

LAPTh – Annecy-le-Vieux – 19th September 2011

PhD thesis defence
Daniel Albornoz Vásquez

Phenomenological and Astroparticle analysis of Light Dark Matter particles

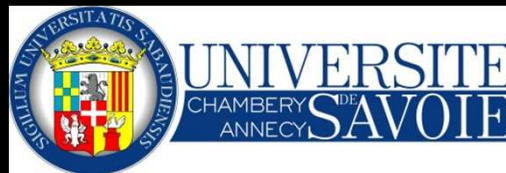
Jury:

President: Paolo Gondolo

Referees: Marco Cirelli
Cryril Hugonie

Julien Laval
Aurélien Barrau
Daniel Santos

Advisors: Pierre Salati
Céline Boehm



UNIVERSITÉ DE
GRENOBLE

OUTLINE

- I. Introduction to Light Dark Matter
- II. Light Neutralino Searches
- III. Light Scalar Dark Matter at the LHC
- IV. Conclusions and Perspectives

I. INTRODUCTION TO LIGHT DARK MATTER

What is the Dark Matter?

Why do we need Dark Matter?

Why Light Dark Matter particles?

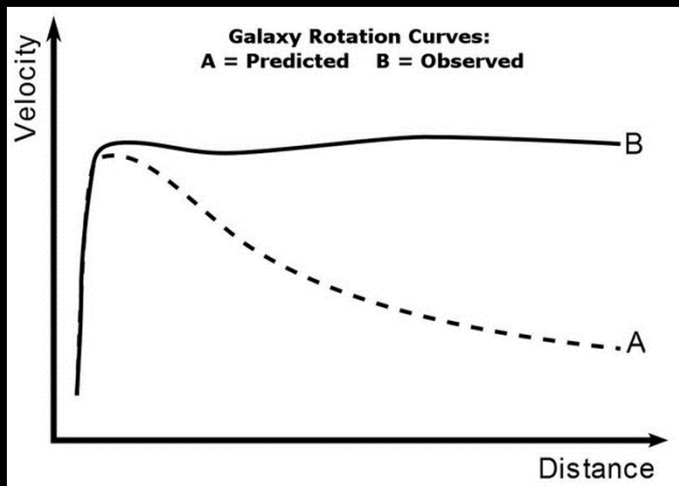
How could we detect Dark Mater?

I. Introduction to Light Dark Matter

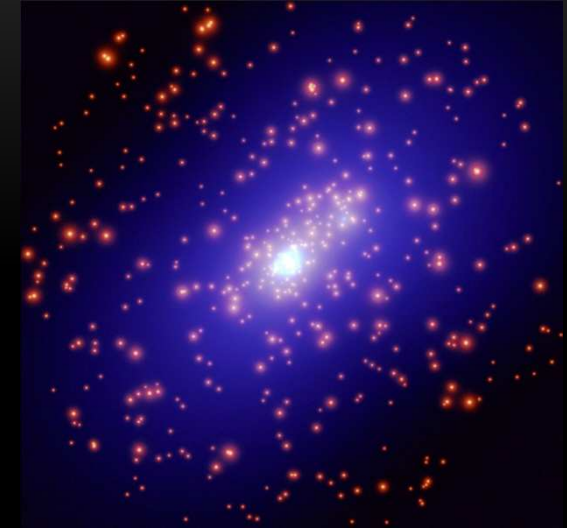
A. INTRODUCTION TO DARK MATTER

THE NEED FOR DARK MATTER

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

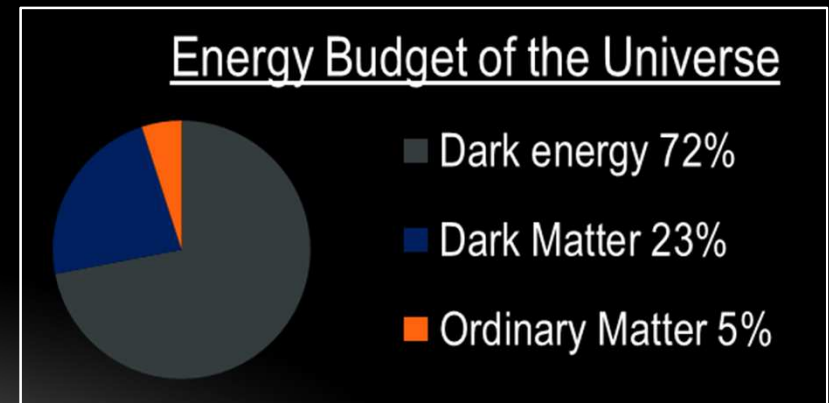


$$M_{\text{Total}} = \frac{2 \langle v^2 \rangle}{G \langle \frac{1}{r} \rangle} > M_{\text{Luminous}}$$



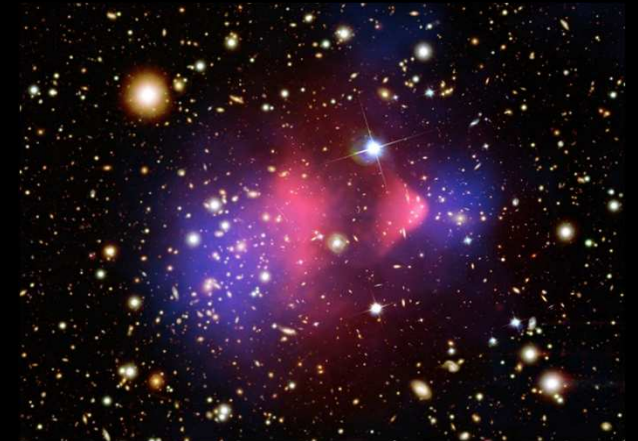
Cluster of galaxies CI0024+1654
J.-P. Kneib et al.

- 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]



WHAT COULD THE DARK MATTER BE?

- All the Dark Matter (DM) evidence is purely gravitational
 - Matter distribution (rotation curves, gravitational lensing...)
 - Λ CDM model (BAO's, structure formation)
- SM particles fail to account for the DM (CMB, BBN, MACHO's)
- Modifying gravity?
 - OK with galaxies, galaxy clusters, structure formation
 - Bullet cluster? Cosmology?
- Hypothesis: DM is made of unknown particles
- (Underlying hypothesis: DM is made of one new species of particles)



Bullet cluster (1E 0657-56)
M. Markevitch et al.
D. Clowe et al.

PARTICLE DARK MATTER “STANDARD” CANDIDATE: THE WIMP

- Neutral
- Massive
- Small interaction rates
- Stable (or very long-lived)
- Thermal relic
- WIMP-miracle
- Typical values: $T^{FO} \simeq \frac{m_{DM}}{(15-25)}$

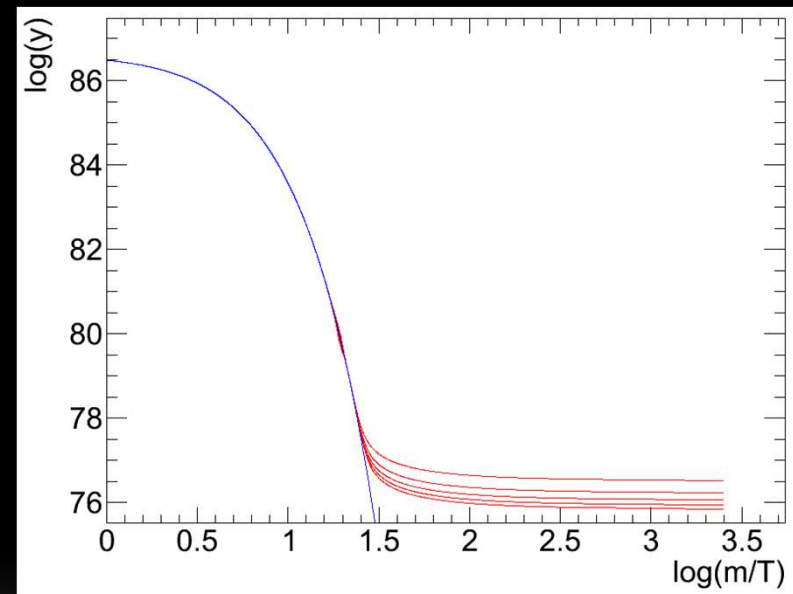
$$m_{DM} = 100 \text{ GeV}$$

$$\langle \sigma v \rangle^{ann} \simeq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

- Fixes the annihilation cross section...
- ... with some caveats

Boltzmann equation for number density

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



I. Introduction to Light Dark Matter

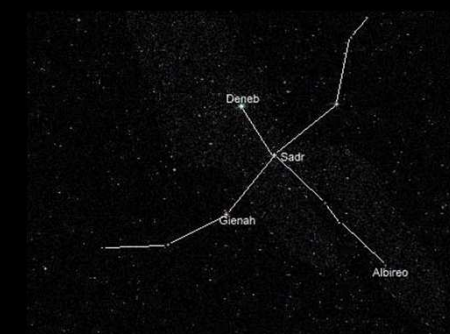
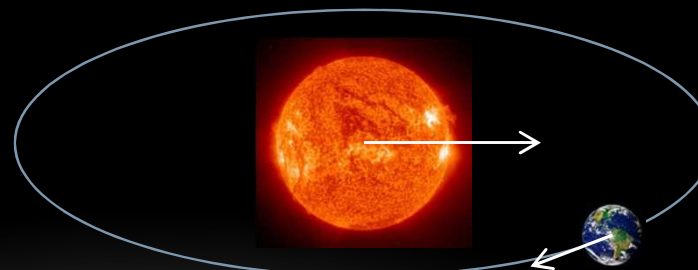
B. DETECTION TECHNIQUES: HINTS FOR LIGHT CANDIDATES?

DIRECT DETECTION OF DARK MATTER

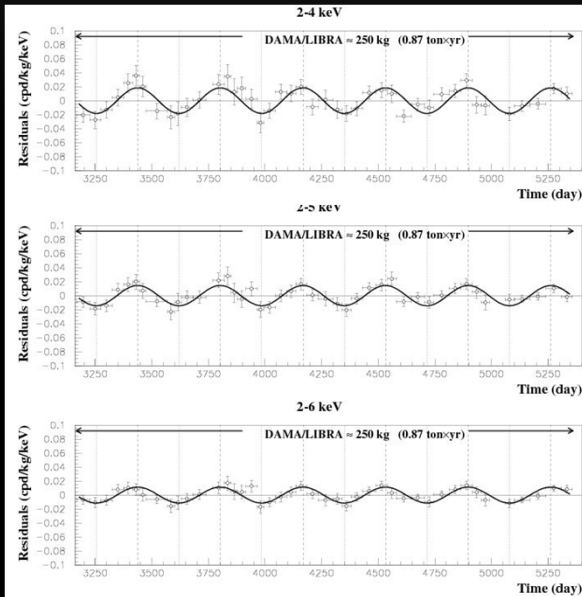
- Principle: elastic scattering events of DM particles with nuclei

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

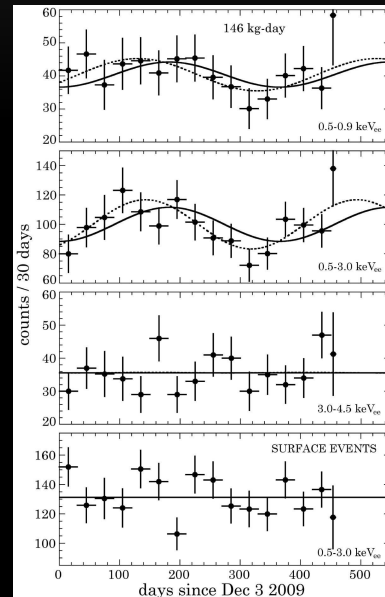
- Small interactions: shielding and technical challenge for detection
- Detectors are sensitive to the cross section, but can express results in terms of spin-independent and spin-independent interactions with nucleons
- Detector's motion in the DM halo:
 - Earth: annual modulated signal
 - Sun: asymmetric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



DIRECT DETECTION RECENT RESULTS: ARE WE OBSERVING DARK MATTER?

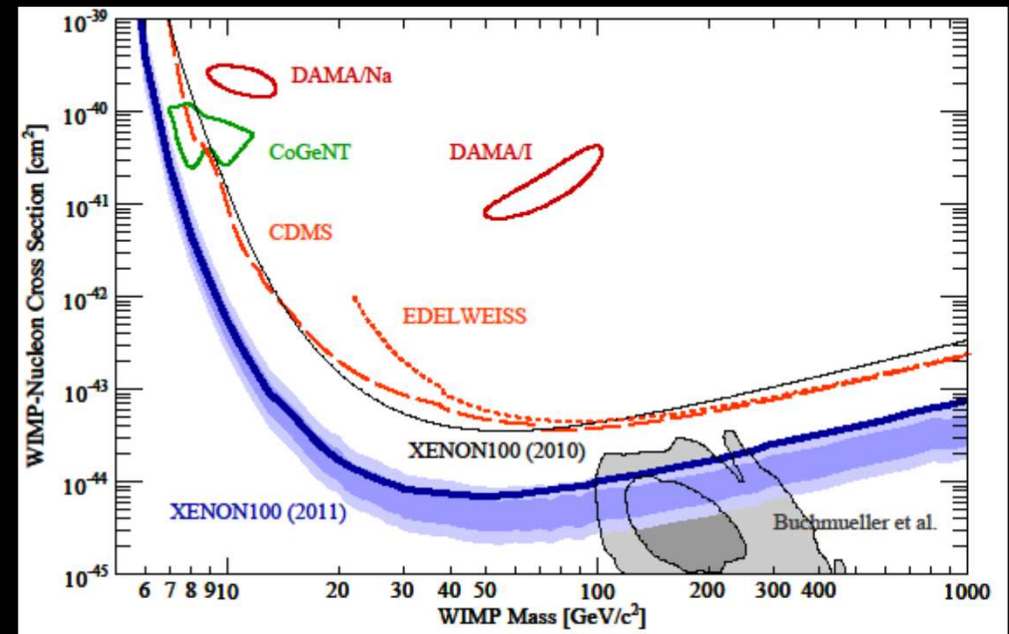


DAMA/Libra annual modulation
R. Bernabei et al.
[arXiv:1002.1028]



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

- No signal: CDMS-II, Edelweiss, XENON100



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

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

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., \[arXiv:1001.4531\]](#)

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:
 - Z invisible width
 - g_μ
 - Rare meson decays and oscillations

II. LIGHT NEUTRALINO SEARCHES

Could the neutralino be the observed phenomenon at Direct Detection experiments?

If so, what does that imply?

D. Albornoz Vásquez et al. [arXiv:1009.4380] [arXiv:1107.1614] [arXiv:1108.1338]

II. Light Neutralino Searches

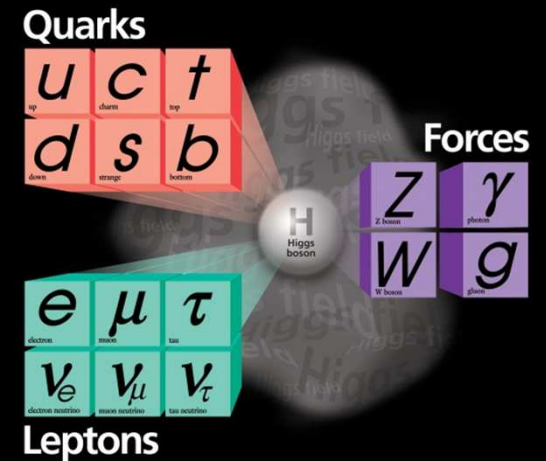
A. FRAMEWORK: SUPERSYMMETRY WITH NEUTRALINO DARK MATTER

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



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: 120 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:

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

- 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-1/2 neutralinos in the MSSM (NMSSM):

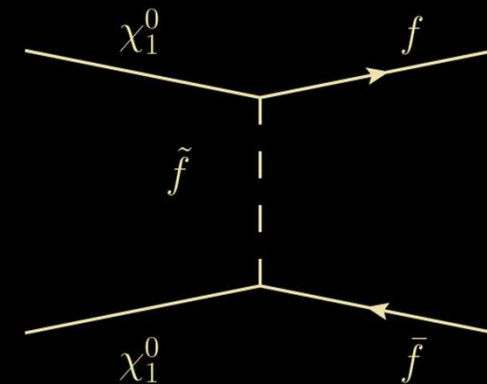
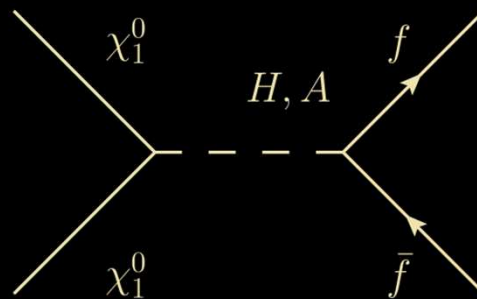
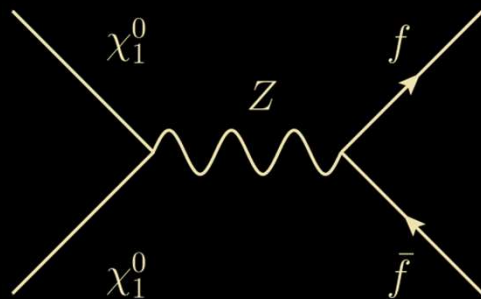
$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u \left(+N_{15}\tilde{S} \right)$$

- 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

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

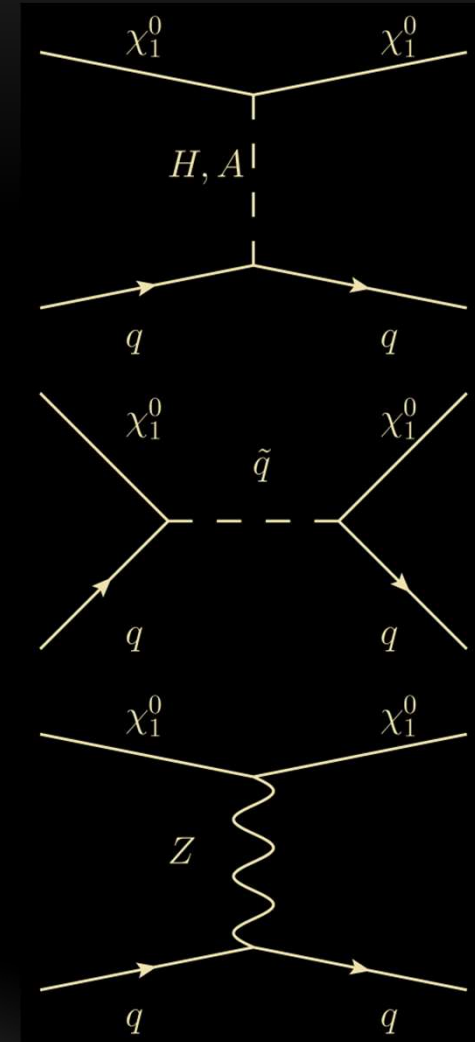
NEUTRALINO ANNIHILATIONS

- 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
- 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



II. Light Neutralino Searches

B. SCANNING THE PARAMETER SPACE: NUMERICAL ANALYSIS AND THE CODE

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. \[arXiv:1102.1898\]](#)

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 paramer 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)

MARKOV CHAIN MONTE-CARLO PRIORS: FITTING THE HYPOTHESIS

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

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

- NB: other priors can be easily implemented for specific cases

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

MARKOV CHAIN MONTE-CARLO LIKELIHOODS: FITTING THE DATA

- Dark Matter: thermal relic
 - WMAP as an upper bound
 - Fit WMAP range
$$\left\{ \begin{array}{l} 10\% \Omega_{WMAP} < \Omega_{\chi} < \Omega_{WMAP} \\ \Omega_{WMAP} h^2 = 0.1131 \end{array} \right\}$$
- 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:

$$\left\{ \begin{array}{l} B(b \rightarrow s\gamma) \\ B(B_s \rightarrow \mu^+\mu^-) \\ B(B \rightarrow \tau\nu_{\tau}) \\ \Delta M_s, \Delta M_d \end{array} \right\}$$

II. Light Neutralino Searches

C. LIGHT NEUTRALINOS IN THE MSSM

THE SCAN

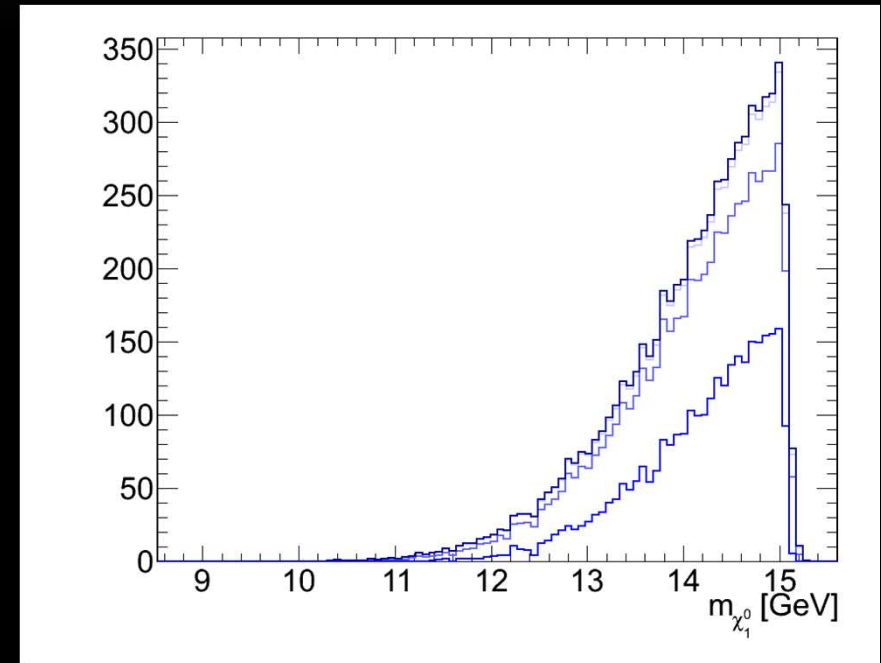
- Neutralino mass prior: 15 GeV
- Lightest neutralino observed at 8.9 GeV
- $Q_{\max} = 0.226$
- Worst likelihoods:

$$B(B \rightarrow \tau \nu_{\tau})$$

$$B(b \rightarrow s \gamma)$$

$$g_{\mu}$$

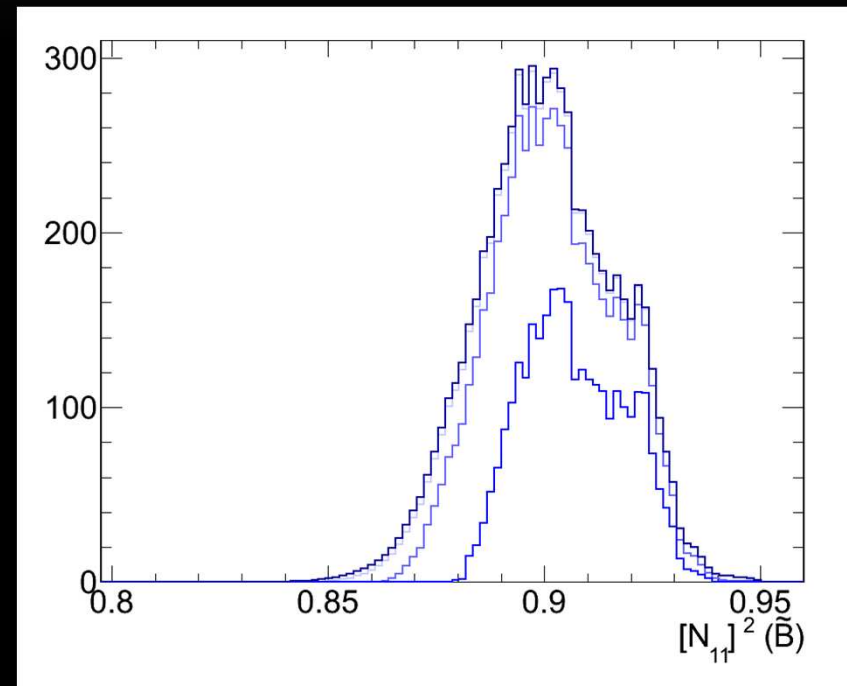
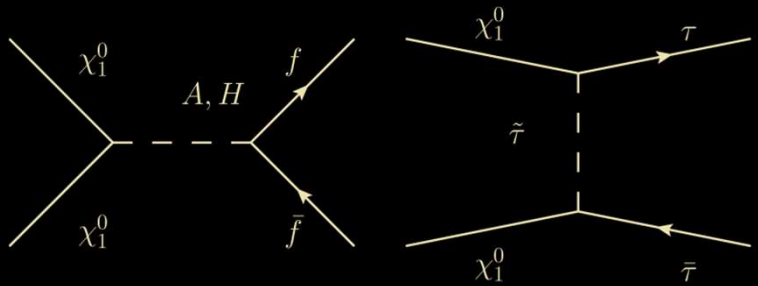
$$Z \rightarrow \chi_1^0 \chi_1^0$$



Neutralino mass frequency in the MSSM for searches below 15 GeV

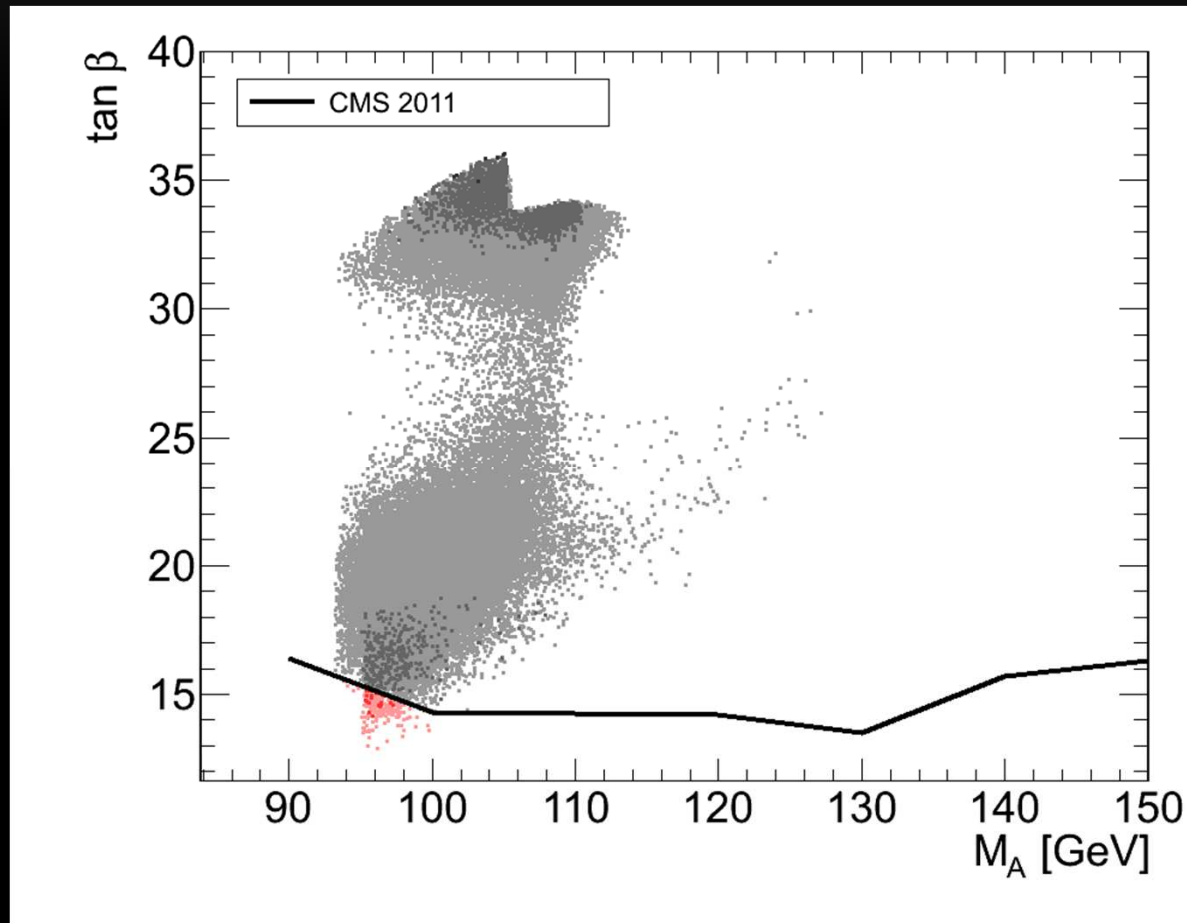
TWO TYPES OF NEUTRALINOS

- Annihilations via exchange of a Higgs
 - $M_A < 120 \text{ GeV}$
 - $M_A \approx M_h$
 - Very constrained Higgs sector!
- Annihilations via exchange of a stau
 - $M_A > 500 \text{ GeV}$
 - Higgs sector less constrained
 - Light slepton masses

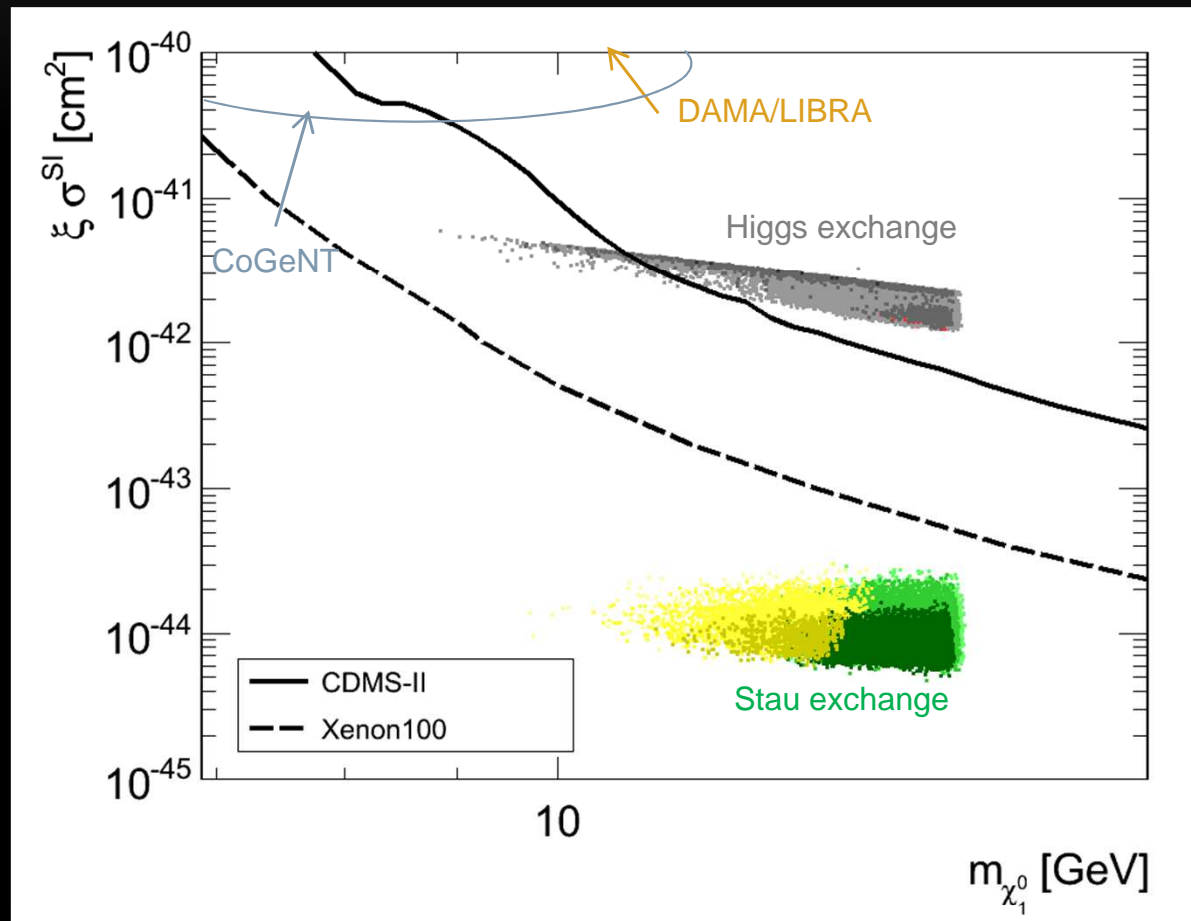


Bino components of the neutralino LSP in the MSSM

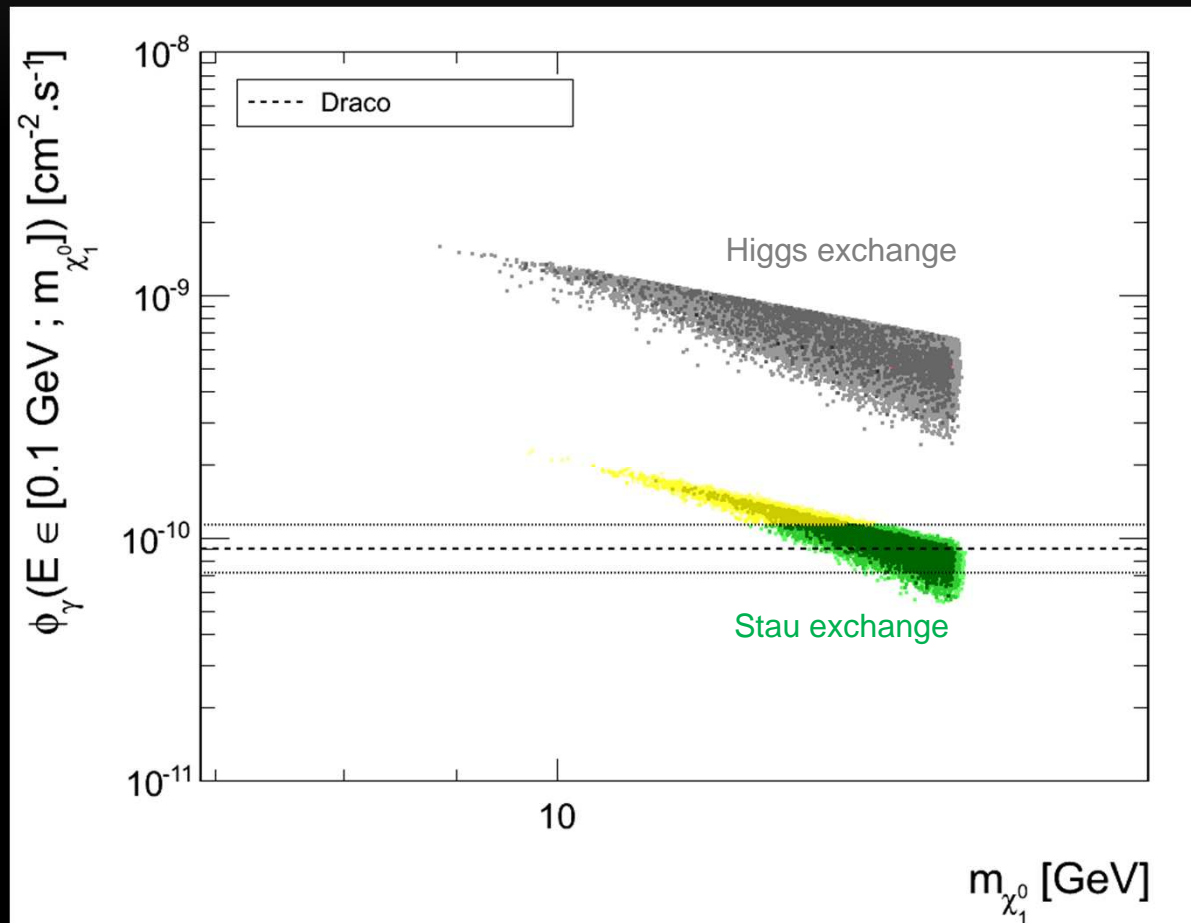
CONSTRAINTS ON THE HIGGS SECTOR



DIRECT DETECTION: SPIN INDEPENDENT INTERACTIONS



INDIRECT DETECTION: GAMMA-RAYS FROM THE DRACO DWARF SPHEROIDAL GALAXY



CONCLUSIONS

- Found neutralinos lighter than 15 GeV
- Two mechanisms of annihilation ensure the correct relic density
- Higgs exchanging neutralinos:
 - Excluded by Fermi-LAT (all of them)
 - Excluded by CMS limits on Higgs searches (most of them)
 - Excluded by XENON100 (all of them)
- Stau exchanging neutralinos are allowed down to 12.6 GeV:
 - Mass limit set by the over production of gamma-rays at lighter masses
 - Allowed by CMS
 - Allowed by XENON100
- Both cases fail to explain DAMA/LIBRA or CoGeNT

II. Light Neutralino Searches

D. LIGHT NEUTRALINOS IN THE NMSSM

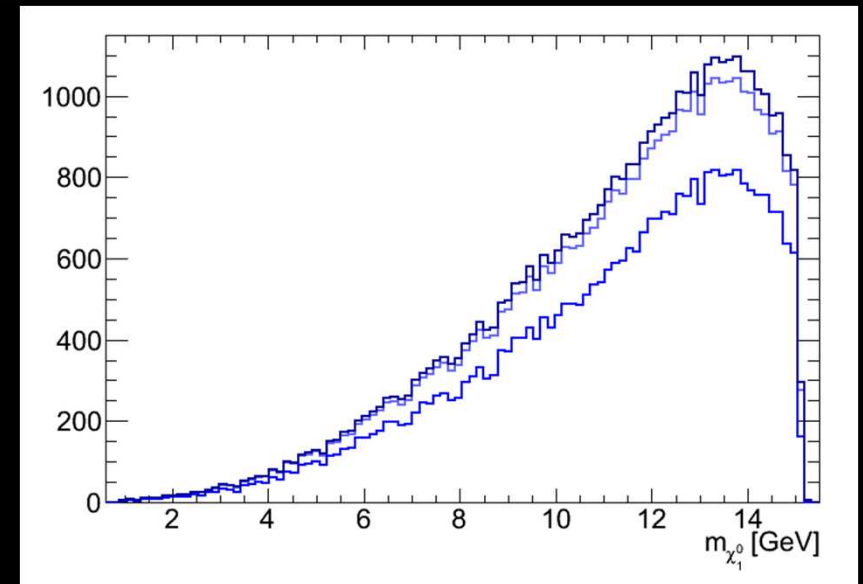
THE SCANS

- Neutralino mass prior: 15 GeV
- Lightest neutralino observed at 0.6 GeV
- $Q_{\max} = 0.642$
- Worst likelihoods:

$$B(b \rightarrow s\gamma)$$

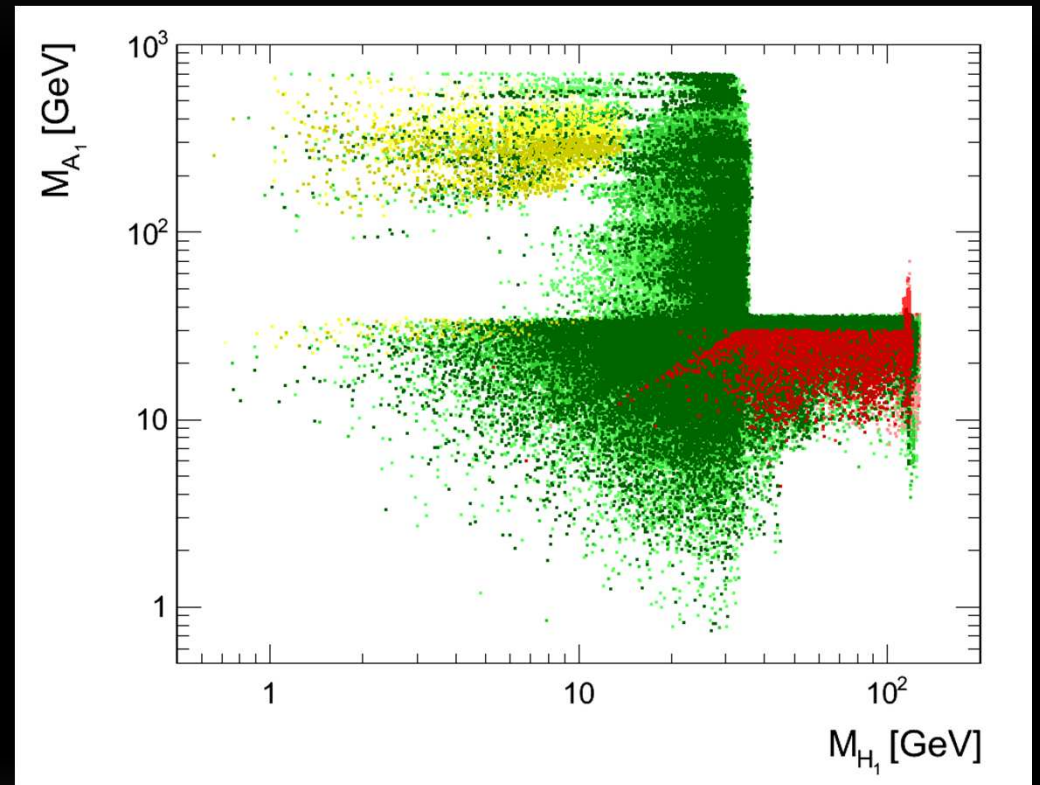
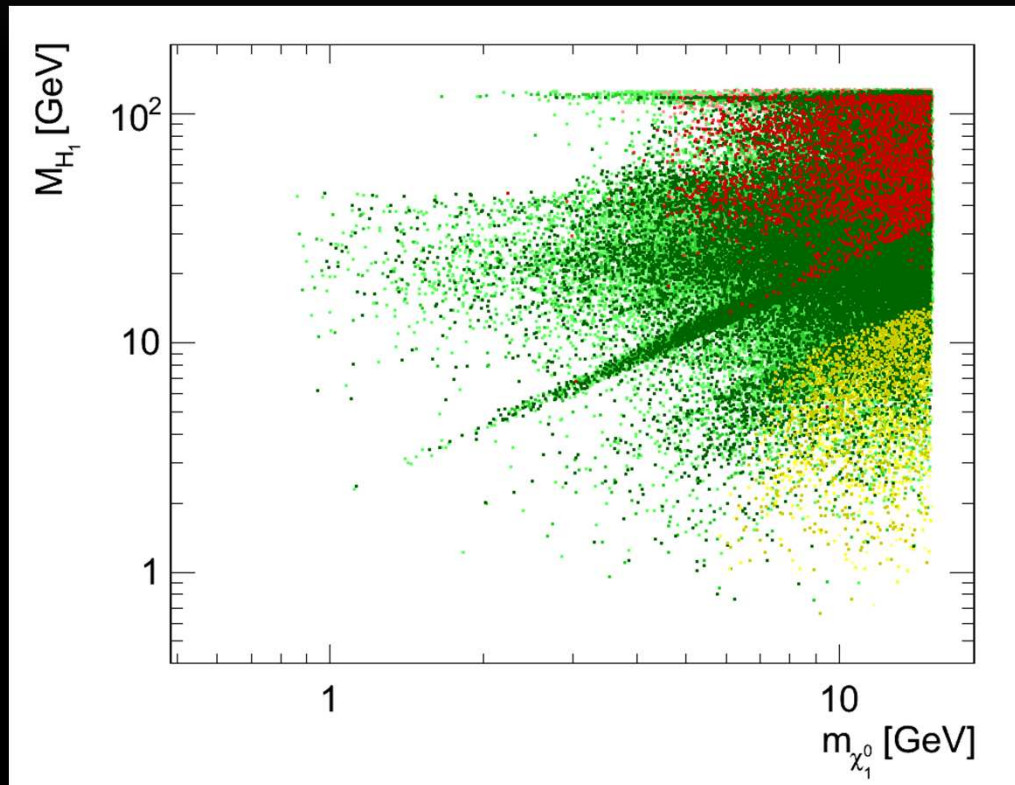
$$g_{\mu}$$

$$\Delta M_s$$



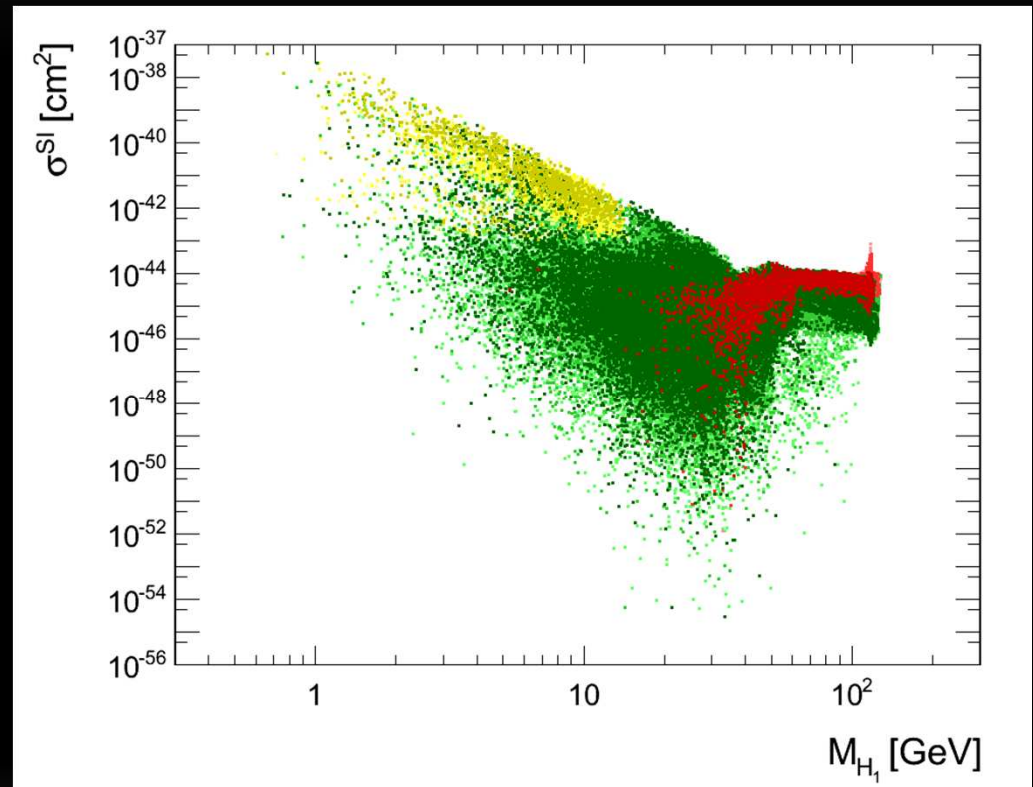
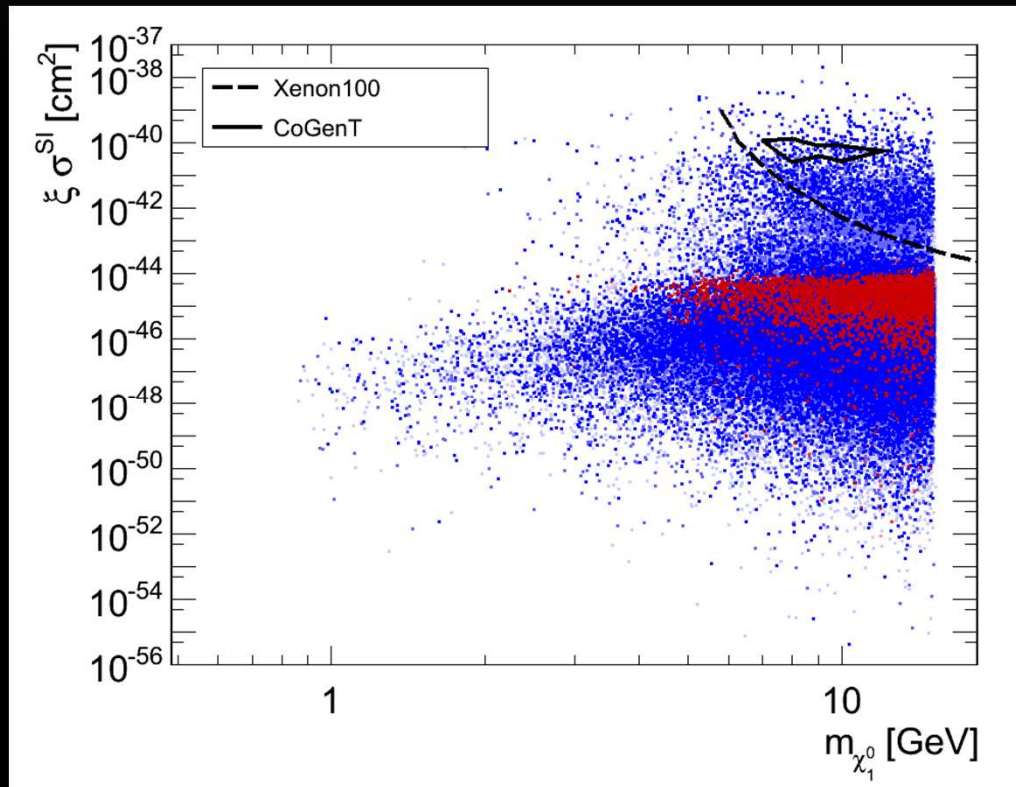
Neutralino mass frequency in the MSSM for searches below 15 GeV

NEUTRALINOS AND LIGHT HIGGS BOSONS



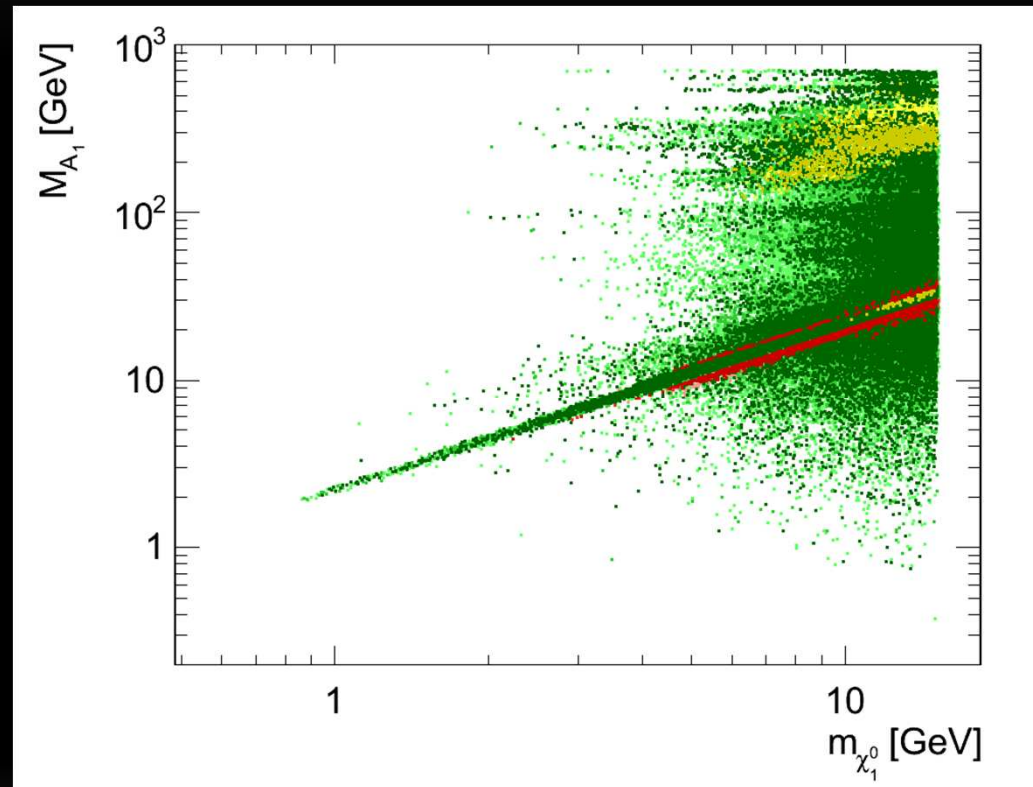
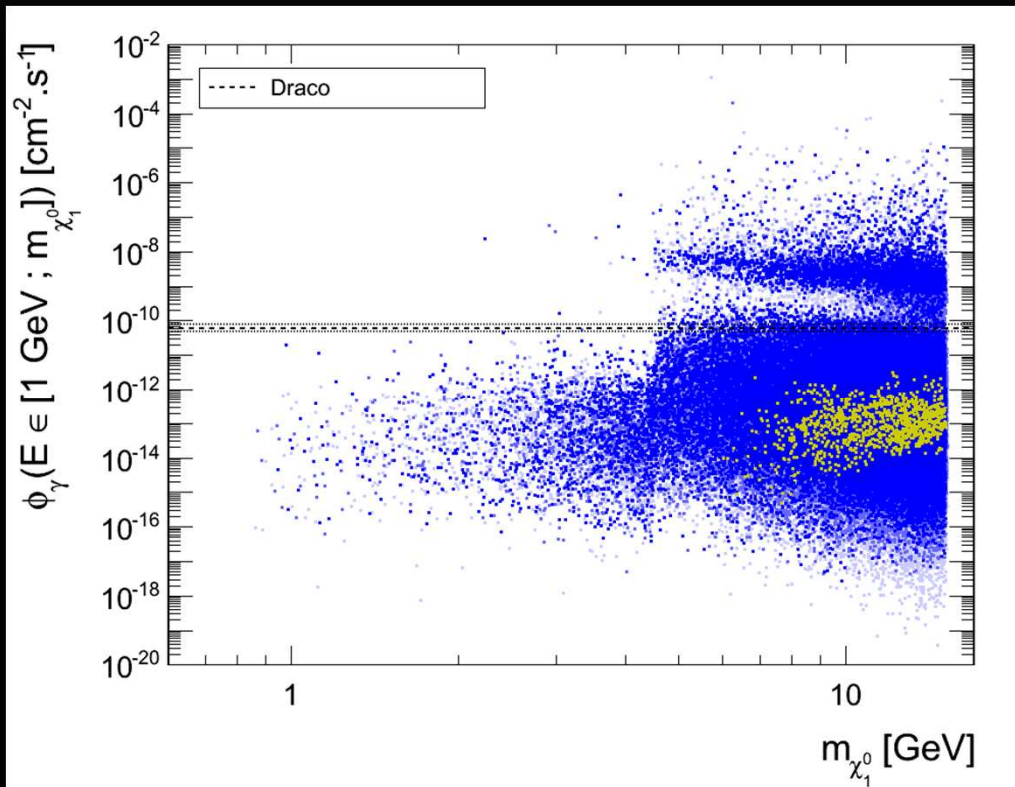
In conflict with Fermi-LAT
In conflict with XENON100
Safe

DIRECT DETECTION: SPIN INDEPENDENT INTERACTIONS AND A LIGHT SCALAR HIGGS



In conflict with Fermi-LAT
In conflict with XENON100
Safe

INDIRECT DETECTION: GAMMA-RAYS AND A LIGHT PSEUDOSCALAR HIGGS



In conflict with Fermi-LAT
In conflict with XENON100
Safe

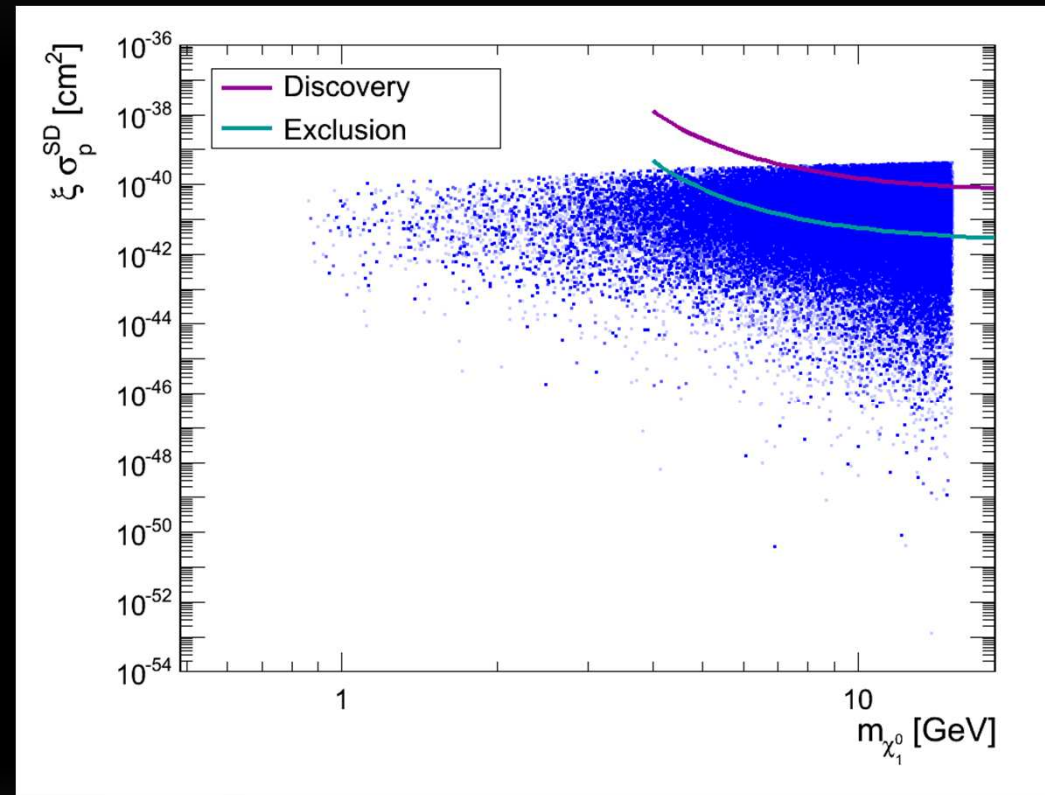
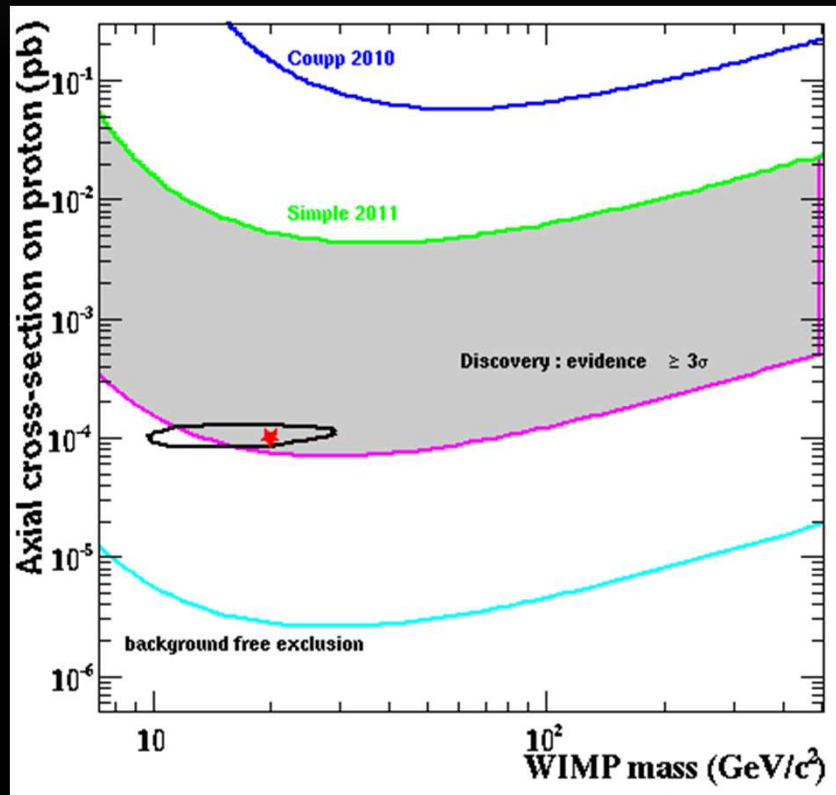
CONCLUSIONS

- Found many neutralinos lighter than 15 GeV
- Main mechanism of annihilation: exchange of light Higgses
- Light scalar Higgs exchanges:
 - Large spin independent cross sections
 - Could explain CoGeNT and/or DAMA, or
 - Excluded by XENON100
- Light pseudoscalar Higgs exchanges:
 - Resonance at low velocities: overproduction of gamma-rays
- Signatures at the LHC?

II. Light Neutralino Searches

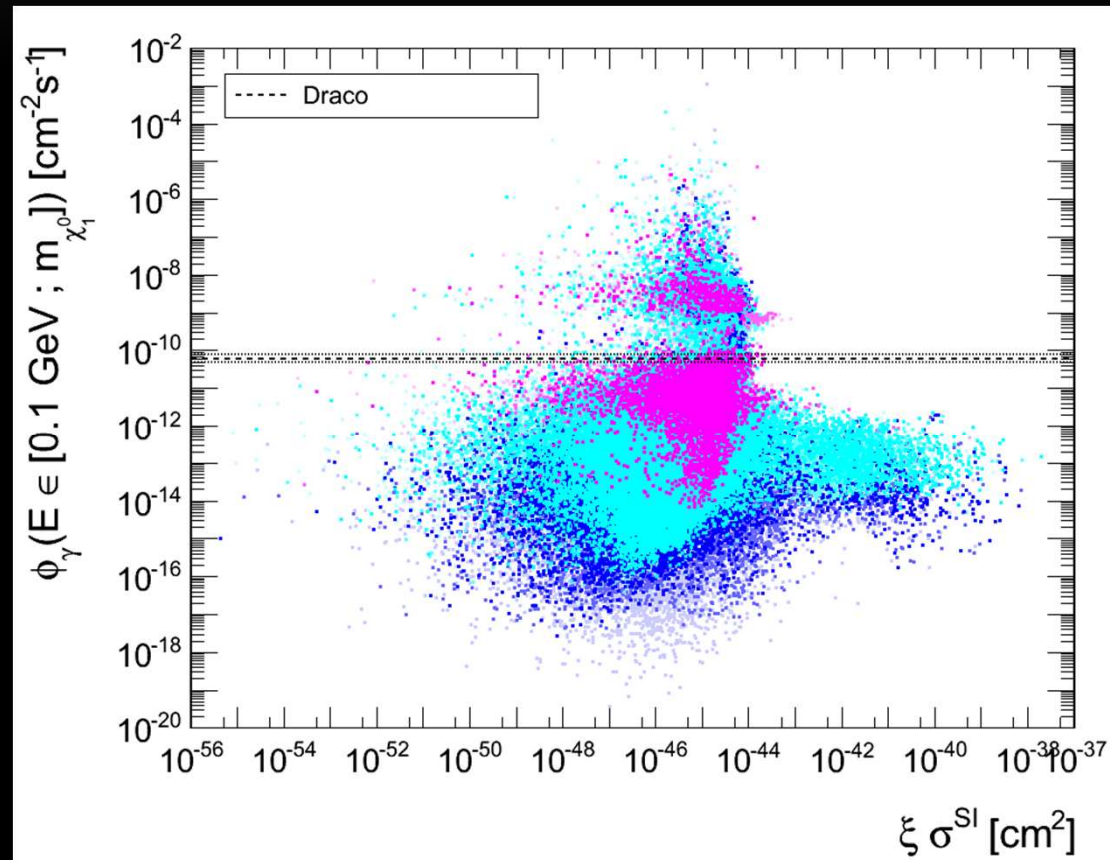
E. ANOTHER APPLICATION: PROSPECTS FOR DIRECTIONAL DETECTION

DIRECTIONAL DETECTION PROSPECTS



Directional detection prospects for a canonical
fluorine detector
F. Mayet, private communication

THE FUTURE: COMPLEMENTARITY OF DIFFERENT TECHNIQUES



Out of reach
Excludable
Discoverable

III. LIGHT SCALAR DARK MATTER AT THE LHC

Can Dark Matter be a scalar particle?

Could it be seen at the LHC?

D. Albornoz Vásquez et al. [arXiv:0912.5373]

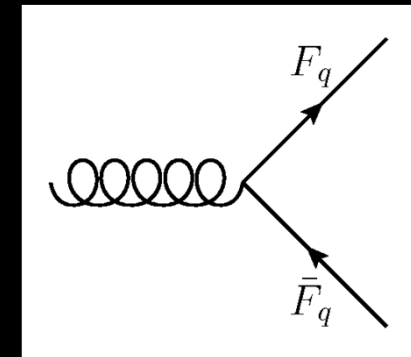
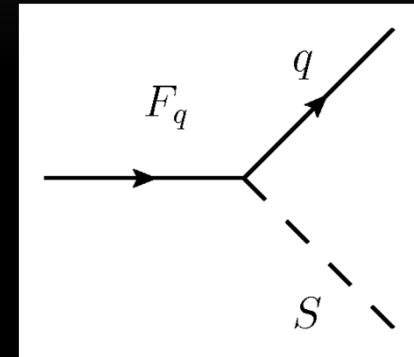
SCALAR DARK MATTER PARTICLES

- New stable scalar particles
- Interactions with SM particles via Yukawa couplings and new Fermions
- Mirror partners
- Relic density: annihilation into neutrinos
- Interaction with electrons: constrained, but could explain the 511 keV line from the galactic center
- Interaction with quarks

$$\mathcal{L} \supset S_{DM} \delta_{ij} \bar{F}^i (c_L P_R + c_R P_L) \bar{q}^j$$

- New colored fermions:

$$\mathcal{L} \supset g G_{\mu}^a \bar{F}^i \gamma^{\mu} T_{ij}^a F_j$$

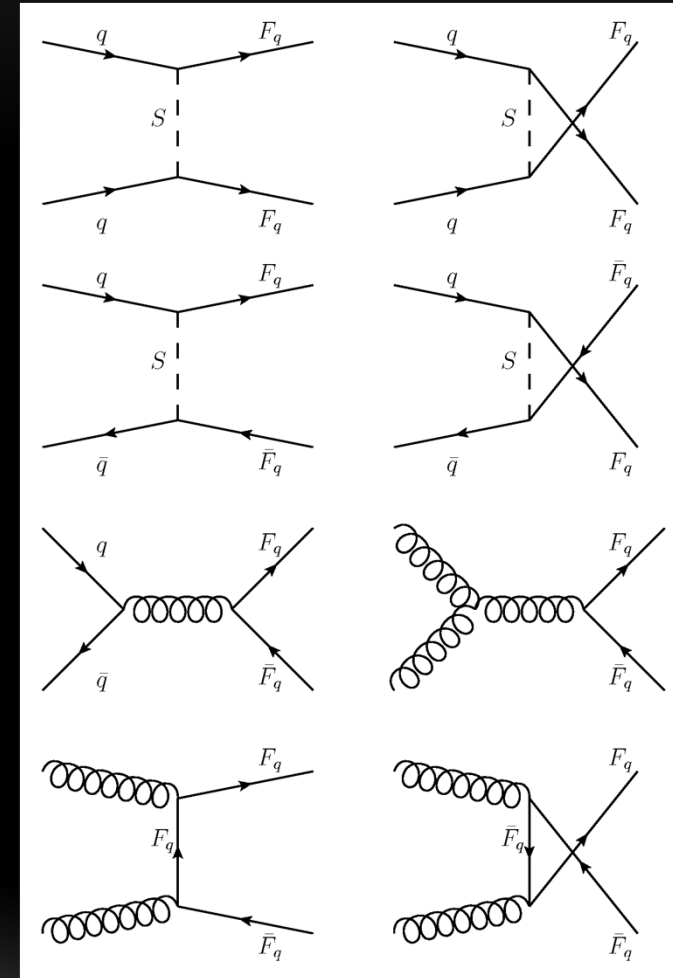
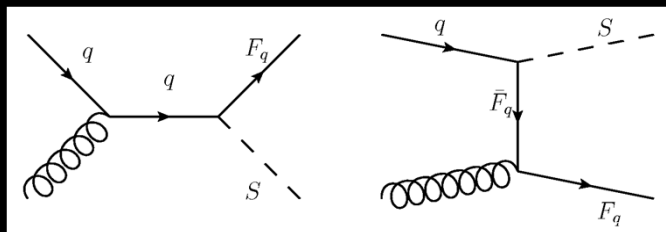


PARAMETERS AND INTERVALS

- Parameters: M_S , M_F , c_L , c_R
- Scalars: relic particles
 - Avoid Early Universe interactions with quarks: $M_S < M_\pi = 135 \text{ MeV}$
 - Avoid injecting energy at BBN times: $M_S > 1 \text{ MeV}$
- F carries both electromagnetic charge and color: $M_F > 250 \text{ GeV}$
- Couplings:
 - Perturbative limit: $c_L, c_R < 3$
 - Large enough to produce something... $c_L, c_R > 0.1$

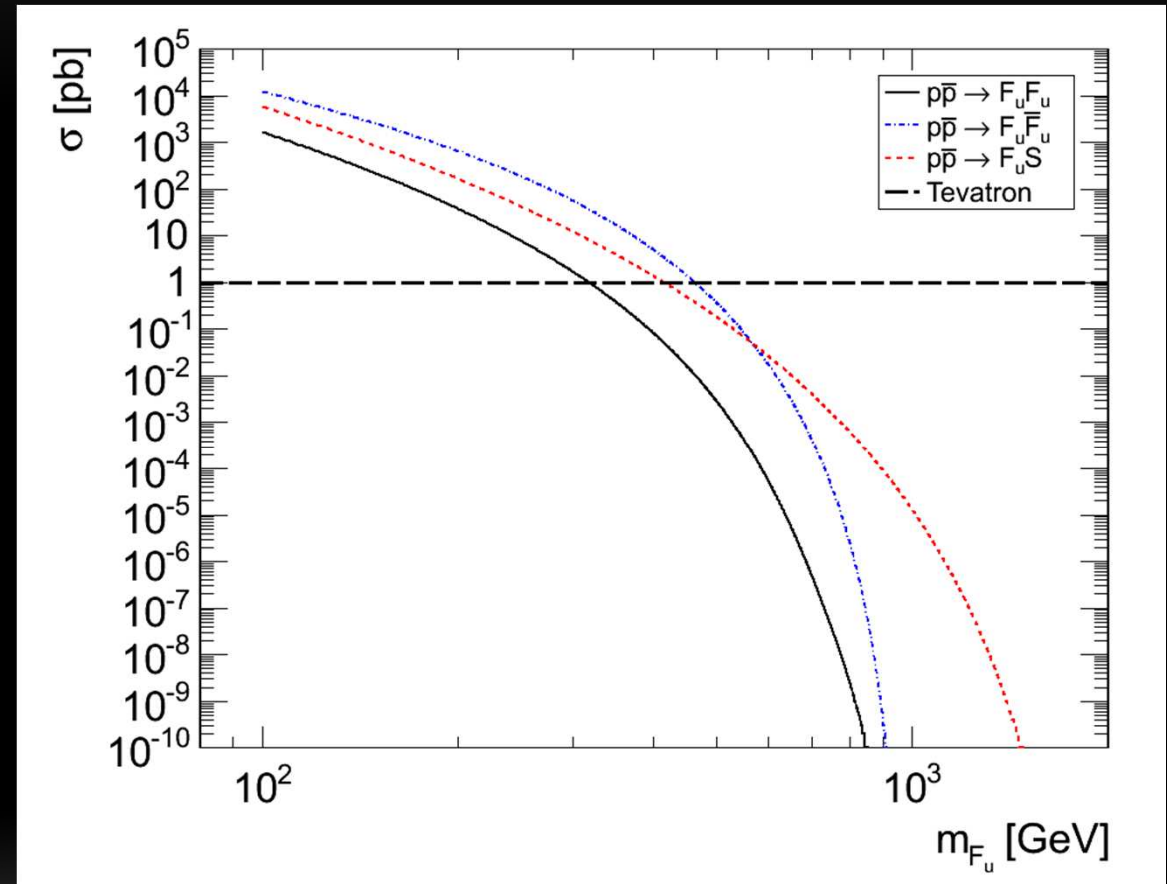
PRODUCTION PROCESSES AT HADRON COLLIDERS

- Large cross section tips:
 - Exchanging a light particle
 - Producing particles on-shell
 - Large couplings
- Production of
 - F pairs
 - F + DM
- Use CalcHEP to compute cross sections
 A. Pukhov [hep-ph/0412191]
- Focus on u-quarks



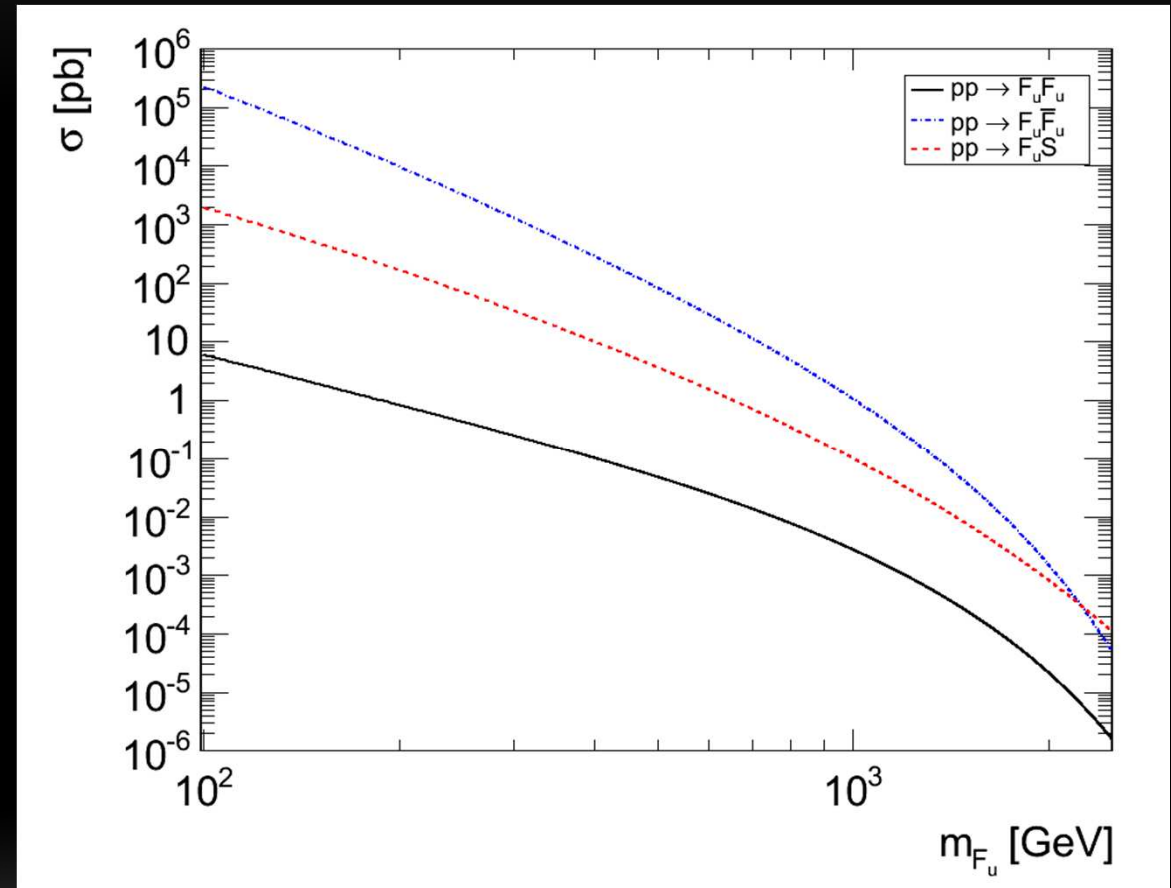
CROSS SECTIONS TEVATRON

- $c_L, c_R = 3$
- 1.96 TeV proton-antiproton collisions (Tevatron)
- Limit from Leptoquark searches
- Masses below 500 GeV are ruled out!



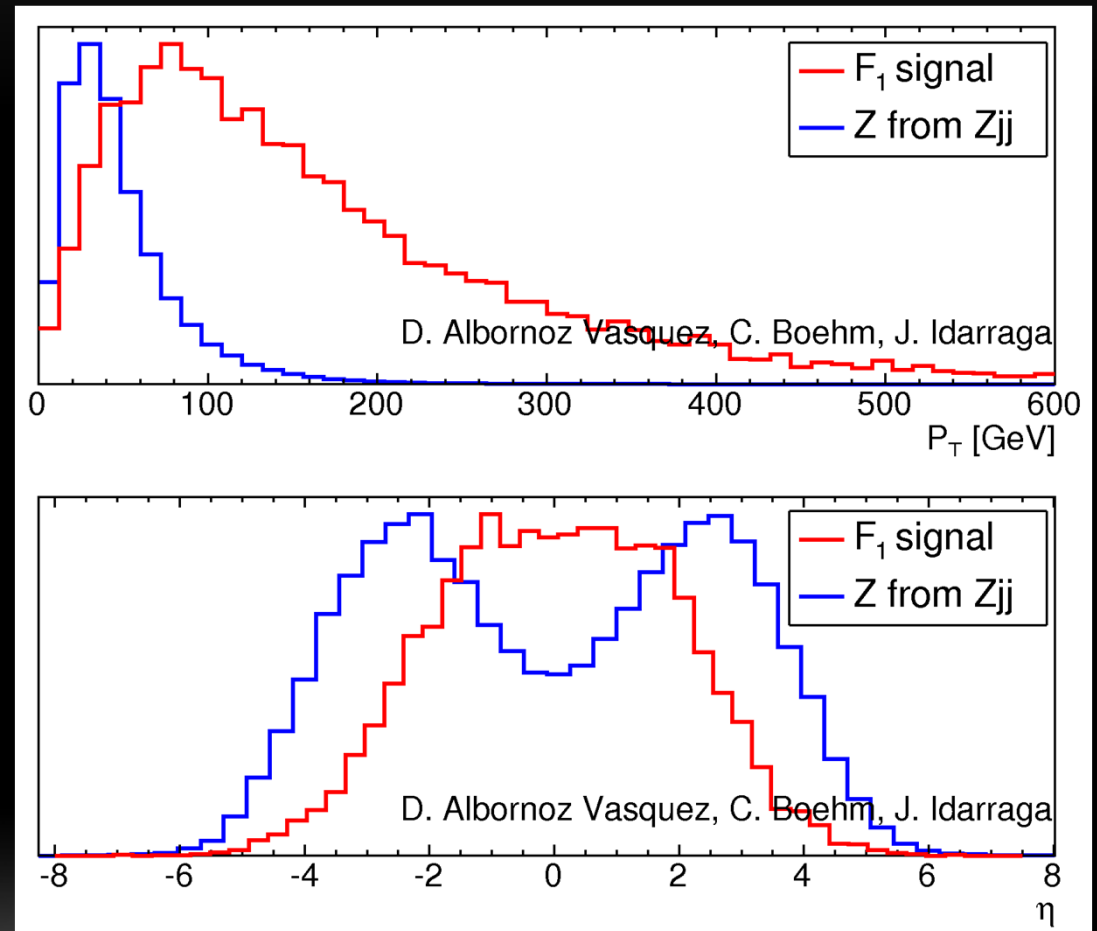
CROSS SECTIONS LHC

- $c_L, c_R = 0.3$
- 7 TeV proton-proton collisions (LHC)
- Could exclude masses up to the TeV scale?



SIGNATURES AND BACKGROUND

- Benchmark point:
 - $C_L, C_R = 1$
 - $M_S = 2 \text{ MeV}$
 - $M_F = 300 \text{ GeV}$
 - 7 TeV collisions
- Background:
 - Z + jets
 - ATLAS detector



CONCLUSIONS

- Scalar DM is possible!
- New colored particles are a good target to look for at the LHC
- Strong interactions constrain the mass (soon to be at the TeV?)
- Dedicated searches are important

IV. CONCLUSIONS AND PERSPECTIVES

ACHIEVEMENTS AND ON-GOING WORK

- Light Dark Matter is an exciting, hot research field!
- Different claims are made by direct detections experiments:
 - MSSM neutralinos cannot explain signals from DAMA or CoGeNT
 - NMSSM neutralinos can
- Other constraints exist and are quickly developing: Fermi-LAT, AMS, LHC...
- Configurations could easily escape detection of one experiment alone
- New techniques will give complementary information: directional detection
- It is crucial to constrain the possibilities from all observables
- Alternative models, such as scalar DM, prove to be interesting and available
- It is possible to constrain them using some of the same techniques

PERSPECTIVES

- Are we interpreting correctly the observations?
- Are our assumptions strictly necessary?
- What if freeze-out was not the mechanism to achieve relic density?
- What if there were more than one dark particle?
- What if DM was composite?
- Data is more and more abundant. The best-loved explanations are weakening. The problematic is still unsolved.

“Those who have handled sciences have been either men of experiment or men of dogmas. The men of experiment are like the ant, they only collect and use; the reasoners resemble spiders, who make cobwebs out of their own substance. But the bee takes a middle course: it gathers its material from the flowers of the garden and of the field, but transforms and digests it by a power of its own. Not unlike this is the true business of philosophy; for it neither relies solely or chiefly on the powers of the mind, nor does it take the matter which it gathers from natural history and mechanical experiments and lay it up in the memory whole, as it finds it, but lays it up in the understanding altered and digested. Therefore from a closer and purer league between these two faculties, the experimental and the rational (such as has never yet been made), much may be hoped.”

Francis Bacon

Novum Organum (1620)

APPENDIX

LOCAL DARK MATTER DISTRIBUTION: THE STANDARD DARK MATTER HALO

- N-body simulations \rightarrow 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:

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

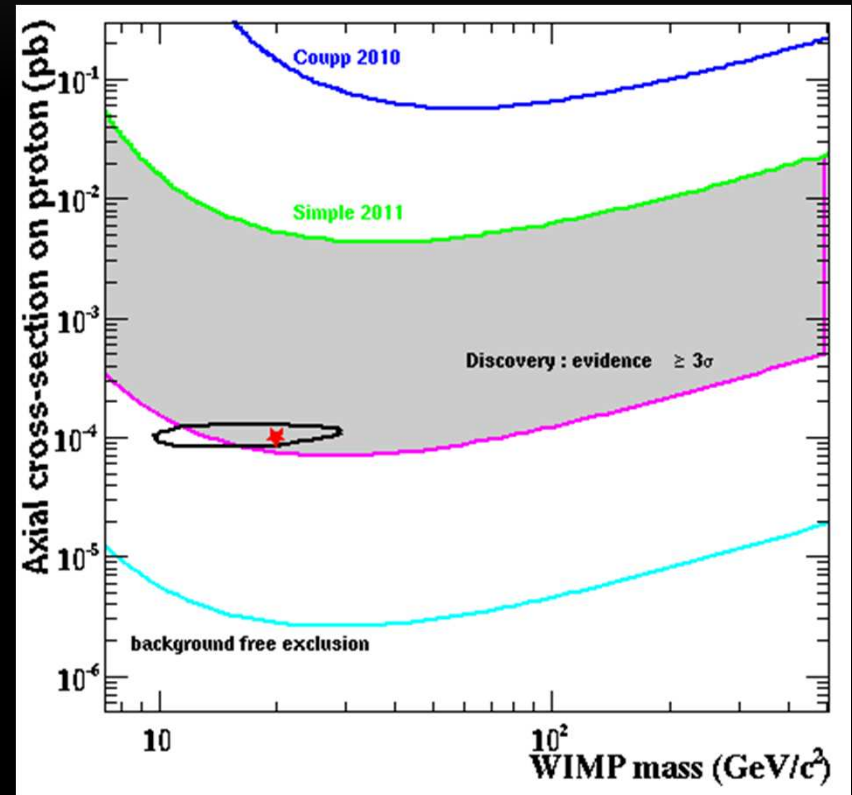
$$v_0 = 220 \text{ km s}^{-1} \quad v_0 = (200 - 280) \text{ km s}^{-1}$$

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

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

DIRECTIONAL DETECTION PROSPECTS

- Fluorine (CF_4) gaz (good ionization)
- 10 kg
- 50 mbar pressure (track reconstruction)
- Energy threshold: 5 keV
- Exposure: 30 kg yr



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

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

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

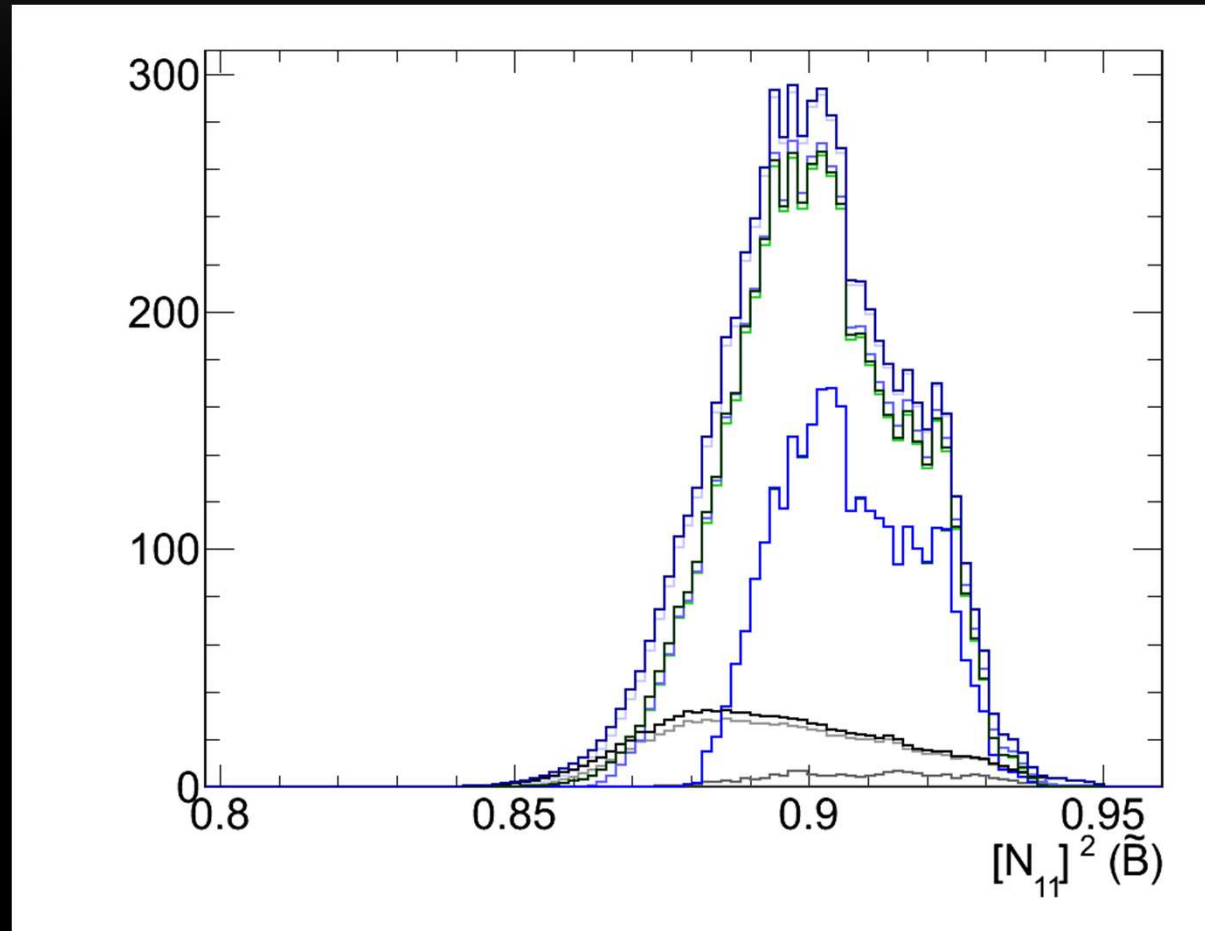
$$l = 86.37^\circ$$

$$b = 34.72^\circ$$

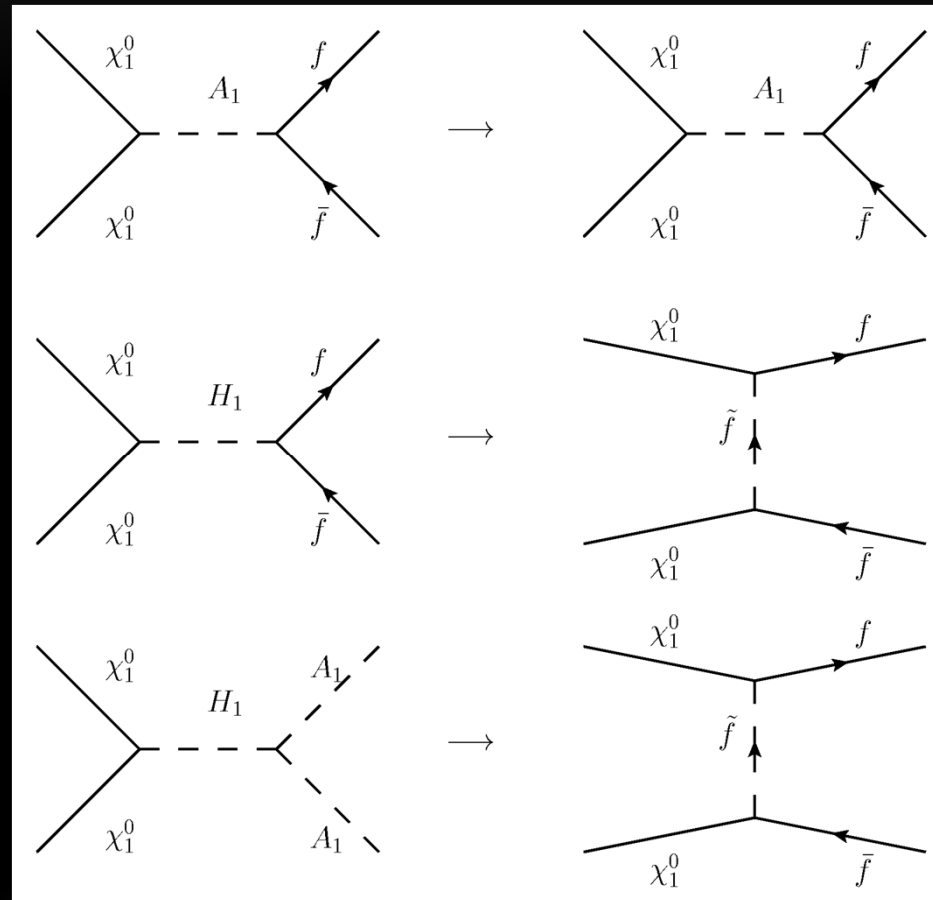
$$\frac{M_{1/2}}{L_{1/2}} = 200_{-60}^{+80}$$

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

BINO FRACTION OF MSSM NEUTRALINOS



NMSSM NEUTRALINOS: FROM EARLY UNIVERSE TO GALACTIC ANNIHILATIONS



CROSS SECTIONS AT PARTON LEVEL

