- Ask the question "How many other μ are within x° of each μ?"
  - As in MACRO's paper
- A weakness:
  - faint signals in low-exposure areas would be swamped (working on an exposure correction)



# Point Source Check

- For a given astrophysical object, do the Poissonnian statistics for a cone around it
- Always enough places to look that you will find something in someone's catalog with a surprising fluctuation
  - Must properly take into account the trials factors for all these searches
- But limits galore for modelers
  - You can test your favorite $\nu$ production/jet model for your favorite source

# Pick a Source, Any Source

| Source | ν | BG | Acceptance $\times 10^6 cm^2$ | 90% c.l. limit $\times 10^{-14} cm^{-2} s^{-1}$ |
|---|---|---|---|---|
| Cyg X-1 | 6 | 2.54 | 3.731 | 1.486 |
| Cyg X-3 | 3 | 2.40 | 3.083 | 1.049 |
| Her X-1 | 2 | 2.53 | 3.718 | 0.680 |
| Sco X-1 | 3 | 2.95 | 6.533 | 0.465 |
| Vela X-1 | 8 | 3.69 | 8.040 | 0.798 |
| Crab N. | 1 | 2.57 | 4.776 | 0.420 |
| 3C273 | 5 | 2.70 | 5.814 | 0.795 |
| Per A | 2 | 2.49 | 3.010 | 0.842 |
| Vir A | 4 | 2.76 | 5.329 | 0.712 |
| Coma cl. | 4 | 2.67 | 4.358 | 0.881 |
| Gal. C. | 1 | 3.51 | 7.144 | 0.269 |
| Geminga | 3 | 2.90 | 5.034 | 0.607 |
| Mrk 421 | 2 | 2.62 | 3.414 | 0.734 |
| Mrk 501 | 3 | 2.33 | 3.233 | 1.008 |
| 1ES1426 | 1 | 2.33 | 2.830 | 0.713 |
| SGR 1900+14 | 2 | 2.51 | 5.483 | 0.461 |
| SGR 0526-66 | 6 | 5.17 | 12.070 | 0.341 |
| 1E 1048-5937 | 5 | 5.98 | 11.920 | 0.273 |
| SGR 1806-20 | 2 | 2.84 | 6.734 | 0.365 |
| GX339-4 | 4 | 4.39 | 9.194 | 0.345 |
| SMC X-1 | 5 | 4.90 | 12.203 | 0.293 |

- No sources seen in an all-sky survey; limits set on any given potential point source
- To test your favorite model of ν production at some high energy astrophysical source:
  - Up-μ near sources counted, 4° ½ angle cone shown here
  - Expected count from atm.ν background calculated
  - Compute flux limits for modelers to play with
  - SGR's/Magnetars of interest
  - **This is from all thru-μ, but selecting just showering up-μ's also sees nothing obvious**

← A microquaser which in MACRO data had an interesting positive fluctuation

# GRB's

- SK $\nu$ data compared to BATSE bursts
  - 1454 GRBs from April 1996 (SK start) through May 2000 (BATSE end)
  - 1371 GRBs (June 1996 onward) used for contained $\nu$ events
- All SK $\nu$ events used
  - "Low-E" (Solar $\nu$ analysis) events (7-80 MeV)
  - "High-E" (Atm. $\nu$ analysis) events (0.2-200 GeV)
  - "Up-$\mu$" events (1.6 GeV-100 TeV)
- Look for time correlations with GRBs
  - Several different time windows used
  - Directional information also used with up-$\mu$ data
  - No correlations found, calc model-independent fluence limits
- SGR correlations also examined, none found
  - see S. Desai's thesis, Boston U., 2004

# GRB ν Search results

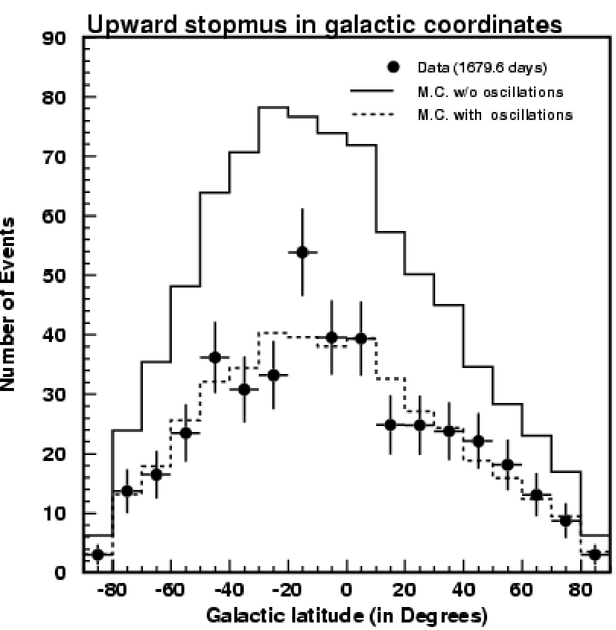
- No correlations observed
- Model-independent ν fluence limits calculated
  - See ApJ 578:317 (2002) for details
- Will continue this watch with SK-II (Dec.’02 onwards) and HETE (and successors)

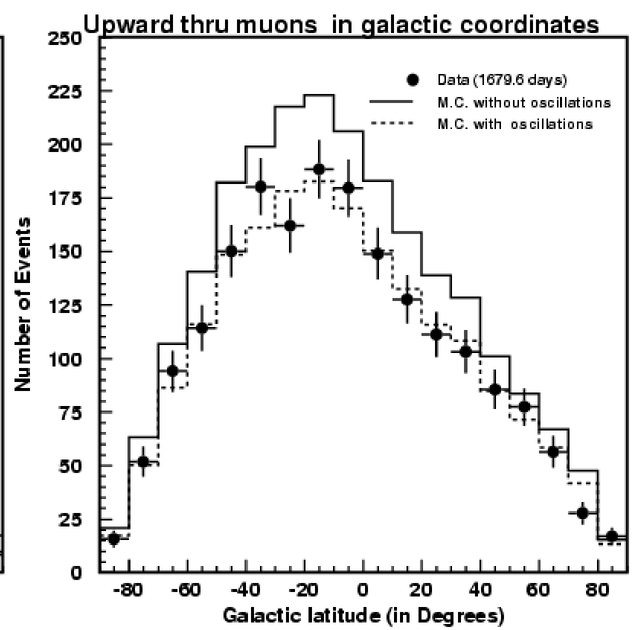
# MRK 501

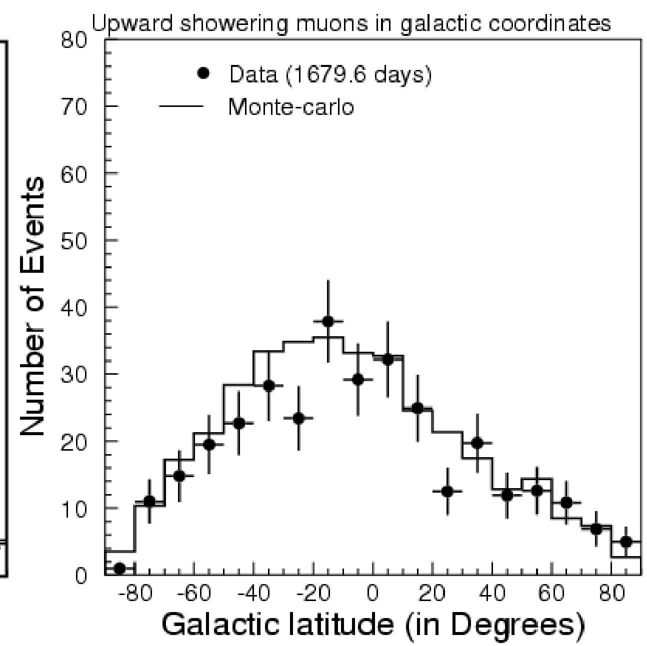
- Major flare from Feb. to Oct. 1997
- Blazar flares are when an AGN jet is pointed right at us and material is being ejected
  - Should be a great natural $\nu$ beam
- 13% of SK-I data solidly during the flare, 68% clearly not
  - Such "beam off" plus same declination but "off source" data take for a background estimate
- $6^o$ half angle cone on-source beam on yielded 2 events compared to 2.3 expected

# Galactic Atmospherics?

- Cosmic rays interact with ISM as well as our atmosphere
  - Would also produce ν
- ISM most dense at low galactic latitudes
  - Do we see excess ν in the galactic plane?
- A search for these ν does not see this weak signal

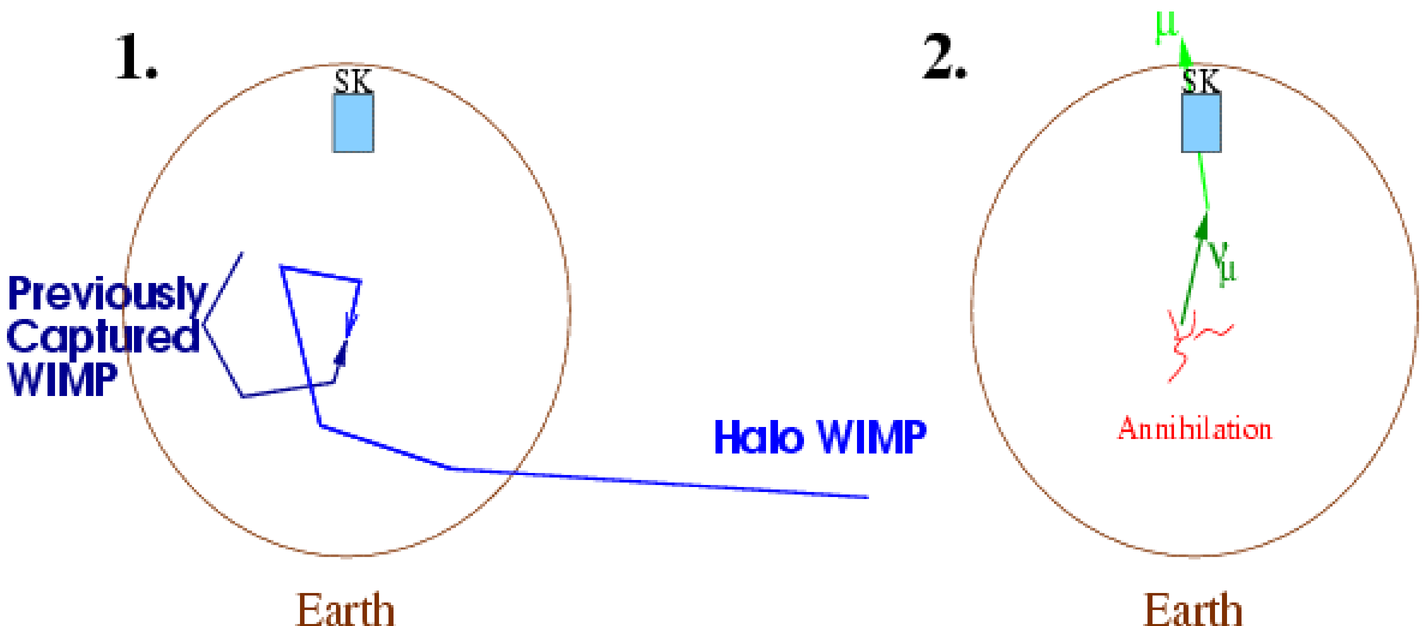


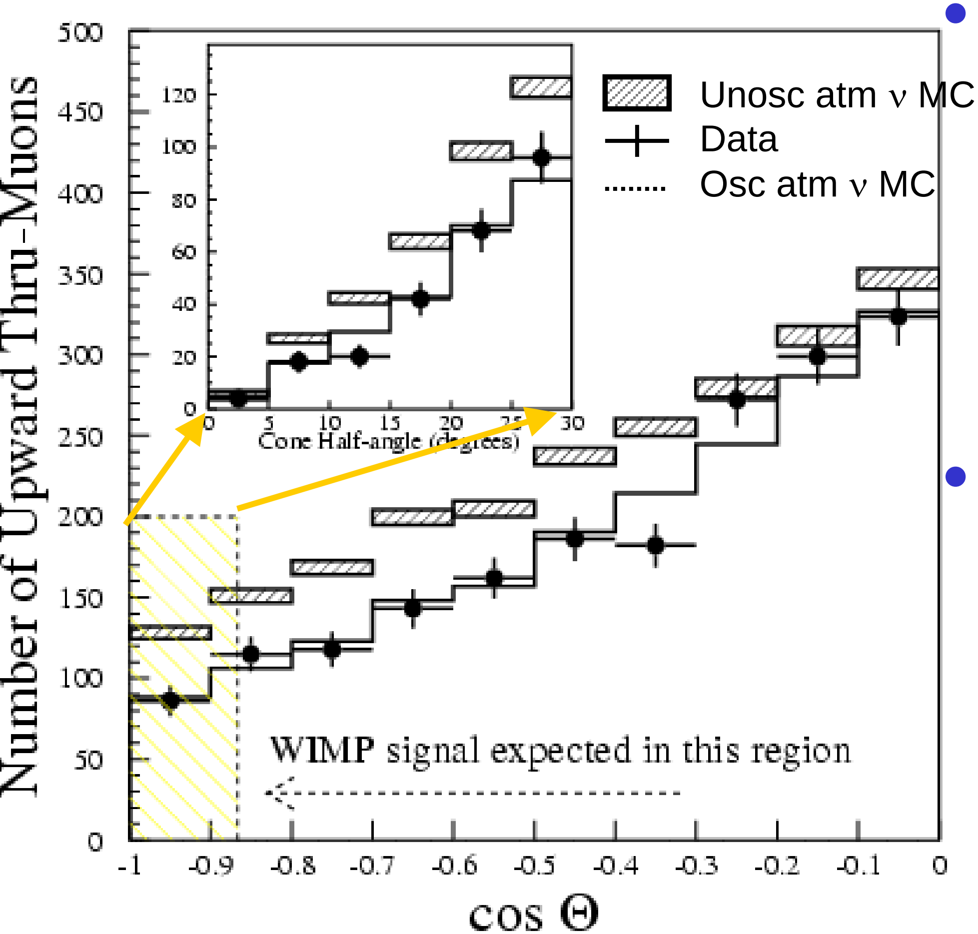



# WIMP Detection

- WIMPs could be seen indirectly via their annihilation products (eventually $\nu_\mu$) if they are captured and settle into the center of a gravitational well (Earth, Sun, GC)
- WIMPs of larger mass would produce a tighter $\nu$ beam of higher $E_\nu$
  - Differently sized angular windows allow searches to be optimized for different mass WIMPs

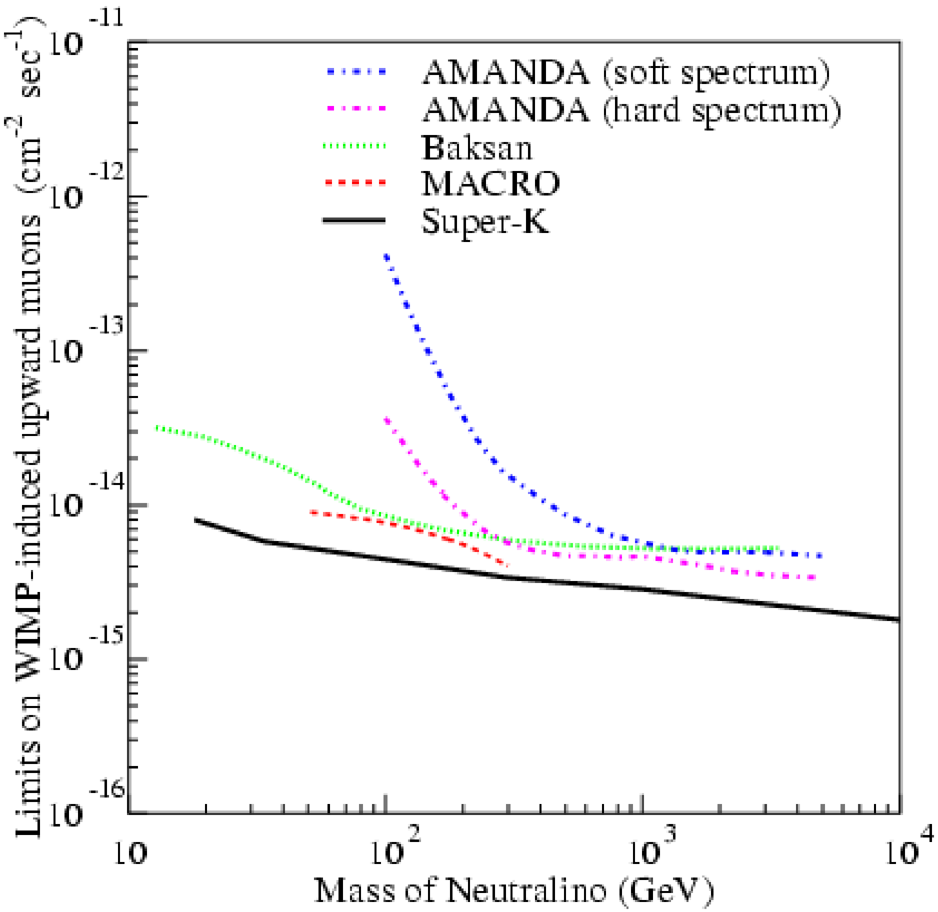


# WIMPs in the Earth



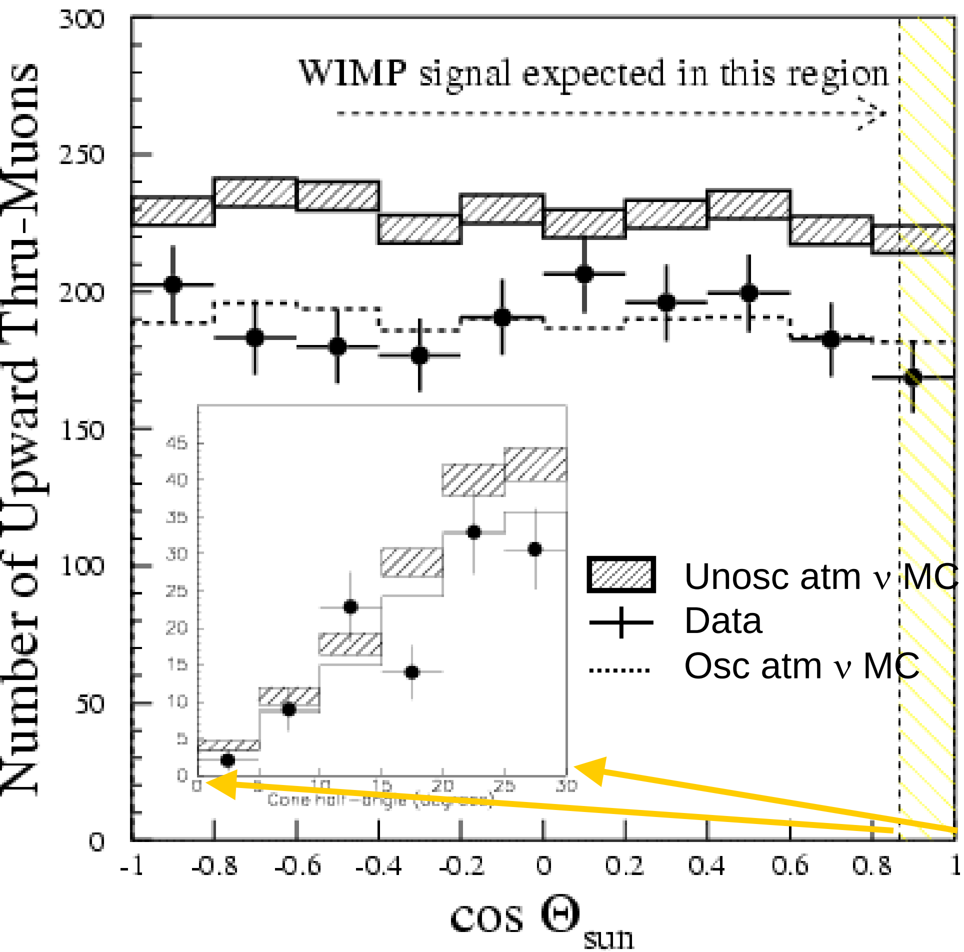

- WIMPs could only get trapped in the Earth by interacting in a spin-independent way
  - All those even heavy nuclei in the Earth with no net spin
- $\nu_\mu$ from WIMP annihilation would come from the nadir
  - No excess seen in any sized angular cone (compared to background of oscillated atmospheric ν Monte Carlo)

# Earth WIMP-induced Up-μ Limits



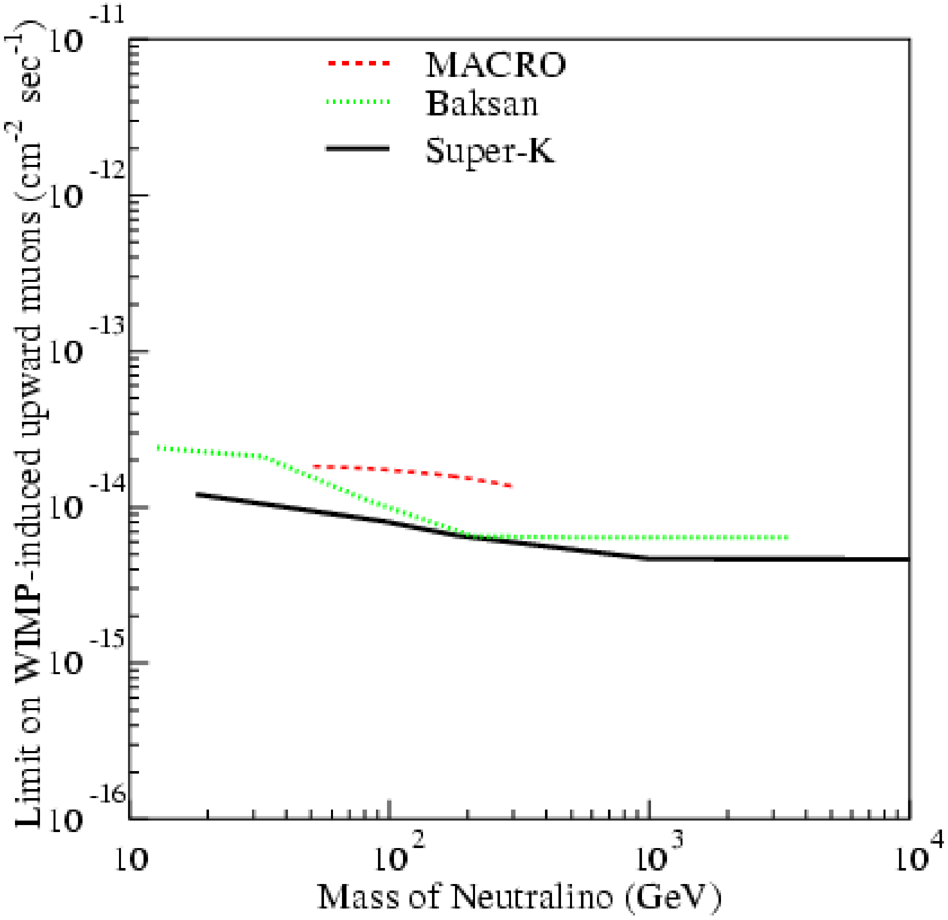

- Resulting upper limits on the WIMP-induced up-μ from the center of the Earth vs. WIMP mass
  - Varies as a function of possible WIMP mass
  - Lower limits for higher masses are due to the better S/N in smaller angular search windows
  - Lowest masses ruled out anyway by accelerator searches

# WIMPs in the Sun



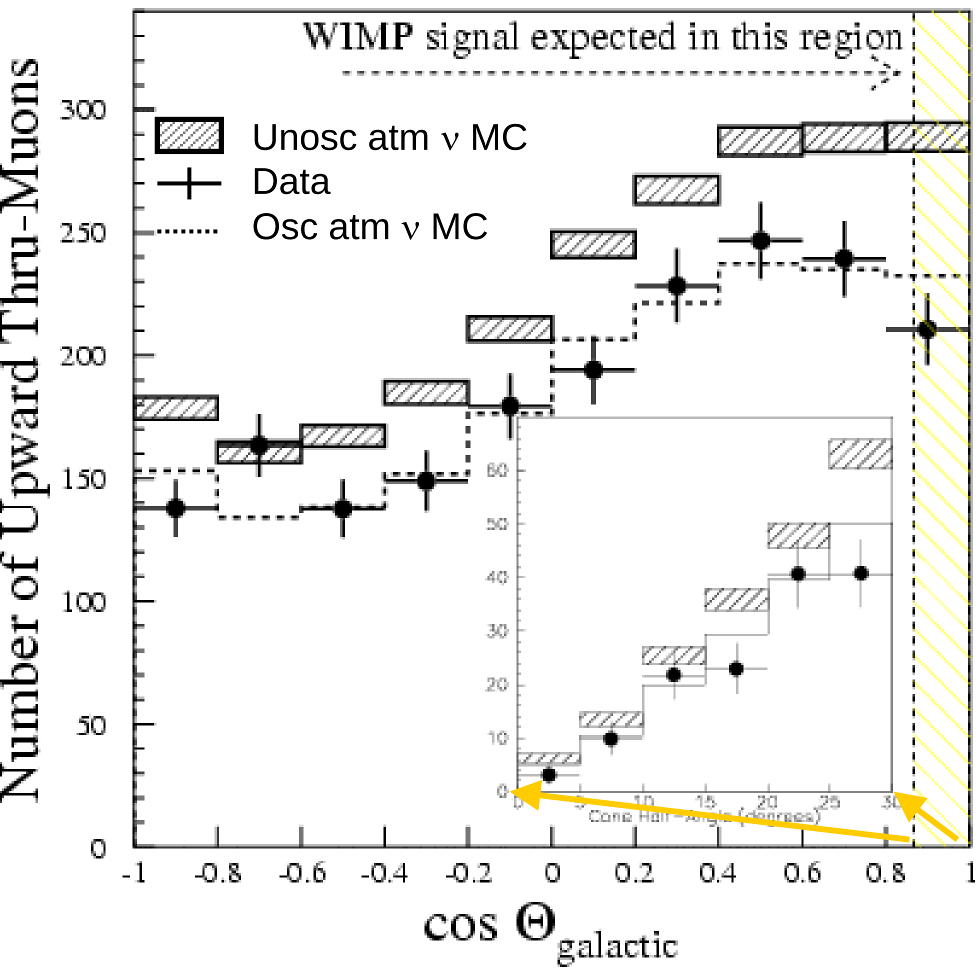

- WIMPs could also get trapped in the Sun if they interact in a spin-dependent way
  - All those spin-½ Hydrogen nuclei
- Make a cos(θ) Sun plot for all the up-μ events
  - No excess seen compared to background of oscillated atmospheric ν Monte Carlo

# Sun WIMP-induced Up-μ Limits



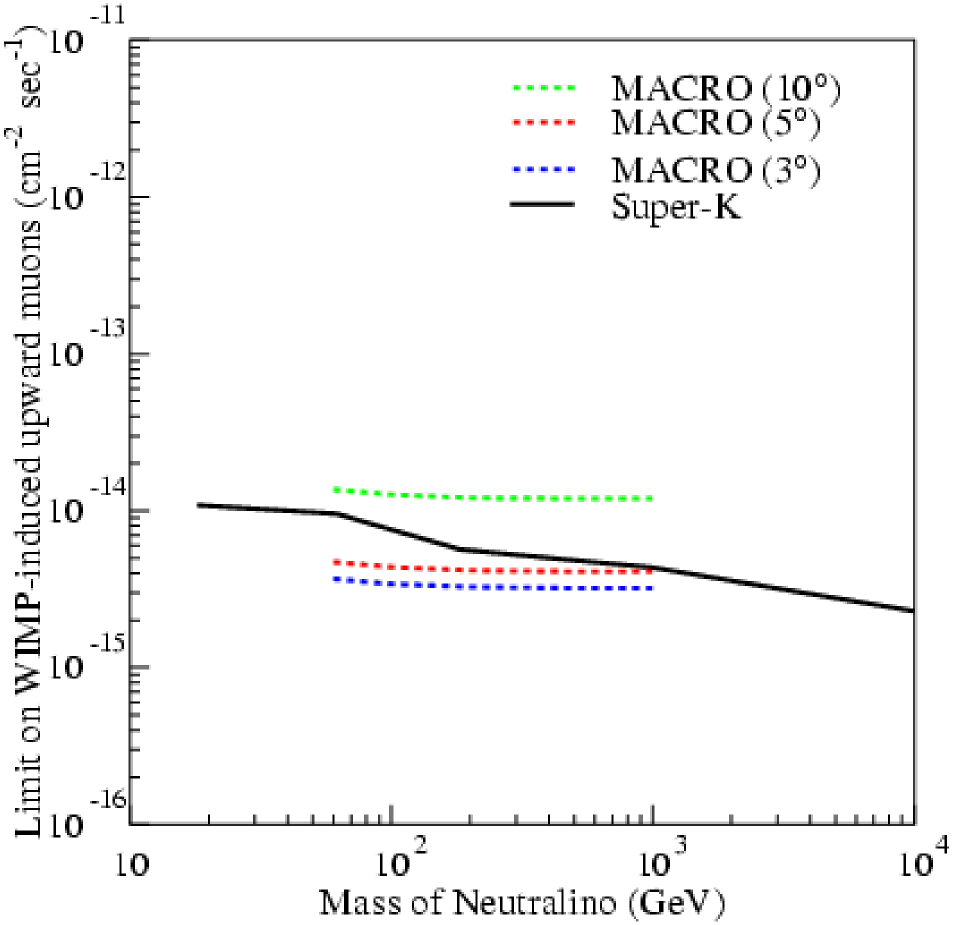

- Resulting upper limits on the WIMP-induced up-μ from the Sun vs. WIMP mass
- Same features as from Earth
  - But probes different WIMP interactions
  - Unfortunately hard for South Pole detectors to see the Sun (it's always near the horizon)

# WIMPs in the Galactic Core




- WIMPs could get caught in the Really Big gravity well at the center of the Milky Way
- Make a cos(θ) Galactic Center plot for all the up-μ events
  - No excess seen compared to background of oscillated atmospheric ν Monte Carlo

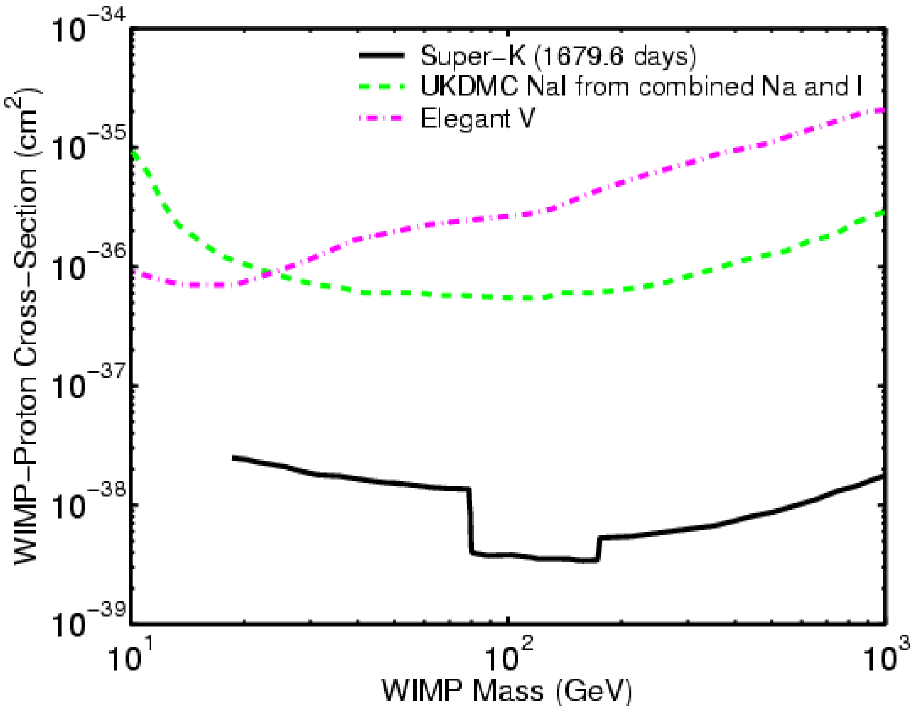
# Galactic WIMP-induced Up-μ Limits

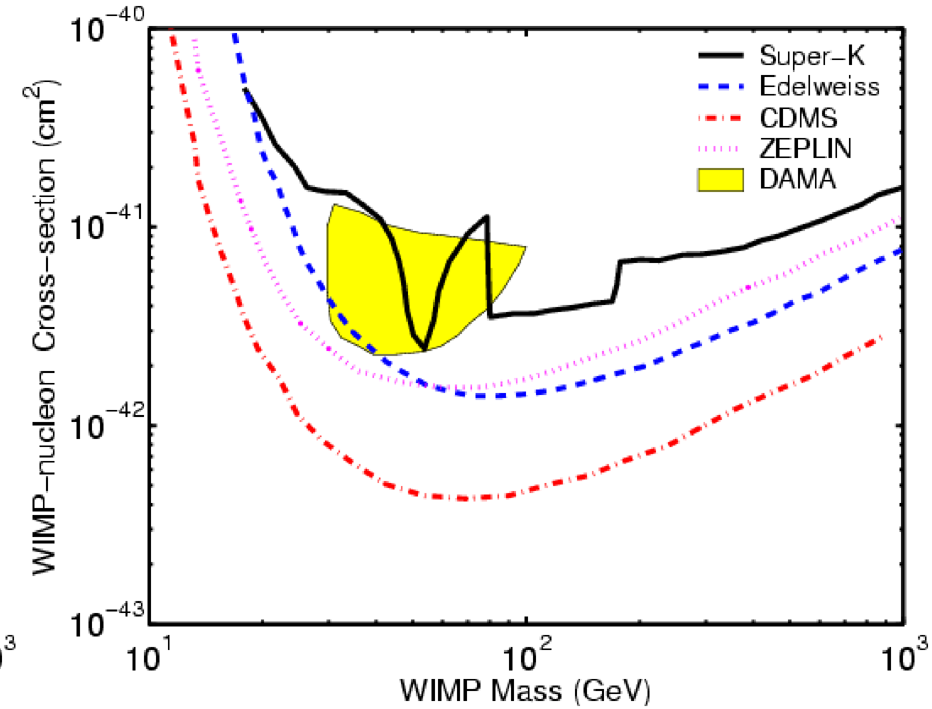



- Resulting upper limits on the WIMP-induced up-μ from the Galactic Center vs. WIMP mass
- If WIMPs exist and annihilate, then this lack of signal actually constrains possible matter distributions around Milky Way's black hole
- Need Antares to see this southern source!

# Probing for WIMPs

- Most model dependence in indirect searches from cross-section
  - Most conservative limits are taken for other uncertainties ($E_\nu$ is largest)
- Direct-detection experiments also do not know cross-sections
  - Comparisons can be made between direct and indirect searches
- Both spin-dependent (left) and spin-independent (right) WIMP-nucleon interactions can be probed (*a la* Kamionkowski, Ullio, *et al*)



# Summary

- High-energy $\nu_\mu$ are observed by Super-K as up-going $\mu$
- Best shot at astrophysical sources is at the highest energies possible
  - By selecting "showering" up-$\mu$ events, parent $\nu$ with typical energy ~1 TeV are observed
- Nothing yet seen in SK, limits set
  - All-sky survey, possible point sources, WIMP annihilation, GRB coincidences



The presenter gratefully acknowledges support for this presentation from the National Science Foundation via its RUI grant #0354848