(Semi) UHE Neutrinos in Super-Kamiokande

Looking for point sources and WIMPs

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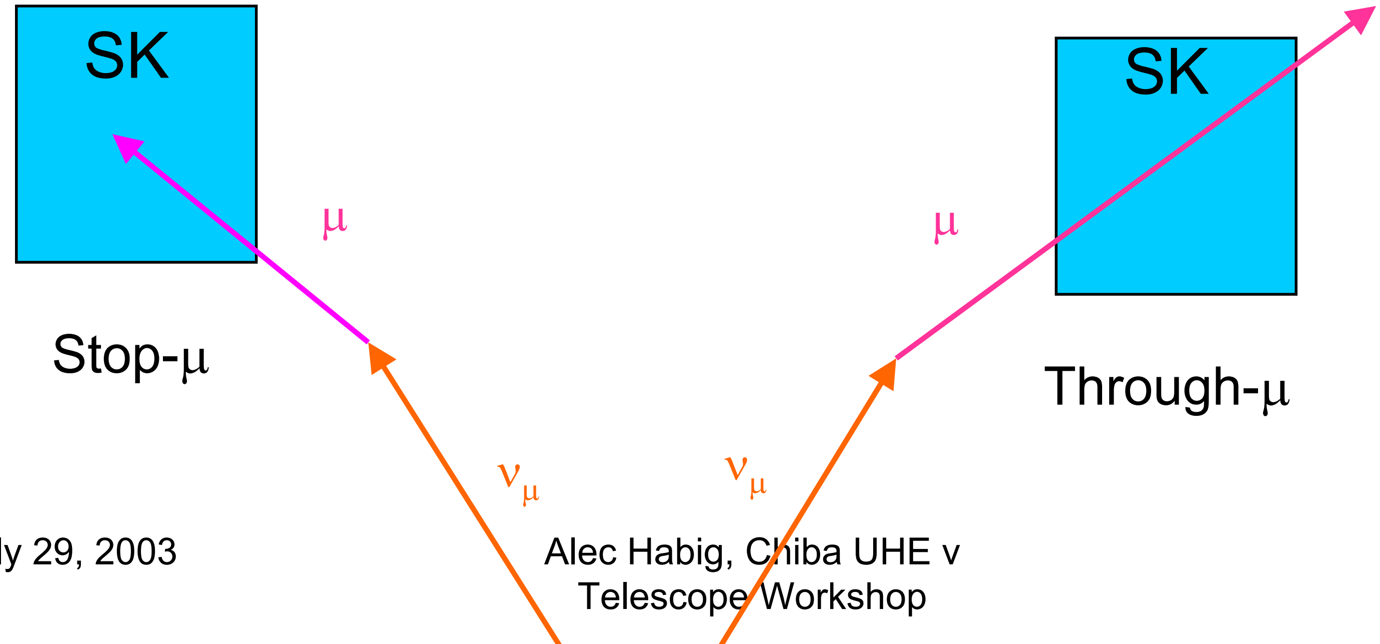
For the Super-Kamiokande Collaboration

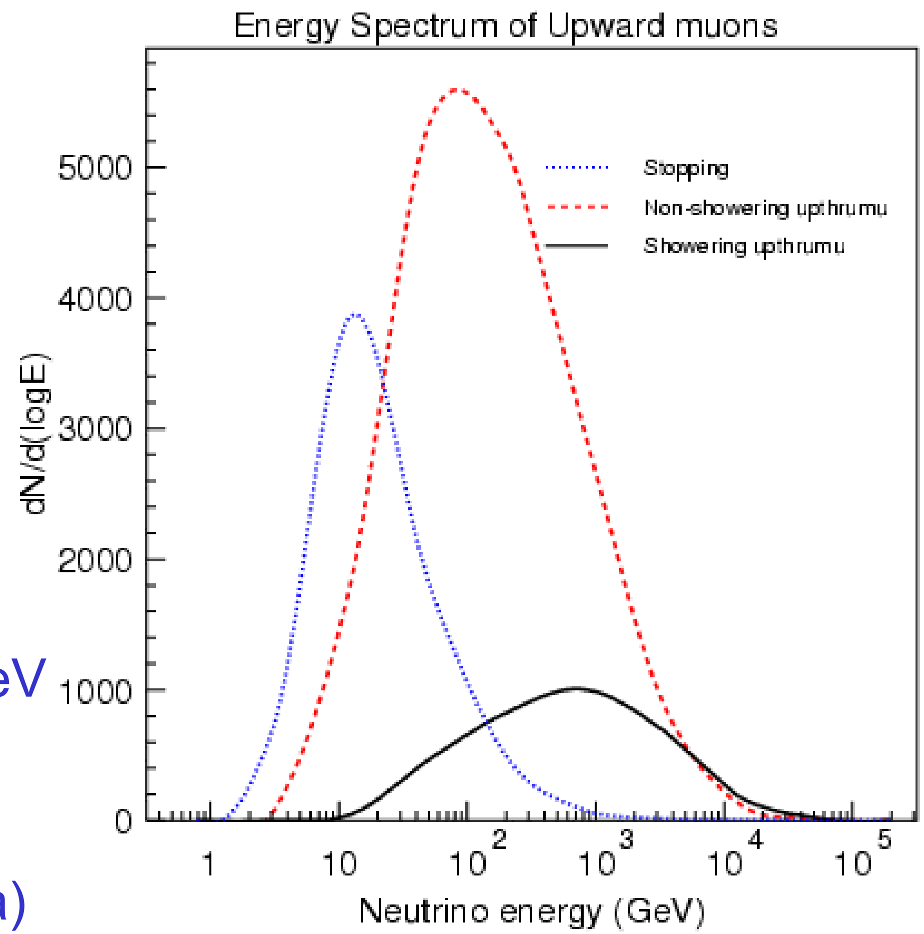
Upward-going μ

- 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

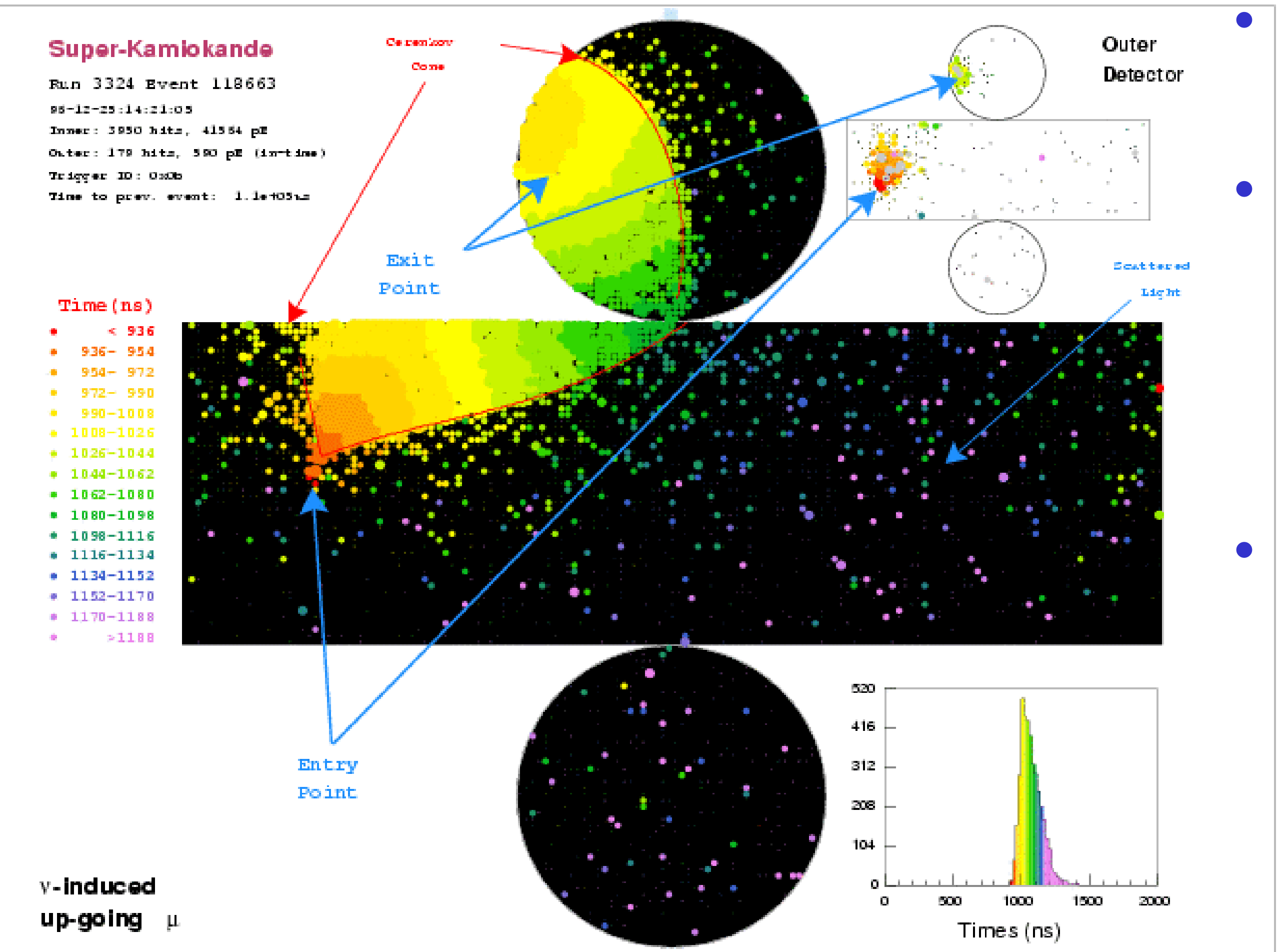


Super-Kamiokande

- Optimized for contained events (< ~10 GeV)
  - Effective area for entering particles only ~1200 m^2
  - Sees higher-energy ν as upward-going muons (UGM)
- 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)



Up-μ's in Super-K

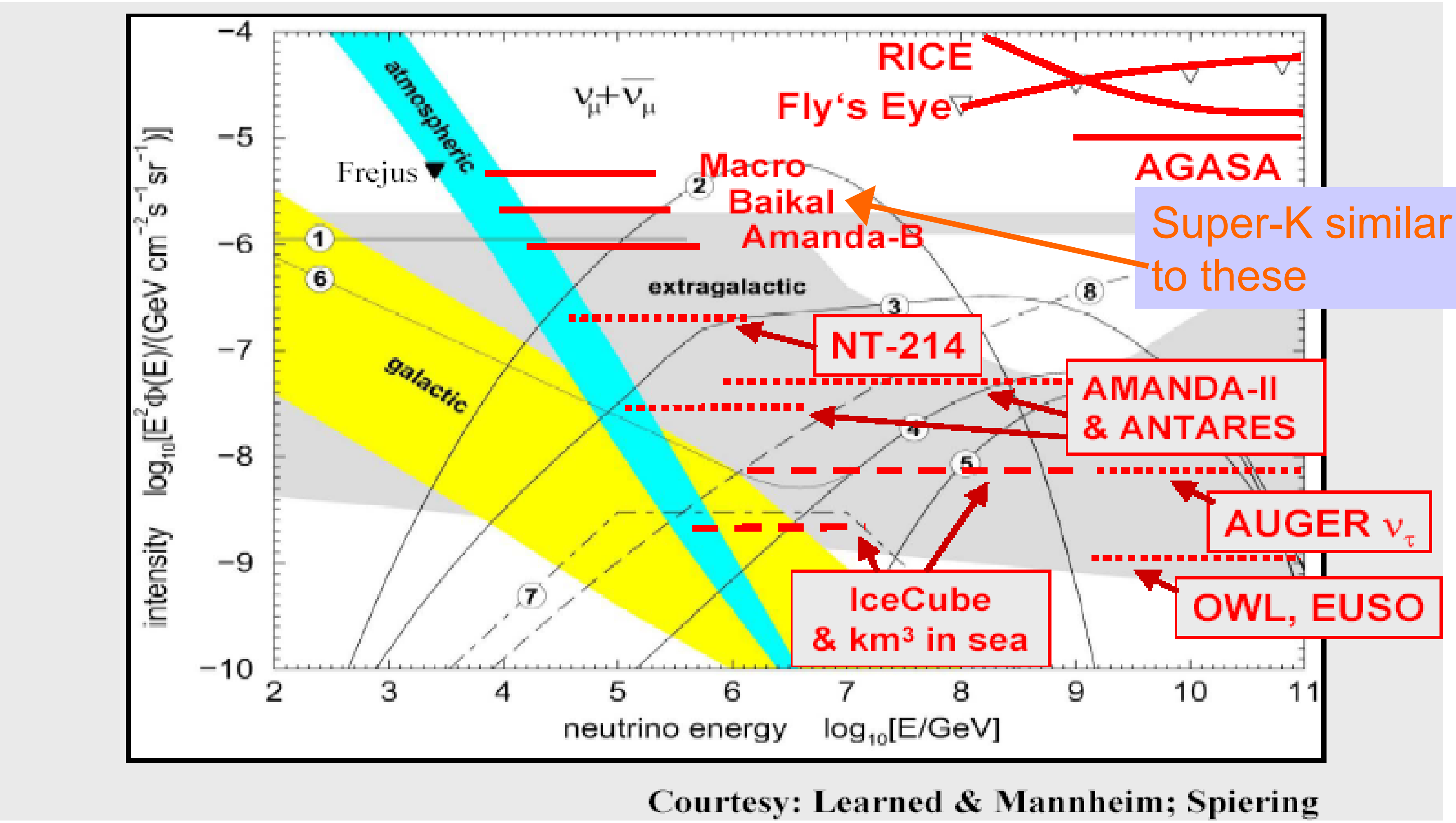


- For "SK-I"
  - 4/96 to 7/01
- 1680 live-days
  - More than other SK analyses, this is insensitive to poor detector conditions
- For >7m path (>1.6 GeV):
  - 1901 thru-μ
    - 354 are showering
  - 468 stop-μ
  - <1.4° tracking res.

Astrophysical ν

- Astrophysical sources we could surely see:
  - Solar (~MeV)
  - Supernovae (~10 MeV)   (*including relic SN ν*)
- Sources which are probably fainter than the atmospheric ν background (or just plain too faint):
  - 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

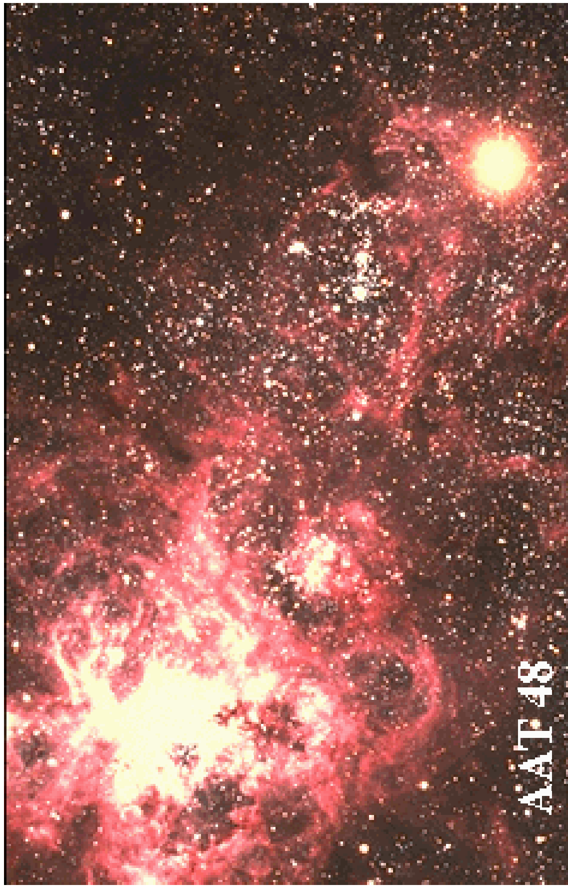
Graphically



From Doug Cowen's ν2002 talk

A Supernova Aside

- Long-string PMT detectors have very high energy thresholds
- But can still see supernovae neutrinos as an increase in the PMT “dark” rate!
  - If dark rate low enough
  - See last talk from Thomas Feser
- Gratuitous plug:
  - Please try to allow your experiment to do something similar, and participate in the SNEWS (SuperNova Early Warning System) coincidence network!
  - http://hep.bu.edu/~snnet/



How to do ν astronomy with Super-K

- Hope models are wrong
  - Maybe there is a bright GeV-TeV ν source
- Beat the Background
  - Time coincidences, say with microquasar or blazar flares
  - or with GRBs
- Why?
  - Maybe something is there
  - We already have the data, might as well
  - Good practice for looking with the big experiments
- Note most of what follows is rather preliminary
  - Work is in progress, don't take the detailed numbers overly seriously!

See ICRC talk by Kristine Washburn (U. Washington)

ν Astro Issues

- This being a workshop, things to think about and discuss as we proceed:
  - What are the pros and cons of the different techniques for searching for sources?
  - Should experiments with a realistic discovery potential do a “closed box” blind analysis to avoid statistically killing themselves with trials penalties?
- Super-K, MACRO, IMB, Soudan have all taken a hodge-podge approach till now, let’s learn from our experience
  - Experience says: you look at noise in enough different ways, you will see surprising things!

Backgrounds

- Our background (and most all our data) are atmospheric ν_μ
- When counting ν from some potential source, how many of them would we expect to be atmospheric ν?
- For comparison, need a set of ν data which matches the characteristics of the atm.ν sample and contains no actual point sources
- Two approaches :
  – Bootstrap
  – Monte Carlo

Bootstrap

- Take the observed events
- Randomly re-assign directions and live times
- Pros:
  - Easily generates background which matches angular and live time distribution of real data
  - Any astrophysical ν will be scrambled in RA and disappear from the background sample
- Cons:
  - For low statistics samples backgrounds are too granular, introducing non-Poissonian effects
  - Trying to smear space or time to combat granularity introduces different non-Poissonian effects

Monte Carlo

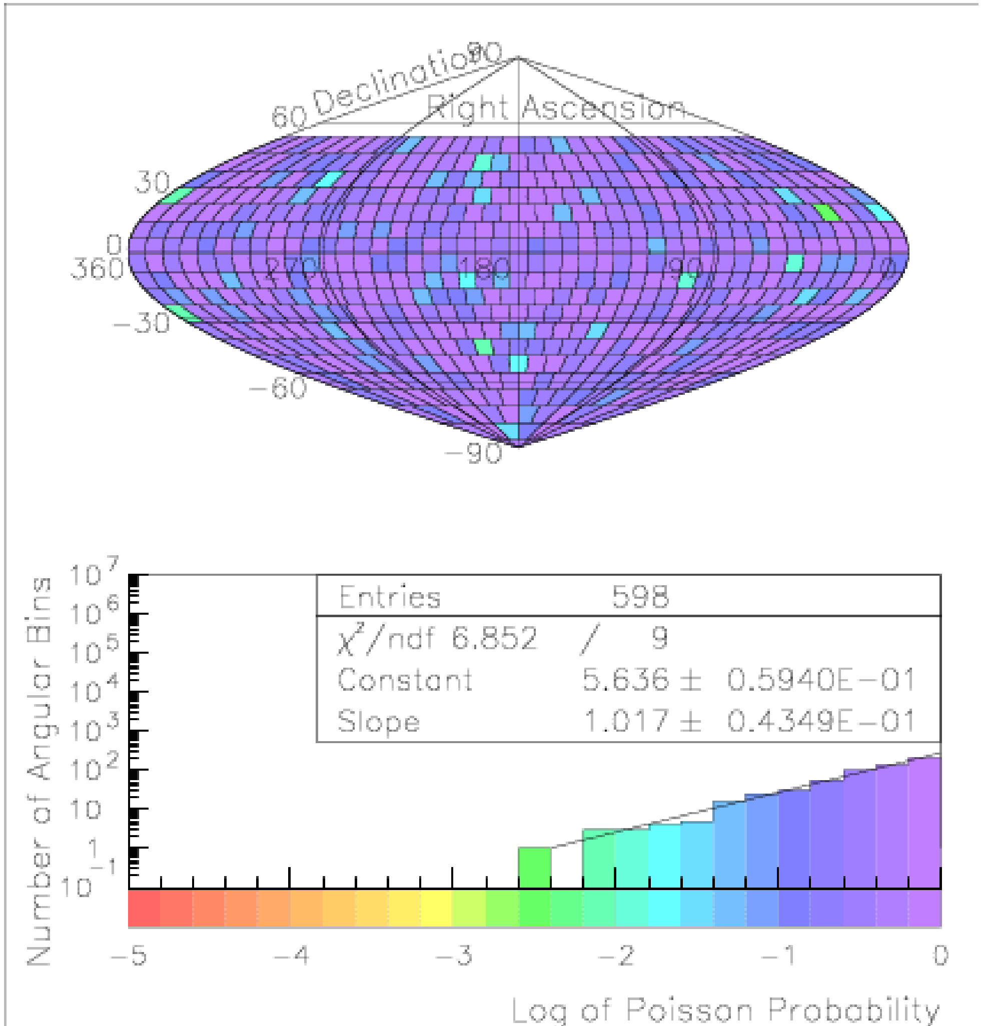
- Use the experiment's atmospheric ν Monte Carlo events, assigned times from the experimental live time distribution
- Pros:
  - Guaranteed to contain no point sources
  - Directly simulates your background
- Cons:
  - Only as good as your MC
  - More work to make, especially the live-time distribution (given ν rates << clock ticks, need to save down-going CR distribution)

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 obvious 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

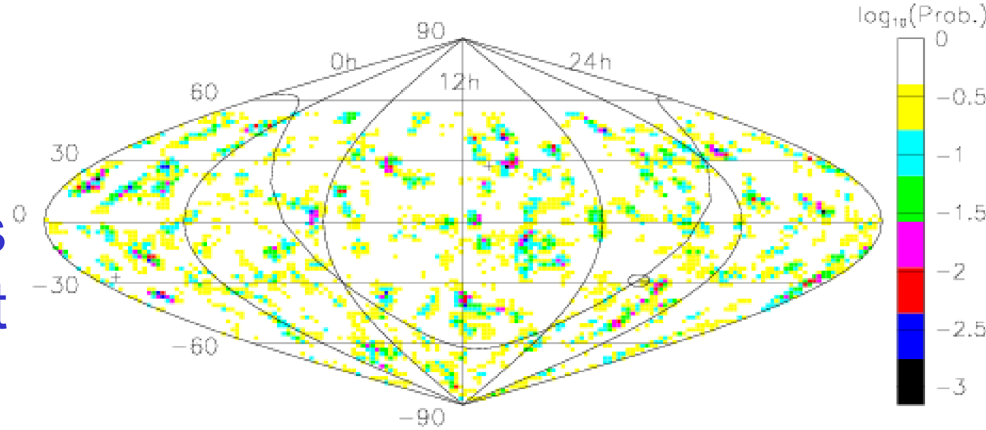
Bins

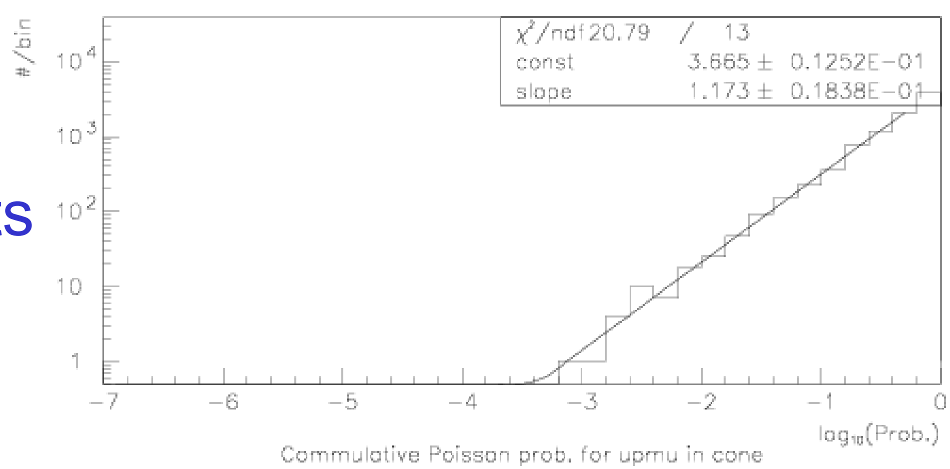
- Being a spherical sky, an igloo pixelization works better than the alternatives
- Problem: a source on a bin boundary would be unnoticed
  - Doing multiple offset surveys solves this but kills sensitivity with trials factors

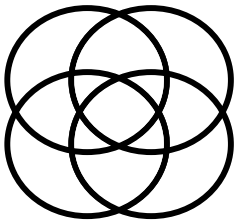


Cones

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

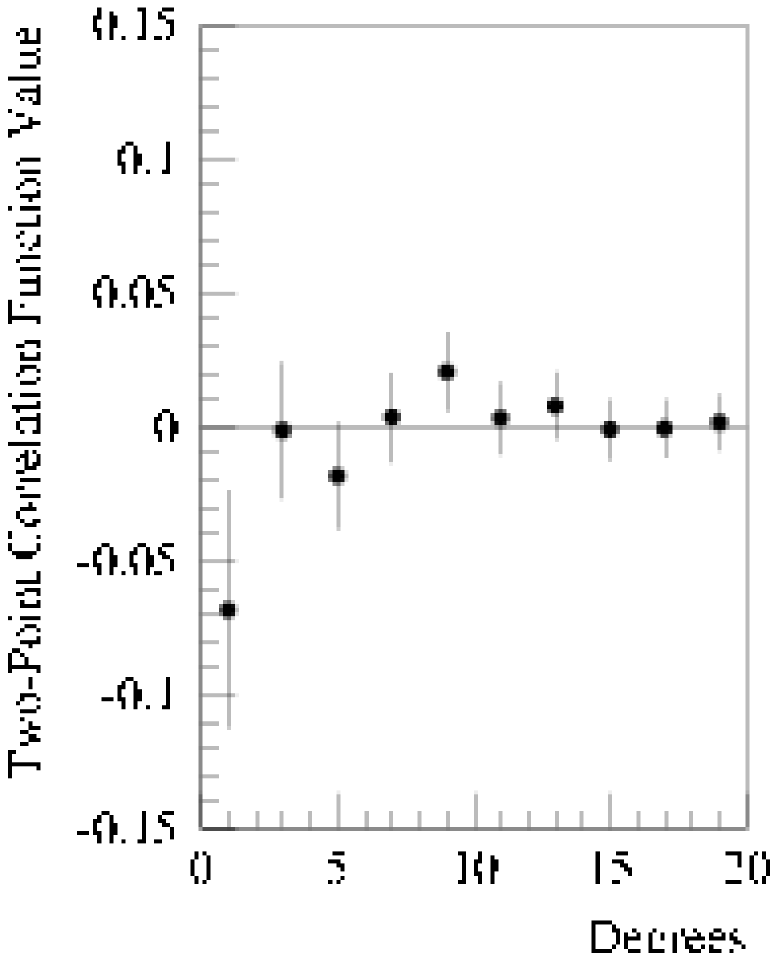






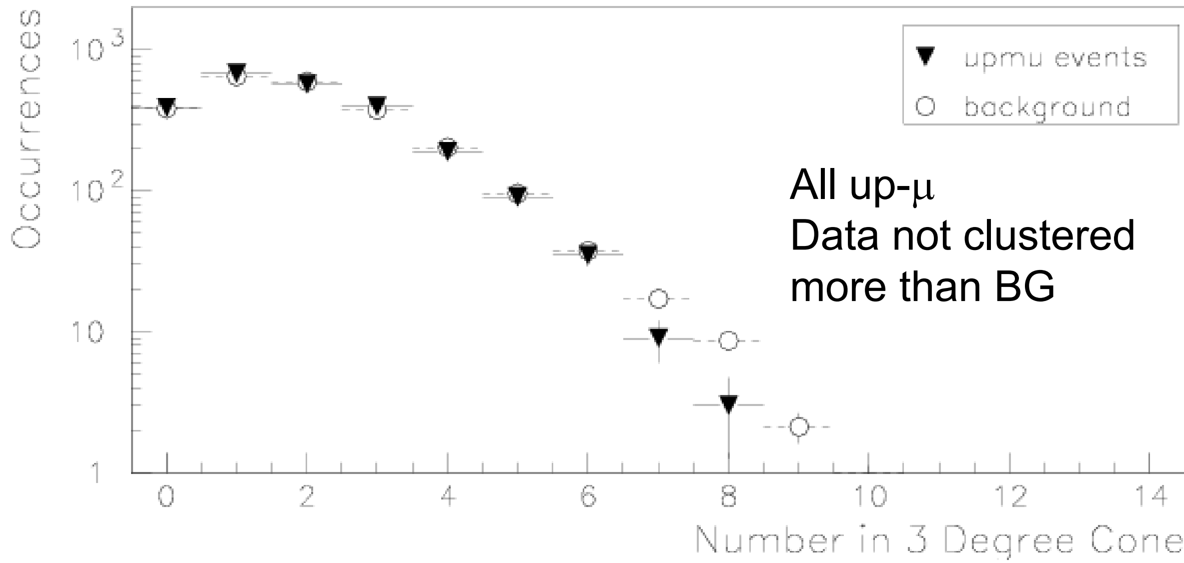
Unbinned Searches

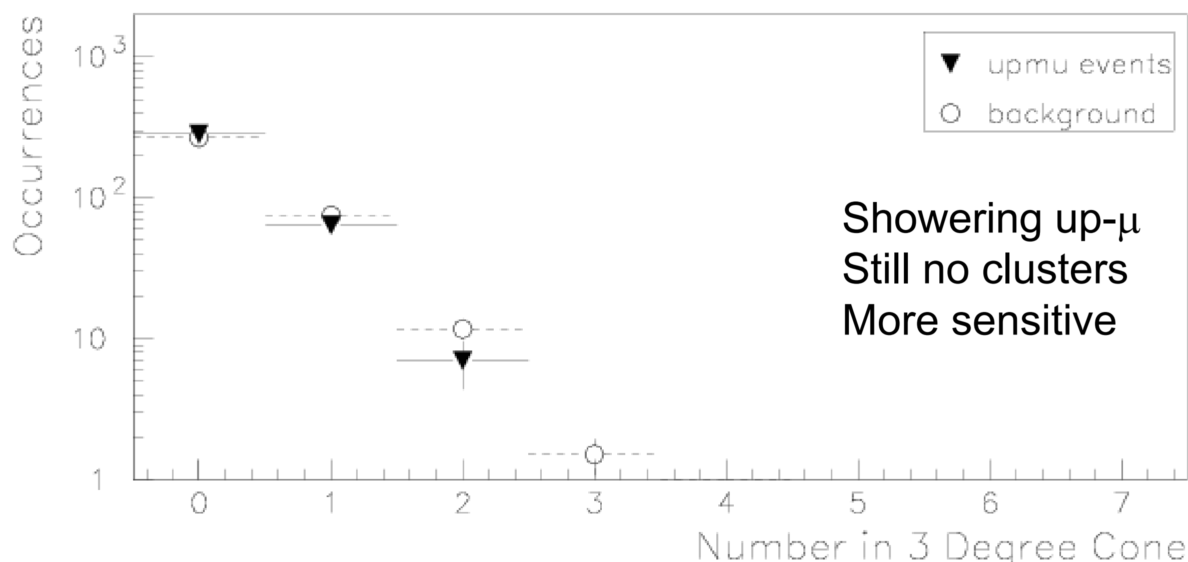
- How about avoiding bin edges entirely?
- Try 2-point correlation function
  - Used for galactic large-scale structure searches
- Problem – best for large scale structure, not so sensitive to small clusters



Clustering

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





PSF Likelihood

- Perhaps the “most correct” way:
  - Compute the point spread function of up-μ seen in the detector given an astrophysical ν spectrum
  - Compare this template to all points on the sky, compute a log-likelihood
  - Look for statistically significant likelihoods

As seen in Aart Heijboer’s talk this morning!

- Takes into account all physics inputs
- Actually works
  - The method used to find very faint shadow of moon in MACRO cosmic ray primaries
- Not been done yet with SK data for ν astronomy
  - Moon shadow seen (*an important front-to-back analysis check!*)

Point Source Check

- For a given astrophysical object, do the Poissonnian statistics for a cone around it
- Limits galore for modelers
- Always enough places to look that you will find something in someone's catalog with a surprising fluctuation
  - How to properly take into account the trials factors for all these searches?

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

- Haven't seen any sources in an all-sky survey, so limits can be 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

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

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

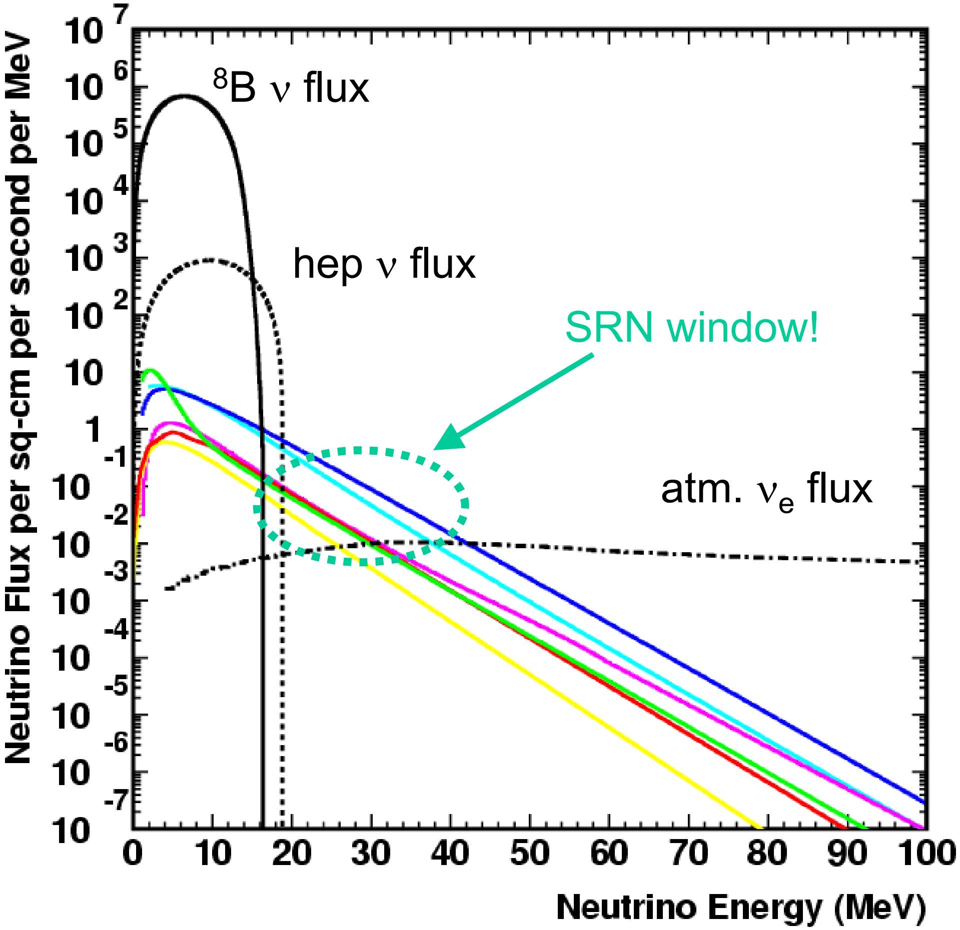
- Major flare from Feb. to Oct. 1997
- Blazar flares are when an AGN jet is pointed right at us and material is being ejected
  - Should be a great natural ν beam
- 13% of SK-I data solidly during the flare, 68% clearly not
  - Such “beam off” plus same declination but “off source” data take for a background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

SN Relic ν

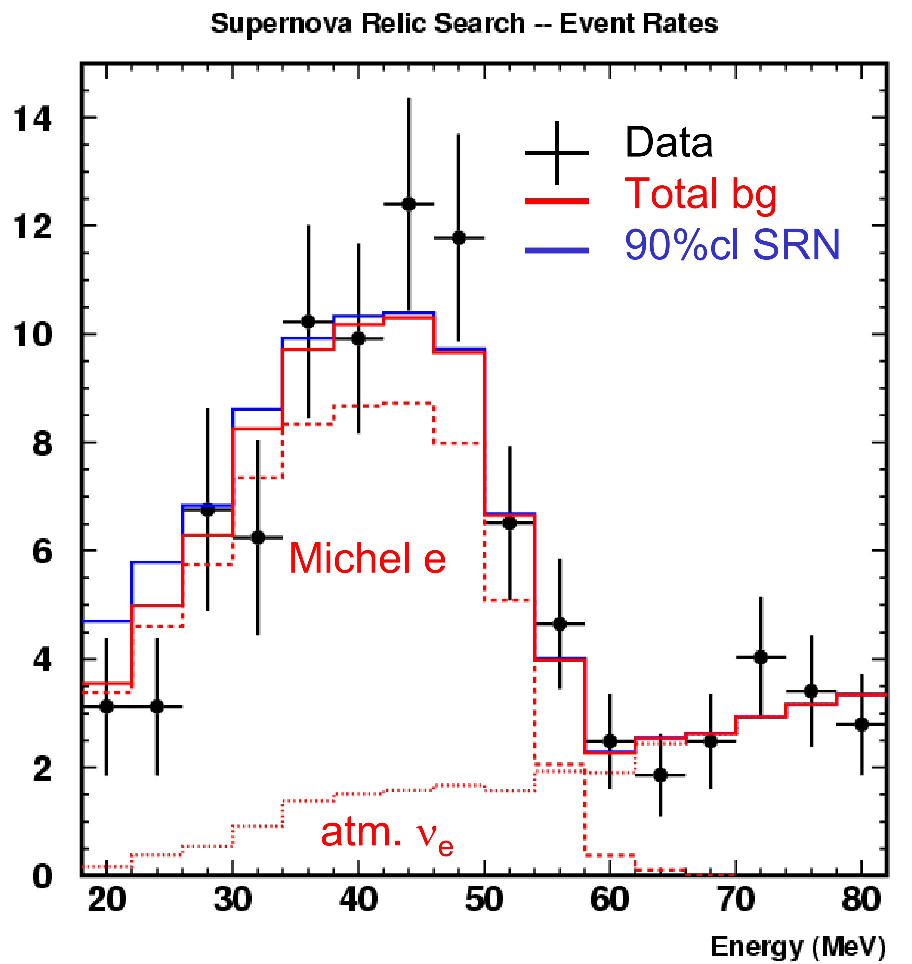
- Rather than just waiting for a galactic SN to blast us with ν, let's look for the sum of all SNe long long ago in galaxies far far away[1]
  - Supernovae Relic Neutrinos (SRN)
- Provides a direct test of various early star-formation models
- Backgrounds:
  - Solar ν at lower energies
  - Atmospheric ν (and μ decay e's) at higher energy
  - There is an open window in the background right at SN ν energies! (10's of MeV)

[1]Lucas, G., 1975

SN Relic ν S/N

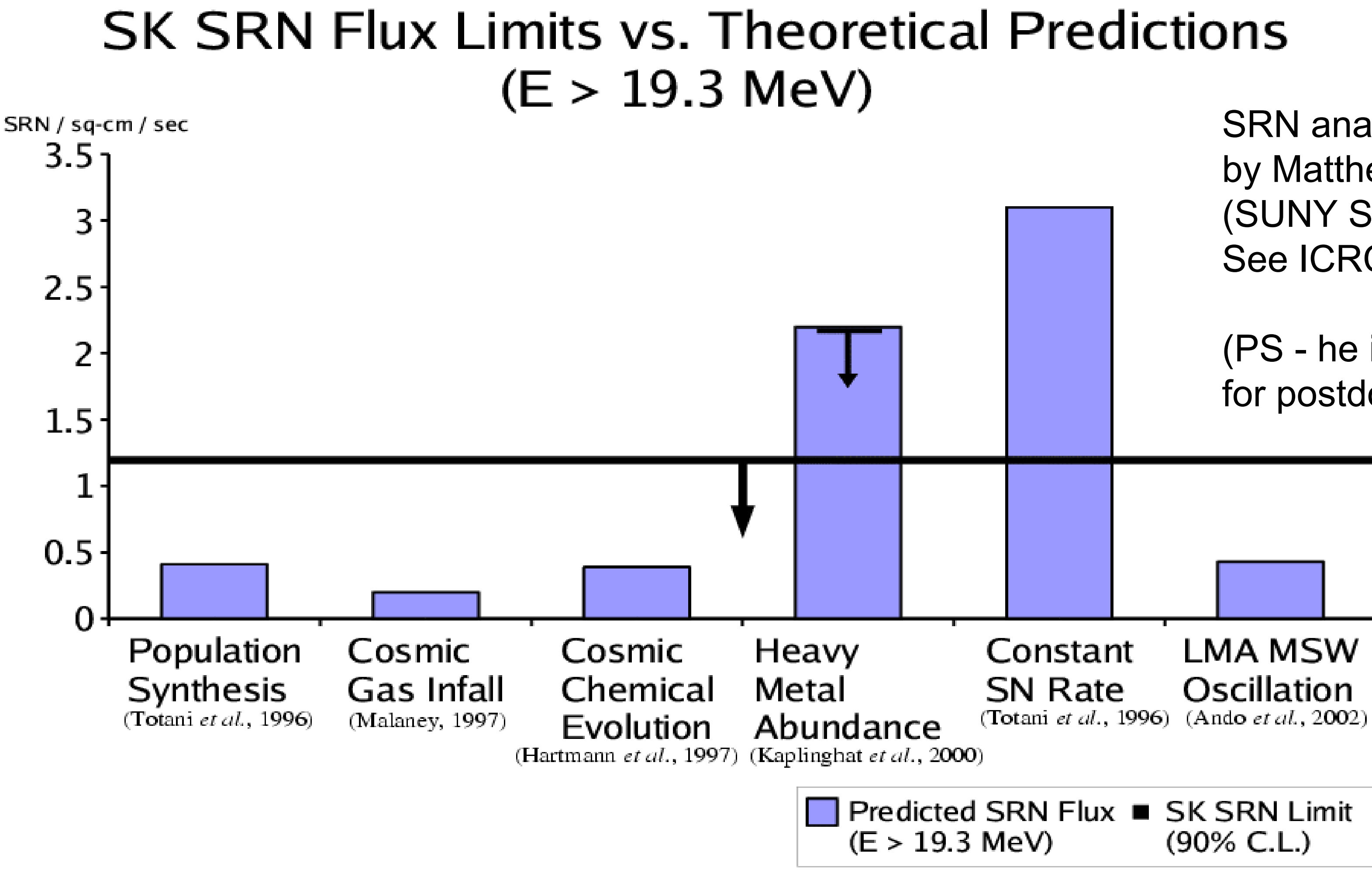


Neutrino Flux per sq-cm per second per MeV
^{8}B ν flux
hep ν flux
SRN window!
atm. ν_e flux
Neutrino Energy (MeV)



Supernova Relic Search -- Event Rates
Data
Total bg
90%cl SRN
Michel e
atm. ν_e
Energy (MeV)

SN Relics

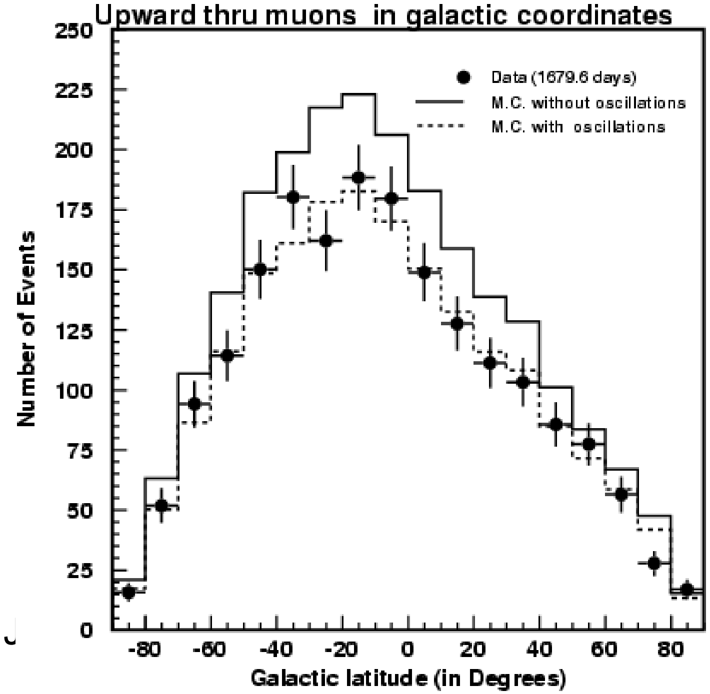


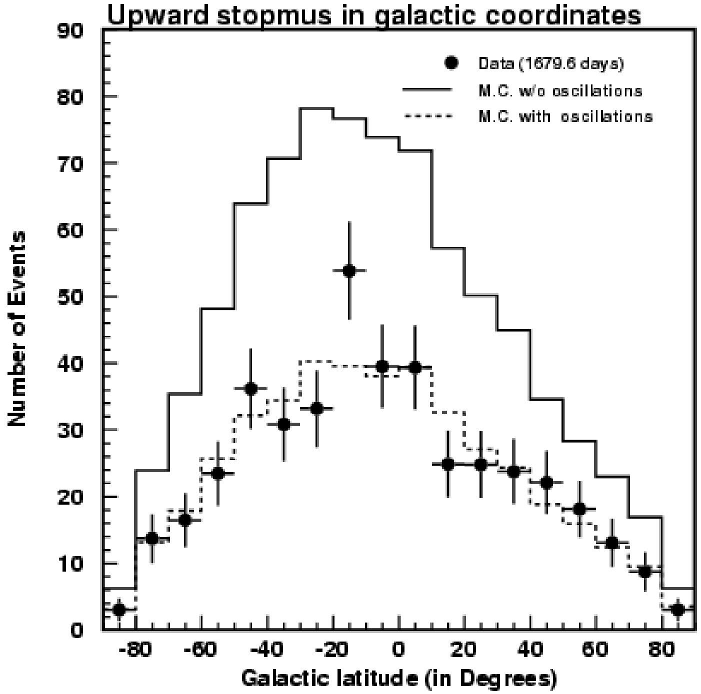
SRN analysis
by Matthew Malek
(SUNY Stonybrook)
See ICRC talk

(PS - he is now looking for postdoc work!)

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

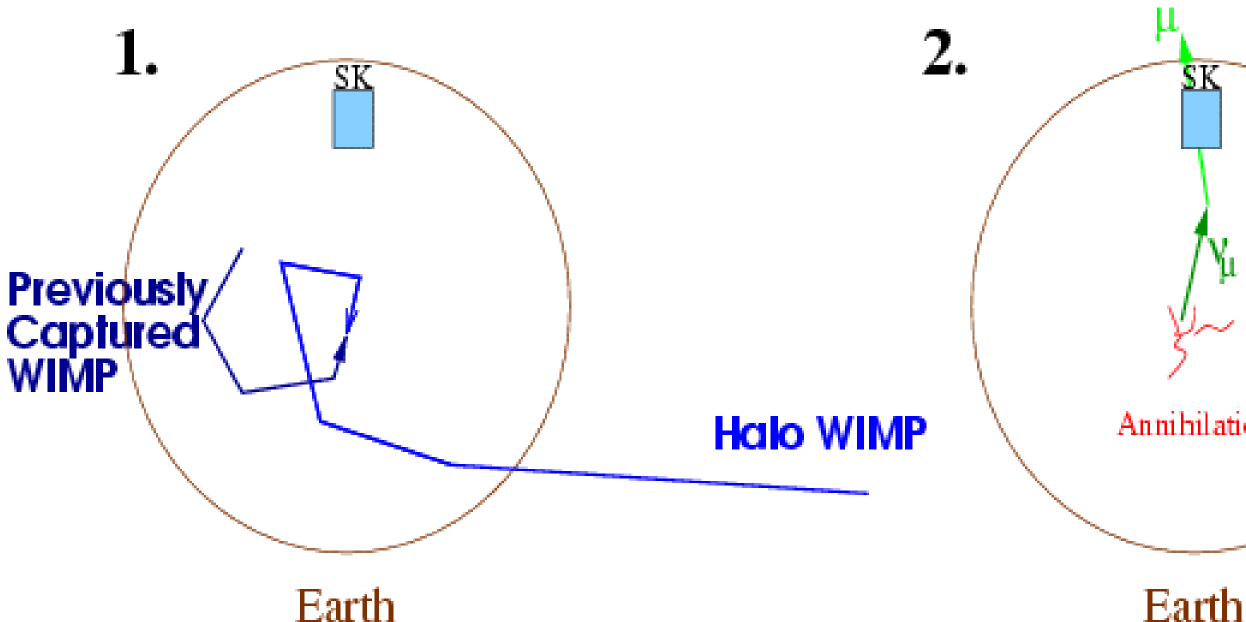




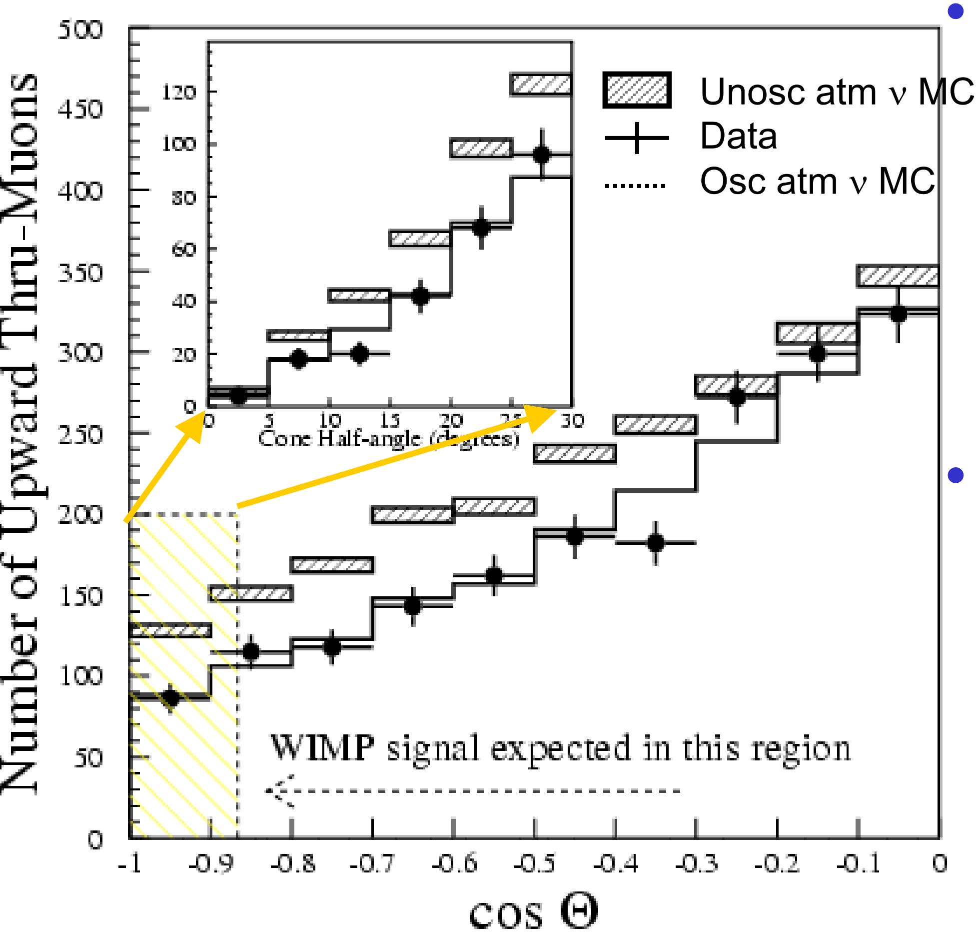
WIMP Detection

- 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
- WIMPs of larger mass would produce a tighter ν beam
  - Differently sized angular windows allow searches to be optimized for different mass WIMPs

See ICRC talk by Shantanu Desai (Boston U.)

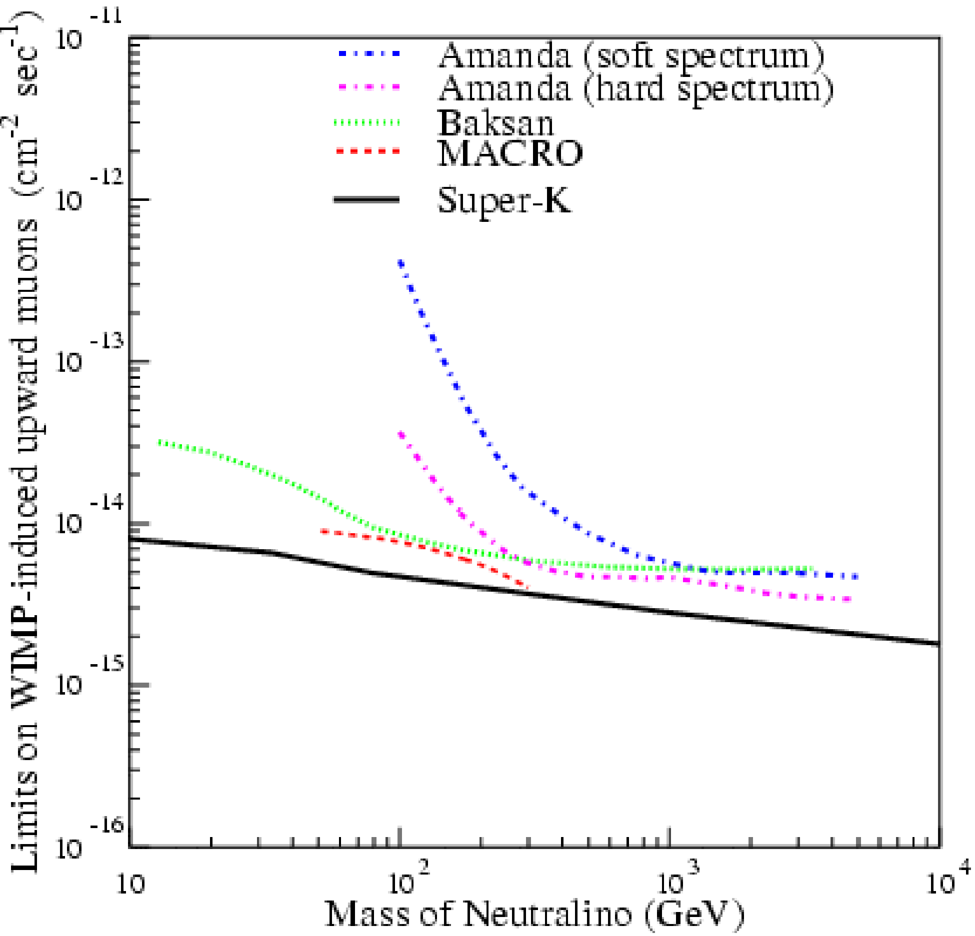


WIMPs in the Earth



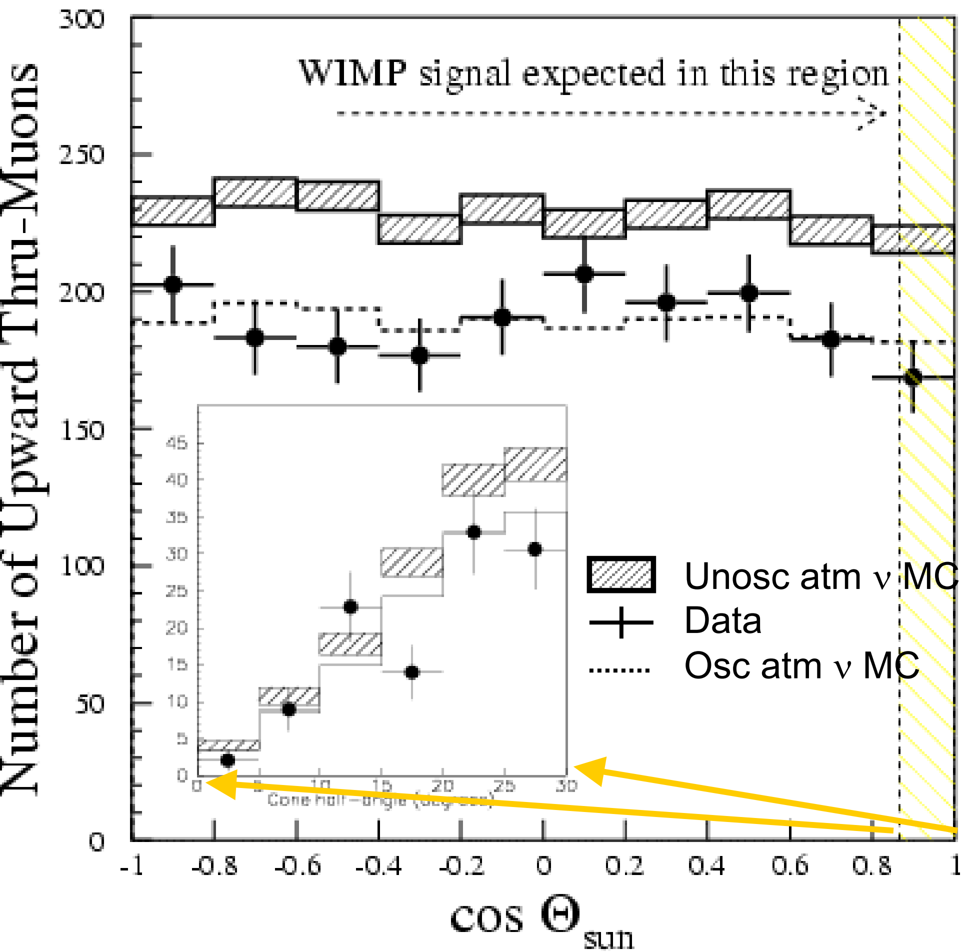
- WIMPs could only get trapped in the Earth by interacting in a spin-independent way
  - All those even heavy nuclei in the Earth with no net spin
- ν_μ from WIMP annihilation would come from the nadir
  - No excess seen in any sized angular cone (compared to background of oscillated atmospheric ν Monte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

Earth WIMP-induced Up-μ Limits



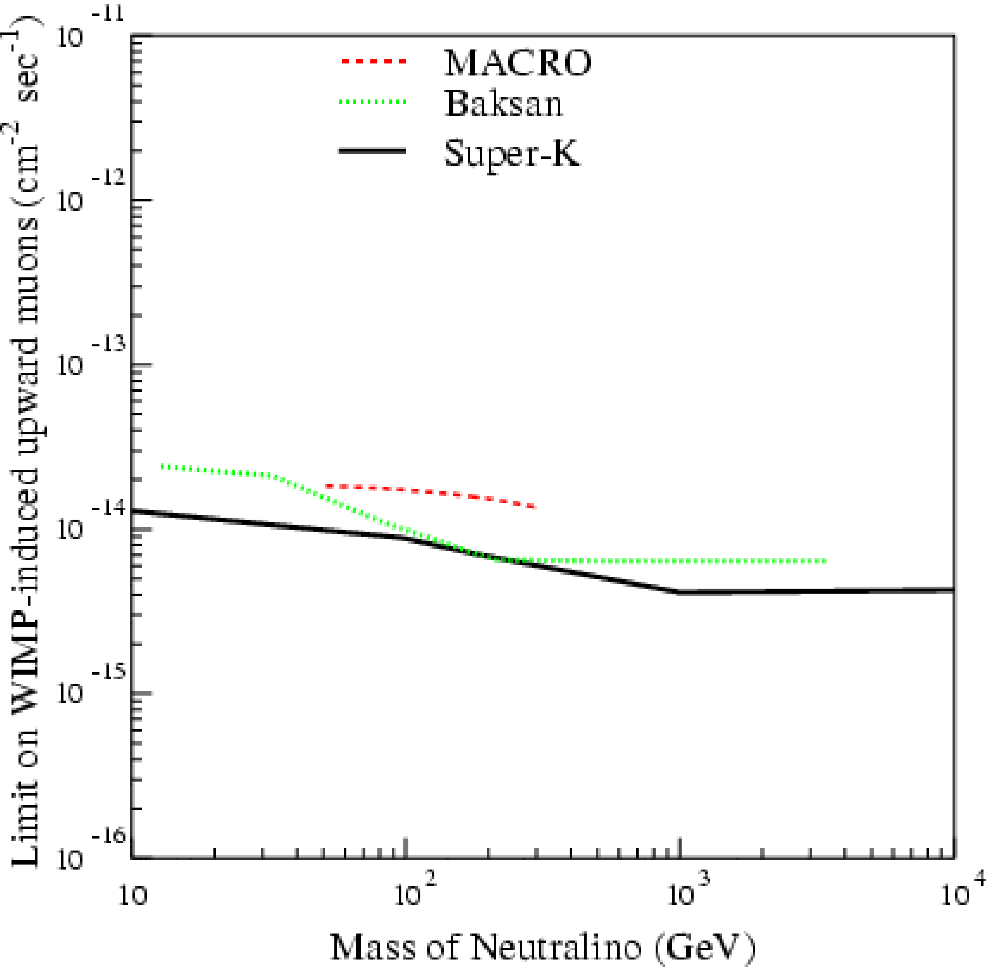
- Resulting upper limits on the WIMP-induced up-μ from the center of the Earth vs. WIMP mass
  - Varies as a function of possible WIMP mass
  - Lower limits for higher masses are due to the better S/N in smaller angular search windows
  - Lowest masses ruled out anyway by accelerator searches

WIMPs in the Sun



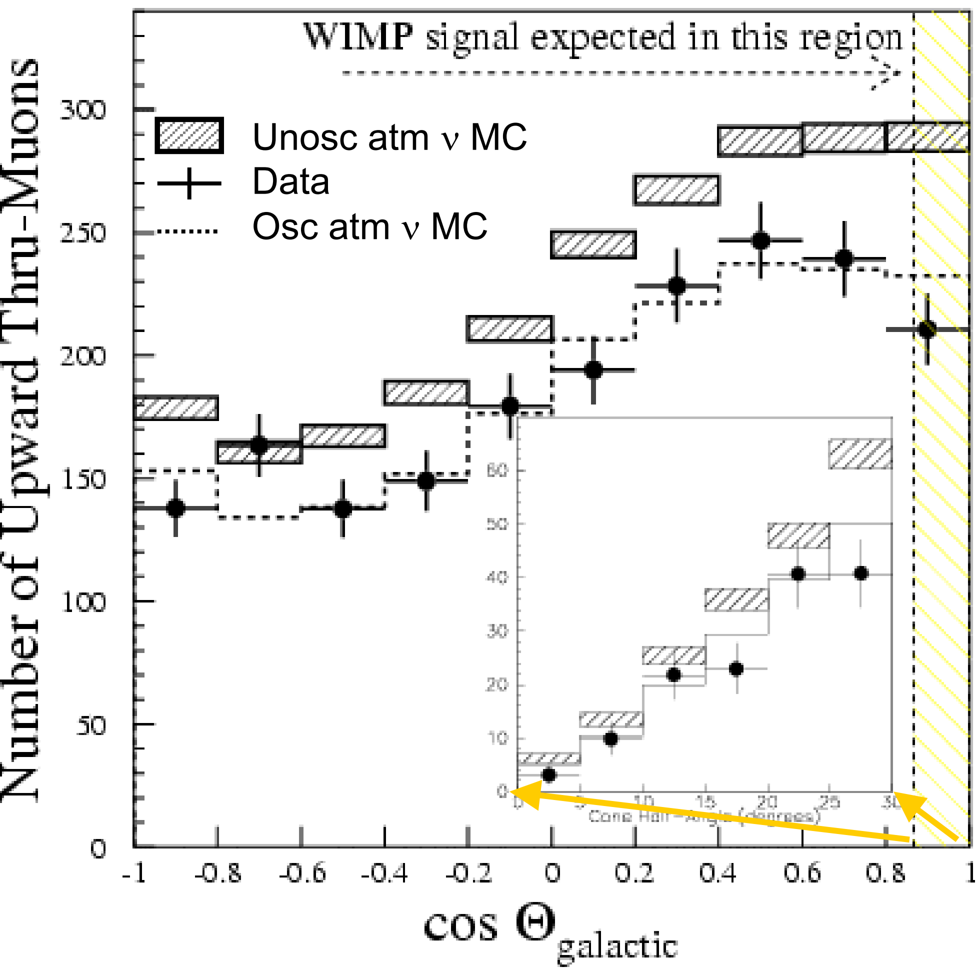
- WIMPs could also get trapped in the Sun if they interact in a spin-dependent way
  - All those spin-½ Hydrogen nuclei
- Make a cos(θ) Sun plot for all the up-μ events
  - No excess seen compared to background of oscillated atmospheric ν Monte Carlo

Sun WIMP-induced Up-μ Limits



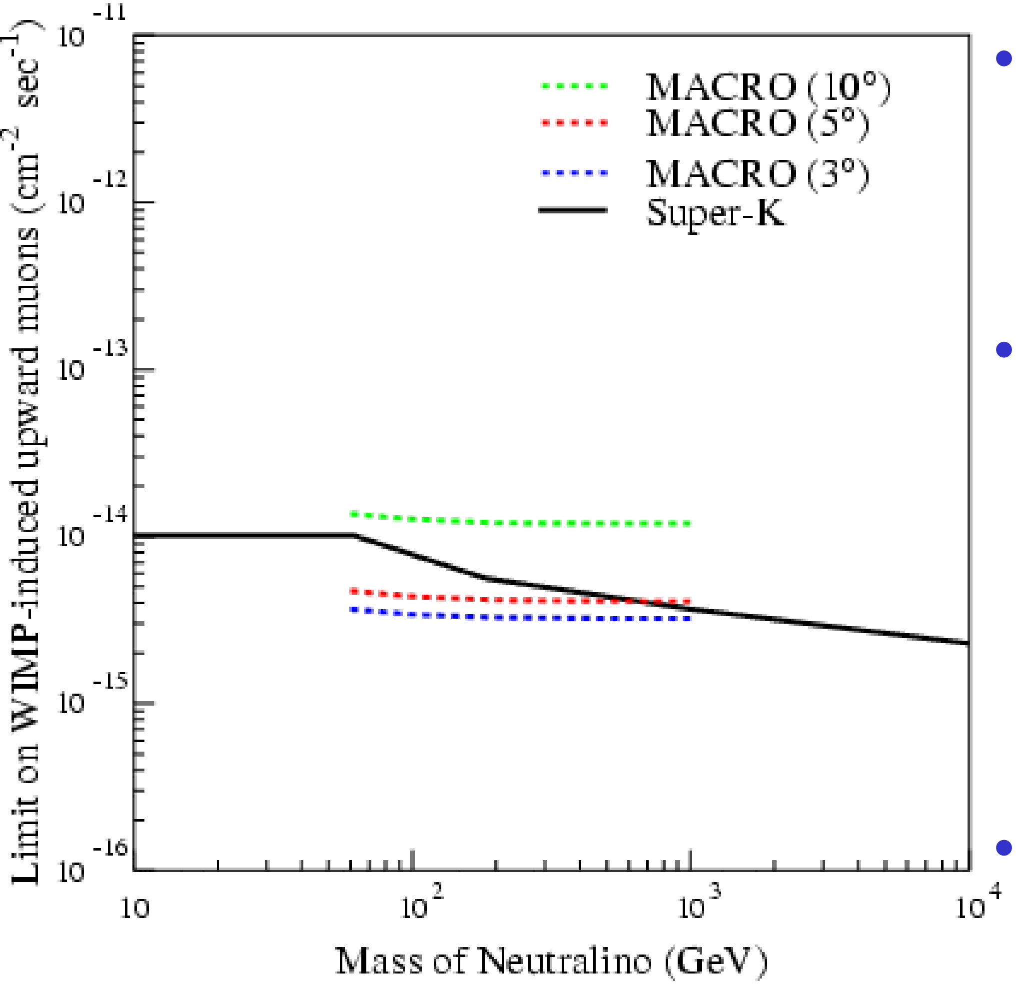
- Resulting upper limits on the WIMP-induced up-μ from the Sun vs. WIMP mass
- Same features as from Earth
  - But probes different WIMP interactions
  - Unfortunately hard for South Pole detectors to see the Sun (it's always near the horizon)

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

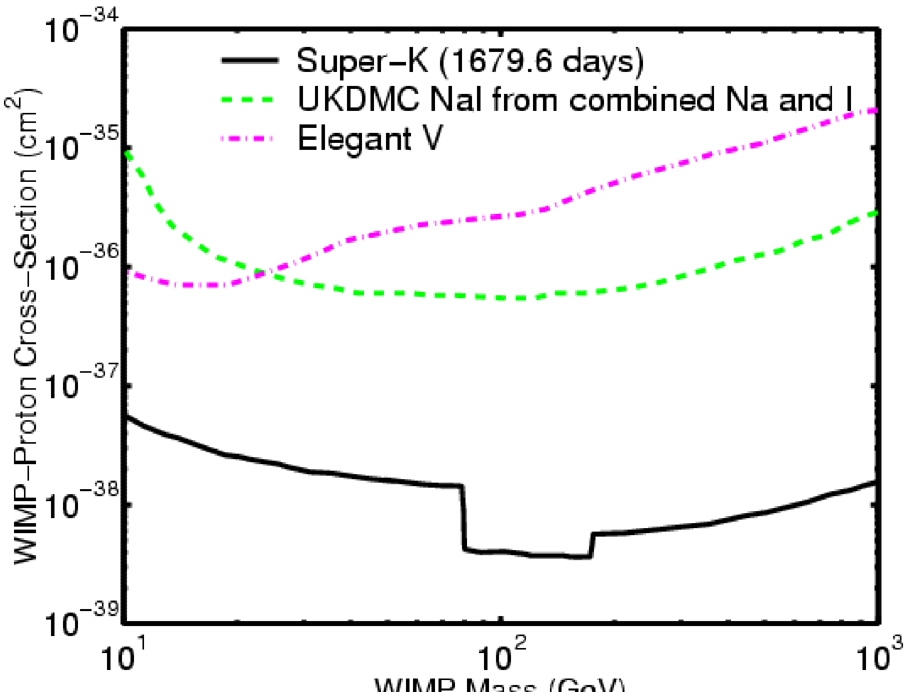
Galactic WIMP-induced Up-μ Limits

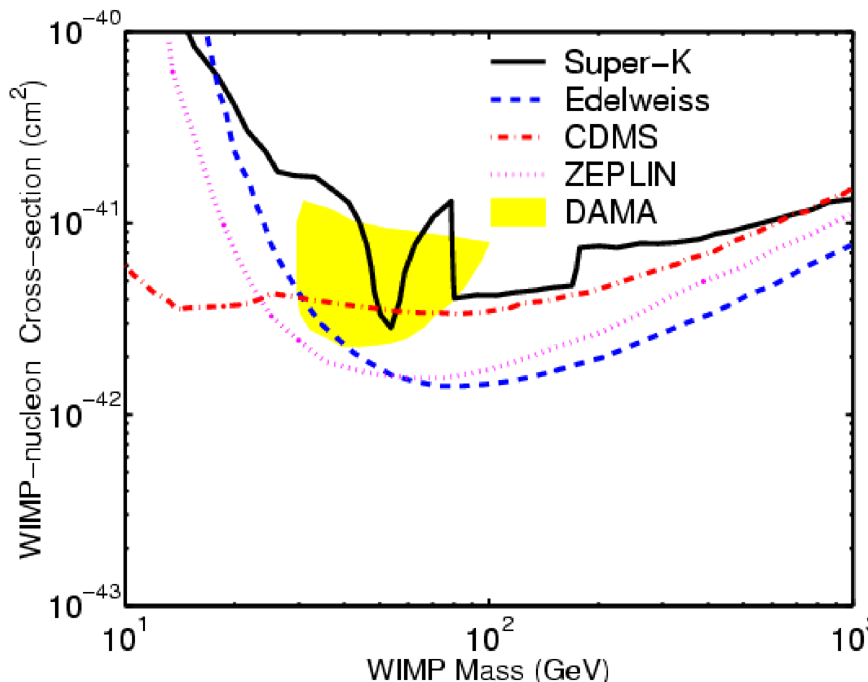


- Resulting upper limits on the WIMP-induced up-μ from the Galactic Center vs. WIMP mass
- If WIMPs exist and annihilate, then this lack of signal actually constrains possible matter distributions around Milky Way's black hole
- Need Antares to see this southern source!

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
- There are many (*too many?*) ways to look for ν point sources
  - Astrophysical objects, WIMP annihilation
- Nothing seen in SK, limits set
  - How badly does looking at the same data in so many ways hurt our sensitivity?
  - What is the best way future ν telescopes could analyze their data?

The presenter gratefully acknowledges support for this presentation from the National Science Foundation via its RUI grant #0098579, and from The Research Corporation's Cottrell College Science Award