Dark Matter in a dark place: DM annihilation in IceCube

Spencer Klein, LBNL & UC Berkeley
for the IceCube Collaboration

- IceCube
- Indirect Detection with neutrinos
- Local Sources: the Sun and the Earth
- The galactic halo & galactic center
- Future prospects
- Conclusions

The IceCube Collaboration

Internationl Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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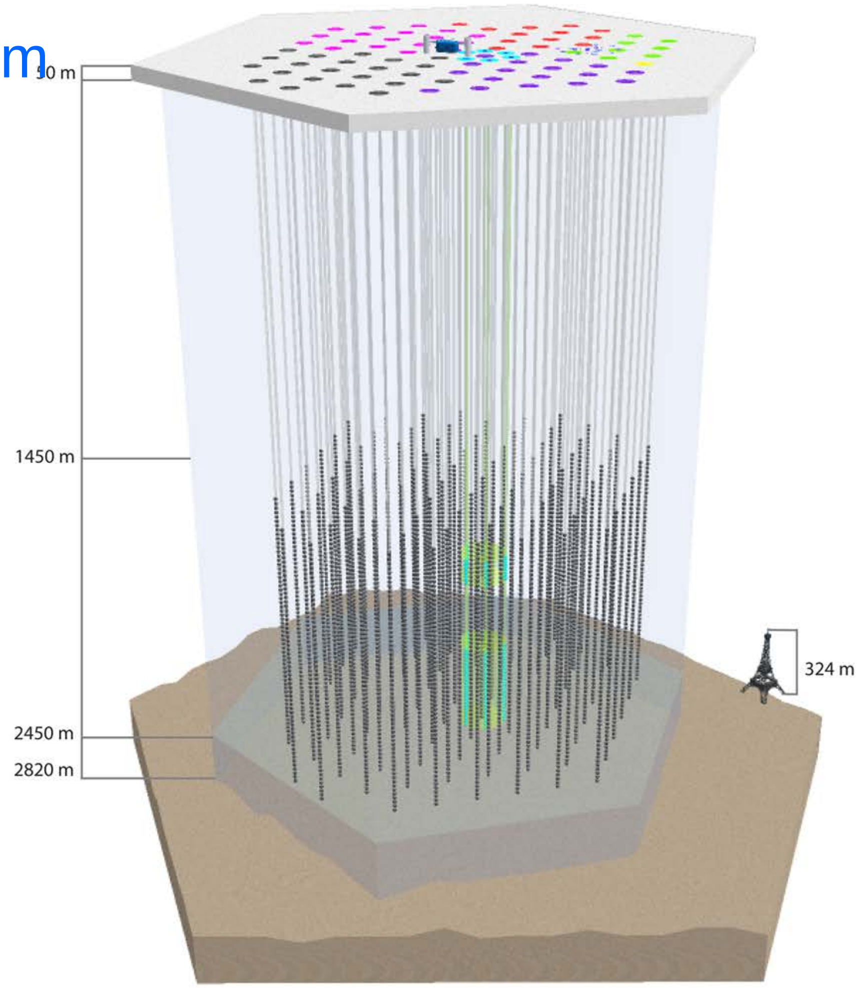
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

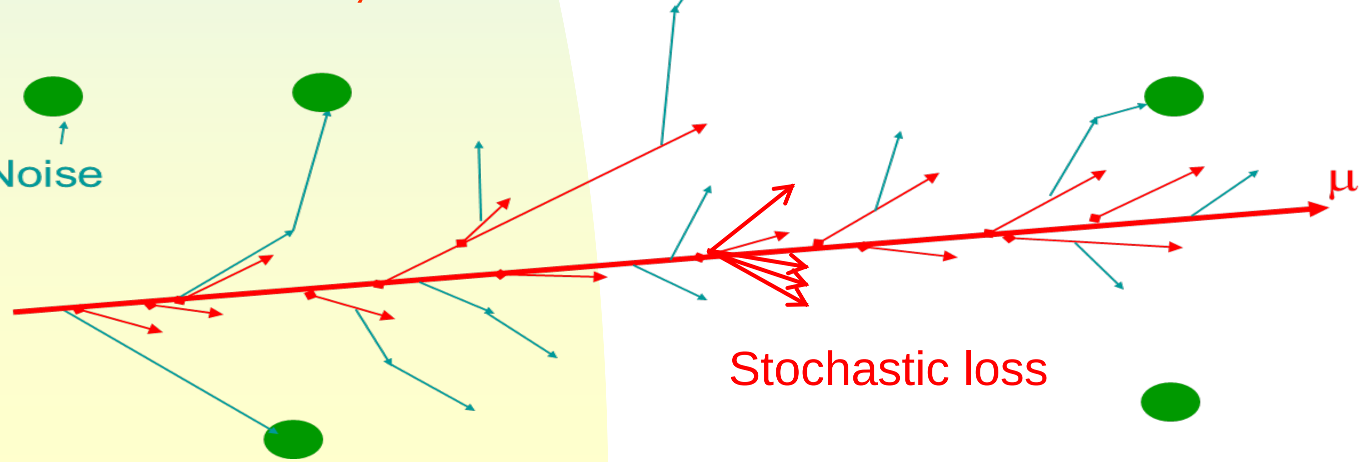
IceCube & DeepCore

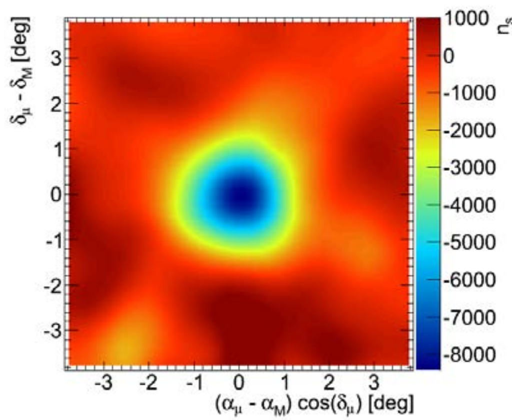
- 1 km³ neutrino detector
- 5,160 optical modules
  - 10” PMT + Complete DAQ system
- 78 ‘standard’ strings
  - 125 m string spacing
  - 17 m DOM spacing
  - ~100 GeV energy threshold
- 8 DeepCore Infill strings
  - with denser spacing
  - 50/60DOMs w/7 m spacing
    - In clearest, deepest ice
  - ~ 10 GeV energy threshold



From light to particle tracks

- All data is sent to surface
- Trigger requires 8 hit HLC (paired) DOMs within 5 μs
- 1st guess algorithms fit light pattern to plane.
- Maximum likelihood fits find final tracks
  - Optical scattering & absorption length of ice vary with depth.
- Background from coincident overlapping events is removed by splitting event in time/space & reconstructing separately.
- Resolution & pointing checked with cosmic-ray μ Moon shadow, horizon…





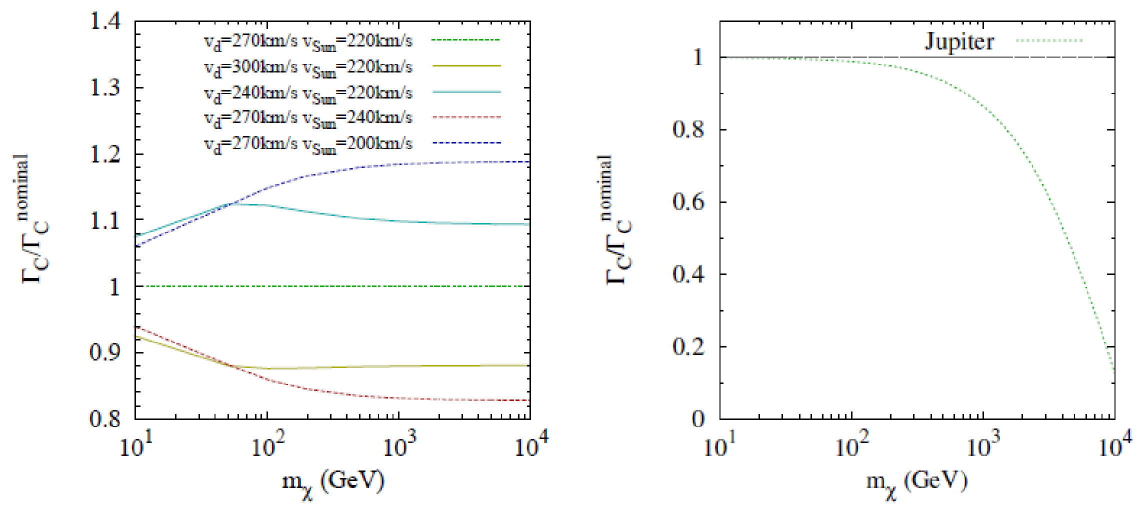
The Moon from
1 mi underground

Neutrinos from dark matter - assumptions

- **What we measure is a limit on the neutrino flux from different dark matter ‘reservoirs.’ These limits are then interpreted in terms of a dark matter model.**
- Dark matter spatial & velocity distributions
  - Maxwellian distribution usually assumed
  - Different halo matter distributions do not give very different answer for matter abundance at Earth
- Searches for dark matter capture (via inelastic interactions) and annihilation in Sun/Earth
  - Sun is the best place to probe spin-dependent couplings
- Searches for dark matter annihilation in the galactic halo and core.
- These assumptions apply to Super-K equally.
  - Many also apply to PAMELA, Fermi results..

Capture in the Sun - rate uncertainties

- Capture rate depends on inelastic cross-section
- 15- 20% variation from velocity profile variations
- For heavy WIMPs, 3-body calculations find a large capture rate decrease caused by the presence of Jupiter.
  - Capture takes a long time.
  - Compensated by WIMPs scattered by Jupiter into the Sun?
- These effects also pertain to Earth WIMPs



C. Rott *et al.*, JCAP 09, 029 (2011); Sivertsson & Edsjo, arXiv:1201.1895

WIMPs build up in Sun & annihilate

- At equilibrium: annihilation rate = capture rate

$$\frac{d\mathcal{N}}{dt} = C_{\mathrm{C}} - C_{\mathrm{A}}\mathcal{N}^2 - C_{\mathrm{E}}\mathcal{N}.$$

Evaporation is negligible

  - For most of considered SUSY parameter range, the Sun has reached equilibrium
- Dark matter annihilates (must be Majorana particle) or decays
- Mass and final states are unknown. Final state choices)
  - $\chi\chi \to \nu\bar{\nu}$
  - "Hard" $\chi\chi \to W^+W^-$ ($\tau^+\tau^-$ for M_χ below threshold)
  - "Soft" $\chi\chi \to b\bar{b}$
  - Dark matter decay also considered.
- Consider these variables by scanning over different possibilities (mass, decays), or as systematic uncertainties

Solar analyses - I

- The sun is dense enough so that neutrinos with E > ~ 200 GeV interact before escaping
  - NC & some CC interactions produce lower energy ν
  - Neutrino energy spectrum is of lesser diagnostic value
- Sun is below horizon 6 months/year
- Combined analysis
  - IceCube 40-string +AMANDA 2008/9
  - AMANDA-II data 2001-2006
    - Denser string spacing, so better for lower masses
      - DeepCore will perform same function in future
- Results from separate analyses were combined.

IceCube – Phys. Rev. D85, 042002 (2012)

Solar analyses - II

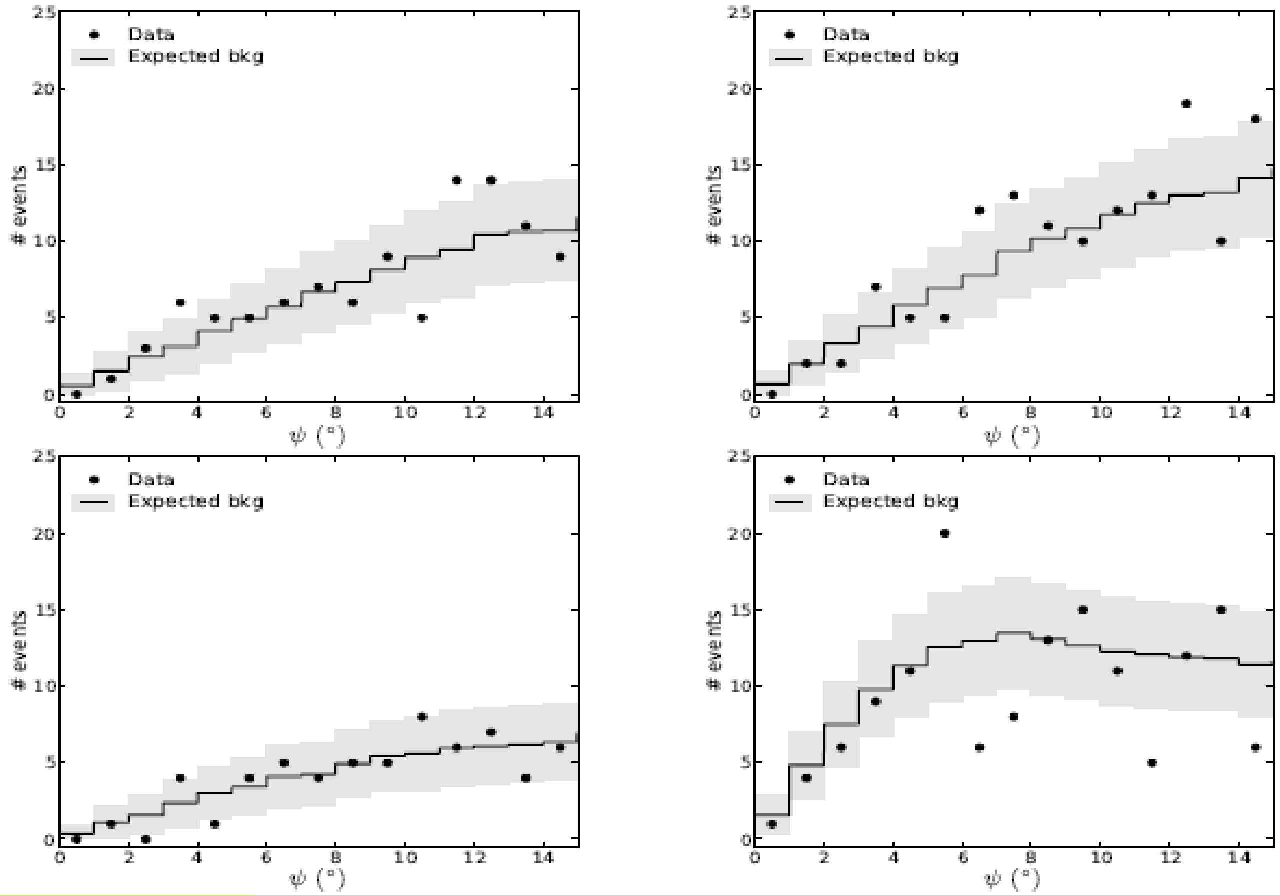
- Initial straight cuts, followed by machine learning (boosted decision tree/support vector machine)
  - Final cut was optimized to maximize model discovery potential/sensitivity
    - Different optimizations for different masses and hard/soft decays
    - Led to relatively loose cuts
- Background determined by time-scrambling data
- The shape of the space angle distribution (ψ) wrt. the sun was used to determine the size of the signal
- Systematic uncertainties due to optical properties of ice, sensitivity of optical modules, ν cross-sections

Solar results

- No excess seen at small ψ

AMANDA only

IC40+ AMANDA

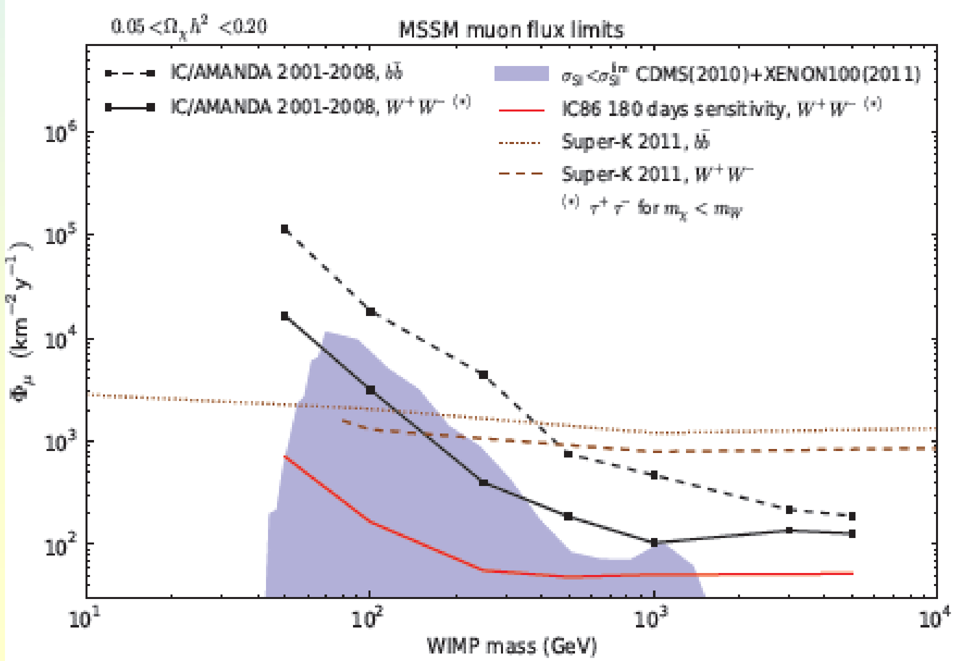


100 GeV $\chi \rightarrow$: $b\bar{b}$

1 TeV $\chi \rightarrow W^+W^-$

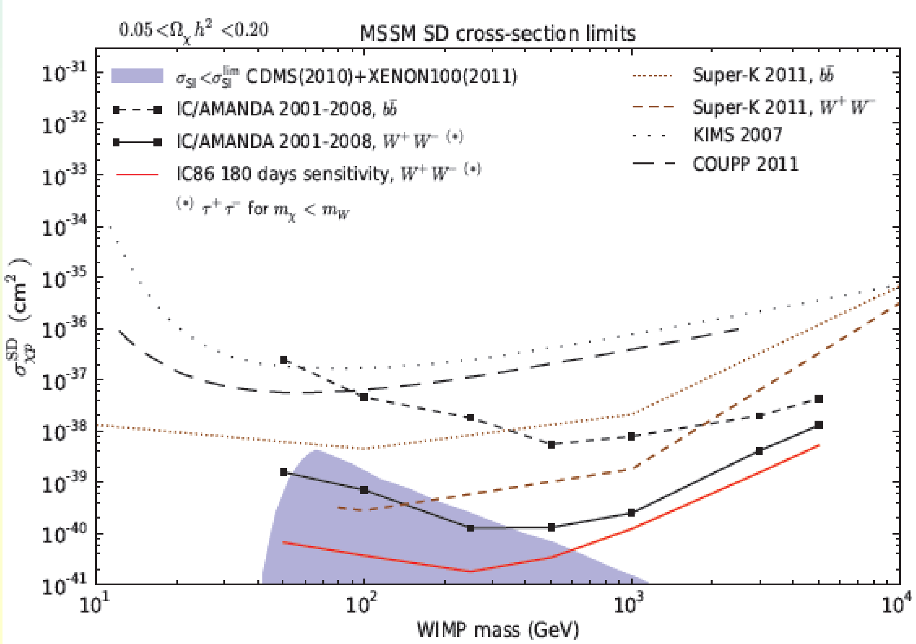
90% CL ν flux combined limits

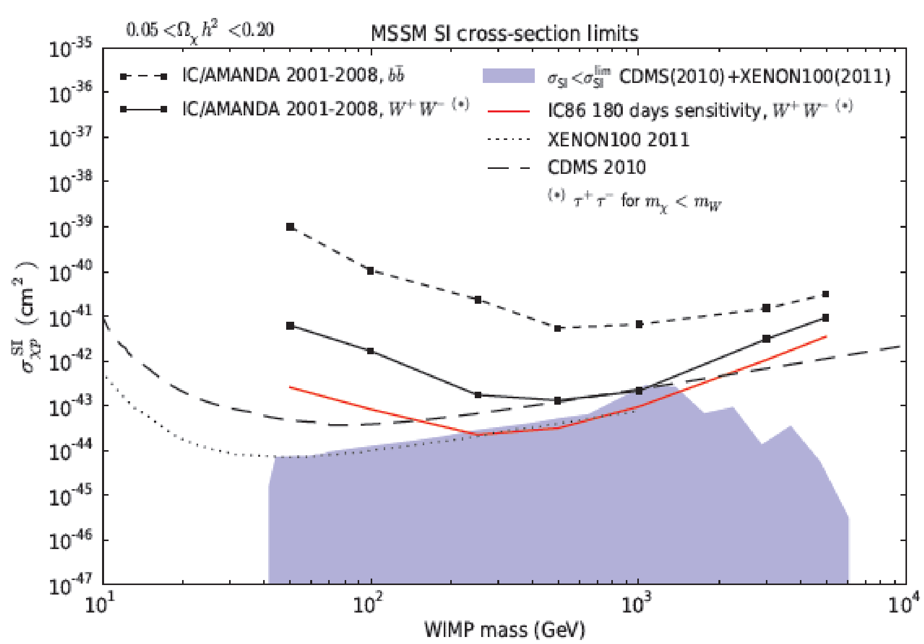
- A model-independent flux limit is obtained for the 2 analyses.
  - Then combined, including IC22 limits.
- Limits are put on the ν flux for specific annihilation products
  - Mass and branching mode
- These limits are compared with the range of predictions from a 7-parameter MSSM scan using DarkSUSY (shaded area)
  - Incorporates LEP, CDMS(2010) and Xenon100 (2011) limits



Cross-section limits

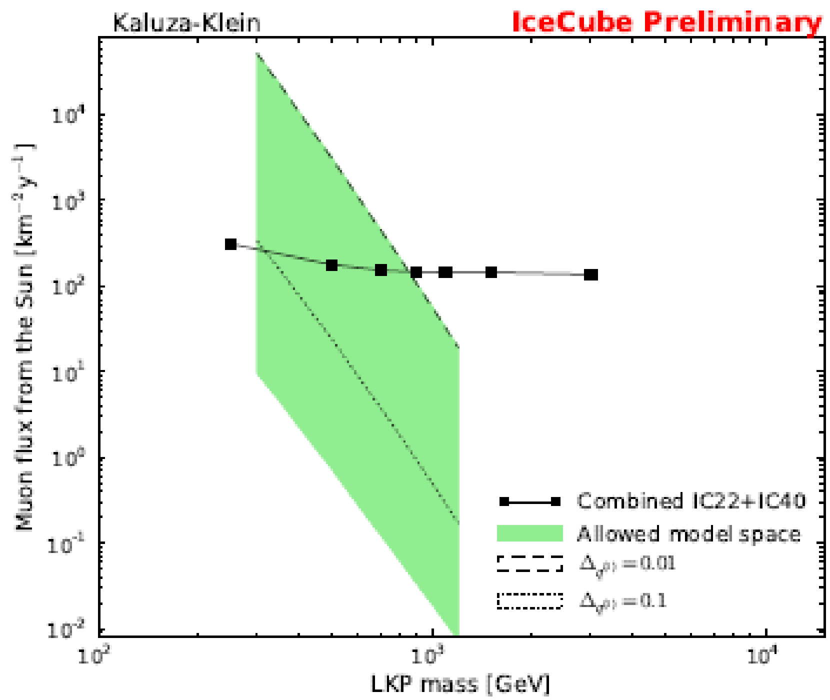
- Assuming equilibrium, these limits are converted to spin-dependent (SD, left) & spin-independent (SI) limits
  - Independent of WIMP model.
- Shaded band shows predictions based on MSSM scans
  - Already, IceCube is sensitive to new regions of MSSM parameter space.





Kaluza-Klein dark matter

- The IC22 & IC40 analyses were also used to put limits on Kaluza-Klein dark matter
  - Probes allowed phase space for LKPs
- Same data, reinterpreted in different parameter space

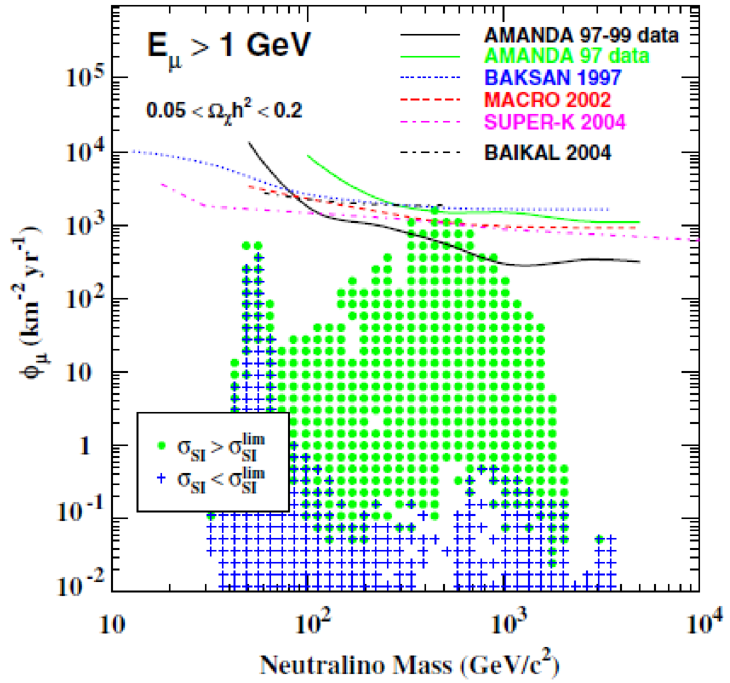


Δq is the mass splitting between q and γ

IceCube – 2011 ICRC, arXiv:1111.2738

The Earth

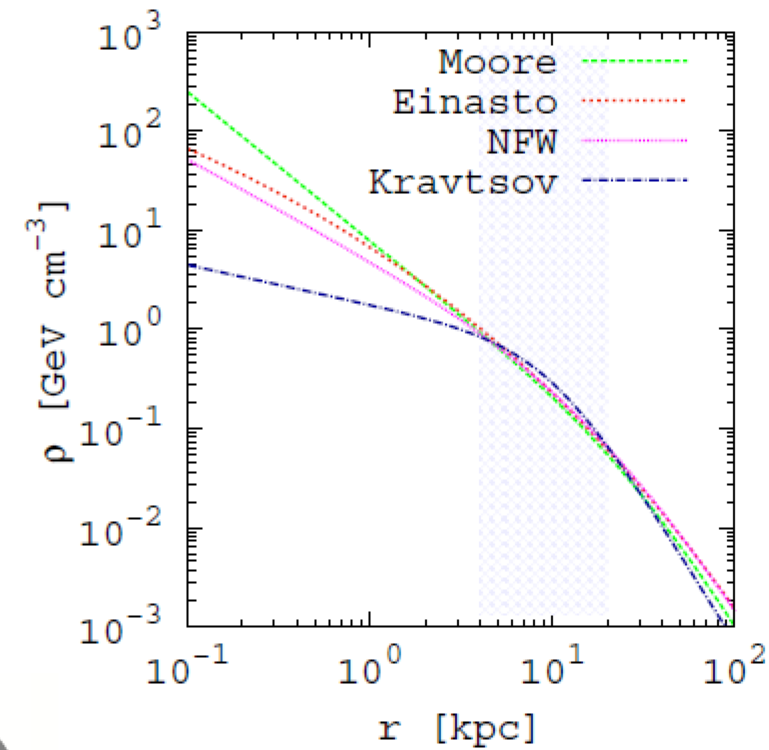
- Best for lighter WIMPs
- Mostly spin-independent couplings
- AMANDA analysis set limits from 50 GeV to 5 TeV
- IC79/86 analysis is in progress



AMANDA – Astropart. Phys. 26, 129 (2006)

Galactic halo search

- Search for ν from WIMP annihilation in the galactic halo
- 1 year of IC22 data
- 4 models of halo density profile
- Sets limits on $<\sigma_A \cdot v>$
- Distant enough for full mixing



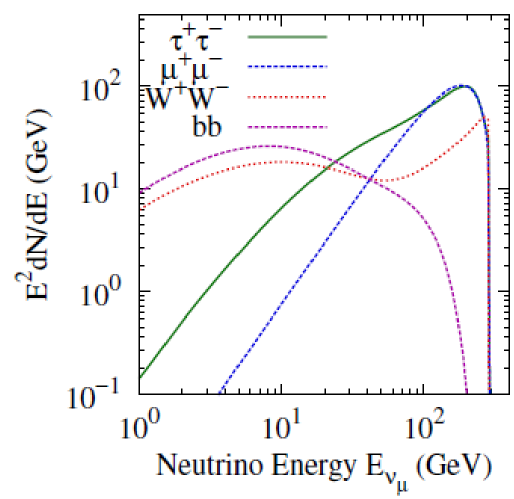
$$\frac{d\Phi_\nu}{dE} = \frac{<\sigma_A \upsilon>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

Measure

Constrain

Galaxy

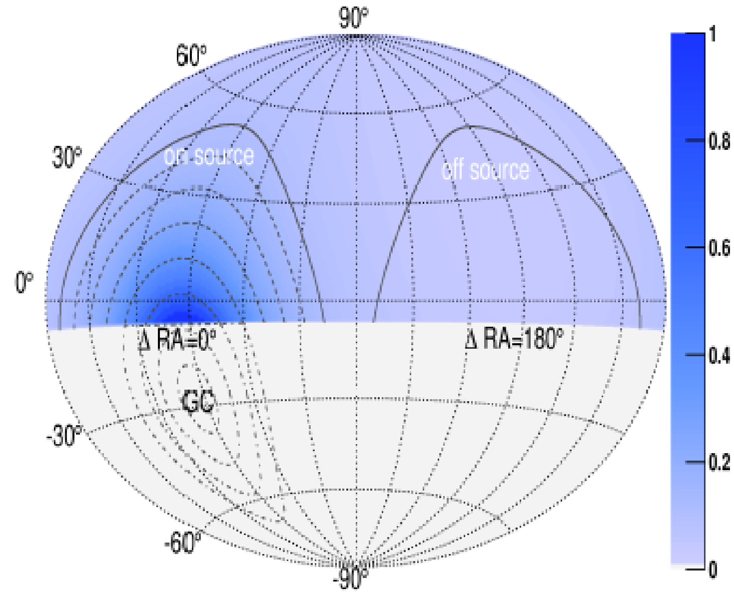
SUSY

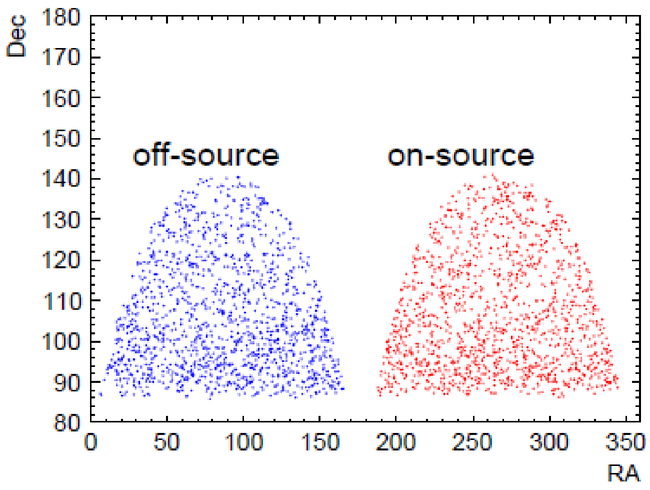


IceCube – Phys. Rev. D84, 022004 (2011)

IceCube field of view

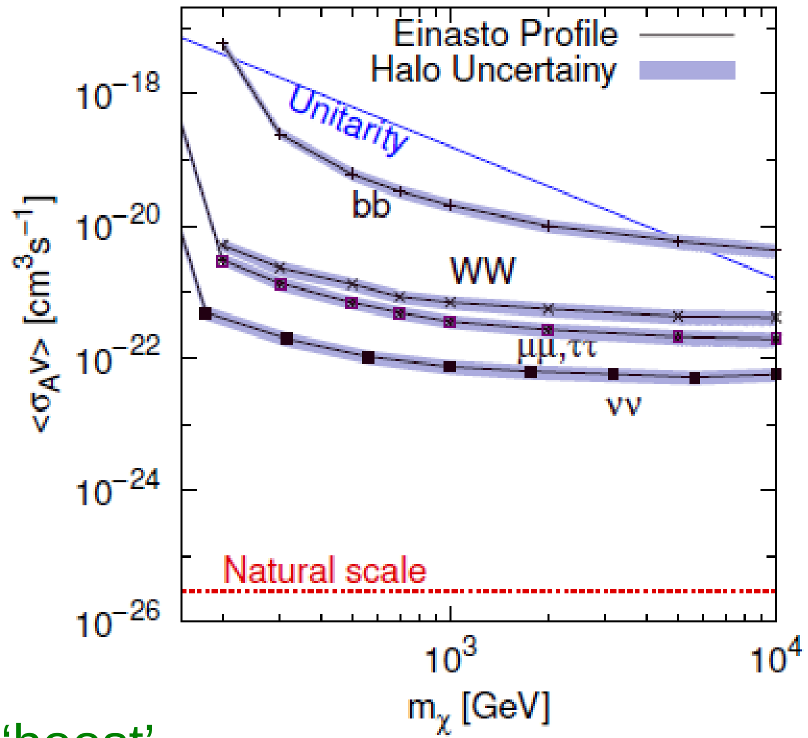
- The galactic center is above the horizon at the South Pole
- This search is limited to the outer that is in the Northern hemisphere
- For each direction in the sky, integ annihilation likelihood ~ density^2 along line of sight.
- On-source region is within 80 degrees of galactic center
  - Only portion below IceCube horizon
- Off-source region is the same declination but shifted 180 degrees in RA





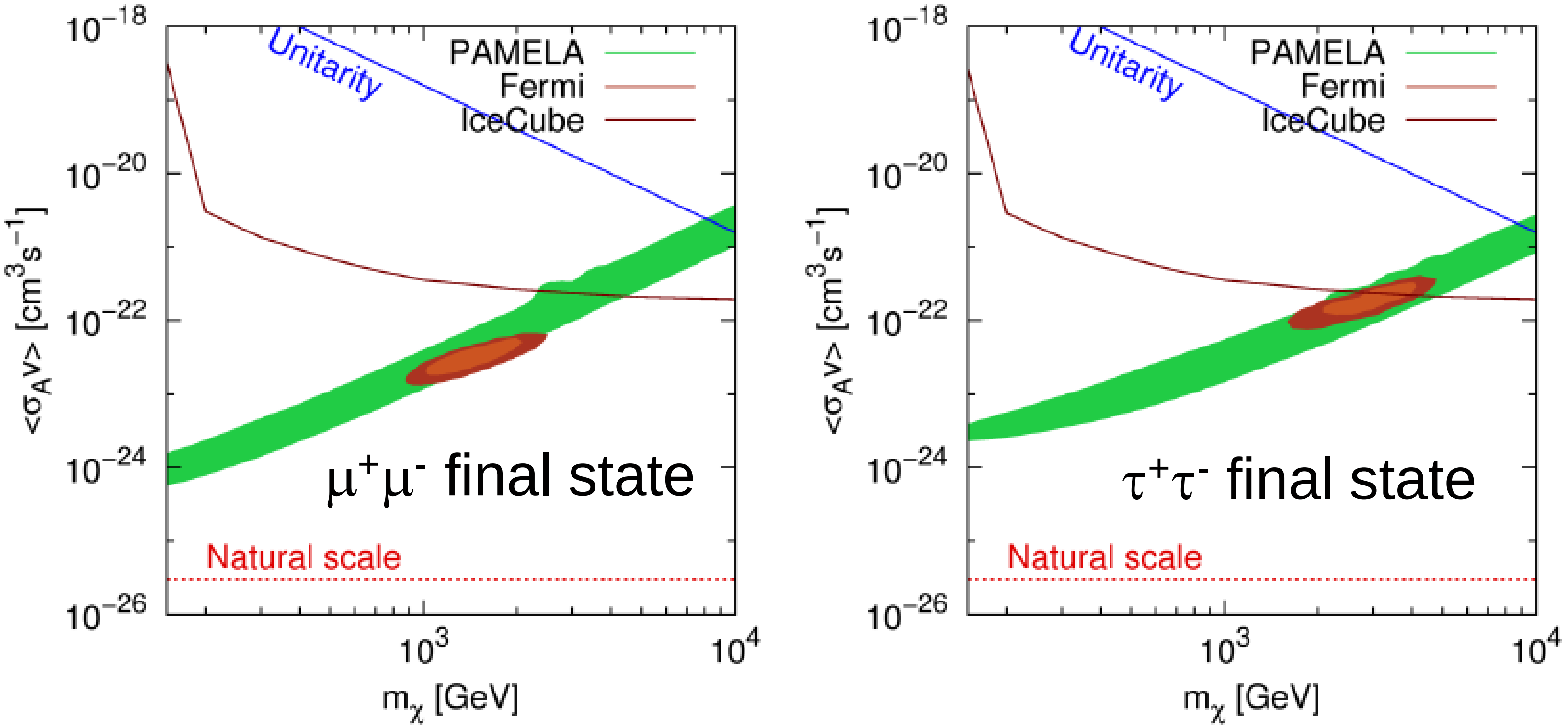
Galactic halo results

- 1367 on-source,
- 1389 off-source
- Limits conservatively assume that dark matter is evenly distributed
  - Substructure will increase the annihilation rate by boosting <ρ^2>
    - Accounting for substructure might ‘boost’ the limits by a factor of ~2
  - Not very sensitive to size of galactic halo & choice of halo model.
    - Widths of lines to right show uncertainty due to halo model.
- “Natural Scale” == consistency with thermal relics



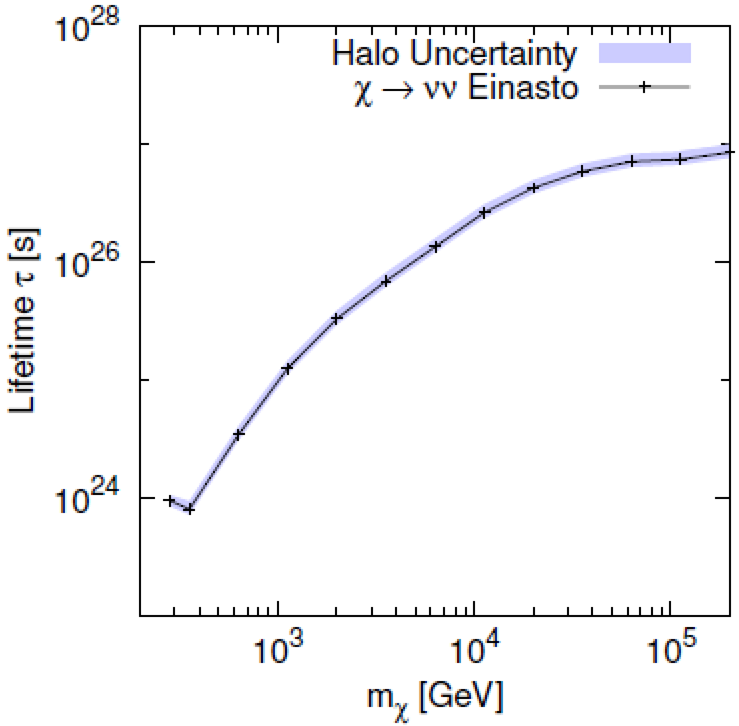
IceCube, PAMELA & Fermi

- PAMELA, Fermi & HESS report excess positrons, electrons & electrons respectively from the galactic center.
  - If from leptophilic dark matter, annihilation should also produce ν.
  - Due to $e^{\pm}$ energy loss, the annihilation must be nearby (1 kpc)
    - IceCube can constrain the masses of this dark matter



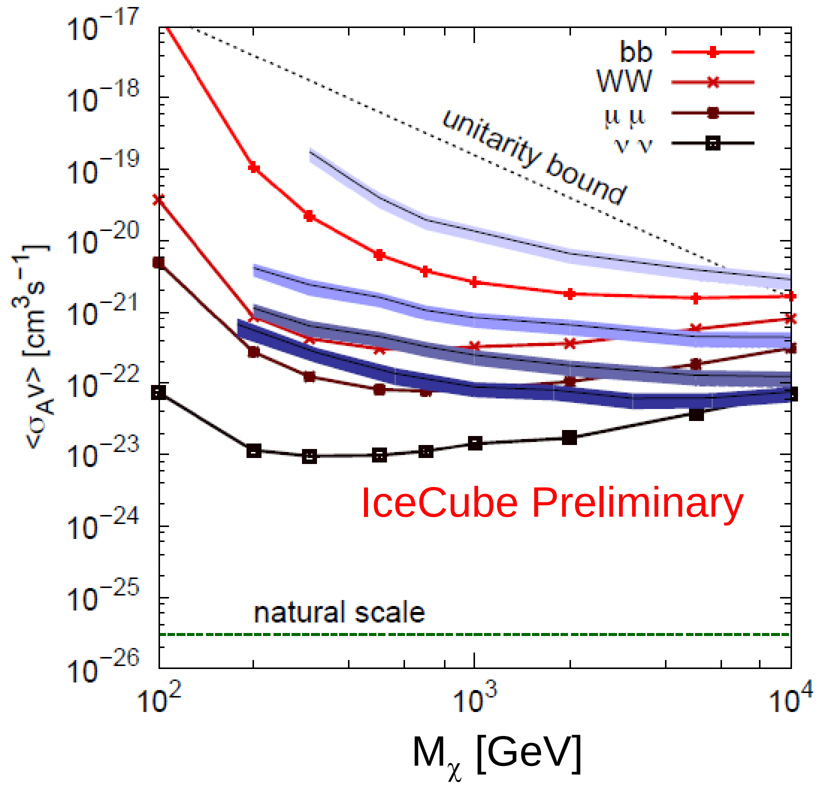
WIMP decay

- The same analysis set limits on WIMP decay, $\chi \to \nu\nu$
- Lifetimes $>10^{24}$ s

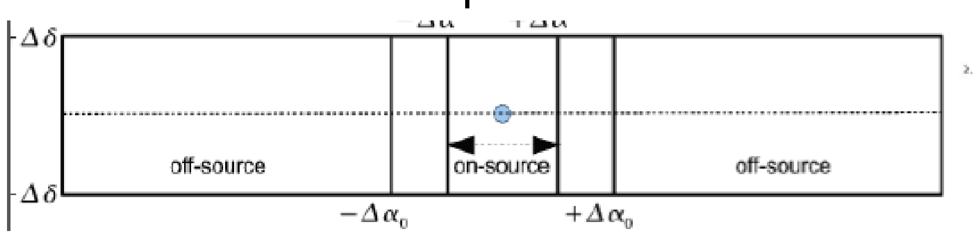


IC40 galactic center analysis

- The galactic center is above the horizon, so there is a much larger background from muons from downgoing cosmic rays
  - Reduce rate by using top/sides of detector to veto incoming particles
- Select events in ± 8^0 ($\Delta\delta$) by ± 9^0 ($\Delta\alpha$) box around the galactic center
- 798842 events in signal region
- 798819 (scaled) events in background region
  - Same declination, all azimuth, less 'guard' region



Blue bands – IC22 halo
Lines w/points IC40 center

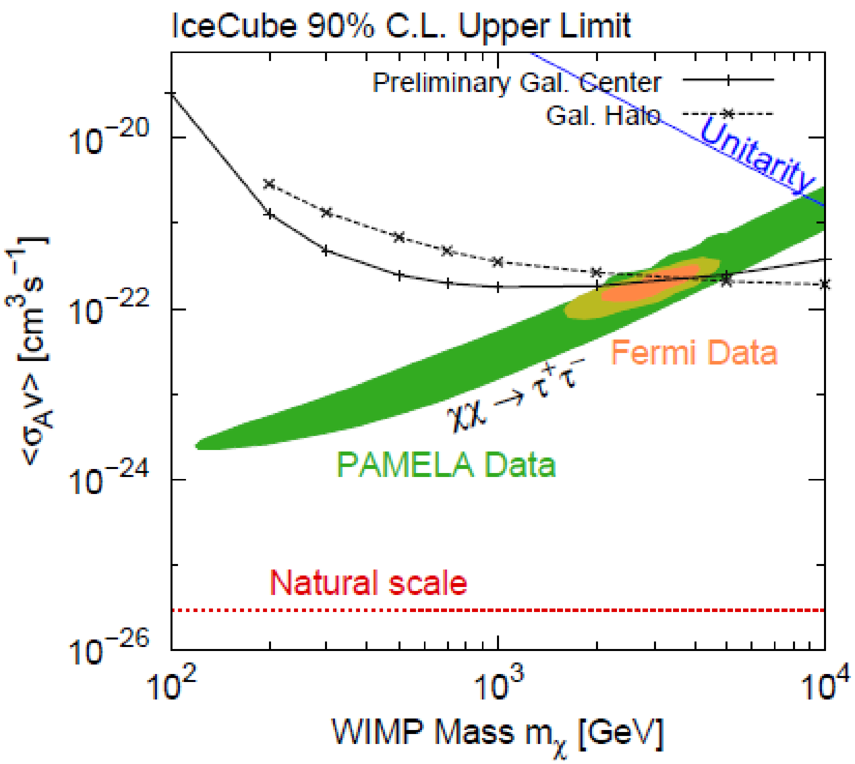


IceCube – 2011 ICRC – arXiv:1111.2738, updated

Back to PAMELA & Fermi

- The galactic center provides a similar constraint as the halo analysis
- N.b. IC40 ~ 2* the data of IC22

IceCube Preliminary

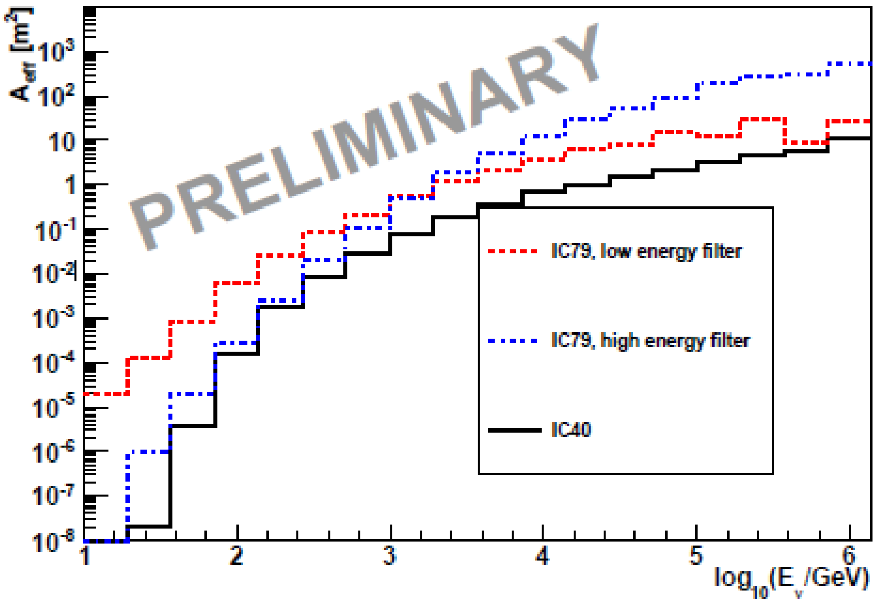


Future plans

- More data
  - IC86 > 2 * IC40
- DeepCore will provide a huge increase in sensitivity down to 10 GeV
- Using the rest of IceCube as a veto, DeepCore should have good sensitivity to neutrinos coming from above the horizon.
  - More sensitive galactic center search
  - 12 month/year solar search
- IceCube Earth WIMP search
- Studies with ν_e
  - Lower backgrounds & good energy resolution
  - Hard because of very limited angular resolution
- Search for ν from dwarf spheroidal galaxies

Sensitivity vs. energy

- Effective area increases with energy.
  - Neutrino cross-section and μ range both increase with energy
- At energies from 10-100 GeV DeepCore provides orders-of-magnitude improvement in sensitivity.
- In longer term, the proposed PINGU/MICA may push this down to ~1 GeV

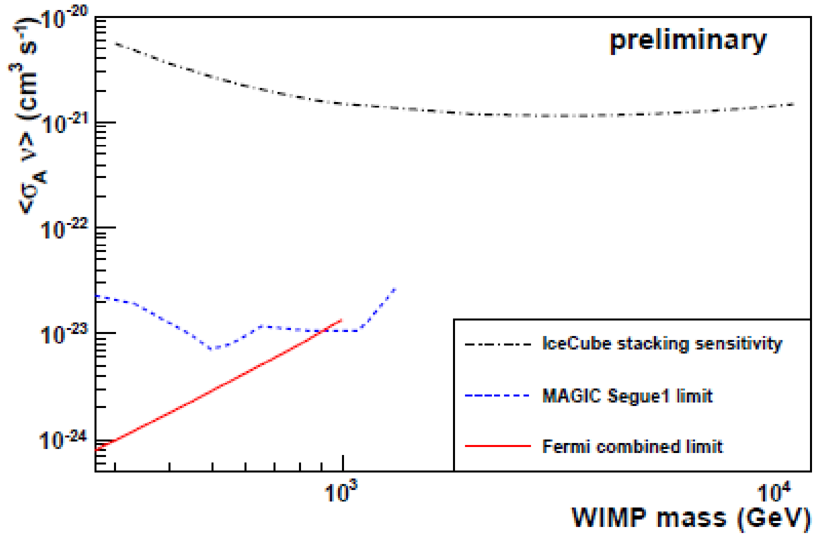


Filter level effective area for IC40 & IC79 low-energy & high-energy filters.

IceCube – 2011 ICRC – arXiv:1111.2738

ν from WIMP annihilation in nearby dwarf spheroidal galaxies

- Dwarf spheroidal galaxies have a high mass to light ratio, so may be a particularly promising place to search for dark matter annihilation.
  - 13 Northern hemisphere galaxies
    - within 417 kpc of Earth
    - from Sloan digital sky survey
- Quasi-point sources
- Stack sources for improved sensitivity
- Current search uses 1 year of IC59 data
- Will set limits on ν flux and $<\sigma_A v>$



IceCube – 2011 ICRC – arXiv:1111.2738

Conclusions

- Searches for ν from WIMP annihilation with ¼ or ½ of IceCube have already yielded interesting limits on WIMP annihilation in the Sun, the galactic halo and the galactic center.
- IceCube limits on ν from the Sun set the best limits on WIMPs with spin-dependent coupling to matter.
- Over the next few years, IceCube analyses using the full power of the full detector will either see a signal or set much tighter limits, while DeepCore will push down to lower masses.

Backups

Equilibrium Times vs. T_{Sun}