# Global Fits beyond the Standard Model with Astroparticle Data

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

# Outline

1. The Problem
   - Moving beyond the Standard Model
   - Beyond the SM with astroparticle probes
   - Global fits
2. Progress
   - Global fits beyond the SM
   - Indirect detection of dark matter
   - Direct detection of dark matter
3. Future Challenges
   - Respectable LHC and astro likelihoods
   - Parameter space → Theory space
   - Coverage & optimisation vs contour mapping

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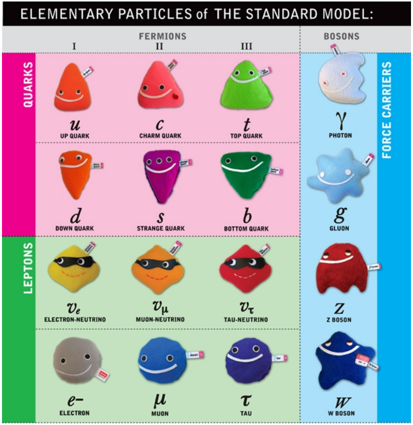
# The Standard Model of particle physics



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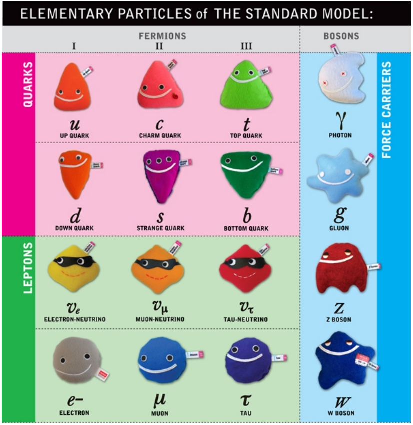


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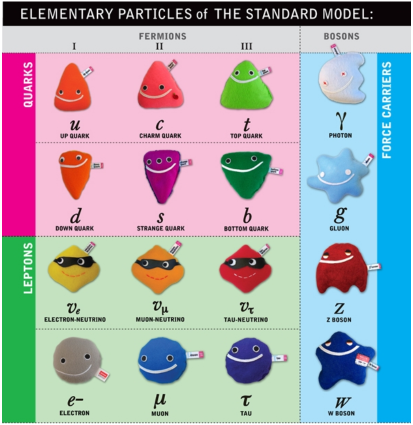



19 free parameters: (10 masses, 3 force strengths, 4 quark mixing parameters, 2 'vacuumy things')

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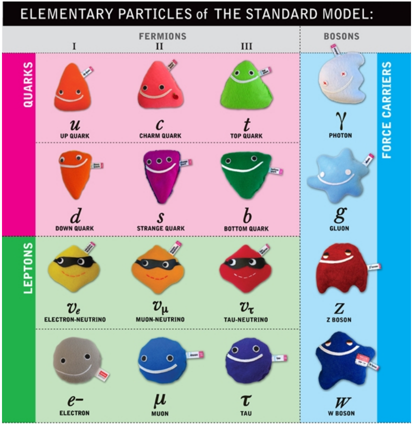




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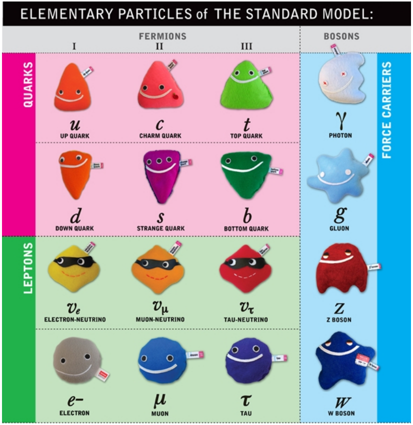


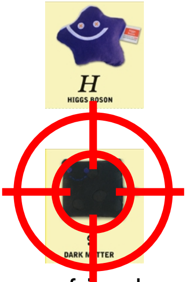


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# Reasons to go beyond the Standard Model

- **Hierarchy problem**
  Higgs mass receives arbitrarily large loop corrections in SM;
  cancelled or at least truncated by new TeV-scale physics
- **Vacuum stability**
  With $m_h = 125\,\mathrm{GeV}$, SM Higgs mass goes negative via renormalisation group running at $E < M_{\mathrm{GUT}}$
  $\implies$ SM vacuum is unstable $\implies$ new particles probably stabilise it
- **Dark matter**
  Exists; absent in SM
- **Matter-antimatter asymmetry**
  More matter than antimatter; no real SM mechanism
- **Neutrino masses**
  Measured; absent in SM

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# Dark matter – properties & models


## Must be:

- massive (gravitationally-interacting)
- unable to interact via the electromagnetic force (dark)
- non-baryonic
- “cold(ish)” (in order to allow structure formation)
- stable on cosmological timescales
- produced with the right relic abundance in the early Universe.

## Good options:

- Weakly Interacting Massive Particles (WIMPs)
- sterile neutrinos
- gravitinos
- axions
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- hidden sector dark matter (e.g. WIMPless dark matter)

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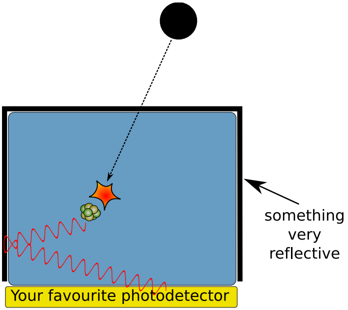

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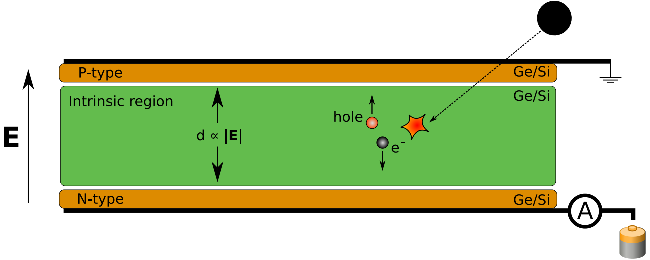

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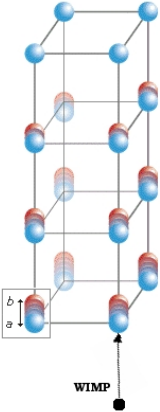

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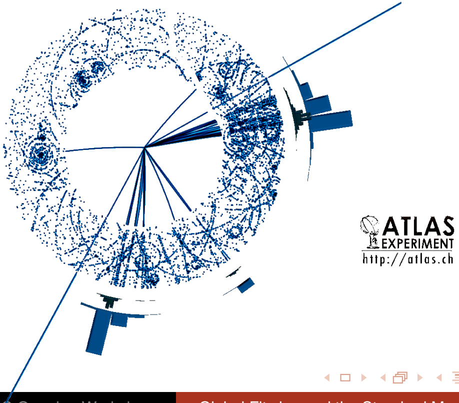

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  - gamma-rays – *Fermi*, HESS, CTA
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  - neutrinos – IceCube, ANTARES
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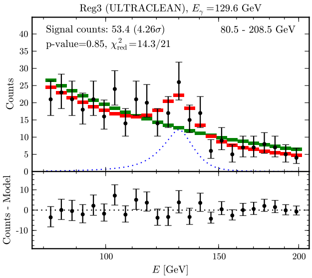
Weniger (2012, *JCAP*)



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- Dark stars – JWST, VLT

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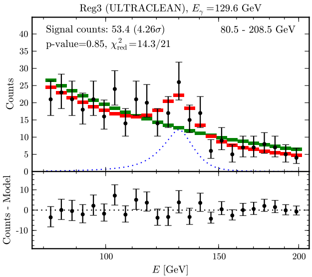

# “The rest”

In order of (my own completely biased opinion of) usefulness for probing BSM physics:

1. Neutrino physics (cosmological, solar, atmospheric)
   - Masses, mixings, additional sterile neutrinos
   - Mass-generation models often require RH $\nu$, extra symmetry groups
2. BBN
   - Extra particles can change elemental yields (decays, resonances, etc)
3. Baryogenesis / Leptogenesis
   - Baryon asymmetry may be generated by some new CP violation
   - May even be linked to dark matter production (‘asymmetric DM’)
4. Inflation
   - Eventually the inflaton needs to actually come from somewhere. . .

# Outline

# Putting it all together: global fits

Goals:

1. given a particular theory, determine which parameter combinations fit all experiments, and how well
2. given multiple theories, determine which fit the data better, and quantify how much better

Issue 1: Combining fits to different experiments
Easy – composite likelihood ($\mathcal{L}_1 \times \mathcal{L}_2 \equiv \chi_1^2 + \chi_2^2$ for simplest $\mathcal{L}$)

- LEP precision electroweak tests, limits on sparticle masses
- $B$-factory data (rare decays, $b \to s\gamma$), muon anomalous magnetic moment
- dark matter relic density from WMAP
- direct detection, indirect detection, LHC, BBN, etc

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1. parameter estimation
2. model comparison

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# Putting it all together: global fits

Issue 2: Including the effects of uncertainties in input data
Easy – treat them as *nuisance parameters*

Issue 3: Finding the points with the best likelihoods
Tough – MCMCs, nested sampling, genetic algorithms, etc

Issue 4: Comparing theories
Depends – Bayesian model comparison, *p* values
($TS$ distribution? $\longrightarrow$ coverage???)

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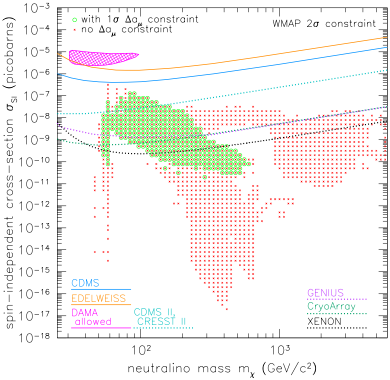
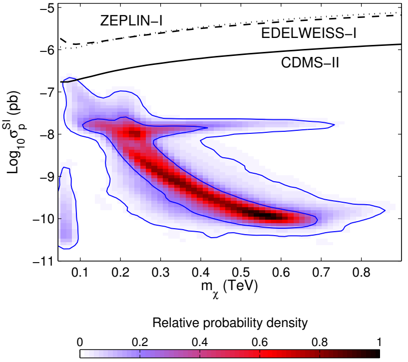
# First BSM global fits 2004–06

Started with Baltz & Gondolo (2004), Allanach & Lester (2006), Ruiz, Roszkowski & Trotta (2006)

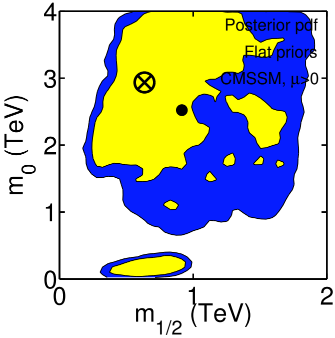
- Supersymmetric models – mSUGRA/CMSSM ($m_0$, $m_{1/2}$, $A_0$, tan $\beta$)
- MCMC-based analyses – likelihood maps and Bayesian posteriors

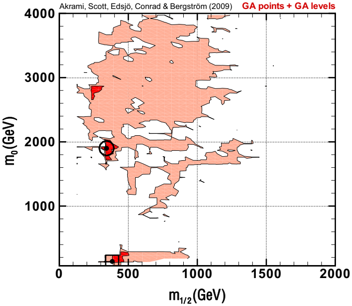


# 2008-09

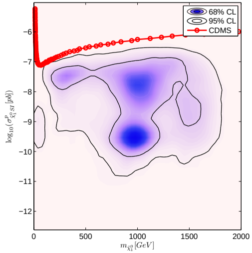
- MultiNest – Faster posterior sampling (Feroz & Hobson, Trotta et al 2008)
- Improved frequentist analyses – profile likelihood (Trotta et al 2008, Akrami, PS et al 2009, Mastercode 2009+)

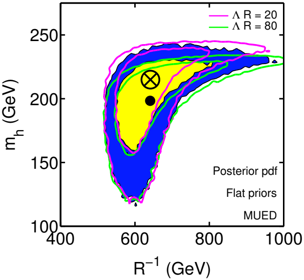


# Theories/Models: Please, anything but the CMSSM!

- General low-energy SUSY
  (AbdusSalam et al 2010)
- Small perturbations on CMSSM:
  NUHM1, NUHM2, VCMSSM
  (Roskowski et al 2009,
  Mastercode 2009+)
- CNMSSM / NmSUGRA
  Extra SM singlet + singlino
  (Lopez-Fogliani et al 2009)
- Universal Extra Dimensions
  with Kaluza-Klein DM
  (Bertone et al 2010)



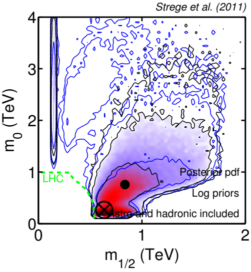



# Addition of LHC data

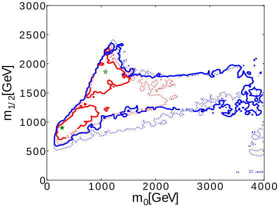
1–5 $fb^{-1}$ data, 7–8 TeV centre of mass energy (2011-12)

- ATLAS/CMS LHC searches for supersymmetry
- Higgs signals

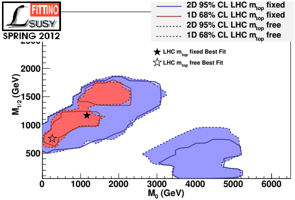
SuperBayes




MasterCode




Fittino



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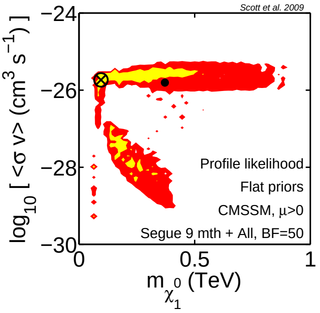
# Gamma-rays

Gammay-ray annihilation searches have been added to the global fits:

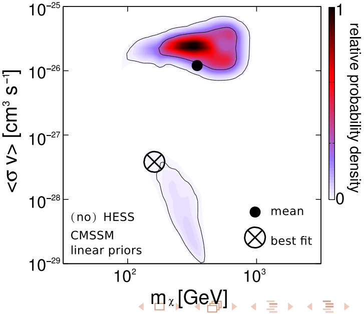
## *Fermi*-LAT

Satellite pair conversion telescope
Dwarf galaxy Segue 1
(PS, Conrad et al 2009)




## HESS

Air Čerenkov telescope
Milky Way+Carina+Sculptor+Sag dwarf
(Ripken, Conrad & PS 2011)



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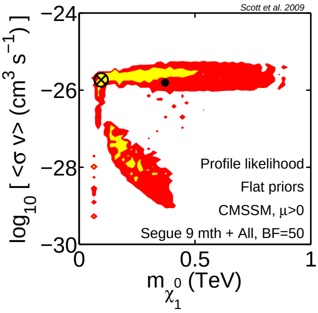


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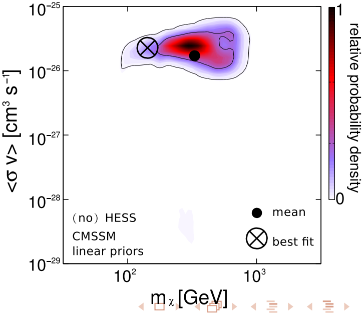


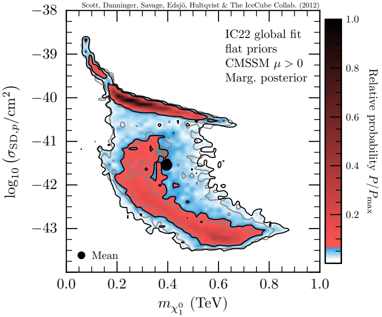
# Neutrinos

New likelihood analysis including IceCube Neutrino Telescope WIMP-search neutrino events

## IceCube 22-string data

Not expected to be very constraining

(PS, Savage, Edsjö & IceCube Collab 2012)



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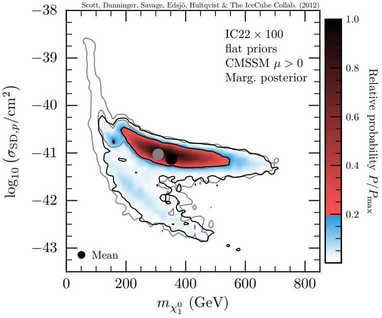

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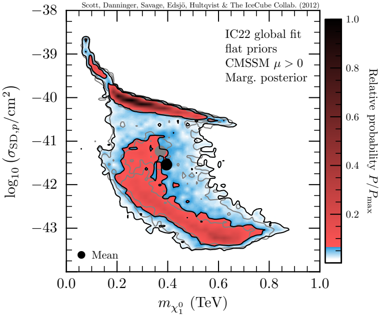
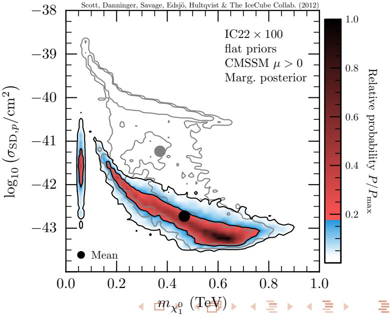



## IceCube-DeepCore (86-string)

Very constraining (projection)



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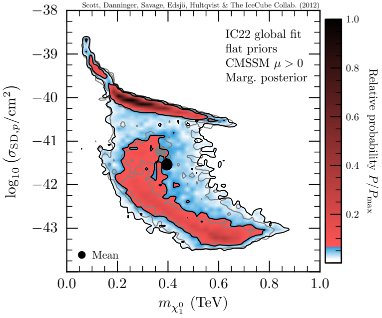
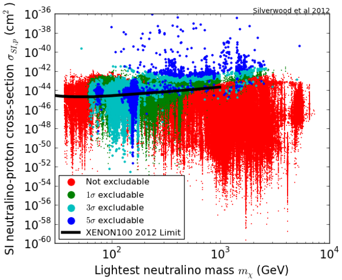



## IceCube-DeepCore (86-string)

Very constraining (projection) $\Longrightarrow$ unique access to pts in more general MSSM

(Silverwood, PS, Danninger et al 2012)



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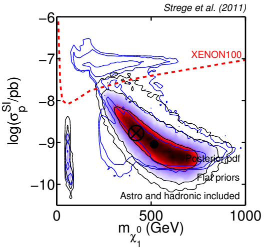
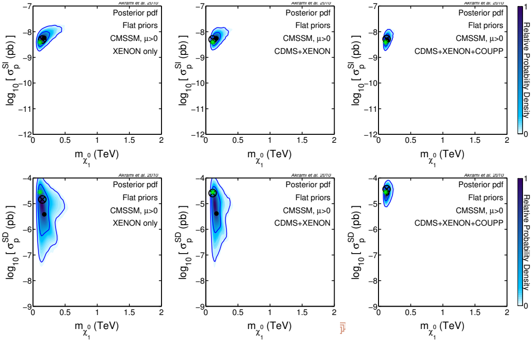
# Direct detection data in global fits

XENON-100 bounds now maybe starting to impact BSM theories (Strege et al 2011, Mastercode 2011+, Fittino 2012)

– depends strongly on hadronic uncertainties

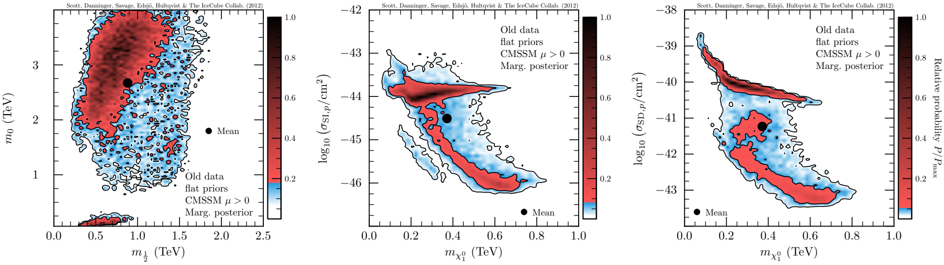
Tonne-scale detection could allow us to zoom in very quickly on the correct parameters (Akrami, Savage, PS et al 2011b)



# Combined Direct + Indirect + LHC constraints

## Base Observables



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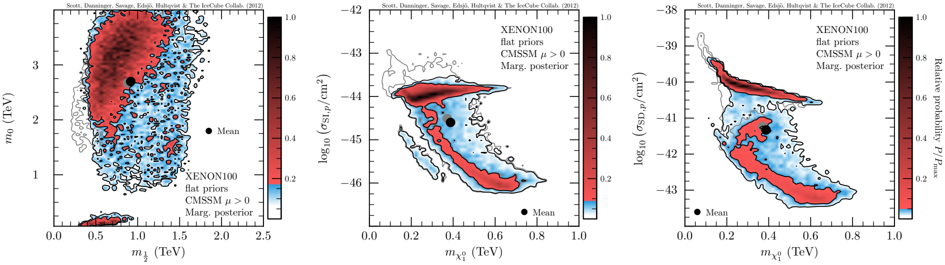
## Base Observables + XENON-100

Grey contours correspond to Base Observables *only*



# Combined Direct + Indirect + LHC constraints

## Base Observables + XENON-100 + CMS $5\,\mathrm{fb}^{-1}$

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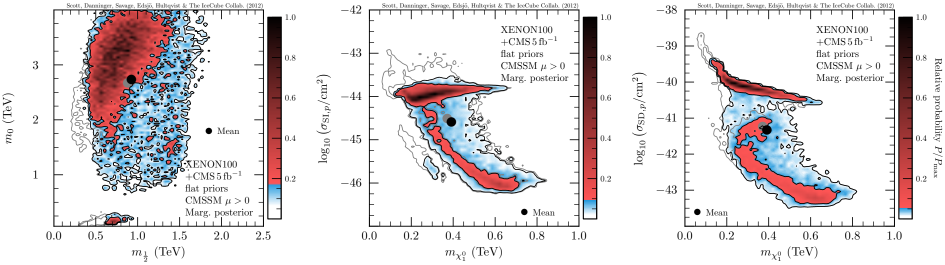

# Combined Direct + Indirect + LHC constraints

## Base Observables + XENON-100 + CMS 5 $\mathrm{fb}^{-1}$ + IC22×100

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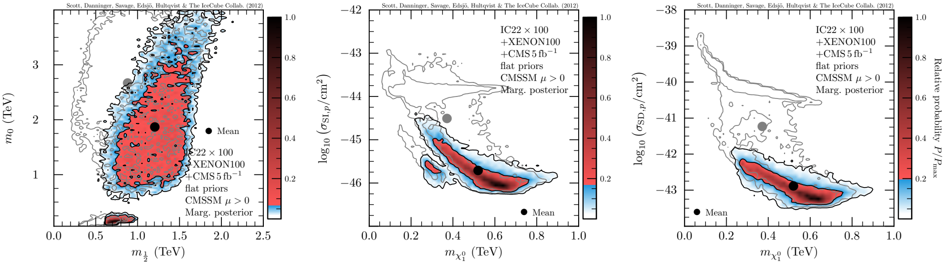


**CMSSM, IceCube-22 with 100× boosted effective area**
(kinda like IceCube-DeepCore)

# Outline

# Getting LHC data into global fits

Typical workflow in a collider phenomenology analysis:

1. Choose your new symmetries or effective operators
2. Augment SM Lagrangian with new terms
3. Derive Feynman rules
4. Derive/calculate cross-sections
5. Simulate events – parton showering
6. Simulate events – hadronisation
7. Rescale rates due to neglected loops (or other reasons)
8. Do ‘fast’ detector simulation of events to get final predicted rate
9. Repeat steps 5-8 for each point in parameter space

# The LHC monster

**Time per point:**

$\mathcal{O}(minute)$ in best cases

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**Challenge:**

About 2 orders of magnitude too slow to actually include LHC data in global fits properly

# Taming the LHC monster

**Zeroth Order Response:**

"Stuff it, just use the published limits and ignore the dependence on other parameters"

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"Stuff it, just use the published limits and ignore the dependence on other parameters"

Obviously naughty – plotted limits assume CMSSM, and fix two of the parameters

- Don't really know dependence on other parameters
- Don't have a likelihood function, just a line
- Can't use this at all for non-CMSSM global fits – e.g. MSSM-25

Those in the room having done this can remain unidentified ☺

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**First Order Response:**

"Test if things depend on the other parameters (hope not), re-simulate published exclusion curve"

Not that great, but OK in some cases

- At least have some sort of likelihood this time
- Still a bit screwed if things do depend a lot on other parameters, but
- allows (potentially shaky) extrapolation, also to non-CMSSM models

Fittino, Mastercode

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**Negative Order Response:**

"I am such an übersmart particle theorist that I know much more about statistics than all those silly experimentalists and global fitters put together.

"I'll just do an undersampled random scan and count the points, that way I don't need to worry about all this sampling/statistics nonsense!"

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(Sadly, people do think like this – and continue to publish such papers. I fight with them at meetings.)

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Maybe – this is the challenge.

- Interpolated likelihoods (how to choose nodes?)
- Neural network functional approximation (how to train accurately?)
- Some sort of smart reduction based on event topology?
- Something else?

# Two different approaches to including astro data in BSM scans

1. Just use the published limits on $\langle \sigma v \rangle$ (or $\sigma_{\mathrm{SI,SD}}$)
   - Fast – can cover large parameter spaces
   - Not so accurate – experimental limits are invariably based on theoretical assumptions, e.g. $b\bar{b}$ spectrum
   - Full likelihood function almost never available
2. Use the data points directly in SUSY scans
   - Slow – requires full treatment of instrument profile for each point
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3. (indirect only: use just flux upper limits)

# Example: Advanced IceCube Likelihood (Part 1)

Simplest way to do anything is to make it a counting problem. . .

Compare observed number of events $n$ and predicted number $\theta$ for each model, taking into account error $\sigma_\epsilon$ on acceptance:

$$\mathcal{L}_{\mathrm{num}}(n|\theta_{\mathrm{BG}}+\theta_{\mathrm{sig}}) = \frac{1}{\sqrt{2\pi}\sigma_\epsilon}\int_0^\infty \frac{(\theta_{\mathrm{BG}}+\epsilon\theta_{\mathrm{sig}})^n e^{-(\theta_{\mathrm{BG}}+\epsilon\theta_{\mathrm{sig}})}}{n!}\frac{1}{\epsilon}\exp\left[-\frac{1}{2}\left(\frac{\ln\epsilon}{\sigma_\epsilon}\right)^2\right]\mathrm{d}\epsilon\,. \tag{1}$$

Nuisance parameter $\epsilon$ takes into account systematic errors on effective area, from theory, etc. $\sigma_\epsilon \sim 20\%$ for IceCube.

# Example: Advanced IceCube Likelihood (Part 2)

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

$$\mathcal{L} = \mathcal{L}_{\rm num}(n|\theta_{\rm signal+BG}) \prod_{i=1}^{n} \mathcal{L}_{{\rm spec},i}\, \mathcal{L}_{{\rm ang},i} \tag{2}$$

with

$$\mathcal{L}_{{\rm spec},i}(N_i, \Xi) = \frac{\theta_{\rm BG}}{\theta_{\rm signal+BG}} \frac{dP_{\rm BG}}{dN_i}(N_i) + \frac{\theta_{\rm signal}}{\theta_{\rm signal+BG}} \int_0^\infty E_{\rm disp}(N_i|E'_i) \frac{dP_{\rm signal}}{dE'_i}(E'_i, \Xi)\, dE'_i \tag{3}$$

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SUSY parameters

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Instrument response function

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Observed BG distribution

Instrument response function

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Event arrival angle

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# Outline

1. The Problem
   - Moving beyond the Standard Model
   - Beyond the SM with astroparticle probes
   - Global fits
2. Progress
   - Global fits beyond the SM
   - Indirect detection of dark matter
   - Direct detection of dark matter
3. Future Challenges
   - Respectable LHC and astro likelihoods
   - Parameter space $\longrightarrow$ Theory space
   - Coverage & optimisation vs contour mapping

# CMSSM, SMS $\neq$ BSM

(SMS = Simplified Model Spectrum; used by ATLAS and CMS for results display due to complaints about CMSSM)

Want to do model comparison to actually work out which theory is right…

**Challenge:**

How do I easily adapt a global fit to different BSM theories?

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**Challenge:**

How do I easily adapt a global fit to different BSM theories?

Somehow, we must recast things quickly to a new theory

- data
- likelihood functions
- scanning code 'housekeeping'
- even predictions

$\Longrightarrow$ a new, very abstract global fitting framework

# Outline

## We don't *really* know the distribution of our test statistic in BSM global fits, as it is too expensive to Monte Carlo

- coverage is rarely spot-on unless mapping from parameters to data-space is linear
(Akrami, Savage, PS et al, Bridges et al 2011, Strege et al 2012)
- *p*-value assessments of goodness of fit should be viewed with scepticism (→MasterCode)

## Convergence remains an issue, especially for profile likelihood

Messy likelihood $\implies$ best-fit point can be (and often is) easily missed (Akrami, PS et al 2010, Feroz et al 2011)

- frequentist CLs are often off, as isolikelihood levels are chosen incorrectly
- can impact coverage (overcoverage, or masking of undercoverage due to non-$\chi^2$ *TS* distribution)
- need to use multiple priors and scanning algorithms (one optimised for profile likelihoods?)

# Closing remarks

- Robust analysis of dark matter and BSM physics requires multi-messenger global fits
- Lots of interesting astroparticle observables to include in global fits
- Quite a bit of technical (statistical/computational) detail to worry about

Ranked Challenges:

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