dark matter searches with IceCube[*]

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[*] excluding the Galaxy
(see Carsten's talk)

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What I am not talking about today: the usual (MSSM neutralino μ flux limits... etc)

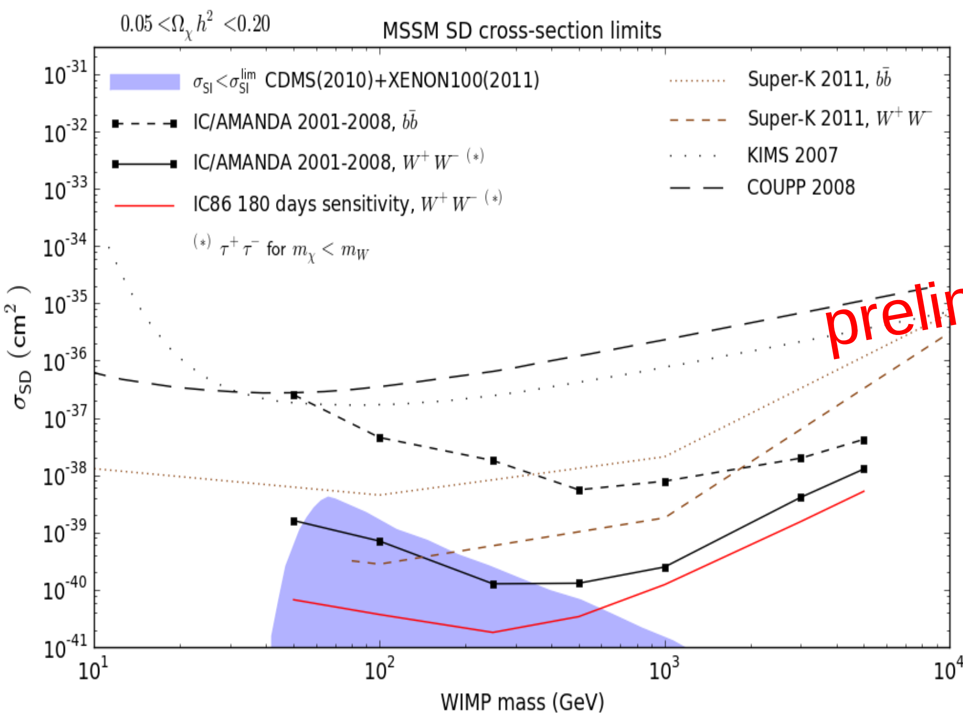
I will concentrate in analyses beyond the vanilla candidates and on new statistical techniques being developed to probe the SUSY parameter space, because:

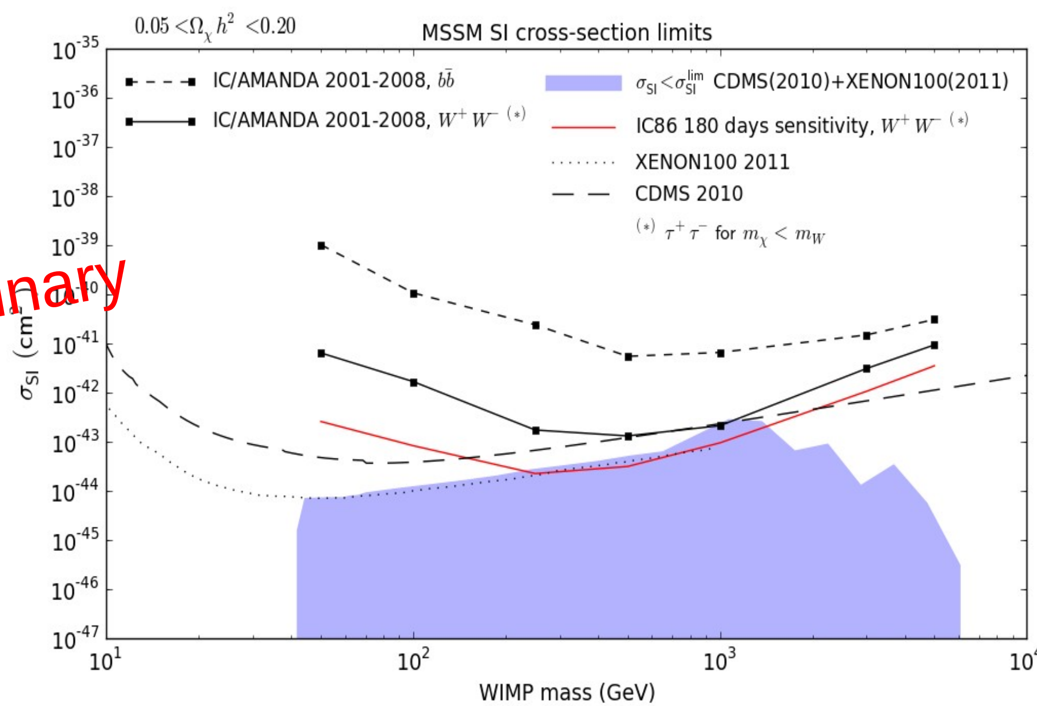
...... **there are many dark matter models that involve neutrinos as a signature that we can probe, and advanced statistical methods to do it**

we should go beyond our 'standard' analyses.

Combined AMANDA-II, IC-22 and IC-40 results

Total livetime of 1065 d between 2001 and 2008





preliminary

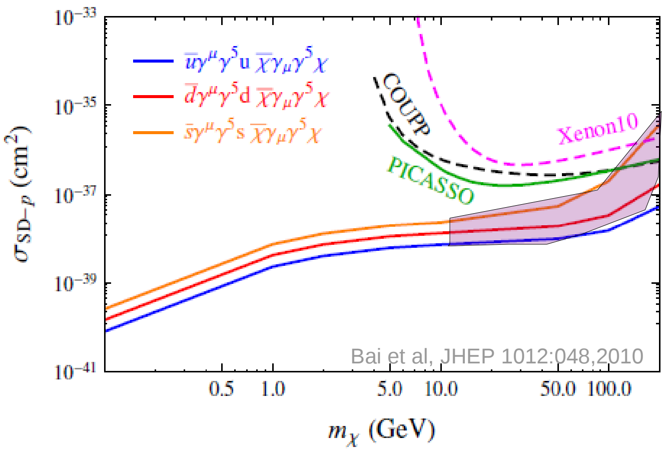
Assume (ie. model dependent) effective quark-DM interaction,

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

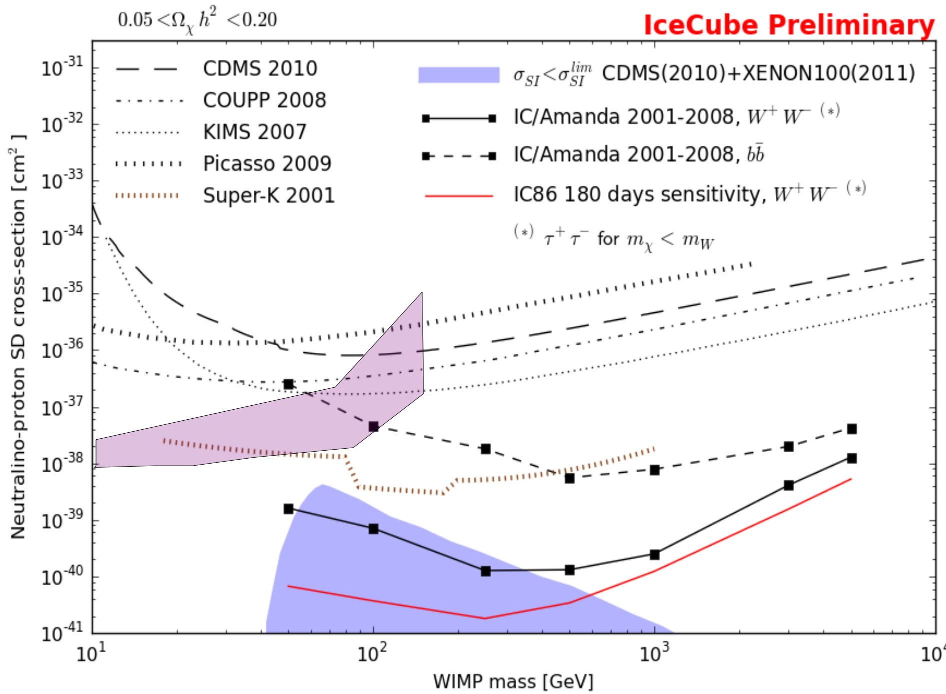
and look for monojets in $p\bar{p}$ collisions,

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

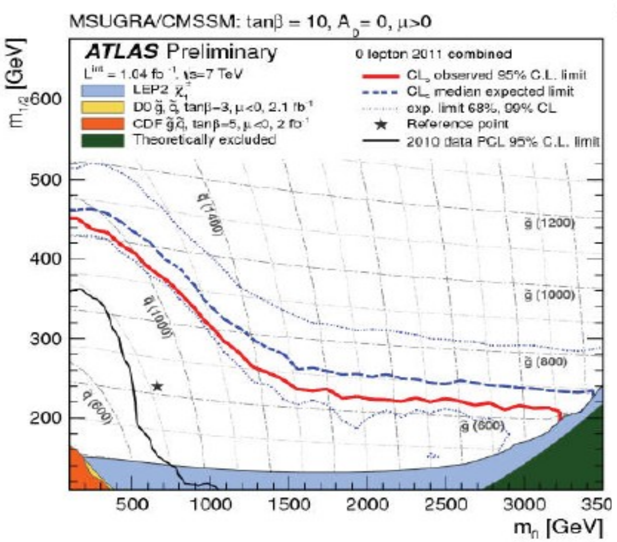
Constrains from monojet searches at the TeVatron:

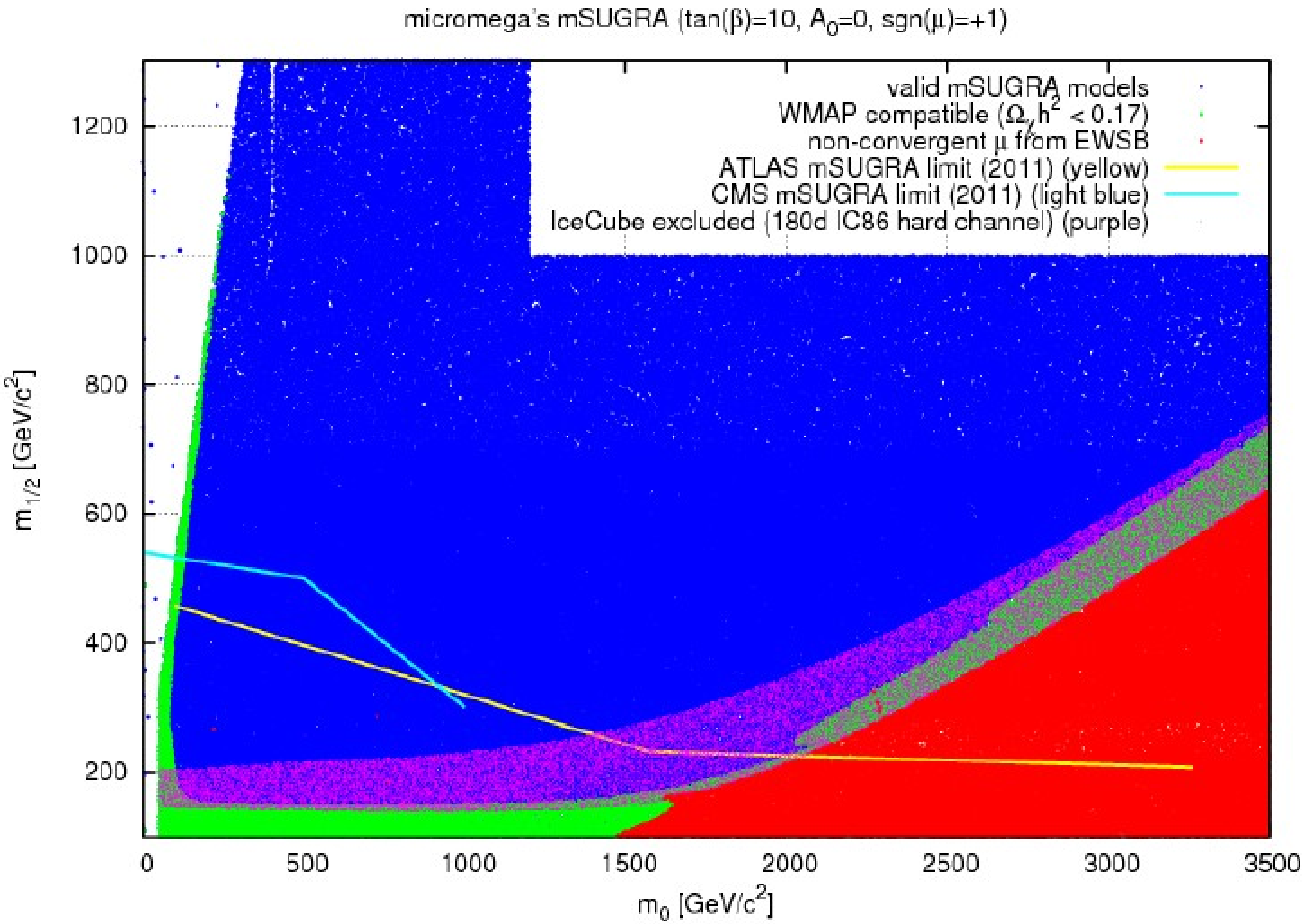


90% CL **neutralino-p Xsection** limit



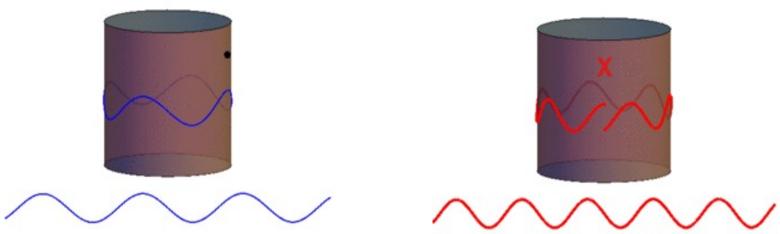
ATLAS and IceCube: even with grid scans the comparison is interesting





- **Universal Extra Dimensions**:

(new competitive limits from ATLAS)



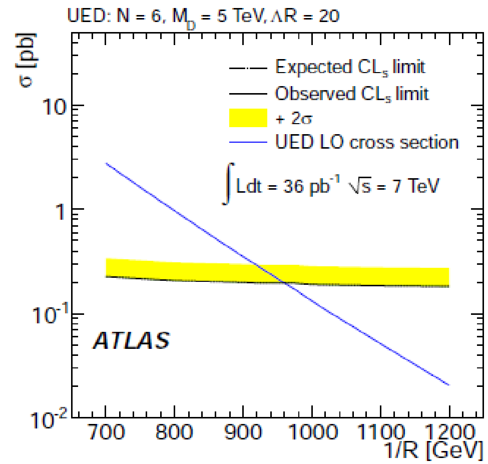
$$n\frac{\lambda}{2} = 2\pi R, \qquad n\frac{h}{2p} = 2\pi R \Rightarrow p = n\frac{h}{4\pi R}$$

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

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

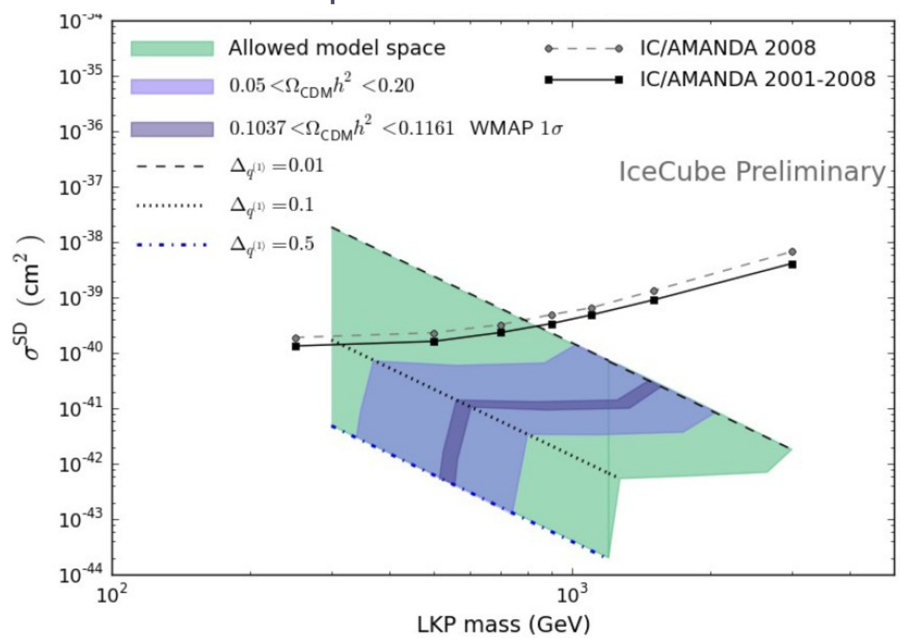
n=1 → Lightest Kaluza-Klein mode, $\mathbf{B}^1$

good DM candidate



arXiv:1107.0561v2

90% CL LKP-p Xsection limit vs LKP mass



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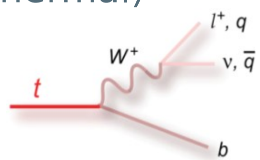
SIMPZILLAS (Superheavy DM)

- 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)

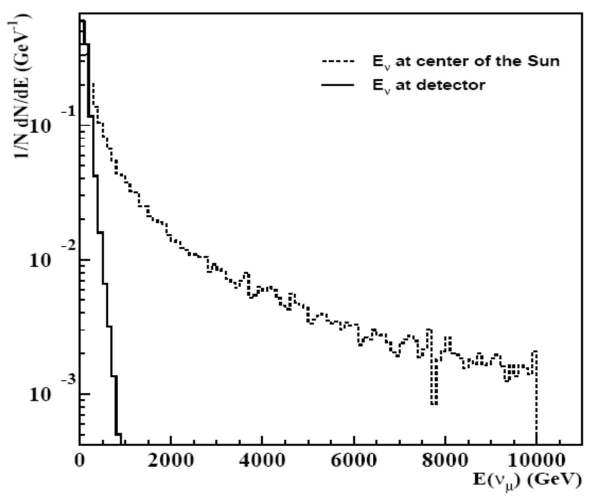
- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

S+S → t $\bar{t}$



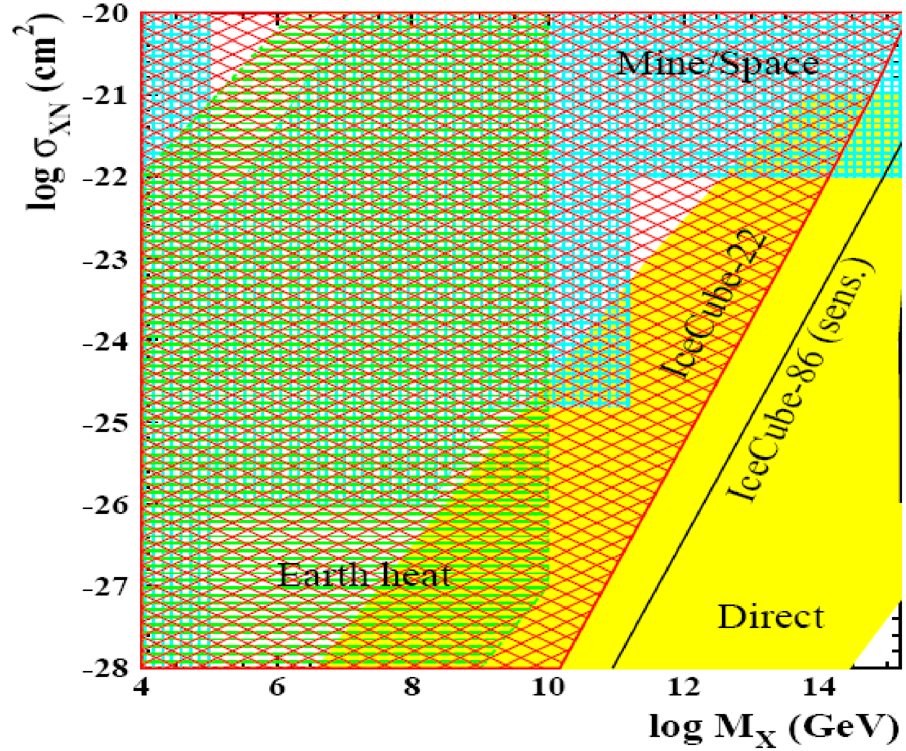
$2.8\times10^5\sqrt{m_{X/12}}$ tops per annihilation

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



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

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



Phys.Rev. D81 (2010) 063510

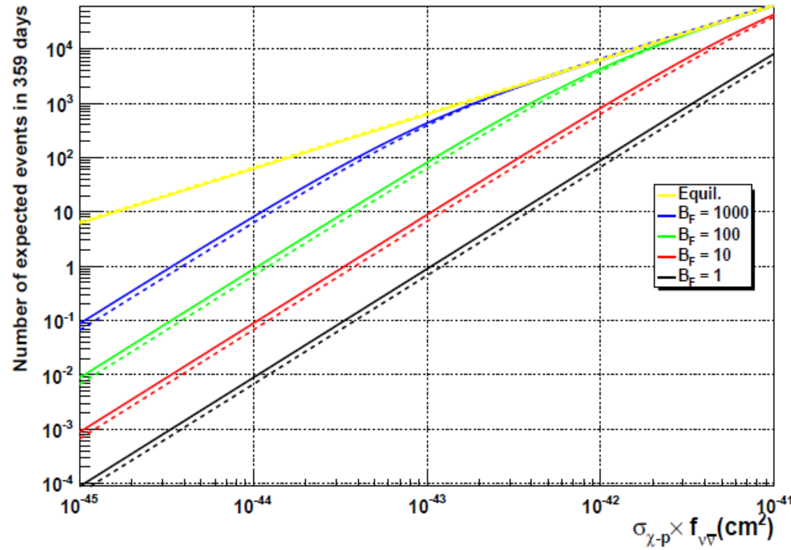
arXiv:1107.2408

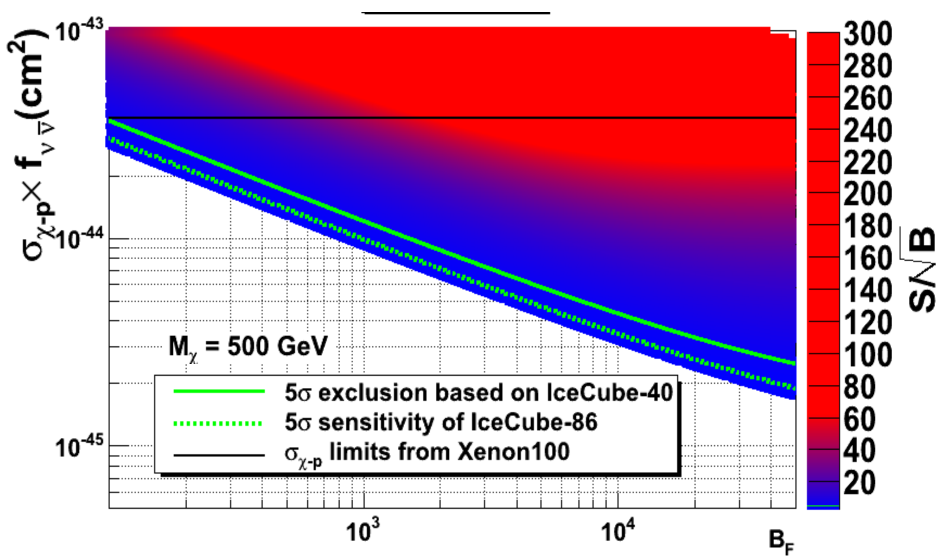
Explaining Fermi/PAMELA data in terms of dark matter favors boost in DM annihilation Xsection

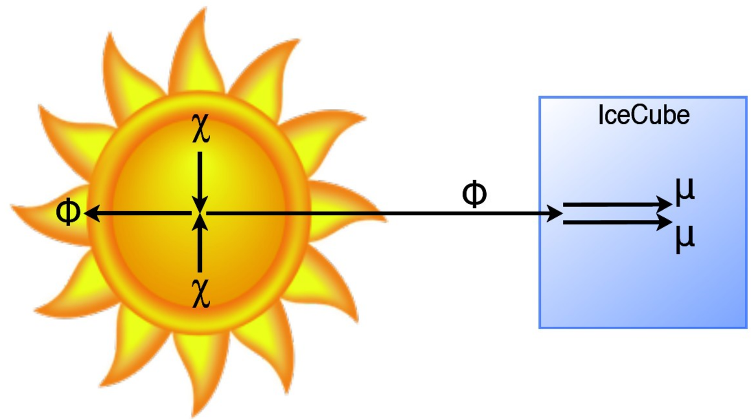
If the dark matter annihilation rate is enhanced, the timescale for equilibrium diminishes → flux of annihilation products can be much larger than away from equilibrium.

→ an enhanced annihilation Xsection could produce a detectable neutrino flux from the center of the Earth (while it is possible not to enhance 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







Secluded dark matter

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

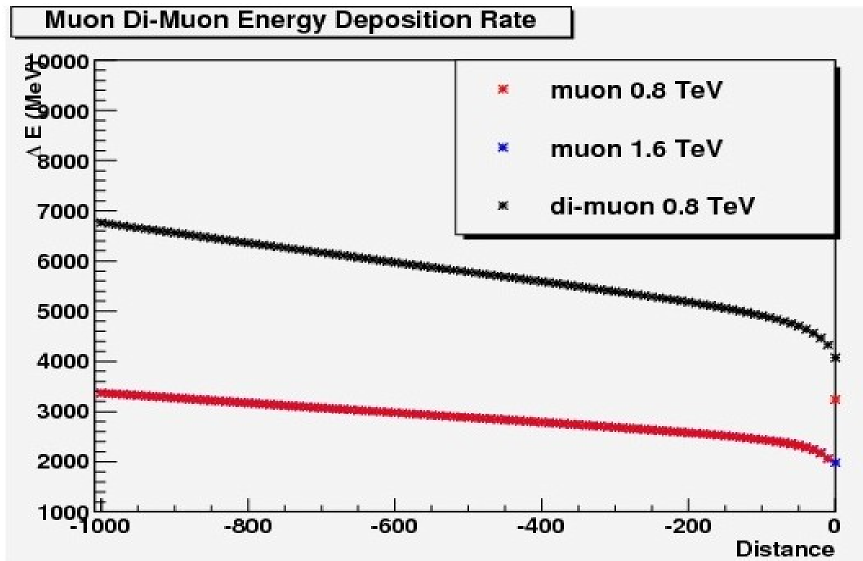
DM annihilates into mediator, $\chi\chi \rightarrow \phi\phi \rightarrow$SM with $m_\phi = \mathcal{O}$(GeV)

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 tracks which do radiate like dimuons until the stopping point, in order to further reduce the background.

work in progress

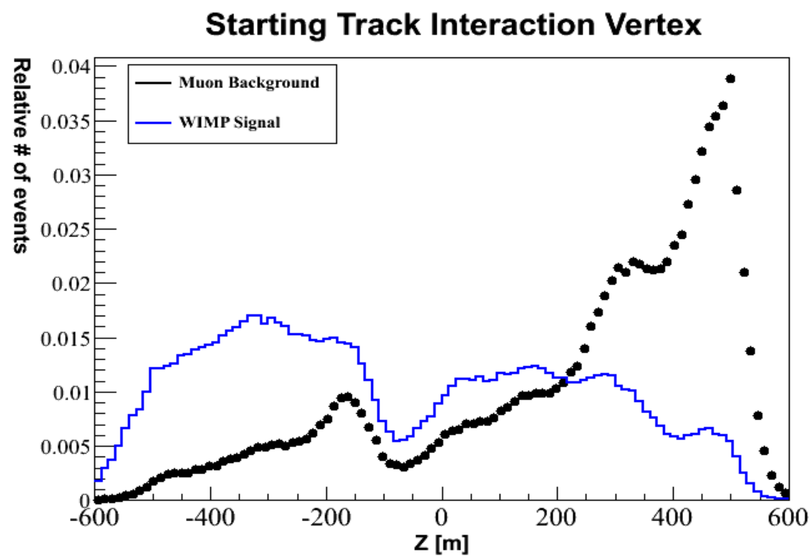


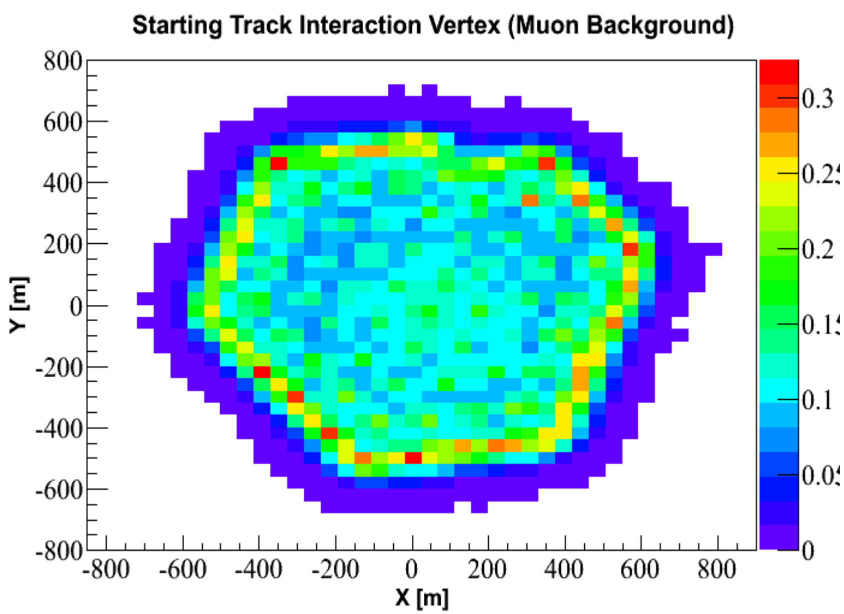
Extend the search to the southern hemisphere by selecting starting events

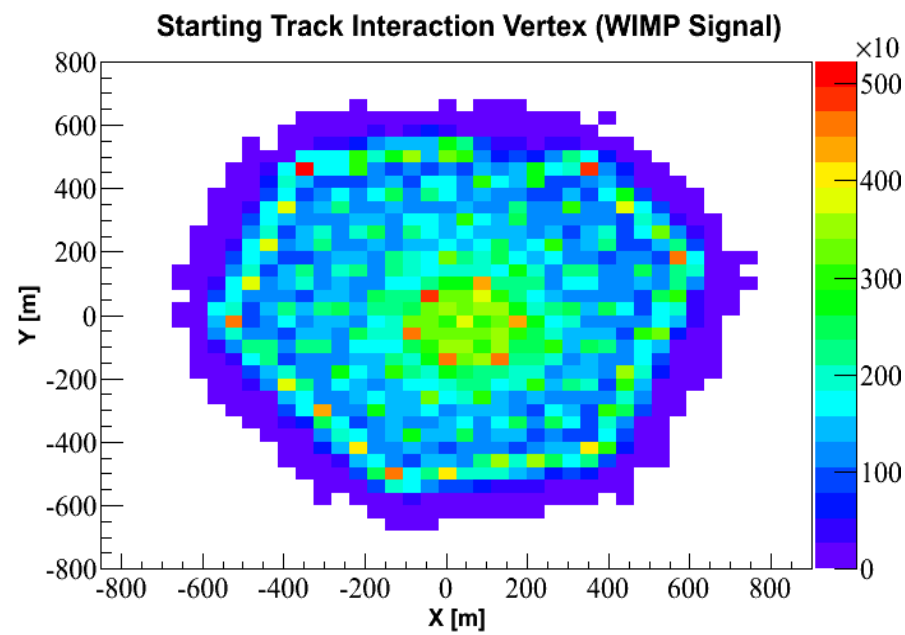
→ Veto background through location of interaction vertex

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

work in progress



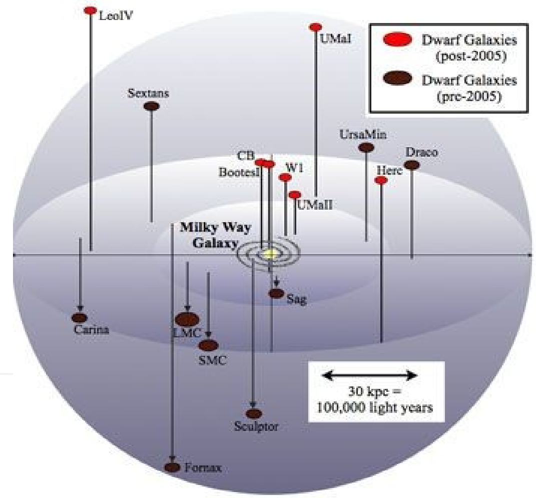




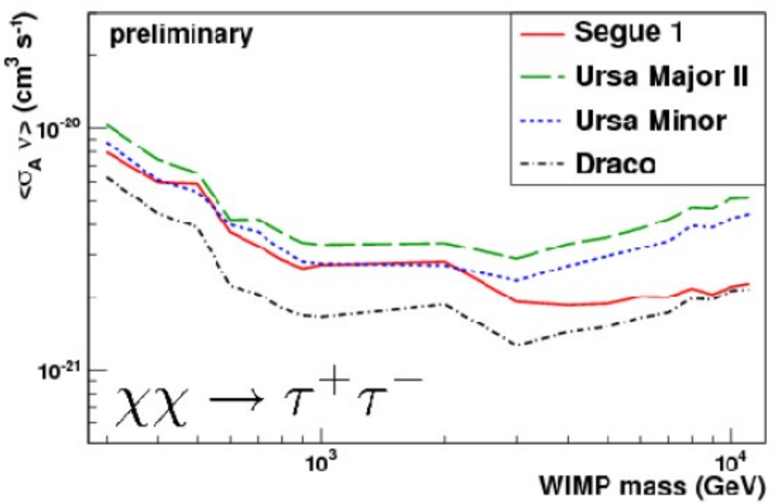
- dwarf galaxies: high mass/light ratio
- → high concentration of DM in the halos
- known location. Distributed both in the north and southern sky.
  - Point-like search techniques: stacking
  - known distance -> determination of absolute annihilation rate if a signal is detected
- same expected neutrino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

Same strategy as in the galactic halo analysis:

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



σ_A sensitivity



advantage for neutrino telescopes if DM is leptophilic, as suggested by PAMELA results

What can the muon signal tell me?

Roughly:

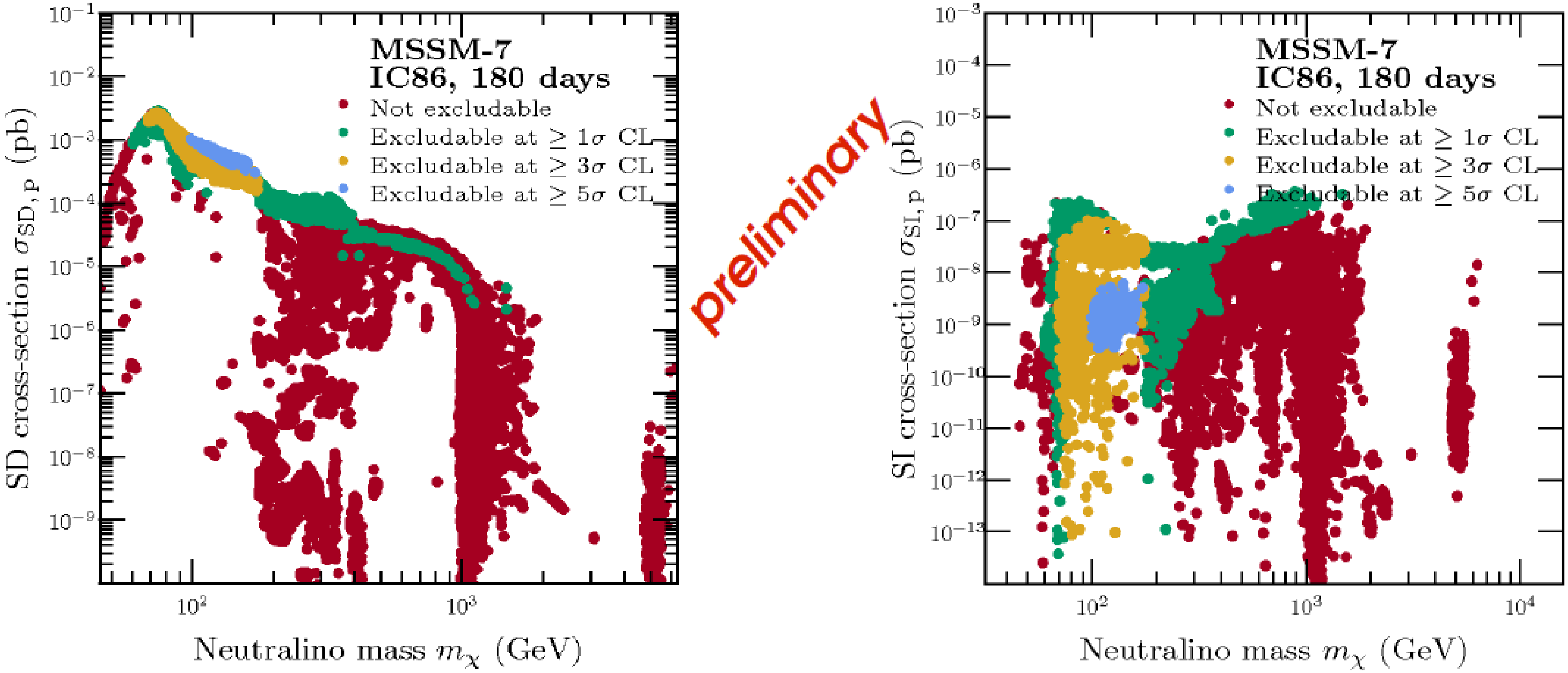
- ✗ **Number** – how much annihilation is going on in the Sun
  ⇒ info on σ_{SD} , σ_{SI} and $\langle\sigma v\rangle$
- ✗ **Spectrum** – sensitive to WIMP mass m_χ and branching fractions **BF** into different annihilation channels χ
- ✗ **Direction** – how likely it is that they come from the Sun

In model-independent analyses a lot of this information is either discarded or not given with final limits

Goal:

Use as much of this information on σ_{SD} , σ_{SI} , $\langle\sigma v\rangle$, m_χ and **BF** (χ) as possible to directly constrain specific points and regions in WIMP model parameter spaces

Assuming preliminary (conservative) estimate of IC-86 effective area



- ✗ Only partial goodness of fit, no measure of convergence, no idea how to generalise to regions or whole space.
- ✗ Frequency/density of models in IN/OUT scans means essentially nothing.

More noble aim: to delineate probability regions in the parameter space of the model under consideration, given current experimental constrains (data)

$\boldsymbol{\Theta} = (m_0, m_{1/2}, A_0, \tan\beta)$ ← parameter space to be scanned

(the cMSSM in the example, could be other)

$\boldsymbol{\Psi} = (m_t, m_b, \alpha_{em}, \alpha_s \ldots)$ ← SM and cosmological measured parameters of importance (nuisance parameters wrt to SUSY)

– $\boldsymbol{\eta} = (\boldsymbol{\Theta}, \boldsymbol{\Psi})$ ← set of basis parameters

– $\boldsymbol{\xi} = (\xi_1, \xi_2, \ldots, \xi_\nu)$ ← derived parameters for the choice η: $m\chi$, $\Omega\chi$, σ, ...

we would like $p(\eta|\text{data})$

$p(\boldsymbol{\eta}|\text{data}) = p(\text{data}|\boldsymbol{\xi})\, p(\boldsymbol{\eta})$ modulo a normalization factor, p(data)

$p(\text{data}|\boldsymbol{\xi}) == \mathcal{L}$, **Likelihood** (prob. of reproducing the data for a given set of ξ)

This is the tricky part: to build the global Likelihood with

dark matter relic density from WMAP

precision electroweak tests at LEP

LEP limits on sparticle masses

B-factory data (rare decays, $b \to s\gamma$)

muon anomalous magnetic moment

LHC searches, direct detection (not yet)

+ IceCube

unbinned likelihood

Full unbinned likelihood with number ($\mathcal{L}_{\rm num}$), spectral ($\mathcal{L}_{\rm spec}$) and angular ($\mathcal{L}_{\rm ang}$) parts

$$\mathcal{L} = \mathcal{L}_{\rm num}(n|\theta_{\rm signal+BG}) \prod_{i=1}^{n} \mathcal{L}_{{\rm spec},i}\, \mathcal{L}_{{\rm ang},i} \tag{3}$$

with Number of lit channels (energy estimator)

theory

$$\mathcal{L}_{{\rm spec},i}(N_i, \Xi) = \frac{\theta_{\rm BG}}{\theta_{\rm signal+BG}} \frac{dP_{\rm BG}}{dN_i}(N_i) + \frac{\theta_{\rm signal}}{\theta_{\rm signal+BG}} \int_0^{\infty} E_{\rm disp}(N_i|E_i') \frac{dP_{\rm signal}}{dE_i'}(E_i', \Xi)\, dE_i' \tag{4}$$

SUSY parameters

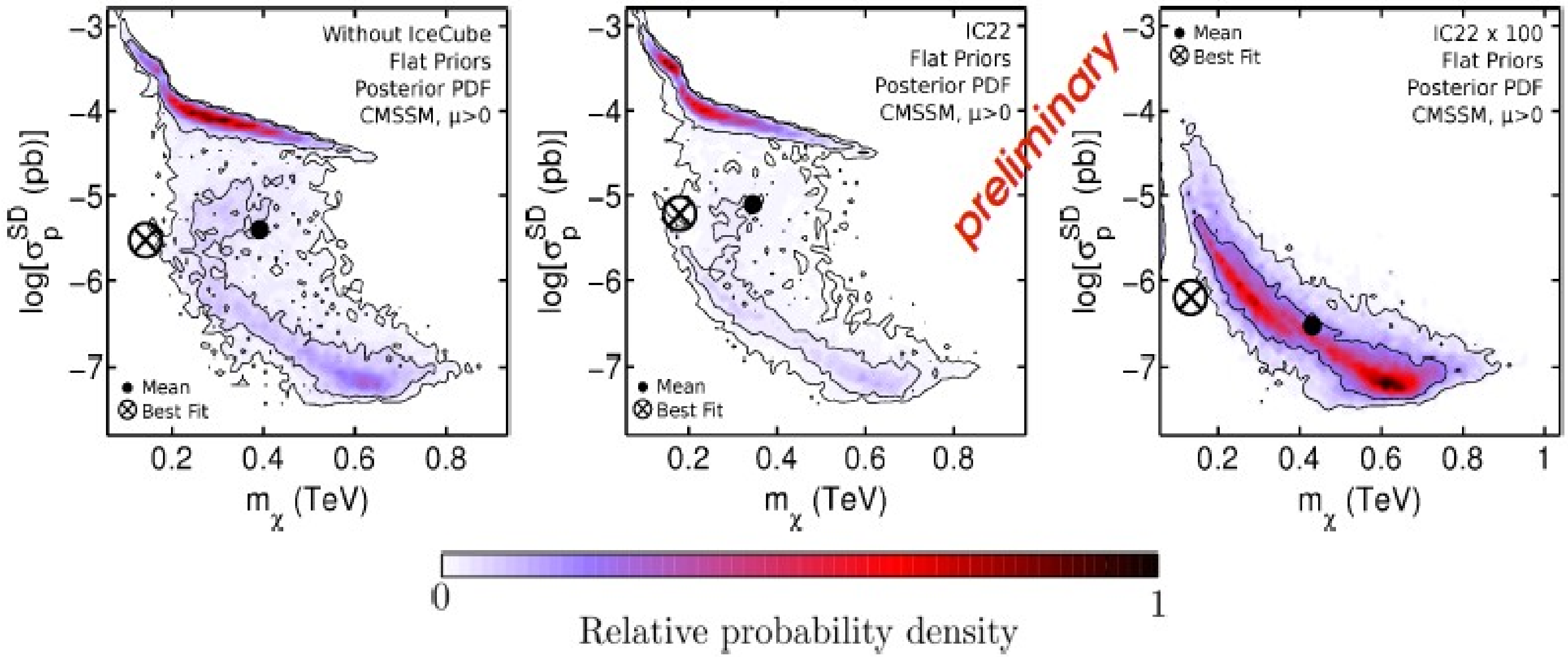
and

$$\mathcal{L}_{{\rm ang},i}(\cos\phi_i) = \frac{\theta_{\rm BG}}{\theta_{\rm signal+BG}} \frac{dP_{\rm BG}}{d\cos\phi_i}(\cos\phi_i) + \frac{\theta_{\rm signal}}{\theta_{\rm signal+BG}} PSF(\cos\phi_i|1) \tag{5}$$

Event arrival angle

Example of what we want in the end (work for IC86 in progress):

SD nuclear scattering cross-section in the CMSSM with IceCube-22 events



- Contours indicate 1σ and 2σ credible regions
- Shading+contours indicate relative probability only, not overall goodness of fit
- Scans performed with modified SuperBayes 1.5.1 and unreleased DarkSUSY

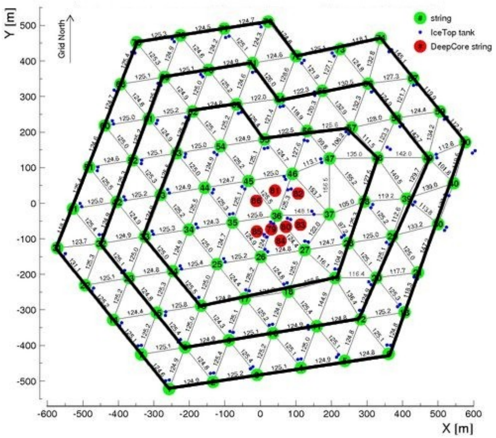
full sky sensitivity using IceCube surrounding strings as a veto:

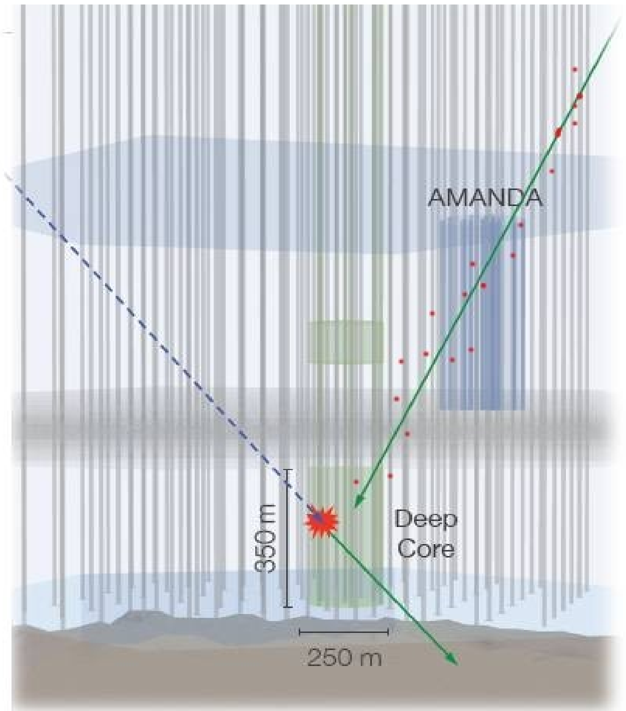
375m thick detector veto: three complete IceCube string layers surround DeepCore

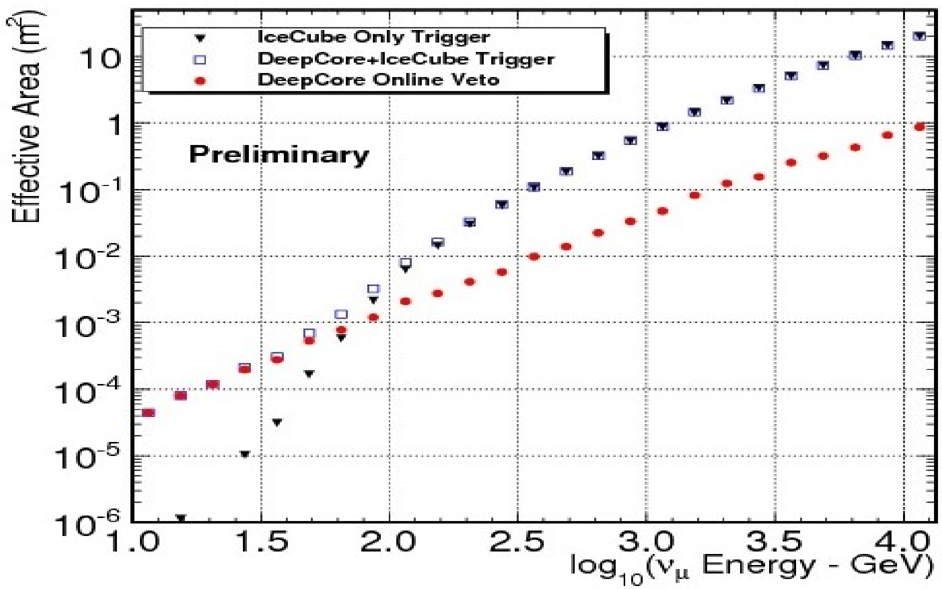
→ possibility of defining starting and contained tracks
→ access to southern hemisphere, galactic center and all-year Sun visibility
→ lower energy threshold to ~10 GeV
→ possibility of using cascades for DM searches

Work in progress

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







conclusions

The LHC is here. The bon vivant times of direct and indirect experiments are over

There still is complementarity between direct, indirect and accelerator searches:

In the parameter regions available

Due to astrophysical conditions

We (neutrino telescopes) need to go beyond the vanilla MSSM analyses

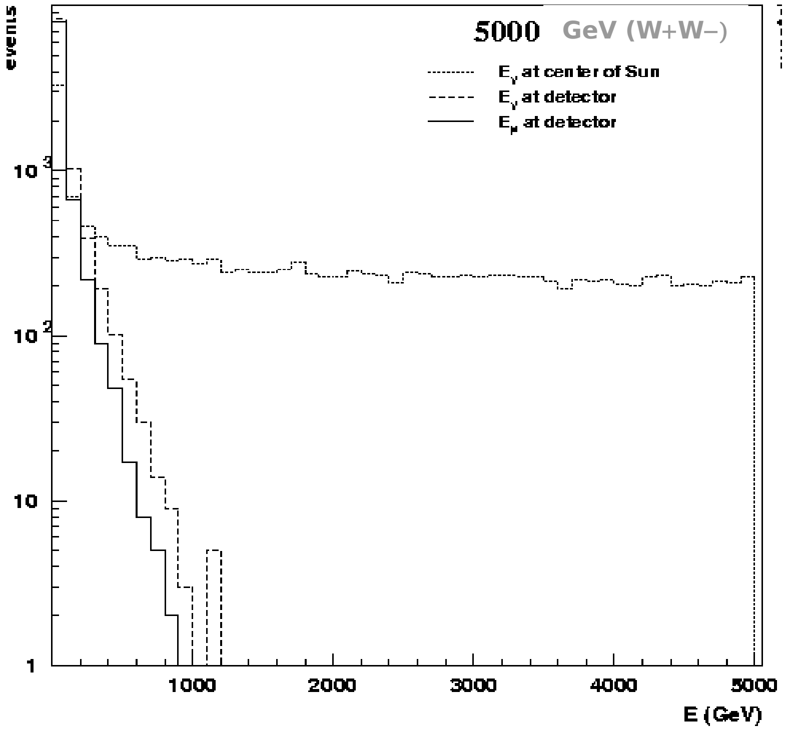
This is perfectly possible. We have mature detectors and analysis techniques

IceCube is preparing global fits to SUSY parameter space with detector information cooked in on an event by event basis

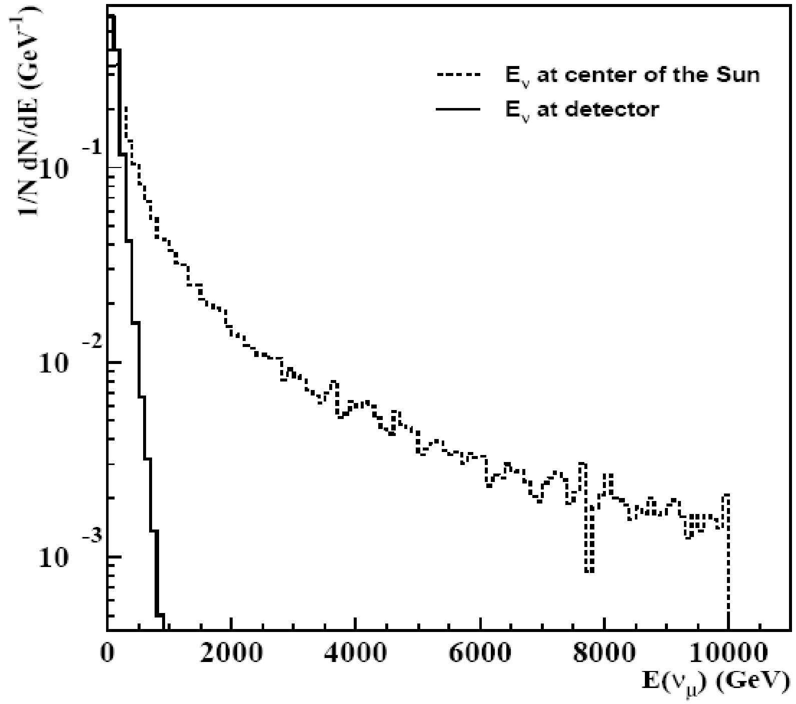
We are also extending our analyses to above the horizon and to the low energy regime

searches from the Sun: neutrino energies at the detector

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

Easy to interpret limits in terms of several candidates

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