Statistical challenges in astroparticle physics

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

Outline

1. Overview
   - New physics
   - Global fits
2. Statistical Challenges
   - Detailed astroparticle likelihoods
   - Which experiments can we trust?
   - Compute time, coverage and scanning
   - Systematisation: Parameter space $\longrightarrow$ Theory space

My view of astroparticle physics

How to define astroparticle physics?

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Option A

Use of known particle physics to tell us something about astronomical objects/processes

- Cosmic rays
- Supernova interiors, remnants
- Blazar, pulsar/magnetar studies
- Gravitational wave astronomy

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Option B
Use of astronomical probes to tell us new things about particle/fundamental physics

- Dark matter searches
- Cosmological neutrino probes
- Big Bang Nucleosynthesis
- Inflationary theory testing

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Both are legitimate – B is what gets me going though, so is what this talk will focus on

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Searching for new physics

Many reasons to look for physics Beyond the Standard Model (BSM) of particle physics:

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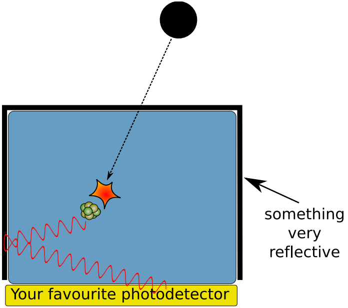
Dark matter searches

- Direct detection – nuclear collisions and recoils – CDMS, XENON, DAMA, CRESST, CoGeNT, etc



(and/or ionisation, phonons)

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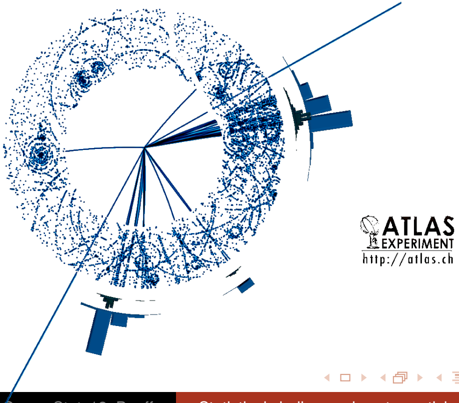

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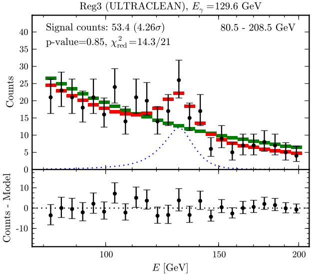
  - e^+e^- – PAMELA, *Fermi*, ATIC, AMS $\rightarrow$ secondary radiation: Compton^{-1}, synchrotron, bremsstrahlung
  - secondary impacts on the CMB

(Weniger *JCAP*, 1204.2797)



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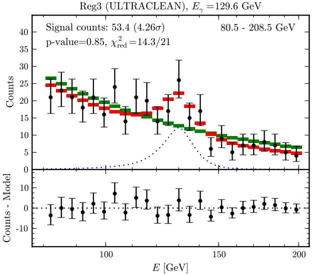

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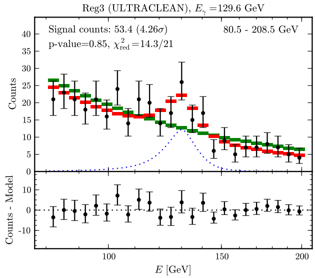

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BSM Model Scanning

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

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

Putting it all together: global fits

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

- dark matter relic density from WMAP
- direct detection
- indirect detection
- LHC searches
- precision electroweak tests at LEP
- LEP limits on sparticle masses
- B-factory data (rare decays, $b \to s\gamma$)
- muon anomalous magnetic moment ("$g-2$")

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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Experimentalists:
Toy models
Real constraints

Theorists:
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1. Detailed astroparticle likelihoods for arbitrary models

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2. Which experiments can we trust?
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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 BSM scans
   - Slow – requires full treatment of instrument profile for each point
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3. (indirect only: use just flux upper limits)

Gamma-rays

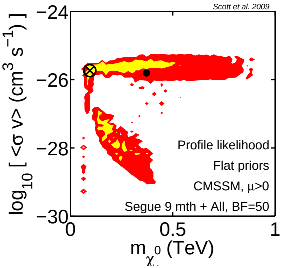
Gamma-ray annihilation searches have been added to the global fits:

Fermi-LAT

Satellite pair conversion telescope

Dwarf galaxy Segue 1

(PS, Conrad et al *JCAP*, 0909.3300)



- Full binned Poissonian likelihood (no χ^2 approximation)
- Full treatment of PSF *and* energy dispersion (with fast convolution library FLATlib)
- Marginalisation over systematic error on effective area
- Diffuse BG from Fermi-LAT Galprop fits
- Isotropic BG best-fit isotropic power law
- *J*-factor from Martinez et al (*JCAP*, 0902.4715; best at the time)

Gamma-rays

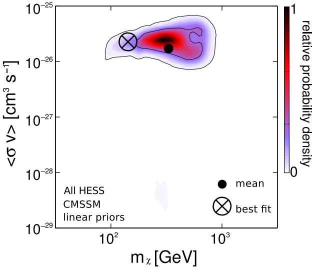
Gamma-ray annihilation searches have been added to the global fits:

HESS

Air Čerenkov telescope

Milky Way+Carina+Sculptor+Sag dwarf

(Ripken, Conrad & PS *JCAP*, 1012.3939)



- χ^2-based analysis using public flux limits
- 'Milky Way' = halo just beyond GC (45–150 pc)
- Virtual internal bremsstrahlung from co-annihilation strip models caught at high-E by HESS
- but: J-factors for Sag dwarf rather uncertain

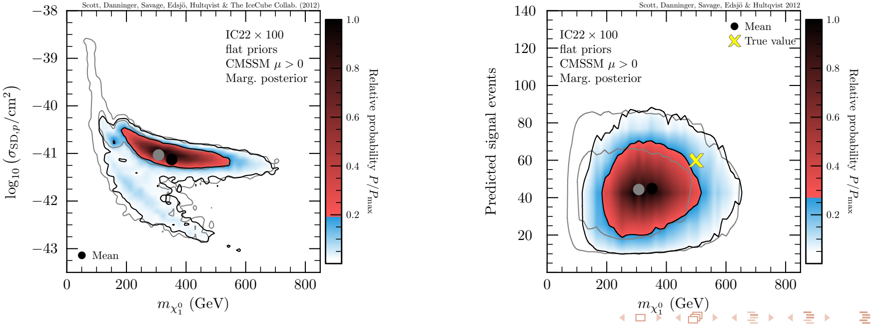
Advanced IceCube Likelihood

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

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

Mock signal reconstruction with IceCube-DeepCore (86-string)

(PS, Savage, Edsjö & IceCube *JCAP*, 1207.0810)



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Limits: IceCube 22-string data vs. IceCube-DeepCore (86-string)

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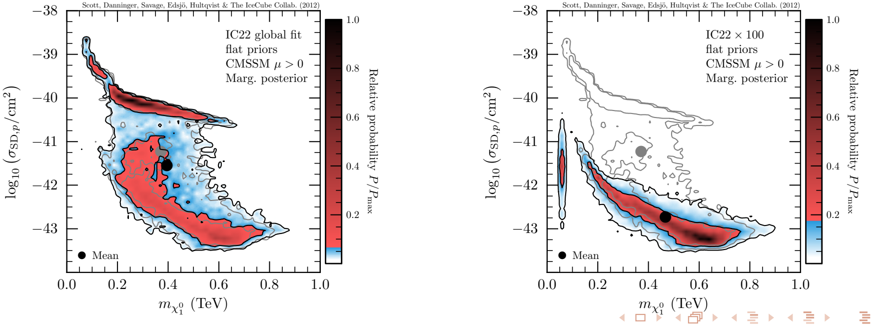

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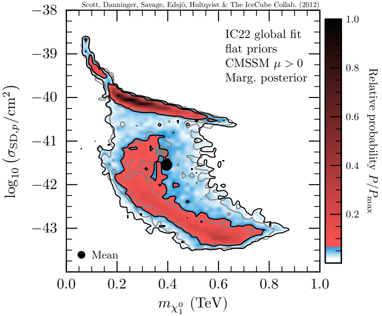
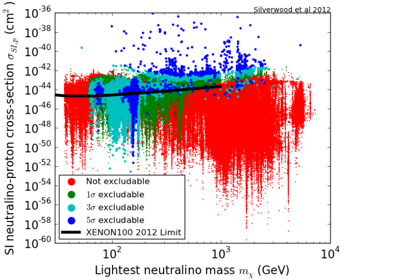


(Silverwood, PS, Danninger et al *JCAP*, 1210.0844)
→ IC86 has unique access to pts in more general MSSM



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The examples here are CMSSM & MSSM-25 – but this about a framework, applicable to any model.

All methods are available implemented in DarkSUSY v5.0.6 and later: www.darksusy.org

All IceCube data used are available at http://icecube.wisc.edu/science/data/ic22-solar-wimp (and in DarkSUSY, for convenience)

Generalised DM CMB likelihood functions

Simple CMB likelihood function, for

- Any combination of annihilation or decay channels
- Any dark matter mass
- Any decay lifetime/annihilation cross-section

→ just requires interpolating one number in a table.

Cline & PS, *JCAP*, 1301.5908, using

- CMB energy deposition from Slatyer, 1211.0283 and Finkbeiner et al, 1109.6322
- PYTHIA annihilation/decay spectra of Cirelli et al, 1012.4515.

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η for decay:

$$\ln \mathcal{L}(\tau|m_\chi, r_i) = -\frac{1}{2}\left(\frac{\delta\Omega}{\Omega_{\rm DM}\tau}\right)^2 \eta^2(\tau, m_\chi, r_i) \quad (3)$$

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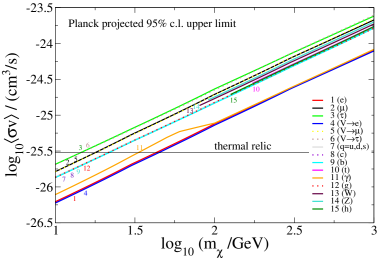
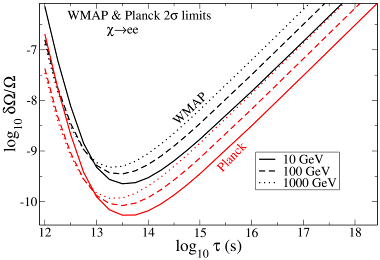


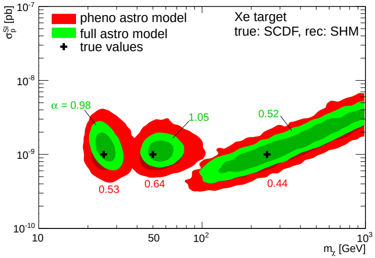


Direct detection likelihoods

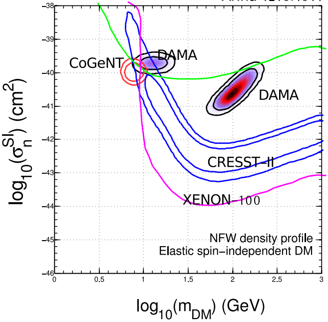
Much solid work done in implementing detailed direct detection likelihoods in pheno analyses – details coming up this afternoon

Akrami, Savage et al 1011.4318, 1011.4297
Pato et al 1012.3458, 1106.0743, 1211.7063
Arina et al 1105.5121, 1210.4011
Strege et al 1107.1715, 1112.4192, 1201.3631, 1212.2636

Pato et al 1211.7063



Arina 1210.4011



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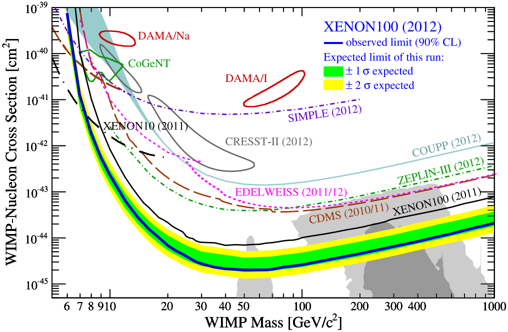
Direct Detection
DAMA vs. CoGeNT vs. CRESST-II vs. Exclusions



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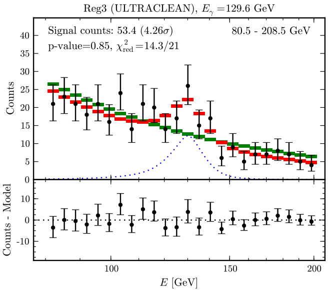
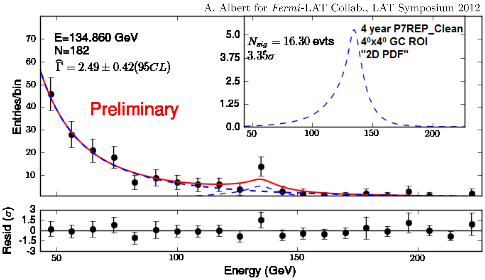
Gamma-ray lines

130 GeV line - to bump or not to bump

(Weniger *JCAP*, 1204.2797)





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5. Try to do something a bit more objective (→ David's talk)

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Compute time example: The LHC likelihood 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

First Order Response:

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

Taming the LHC monster

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

Taming the LHC monster

Second Order Response:

"That's ridiculous. I've never met a calculation I can't speed up. There must be some way to have my cake and eat it too"

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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?

Coverage

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 *JCAP*, 1011.4297, Bridges et al *JHEP*, 1011.4306, Strege et al *PRD*, 1201.3631)
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  (Akrami, Savage, PS et al *JCAP*, 1011.4297, Bridges et al *JHEP*, 1011.4306, Strege et al *PRD*, 1201.3631)

- *p*-value assessments of goodness of fit should be viewed with scepticism (→MasterCode)

What do we do for a CL/*p*-value when we can't obtain the distribution of our test statistic??

Scanning and Convergence

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 *JHEP*, 0910.3950, Feroz et al *JHEP*, 1101.3296)

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

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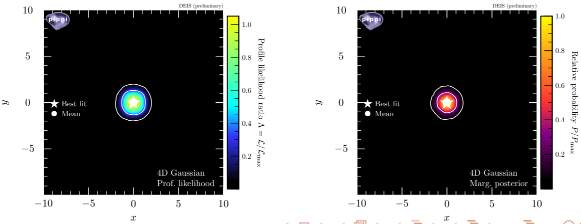
→ Differential Evolution may help

DEIS algorithm (Differential Evolution with Importance Sampling)

Roebber, PS, Putze & Holder, in prep



Outline

CMSSM, SMS $\neq$ BSM

(SMS = Simplified Model Spectrum)

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

Hitting the wall

Issues with current global fit codes:

- Strongly wedded to a few theories (e.g. constrained MSSM / mSUGRA)
- Strongly wedded to a few theory calculators
- All datasets and observables basically hardcoded
- Rough or non-existent treatment of most experiments (astroparticle + collider especially)
- Sub-optimal statistical methods / search algorithms
- $\Longrightarrow$ *already hitting the wall on theories, data & computational methods*

Closing remarks

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- Coverage, scanning and general compute time all mess with each other – some progress, but more work needed
- The move to theory space has begun – but requires all the rest to be solved too!