Direct supersymmetric analyses with IceCube

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Slides available from www.physics.mcgill.ca/~patscott

Introduction

Thanks Carlos.

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Recap:

1. Halo WIMPs scatter on nuclei in the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the south pole, convert into muons in the ice
6. Look for Čerenkov radiation from the muons

What can the muon signal tell me?

Roughly:

Number – how much annihilation is going on in the Sun
$\implies$ info on $\sigma_{\rm SD}$, $\sigma_{\rm SI}$ and $\langle\sigma v\rangle$

Spectrum – sensitive to WIMP mass m_χ and branching fractions BF into different annihilation channels X

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 $\sigma_{\rm SD}$, $\sigma_{\rm SI}$, $\langle\sigma v\rangle$, m_χ and $BF(X)$ as possible to directly constrain specific points and regions in WIMP model parameter spaces

What can the muon signal tell me?

The focus here is supersymmetry (SUSY) – but this talk is on a framework, applicable to any model.

All the methods discussed here will be available in a future release of DarkSUSY

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SUSY Scanning with IceCube – Physics

DarkSUSY for computing neutrino fluxes:

- No assumption of equilibrium between capture and annihilation
- No assumption of particular annihilation final state
- Inclusion of perturbations to WIMP orbits by Jupiter
- Full numerical capture, SD and SI scattering on many more isotopes than just ^{1}H
- Full neutrino production, propagation and oscillation via tabulated WIMPSim results

Explicit example models – lightest neutralino in SUSY, as realised in:

- MSSM-7 (μ, M_2, $m^2_{\tilde{f}}$, m_A, $\tan\beta$, A_t, A_b)
- CMSSM (m_0,$m_{\frac{1}{2}}$, A_0, $\tan\beta$, $\mathrm{sgn}\mu$)

SUSY Scanning with IceCube – Statistics I

The simplest way to do anything is to turn it into a counting problem…

Compare observed number of events n and predicted number θ for each model, taking into account error σ_ϵ on acceptance:

$$\mathcal{L}_{\mathrm{num}}(n|\theta) = \frac{1}{\sqrt{2\pi}\sigma_\epsilon} \int_0^\infty \frac{(\epsilon\theta)^n e^{-\epsilon\theta}}{n!} \exp\left[-\frac{1}{2}\left(\frac{1-\epsilon}{\sigma_\epsilon}\right)^2\right] \mathrm{d}\epsilon. \quad (1)$$

From this, construct a modified p-value as

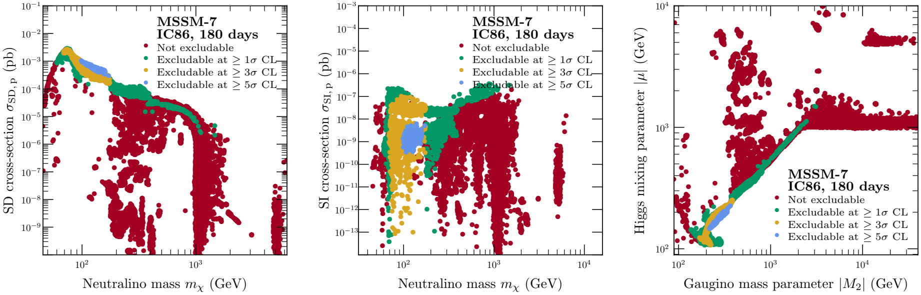
$$p(n) = \frac{p_{\mathrm{signal+BG}}(n)}{p_{\mathrm{BG}}(n)} = \frac{\sum_{n_i \le n} \mathcal{L}_{\mathrm{num}}(n_i|\theta_{\mathrm{signal+BG}})}{\sum_{n_i \le n} \mathcal{L}_{\mathrm{num}}(n_i|\theta_{\mathrm{BG}})} \quad (2)$$

Can now say immediately, for a single point, that the point is excluded at a confidence level of $1 - p$.

$\Longrightarrow$ **model exclusion** exercise – IN/OUT analysis

SUSY Scanning with IceCube – Simple IN/OUT analyses

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



OK, that's a nice start, but…

- 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 information comes from a **global statistical fit.** $\Longrightarrow$ **parameter estimation exercise**

Composite likelihood made up of observations from all over:

- 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)

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

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

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SUSY Scanning with IceCube – Full Likelihood

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with Number of lit channels (energy estimator)

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Event arrival angle

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SUSY parameters

and

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and

Observed background distributions

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

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Predicted signal spectrum (from theory)

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Predicted signal direction (δ function at Sun)

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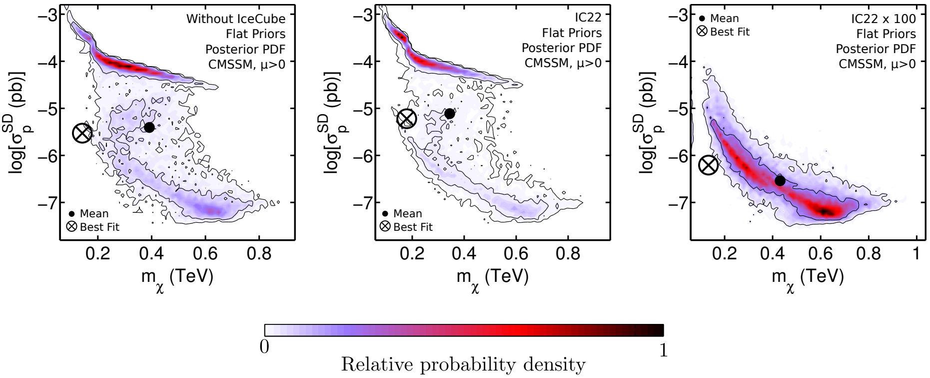
and

Instrument response functions

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

Predicted signal direction (δ function at Sun)

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



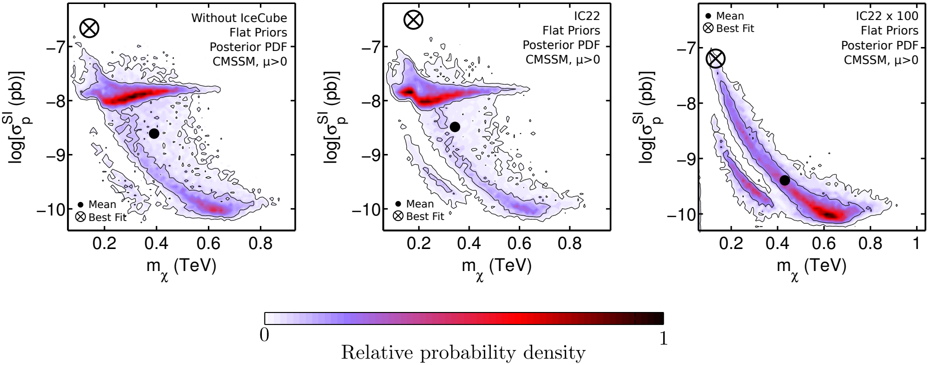
Contours indicate 1σ and 2σ credible regions

Shading+contours indicate **relative** probability only, not overall goodness of fit

Scans performed with modified SuperBayes 1.5.1 and unreleased DarkSUSY

SUSY Scanning with IceCube – Global Fits

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



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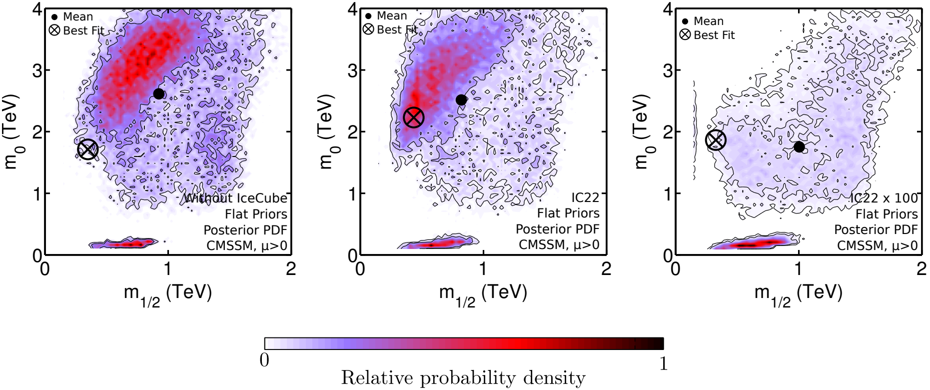
Mass parameters in the CMSSM with IceCube-22 events



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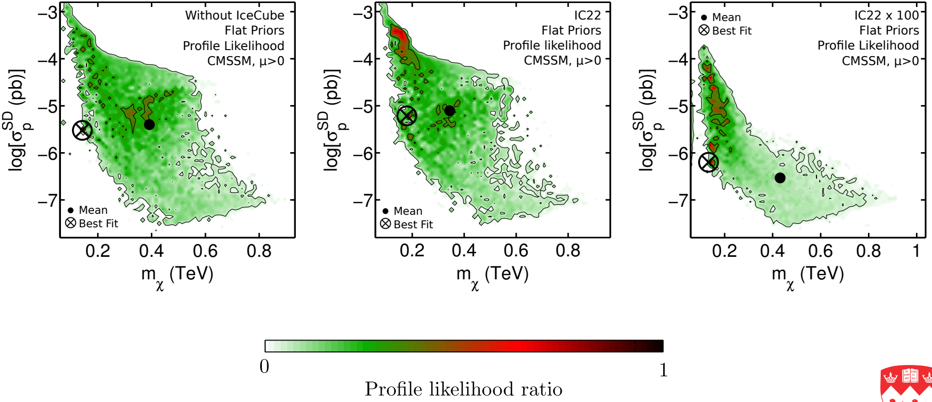
Closing remarks

- A framework for directly comparing event-level IceCube data to individual points in theory parameter spaces is in place
- The requisite tools will be available in DarkSUSY in the future
- Event data will eventually be released in a form digestible by the tools
- Direct SUSY analyses of IC79 data are on the way
- Many models exist in low-energy (p)MSSM variants that only IC86 will be sensitive to

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



Backup Slides: Profile Likelihoods

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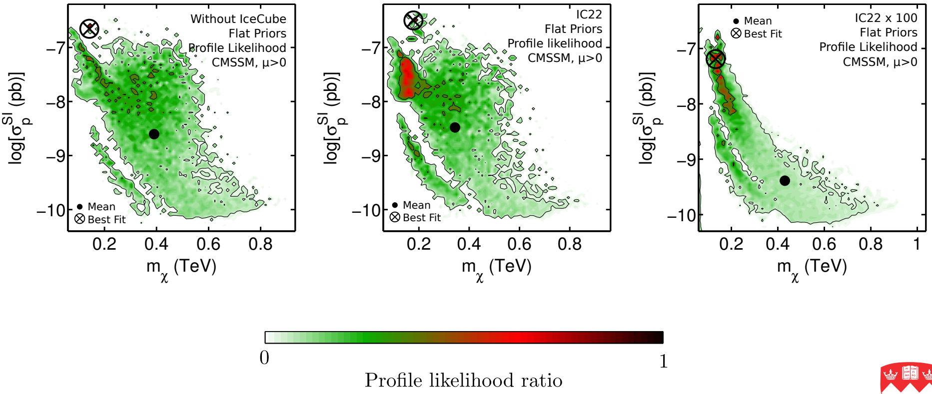

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