dark matter searches with IceCube

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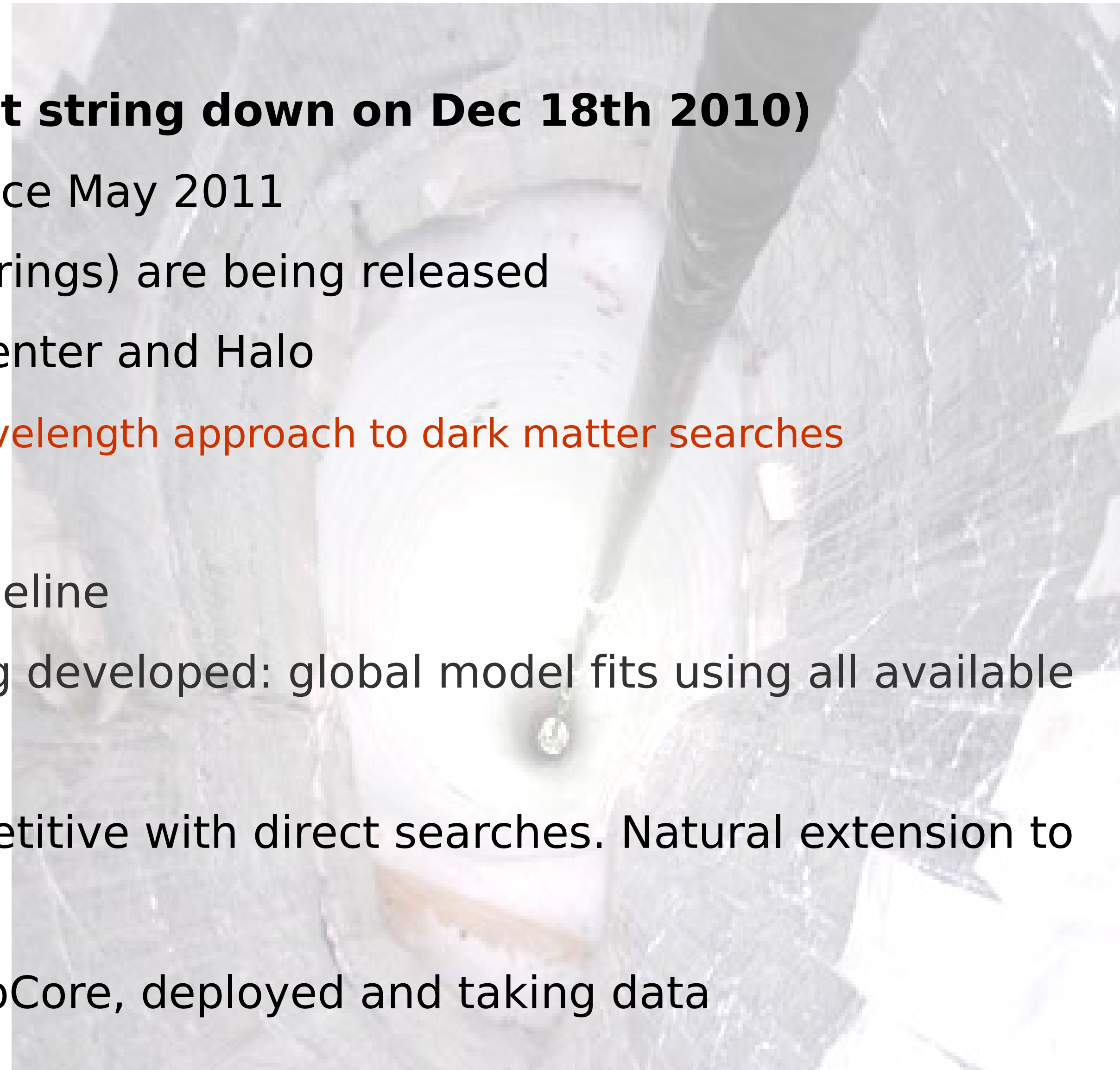
conclusions



- **IceCube is complete !   (last string down on Dec 18th 2010)**

  taking data with 86 strings since May 2011

- Results from 2008/09 (22/40 strings) are being released
- IceCube reaches the Galactic Center and Halo

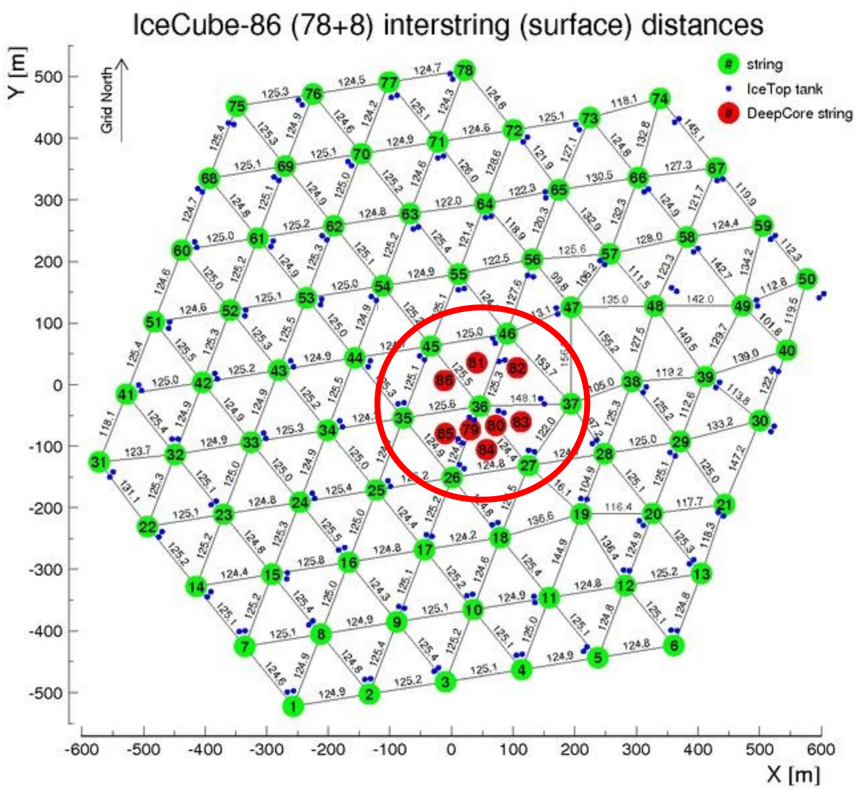
  opens possibility for a multi-wavelength approach to dark matter searches

- Analysis on 79 strings in the pipeline
- New statistical techniques being developed: global model fits using all available data
- IceCube searches for DM competitive with direct searches. Natural extension to collider searches
- The low-energy extension, DeepCore, deployed and taking data

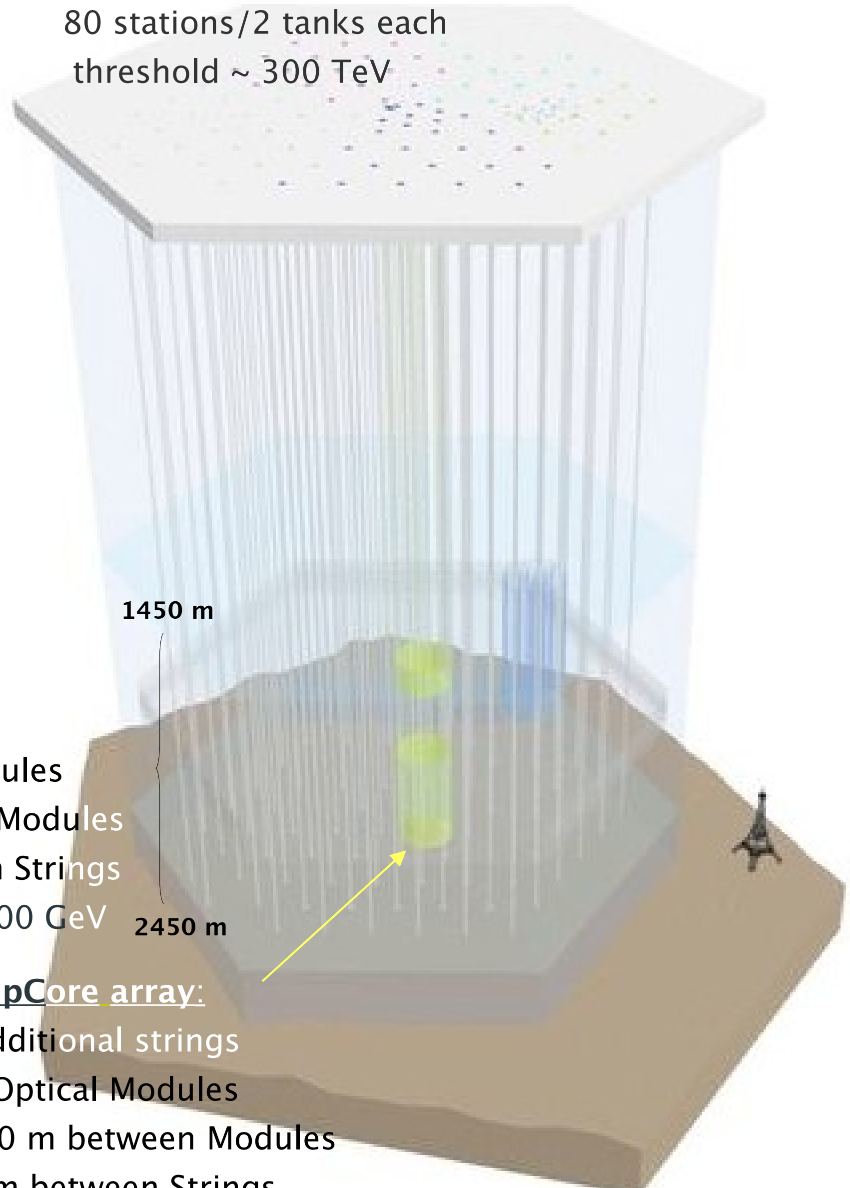
7 last strings installed during Dec 2010

86 strings and 80 IceTop tanks

complete!



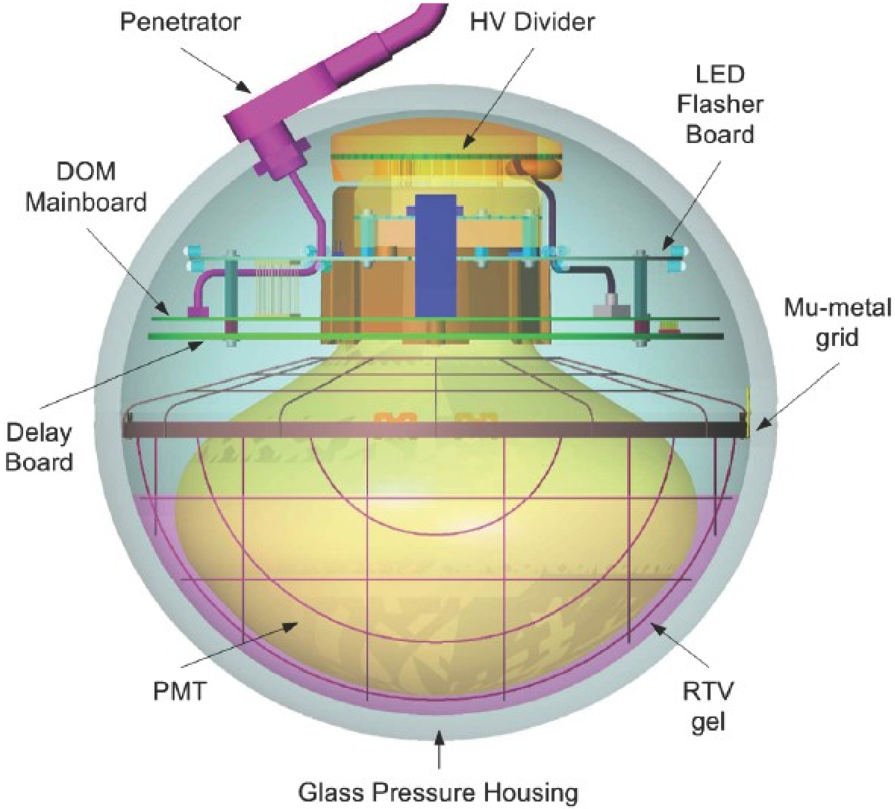
__IceTop__: Air shower detector
80 stations/2 tanks each
threshold ~ 300 TeV



__InIce array__:
80 Strings
60 Optical Modules
17 m between Modules
125 m between Strings
ν threshold ≲100 GeV

__DeepCore array__:
6 additional strings
60 Optical Modules
7/10 m between Modules
72 m between Strings
ν threshold ~10 GeV

Each DOM is an autonomous data collection unit



- Dark Noise rate ~ 400 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2-3 ns
- Power consumption: 3W

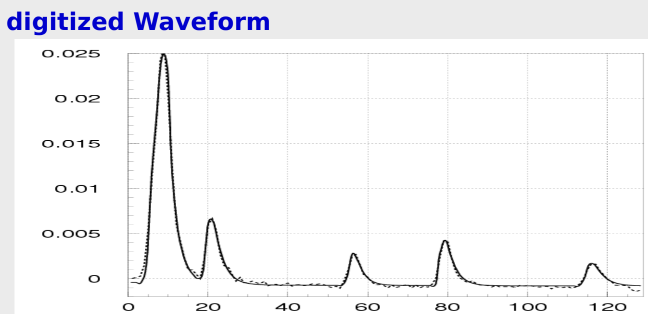
– **PMT**: Hamamatsu, 10''

– **Digitizers**:

<u>ATWD</u>: 3 channels. Sampling 300MHz, capture 400 ns

<u>FADC</u>: sampling 40 MHz, capture 6.4 μs

Dynamic range 500pe/15 nsec, 25000 pe/6.4 μs



– **Flasher board**:
12 controllable LEDs at 0o or 45o

Clock stability: 10−10 ≈ 0.1 nsec / sec
Synchronized to GPS time every ≈5 sec at 2 ns precision

dark matter candidates

<u>WIMPS</u>
- Arise in extensions of the Standard Model
- Assumed to be stable: relics from the Big Bang
- weak-type Xsection gives needed relic density

$$\Omega_\delta h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann} v \rangle_{fr}} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- mass from few GeV to few TeV
- **MSSM** candidate: lightest neutralino,

$$\tilde{\chi}^0_1 = N_1 \mathbf{B} + N_2 \mathbf{W}^3 + N_3 \mathrm{H}^0_1 + N_4 \mathbf{H}^0_2$$

- **UED**: lightest 'rung' in the Kaluza-Klein ladder

<u>SIMPZILLAS</u>
- Non-thermal, non-weakly interacting stable relics

A wealth of candidates from different theoretical models:

- dark baryons (primordial nucleosynthesis constraints)
- MACHOs – BHs, neutron stars, white/brown dwarfs… (microlensing constraints)
- neutrinos (mass constraint)
- primordial Black Holes (cosmological constraints)
- **W**eakly **I**nteracting **M**assive **P**articles (LSPs from "x"MSSM, Kaluza-Klein modes…)
- Non-weakly Interacting Supermassive particles (Simpzillas)
- axions (too light+astrophysical constrains)
- many others

… + (alternative gravity theories)

DM-induced SM particles:

$\kappa\kappa, \chi\chi, SS \rightarrow \left\{ \begin{array}{c} q\bar{q} \\ \ell^+\ell^- \\ W, Z, H \\ \ldots \end{array} \right\} \rightarrow \nu, \gamma, e^+e^-, \bar{p}$

Kaluza-Klein modes an additional useful channel:

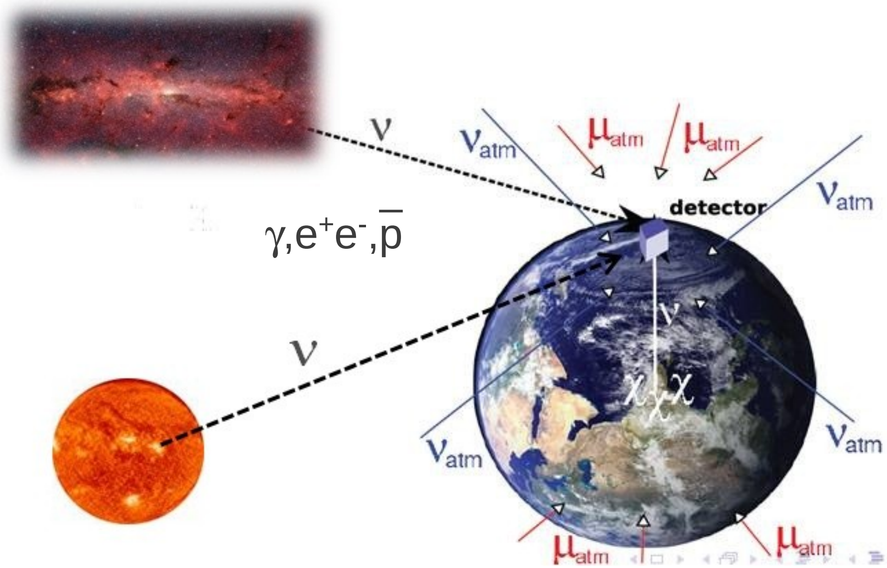
$\kappa\kappa \rightarrow \nu\nu$

signature:
ν excess over background from Sun/Earth/Galactic Halo/nearby galaxies

A lot of physics uncertainties involved:
- relic density calculations
- DM distribution in the halo
- velocity distribution
- χ,K,S properties (MSSM/UED...)
- interaction of χ,K,S with matter (capture)
- self interaction (annihilation)

Look at objects where dark matter can have accumulated gravitationally over the evolution of the Universe

Sun, Earth, Galactic Halo/Center, dwarf spheroids



Atmospheric muons ~$O(10^{10})$ events/year (downwards)

Atmospheric neutrinos ~$O(10^4)$ events/year (all directions)

Triggered data still dominated by atmospheric muons

Reject misreconstructed atmospheric muon background through event and track quality parameters

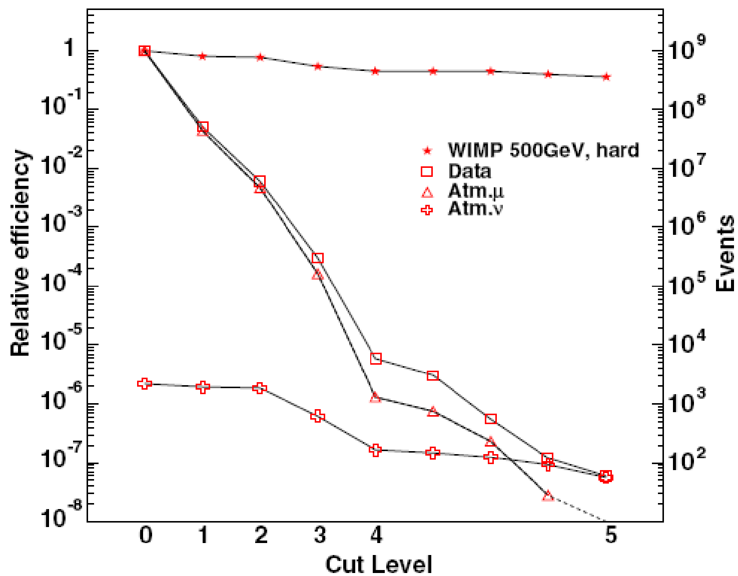
Use of **linear cuts** and/or multivariate methods to extract irreducible atmospheric neutrino background
(Neural Nets, Support Vector Machines, Boosted Decision Trees)

DM searches directional: good additional handle on event selection

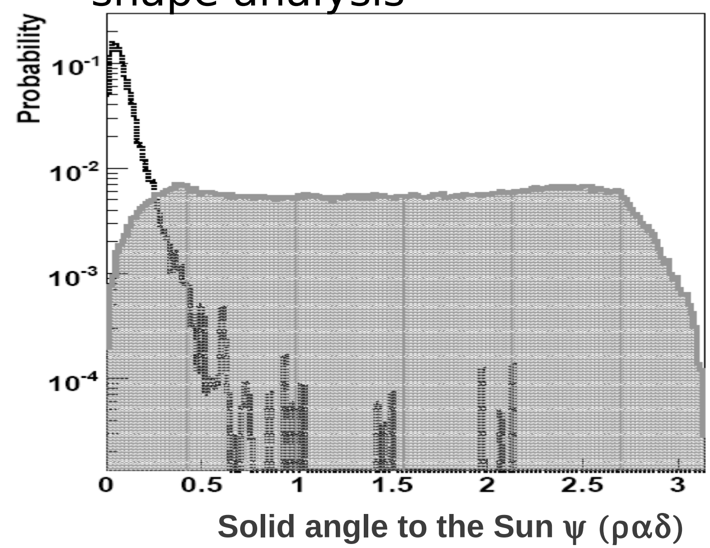
→ **distribution-shape analysis**

(allow for a higher background contamination)

sequential cuts



shape analysis



N_{data}, N_{bck}

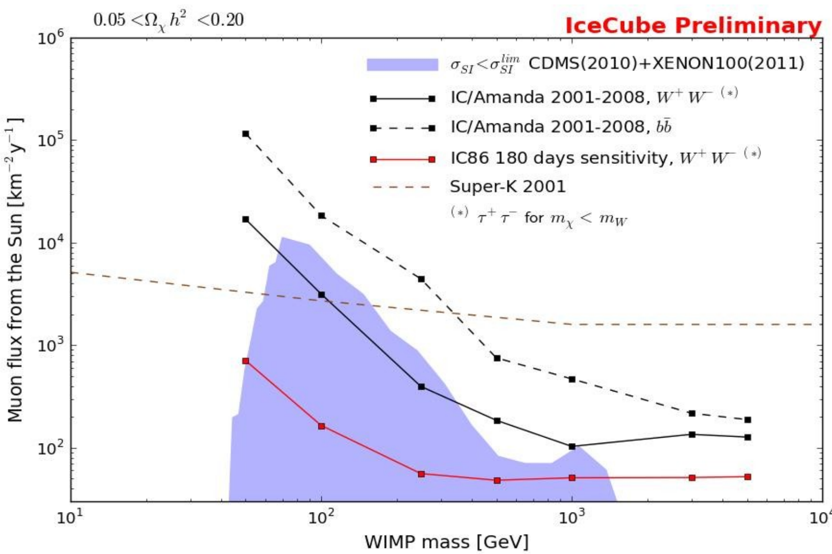
Ψ_{data}, Ψ_{bck} $\rightarrow N_{90}$ $\longrightarrow$ $\Gamma_{\nu\mu} \leqslant \dfrac{N_{90}}{V_{eff} \cdot t}$

Experimentally obtained quantity: allowed number of signal events still compatible with background, at 90% confidence level

Use model to convert to a muon flux

$$\Gamma_{\nu\mu}(m_\chi) = \Gamma_A \cdot \frac{1}{4\pi R_\oplus^2} \int_0^{m_\chi} \sum B_{\chi\bar{\chi}\to X} \left(\frac{dN_\nu}{dE_\nu}\right) \times \sigma_{\nu+N\to\mu+\ldots}(E_\nu | E_\mu \geqslant E_{thr})\, \rho_N\, dE_\nu$$

$$\longrightarrow \quad \phi_\mu(E_\mu \geqslant E_{thr}) = \frac{\Gamma_A}{4\pi D_\odot^2} \int_{E_{thr}}^{\infty} dE_\mu \frac{dN_\mu}{dE_\mu}$$

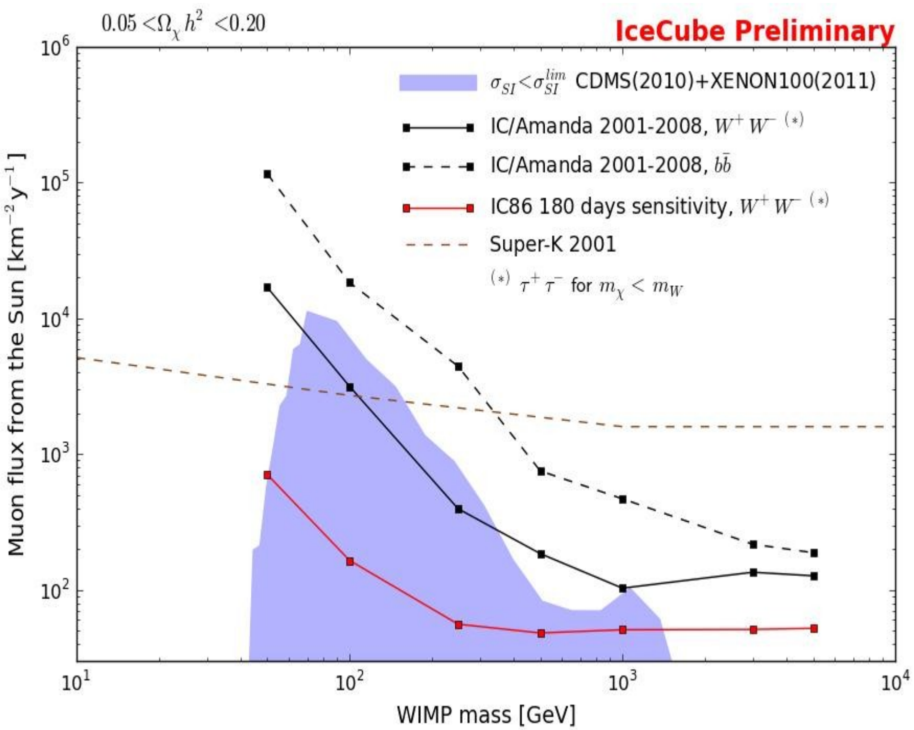


see Pat Scott's talk for a comprehensive statistical approach

IceCube results from 1065 days of livetime between 2001-2008

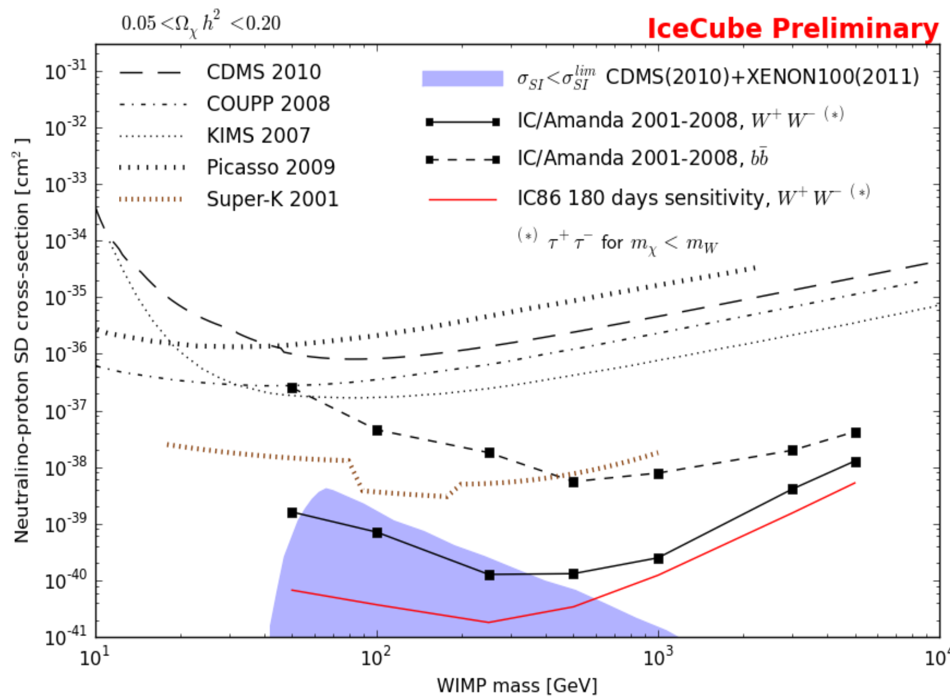
90% CL **muon flux limit** from the Sun

(compared to MSSM scans)



90% CL **neutralino-p Xsection** limit

(compared to MSSM scans)



$$\Phi\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{Xp}$$

(particle physics and solar model)

Assume (ie. model dependent) effective quark-DM interaction,

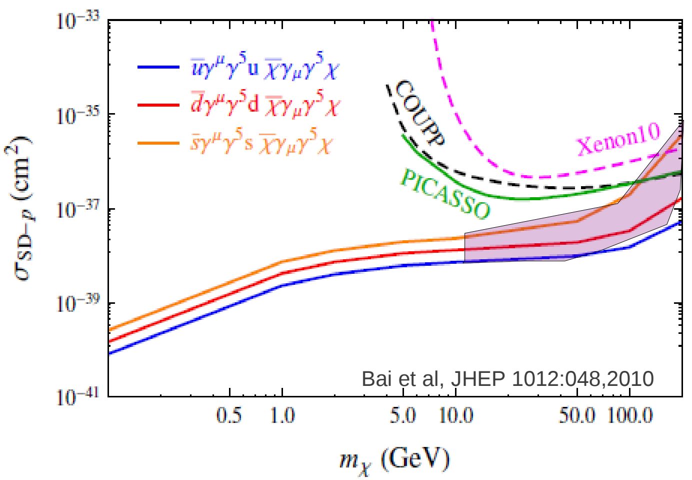
$$\lambda^2/\Lambda^2\,(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi)$$

and look for monojets in $p\bar{p}$ collisions,

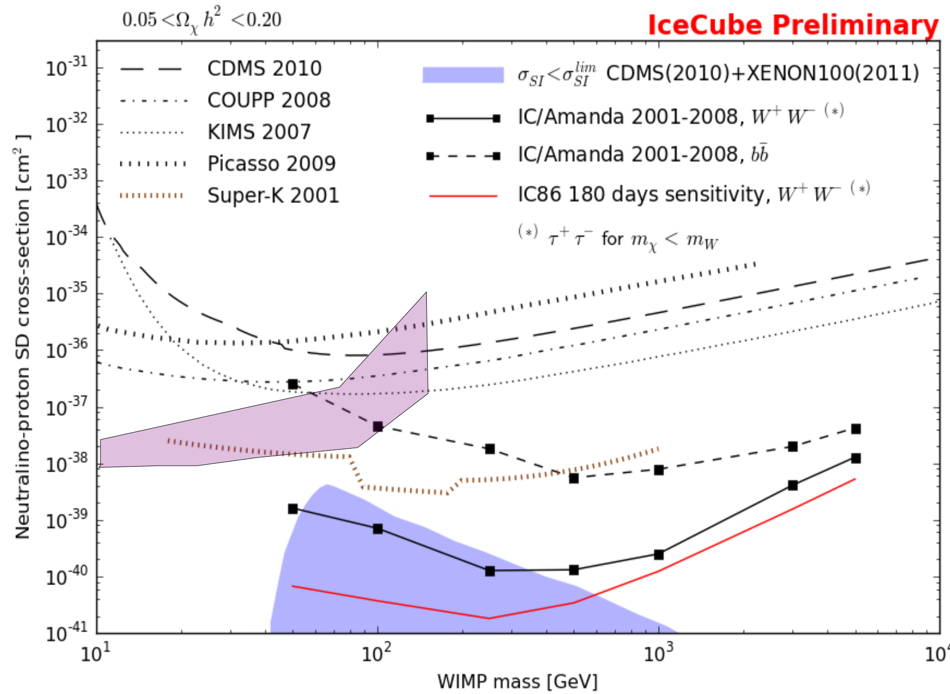
$$p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet}$$

(as opposed to the SM process $p\bar{p} \rightarrow$ Z+jet and $p\bar{p} \rightarrow$ W+jet)

Constrains from monojet searches at the TeVatron:

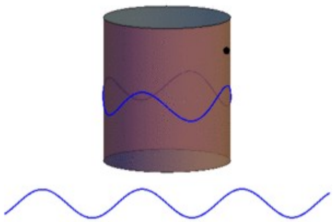


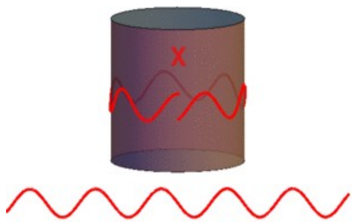
90% CL **neutralino-p Xsection** limit



searches from the Sun: Kaluza-Klein DM

- **Universal Extra Dimensions**:





$$n\frac{\lambda}{2} = 2\pi R, \qquad n\frac{h}{2p} = 2\pi R \Rightarrow p = n\frac{h}{4\pi R}$$

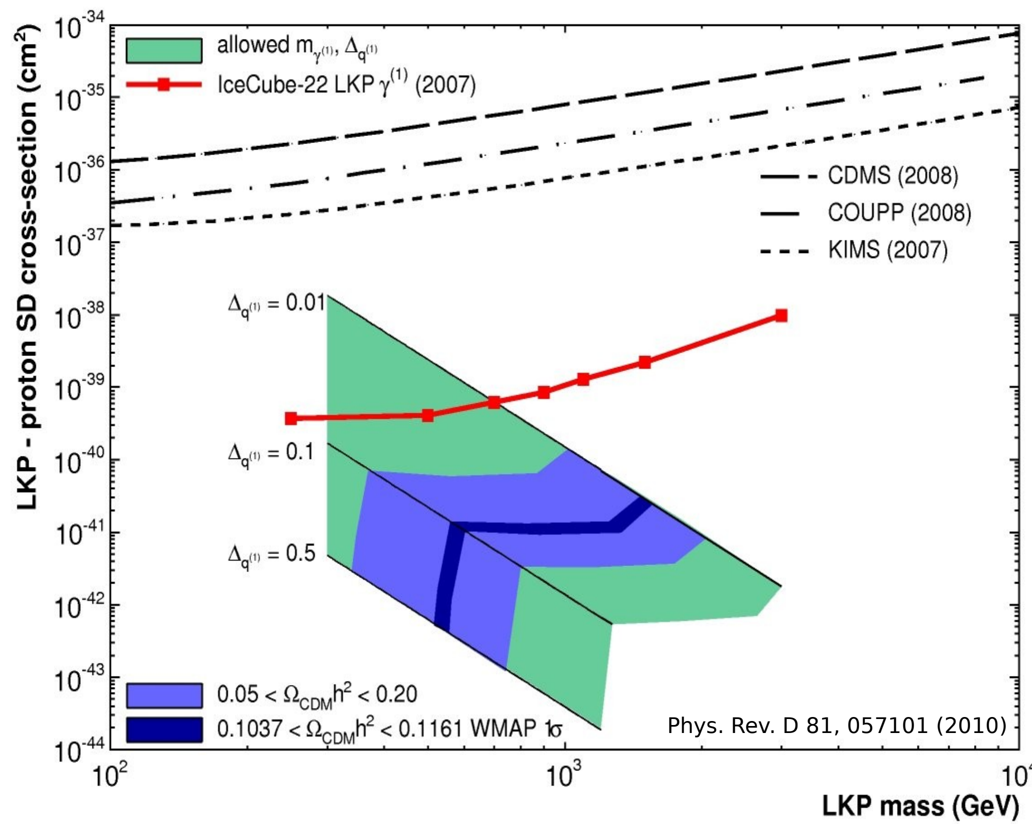
$$E^2 = p^2c^2 + m_o{}^2c^4 = n^2\frac{1}{R^2}c^2 + m_o{}^2c^4 = m_n{}^2c^4$$

$$m_n^2 = \frac{n^2}{c^2R^2} + m_o^2$$

n=1 → Lightest Kaluza-Klein mode, **B**^{1}

good DM candidate

90% CL LKP-p Xsection limit vs LKP mass



SIMPZILLAS (Superheavy DM)

- Produced **non-thermally** at the end of inflation through vacuum quantum fluctuations or decay of the inflaton field

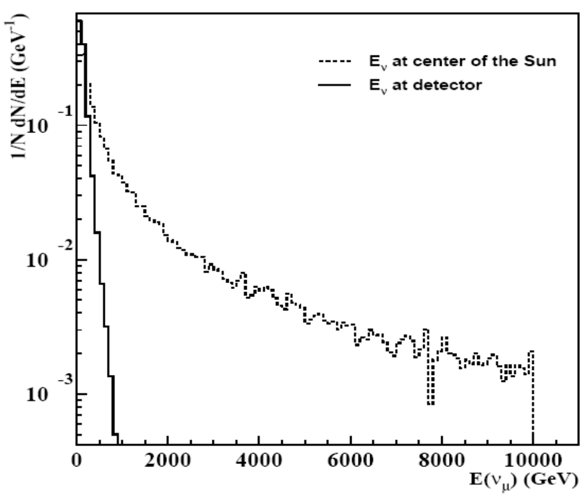
- strong Xsection (simply means non-weak in this context)

- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

S+S → t $\bar{t}$

$2.8\times10^5\sqrt{m_{X/12}}$ tops per annihilation

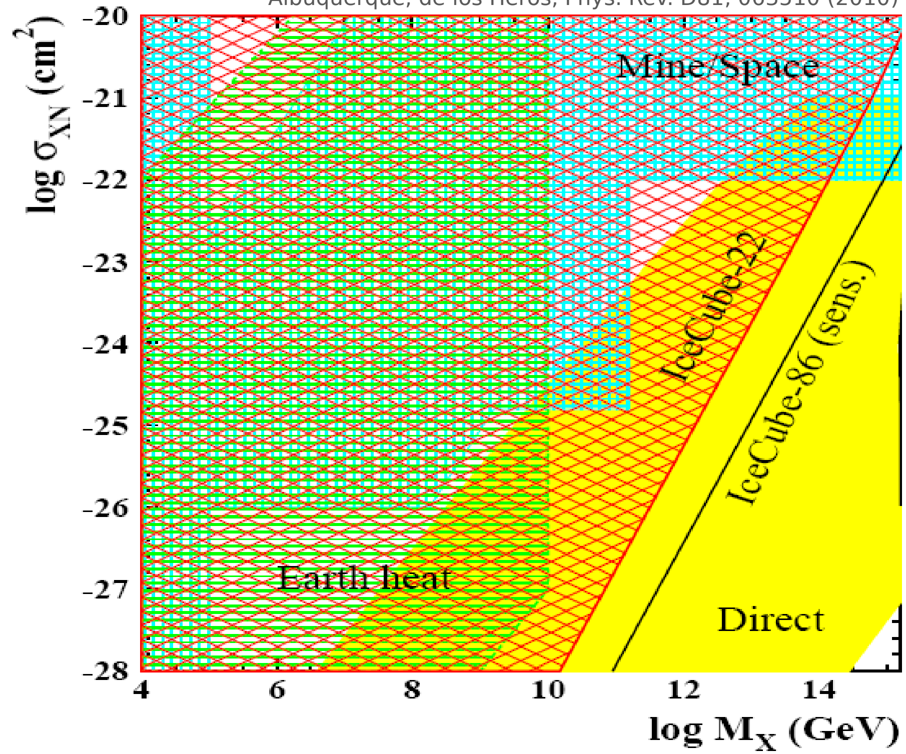
$$\frac{dN}{dE_\nu} \propto \frac{E_\nu + \mathrm{m_W}}{\sqrt{(E_\nu + \mathrm{m}_t)[(E_\nu + \mathrm{m}_t)^2 - \mathrm{m}_t^2][(E_\nu + \mathrm{m_W})^2 - \mathrm{m_W^2}]}}$$



$$N_s(m_X, \sigma_{XN}) = N_t \cdot BR_W \cdot \Gamma_A(m_X, \sigma_{XN}) \cdot T \cdot \int \frac{dN_\nu}{dE} A_{eff}\, dE$$

90% CL simpzilla-p Xsection limit *vs* simpzilla mass

Albuquerque, de los Heros, Phys. Rev. D81, 063510 (2010)

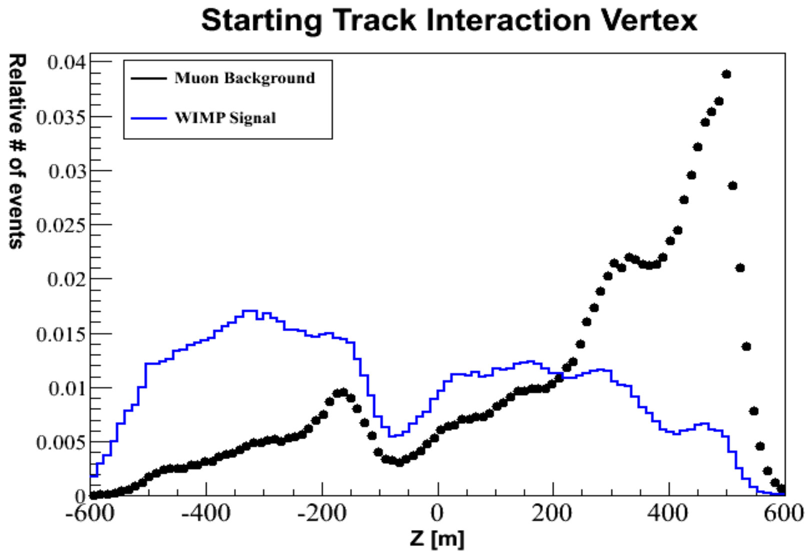


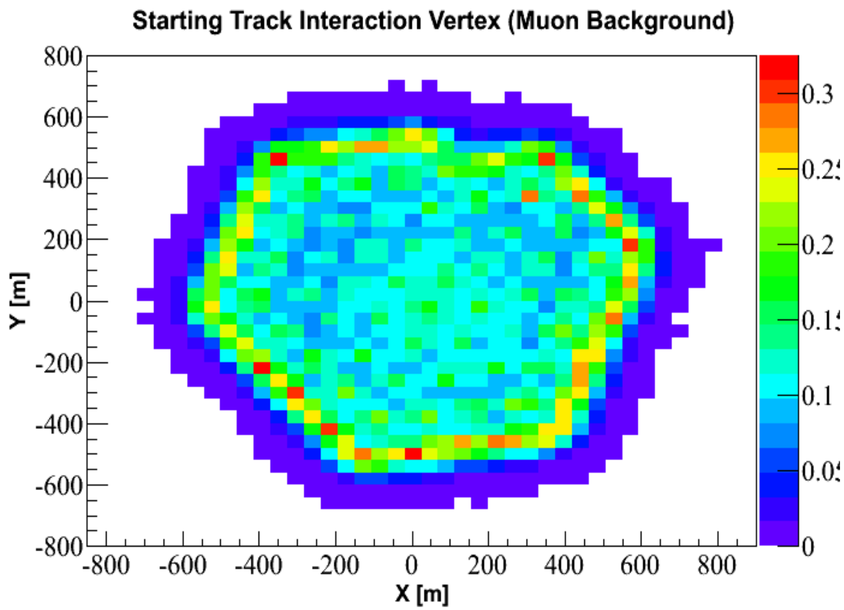
Extend the search to the southern hemisphere by selecting starting events

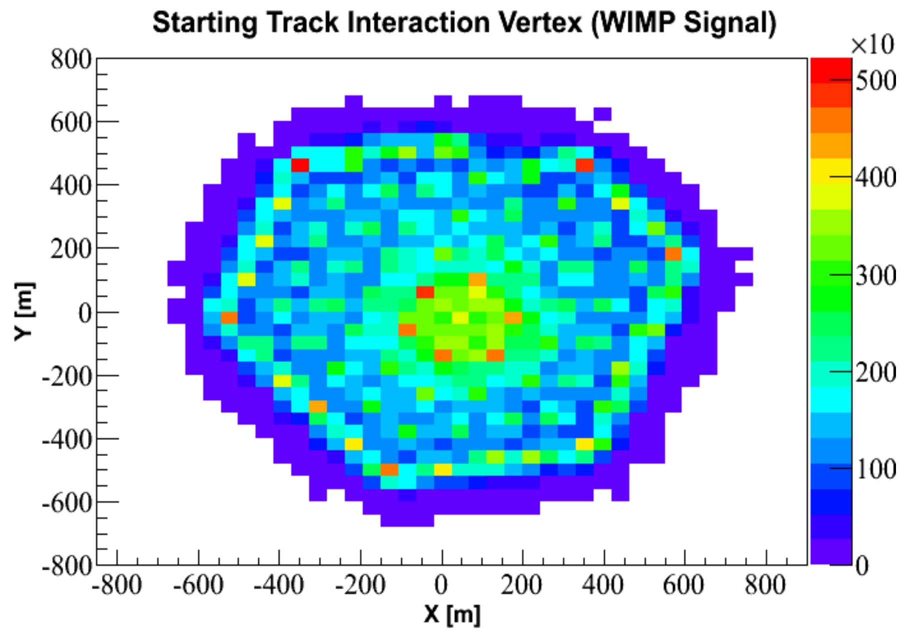
→ Veto background through location of interaction vertex

- muon background: downgoing, no starting track
- WIMP signal: interaction vertex within detector volume

work in progress







Secluded dark matter

$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{WIMP} + \mathcal{L}_{mediator}$

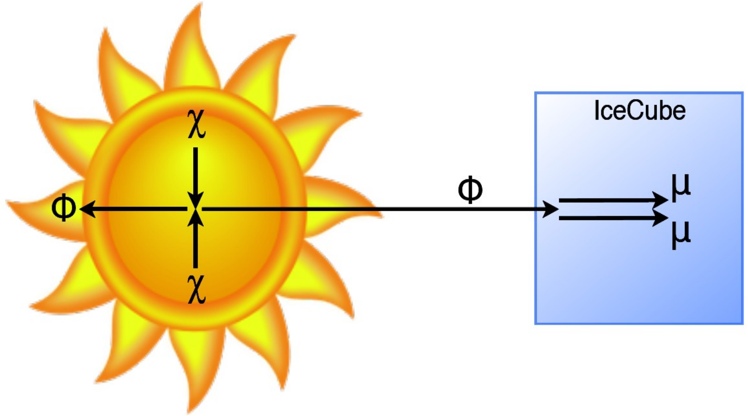
DM annihilates into mediator, $\chi\chi \rightarrow \phi\phi \rightarrow SM$
with $m_\phi = \mathcal{O}(GeV)$

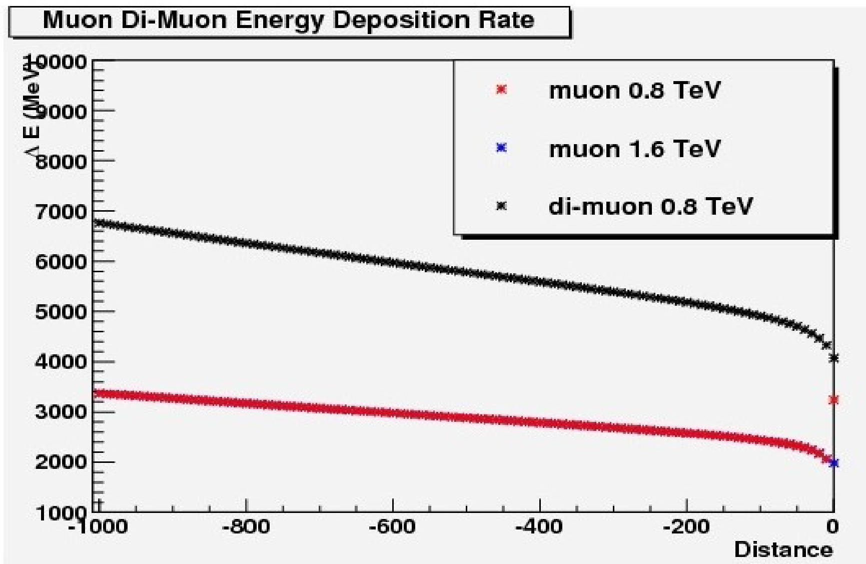
ϕ is long lived, escapes the Sun and decays into $\mu^+\mu^-$ in or near the detector

→ signature: two closely separated muon tracks (~ 1m)

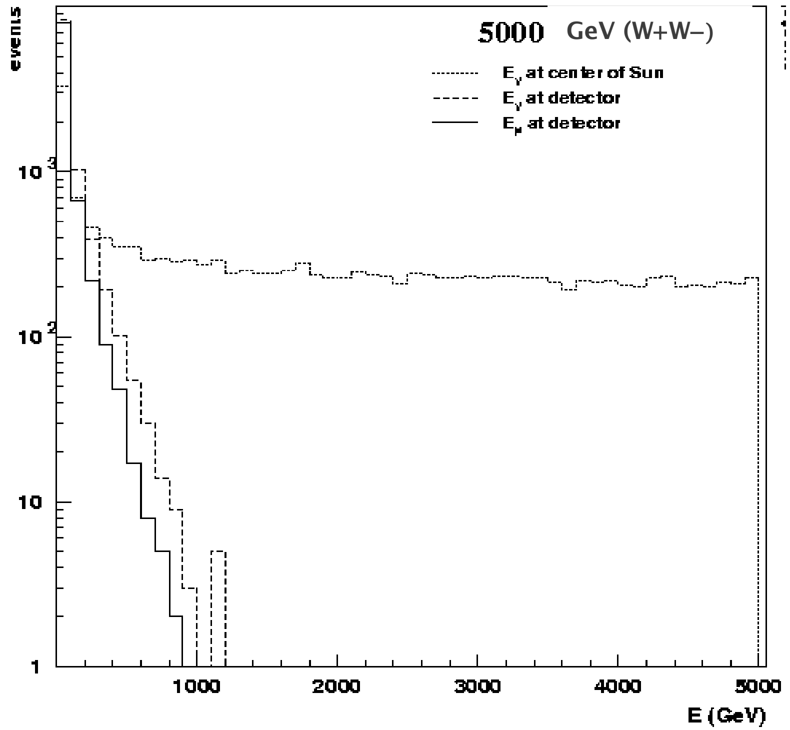
look for stopping pairs of tracks in order to further reduce the background.

work in progress

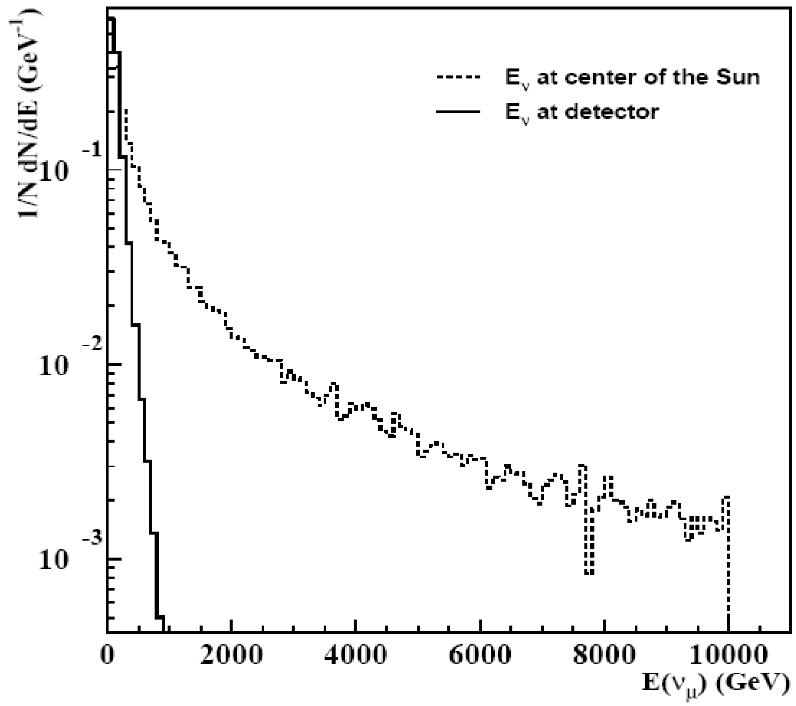




5000 GeV Neutralino → WW @ Sun



Simpzilla → $t\bar{t}$ @ Sun



: Indirect dark matter searches from the **Sun** are a low-energy analysis in neutrino telescopes: even for the highest DM masses, we do not get muons above few 100 GeV

Not such effect for the Earth and Halo (no ν energy losses in dense medium)

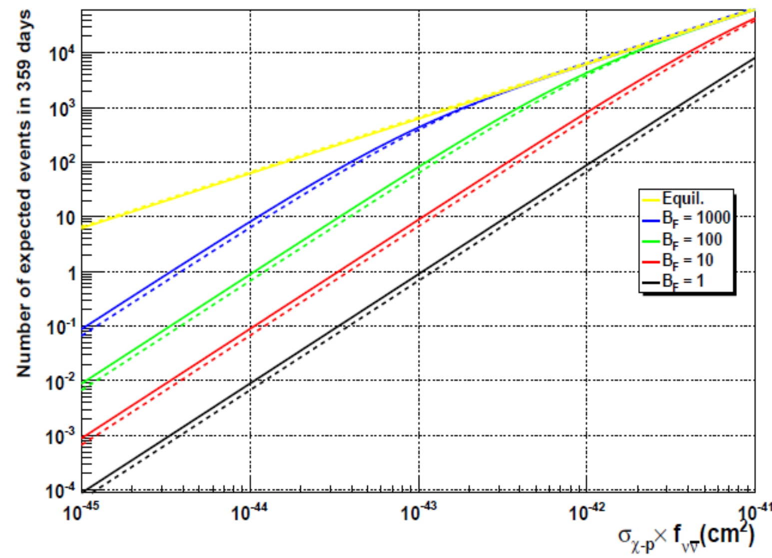
Explaining Fermi/PAMELA data in terms of dark matter favors boost in DM annihilation Xsection

If the dark matter annihilation rate is enhanced, the timescale for equilibrium diminishes → flux of annihilation products can be much larger than away from equilibrium.

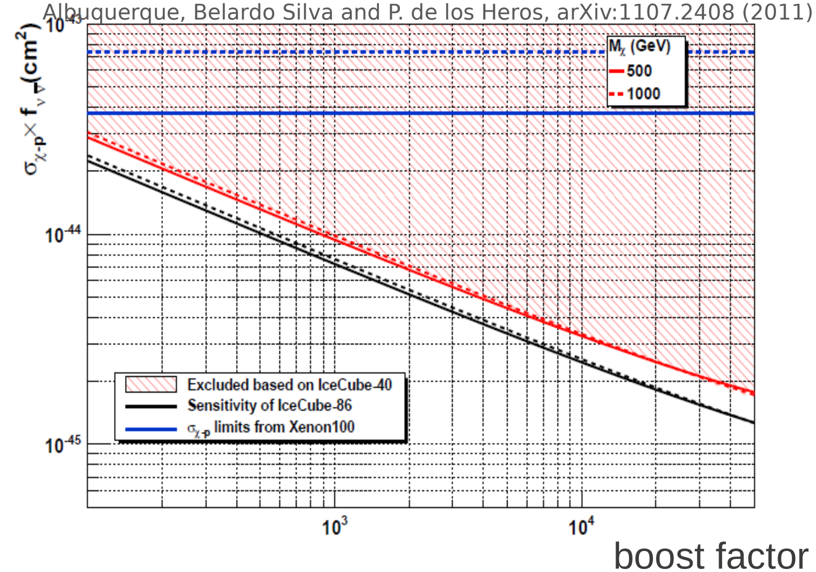
→ an enhanced annihilation Xsection can produce a detectable neutrino flux from the center of the Earth (while not enhancing the Solar flux)

(C. Delaunay, P. J. Fox and G. Perez, JHEP 0905 , 099 (2009)).

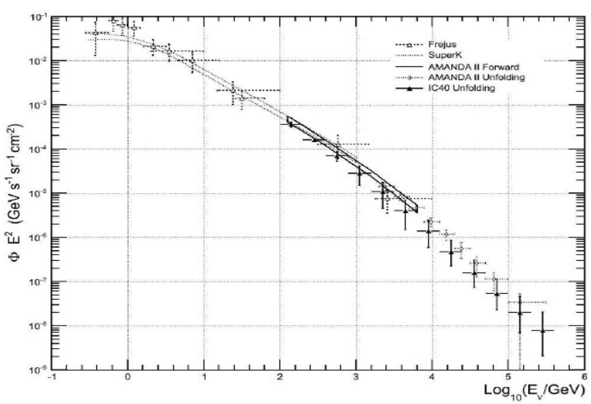
Using the atmospheric neutrino measurement of IceCube-40, model-independent limits on boost factors can be set

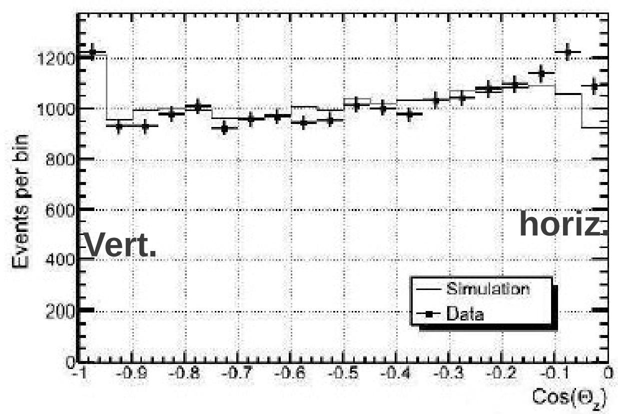


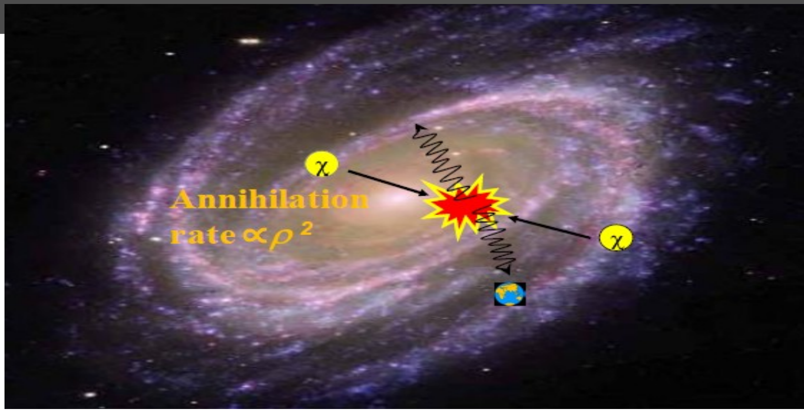
Albuquerque, Belardo Silva and P. de los Heros, arXiv:1107.2408 (2011)

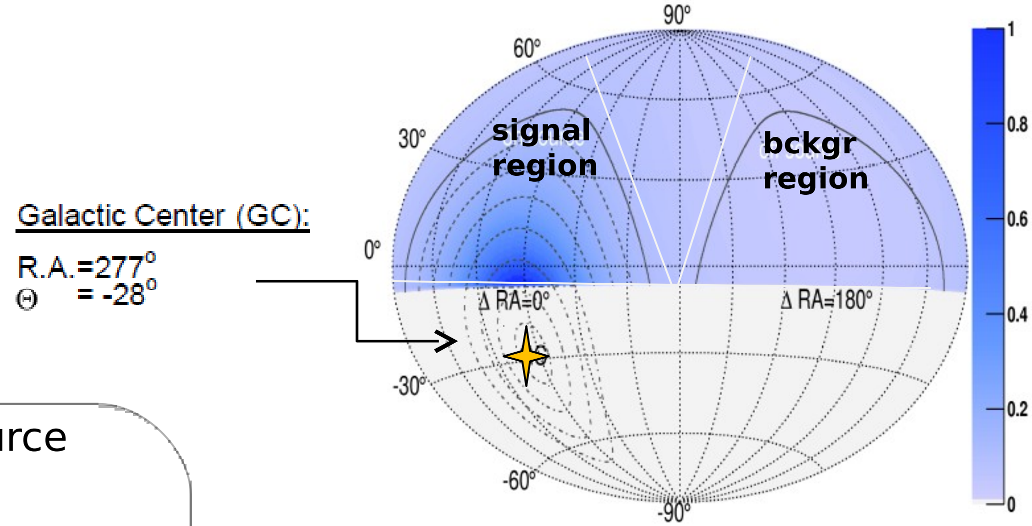


Phys.Rev. D83 (2011) 012001









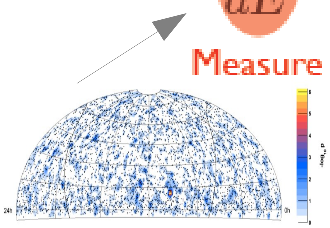
Look for an excess of events in the on-source region w.r.t. the off-source:

IC22: observed on-source: 1367 evts

observed off-source: 1389 evts

Need expected neutrino flux from SUSY and halo model. Limit on the self annihilation cross section:

$$\frac{d\Phi}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

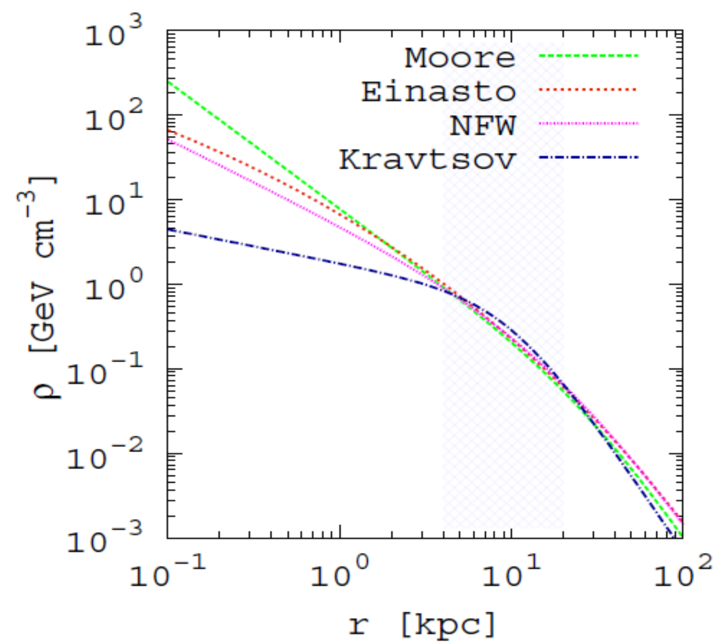


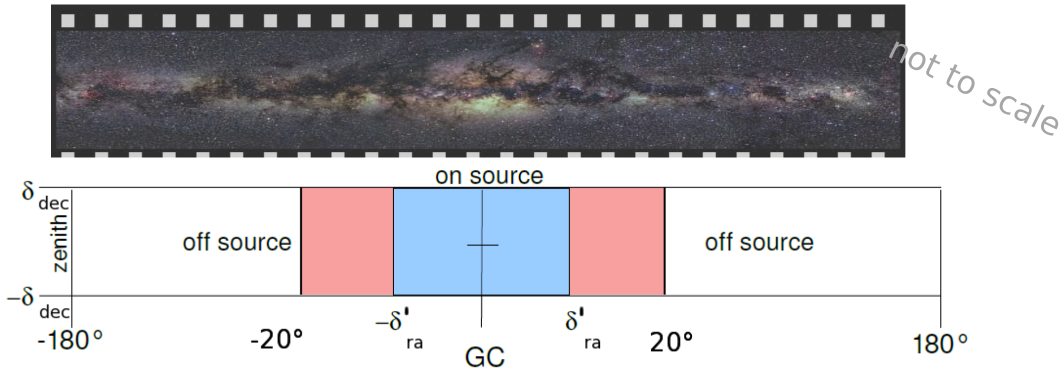
Measure

Constrain

Halo

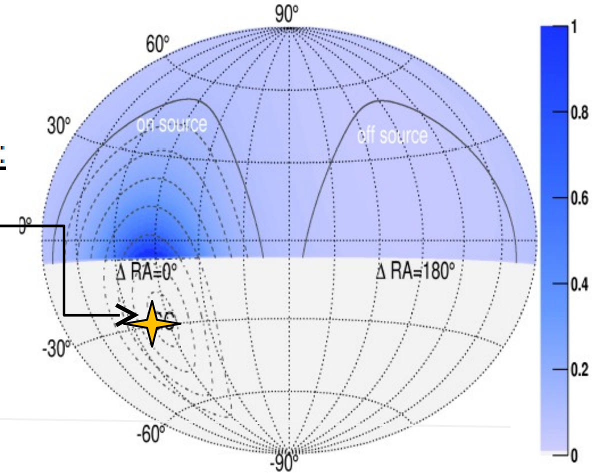
SUSY





Galactic Center (GC):

R.A.=277°
Θ = -28°

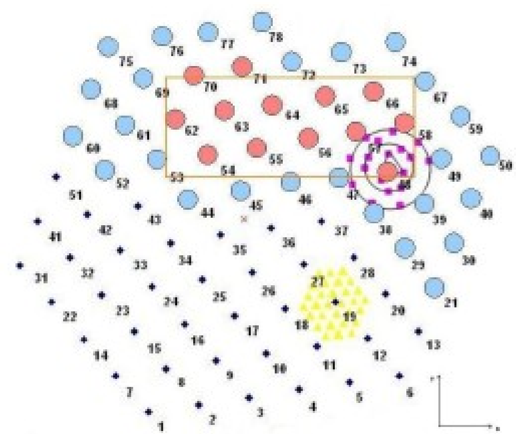


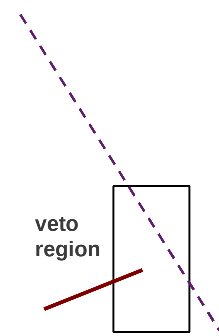
Look for an excess of events in the on-source region w.r.t. the off-source

on-source region below the horizon: need to veto downgoing μs.

Use central strings of detector as fiducial volume, surrounding layers as veto.
Only from IC40 this is possible.

IC40: observed on-source: 798842 evts
observed off-source: 798819 evts





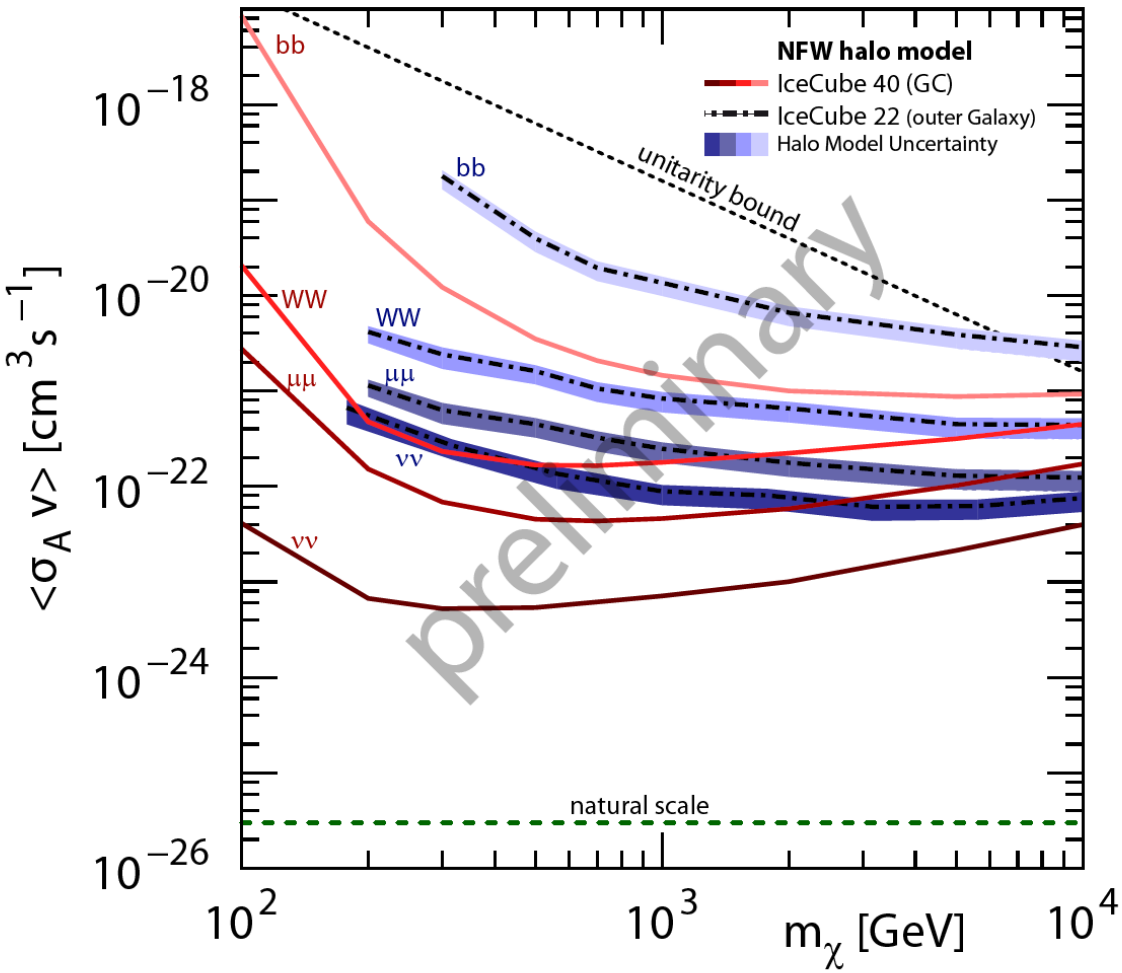
Same strategy as in the galactic halo analysis:

$$\frac{d\Phi}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

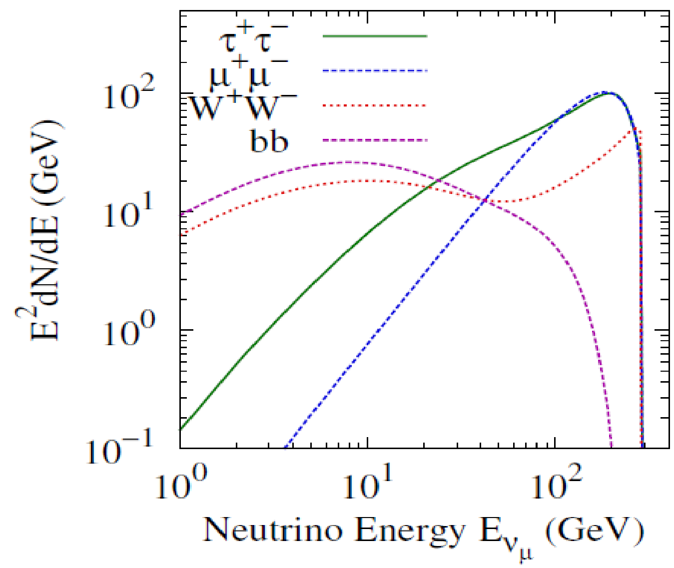
Measure
Constrain
Halo
SUSY

IceCube22/40 results from DM searches from the Galaxy

Limits (90% C.L.) on the self annihilation cross section (χχ -> bb, WW, μμ, νν)



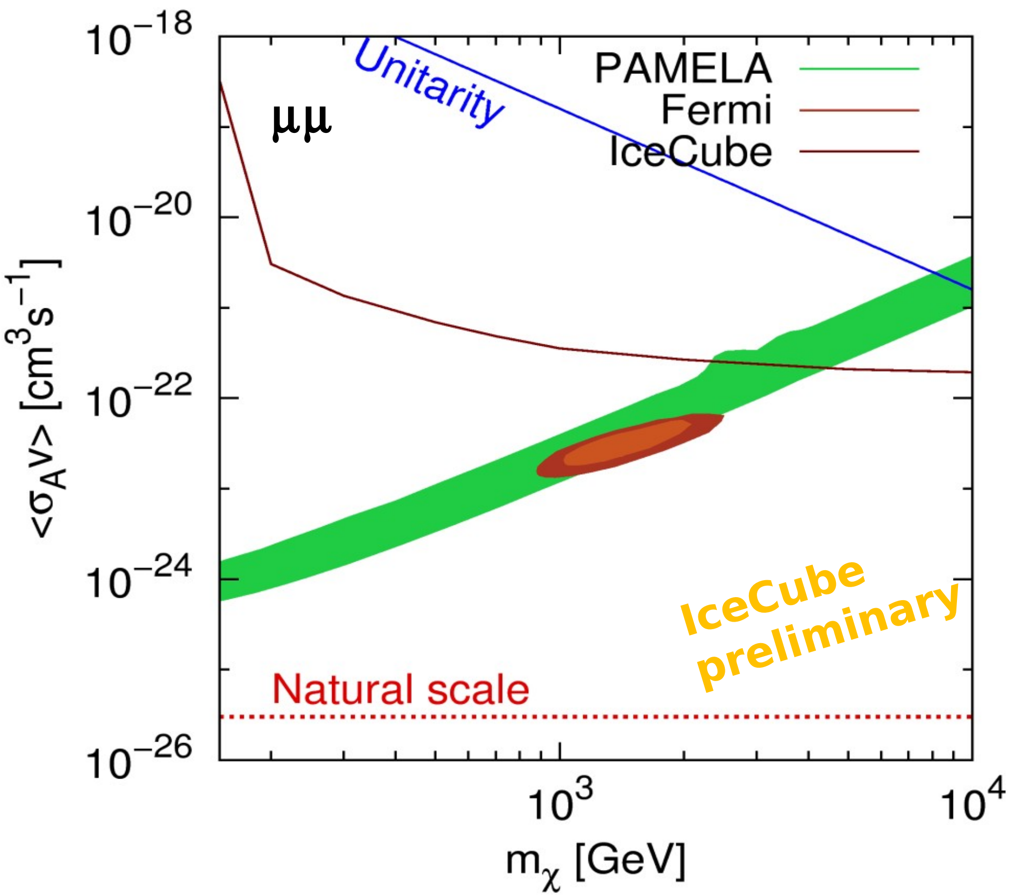
- line thickness in IC22 results reflects uncertainty due to halo profile
- no energy loss of secondaries before decay: harder spectra than in Sun for same annihilation channel

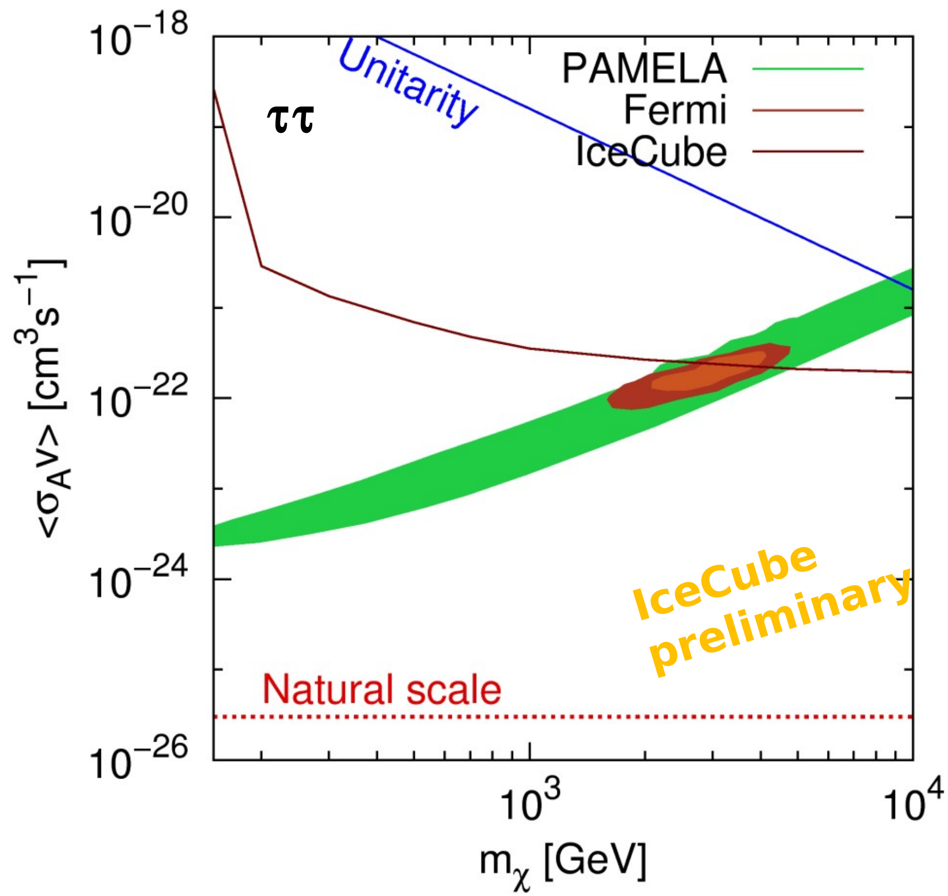


IC22: Phys. Rev. 84, 022004 (2011)
IC40: in preparation

- multi-wavelength approach to dark matter searches:

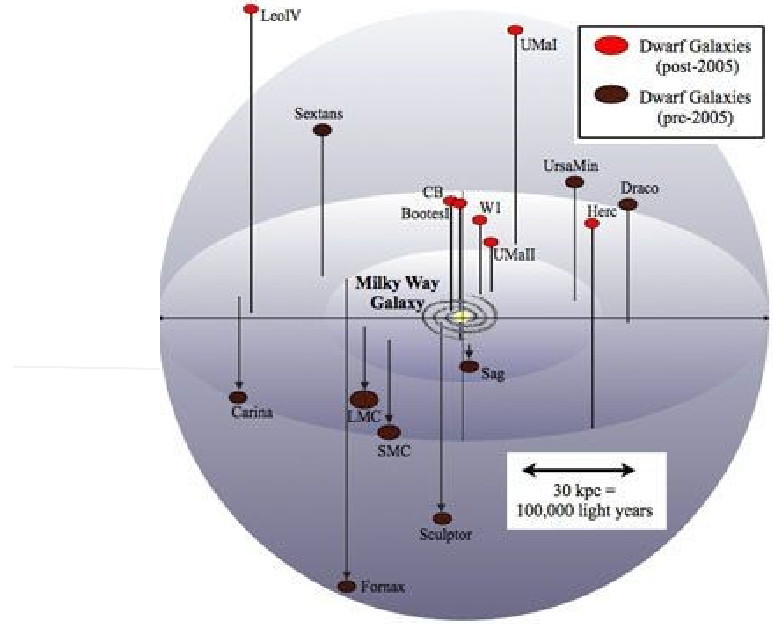
IceCube results in the context of Pamela and Fermi anomaly





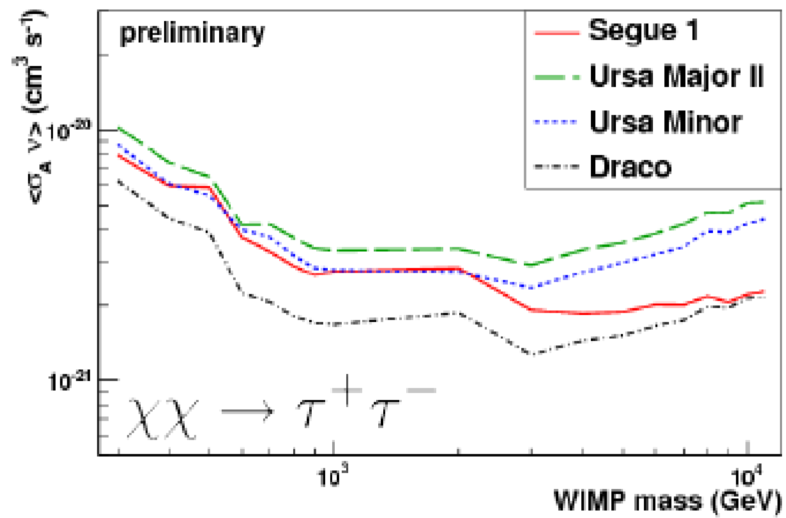
searches from nearby dwarf galaxies: strategy

- dwarf galaxies: high mass/light ratio
- → high concentration of DM in the halos
- known location. Distributed both in the north and southern sky.
  - Point-like search techniques: stacking
  - known distance -> determination of absolute annihilation rate if a signal is detected
- same expected neutrino spectra as for the galactic center/halo
- IceCube analysis in progress



Same strategy as in the galactic halo analysis:

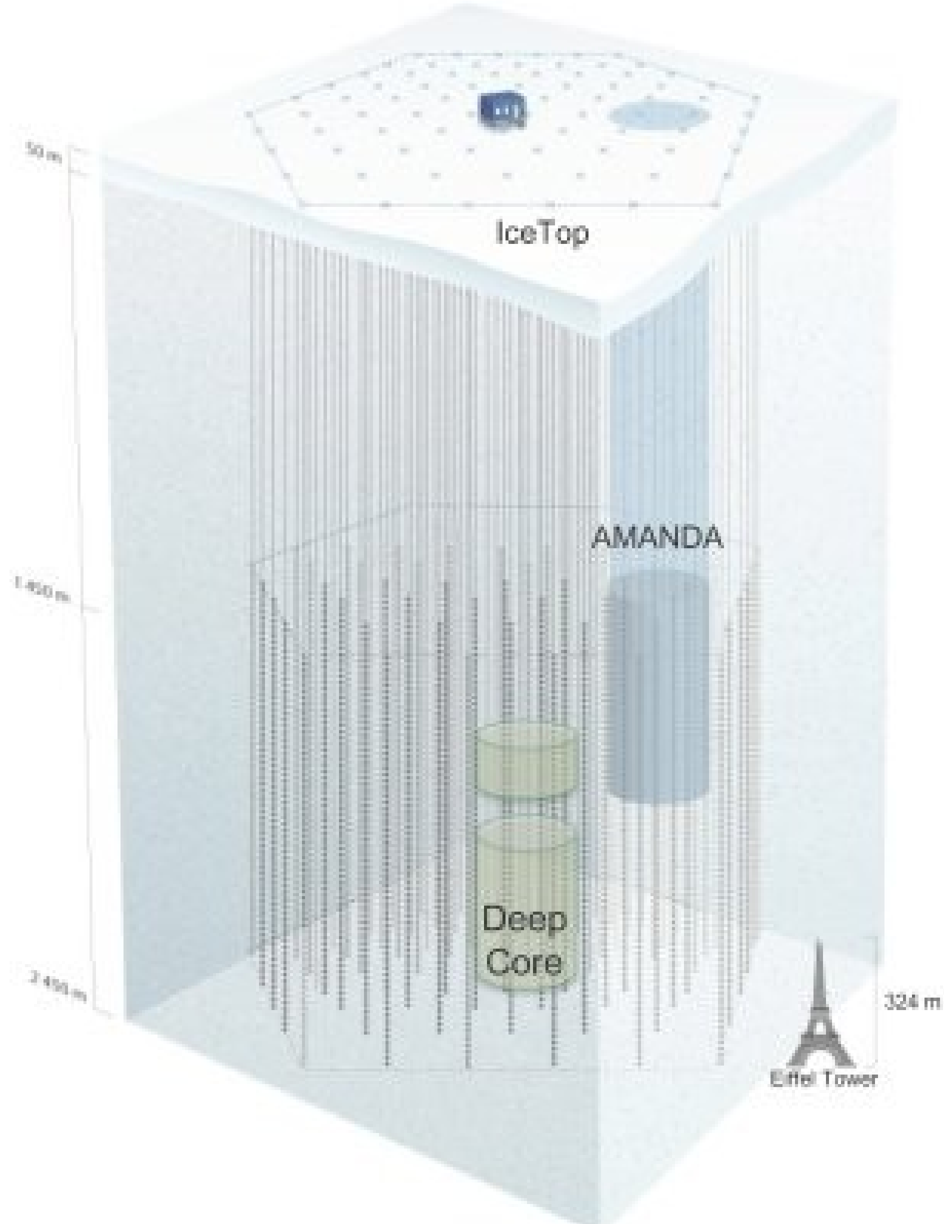
$$\frac{d\Phi_j(\Delta\Omega, E_j)}{dE_j} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_j}{dE_j}J(\Delta\Omega)$$



· Aim: lower energy threshold through a denser core in the center of the IceCube array

· 6 additional strings of 60 high quantum efficiency PMTs

· denser instrumentation:
7 m DOM vertical spacing (17m in IceCube),
72 m inter string spacing (125m in IceCube)



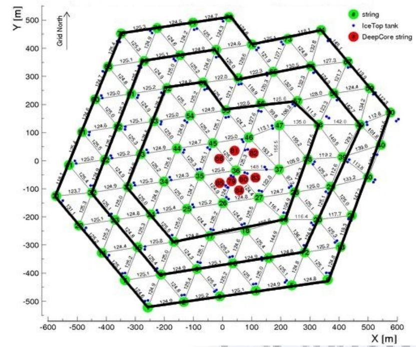
DeepCore veto capabilities

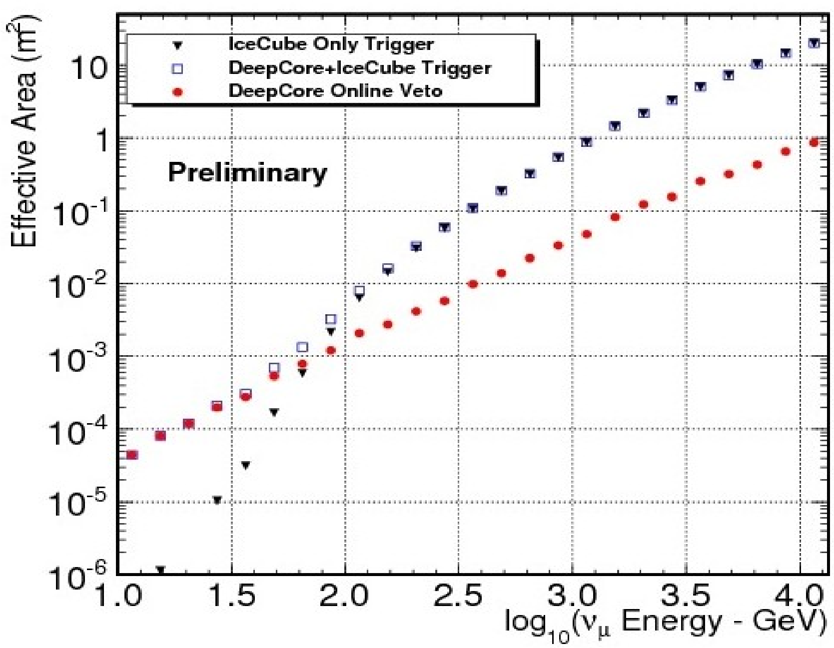
full sky sensitivity using IceCube surrounding strings as a veto:

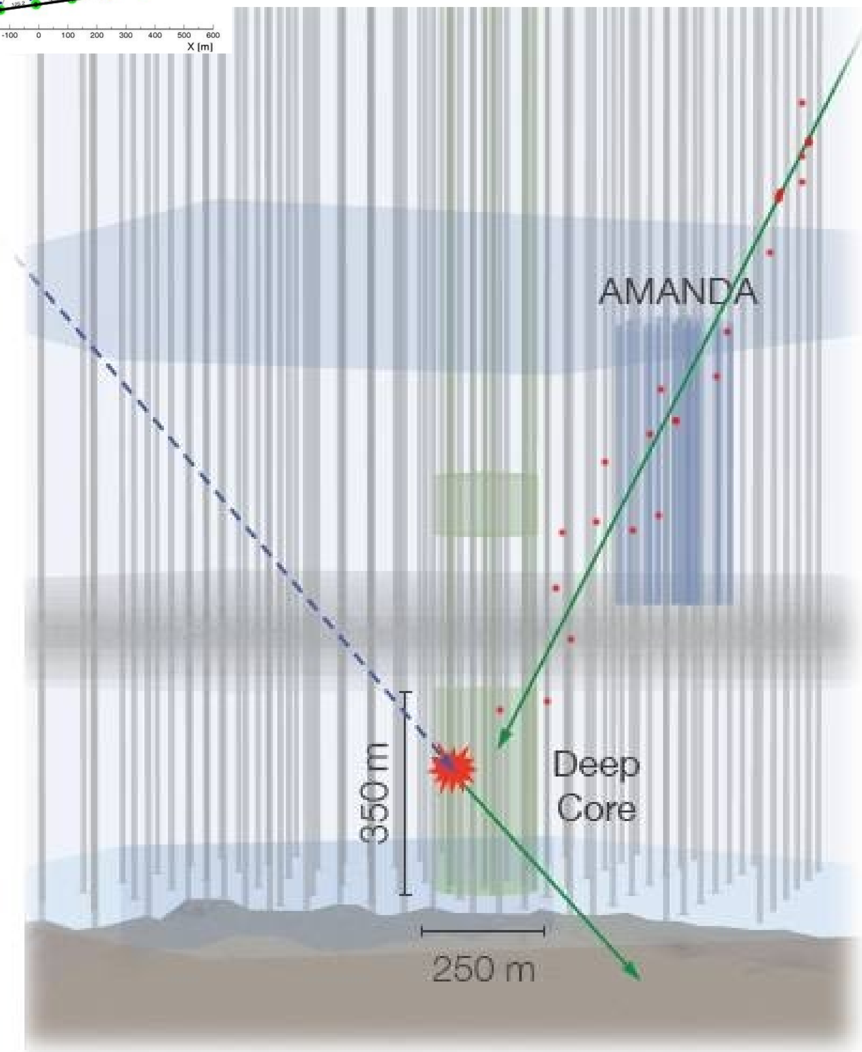
375m thick detector veto: three complete IceCube string layers surround DeepCore

—> access to southern hemisphere, galactic center and all-year Sun visibility

Preliminary studies show 10^3 background rejection with 99% signal efficiency possible at filter level







- we have 1 km^3 of ice instrumented with optical modules
- we can detect flavours (muon tracks, e/τ cascades)
- we can define through-going, starting and contained tracks
- we cover a wide neutrino energy range, from few tens GeV to PeV
- we can look at all the sky (at once and continuously)

...... **if you have a model of exotic physics that involves neutrinos, we can probe it**