

Directional detection and neutralino dark matter

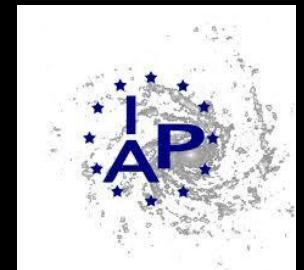
[Phys.Rev. D85 \(2012\) 055023](#)

In collaboration with J. Billard, F. Mayet (LPSC) and G. Bélanger (LAPTH)



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24th April 2012



PHYSICAL REVIEW D 85, 055023 (2012)

Probing neutralino dark matter in the MSSM and the NMSSM with directional detection

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(Received 30 January 2012; published 28 March 2012)

We investigate the capability of directional detectors to probe neutralino dark matter in the minimal supersymmetric standard model and the next-to-minimal supersymmetric standard model with parameters defined at the weak scale. We show that directional detectors such as the future MIMAC detector will probe spin-dependent dark matter scattering on nucleons that are beyond the reach of current spin-independent detectors. The complementarity between indirect searches, in particular, using gamma rays from dwarf spheroidal galaxies, spin-dependent and spin-independent direct search techniques is emphasized. We comment on the impact of the negative results on squark searches at the LHC. Finally, we investigate how the fundamental parameters of the models can be constrained in the event of a dark matter signal.

MSSM AND NMSSM SEARCHES WITH NEUTRALINO DARK MATTER

TOOLS

- micrOMEGAs 2.4 G. Bélanger et al. [arXiv:hep-ph/0505142] [arXiv: 0803.2360][arXiv: 1004.1092]
 - Computation of Relic Density including high order corrections
 - Computation of cross sections (annihilation, elastic scattering)
 - User-friendly application of particle physics constraints
- Spectrum calculators (from soft terms to physical terms)
 - MSSM: SuSpect A. Djouadi et al. [arXiv:hep-ph/0211331]
 - NMSSM: NMSSMTools U. Ellwanger et al. [arXiv: hep-ph/0508022]
- Further links (MSSM)
 - Susy-HIT: Higgs-gluon-gluon vertex missing in SuSpect A. Djouadi et al. [arXiv:hep-ph/0609292]
 - HiggsBounds: up-to-date and comprehensive checking on limits on the Higgs sector P. Bechtle et al. [arXiv:1102.1898]

MARKOV CHAIN MONTE-CARLO PRIORS: FITTING THE HYPOTHESIS

- Parameter spaces
- Physical solution of the spectrum calculator
- Neutralino mass interval...

$$M_{\chi_1^0}^{\min} < M_{\chi_1^0} < M_{\chi_1^0}^{\max}$$

- Spin dependent cross section vs neutralino LSP mass constraint...

MSSM	NMSSM
$1 < M_1 < 1000$	$1 < M_1 < 1000$
$100 < M_2 < 2000$	$100 < M_2 < 2000$
$500 < M_3 < 6500$	$500 < M_3 < 6000$
$0 < \mu < 1000$	$0 < \mu < 1000$
$1 < \tan \beta < 75$	$1 < \tan \beta < 75$
$1 < M_A < 2000$	$0 < \lambda < 0.75$
$-3000 < A_t < 3000$	$0 < \kappa < 0.65$
$70 < M_{\tilde{l}_L} < 2000$	$-2000 < A_\lambda < 5000$
$70 < M_{\tilde{l}_R} < 2000$	$-5000 < A_\kappa < 2000$
$300 < M_{\tilde{q}_{1,2}} < 2000$	$-3000 < A_t < 3000$
$300 < M_{\tilde{q}_3} < 2000$	$100 < M_{\tilde{l}} < 2000$
	$300 < M_{\tilde{q}} < 2000$

MARKOV CHAIN MONTE-CARLO LIKELIHOODS: FITTING THE DATA

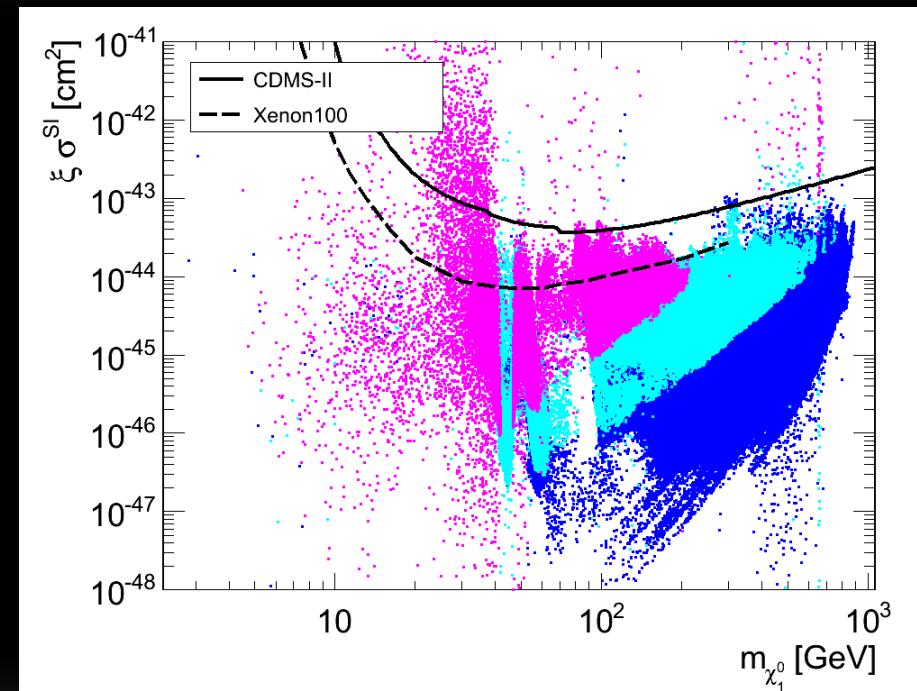
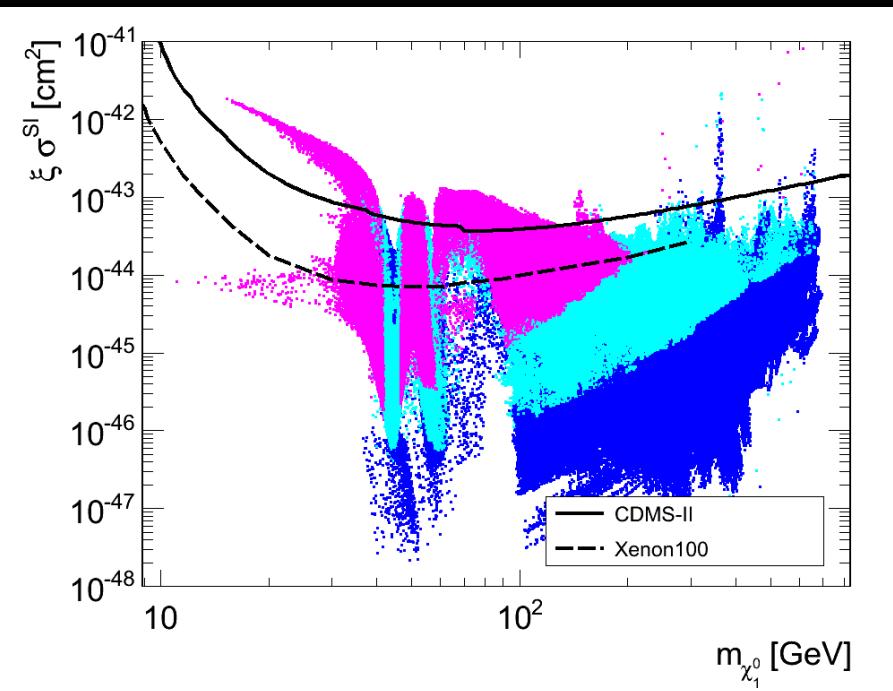
- Dark Matter: thermal relic
 - WMAP as an upper bound
 - Fit WMAP range
- Unfruitful searches of new particles: check the complete physical spectrum
- Electroweak observables:
$$\left\{ \begin{array}{l} (g-2)_\mu, \Delta\rho \\ Z \rightarrow \chi\chi \\ e^+e^- \rightarrow \chi_1\chi_{2,3} \rightarrow \chi_1\chi_1 Z \end{array} \right\}$$
- B-physics:
$$\left\{ \begin{array}{l} B(b \rightarrow s\gamma) \\ B(B_s \rightarrow \mu^+\mu^-) \\ B(B \rightarrow \tau\nu_\tau) \\ \Delta M_s, \Delta M_d \end{array} \right\}$$

OUTCOME OF THE SCANS

	Points	\mathcal{Q}_{\max}	1σ	2σ	3σ
MSSM	1208949	0.755	0.25	0.68	0.97
NMSSM	2092875	0.812	0.30	0.72	0.98

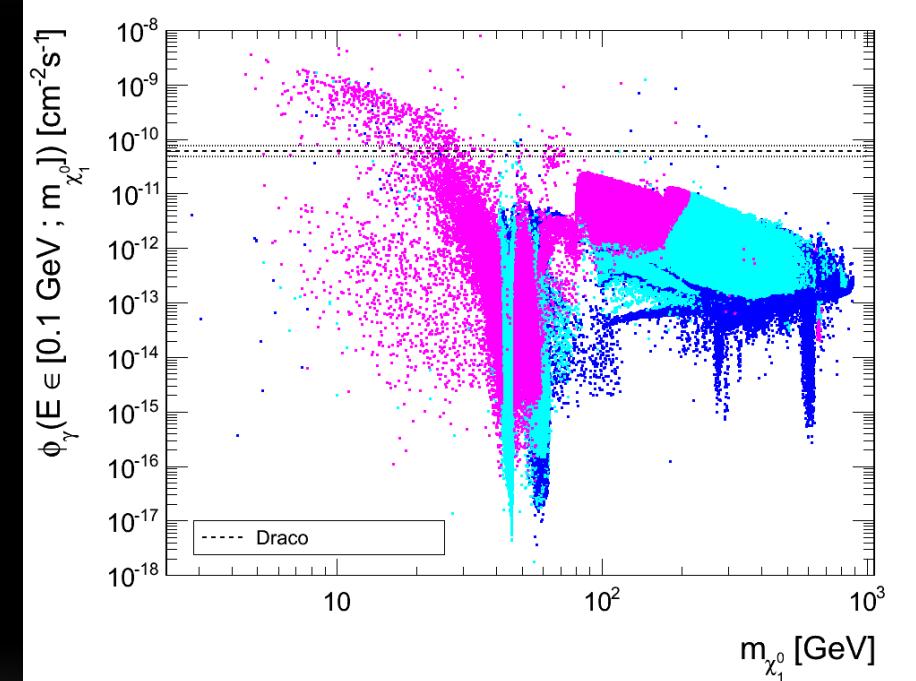
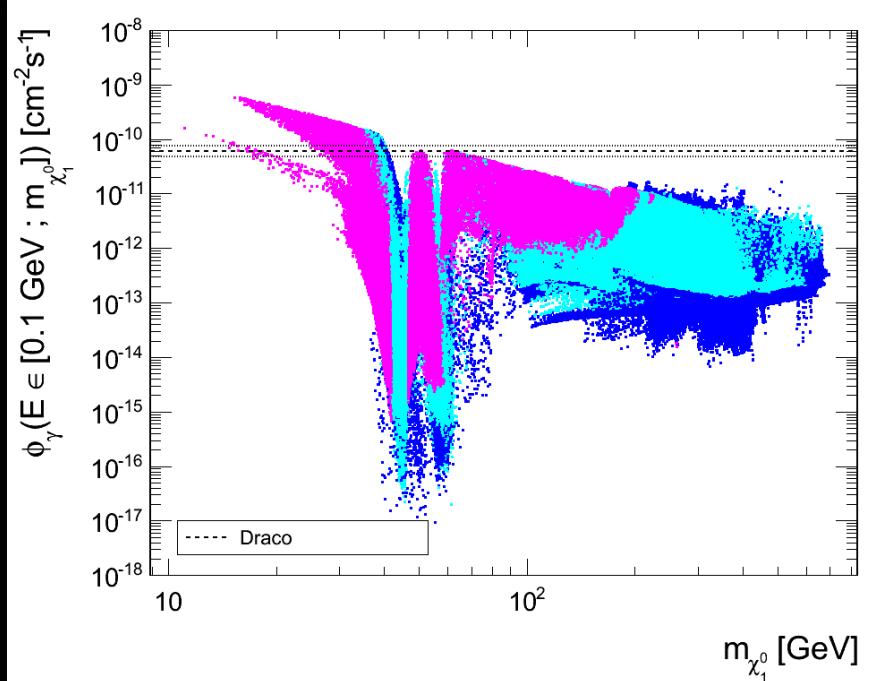
- For each accepted point compute
 - Elastic scattering interactions
 - Gamma-ray flux from Draco dSph
- Apply constraints
 - Direct detection: XENON100
 - Gamma-rays: Fermi-LAT
 - MSSM: CMS results on Higgs searches

SPIN INDEPENDENT INTERACTIONS



NB: plots produced using ROOT

GAMMA-RAYS

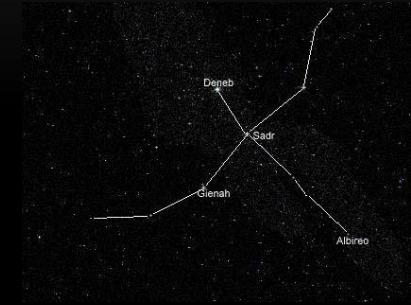
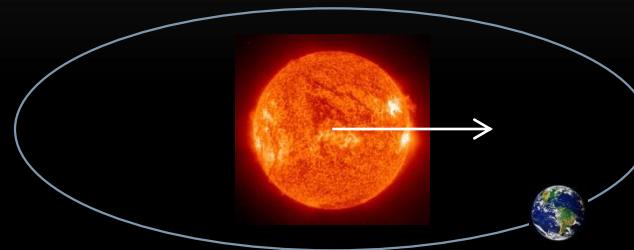


NB: plots produced using ROOT

DIRECTIONAL DETECTION PROSPECTS

DIRECTIONAL DETECTION: IN PRINCIPLE

- Principle: record the energy and the 3D track of nuclear recoil events. Hence, measure



$$\frac{d^2R}{dE_r d\Omega_r} = \frac{\rho_0 \sigma_0}{4\pi m_\chi \mu^2} F^2(E_r) \hat{f}(\nu_{\min}, \hat{q})$$

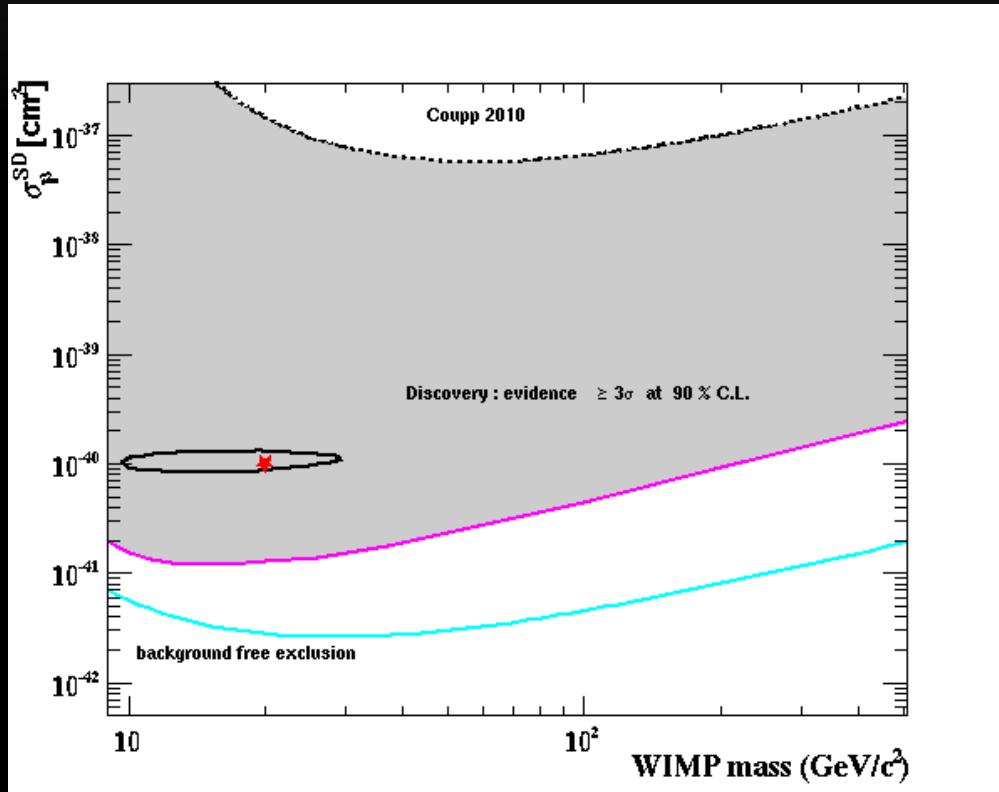
- At galactic velocities ($\sim 200 \text{ km.s}^{-1}$), typical DM masses ($\sim 50 \text{ GeV}$) and a typical nucleus (^{19}F), recoil energy of $O(10 \text{ keV}) \rightarrow$ the lower end of the energy spectrum is the most interesting
 - Low energy threshold
 - Low energy tracks

A MIMAC-LIKE DIRECTIONAL DETECTOR AND A STANDARD ASTROPHYSICAL PARADIGM

- Track reconstruction: gaseous environment at low pressure (50-100 mbar)
→ low exposure mass compared to crystalline detectors
- Directional detectors: low-pressure time projection chambers
- Focus on spin dependent interactions
- Target medium choice: CF_4
- Consider an exposure of 30 kg.yr and 5 keV threshold with track recognition
- Treat astrophysical parameters as nuisance parameters
- Include experimental uncertainties

Nuisance parameters	Gaussian parametrization
ρ_0 [GeV/c ² /cm ³]	0.3 ± 0.1
v_\odot [km/s]	220 ± 30
σ_x [km/s]	$220/\sqrt{2} \pm 20$
σ_y [km/s]	$220/\sqrt{2} \pm 20$
σ_z [km/s]	$220/\sqrt{2} \pm 20$

PREDICTED BEHAVIOR OF A CANONICAL DIRECTIONAL DETECTOR



J. Billard, F. Mayet, D. Santos, PRD82,055011 (2010) / PRD83,075002 (2010)

- Exclusion:
 - 0 observed event
 - Classical Poisson statistics
- Discovery sensitivity:
 - DM signal
 - Profile likelihood ratio test statistics
- Discovery scenario:
 - Constrain mass and cross section with MCMC analysis
 - Input: $m_\chi = 20 \text{ GeV}$

$$\sigma_p^{SD} = 10^{-4} \text{ pb}$$

SPIN DEPENDENT INTERACTIONS

- Looking closely at the contribution of protons and neutrons:

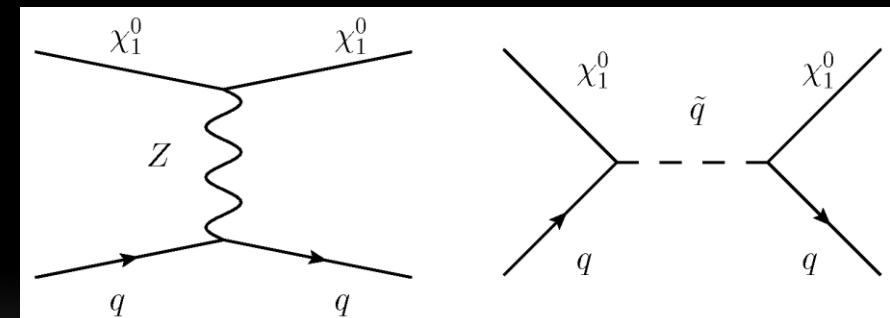
$$\sigma^{SD}({}^AX) \propto (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

- Sensitivity to spin dependent interactions of a nucleus AX relies on an unpaired nucleon
- Constraining SD interactions is often achieved by marginalizing the interaction to just one or the other (assuming $a_n=0$ or $a_p=0$)
- For a pure Z exchange, the amplitude reads

$$a_N = -(\Delta_u^N - \Delta_d^N - \Delta_s^N)(N_{13}^2 - N_{14}^2)$$

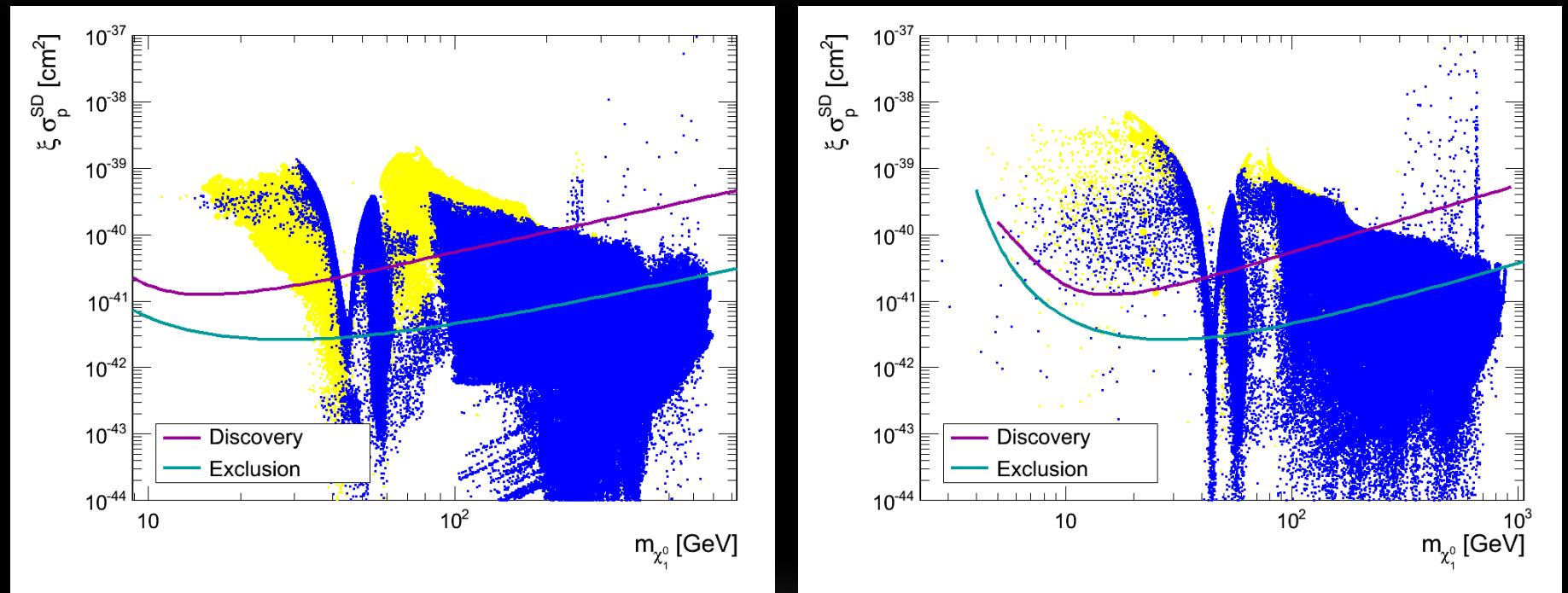
- Which leads to $\left(\frac{a_p}{a_n}\right)_Z = -1.14 \pm 0.03$

- For squarks: $\left(\frac{a_p}{a_n}\right)_{\tilde{q}} = -3.38 \pm 0.22$



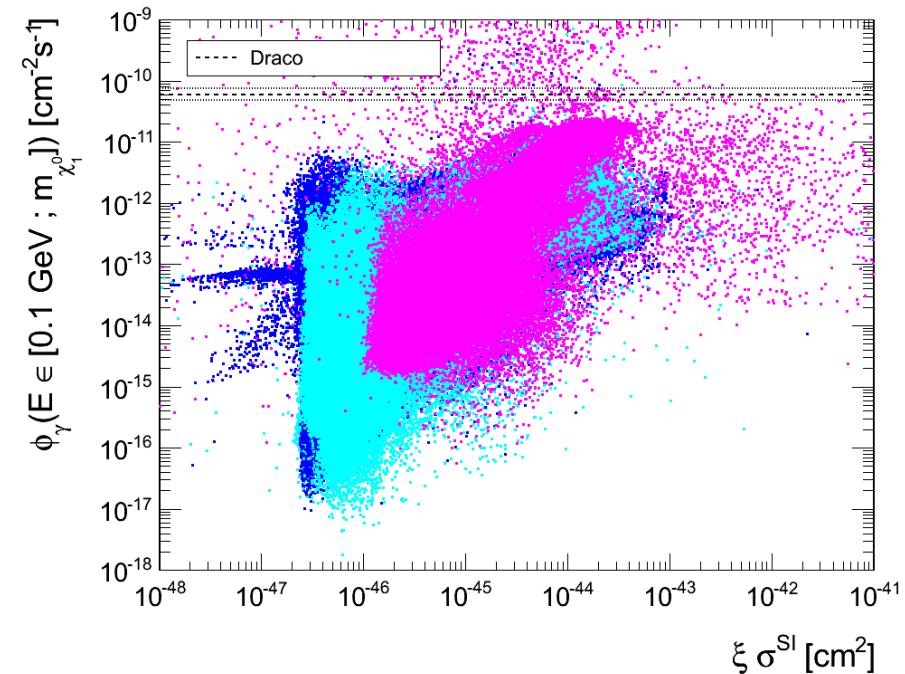
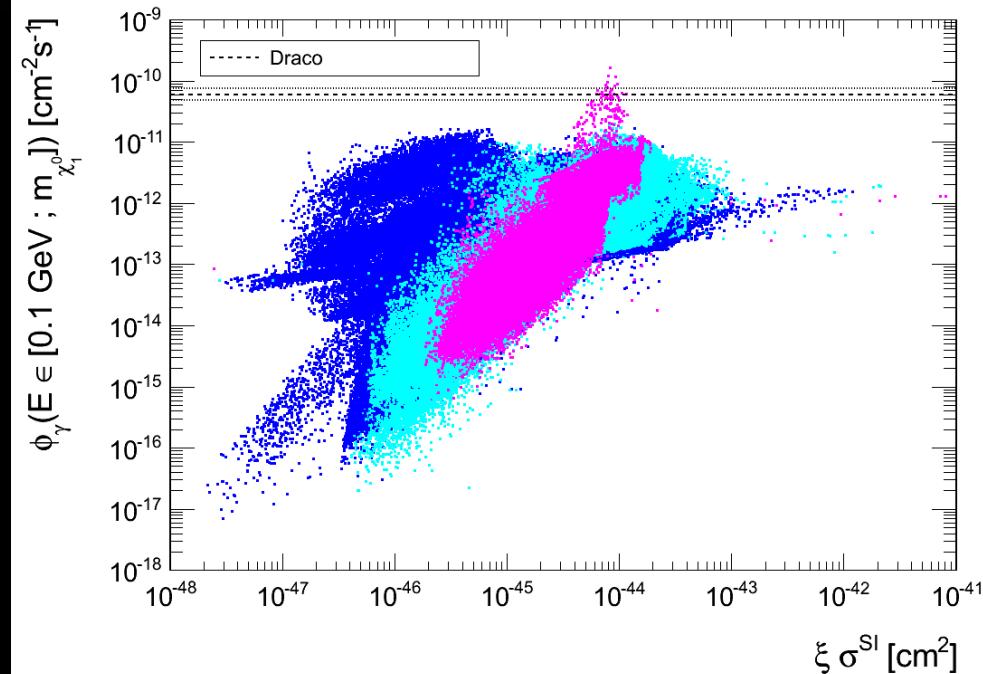
DIRECTIONAL DETECTION REACH

SPIN DEPENDENT INTERACTIONS



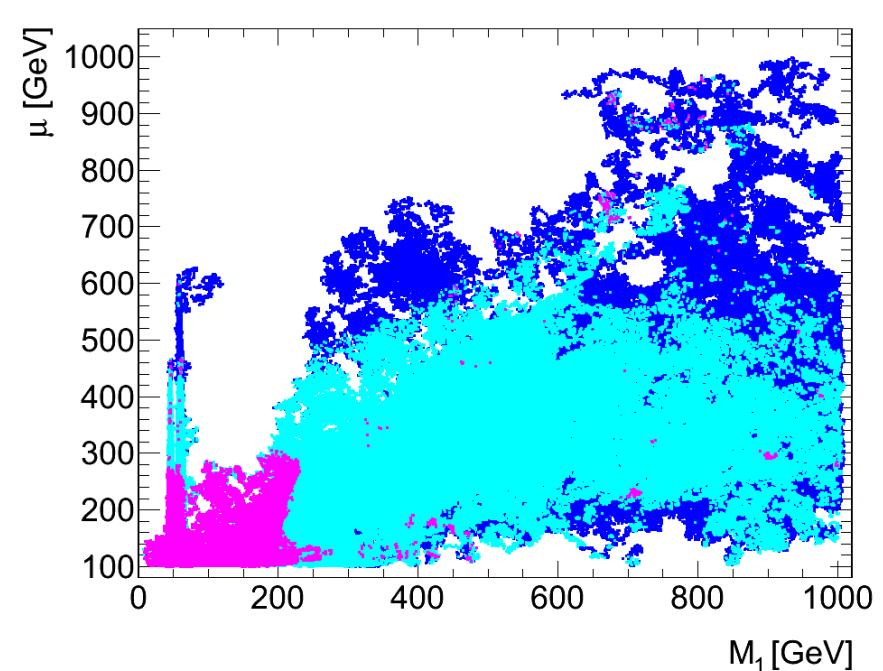
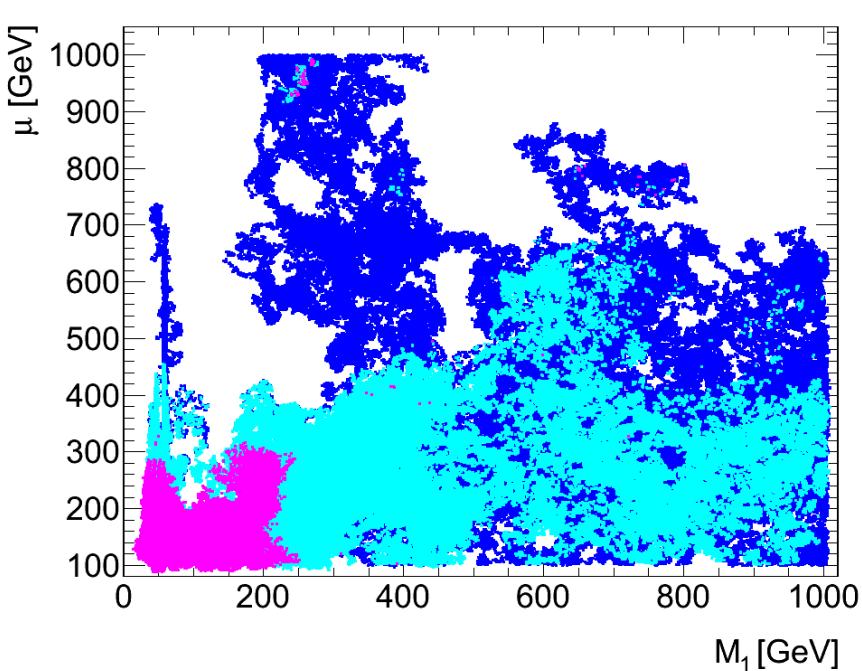
NB: plots produced using ROOT

COMPLEMENTARITY BETWEEN DETECTION TECHNIQUES



NB: plots produced using ROOT

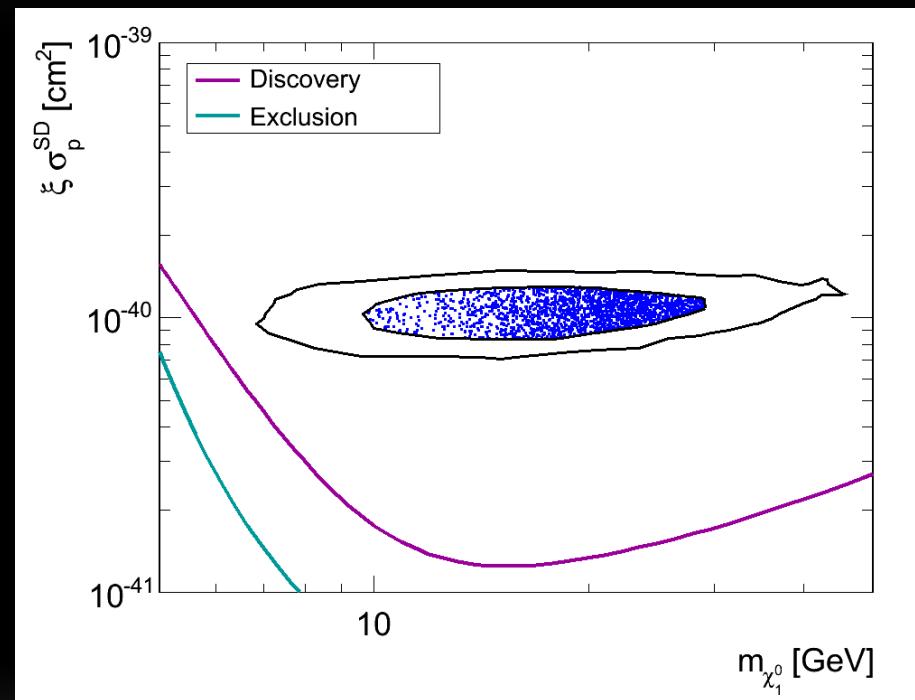
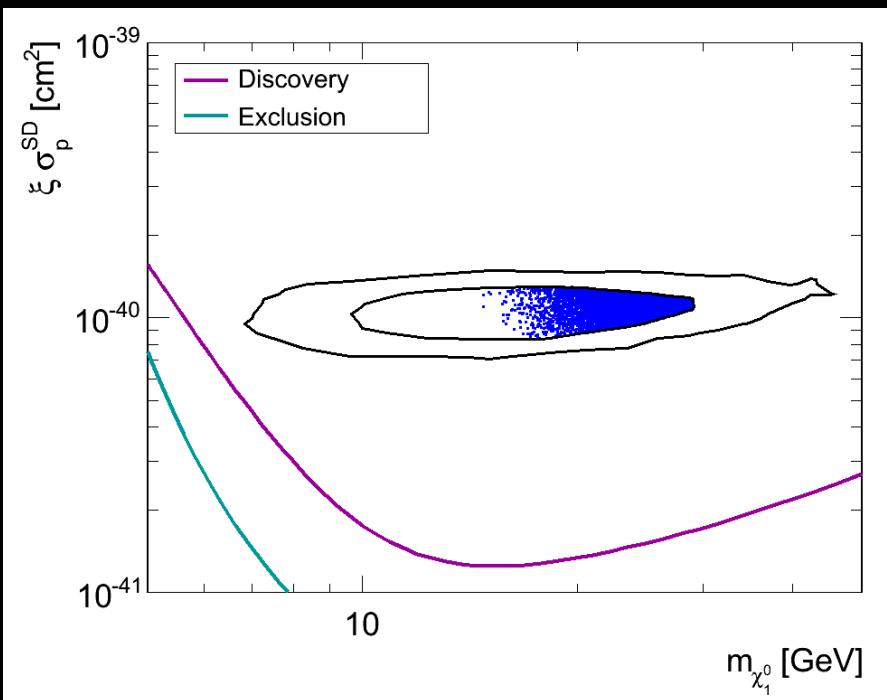
CONSTRAINING THE PARAMETER SPACE



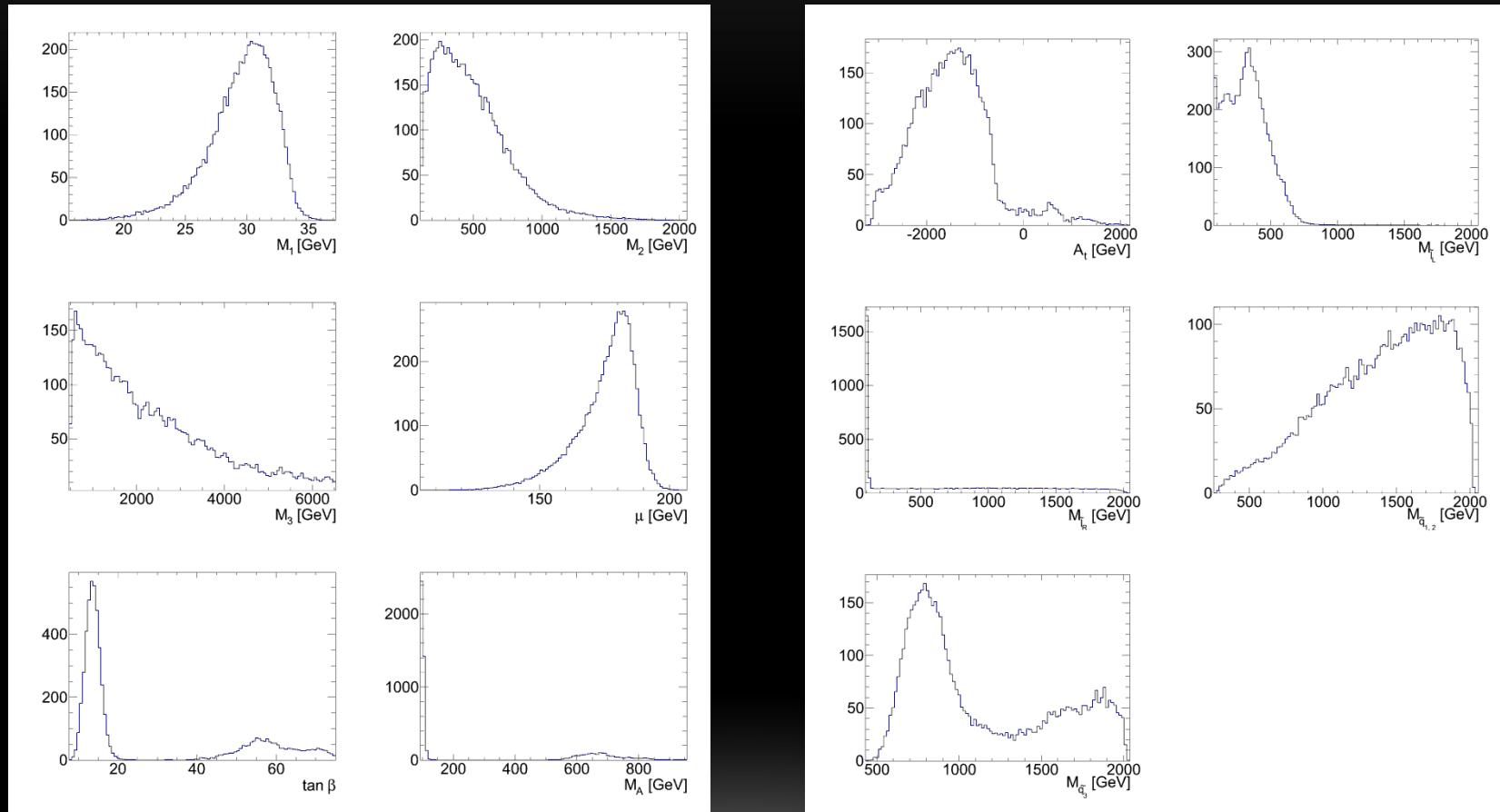
NB: plots produced using ROOT

A DISCOVERY SCENARIO

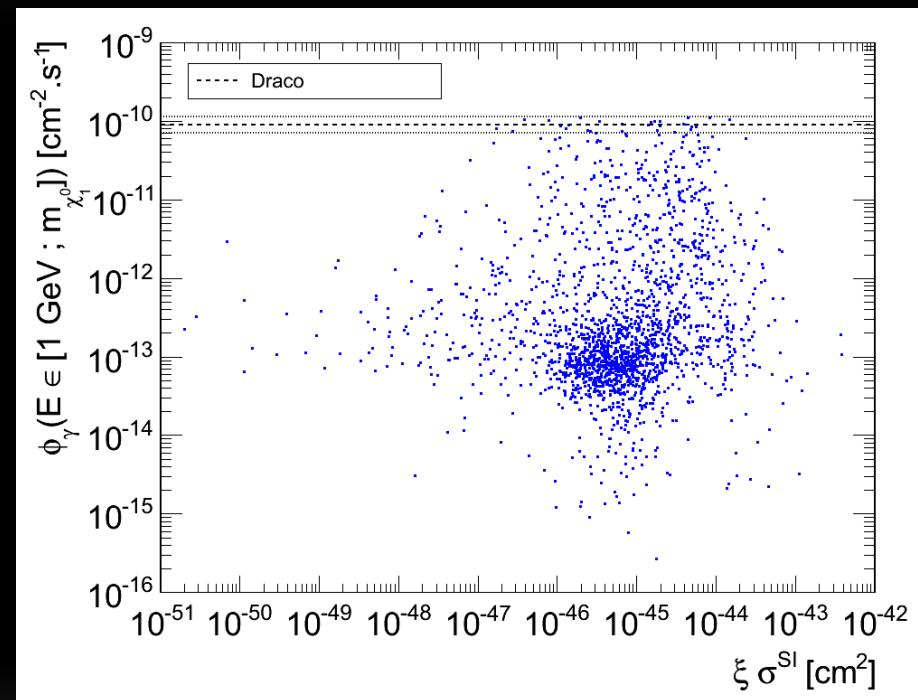
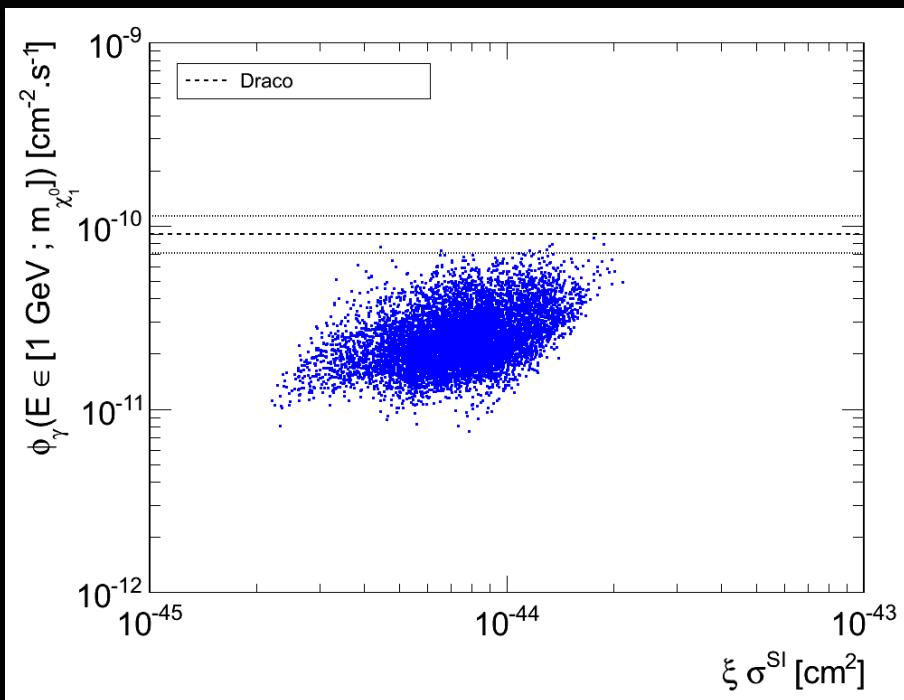
SEARCH FOR MATCHING CONFIGURATIONS



DETERMINING THE PARAMETER SPACE



MAKING PREDICTIONS



CONCLUSIONS

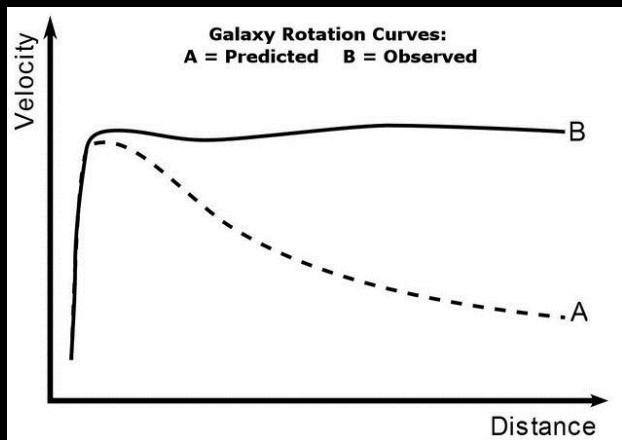
CONCLUSIONS

- ✓ Directional detection focused on SD interactions gives a fundamental complementarity to other DM search techniques
- ✓ Directional detectors could highly constrain the supersymmetric parameter space if they were to observe DM events
- ✓ Uncertainties on the astrophysical parameters and the kind of model behind DM will be narrowed!

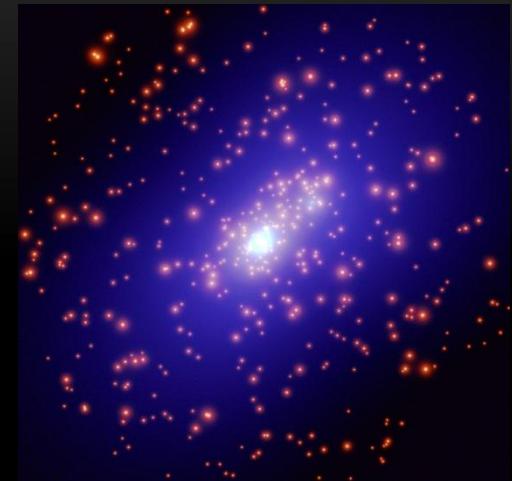
BACK UP SLIDES

DARK MATTER

- Galaxy cluster orbital velocities (F. Zwicky, 1933)
- Galaxy rotation curves

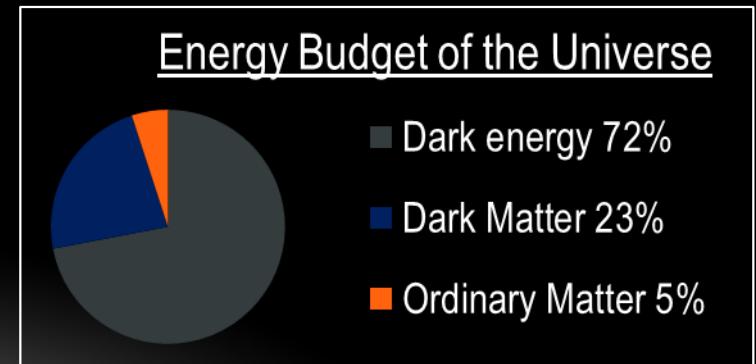


$$M_{\text{Total}} = \frac{2 \langle v^2 \rangle}{G \left\langle \frac{1}{r} \right\rangle} > M_{\text{Luminous}}$$



Cluster of galaxies Cl0024+1654
J.-P. Kneib et al.

- Modern Cosmology: concordance model
- Well tested by observing the CMB
- WMAP 7yr: $\Omega_{\text{DM}} h^2 = 0.1120$ E. Komatsu et al.,
[arXiv:1001.4538]

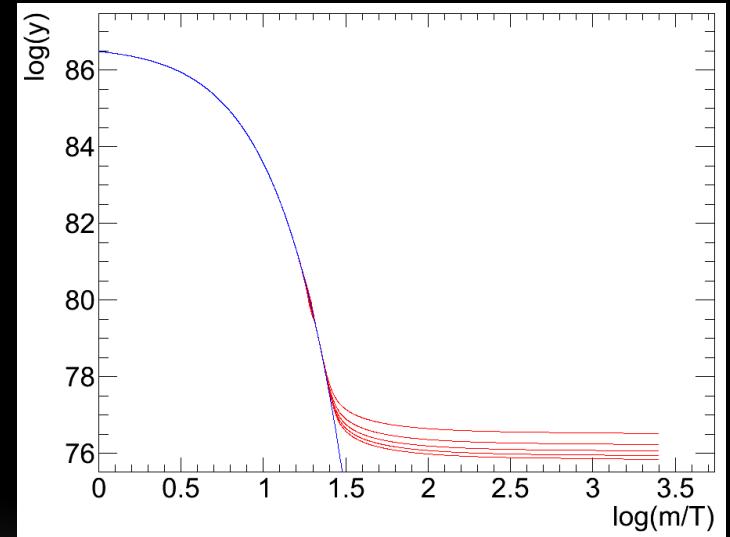


PARTICLE DARK MATTER “STANDARD” CANDIDATE: THE WIMP

- Neutral
- Massive
- Small interaction rates
- Stable (or very long-lived)
- Thermal relic
- WIMP-miracle
- Typical values: $T^{FO} \simeq \frac{m_{DM}}{(15 - 25)}$
 $m_{DM} = 100 \text{ GeV}$
 $\langle \sigma v \rangle^{ann} \simeq 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$
- Fixes the annihilation cross section...
- ... with some caveats

Boltzmann equation for number density

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle^{ann} (n^2 - n_{eq}^2)$$

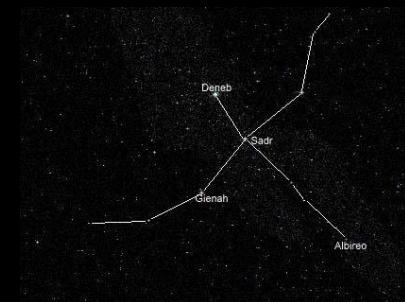
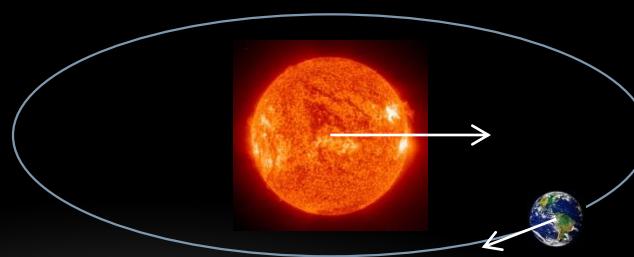


DIRECT DETECTION OF DARK MATTER

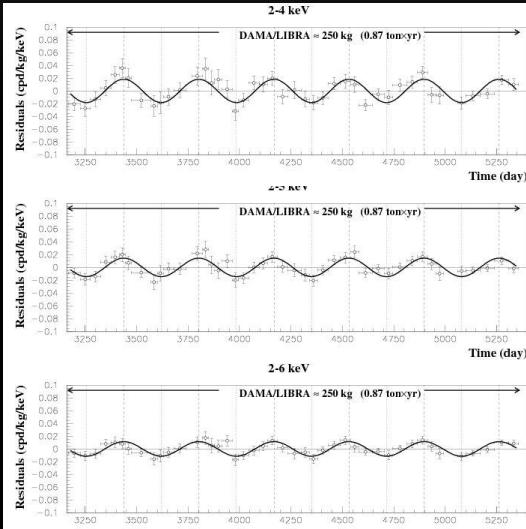
- Principle: elastic scattering events of DM particles with nuclei

$$\frac{dR}{dE_{\text{det}}} = \frac{\xi \rho_{\odot}}{m_{DM}} \int_{v_{\min}}^{v_{\text{esc}}} \sum_{x=nuclei} N_T^x \left(\int_{E_{\min}}^{E_{\max}} K_x(E_{\text{det}}, E_R) \frac{d\sigma}{dE_R}(E_R, v) dE_R \right) v f(\vec{v}) d^3\vec{v}$$

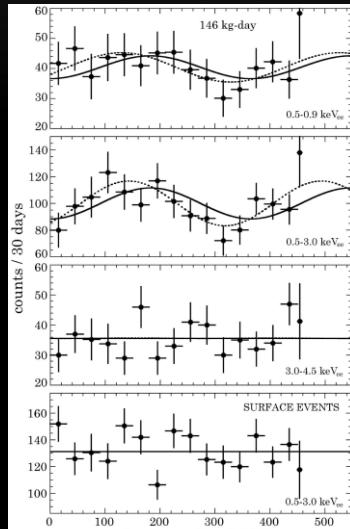
- Small interactions: shielding and technical challenge for detection
- Detectors are sensitive to the cross section, but can express results in terms of spin-independent and spin-independent interactions with nucleons
- Detector's motion in the DM halo:
 - Earth: annual modulated signal
 - Sun: asymmetric signal → directional detection technique



DIRECT DETECTION RECENT RESULTS: IS THE DARK MATTER BEEN OBSERVED?



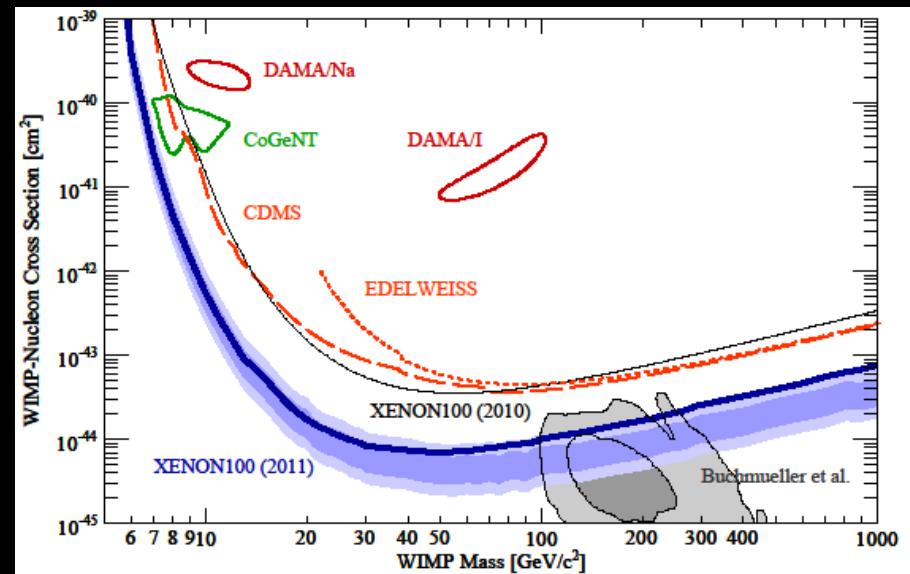
DAMA/Libra annual modulation
R. Bernabei et al.
[arXiv:1002.1028]



CoGeNT annual modulation
C. Aalseth et al.
[arXiv:1106.0650]

- Observation of annual modulation by DAMA/Libra, CoGeNT, CRESST...

- No signal: CDMS-II, Edelweiss, XENON100



XENON100 limits
E. Aprile et al.
[arXiv:1104.2549]

PARTICLE PHYSICS COLLIDERS

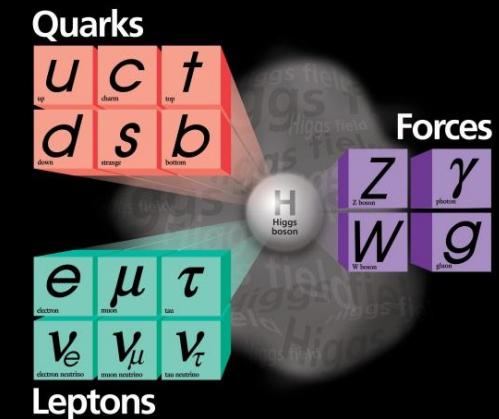
- Produce Dark Matter in the laboratory? Dark Matter candidates do not come alone!
- Spectrum of new particles, potentially including electroweak and/or strong interactions
 - New particles
 - New effects
- Colliders have not seen any particle beyond the Standard Model, nor the SM Higgs boson → limits on masses, cross sections, decay rates and/or couplings
- Particle physics observables at LEP, Tevatron, B-factories, LHC...:
 - Z invisible width
 - g_μ
 - Rare meson decays and oscillations...

FROM THE STANDARD MODEL TO THE MSSM

- Supersymmetry: a framework for physics beyond the Standard Model
- Supercharge: fermions \leftrightarrow bosons
- Fermions and bosons unified in superfields
- New particles: squarks, sleptons, gauginos, higgsinos
- Broken symmetry

$$\mathcal{L} \supset \mathcal{L}_{SUSY} + \mathcal{L}_{SOFT}$$

- U(1) symmetry: R-parity
- Lightest R-odd particle is stable (crucial for DM)
- Minimal construction: an entire replication of the SM



Standard Model constituents
(credits: FermiLab)

MINIMAL SUPERSYMMETRIC STANDARD MODEL

- Higgs sector: masses are acquired by electroweak symmetry breaking as in the SM, but with two Higgs doublets: h_1 and h_2 , with

$$v_1 / v_2 = \tan \beta$$

- Higgs Superpotential:

$$\mathcal{W}_{MSSM} = \mu H_1 \cdot H_2 - f_{ij}^e H_1 \cdot L_i \bar{E}_j - f_{ij}^d H_1 \cdot Q_i \bar{D}_j - f_{ij}^u Q_i \cdot H_2 \bar{U}_j$$

- Parameters:
 - Higgs sector $\tan \beta$, M_A , μ
 - Soft sfermion masses
 - Gaugino masses M_1 , M_2 , M_3
 - Trilinear couplings
- Complex scenario: 124 free parameters in the MSSM!

FROM THE MSSM TO THE NMSSM

- MSSM's μ -term scale must be set to match EW physics: $100 \text{ GeV} \leq \mu \leq M_{SUSY}$
- Solution: addition of a Higgs superfield containing:
 - A singlet s of the SM ($U(1) \times SU(2) \times SU(3)$)
 - The correspondent singlino
- New Higgs superpotential:

$$\left\{ \mathcal{W}_{MSSM} \longrightarrow \mathcal{W}_{NMSSM} \right\} \Leftrightarrow \left\{ \mu H_1.H_2 \longrightarrow \lambda S H_1.H_2 + \frac{1}{3} \kappa S^3 \right\}$$

- New parameters, Higgs particles and couplings

$$\mu \longrightarrow \mu_{eff} = \lambda \langle s \rangle$$

$$\mu, M_A \longrightarrow \mu_{eff}, \lambda, \kappa, A_\lambda, A_\kappa$$

$$h, H, H^\pm, A \longrightarrow H_1, H_2, H_3, H^\pm, A_1, A_2$$

THE NEUTRALINO

- Neutral bino and wino gauginos mix with neutral higgsinos (and singlinos) to form spin-½ neutralinos in the MSSM (NMSSM):

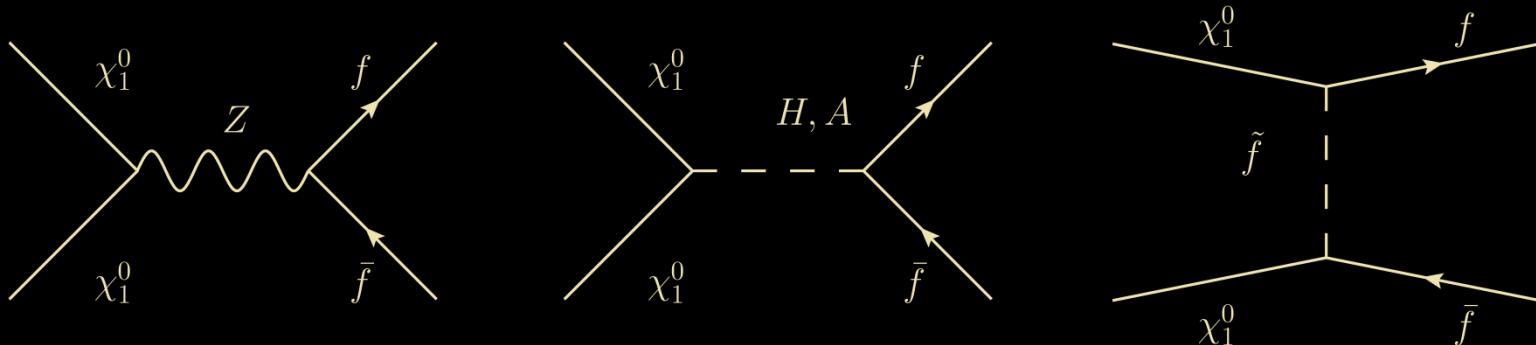
$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u (+N_{15}\tilde{S})$$

- Lightest mass term ($M_1, M_2, \mu, \mu\kappa/\lambda$) defines the nature of the lightest neutralino, thus of the lightest supersymmetric particle (LSP), the DM candidate

$$M_{\chi^0}^{MSSM} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \quad M_{\chi^0}^{NMSSM} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu & -\frac{\lambda v_1}{\sqrt{2}} \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 & -\frac{\lambda v_2}{\sqrt{2}} \\ 0 & 0 & -\frac{\lambda v_1}{\sqrt{2}} & -\frac{\lambda v_2}{\sqrt{2}} & 2\frac{\mu\kappa}{\lambda} \end{pmatrix}$$

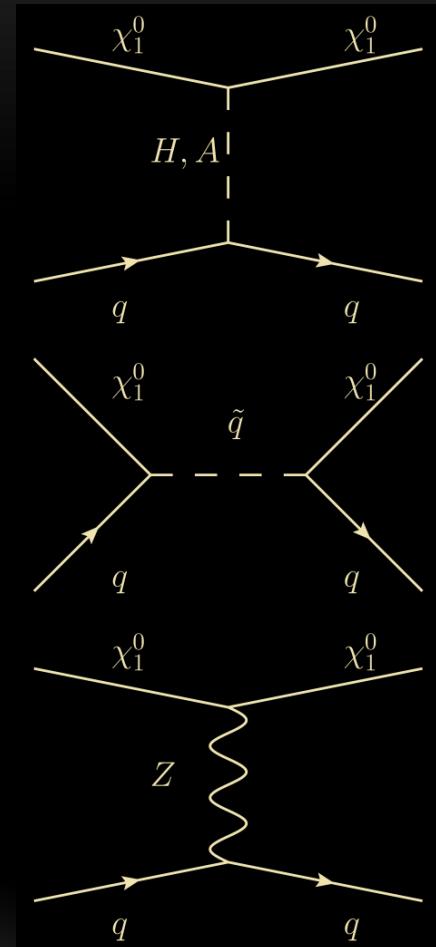
NEUTRALINO ANNIHILATIONS

- Neutralino DM acquiring the relic density via thermal freeze-out: need for efficient annihilations
- Light (< 50 GeV) neutralinos: exchange mediators as close in mass as possible \rightarrow Z boson, SM-like Higgs, light sfermions



NEUTRALINO ELASTIC SCATTERING WITH QUARKS

- Direct detection of neutralinos: quark-neutralino elastic scattering processes
- Neutralino is a Majorana particle.
- Two kinds of interactions:
 - spin independent (top and middle)
 - spin dependent (bottom and middle)
- Interference may happen!
- Squarks are heavy: preferred Z and Higgs exchanges
- Interaction at small momentum transfer: pseudoscalar exchanges get chirally suppressed



NUMERICALLY TESTING A CONFIGURATION

- We only want *allowed* configurations!
 - Define a likelihood function L : quantify the fit to the experimental data and bounds
- And, we want physical realizations with neutralino DM in a certain mass range!
 - Define a prior function P : quantify a configurations correspondance with our search (is it within the parameter space we are scanning, does it yield neutralino DM?)
- We want to know the predictions!
 - Compute observables for each allowed point
 - Elastic scattering processes (spin independent, spin dependent, neutralino-proton, neutralino-neutron)
 - Annihilation cross sections
 - Gamma-ray fluxes

MARKOV CHAIN MONTE-CARLO METROPOLIS HASTINGS ALGORITHM

- Iteration
 1. From a parameter set i , generate a parameter set j
 - Gaussian step in every dimension of parameter
 - Compute the point j 's spectrum
 2. Test point j
 - Compute its prior P
 - Compute its likelihood L
 - Compute its total weight $Q = P \times L$
 3. Accept or reject the point j
 - Acceptance probability: $\text{Min}(1, Q_j/Q_i)$
 - Accepted: $i+1 = j$; Rejected: $i+1 = i$
- The starting point problem
 1. Randomly look for a point
 2. Make previous chains to find a suitable point (burning chain method)
 3. Impose the starting point (and expose the scan to a bias)

DIRECTIONAL DETECTION

- DM velocity distribution in the laboratory frame using the multivariate Gaussian distribution

$$f(\vec{v}) = \frac{1}{\sqrt{8\pi^3 \text{Det}\sigma_v^2}} \exp\left(-\frac{1}{2}(\vec{v} - \vec{v}_\odot)^T \sigma_v^{-2} (\vec{v} - \vec{v}_\odot)\right)$$

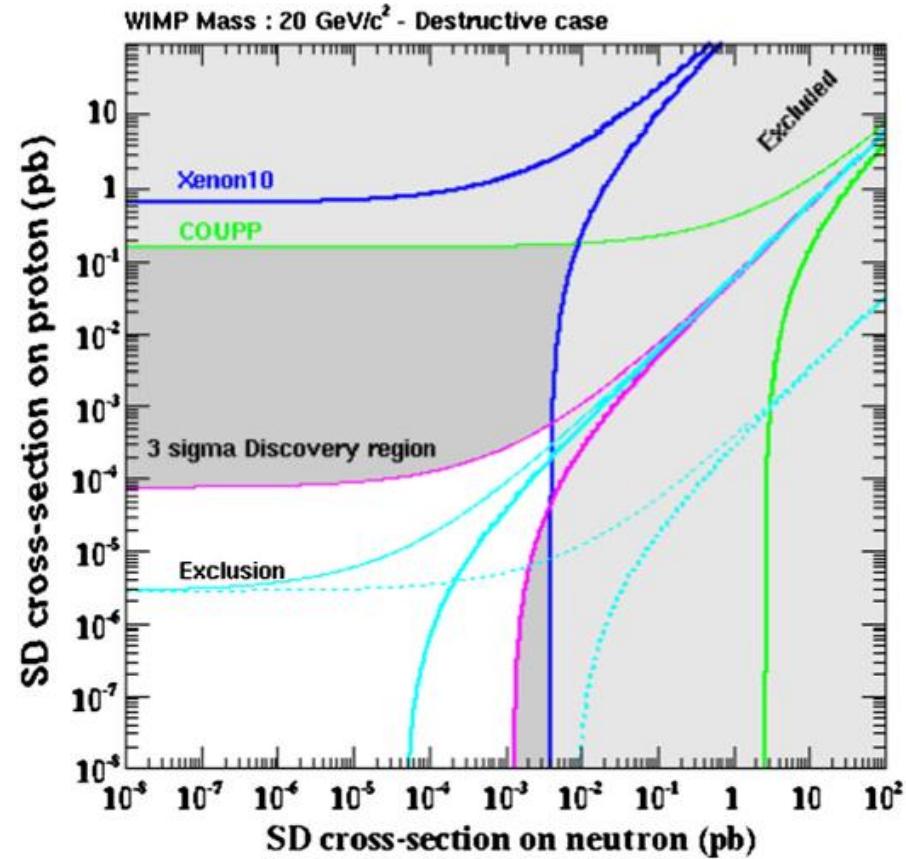
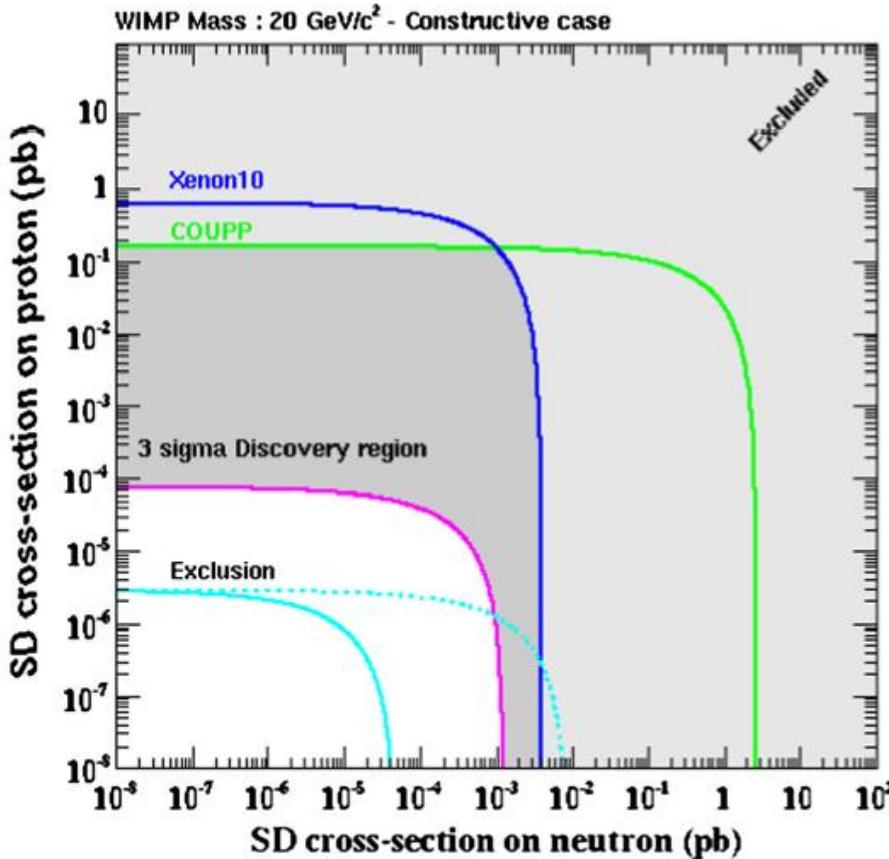
- Anisotropy: $\beta = 1 - \frac{\sigma_y^2 + \sigma_z^2}{2\sigma_x^2}$ consider $\beta = 0 \pm 0.25$

- Constraining SD interactions model independently:
- Case of ^{19}F :

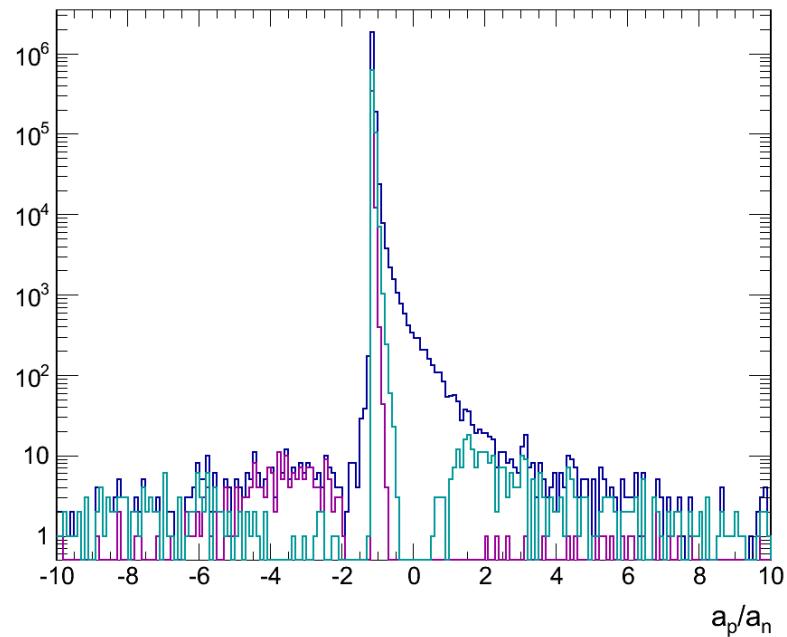
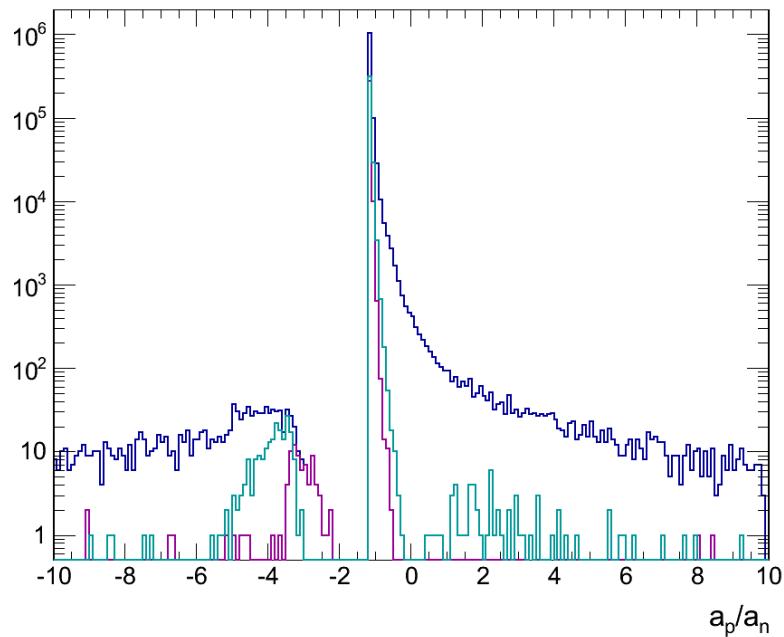
Model	$\langle S_p \rangle$	$\langle S_n \rangle$
odd-group	0.5	0.
Pacheco and Strottman	0.441	-0.109
Divari <i>et al.</i>	0.475	-0.0087

$$\left(\sqrt{\sigma_p} \pm \frac{\langle S_n \rangle}{\langle S_p \rangle} \sqrt{\sigma_n} \right)^2 < \sigma_p^{\text{lim}}$$

PREDICTED BEHAVIOR OF A CANONICAL DIRECTIONAL DETECTOR



AMPLITUDES



NB: plots produced using ROOT

LOCAL DARK MATTER DISTRIBUTION: THE STANDARD DARK MATTER HALO

- N-body simulations → Navarro-Frenk-White profile: $\rho^{NFW}(r) = \frac{\rho_s r_s^3}{r(r_s + r)^2}$
- Maxwellian velocities: $f(v) = \frac{4N}{\sqrt{\pi} v_0} \exp\left(-\frac{v^2}{v_0^2}\right) \times \Theta(v_{esc} - v)$
- In the Milky-Way, at the Sun's position:

$$\rho_{\odot}^{Canonical} = 0.3 \text{ GeV cm}^{-3} \quad \rho_{\odot} = (0.42 \pm 0.15) \text{ GeV cm}^{-3}$$

$$v_0 = 220 \text{ km s}^{-1} \quad v_0 = (200 - 280) \text{ km s}^{-1}$$

$$v_{esc} = 650 \text{ km s}^{-1} \quad v_{esc} = (498 - 608) \text{ km s}^{-1}$$

- The fraction of a given candidate: $\rho_i = \xi \rho_{DM} = \rho_{DM} \min\left(\frac{\Omega_i}{\Omega_{DM}}, 1\right)$

INDIRECT DETECTION OF DARK MATTER

- DM annihilation in galaxies

$$\phi_k(E, \psi) = \left[\int_{l.o.s.} dl(\psi) \xi^2 \rho_{DM}^2(l(\psi)) \right] \times \left[\frac{1}{2} \frac{\langle \sigma v \rangle}{4\pi m_{DM}} \frac{dN_k(E)}{dE} \right] = J(\psi) \times \phi_k^{PP}(E)$$

- Annihilation final states: SM particles
- Signal:
 - Antiparticles, gamma-rays, radio light
 - Energies below DM mass
- Regions of interest: bright signal, DM dominated, clean of background, not far
 - Milky Way's galactic center
 - Dwarf spheroidal galaxies
- Hints?
 - 511 keV line from the galactic center: MeV DM? [Y. Ascasibar et al. \[arXiv:astro-ph/0507142\]](#)
[C. Boehm et al. \[astro-ph/0309686\]](#)
 - Stringent limits by Fermi-LAT from Dwarf galaxies [A. Abdo et al., \[arXiv:1001.4531\]](#)

LIMITS ON GAMMA-RAY FLUXES FROM DWARF SPHEROIDAL GALAXIES BY FERMI-LAT

- Large Area Telescope in the Fermi satellite: search for gamma-rays

$$\Delta E = [20 \text{ MeV} - 300 \text{ GeV}]$$

$$\psi = 0.5^\circ$$

$$\Omega = 2.4 \cdot 10^{-4} \text{ sr}$$

- No signal: extract a limit on the flux assuming a power law spectrum

$$\frac{dN}{dEdAdt} = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma}$$

- Take: $\Gamma=1$

Draco dwarf spheroidal galaxy

$$d = (75 \pm 5) \text{ kpc}$$

$$R = (0.47 \pm 0.04)^\circ$$

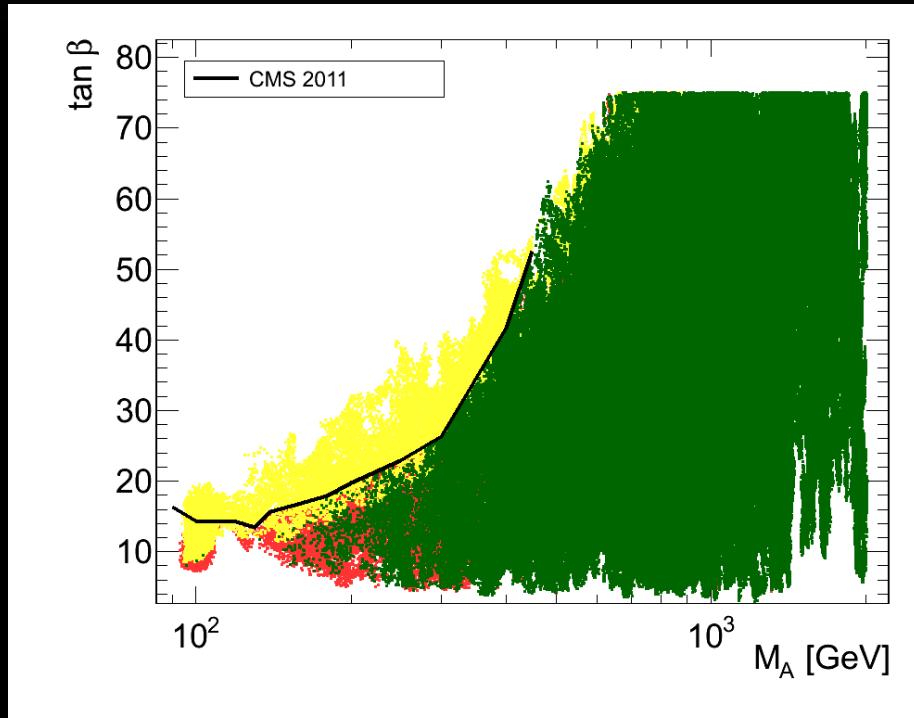
$$l = 86.37^\circ$$

$$b = 34.72^\circ$$

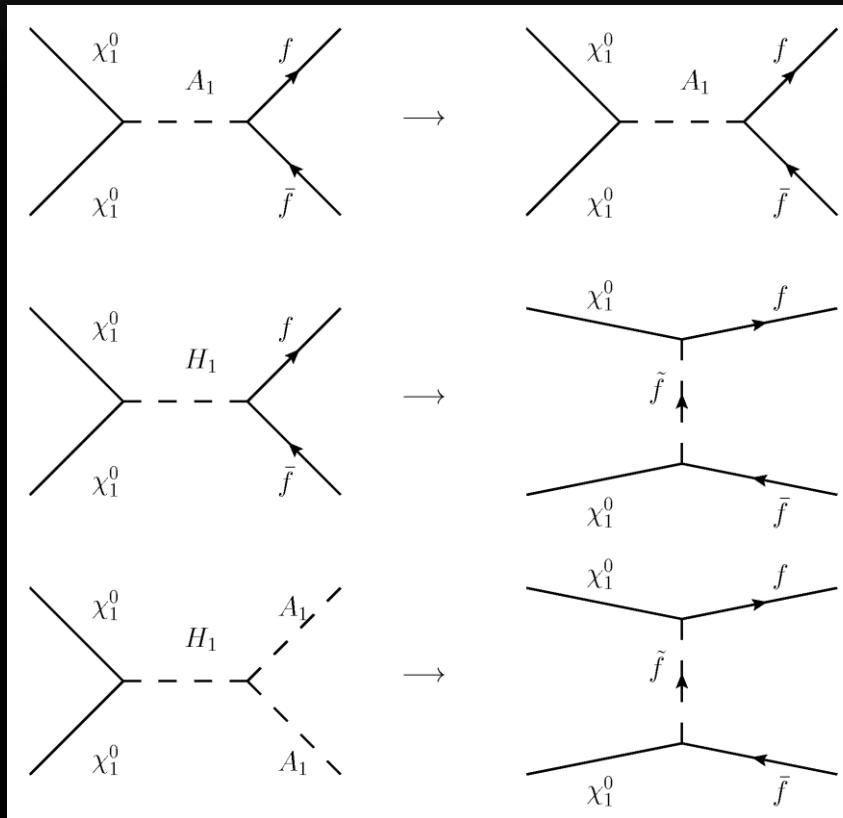
$$\frac{M_{1/2}}{L_{1/2}} = 200^{+80}_{-60}$$

$$J^{NFW} = (1.20^{+0.31}_{-0.25}) \times 10^{19} \text{ GeV}^2 \text{ cm}^{-5}$$

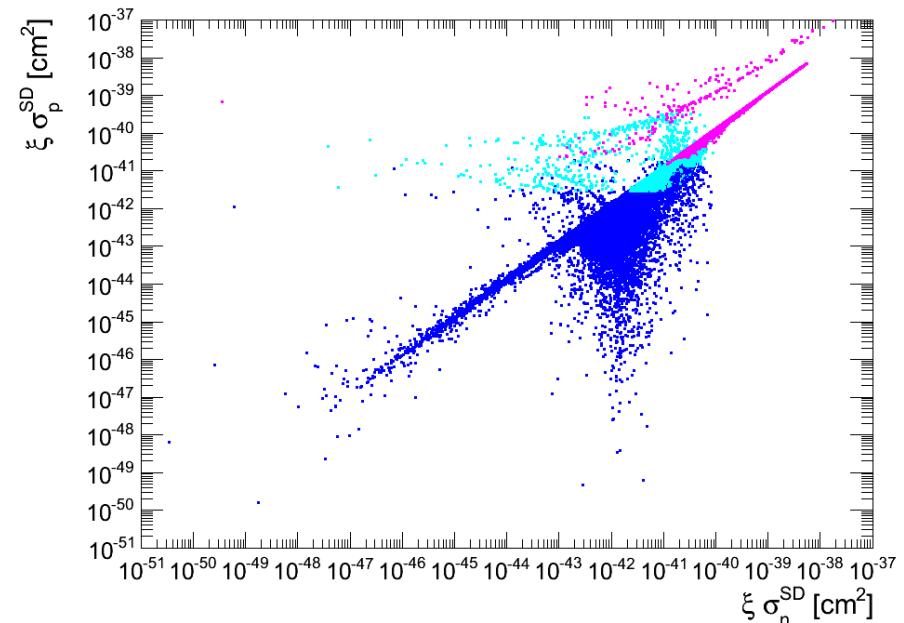
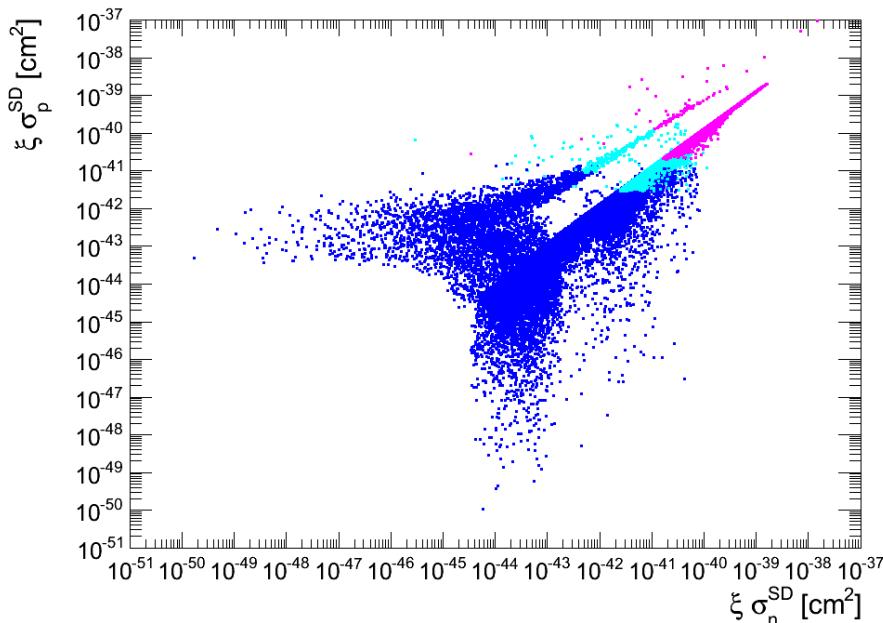
MSSM HIGGS SEARCHES



NMSSM NEUTRALINOS: FROM EARLY UNIVERSE TO GALACTIC ANNIHILATIONS



SPIN DEPENDENT INTERACTIONS



NB: plots produced using ROOT

IMPACT OF ATLAS CONSTRAINTS ON SQUARKS AND GLUINOS

