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UNIVERSITY OF MINNESOTA UMD DULUTH

Upward Showering muons in Super-Kamiokande

From SK's Highest Energy ν's

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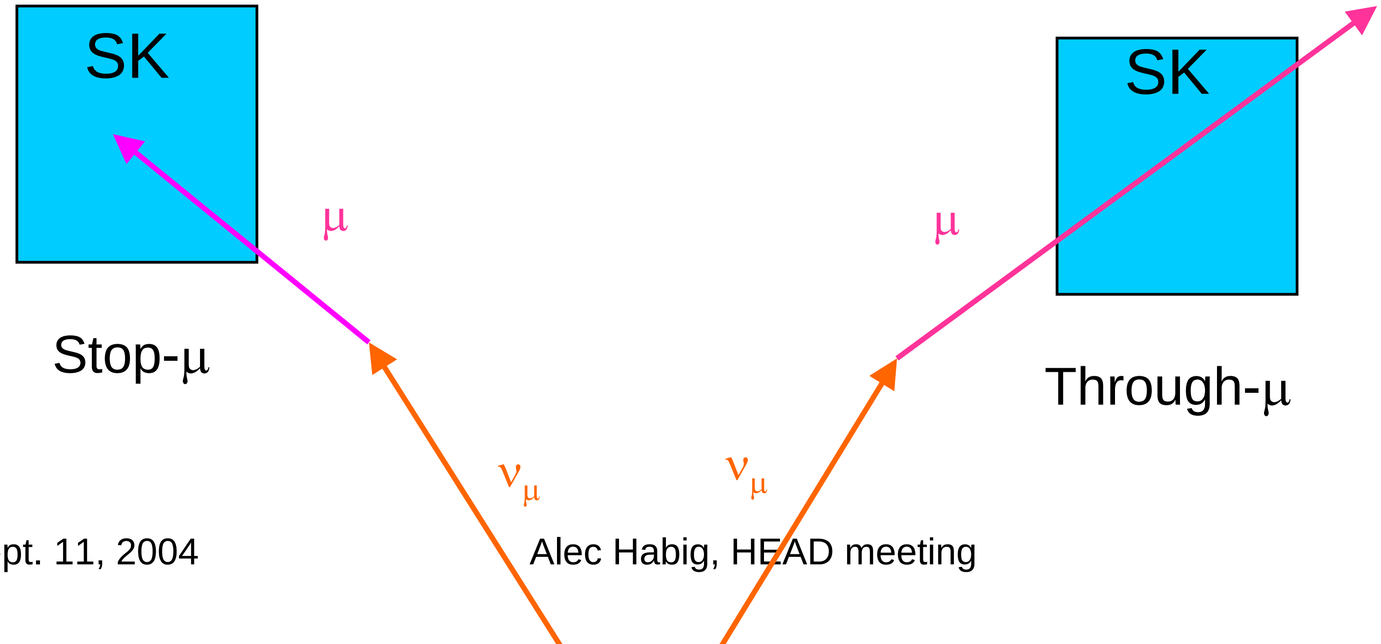
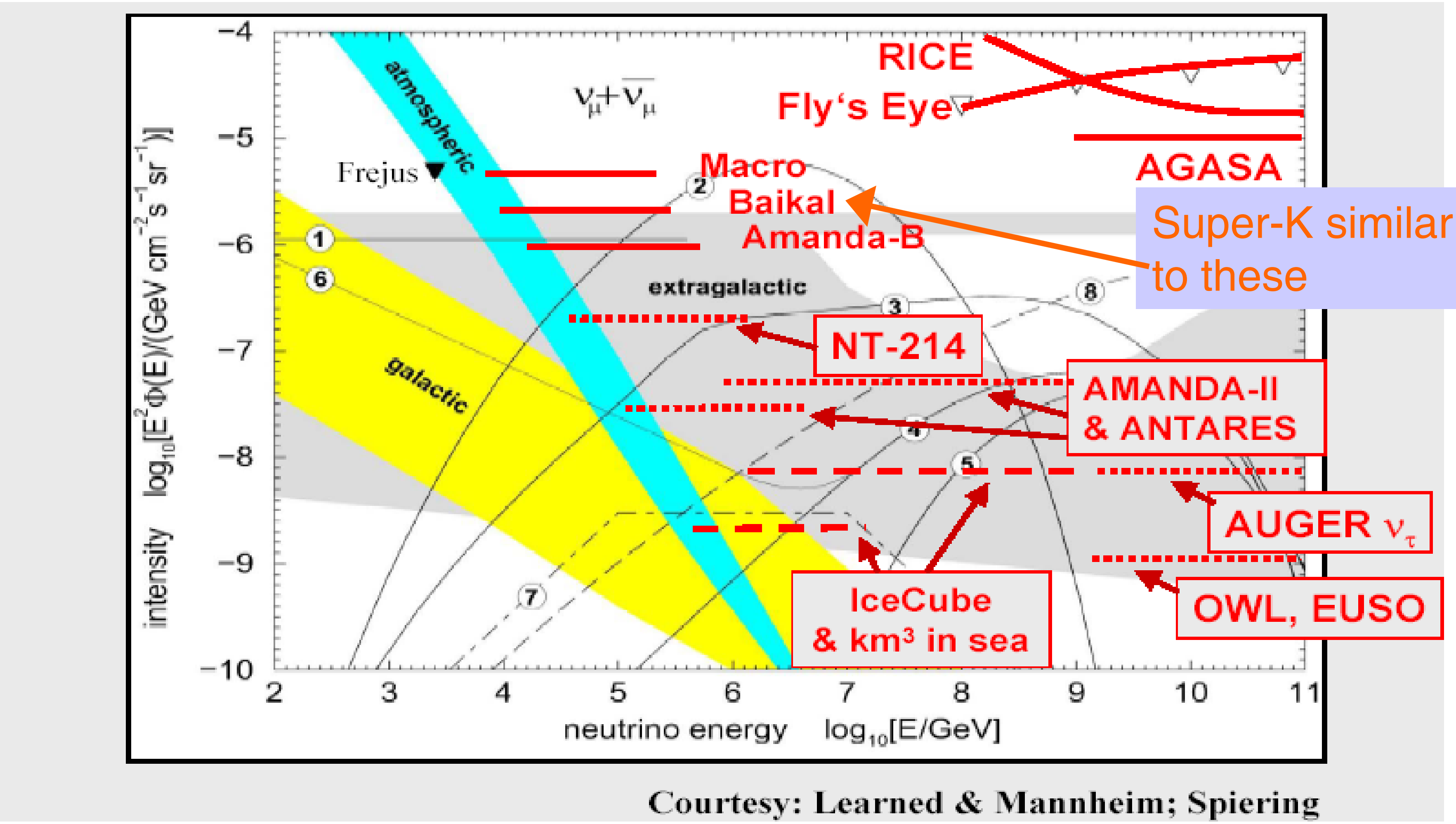
(*and Shantanu Desai in particular*)

Upward-going μ

- High energy ν_μ 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 ν_μ spectra
- Down-going entering cosmic ray muons restrict this technique to upward-going entering muons



Highest Energies best for ν-astronomy

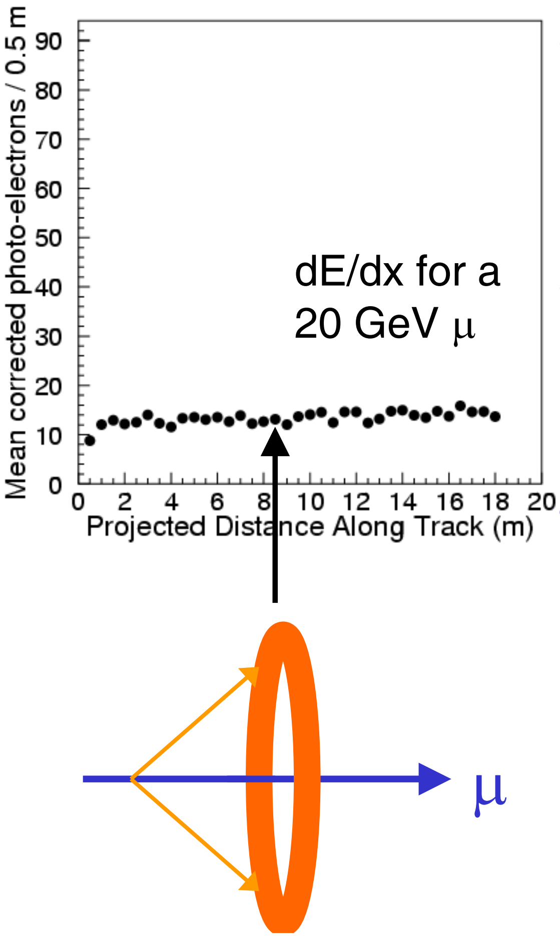


From Doug Cowen's ν2002 talk

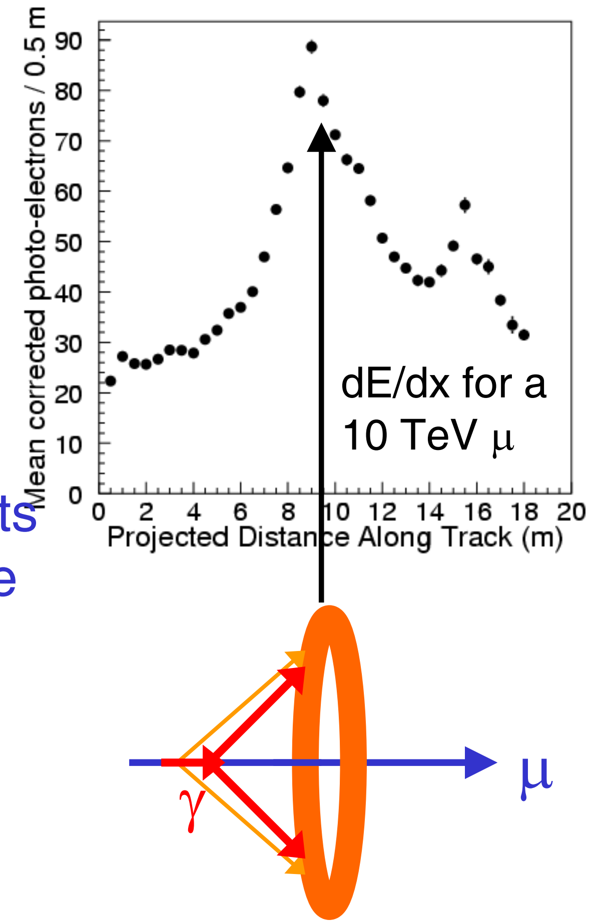
Astrophysical ν

- 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

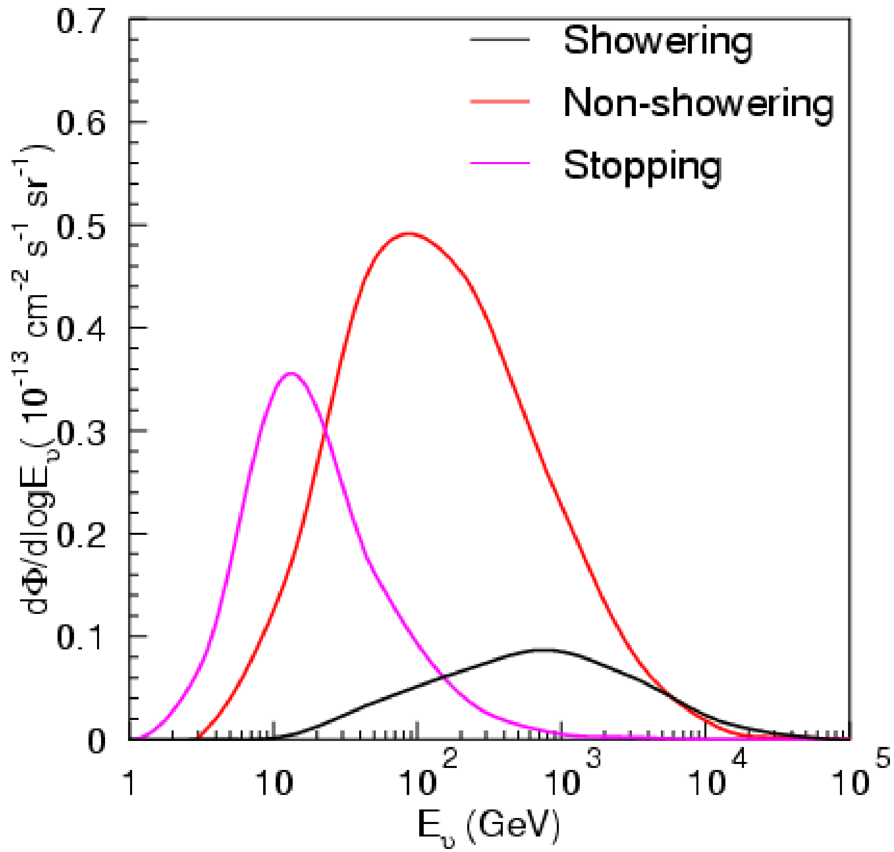
Bremsstrahlung happens, Cherenkov light from EM shower also contributes

Data Selection

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

SK Up-μ ν Spectra

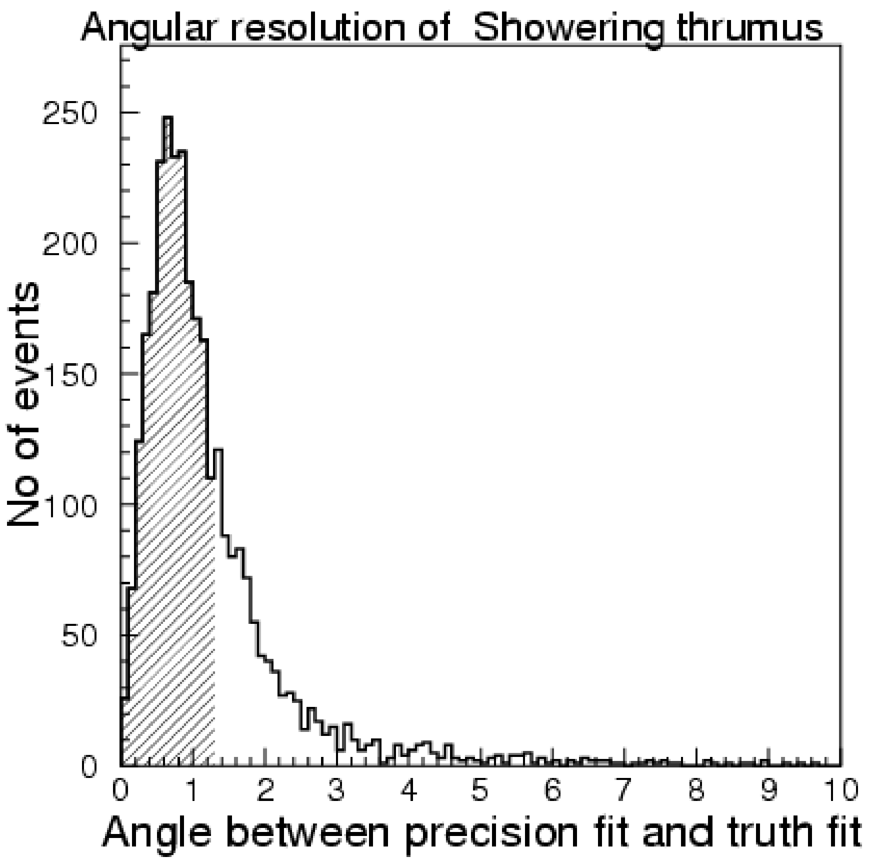
- Three classes of UGM:
  - Stopping μ: E_ν ~10 GeV
  - Through-going μ: E_ν ~100 GeV
  - Showering μ: E_ν ~ 1 TeV
    - Selected by high dE/dx
  - (*energies from atm. ν spectra*)
- Also available:
  - Extremely high energy μ's (saturate all PMTs)
  - Collected, but not yet understood well enough to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



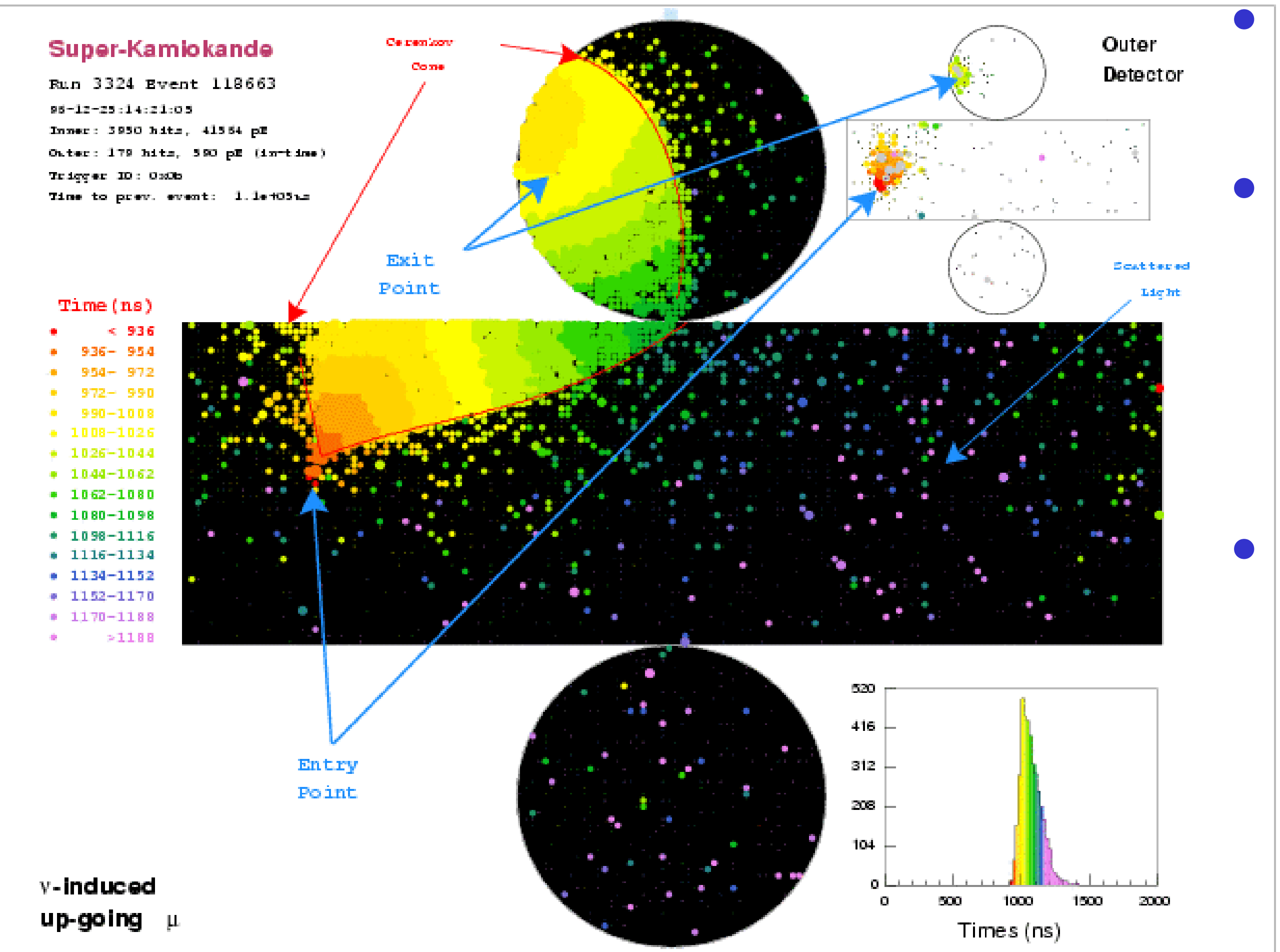
Spectra of parent ν Producing SK's up-μ

Angular Resolution

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



Up-μ's in Super-K



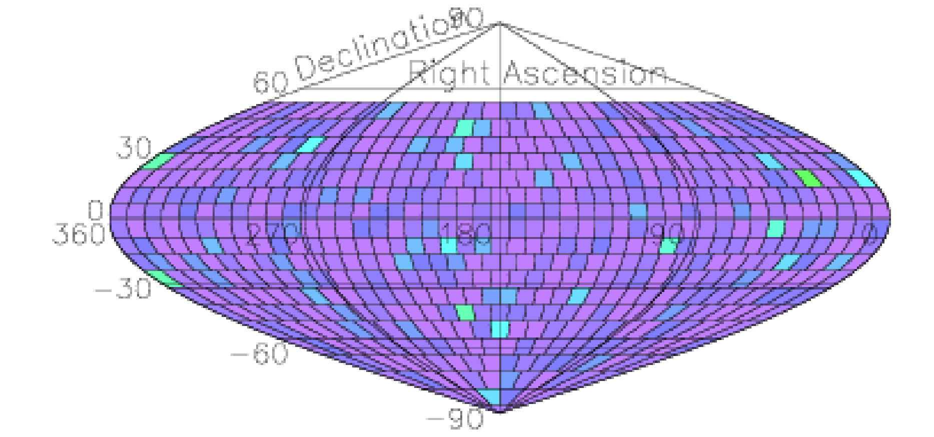
- For "SK-I"
  - 4/96 to 7/01
- 1680 live-days
  - More than other SK analyses, this is insensitive to poor detector conditions
- For >7m path (>1.6 GeV):
  - 1892 thru-μ
    - <1.4° tracking res.
    - 332 are showering
  - 467 stop-μ

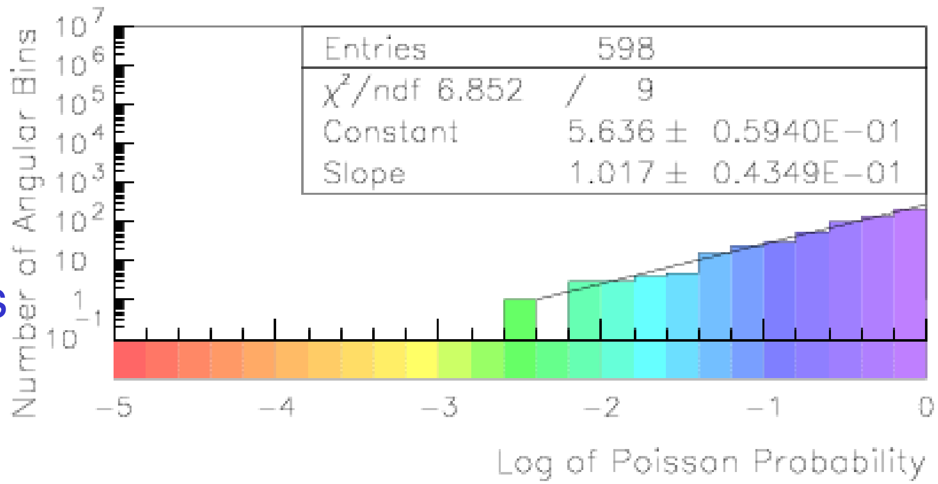
All-sky survey

- 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. ν background in bins
  - Apply Poisson statistics, discover things or set limits

Bins

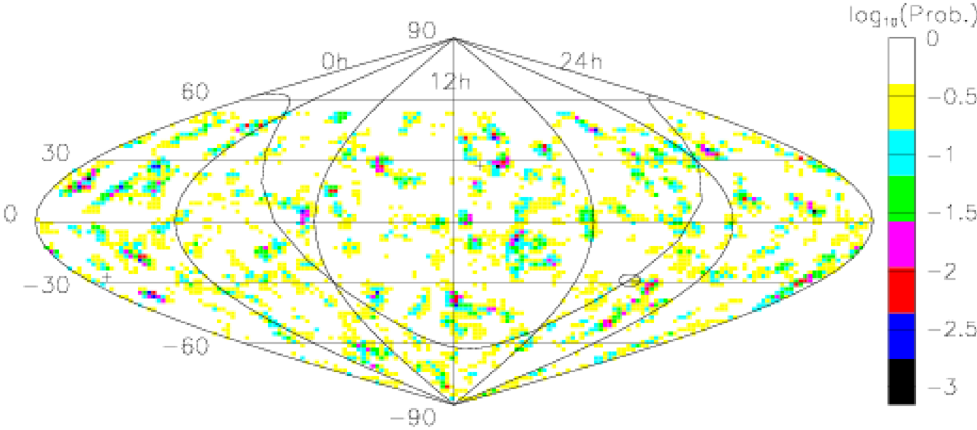
- Being a spherical sky, an igloo pixelization works better than the alternatives
  - Although size is hard to optimize
- Problem: a source on a bin boundary would be unnoticed
  - Doing multiple offset surveys solves this but hurts sensitivity with trials factors

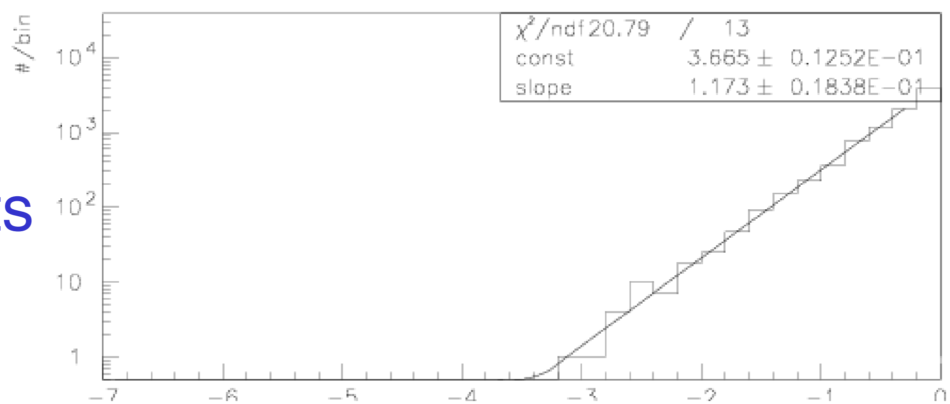


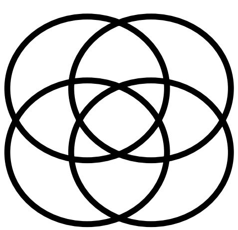


Cones

- 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





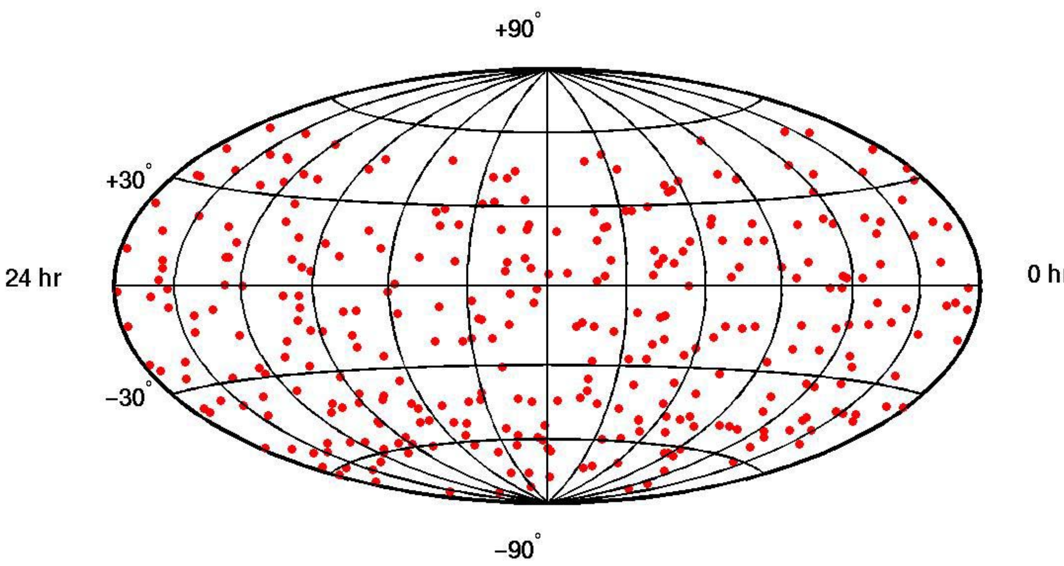


(Unbinned searches also turn nothing up)

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

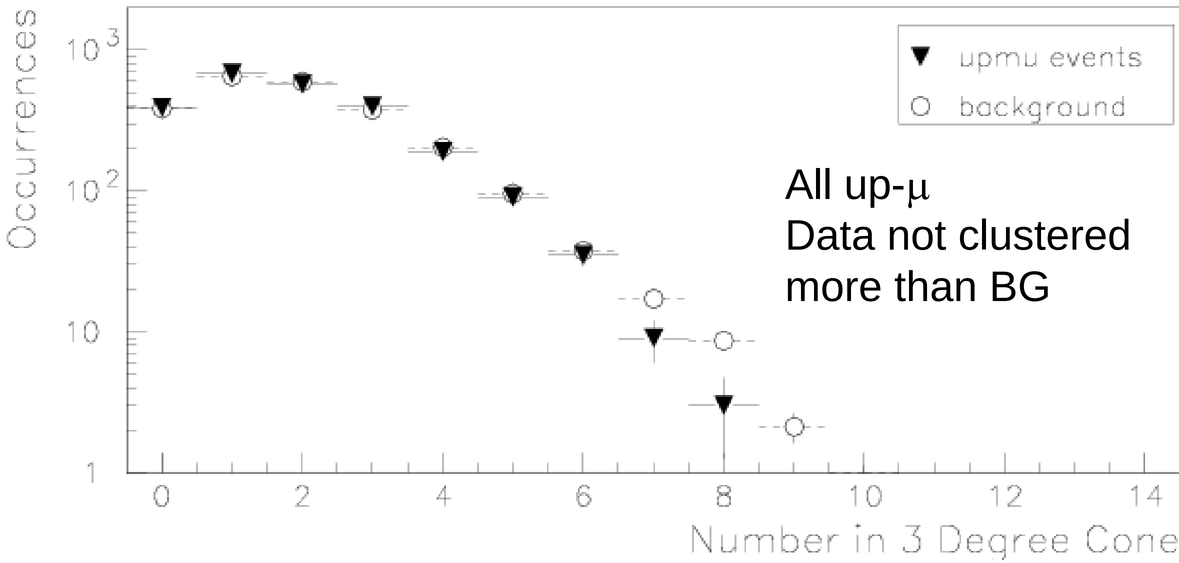
Showering up-μ Sky

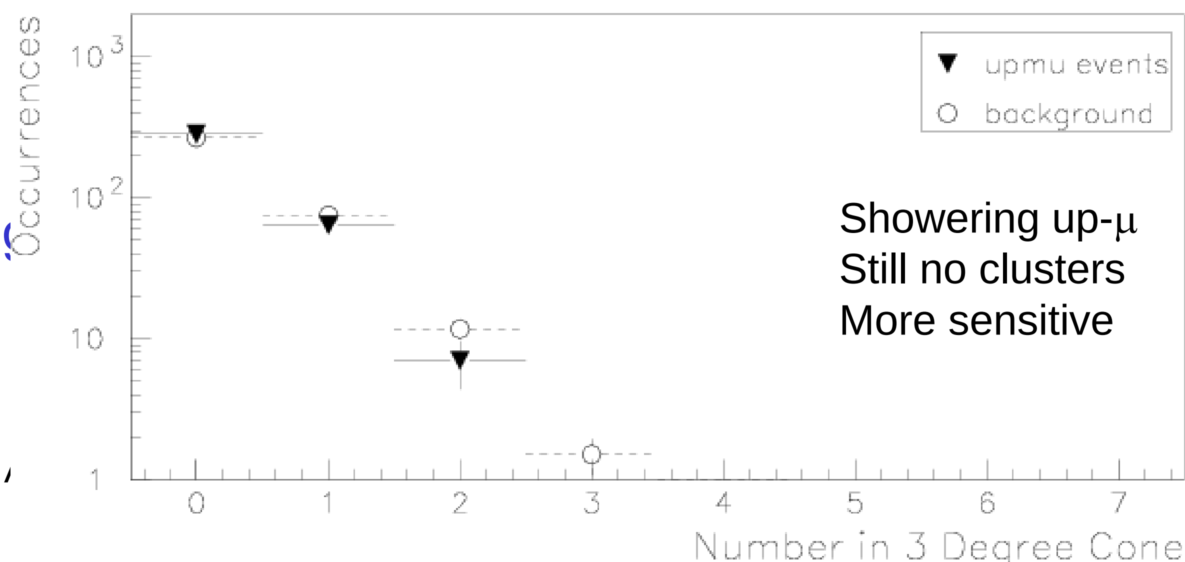
- The sky seen in showering up-μ is below
  - Should be better S/N at these higher energies, where Signal is AGN's etc and Noise is atmospheric ν
  - No statistically significant clusters seen



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 ν 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 ν 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 ν events
- All SK ν events used
  - "Low-E" (Solar ν analysis) events (7-80 MeV)
  - "High-E" (Atm. ν analysis) events (0.2-200 GeV)
  - "Up-μ" events (1.6 GeV-100 TeV)
- Look for time correlations with GRBs
  - Several different time windows used
  - Directional information also used with up-μ 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)

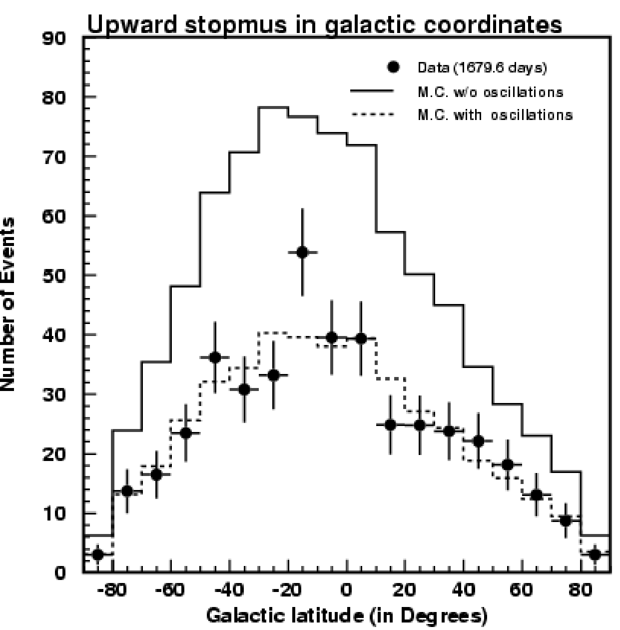
S K

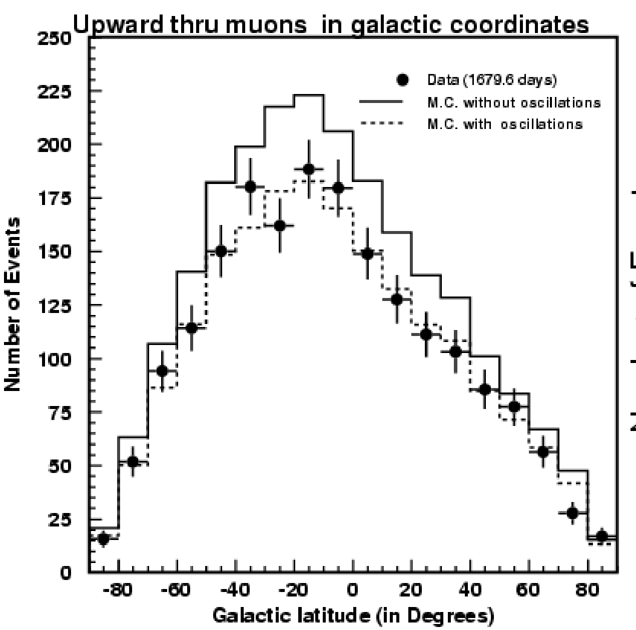
MRK 501

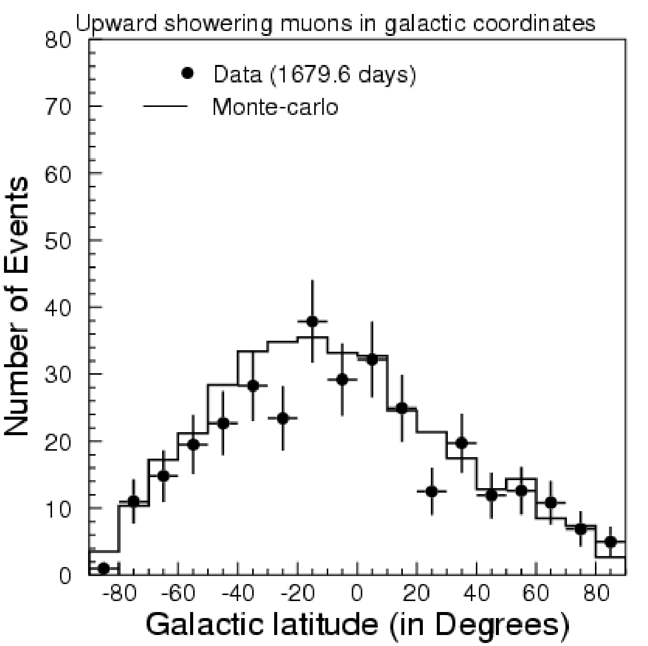
- Major flare from Feb. to Oct. 1997
- Blazar flares are when an AGN jet is pointed right at us and material is being ejected
  - Should be a great natural ν beam
- 13% of SK-I data solidly during the flare, 68% clearly not
  - Such "beam off" plus same declination but "off source" data take for a background 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

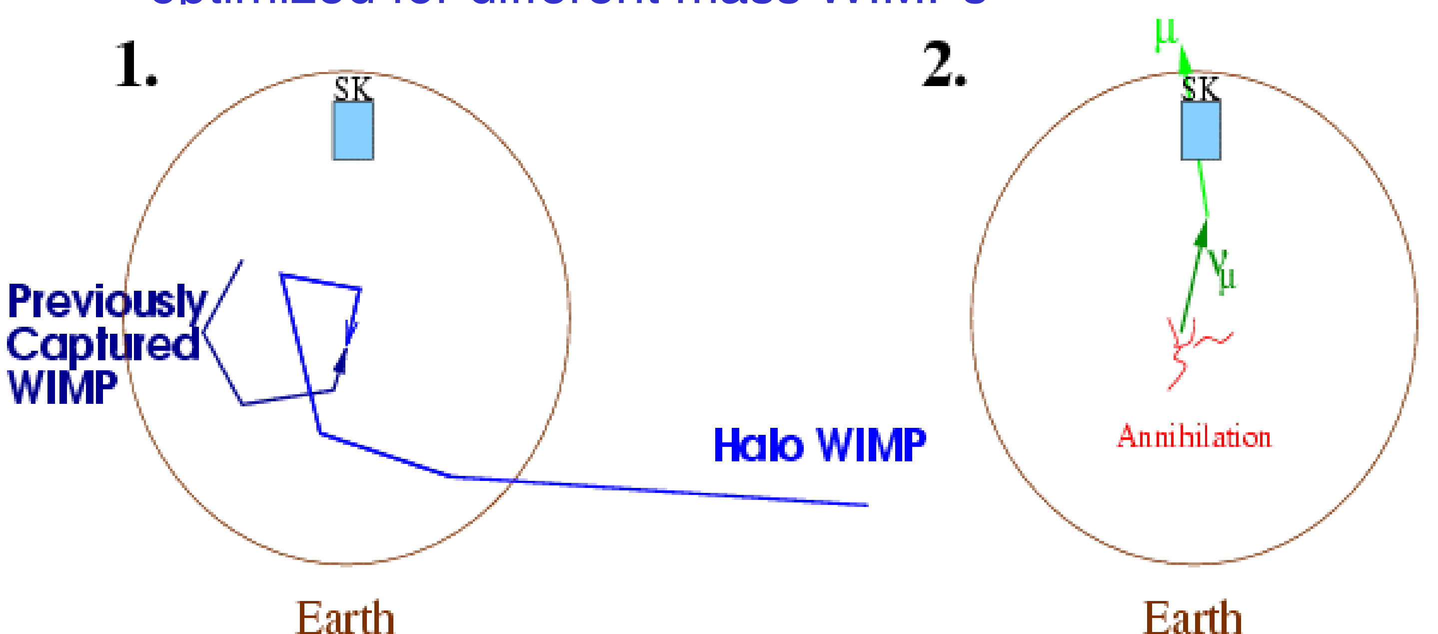




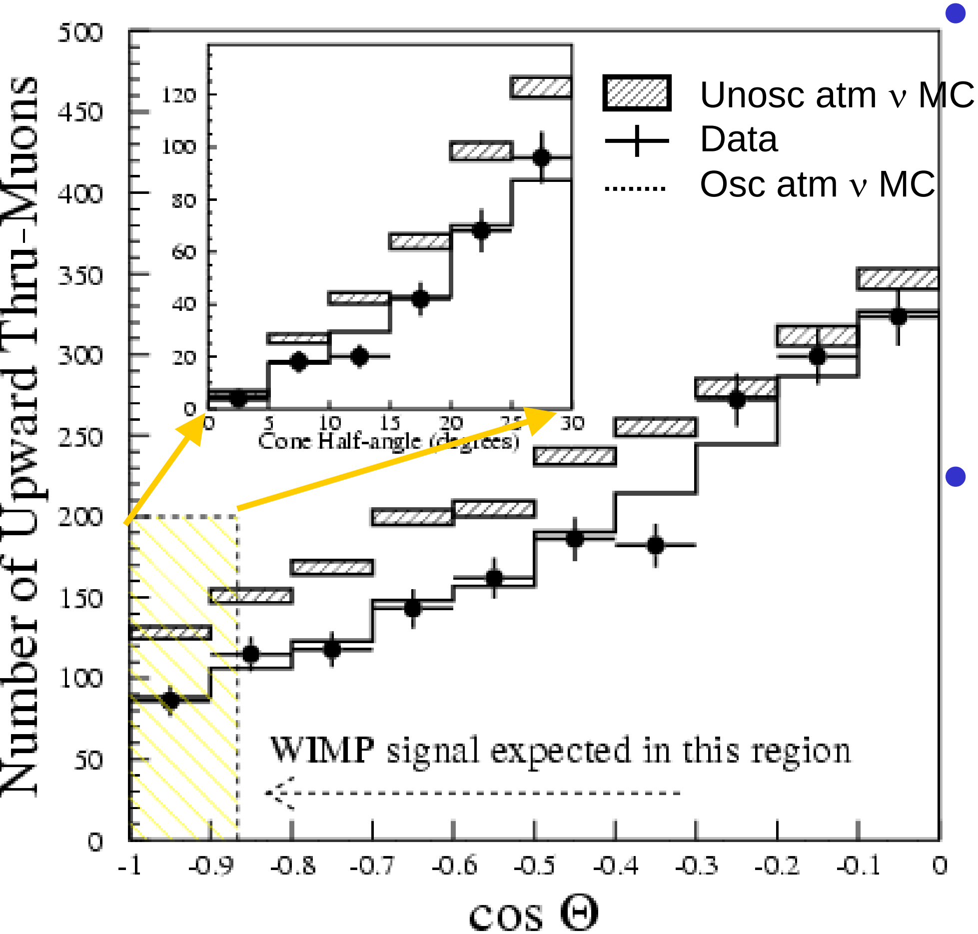


WIMP Detection

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

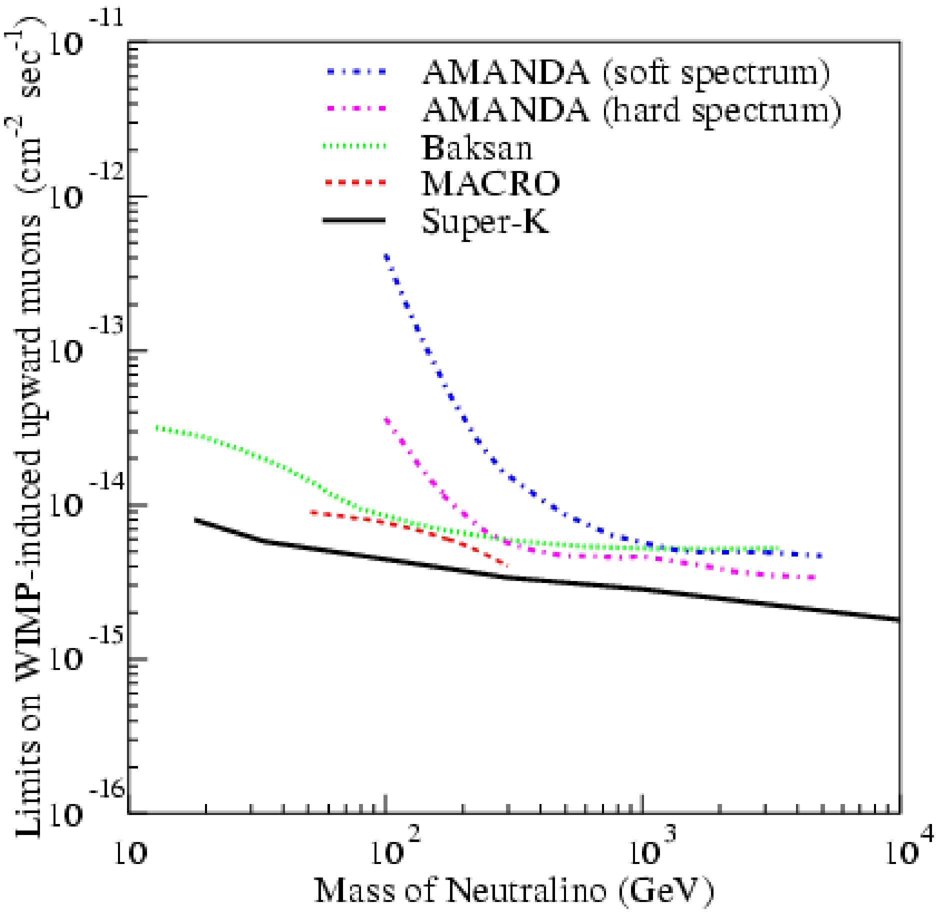


WIMPs in the Earth



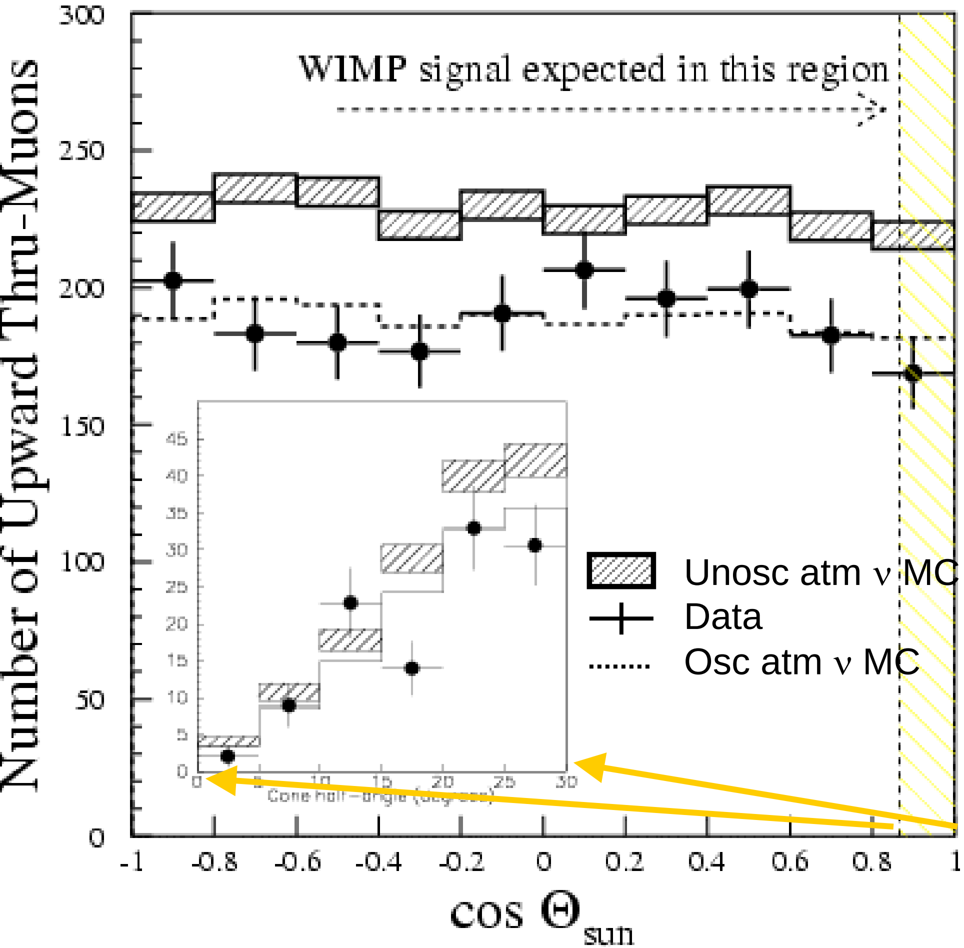
- WIMPs could only get trapped in the Earth by interacting in a spin-independent way
  - All those even heavy nuclei in the Earth with no net spin
- ν_μ from WIMP annihilation would come from the nadir
  - No excess seen in any sized angular cone (compared to background of oscillated atmospheric ν Monte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

Earth WIMP-induced Up-μ Limits



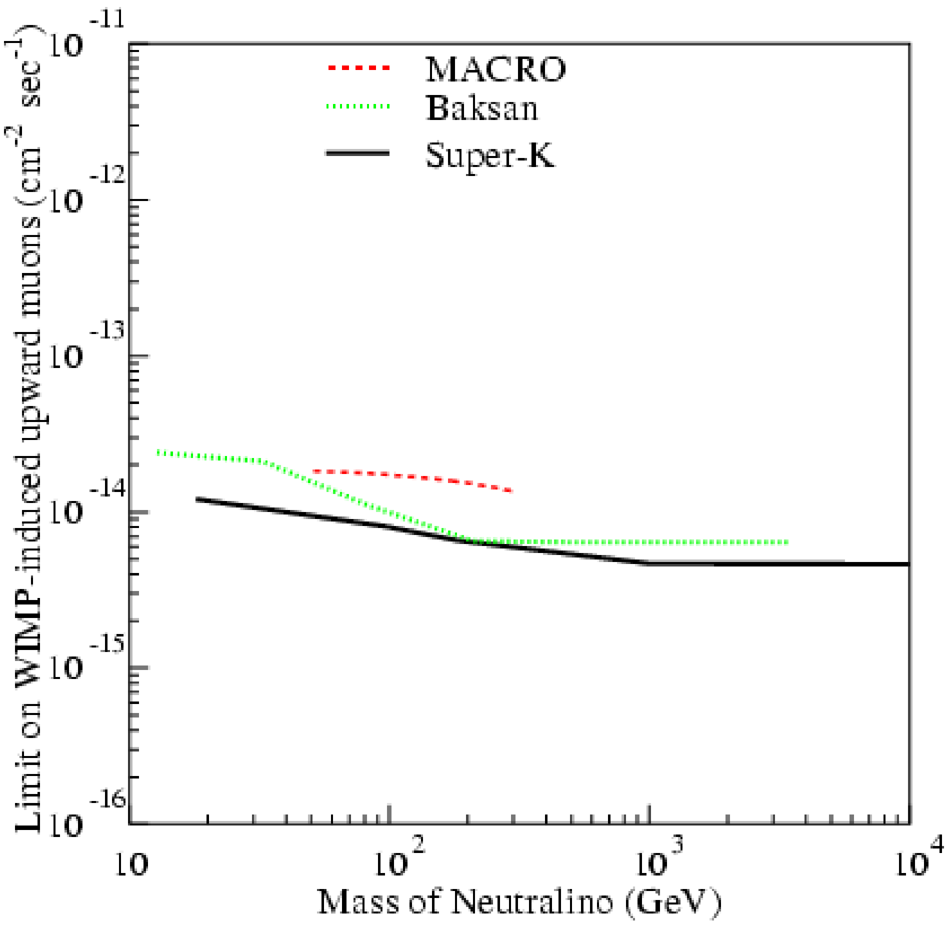
- Resulting upper limits on the WIMP-induced up-μ from the center of the Earth vs. WIMP mass
  - Varies as a function of possible WIMP mass
  - Lower limits for higher masses are due to the better S/N in smaller angular search windows
  - Lowest masses ruled out anyway by accelerator searches

WIMPs in the Sun



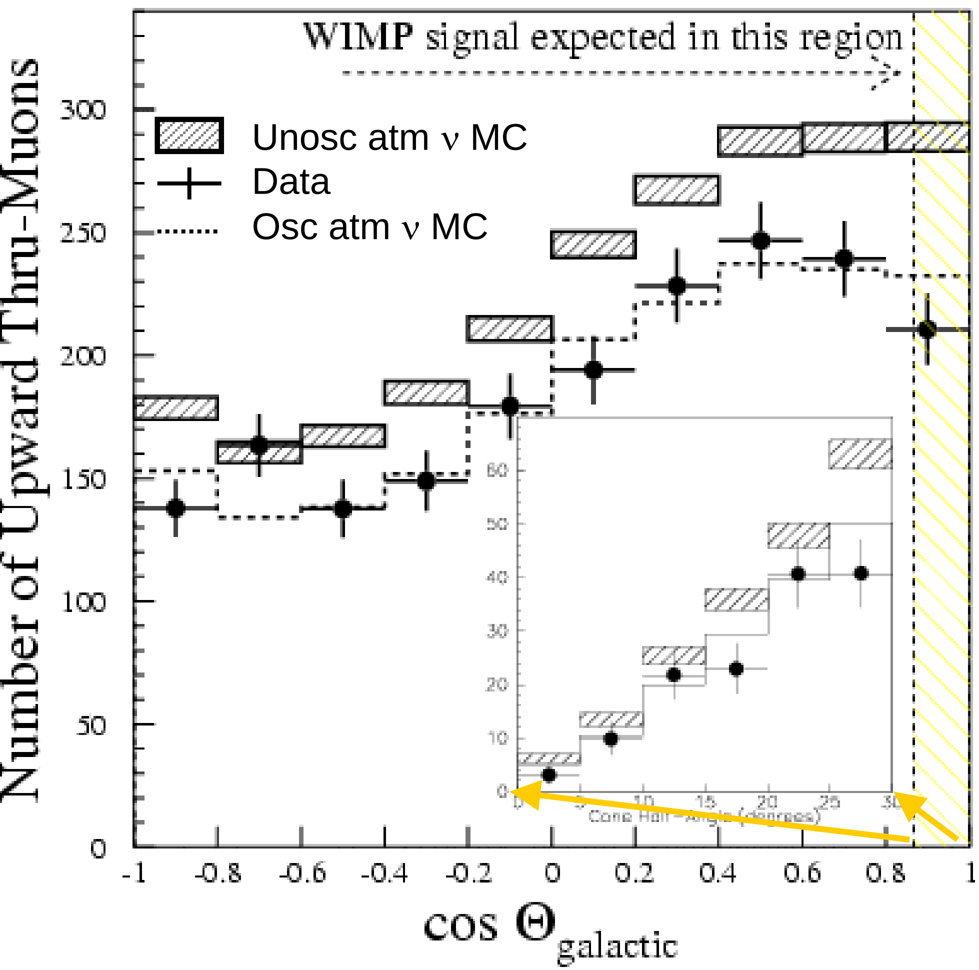
- WIMPs could also get trapped in the Sun if they interact in a spin-dependent way
  - All those spin-½ Hydrogen nuclei
- Make a cos(θ) Sun plot for all the up-μ events
  - No excess seen compared to background of oscillated atmospheric ν Monte Carlo

Sun WIMP-induced Up-μ Limits



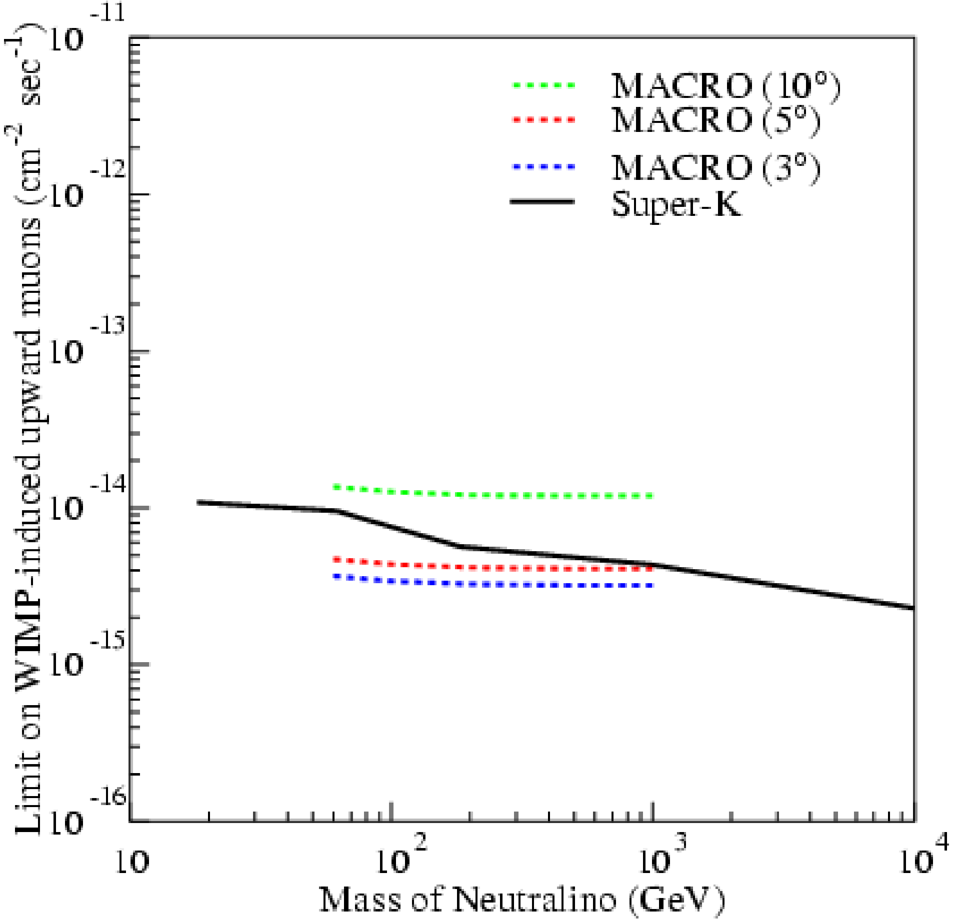
- Resulting upper limits on the WIMP-induced up-μ from the Sun vs. WIMP mass
- Same features as from Earth
  - But probes different WIMP interactions
  - Unfortunately hard for South Pole detectors to see the Sun (it's always near the horizon)

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

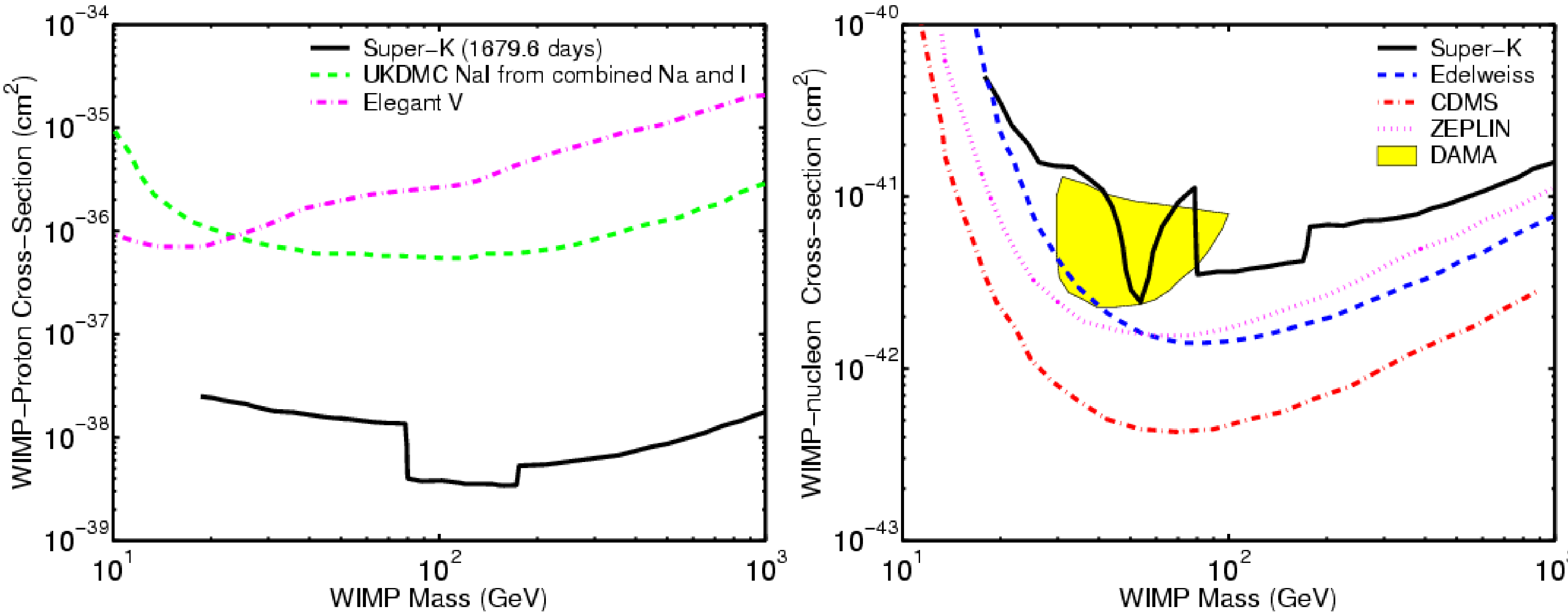
Galactic WIMP-induced Up-μ Limits



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

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