Global **BSM** Fits & **Astrophysical** Data:

Three Examples

Global BSM Fits and LHC Data, CERN/ February 10, 2011

Yashar Akrami

In collaboration with:

Lars Bergström, Jan Conrad, Joakim Edsjö, Christian Farnier, Joachim Ripken, Chris Savage and Pat Scott

JCAP 01, 031 (2010) [arXiv:0909.3300]

arXiv:1011.4318

arXiv:1012.3939

Stockholm University

Oskar Klein centre

Oskar Klein Center for Cosmoparticle Physics (OKC)

Peter's talk (publish experimental results):

Peter Wienemann: SUSY/

Possible strategies:

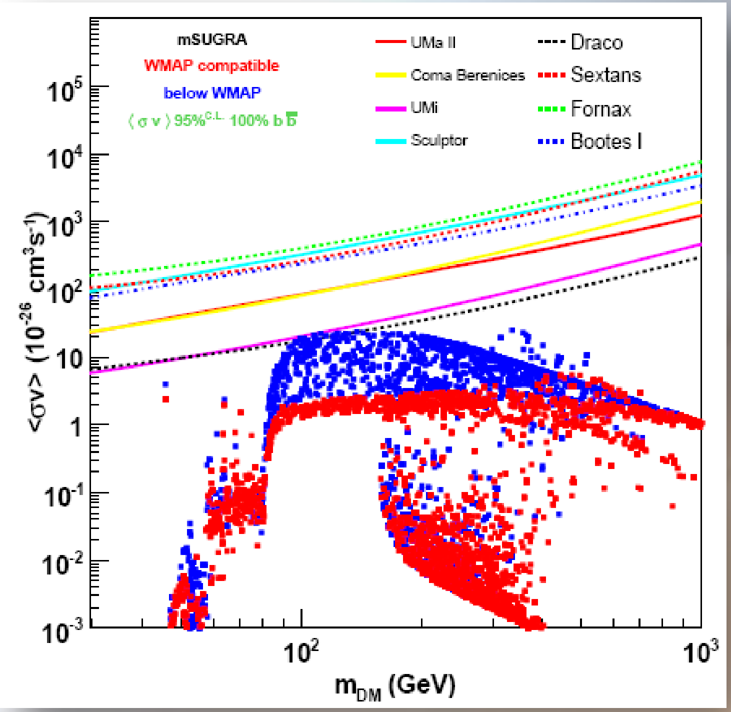
- Publication of detector unfolded fiducial cross-sections
  Cons: model-dependence of unfolding, analysis optimisation model specific
- Publication of measurements without detector unfolding
  Cons: test of alternative models requires detector simulation, analysis optimisation model spec.
- Publication in terms of simplified models
  Cons: mapping of specific model onto simplified models only approximate

Astrophysical Data:

Until recently:

- **Simplified** models

Example: 100% annihilation to $b\bar{b}$

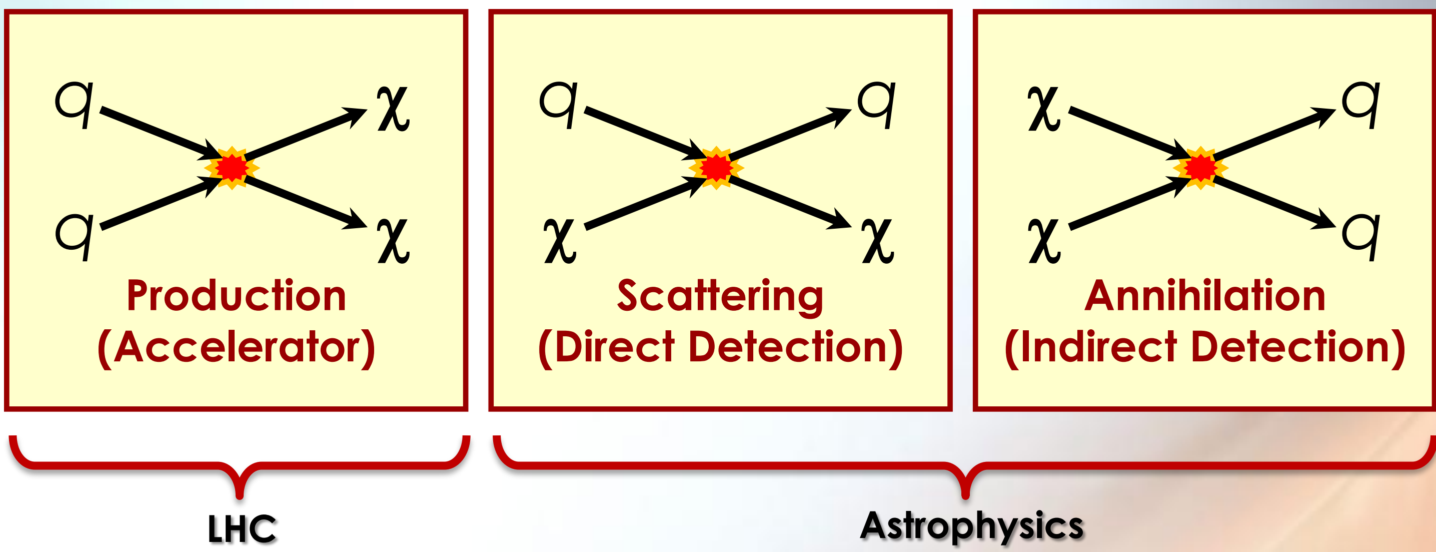


Fermi Collaboration, Astro. J. (2010) [arXiv:1001.4531]

More recently:

- **Unfolded** data
  - Indirect Detection: **H.E.S.S.** (GC/Sagittarius)
- rawdata
  - Model **folded with detector response**
    - Indirect detection: ***Fermi*** (Segue 1)
    - Direct detection: **Future ton-scale** experiments

WIMP Dark Matter



Astophysicits are interested in Dark Matter problem.

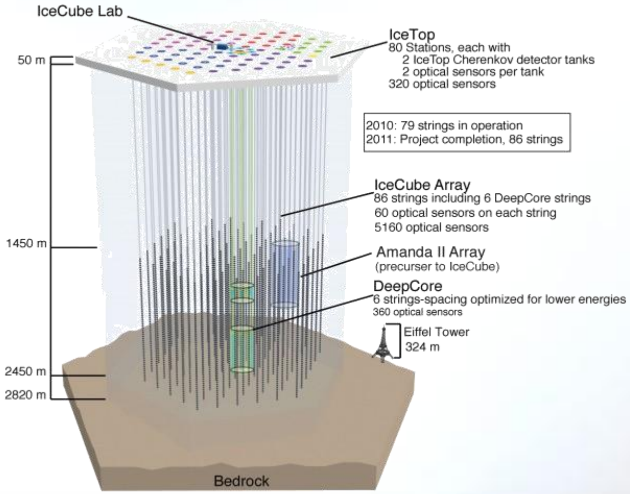
Simpler than LHC:

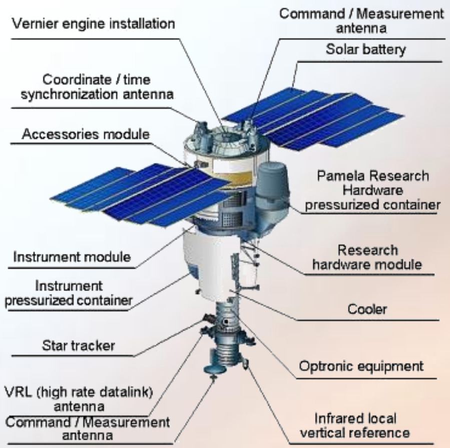
Astrophysical constraints are sensitive only to the following observables:

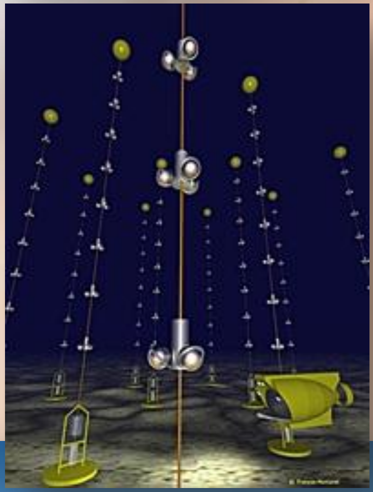
- **WIMP mass and cross-sections**
- **Some branching fractions (different annihillation channels in ID)**

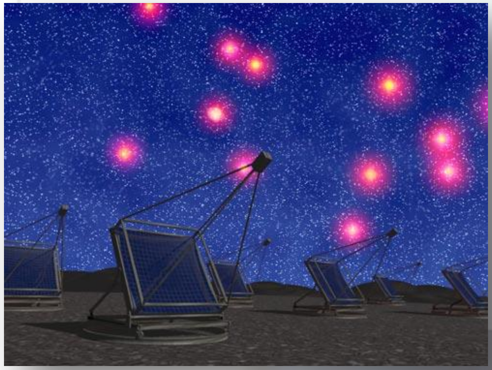
Indirect Detection – WIMP annihilation into:

- positrons – **PAMELA, *Fermi*, ATIC, AMS**
- gamma-rays – ***Fermi*, H.E.S.S., CTA**
- anti-protons – **PAMELA, AMS**
- anti-deuterons – **AMS, GAPS**
- neutrinos – **IceCube, ANTARES**









Gamma-rays from dark matter:

Theoretical differential gamma-ray flux per unit solid angle:

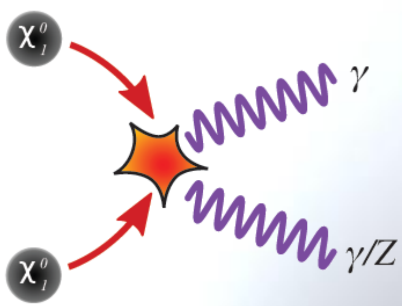
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1+BF}{8\pi m_\chi^2} \sum_f \frac{\mathrm{d}N_f^\gamma}{\mathrm{d}E} \sigma_f v \int_{\mathrm{l.o.s.}} \rho_\chi^2(l)\mathrm{d}l$$

Theoretically predicted spectrum
(differential photon yield from any particular final state)

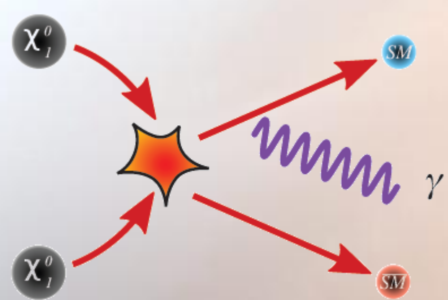
Likely targets:

- Galactic centre - **large signal, large BG**
- Galactic halo - **moderate signal, moderate BG**
- Dark clumps - **low statistics, low BG**
- Dwarf galaxies - **low statistics, low BG**
- Clusters/extragalactic diffuse - **large modelling uncertainties, low signal, low BG**
- The Sun - **neutrinos only, very model-dependent**

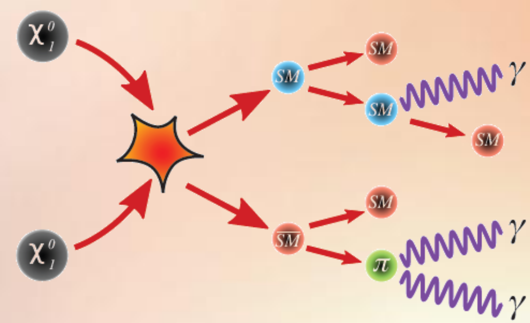
3 main gamma-ray channels:



2 photons or Z+photon:
Monochromatic Lines



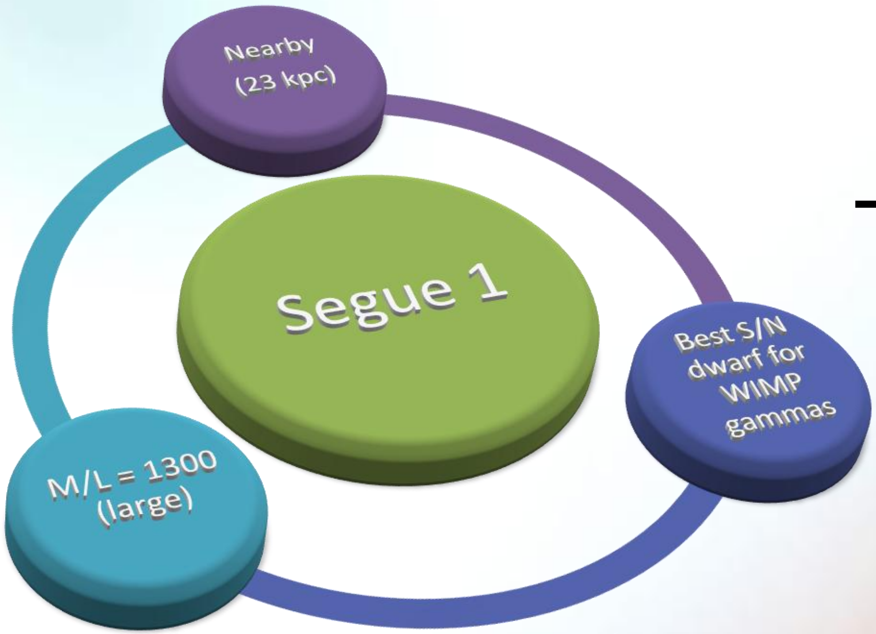
Internal Bremsstrahlung:
Hard Spectrum



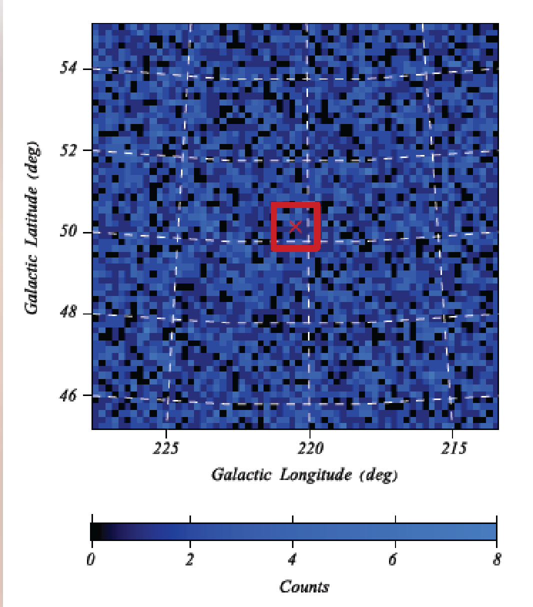
Secondary Decay:
Sof(ter) Continuum Spectrum

Example 1: *Fermi* Observations of Segue 1 + CMSSM Scans:

Why Segue 1?



→ **Leads the pack in Fermi DM upper limit analyses**
(1–2 orders of magnitude better than UMi & Draco)



Purpose:

see how Segue observations impact real models, considering 'soft bounds' (i.e. full likelihood function).

Some Technicalities:

- Same **cuts**:
  - "DIFFUSE" event class
  - 105 zenith angle cut
  - 10 ROI
  - 14 energy bins from 100MeV–300 GeV
- **Binned Poissonian** likelihood
- **Spatial-spectral fit** to inner 6 x 6 bins of 64 x 64 region of interest
- Dark matter **halo profile** from best-fit Einasto profile from stellar kinematic data (Martinez et al., JCAP 2009)
- **Galactic diffuse BG** from preliminary *Fermi* all-sky *GALPROP* fits
- Isotropic powerlaw **extragalactic BG** (as seen by *EGRET*)
- **BG normalisations** from dwarf UL fits (i.e. full 10˚ x 10˚)
- **Fast integration** over energy-dependent IRFs (P6v3) with **FLATlib** – (dwarf UL analysis skips energy dispersion)
- Inclusion of **systematic errors** from effective area and theoretical calculations – (dwarf UL analysis skips systematics)
- Integration into **SuperBayeS**, upgraded with **DarkSUSY 5** (including internal bremsstrahlung), bug fixes, etc.
- **515 data points** in the global fit, vs 11 previously with SuperBayeS 1.35 (admittedly not such a fair comparison)

LAT IRFs (Instrument Response Functions):

- IRF is the mapping between the incoming photon flux and the detected events. IRF can be framed as an area times the probability that a photon with a given set of input parameters is detected as an event with a set of observables.

- For the LAT, the photon parameters are the energy E and the inclination angle φ (the angle between the LAT normal and the true source position) and the event is characterized by the apparent energy E' and the apparent source position φ'. Note that φ is an angle while φ' is a vector.

- Current formulation of the IRF is:

$$R(E',\varphi' ; E,\varphi) = \underbrace{A_{eff}(E,\varphi)}_{\text{Effective Area}}\ \underbrace{p_{PSF}(\varphi' ;E,\varphi)}_{\text{Point Spread Function}}\ \underbrace{p_E(E' ;E)}_{\text{Energy Redistribution}}$$

  - A_{eff} is the effective area (with units of area),
  - p_{PSF} is the point-spread function (PSF)
  - p_E is the energy redistribution function.
  - φ is the inclination angle for the photon's actual direction
  - φ' is the vector for the photon's apparent direction.

We convolved our modelled GR fluxes with LAT IRF using the publicly-available Fortran90 library FLATlib

- A number of assumptions are embedded in this formulation:
  - the energy redistribution function is assumed to have no dependence on the actual or apparent inclination angles
  - the PSF has no dependence on the apparent energy.
  - in addition, it is assumed that p_{PSF} is actually $p_{PSF}(\theta ;E,\varphi)$, where θ is the angle between the true and apparent source positions; thus we assume that the PSF is circular around the true source position.

- The LAT IRF is determined by Monte Carlo simulations of the response of the LAT to a photon of energy E and inclination angle φ, and then reconstructing the resulting event. The comparison between the calculated properties of the event and the incoming photon gives the IRF.

Likelihoods from Segue 1:

9 months of real data:

- Because of the very low statistics observed in LAT photon counts towards Segue 1, a X^2 estimation of the likelihood is inappropriate in this case. We calculated the likelihood using a binned Poissonian measure:

$$\mathcal{L} = \prod_j \frac{\theta_j^{n_j} e^{-\theta_j}}{n_j!}$$

  - n_j is the observed number of counts in the j^{th} bin
  - θ_j is the predicted number of counts

- If we consider a systematic error that has the impact of consistently rescaling the observed number of counts as $n_j \rightarrow \varepsilon n_j$ (i.e. a constant percentage systematic error $|1-\varepsilon|$), and assume a Gaussian form with width σ_ε for the PDF of ε, the marginalised log-likelihood is:

$$\begin{aligned} -\ln \mathcal{L} &= -\sum_j \ln \left\{ \frac{1}{\sqrt{2\pi}\sigma_\epsilon} \int_0^\infty \frac{(\epsilon\theta_j)^{n_j} e^{-\epsilon\theta_j} \exp\left[-\frac{1}{2}\left(\frac{1-\epsilon}{\sigma_\epsilon}\right)^2\right]}{n_j!} d\epsilon \right\} \\ &= -\sum_j \ln \left\{ \frac{\theta^{n_j}}{\sqrt{2\pi}\sigma_\epsilon n_j!} \int_0^\infty \epsilon^{n_j} \exp\left[-\epsilon\theta_j - \frac{1}{2}\left(\frac{1-\epsilon}{\sigma_\epsilon}\right)^2\right] d\epsilon \right\} \end{aligned}$$

Extrapolation to 5 years of observations:

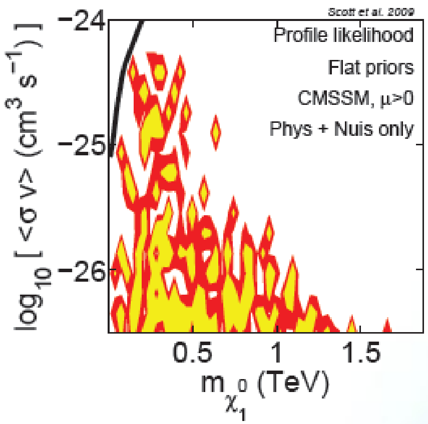
- We explicitly assume that no excess events will have been observed after this time.

$$\chi^2 = \sum_j \frac{\left(\Phi_{\mathrm{model},j} - \Phi_{\mathrm{observed},j}\right)^2}{\frac{\Phi_{\mathrm{model},j}}{\mathcal{E}_j} + \Phi^2_{\mathrm{observed},j} f(E_j)^2 + \tau^2 \Phi^2_{\mathrm{model},j}}$$

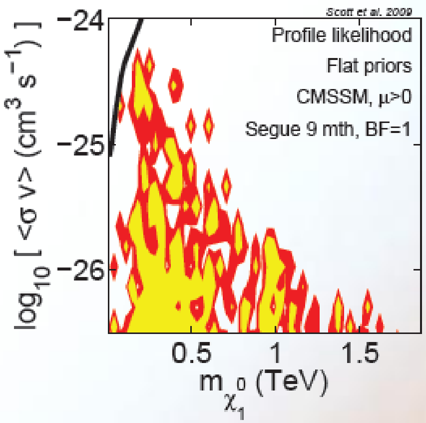
Annihilation Cross-Section (Segue 1 Only):

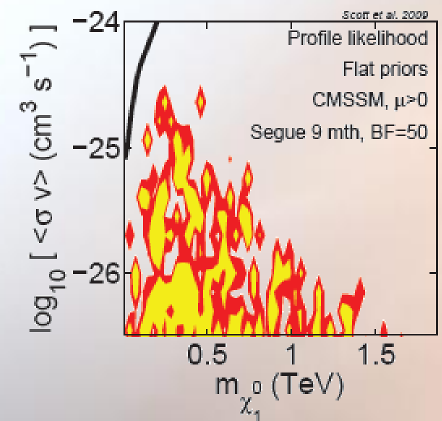
Scott, Conrad, Edsjö, Bergström, Farnier & YA, JCAP 2010

No *Fermi* data

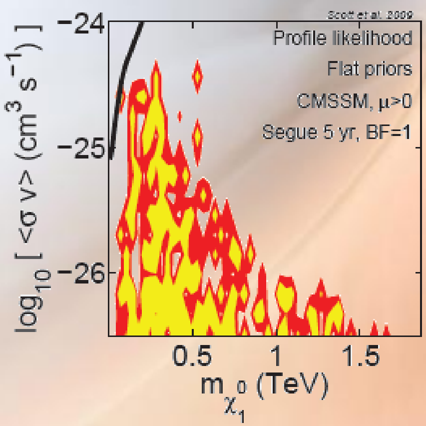


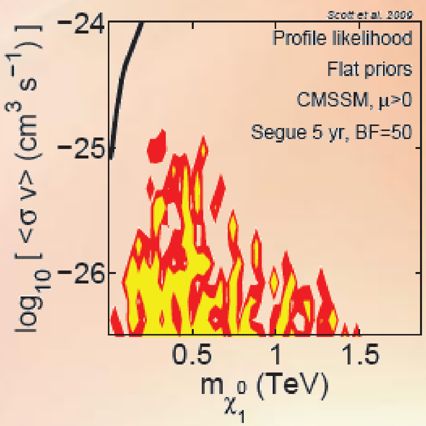
9 months of real data





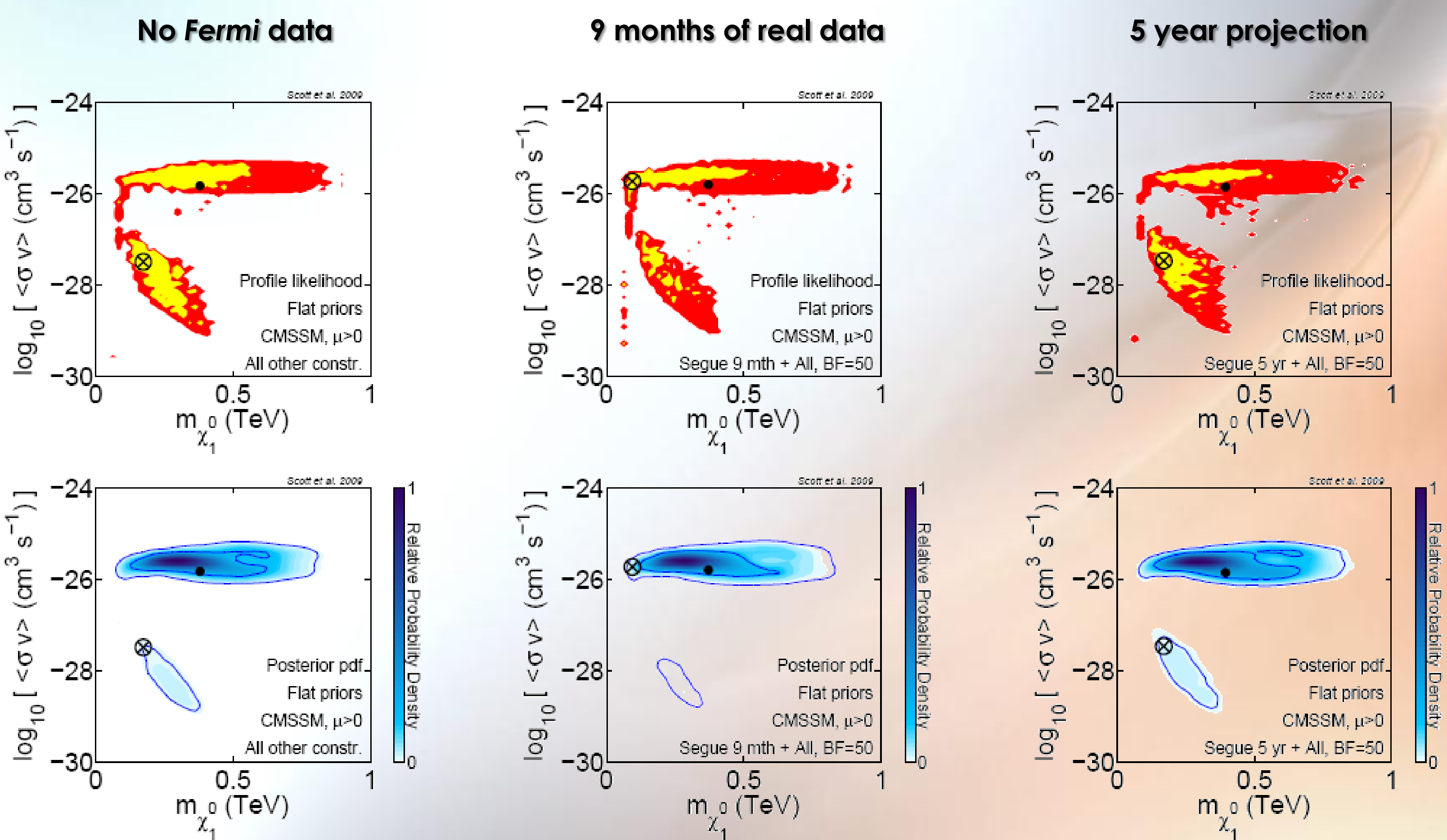
5 year projection





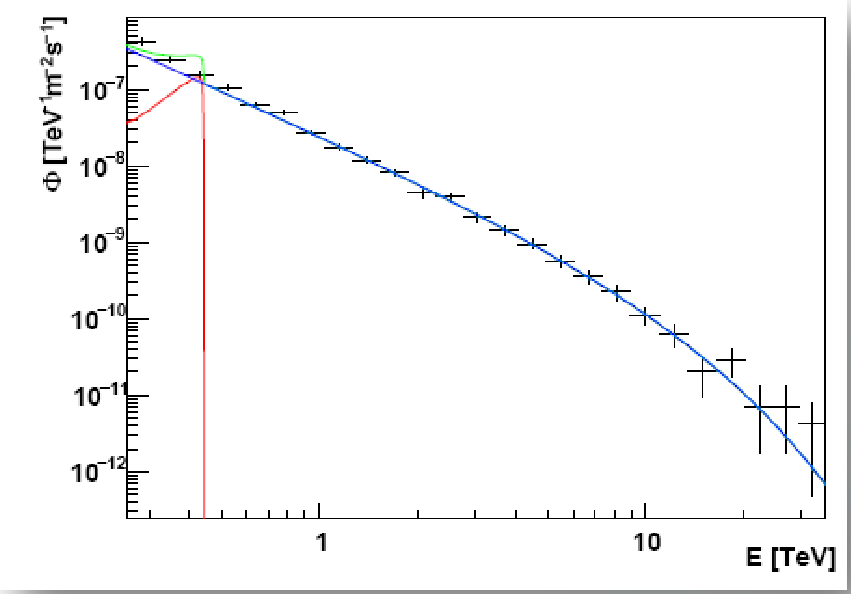
Annihilation Cross-Section (Segue 1 + All Other Observables):

Scott, Conrad, Edsjö, Bergström, Farnier & YA, JCAP 2010

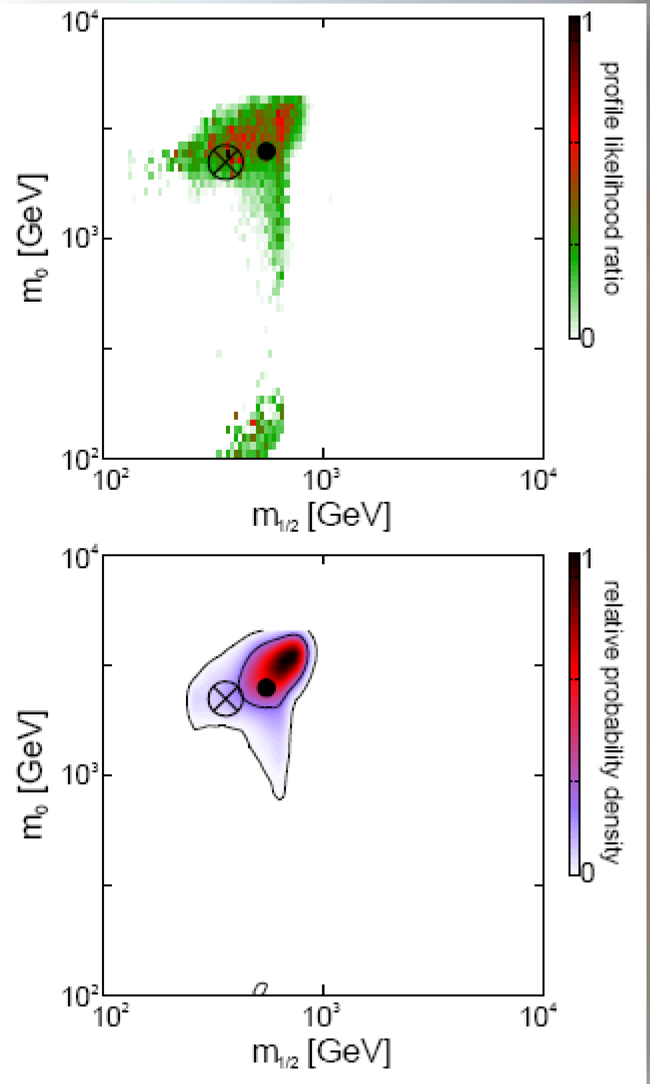


Example 2: H.E.S.S. Observations of GC & Sagittarius + CMSSM Scans:

Unfolded spectrum:



93 hr, $\bar{J}(\Delta\Omega)\Delta\Omega = 100$ sr



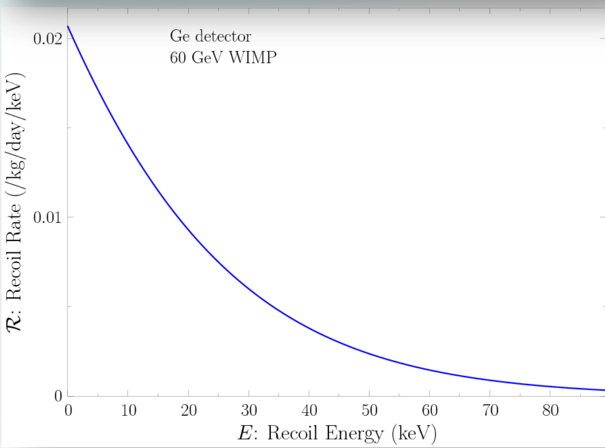
Ripken, Conrad & Scott [arXiv:1012.3939]

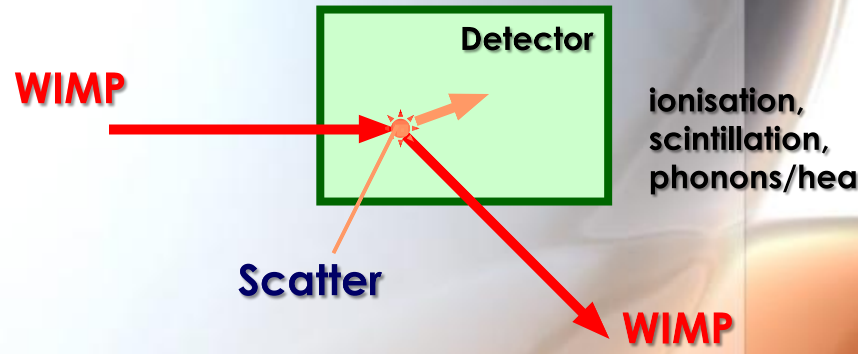
Direct Detection - Elastic Scattering of WIMP Off Detector Nuclei:

Theoretical differential recoil rate per unit detector mass:

Goodman & Witten (1985)

$$\frac{dR_{nr}}{dE_{nr}} = \frac{1}{2m\mu^2}\,\sigma\,F^2(q)\,\rho_0\,\eta(E_{nr},t)$$





CDMS, EDELWEISS, CRESST, ZEPLIN, XENON, LUX, COUPP, CoGeNT, TEXONO, etc.

Real experimental apparatus cannot determine the event energies with perfect precision (Efficiencies, quenching, energy resolution, multiple elements).

$\longrightarrow$ **In a real experiment, the expected observed spectrum is:**

$$\frac{dR}{dE} = \int_0^\infty dE_{nr}\,\underbrace{\phi(E,E_{nr})}_{\text{IRF}}\,\frac{dR_{nr}}{dE_{nr}}(E_{nr},t)$$

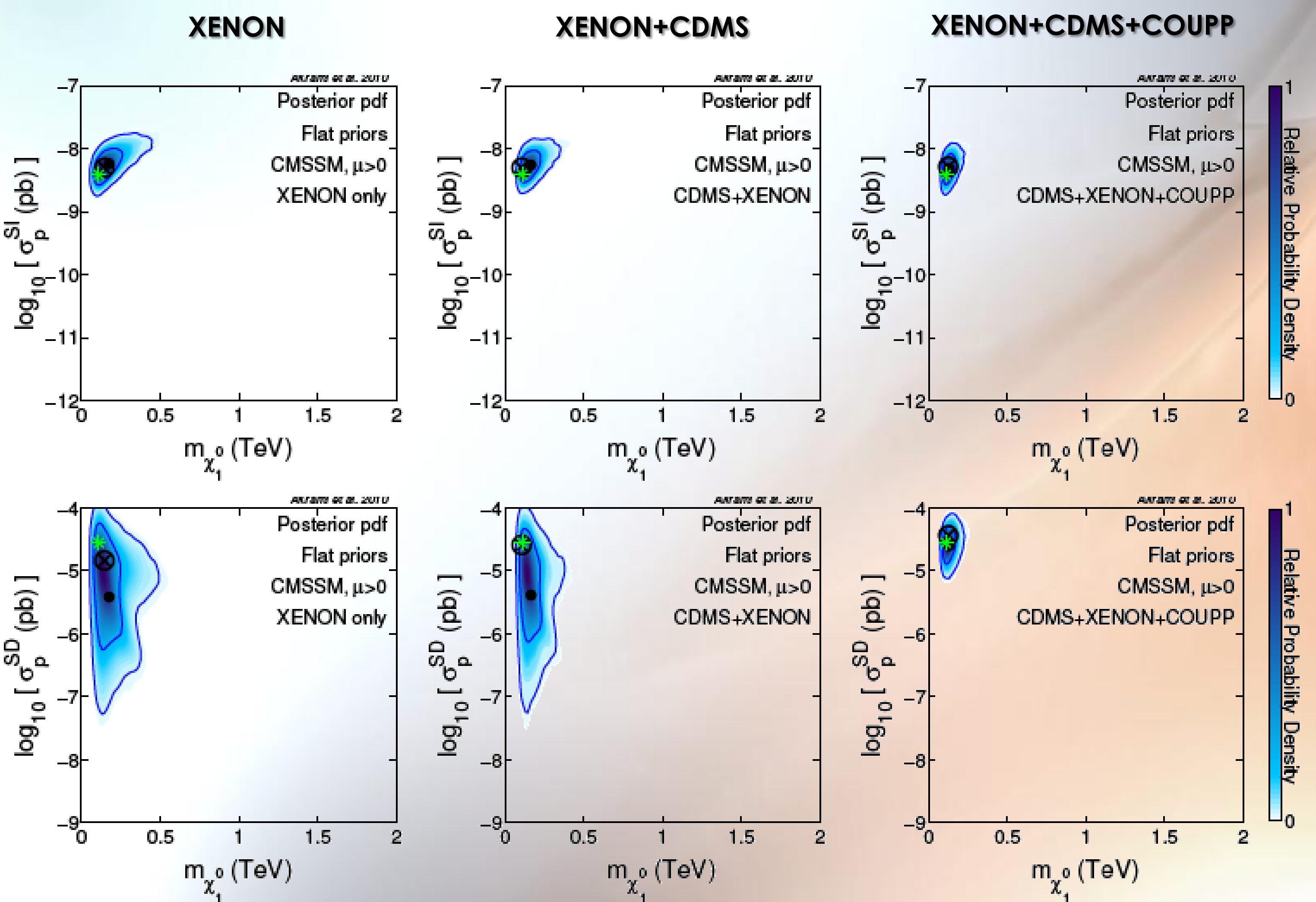
- E_{nr} is the true recoil energy
- E is the estimated recoil energy

Likelihood:

$$\mathcal{L}_{DD}(N,E_{1,..,N}) \;=\; P(N|\mu_{tot}) \prod_{i=1..N} f(E_i)$$

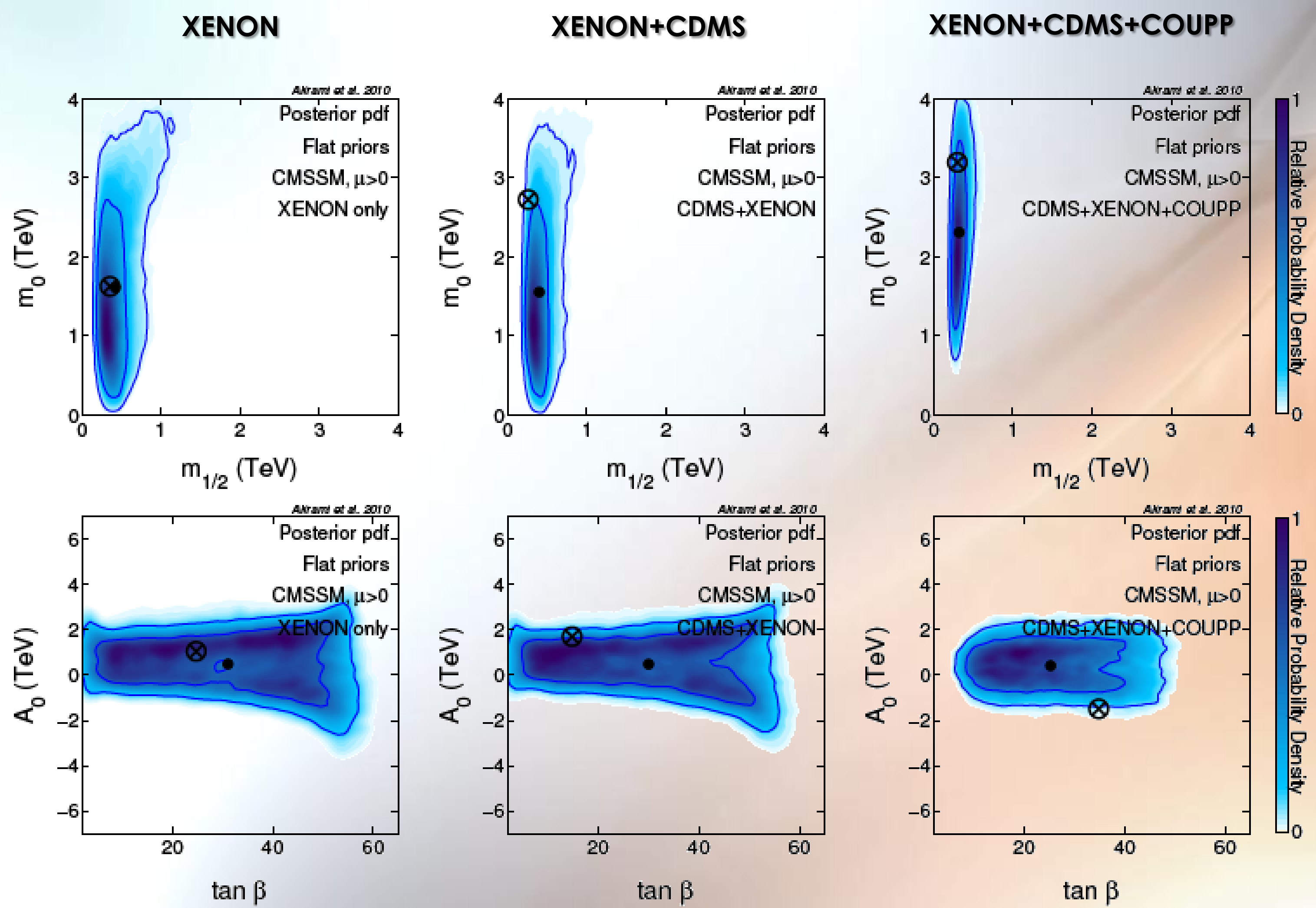
Scattering Cross-Sections (Future Ton-Scale DD Experiments Only):

YA, Savage, Scott, Conrad & Edsjö [arXiv:1011.4318]



CMSSM Parameters (Future Ton-Scale DD Experiments Only):

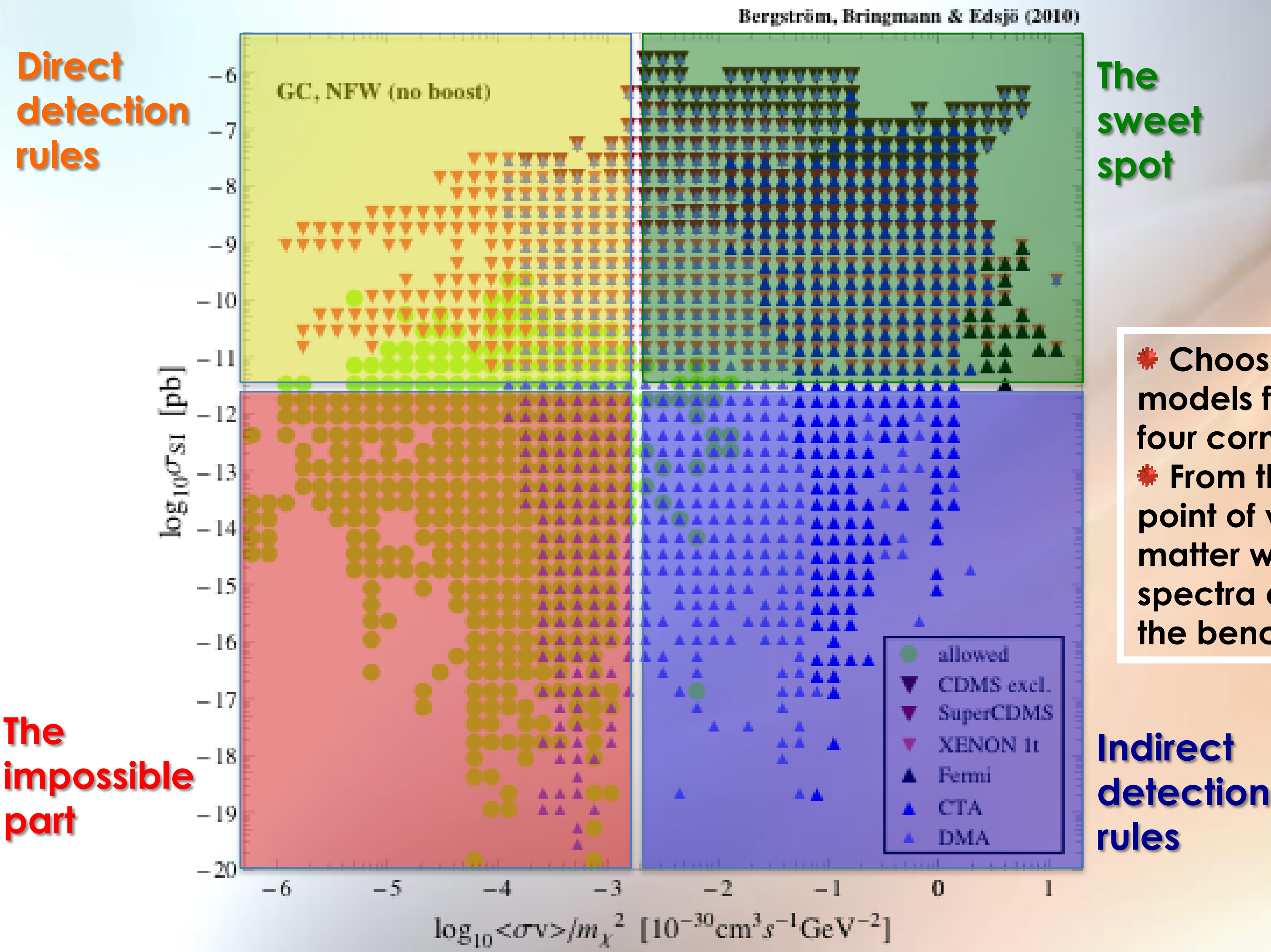
YA, Savage, Scott, Conrad & Edsjö [arXiv:1011.4318]



Direct vs Indirect and LHC:

- Large scan of MSSM and CMSSM models:

Bergström, Bringmann & Edsjö [arXiv:1011.4514]



- Choose benchmark models for LHC in the four corners.
- From the astrophysical point of view, it does not matter what mass spectra are chosen for the benchmarks.

Summary and Concluding Remarks:

- Astrophysicits are using all three *"possible strategies"* for publishing their experimental results all the time.

- It is however a much simpler case compaired to the LHC: not many observables are used.

- The main goal of astrophysical analyses is to solve the DM problem, and the data need to be integrated with LHC data to put strong constraints upon BSM parameters.

- Astrophysical analyses can suggest interesting benchmarks, although they are basically benchmark classes of BSM points rather than actual benchmark points.