IceCube

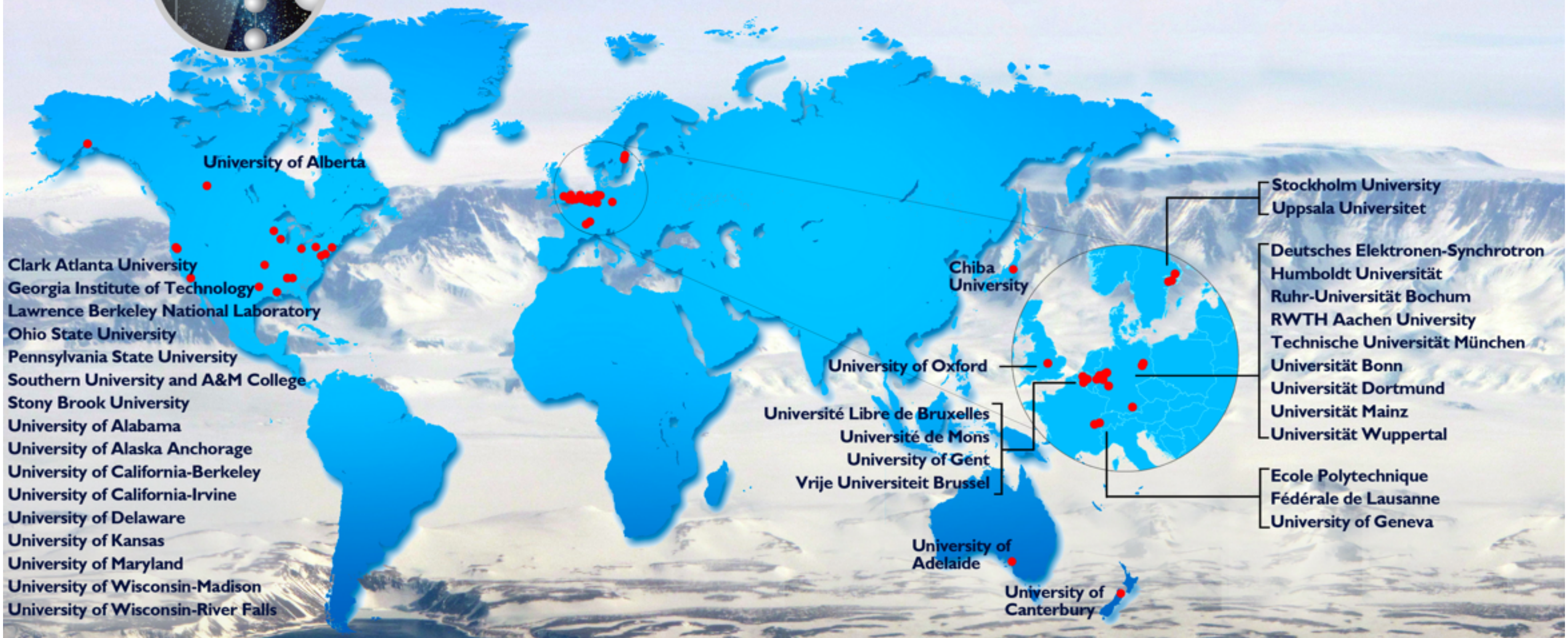
Searches for Neutrinos from WIMP Dark Matter

Doug Cowen, Penn State

- Potential Sources
- The IceCube Neutrino Detector
- Results from IceCube
- Future Prospects

July 29 - August 6 · Snowmass on the Mississippi · U. Minnesota, Minneapolis, MN

The IceCube Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

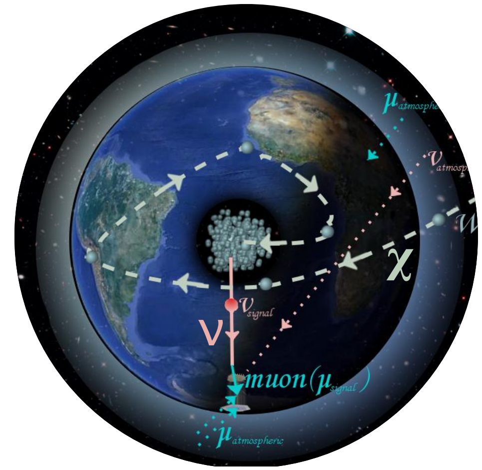
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

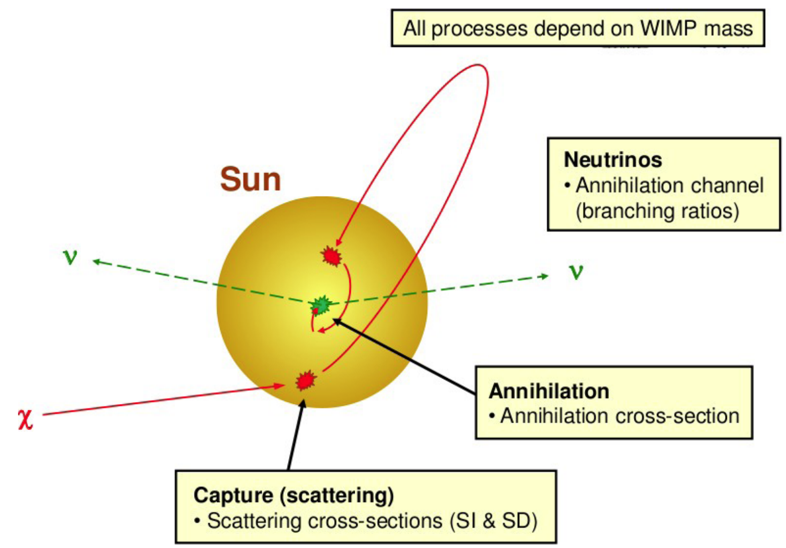
IceCube includes about 250 researchers from 39 institutions around the world. Prof. Francis Halzen, University of Wisconsin – Madison is the principal investigator and Prof. Olga Botner from Uppsala University serves as the collaboration spokesperson.

Candidate WIMP Accumulators

- Earth (ν−accessible only)
  - Capture depends on WIMP velocity distribution
    - Only slow, light ($M_\chi < 50$ GeV) WIMPs accessible
  - Unlikely to be in capture-annihilation equilibrium
    - Hard to link to physical quantities
  - Focus on spin-independent (SI) interactions

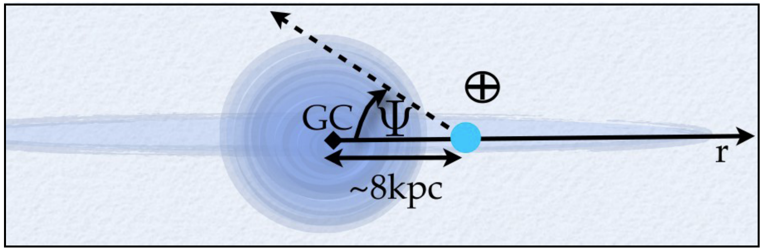


- Sun (ν only)
  - Wide range of WIMP masses accessible
    - WIMP evaporation for $M_\chi <\sim 4$ GeV
    - ν absorption in sun for $M_\chi >\sim 1$ TeV
  - In equilibrium ($\Gamma_{Ann} = (1/2)\Gamma_C$)
    - extract $\sigma_{\chi\text{-}p}$
  - Access both spin-dependent (SD) and SI interactions



Candidate WIMP Accumulators

- Galactic Center (ν plus γ, antimatter)
  - WIMPs collisionless
  - Inner halo cusp/core structure not well known:
    - extract $<\sigma_{Ann} \cdot v>$
      - average is over expected WIMP velocity distribution
    - or look for spectral lines



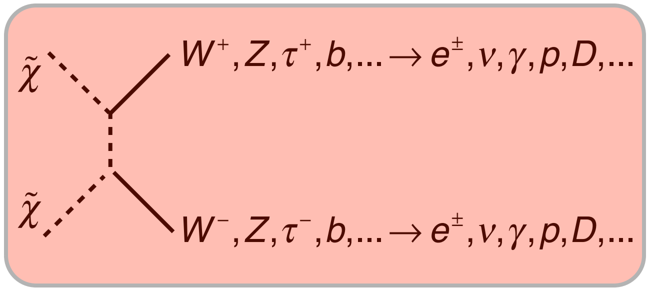
- Galactic Halo (ν plus γ, antimatter)
  - WIMPs collisionless
  - matter density known pretty well
    - extract $<\sigma_{Ann} \cdot v>$
- Dwarf spheroidal galaxies, galaxy clusters (ν plus γ)
  - attractively high mass-to-light ratio (dSph's)
    - extract $<\sigma_{Ann} \cdot v>$
  - lots of mass, possible clumpiness

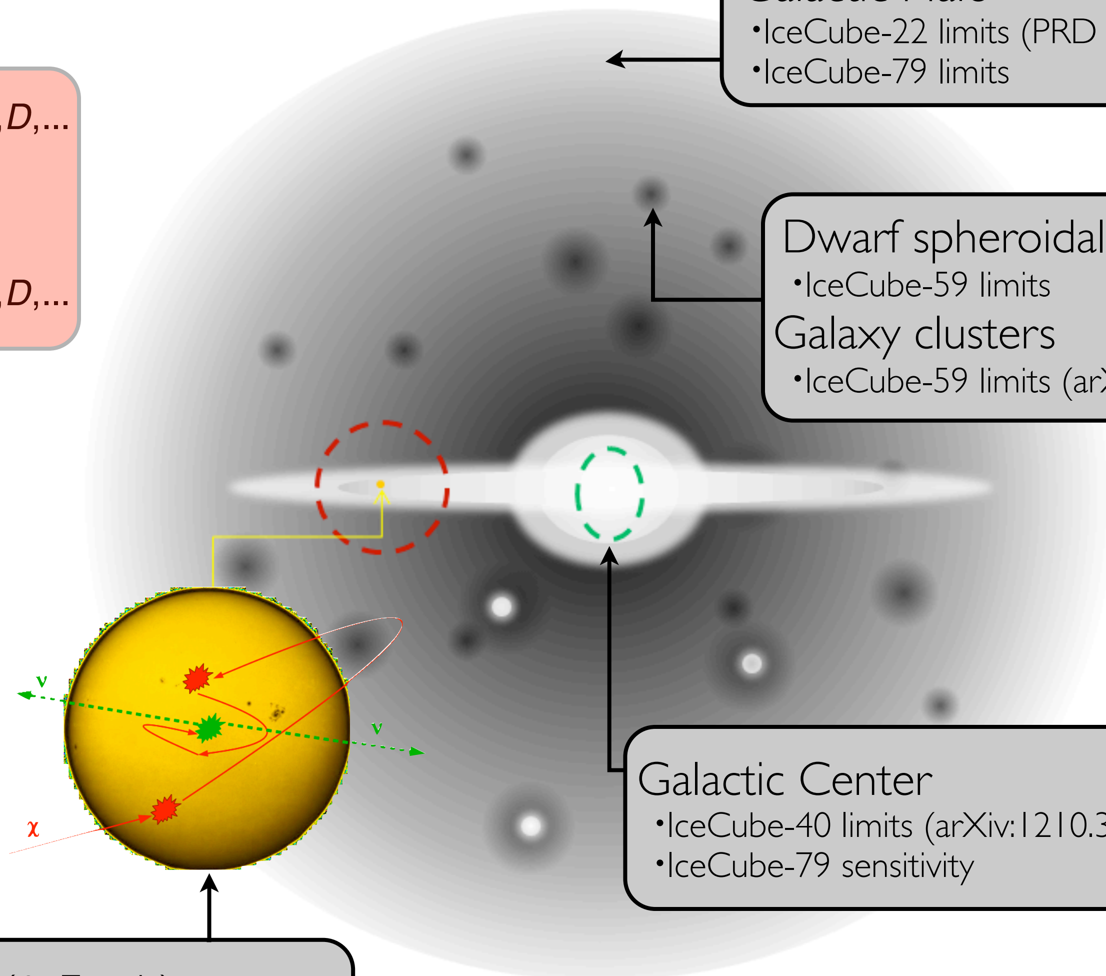
WIMP→Neutrino Channels

- Consider "extrema" to bracket possible neutrino energy spectrum
  - Hard channel
    - e.g., $\chi\chi \rightarrow W^+W^-$ and $\chi\chi \rightarrow \tau^+\tau^-$
    - Average $E_\nu \sim M_\chi/3$
  - Soft Channel
    - e.g., $\chi\chi \rightarrow bb$
    - Average $E_\nu \sim M_\chi/6$
  - Line Search
    - $\chi\chi \rightarrow \nu\nu$
    - $E_\nu \sim M_\chi$
- Search for $\underline{\nu_\mu}$-induced muons in detector

Summary of IceCube Searches

Search for dark matter annihilations to ν at E_ν from 10 GeV – 10 TeV





Galactic Halo
- IceCube-22 limits (PRD 84 (2011) 022004)
- IceCube-79 limits

Dwarf spheroidal galaxies
- IceCube-59 limits

Galaxy clusters
- IceCube-59 limits (arXiv:1210.3557 2012)

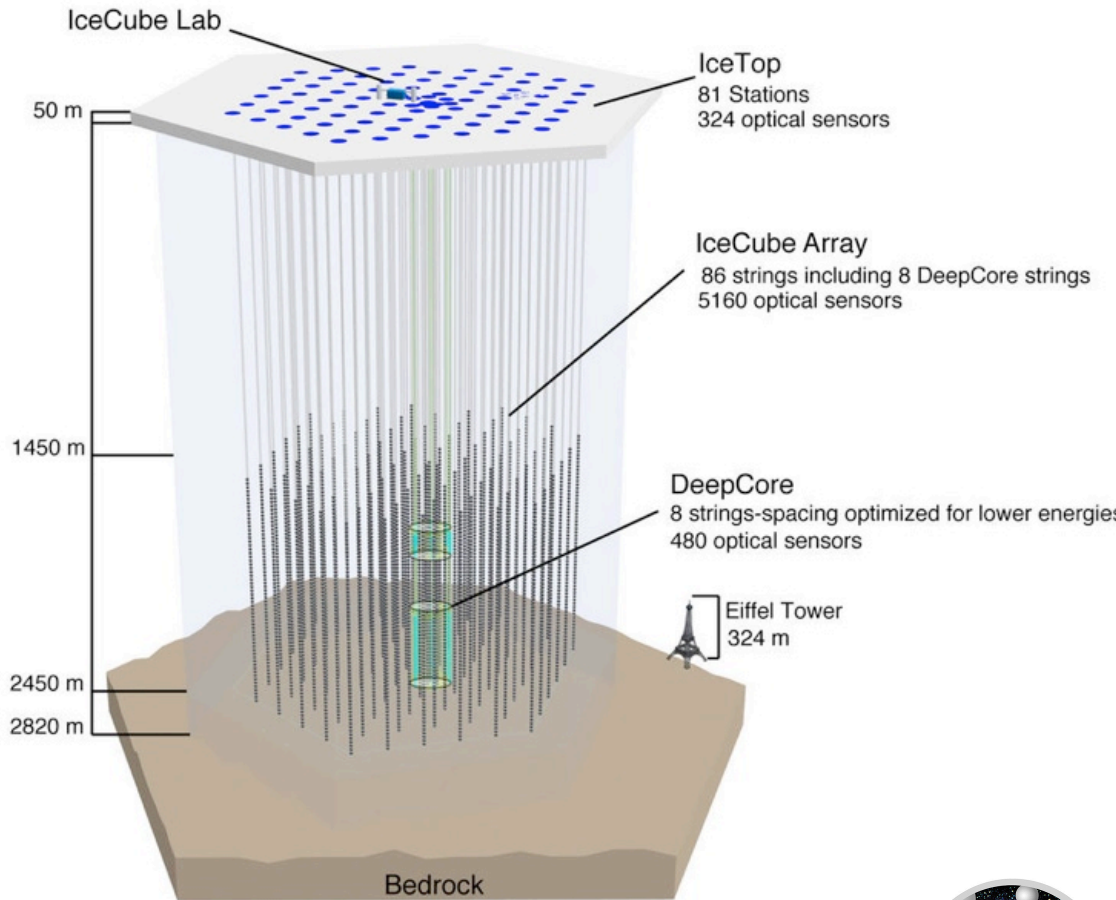
Galactic Center
- IceCube-40 limits (arXiv:1210.3557 2012)
- IceCube-79 sensitivity

Local sources: Sun (& Earth)
- IceCube-79 limits (PRL 110 (2013) 131302)

Image: M. Strassler

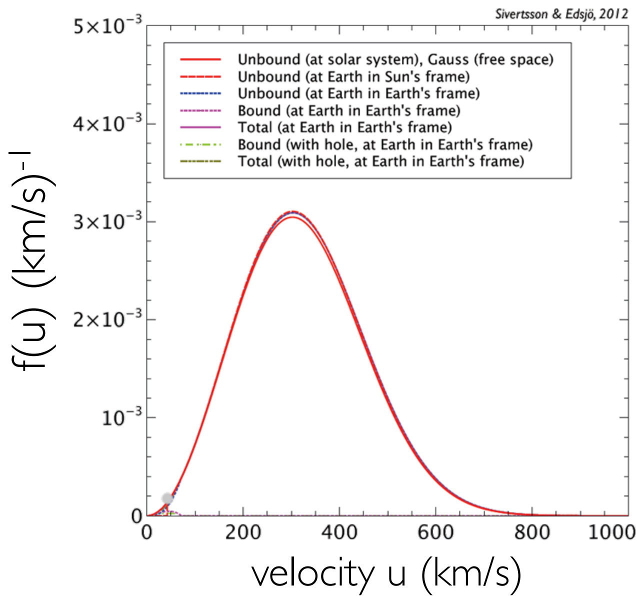
The IceCube Detector

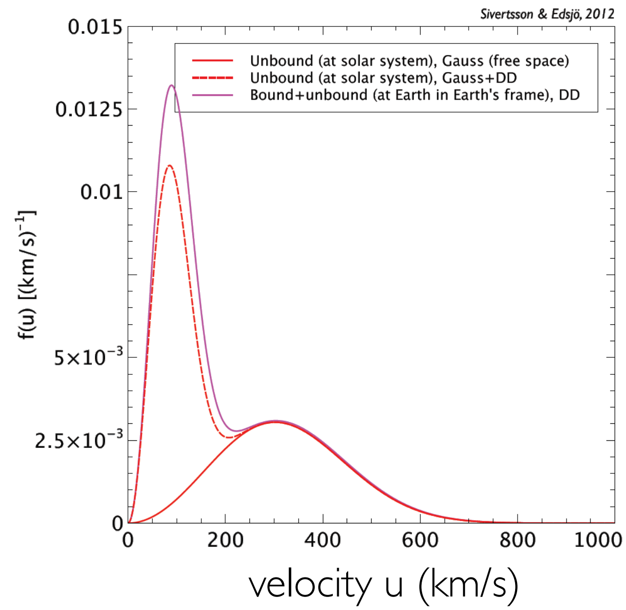
- First operating km-scale neutrino detector
  - ~5000 10'' PMTs
  - 78 strings: 125 m horiz., 17 m vert.
- Originally optimized for TeV-PeV energies
  - now also sensitive to ~10 GeV scale with DeepCore in-fill
    - 8 in-fill strings mostly 72 m & 7 m
- Sensitive to M_χ from below ~50 GeV to above ~100 TeV
- Physics-quality data taken with partially completed detector
  - IC-22, IC-40, IC-59, IC-79
    - IC-79 volume is about 1 km^3

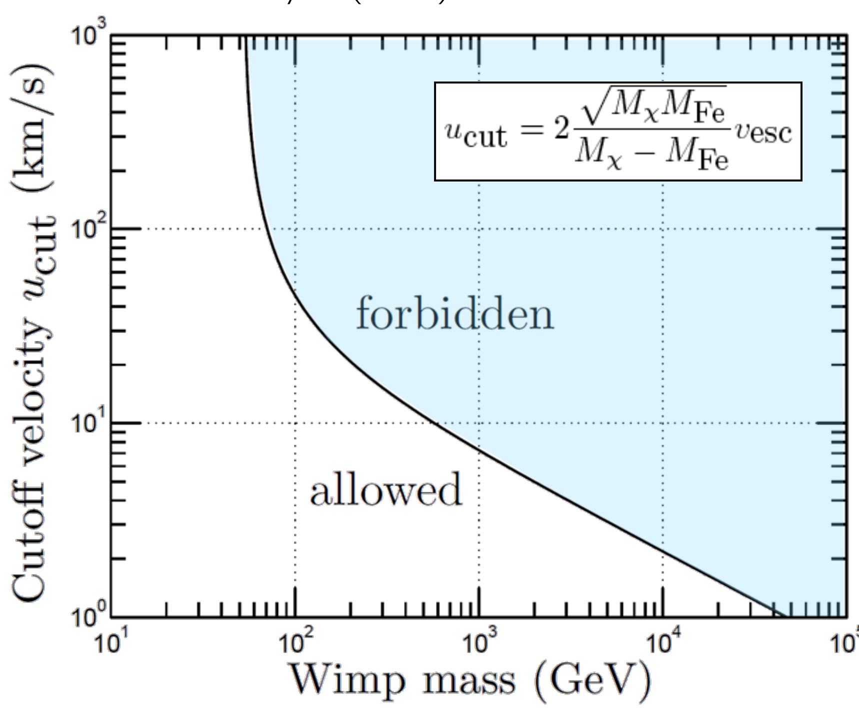


Earth WIMPs

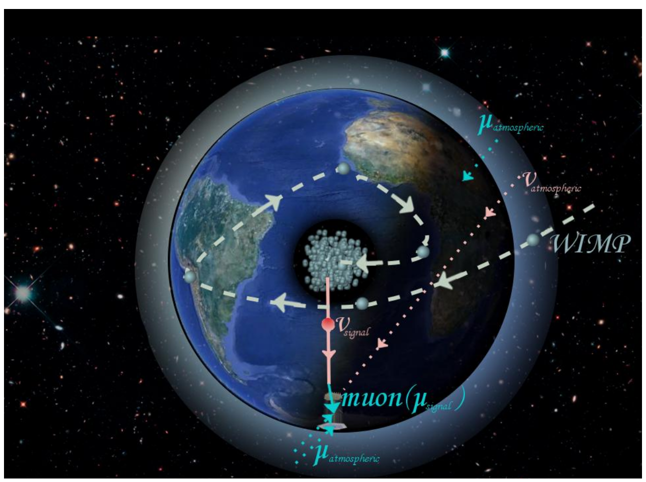
- Assumptions/Issues/ Observations
  - Assumed velocity distribution matters
  - Earth is a shallow gravitational well
  - Neutrino oscillations can be relevant
  - "Dark disk" can increase earth's accumulation





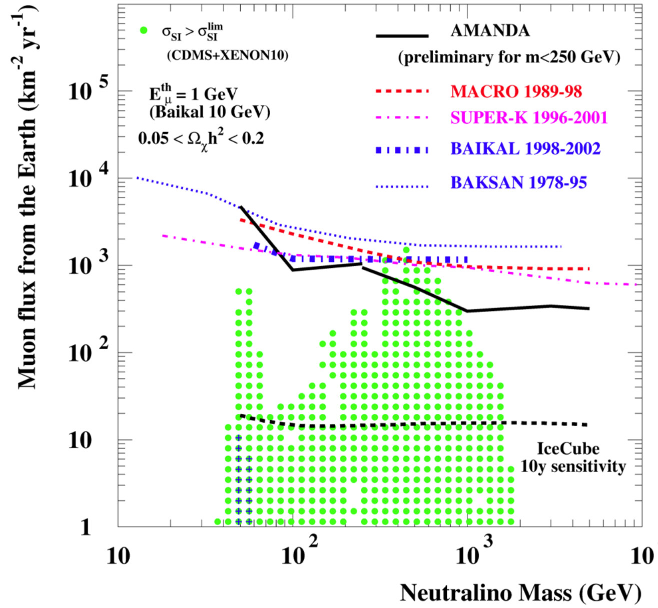


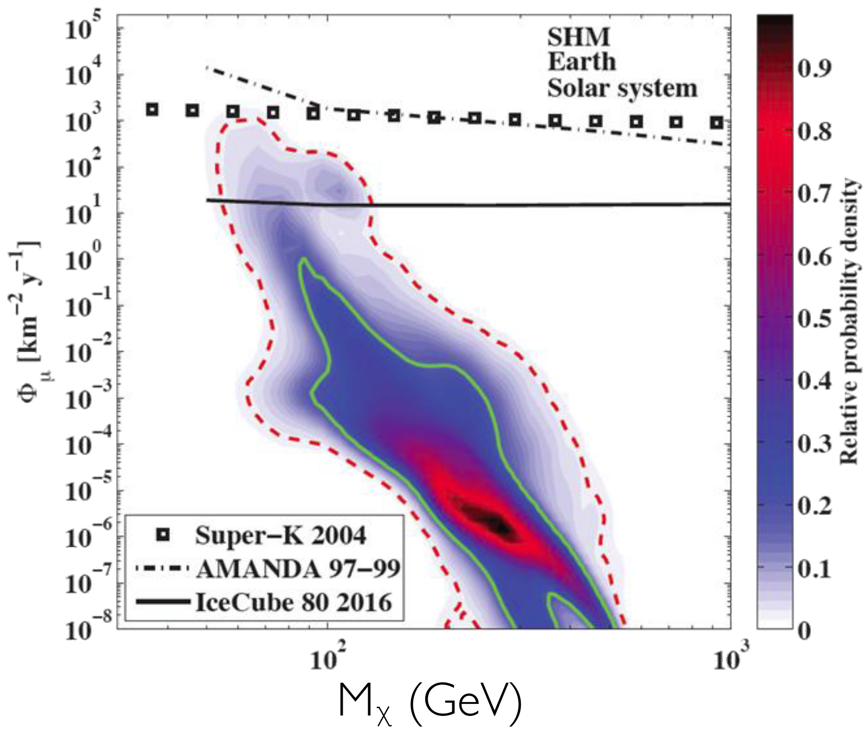
Minimum velocity for WIMP to be captured by Earth after scattering off iron

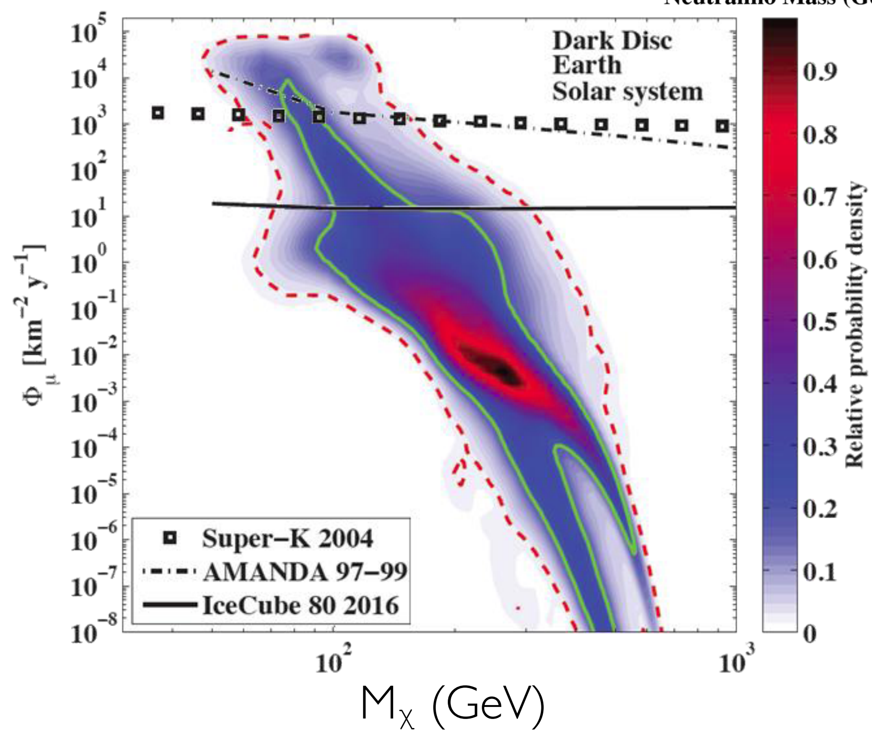


Results and Predicted Sensitivity: Earth WIMPs

- Earth WIMPs
  - Dedicated online trigger/filter in place at Pole
    - selects vertically upward-going events w/low E threshold
  - No "off-source" region: analysis more challenging
    - atmospheric neutrinos are main background
    - can't check with data
  - AMANDA analysis (published 2006)
    - Expected IceCube 10-yr sensitivity overlaid
    - Below: With and without "dark disc" assumption







T. Bruch et al., Phys. Lett. B674:250-256, 2009

IceCube Solar WIMP Search

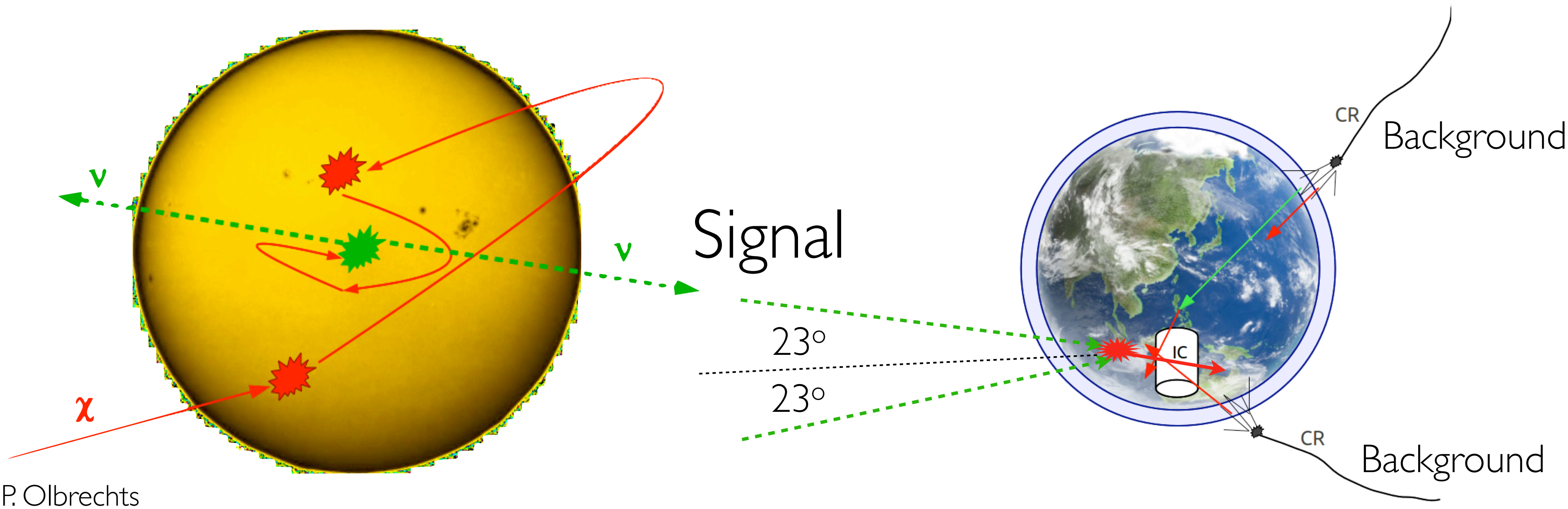


Image: P. Olbrechts

- Solar WIMPs
  - extract neutrino sample, vetoing downgoing cosmic ray muons
    - sample dominated by atmospheric neutrinos
  - maximize efficiency for ~horizontal events
    - sun is ±23° from horizon
  - striking signature: high energy ν excess from direction of sun

Solar WIMPs

- Assumptions/Issues/Observations
  - In equilibrium: $\Gamma_{\text{Ann.}} = (1/2)\Gamma_{\text{Cap.}}$
    - annihilation rate depends only on capture rate, i.e., on scattering cross sections
    - analyses can place limit on σ_{scatt}.
  - Daughter neutrinos' oscillations can be relevant
  - Daughter neutrinos' absorption can be relevant
  - No known astrophysical source can mimic neutrino signal

IceCube Solar WIMP Search

- Solar WIMPs
  - Recent (IC-79) analysis improvements:
    - Uses full year's data, including summer (317 days livetime)
    - Uses DeepCore to reach neutrino energies of 10-20 GeV

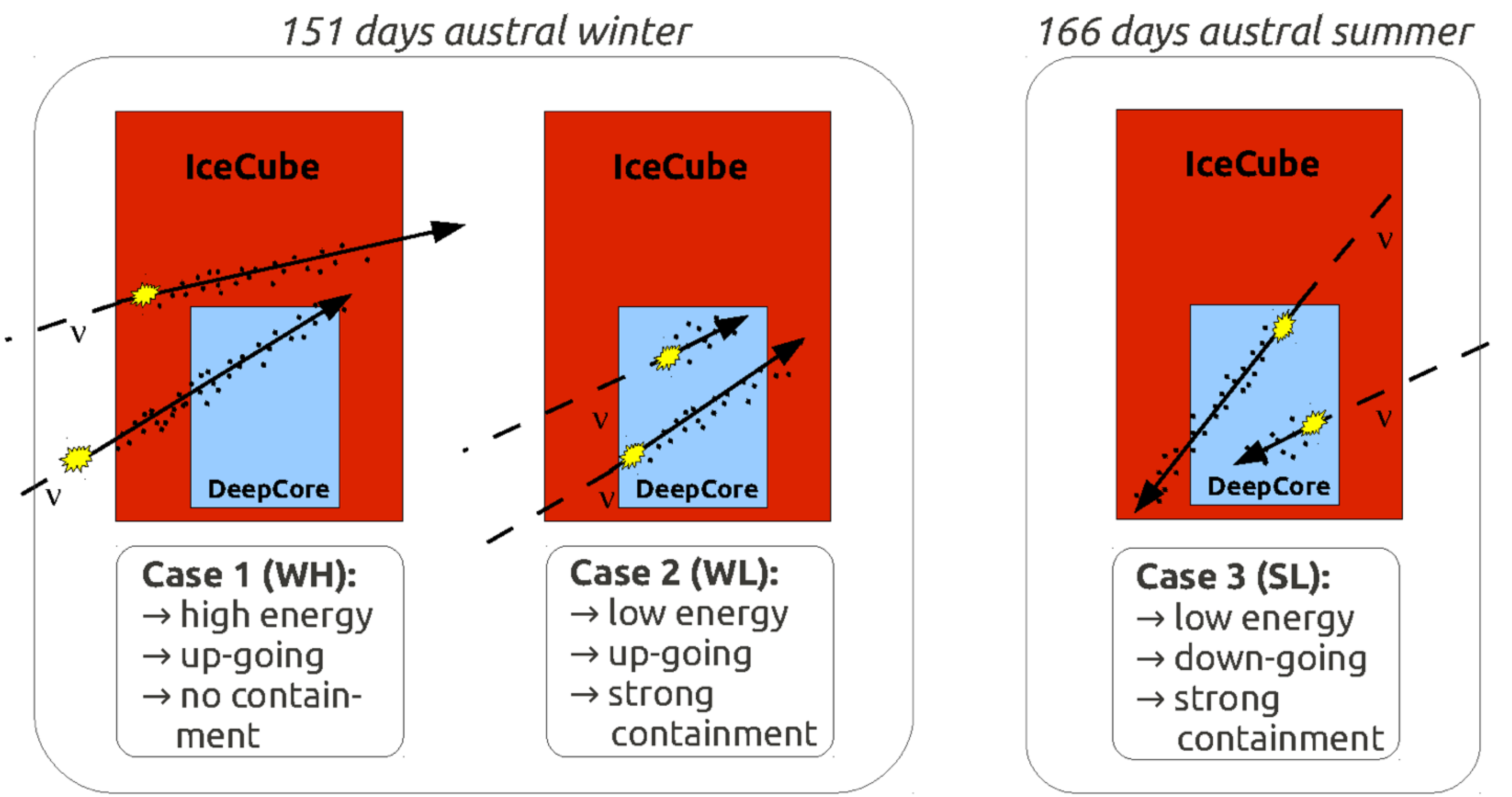
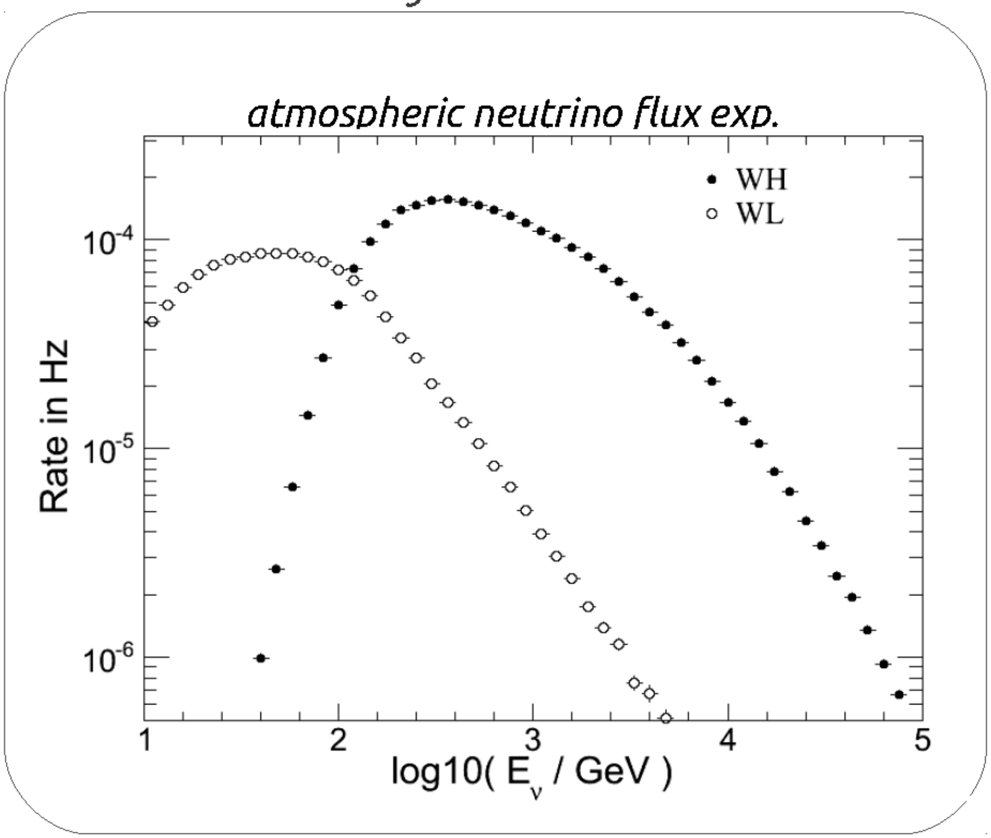


Image: M. Danninger

IceCube Solar WIMP Search

- Solar WIMPs
  - Recent (IC-79) analysis improvements:
    - Uses full year's data, including summer (317 days livetime)
    - Uses DeepCore to reach neutrino energies of 10-20 GeV

151 days austral winter



Expected atmospheric neutrino flux.

Contained events (WinterLow) have lower energies than uncontained events (WinterHigh):

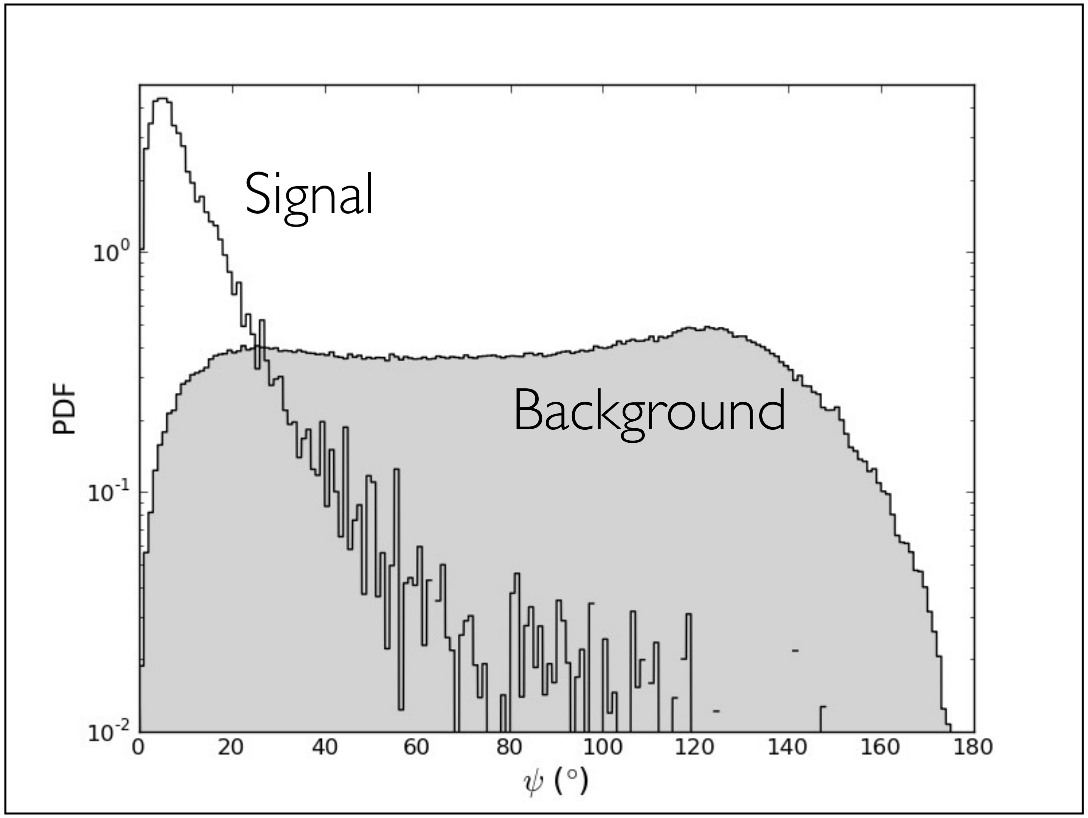
Probe different M_χ

Image: H. Danninger

IceCube Solar WIMP Search

- Solar WIMPs
  - Use shape of distribution of space angle (ψ) w.r.t. sun
  - Estimate background using off-source data
  - Systematics include
    - ice properties
    - module efficiencies
    - ν cross sections

IC-79



M. Danninger

Space Angle w.r.t. Sun

IceCube Solar WIMP Search

- Solar WIMPs
  - Use shape of distribution of space angle (ψ) w.r.t. sun
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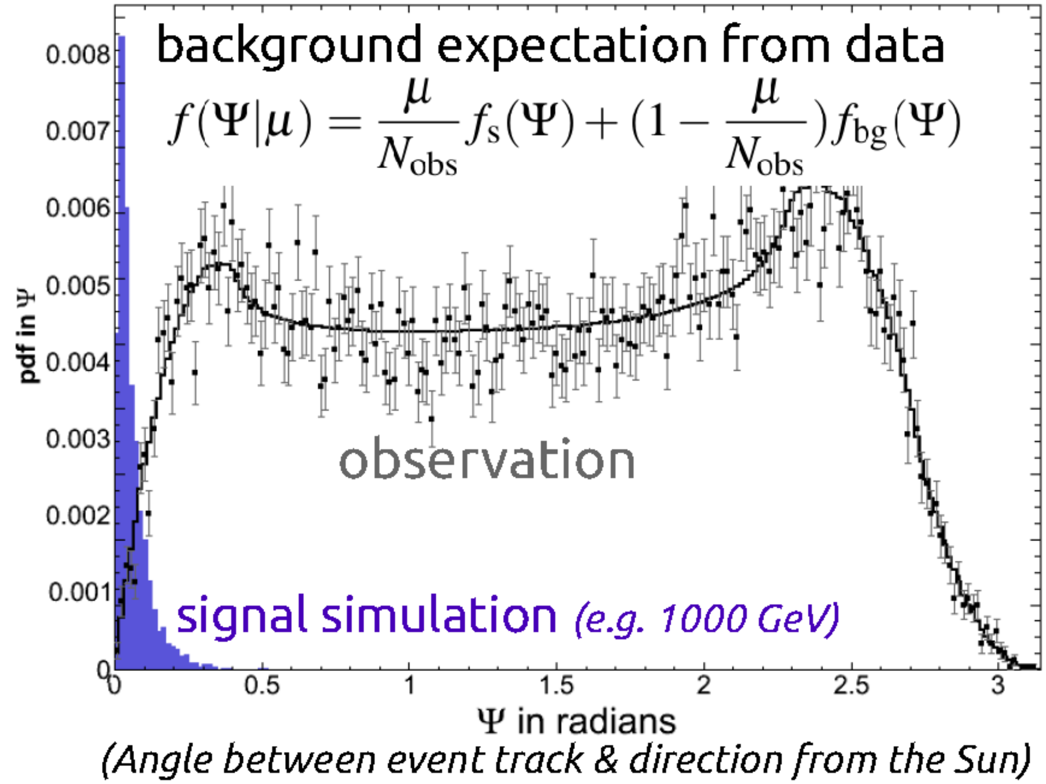
    - ice properties
    - module efficiencies
    - ν cross sections

IC-79



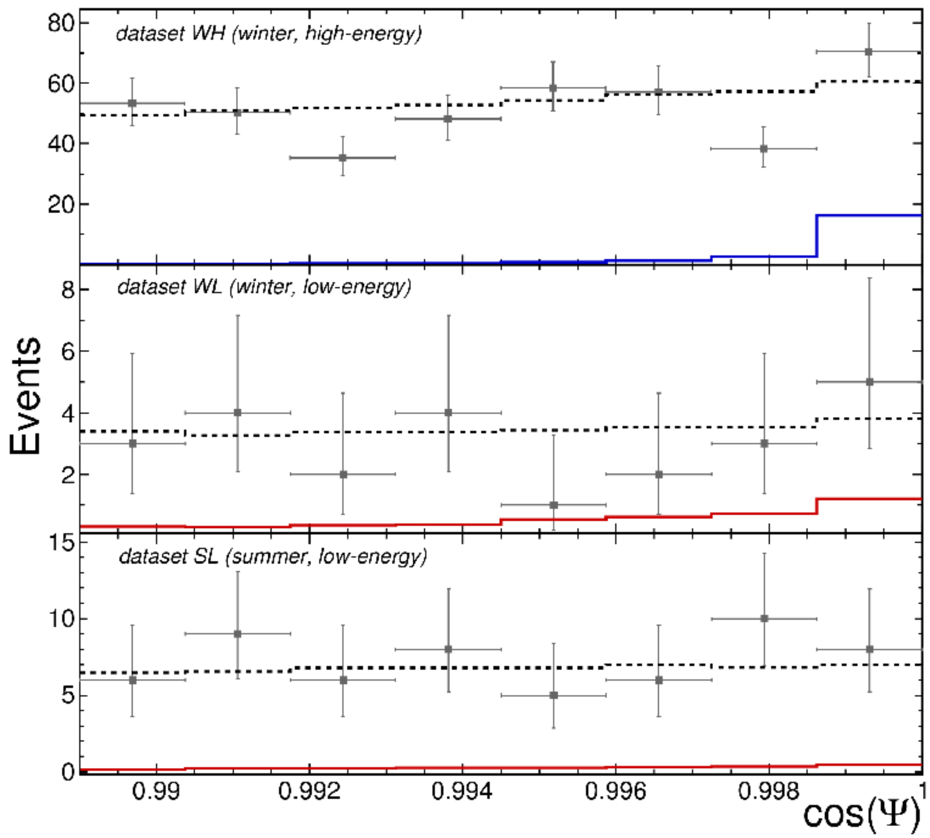
M. Danninger

Space Angle w.r.t. Sun

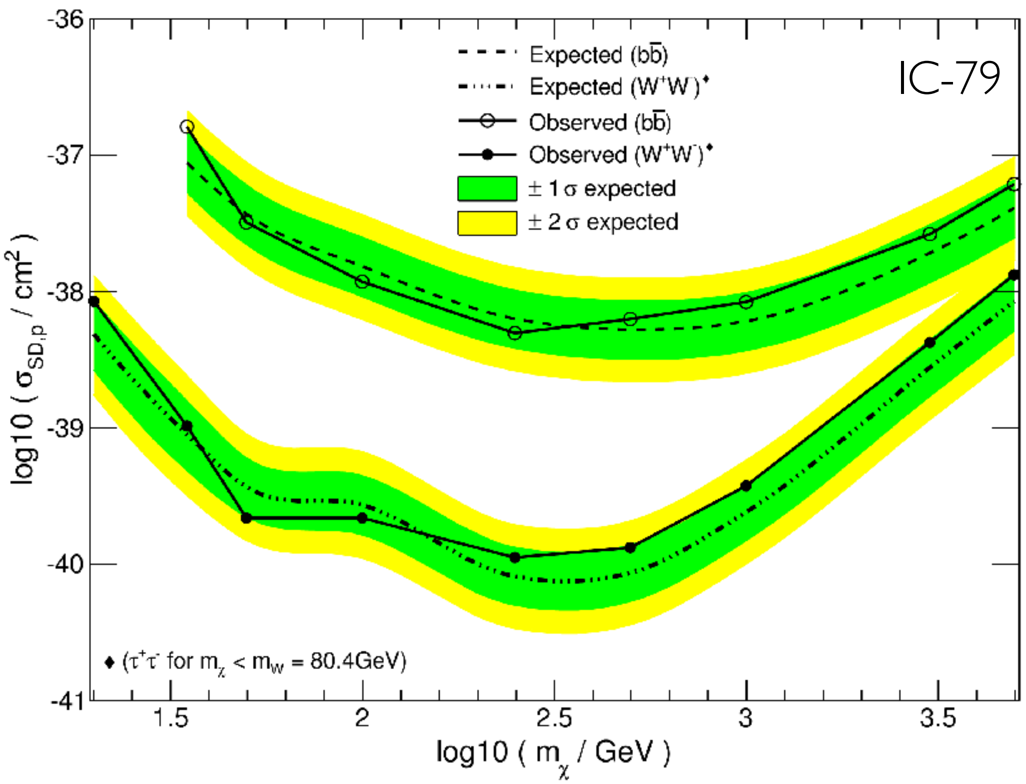
IceCube Solar WIMP Search: Results

- Solar WIMPs
  - final sample
  - final limits (with expected sensitivity overlaid)

Unblinded events in different samples

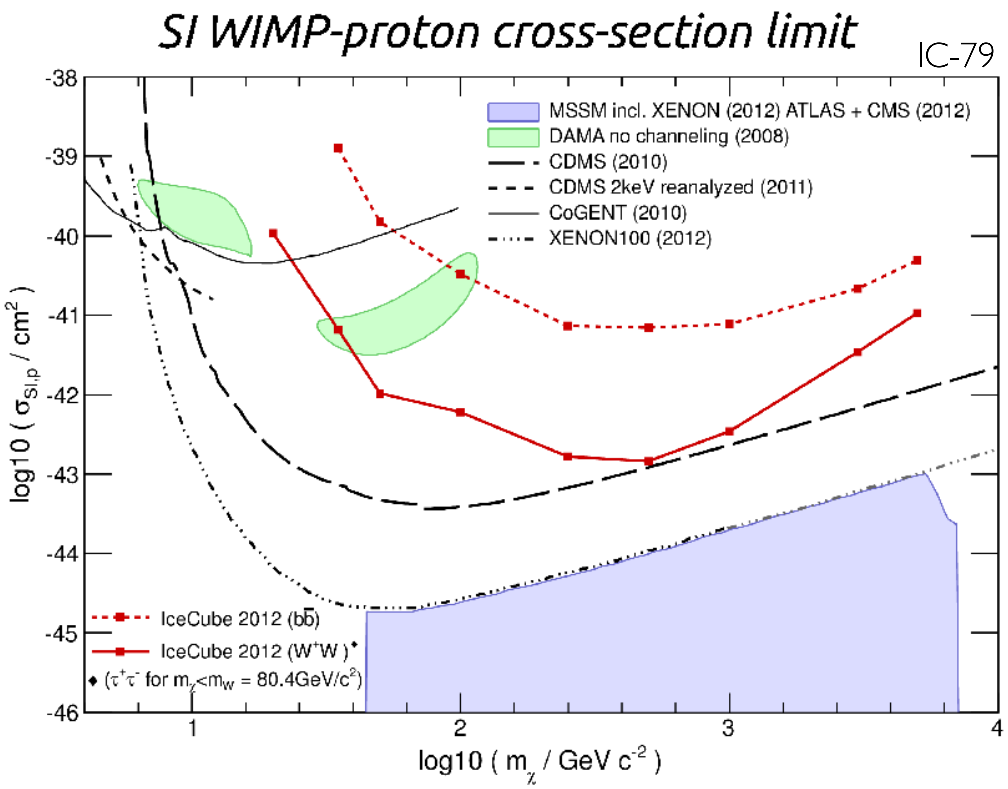


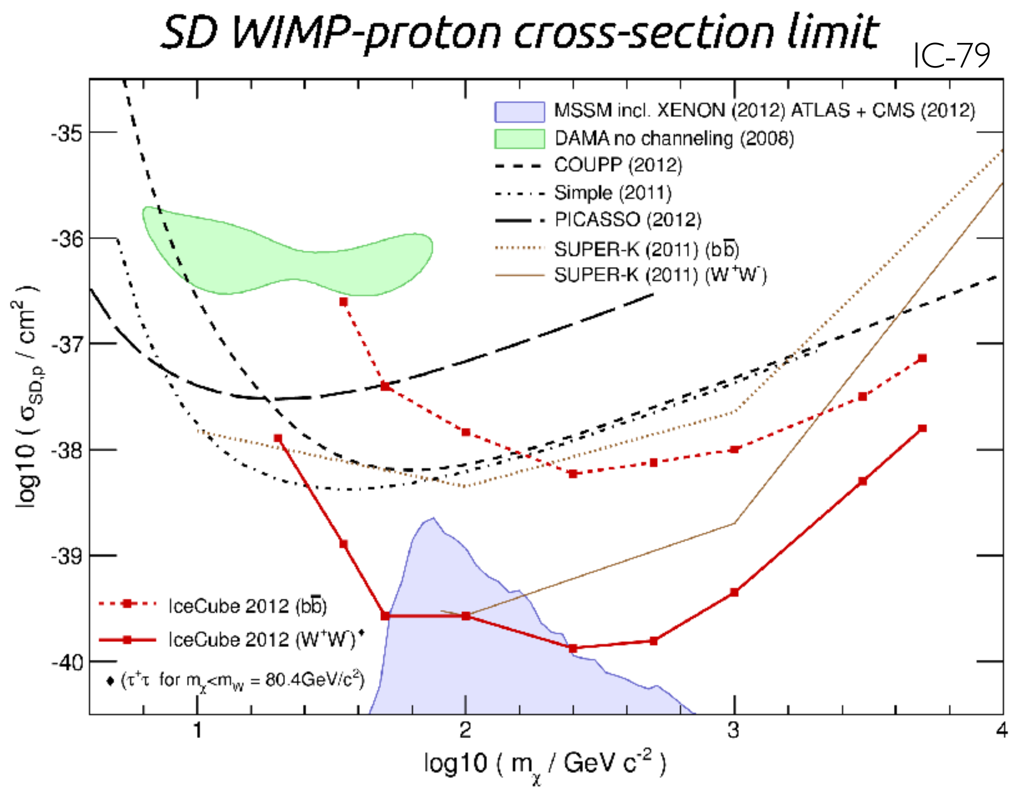
Expected sens. vs. observed result



IceCube Solar WIMP Search: Results

- Solar WIMPs
  - Final limits

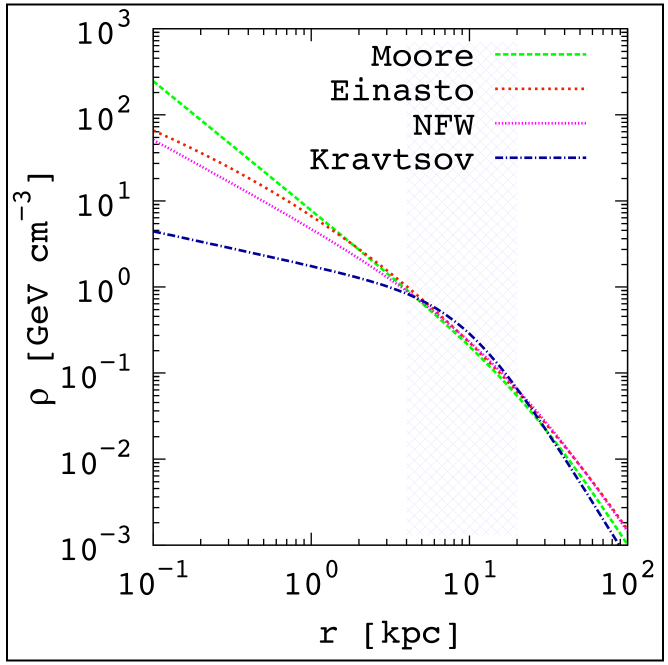




  - Most stringent σ_{SD} limit for most models (reaches M_χ~20 GeV)
  - Complementary to direct detection efforts
  - Different (and fewer) astrophysical uncertainties

IceCube Galactic Center & Halo WIMPs

- Assumptions/Issues/ Observations
  - Halo: predict ρ(dark matter)
    - N-body simulations
    - Gravitational lensing observations
    - Models agree at r ~3-30 kpc
  - Galactic Center: unknown ρ
    - simulations can't get there
    - no direct measurements
    - but can still look for excess neutrinos therefrom
  - Interplay of decay channel and neutrino oscillations is relevant



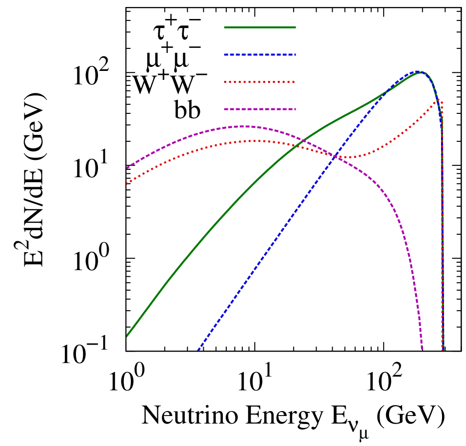
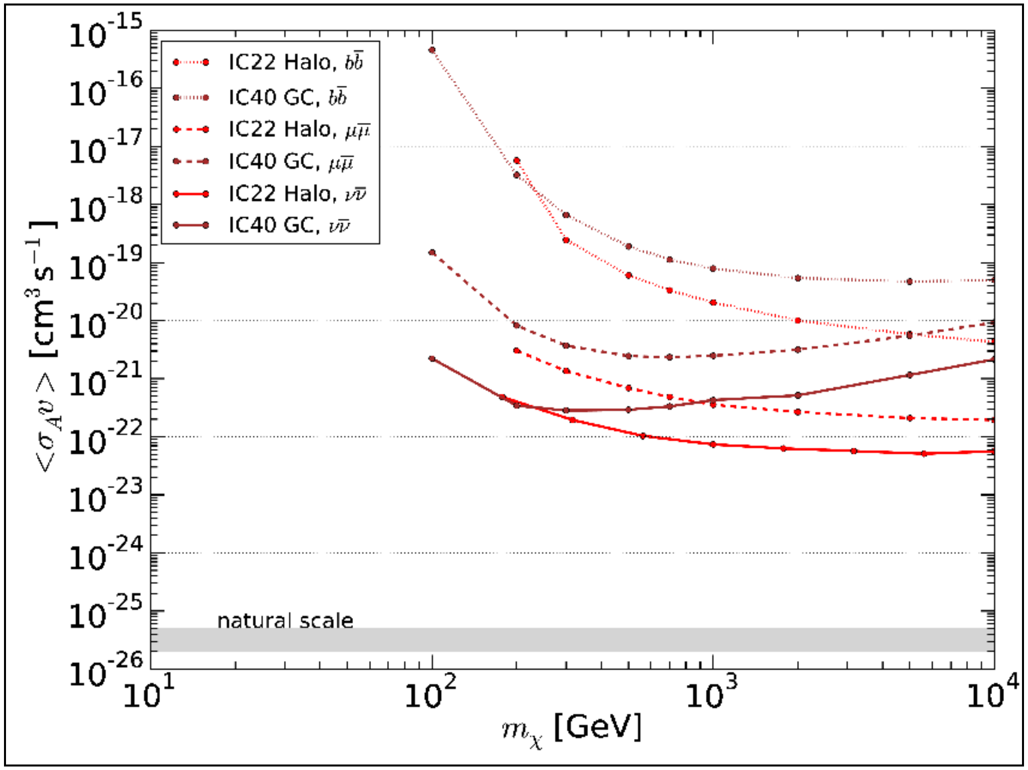


FIG. 3. Differential muon neutrino energy spectrum per annihilation, taking neutrino oscillations into account. In this example we assume a WIMP mass of 300 GeV and 100% branching fraction into the corresponding annihilation channel.

IceCube, PRD 84 022004

IceCube GC & Halo WIMP Searches

- Galactic Center and Halo
  - 90% CL limits for several annihilation channels (assuming 100% BRs)
  - Early IC-22&40 analyses shown



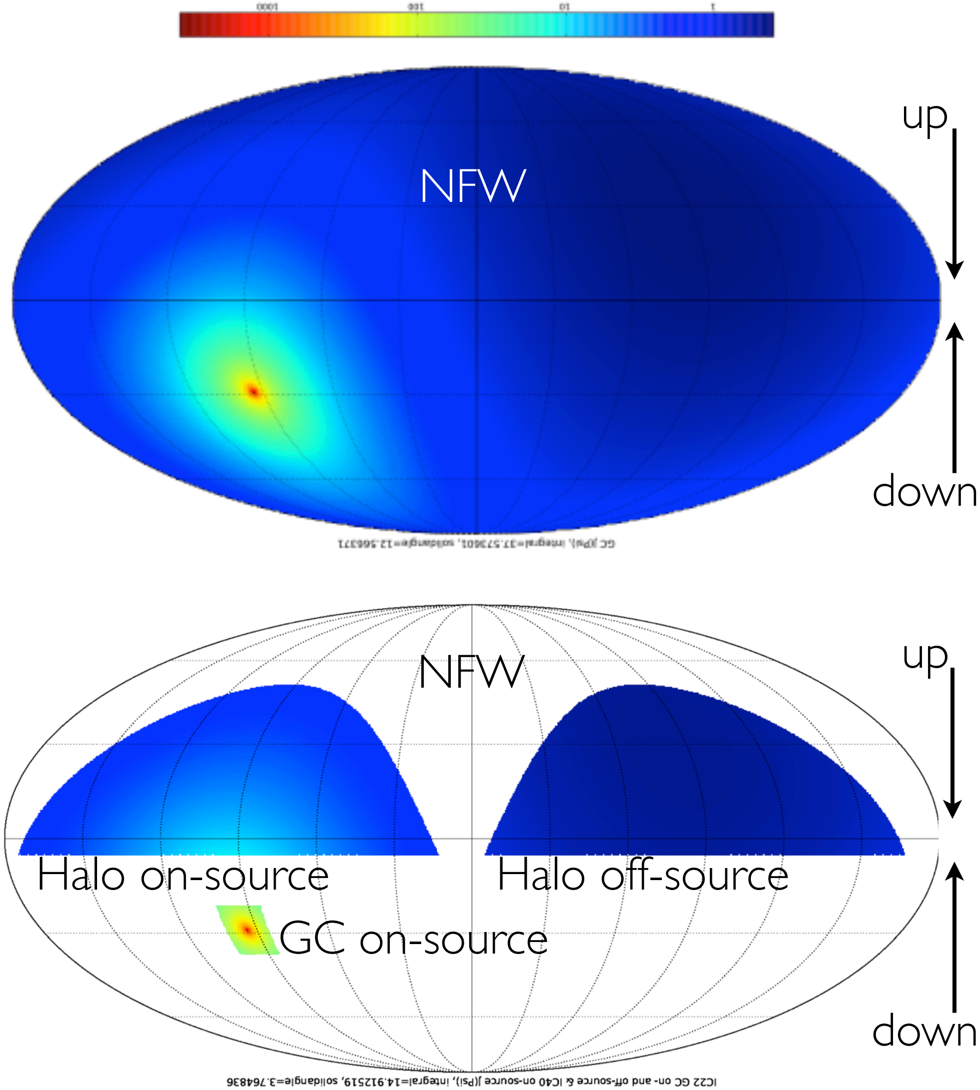


Image: C. Rott

IceCube GC WIMP Search

- Galactic Center
  - Extend previous search, adding IC-79 data with DeepCore
  - Two independent analyses:
    - Low energy (M_χ < 300 GeV)
    - High energy (M_χ > 300 GeV)

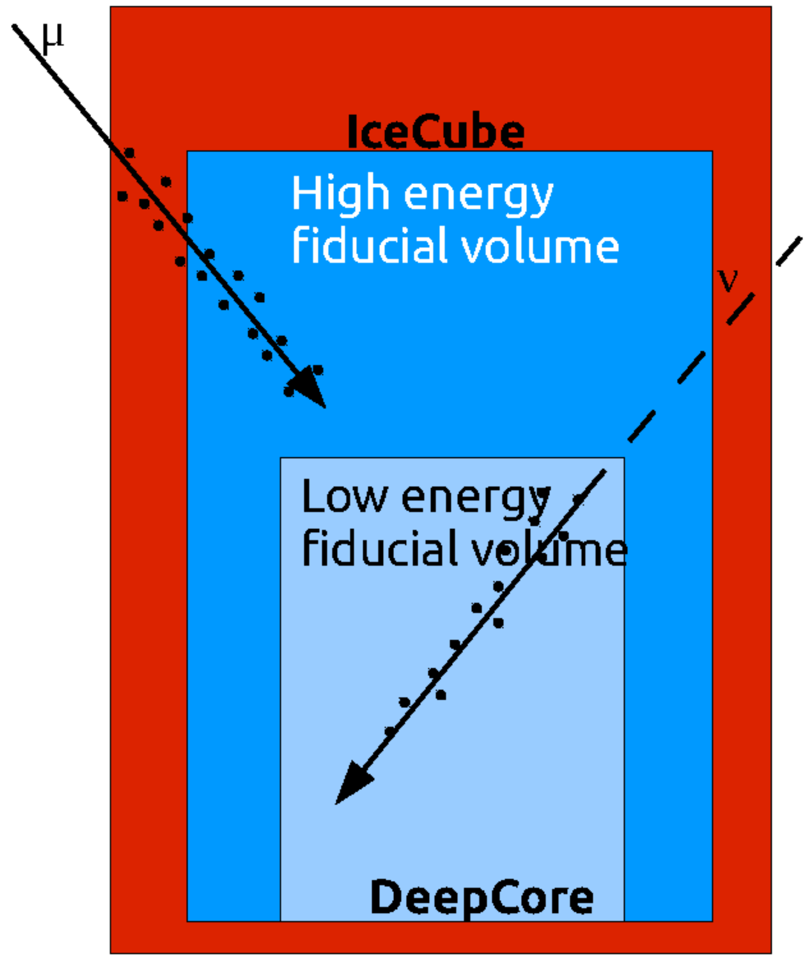


Image: M. Danninger

IceCube GC WIMP Searches

- Galactic Center
  - Extend previous search, adding IC-79 data with DeepCore
  - Two independent analyses:
    - Low energy (M_χ < 300 GeV)
    - High energy (M_χ > 300 GeV)
  - "Starting events" sample opens up southern sky
    - relies on muon vetoing

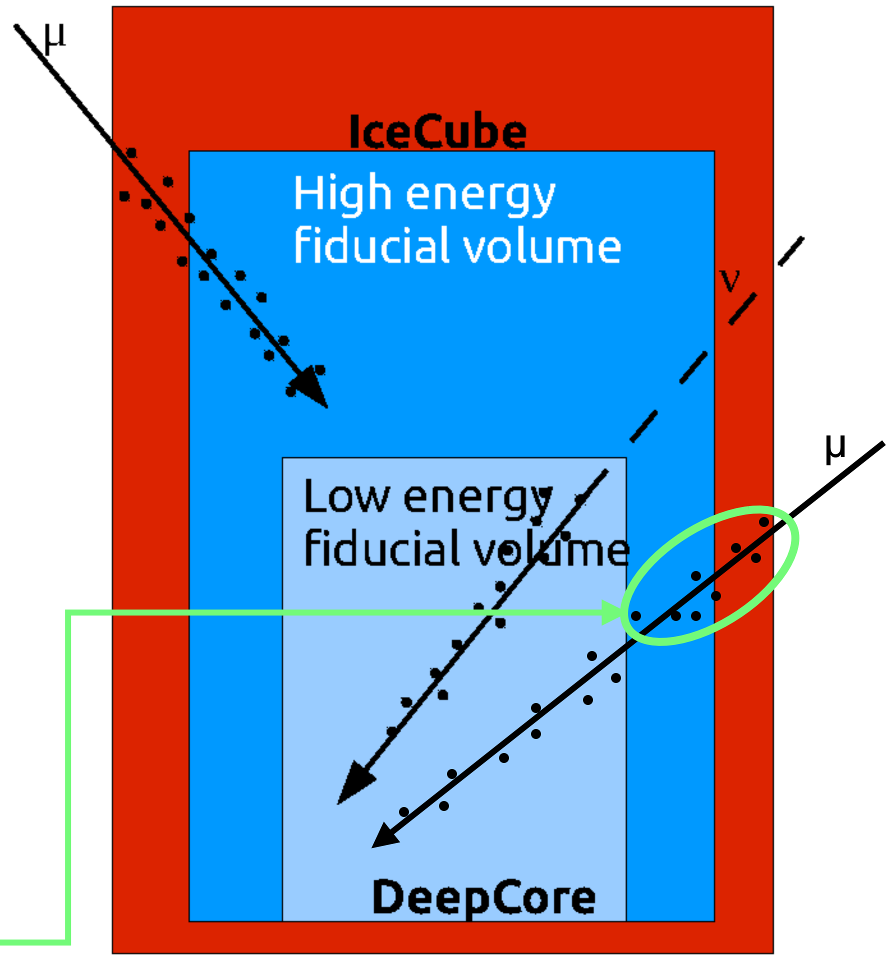
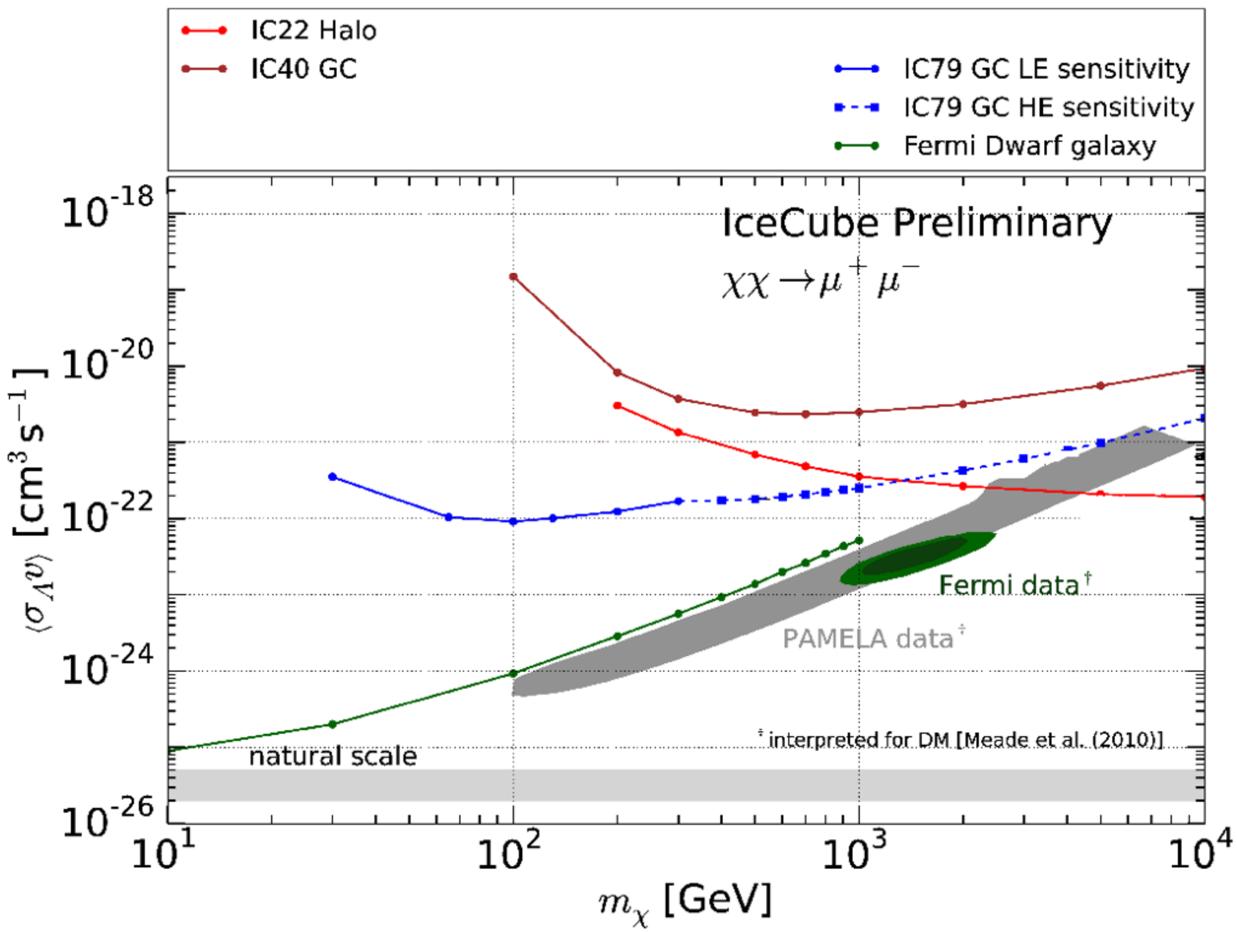


Image: M. Danninger

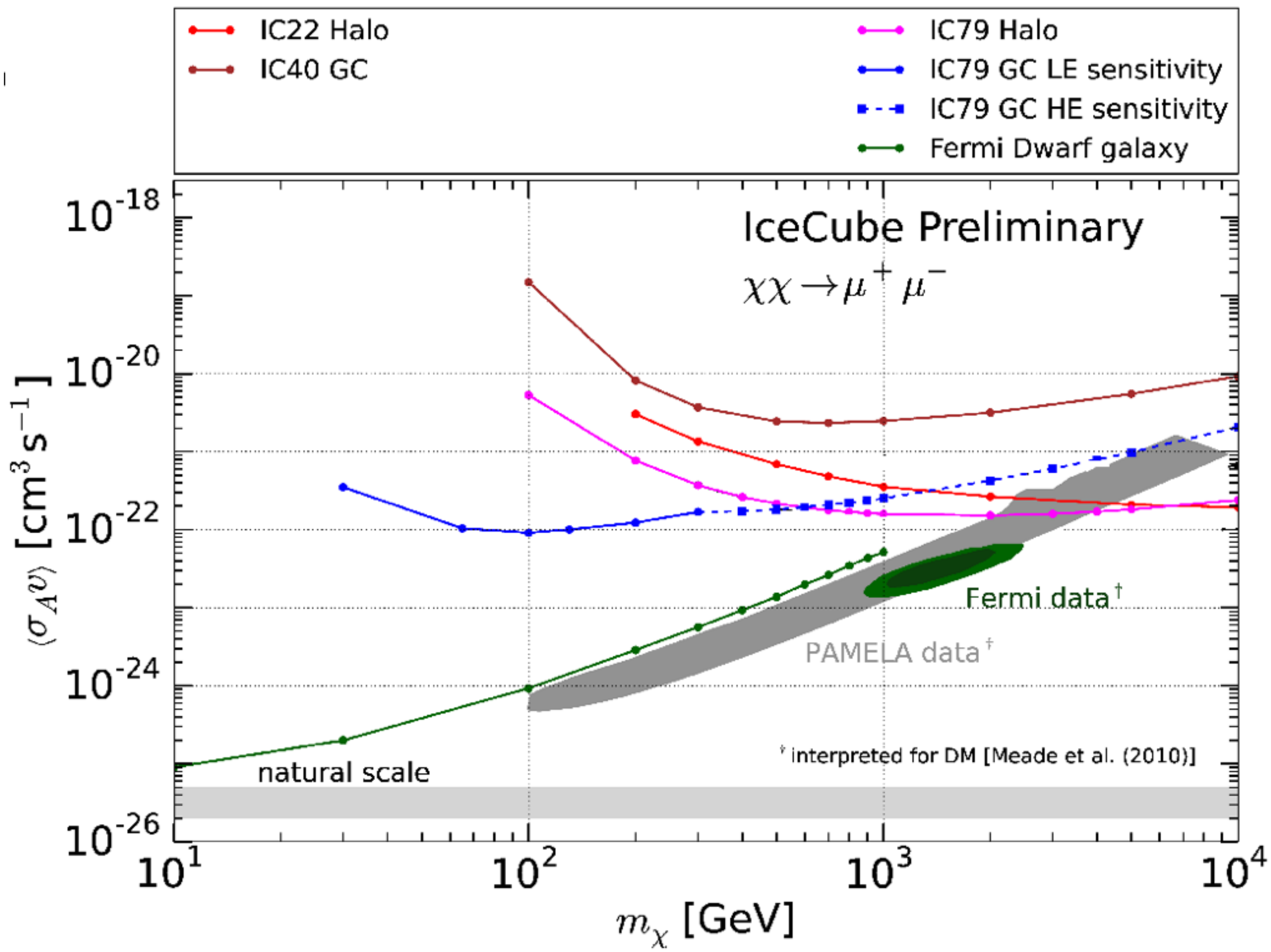
IceCube GC WIMP Sensitivity

- Galactic Center: IC-79 sensitivity
  - first time IceCube can reach <100 GeV masses for GC
    - 4 orders of magnitude improvement at this scale
  - unblinding of analysis underway



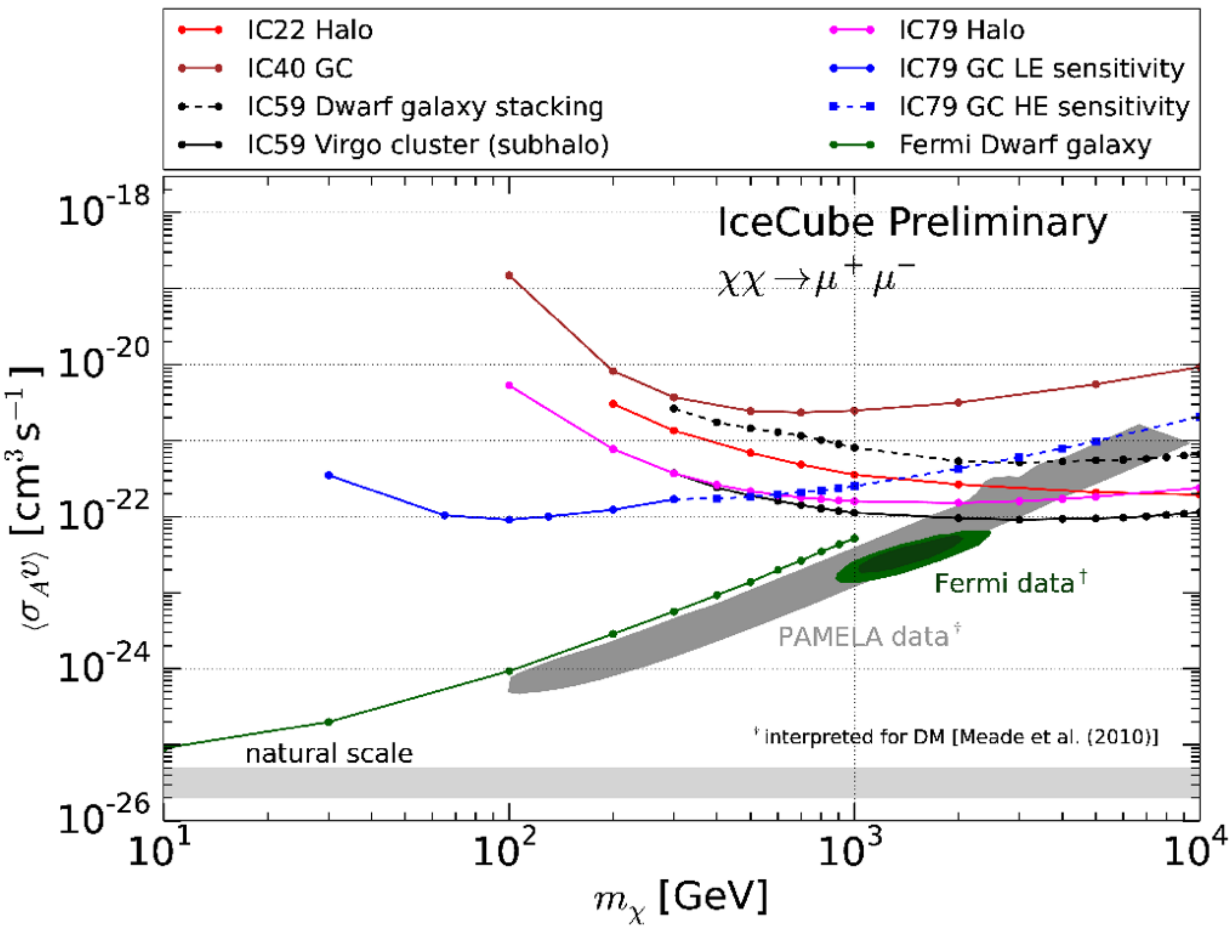
IceCube Halo WIMP Result

- Galactic Halo: IC-79 result
  - multipole analysis focuses on large scale anisotropies (ℓ<100)
  - small halo-model dependencies
  - results compatible with background-only hypothesis



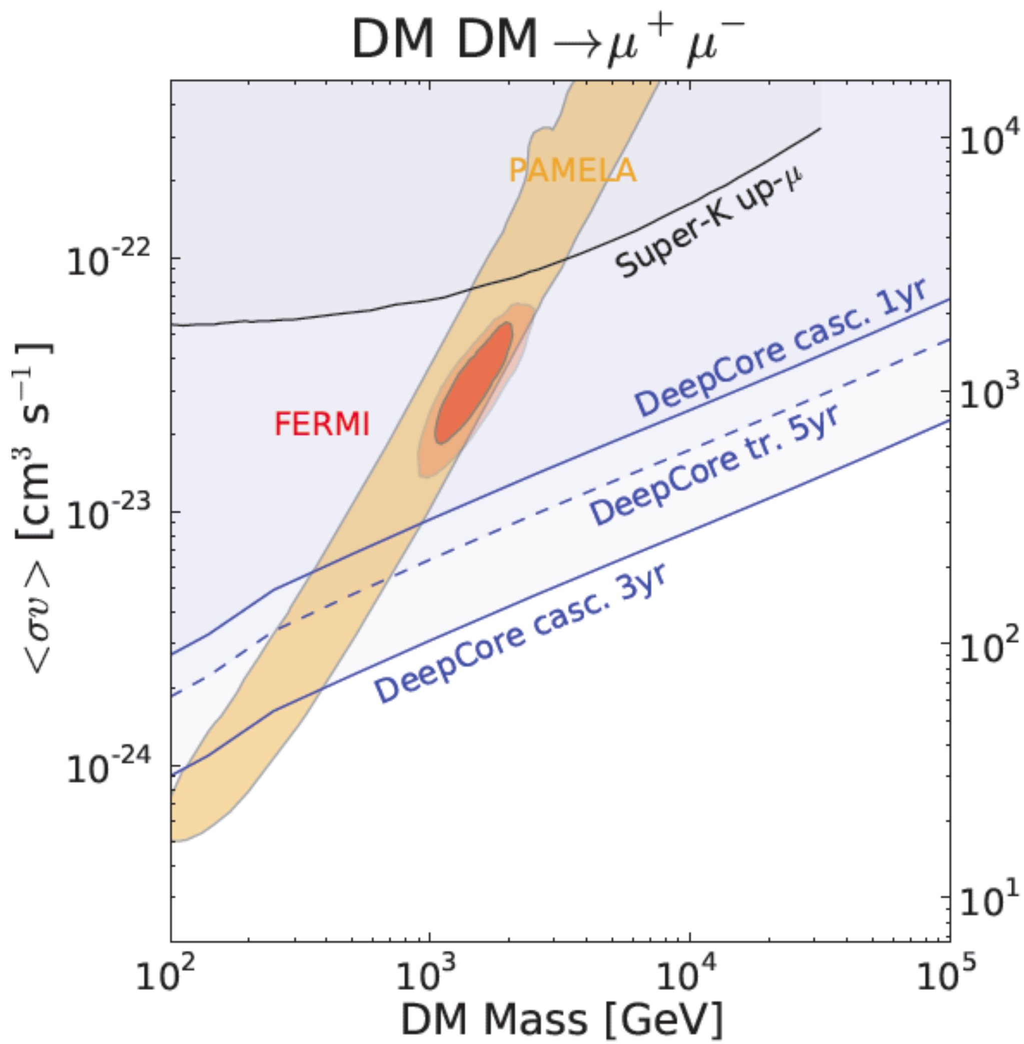
IceCube Dwarf Galaxy & Cluster WIMP Result

- Dwarf galaxy and galaxy clusters: IC-59 results
  - IC-59 dwarf galaxy (stacking analysis)
  - IC-59 galaxy cluster (point source search)



Future Work: IceCube/DeepCore

- IceCube/DeepCore can use cascade channel to test possible signals in PAMELA and Fermi data
  - background from downward-going neutrino-induced muons is reduced
- (Highly effective veto and low energy reconstructions will keep muon neutrinos competitive, though.)



Mandal et al. PRD 81:043508 (2010)

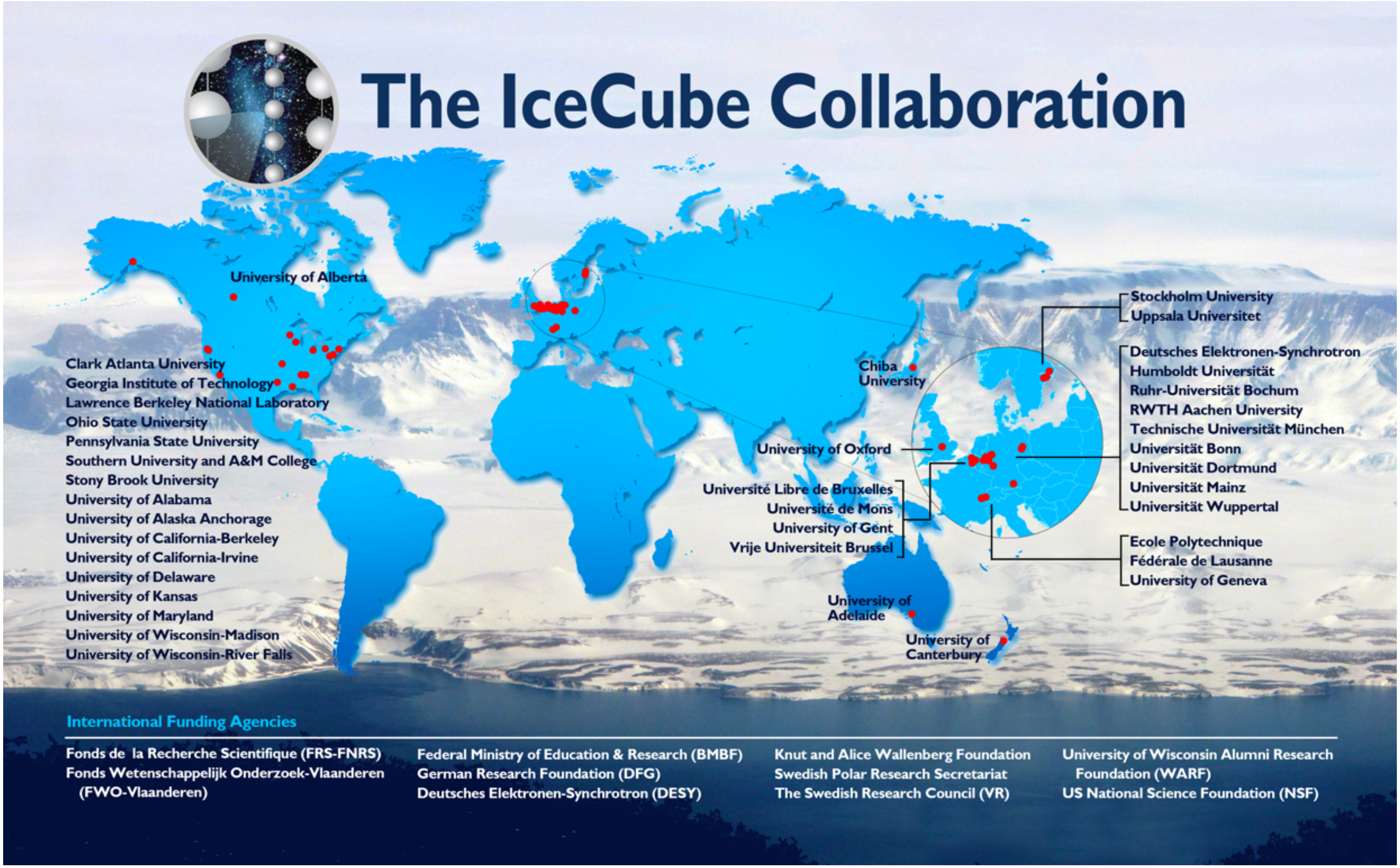
Conclusions

- Neutrinos are sensitive probes for detecting dark matter
- Searches for WIMP→ν signatures from distinct sources are "self-complementary," and complementary to searches using other astrophysical messengers
- Solar WIMP annihilations to neutrinos would provide a "smoking gun" signature with minimal model assumptions
- Clever new ideas for detection channels and sources spur new analyses
- Future detectors with lower energy thresholds will probe region of parameter space made interesting by direct detection experiments
  - See PINGU talk, next.

PINGU & WIMPs

- PINGU: Precision IceCube Next Generation Upgrade
  - New IceCube in-fill array, to be proposed in fall 2013
  - Main physics goal: neutrino mass hierarchy with atmospheric neutrinos
    - see talk by T. DeYoung
      - 11:00 Weds., Anderson 250
  - But also has sensitivity to WIMPs, especially at lower WIMP masses

The PINGU Collaboration

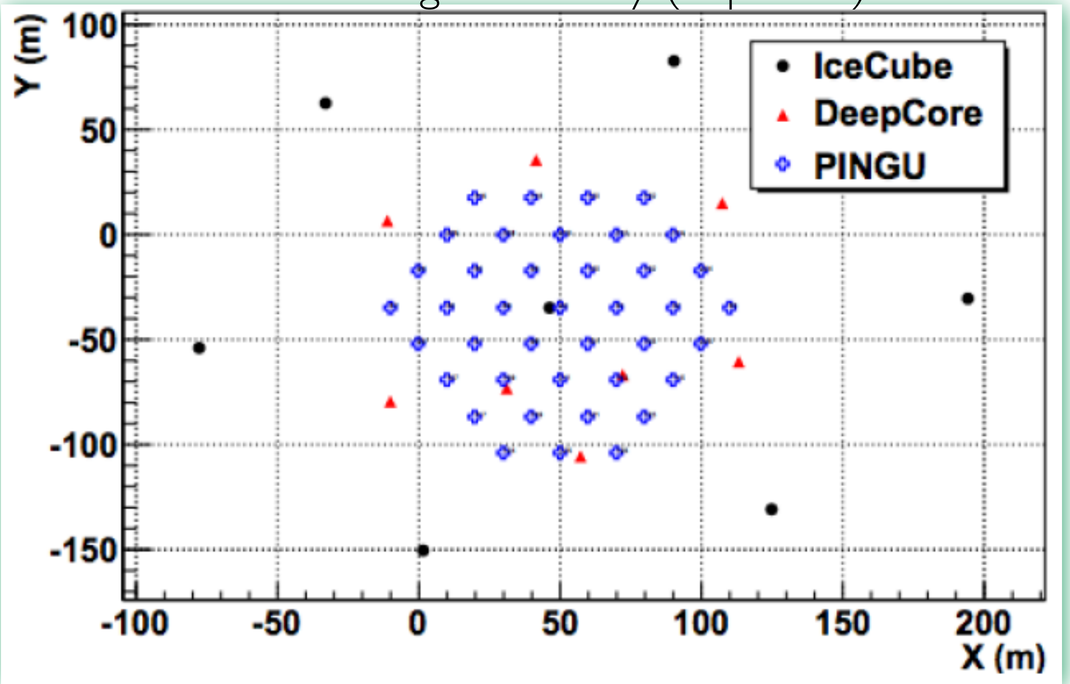


Plus: U. Erlangen, U. Manchester, NBI Copenhagen, Sungkyunkwan U., U. Tokyo, U. Toronto

PINGU Detector

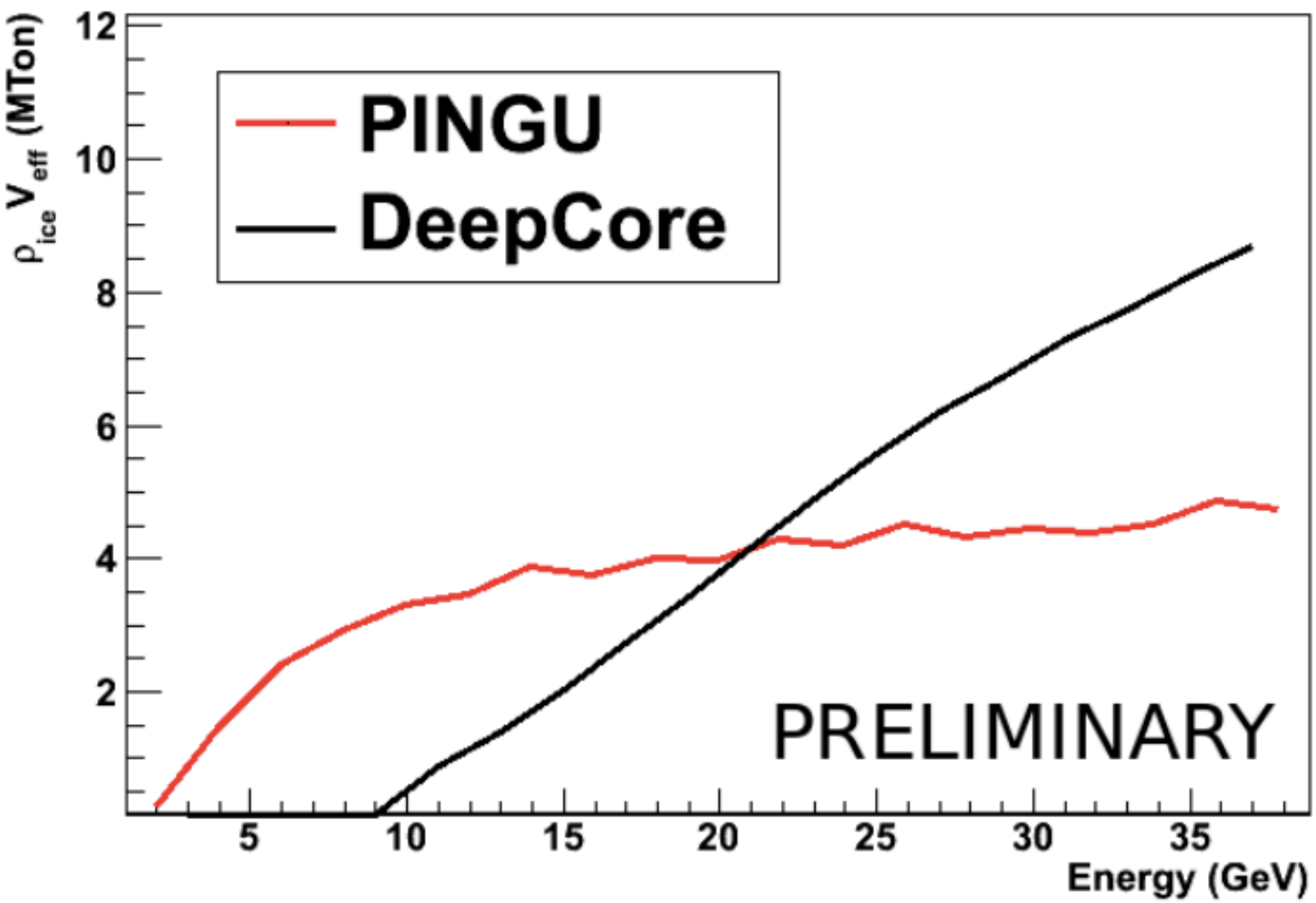
- Further increase sensor density relative to DeepCore
  - Baseline geometry has ~40 additional strings @ 60 DOMs
    - IceCube-based technology plus R&D modules
    - Include new low-E calibration devices
    - Geometry optimization underway
  - Aims:
    - Physics program at E_{thr} ~ few GeV
      - Neutrino mass hierarchy
      - Low mass WIMPs (M_χ~10-100 GeV)
    - R&D: Cherenkov ring segment reco.?

40-String Geometry (Top View)



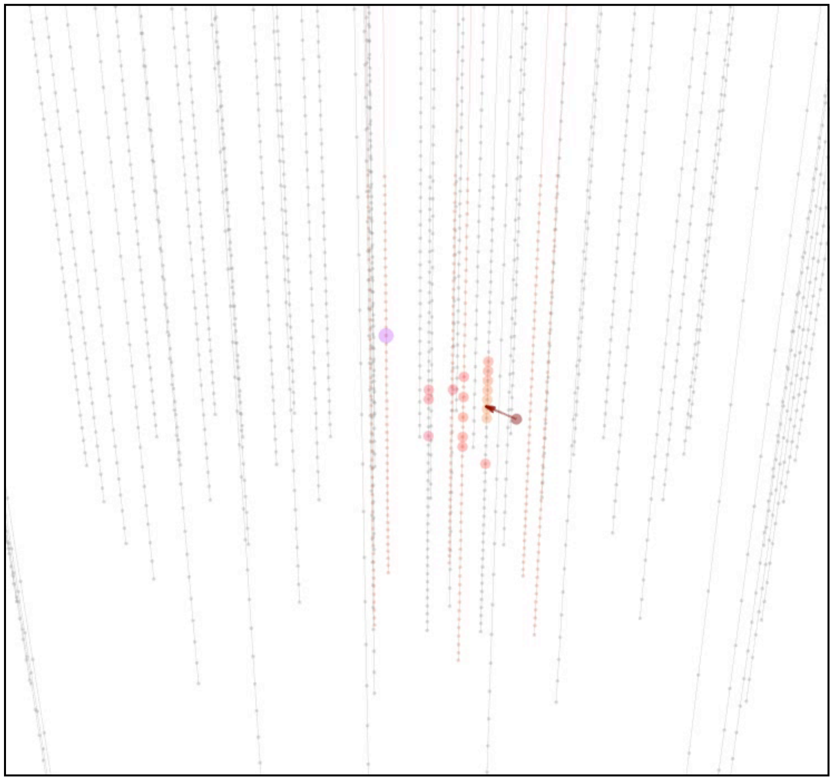
PINGU Fiducial Volume

- Below E_ν ~ 20 GeV, PINGU provides gain in fiducial mass relative to the existing low E_ν in-fill, DeepCore

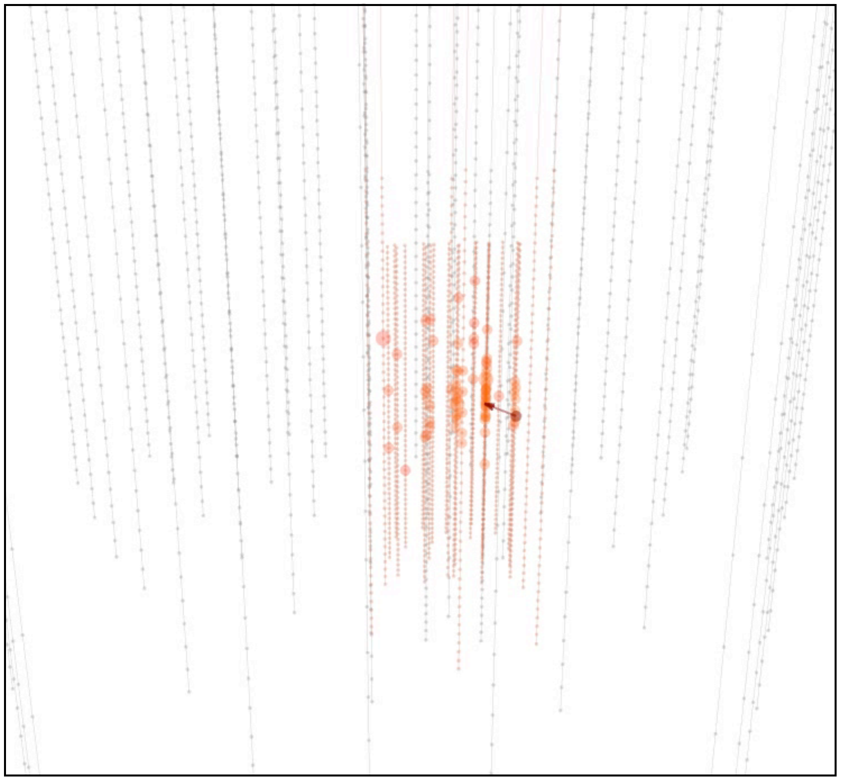


PINGU vs. DeepCore

- Simulated event:
  - 9.3 GeV neutrino
    - 4.4 GeV initial cascade
    - 4.9 GeV muon
- Showing physics hits only
  - no noise shown, but noise is not hard to remove



DeepCore Only

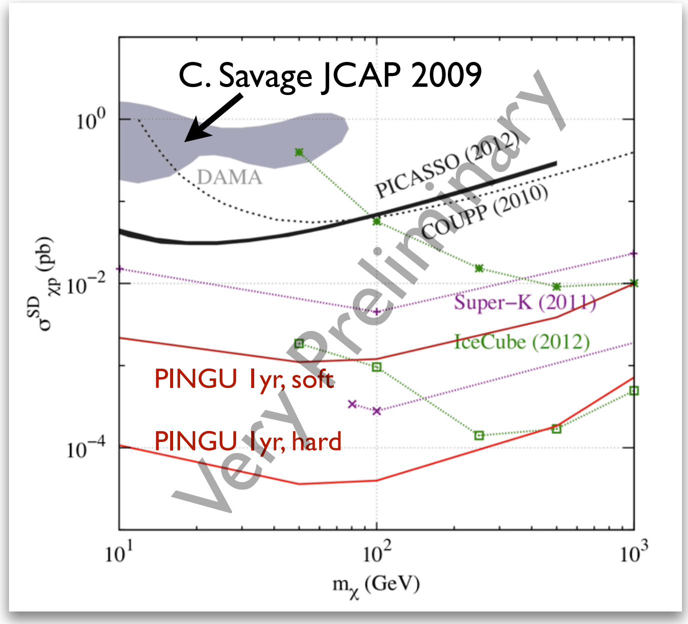


DeepCore + PINGU

D. J. Koskinen

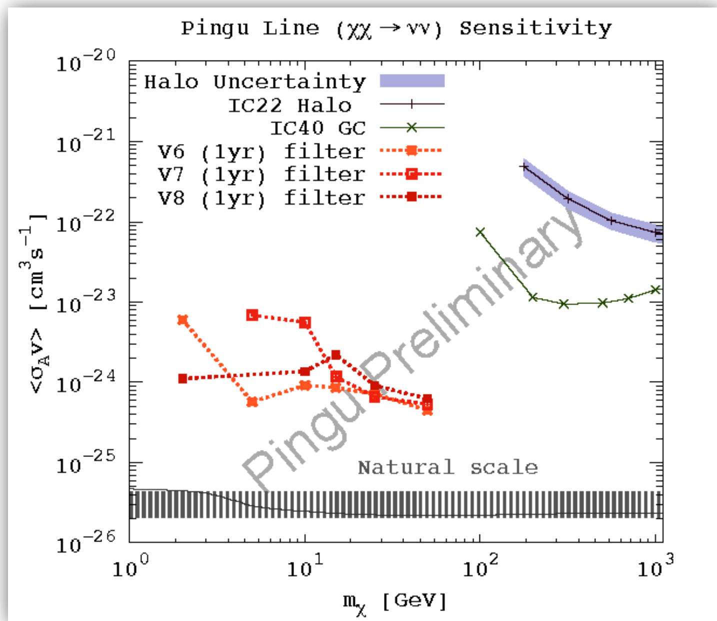
Predicted PINGU WIMP Sensitivities

- Solar WIMP sensitivity
  - PINGU can probe interesting WIMP mass range
- GC Line sensitivity
  - Again, PINGU reaches interesting masses
- _N.B._ Plots at trigger level
  - somewhat optimistic



Solar

C. Rott



GC Line

C. Rott

PINGU Details

- Letter of Intent out in next 1-2 months
- Proposal submissions in fall
- Detector time frame
  - Could start full-detector data taking as early as 2019
- Detector cost estimate
  - $8-12M startup costs for drill
  - $1.25M per string

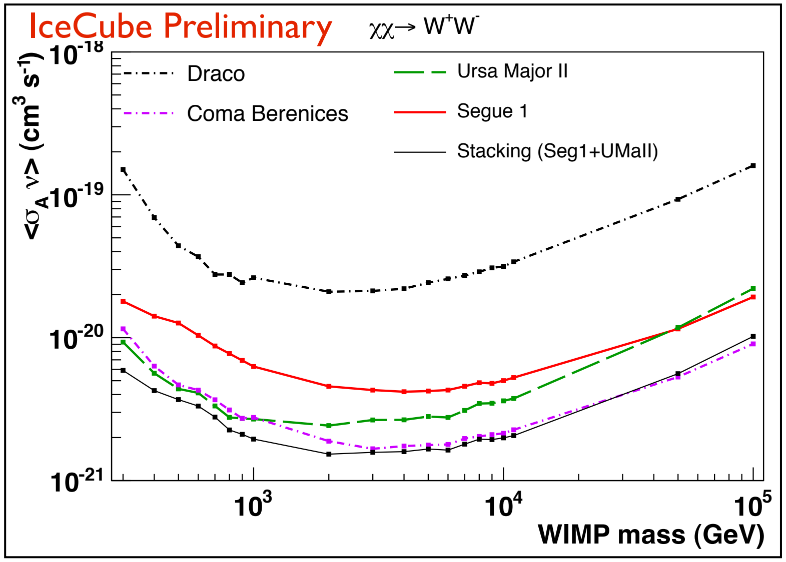
Conclusions

- PINGU can probe solar WIMPs with masses as low as 10 GeV
- Surrounding IceCube (and DeepCore) modules veto cosmic ray muons, giving PINGU access to downward-going starting events
  - solar WIMPs during austral summer
  - galactic center
- If approved, PINGU can be up and running in ~6 years

Backup Slides

IceCube Dwarf Galaxy & Cluster WIMP Results

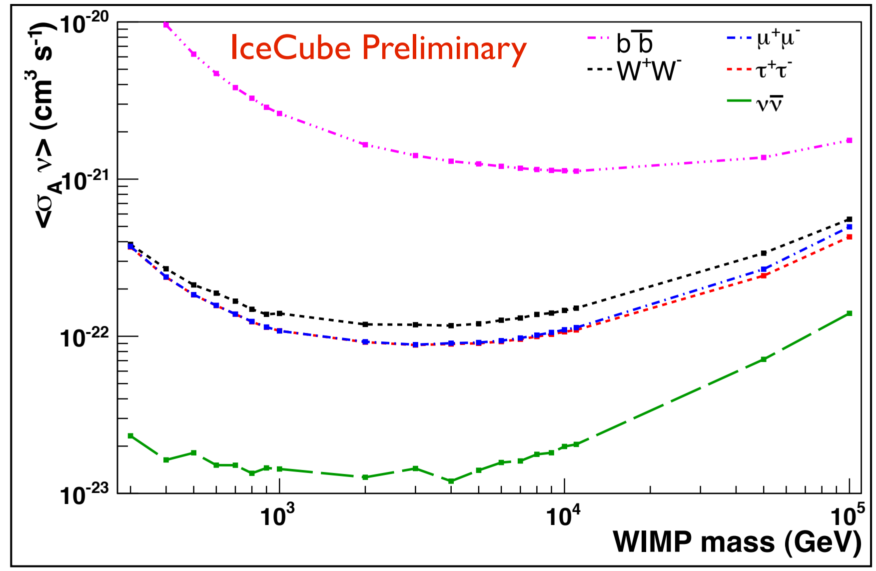
- Dwarfs



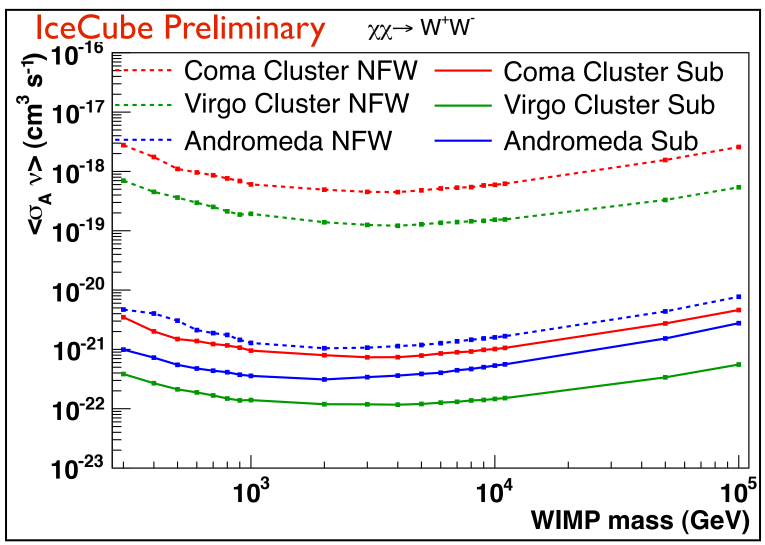
Luenemann & Rott, ICRC 2011

100% WW, NFW profile

- Virgo with subclusters

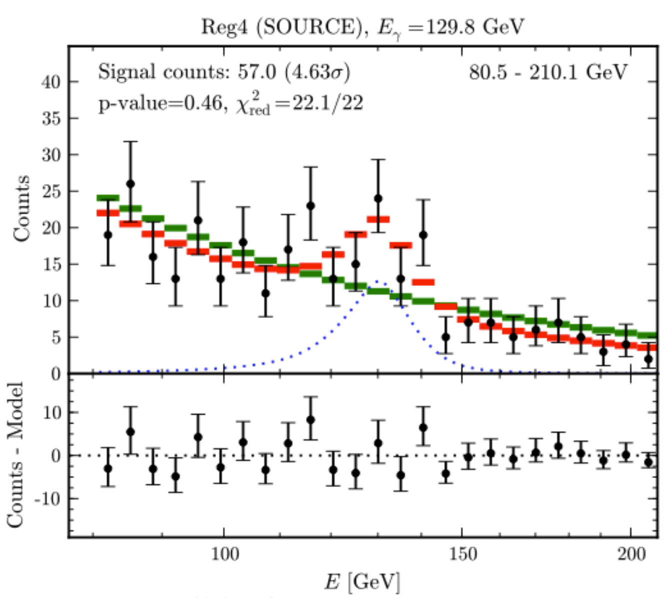


- Galaxy clusters

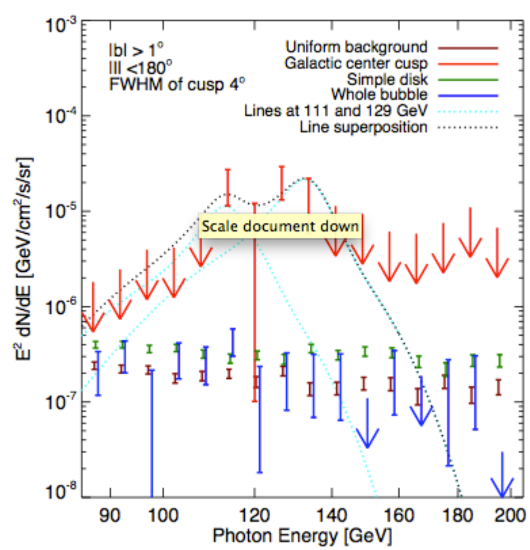


Future Results: IceCube

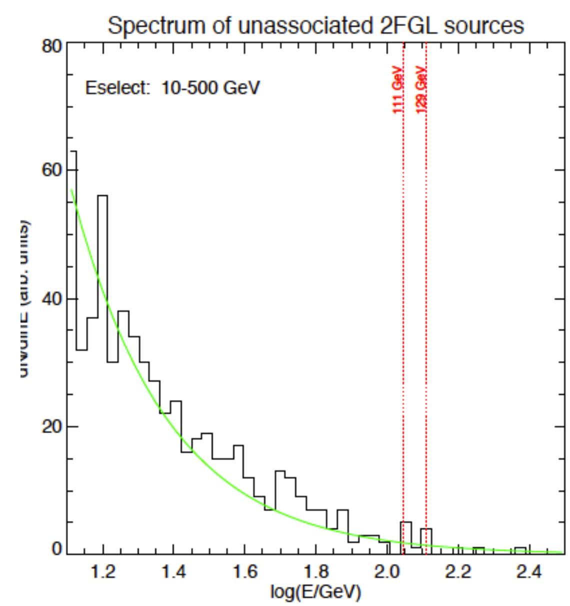
- Perform line search for neutrinos motivated by
  - 130 GeV gamma ray line discussion
  - general principles
    - it's a new way to search



Weniger (2011)



Su, Finkbeiner (2012)

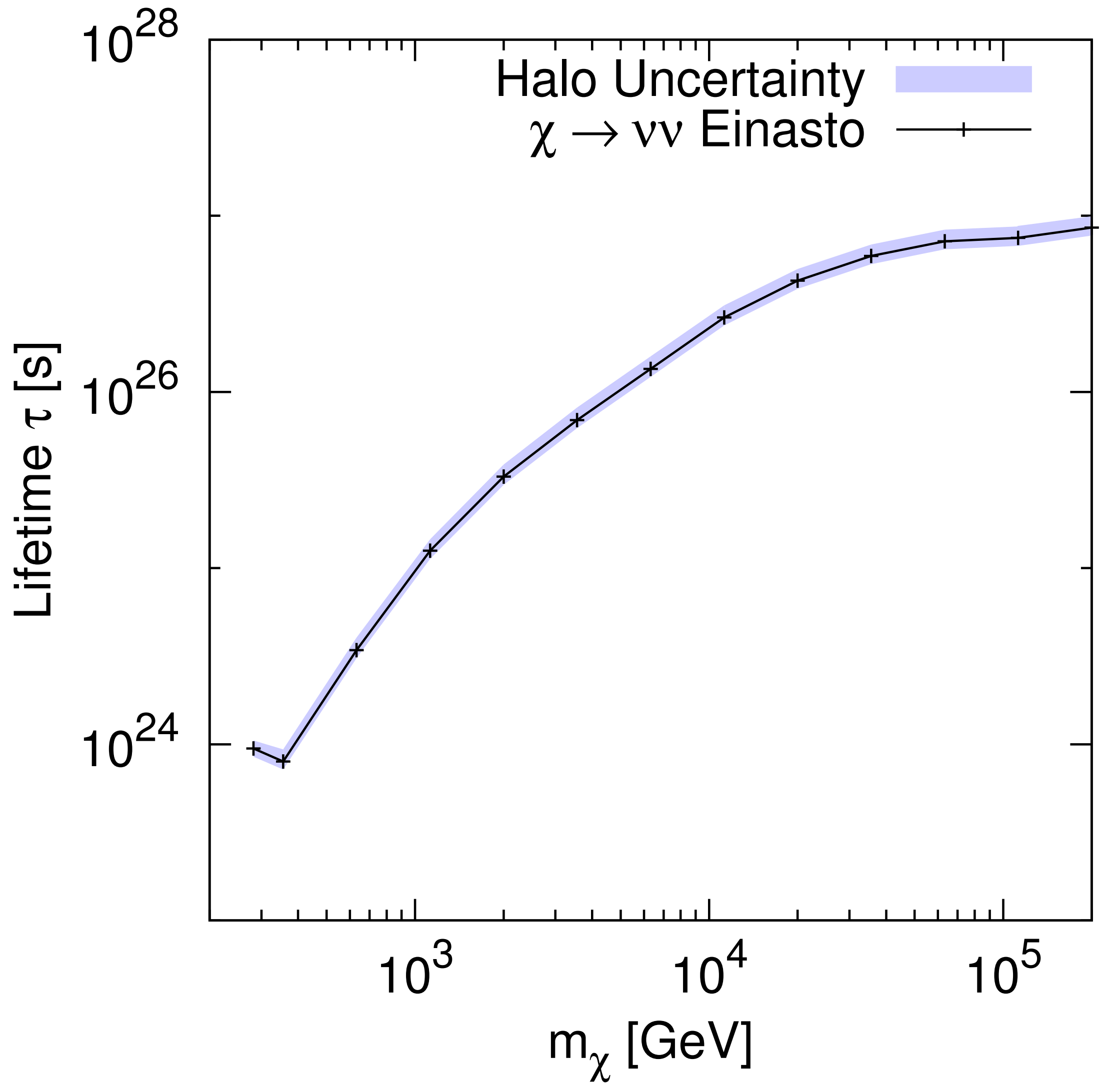


Su, Finkbeiner (2012)

Rott, Astroteilchenphysik in Deutschland 2012

IceCube Results

- WIMP Decay: Assumptions
  - Dark matter is thermal relic and unstable
  - For them still to be here
    - $\tau(\chi) > \tau(\text{universe}) = 4\times10^{17}$ s
  - Line spectrum from $\chi\rightarrow\nu\nu$



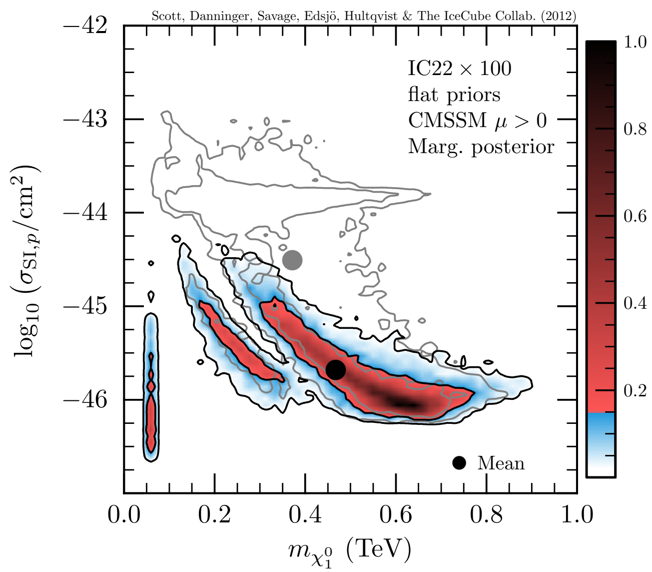
Dwarf Spheroidals, Galaxy Clusters

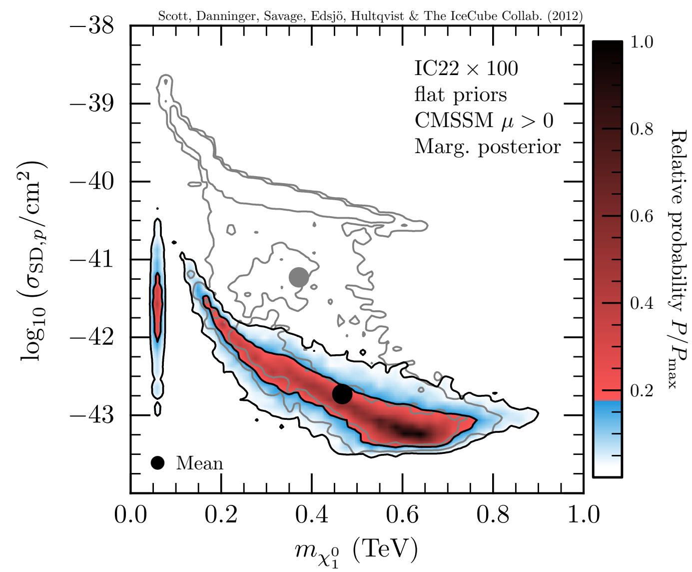
- Assumptions/Issues/Observations
  - Dwarf galaxies:
    - attractive due to high mass-to-light ratio
    - many newly identified by Sloan
    - assume profile for dark matter (e.g. NFW*)
  - Galaxy clusters:
    - factor in presence of substructures
  - Neutrinos can probe higher WIMP masses than photons
    - Effective area for neutrinos increases with neutrino energy

*Navarro, Frenk and White, Astrophys. J. 462, 563,(1996)

Solar WIMPs

- Global SUSY analysis with IceCube
- Contours show 1-2σ credible regions
  - grey regions are without IceCube data
  - colored regions are with IceCube (but indicate relative probability only, not goodness of fit)





Challenges: Event Reconstruction

- The ice could have been designed a little better for us.
  - Photon scattering and absorption lengths are high below 2100 m
    - $<\lambda_{eff}>$ ~ 50 m
    - $<\lambda_{abs}>$ ~ 150 m
  - ...but they vary with depth throughout.
  - Our simulations must include all these variations in as much detail as we can measure.
- Be nice to be able to move in a calibrated light source next to each deployed DOM. Instead, use
  - muons
  - DOM LEDs