# Particle studies of Dark Matter

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# Outline

1) Brief introduction to dark matter, and where gamma rays fit into the picture

2) Very brief introduction to the *particle physics* of dark matter

- what does the Standard Model of Particle Physics tell us?
- what has the LHC told us so far?
- what possible theories of dark matter are there?

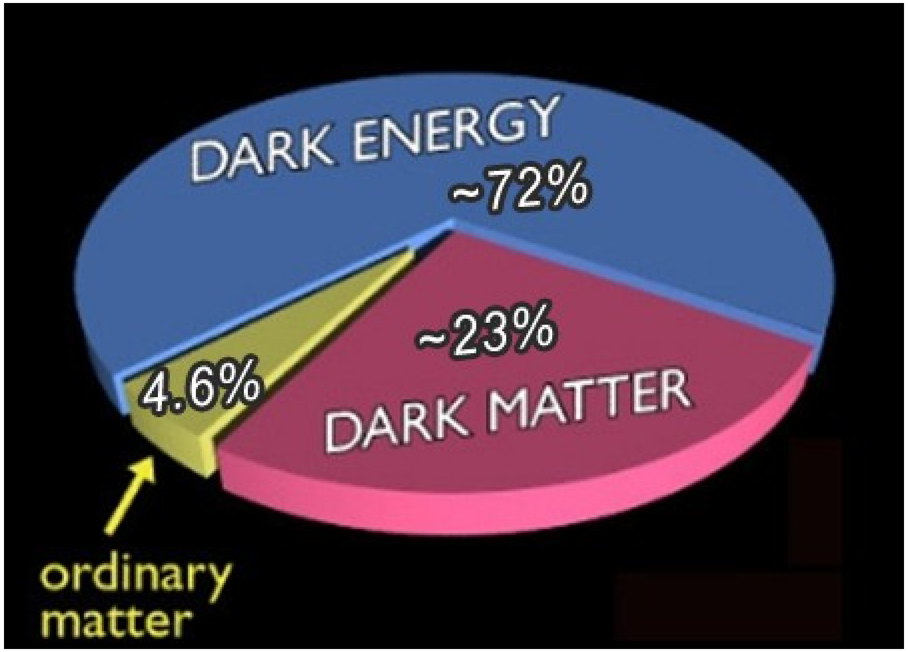
3) Advertisements for recent Australian particle astrophysics work:

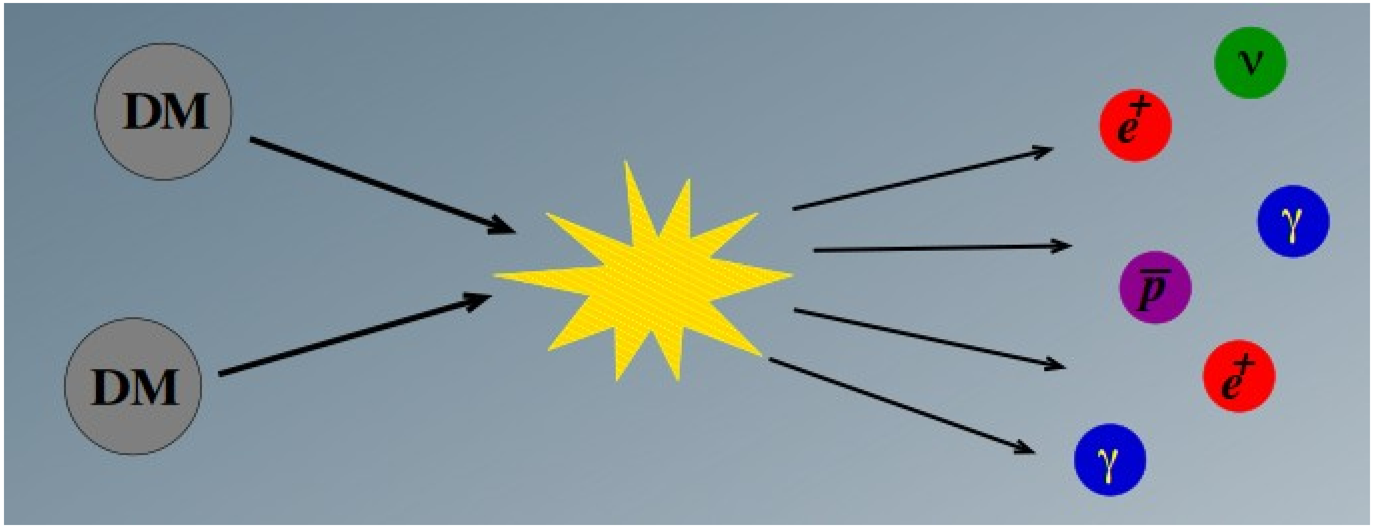
- Bayesian analyses of supersymmetric models
- GAMBIT collaboration
- Bayesian analyses of cosmic electron-positron anomaly
- ongoing projects

Evidence from e.g.

- galaxy rotation curves
- gravitational lensing
- CMB
- Bullet cluster

- *Cold* dark matter is preferred
    - i.e. non-relavisitic when structure formation starts
- DM should be electrically neutral
- WIMP paradigm is highly favoured
    - need a *Weakly Interacting Massive Particle*
    - typical weak interaction cross-section can give correct relic density






- Dark matter should be (mostly) stable
- Can usually pair-annihilate into SM particles
    - also get coannihilations in complex new physics models
- Can try observing the annihilation products in various channels

# Gamma rays are *particularly* good

A nice recent review: Bringmann & Weniger, arXiv: 1208.5481

- Gamma rays propagate without being perturbed

  - they thus point back to the source
  - we get distinct spatial and spectral signatures

Expected flux ($GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\psi) = \frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \cdot \int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\rm l.o.s} d\ell(\psi)\rho^2(\mathbf{r})$$

particle physics — astrophysics

$\langle\sigma v\rangle_{\rm ann}$ : total annihilation cross section

$m_\chi$ : WIMP mass $(50\,{\rm GeV} \lesssim m_\chi \lesssim 5\,{\rm TeV})$

$B_f$ : branching ratio into channel $f$

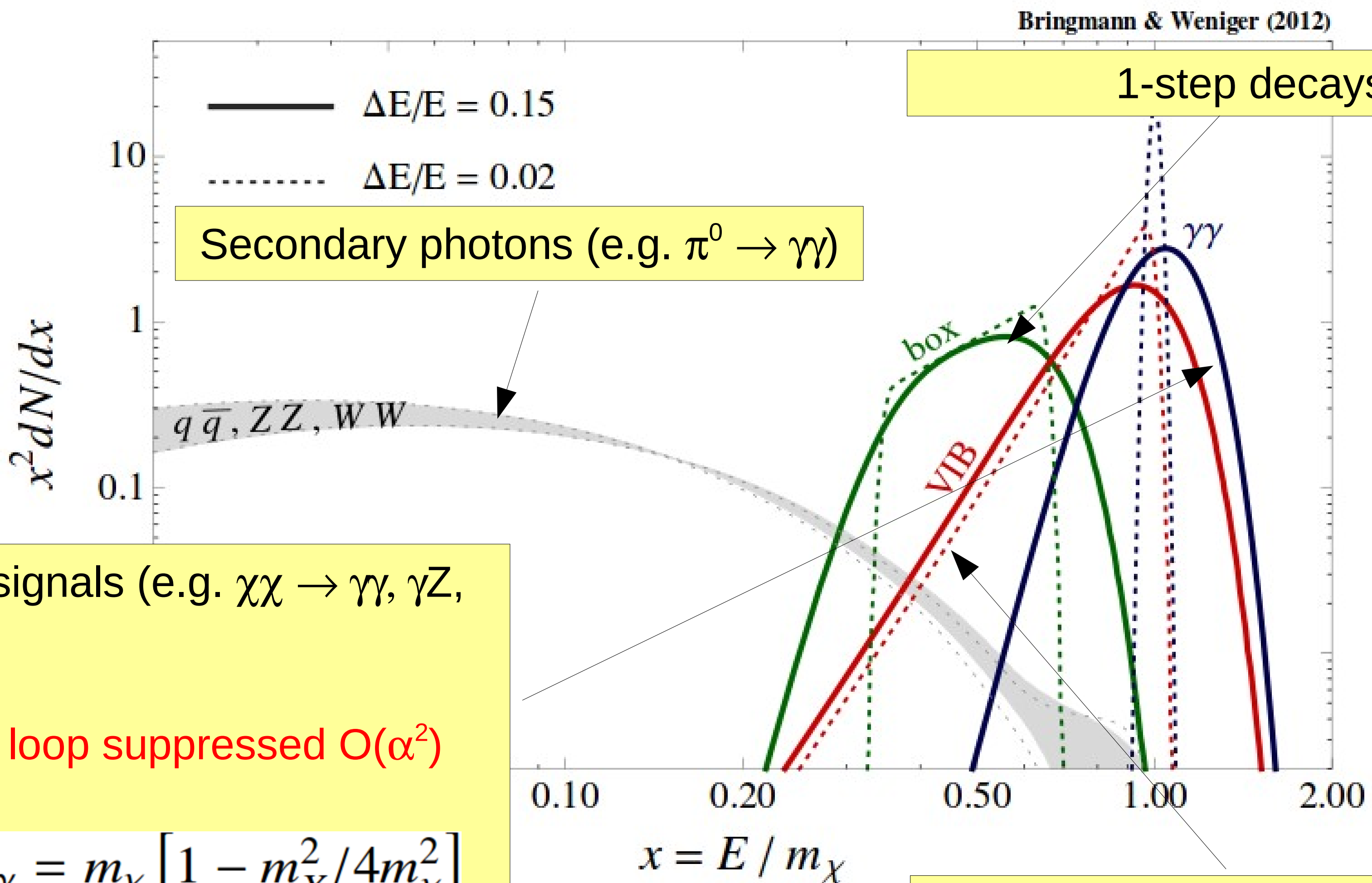
$N_\gamma^f$ : number of photons per ann.

for point-like sources: $\simeq (D^2\Delta\psi)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\Delta\psi$ : angular res. of detector

$D$ : distance to source

- Given a physics model, we can calculate the gamma ray spectrum
- Have a number of possible gamma ray production mechanisms




1-step decays

Secondary photons (e.g. $\pi^0 \rightarrow \gamma\gamma$)

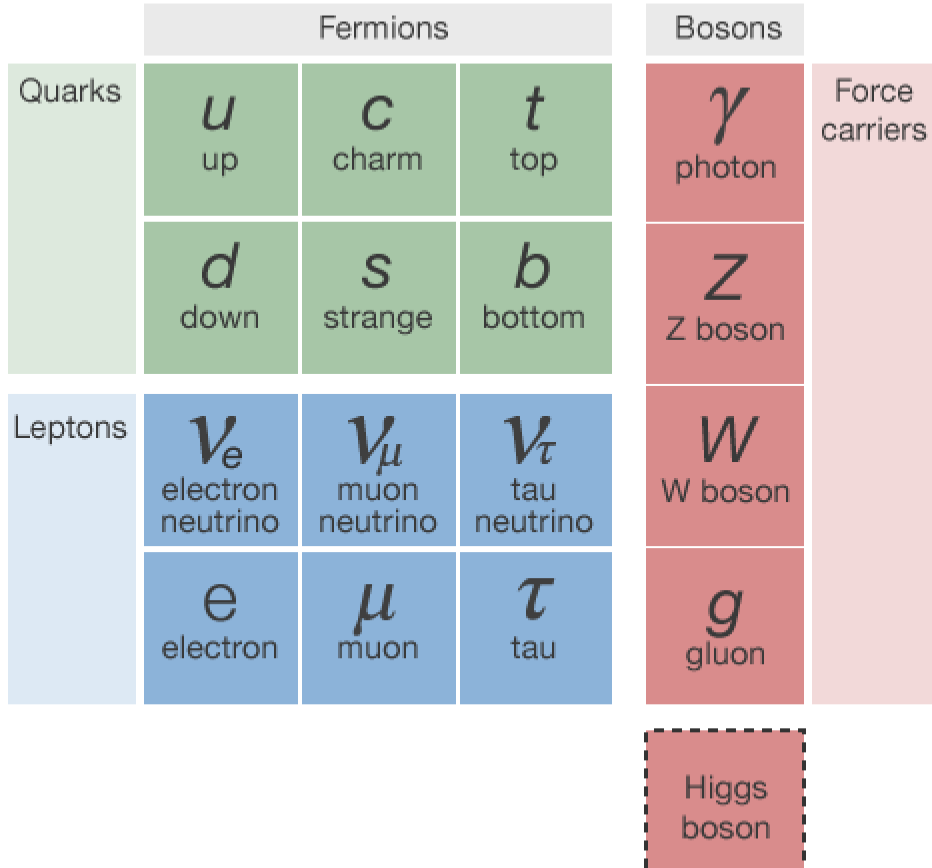
Line signals (e.g. $\chi\chi \rightarrow \gamma\gamma$, $\gamma Z$, $\gamma H$)

- loop suppressed $O(\alpha^2)$

$$E_\gamma = m_\chi \left[1 - m_X^2/4m_\chi^2\right]$$

Virtual internal brehmsstrallung

# The particle physics of dark matter: The Standard Model




Source: AAAS

- Nothing here provides a viable WIMP candidate

  - neutrino mass is too small

- *We are forced to ponder Beyond the Standard Model (BSM) physics...*

# Possible WIMP models

- There are an infinite number

  - a surprising proportion have been published!

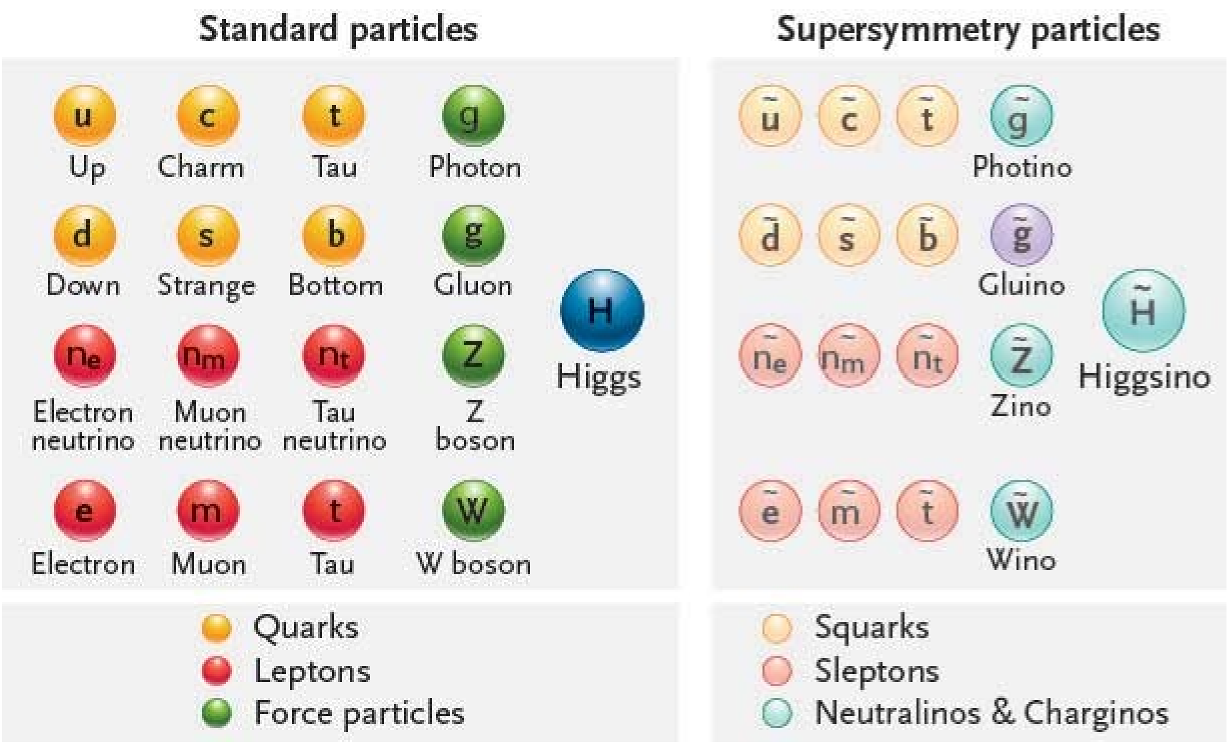
- Generic dark matter model:

  - add some new field content to the Standard Model
  - impose a $Z_2$ symmetry to prevent decay of lightest new particle
  - a WIMP is born

- Examples:

  - supersymmetry with R-parity
  - Universal Extra Dimensions with KK parity
  - Little Higgs models with T parity
  - Higgs portal models with arbitrary field content and an arbitrary $Z_2$ symmetry

# Supersymmetry: The most popular BSM theory




SUSY proposes a fundamental symmetry of Nature relating fermions and bosons

Introducing SUSY doubles the particle content of the SM

- Invented in the 1970s, solves lots of problem of the SM
  - e.g. gauge unification, cancelling unpleasant corrections to Higgs mass
  - can impose a $Z_2$ symmetry (R-parity) that protects lightest sparticle (LSP) from decay
- The LSP could be ideal WIMP candidate
  - LSP can easily be the lightest neutralino or a sneutrino

# Supersymmetry breaking

• Minimal Lagrangian of broken SUSY has over 100 new parameters

- assumptions about physics at high scales can reduce this
- many parameters have to be small to prevent e.g. proton decay

• Many simplified SUSY models exist

- e.g. CMSSM: 4.5 parameters ($m_0$,$m_{1/2}$, $A_0$, tan$\beta$, sgn($\mu$))
- pMSSM: 19-24 parameters (encodes most of the dependence of interesting observables)

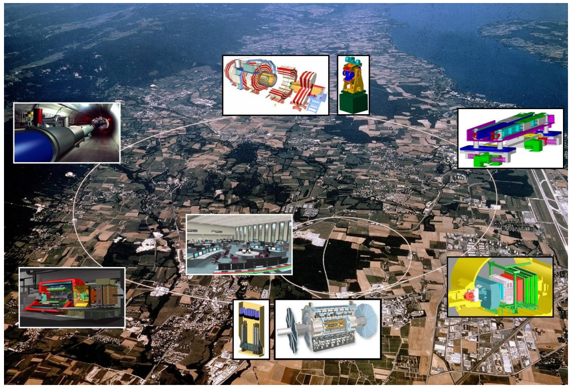
• In SUSY:

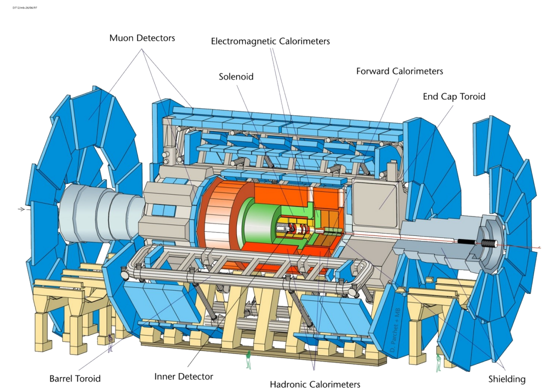
- we can calculate everything for a given SUSY model
- exploring all possible options is immensely challenging

• Have plenty of non-minimal SUSY models with extra field content

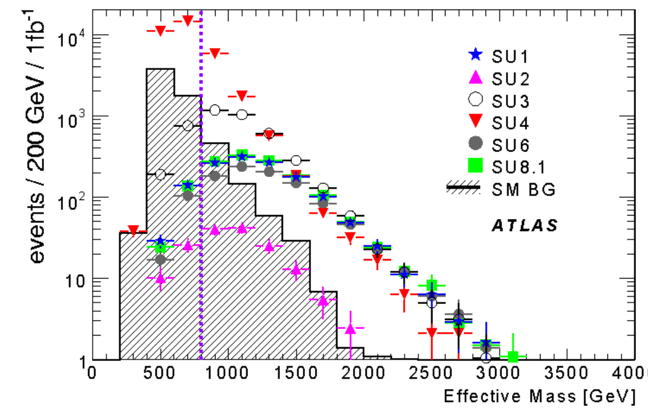
- give even more options for dark matter...

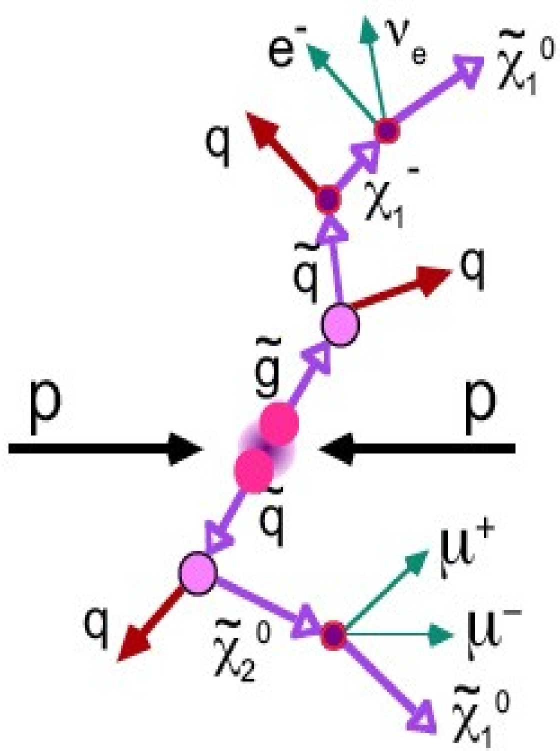
# SUSY dark matter at the Large Hadron Collider





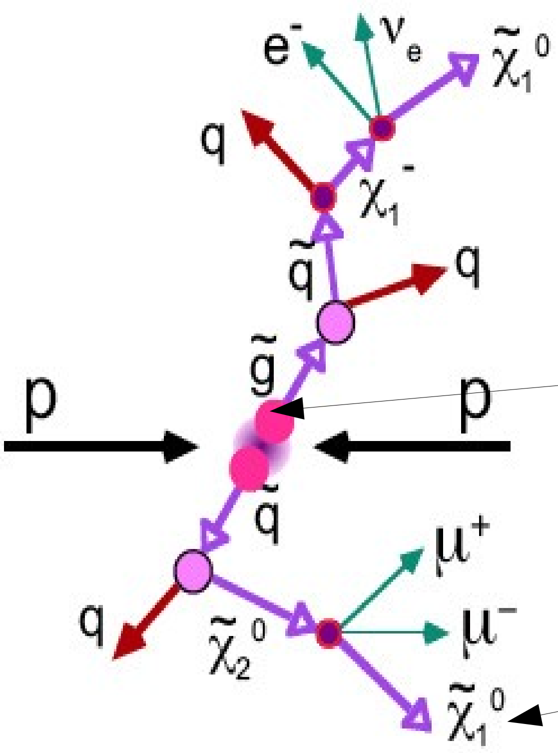

Four vectors




- The dark matter particles are invisible at the LHC
  - we can tell something left the detector
  - *missing energy*
- SUSY events typically look different to SM events
  - we can discover SUSY by looking for excesses of events in inclusive search channels
  - can also extract mass and coupling information

# LHC SUSY conclusions are usually *model dependent*



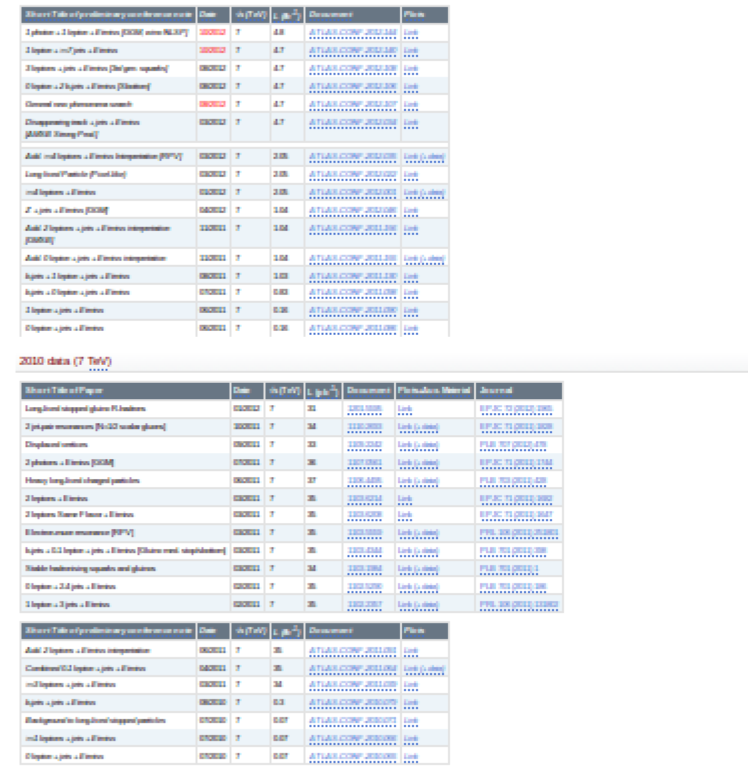

Smacking protons together will tend to produce *coloured* particles in preference to non-coloured particles

These particles decay to dark matter (eventually)

- We can only get direct constraints on DM couplings by searching for weak production processes

  - much rarer
  - smaller reach in masses

# Status of SUSY searches at the LHC




*No evidence for SUSY!*

# What do we learn from the LHC data?

- Some models are now rubbish, others should be studied with high priority

- Given a specific SUSY model (e.g. a set of CMSSM parameters)

  - can calculate number of expected events at the LHC
  - can use the LHC data to assign a likelihood to the model (Poissonian)
  - can also use precision collider data and dark matter data to assign extra likelihood terms

- Can use statistical fits in the parameter space to quantify:

  - which regions are still viable
  - whether a given model (e.g. CMSSM) is favoured with respect to the Standard Model

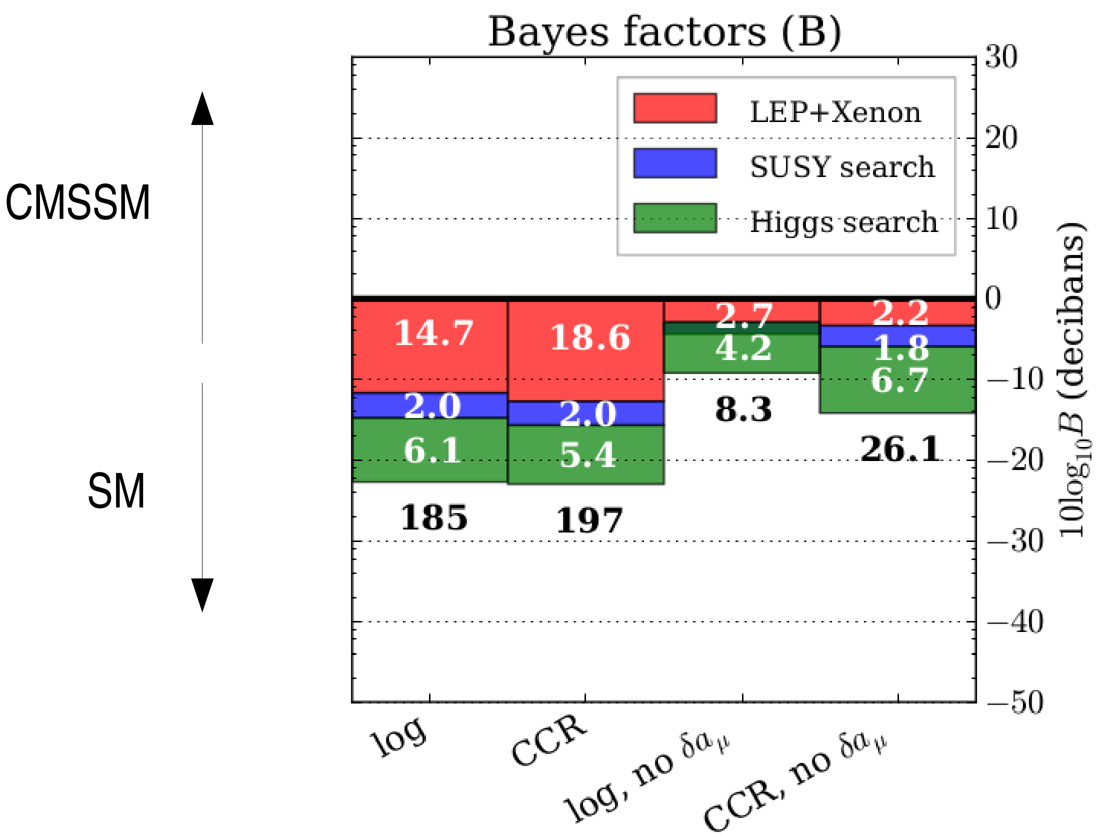
- This represents a formidable technical challenge

  - standard codes for evaluating observables can be very slow (hours)
  - have developed techniques for speeding up calculations
  - use state of the art sampling technology to perform the fits

# Example: Bayes factors for CMSSM

- The Bayesian evidence is a standard quantity for model selection

  - ratios of evidence values for two models allow one to quantify faith in models




***The CMSSM is disfavoured with respect to the SM by ~ 3 orders of magnitude!***

| $B$ | Strength of evidence |
|---|---|
| $< 1:1$ | Negative |
| 1:1 to 3:1 | Barely worth mentioning |
| 3:1 to 10:1 | Substantial |
| 10:1 to 30:1 | Strong |
| 30:1 to 100:1 | Very strong |
| $> 100:1$ | Decisive |

The Jeffreys scale for interpreting Bayes factors

Balazs, Farmer, MJW et al, arXiv:1205.1568

# The next step: GAMBIT

- Any solution to the dark matter problem involves a similar challenge

    - taking all available astro and particle data and testing particle models
    - direct, indirect and collider data often provide highly complementary constraints

<u>Global and Modular BSM Inference Tool (GAMBIT)</u>

- An open source BSM inference tool (in development)

    - separate packages for scanning, physics and likelihood calculations
    - fully modular design (easy to write new modules)

- Allows generic testing of BSM physics models with all relevant data

    - will contain a large repository of existing models & data
    - easy implementation of new models and datasets

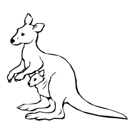
- Statistical routines fully configurable (e.g. frequentist/Bayesian, scanning, likelihoods)

- A mix of standard codes (e.g. DarkSUSY), new codes, and interfaces to standard packages

    - in particular, a new *fast* Large Hadron Collider module is being developed
    - will contain code necessary to evaluate gamma ray yields

# Who is GAMBIT?

| | |
|---|---|
| **FERMI LAT** | P. Scott, J. Conrad, J. Edsjö, G. Martinez |
| **Ice Cube** | P. Scott, J. Edsjö, C. Savage |
| **ATLAS** | M. White, A. Buckley, P. Jackson, C. Rogan, A. Saavedra |
| **HESS** | J. Conrad |
| **AMS-02** | A. Putze |
| **CTA** | M. White, T. Bringmann, J. Conrad |
| **DARWIN** | J. Conrad |
| **LHCb** | N. Serra |
| **Theory** | M. White ,P. Scott, C. Balázs, T. Bringmann, L.-A. Dal, J. Edsjö,B. Farmer, A. Krislock, A. Kvellestad, N. Mahmoudi, A. Raklev, C. Savage, C. Weniger |

■ = 

| | | | |
|---|---|---|---|
| Aachen University | DESY | Max-Planck Munich | University of Sydney |
| Adelaide University | University of Glasgow | McGill University | Stockholm University |
| University of Amsterdam | University of Hamburg | Monash University | University of Utah |
| Clermont-Ferrand | Harvard University | University of Oslo | University of Zurich |

# Possible uses of GAMBIT in supporting CTA effort

- After development, will use GAMBIT to explore a variety of BSM physics models:

  - general SUSY models
  - non-SUSY alternatives
  - first physics paper expected next summer

- Can easily spin off sensitivity studies for CTA

  - will have lots of tools and expertise to do so
  - GAMBIT collaboration allows small author papers with interested parties
  - existing GAMBIT/CTA overlap will facilitate collaboration

# Adverts for other indirect detection work

SUSY models with large gamma ray signatures (focus point models) MJW

- how to improve LHC measurements of dark matter (including improved gamma ray flux predictions): JHEP 1007 (2010) 064
- complementarity of gamma ray and LHC measurements: Phys.Rev. D77 (2008) 055014

Extracting the size of the cosmic electron-positron anomaly (Csaba Balazs)

- uses Bayesian inference techniques to quantify size of anomaly in PAMELA and FERMI data: Astrophys.J. 749 (2012) 184

Constraining couplings of effective theories of dark matter (Csaba Balazs, Jayden Newstead)

- used direct search and collider data to probe couplings of generic dark matter models
- masters thesis

Higgs portal models for dark matter (MJW, Tony Williams, Filip Radjec)

- honours project on devising new, viable Higgs portal DM models

# Summary

- If the WIMP paradigm is correct, much of the dark matter problem involves particle physics

  - understanding this physics using all data over the next ten years is challenging
  - even in the case of negative results, we can learn a lot about possible candidates

- We have lots of expertise in Australia that will be useful to CTA

  - development of tools (GAMBIT)
  - devising new dark matter models
  - testing popular dark matter candidates