

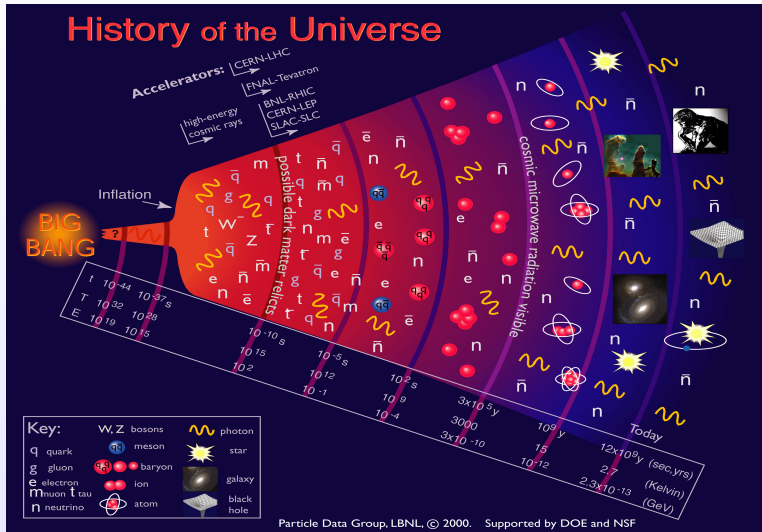
Applying Dark Matter constraints to SUSY: theory uncertainties

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“Collider Physics and the Cosmos” Workshop

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What happened before recombination?

- Quantum gravity? Branes? Other gravitation theories?
- Inflation
- Topological defects (cosmic strings, magnetic monopoles, domain walls, ...)?
- Primordial Black Holes?
- Leptogenesis
- Baryogenesis
- Particle-antiparticle asymmetry
- QCD-dominated plasma
- Relic particle freeze-out
- Big-Bang nucleosynthesis

Extra-dimensions?

- Predicted by brane theories
- Possibility of extra-dimensions in the Early Universe
- Could they survive until Big-Bang nucleosynthesis?
- Did they play a role in Universe evolution?

New gravitation theories?

- Scalar-Tensor theories
- Tensor-Vector-Scalar theories (TeVeS)
- Loop quantum gravity
- $f(R)$ gravity
- ...

Inflation: Rapid exponential expansion of the Early Universe

- Can explain why different regions of the sky seem causally connected
- Can explain why the Universe appears flat
- Can explain why inhomogeneities have appeared
- Ends by a reheating: generation of SM particles from the inflation energy and thermalization of the primordial soup

Observations of the Cosmic Microwave Background help constraining inflation models...

But many questions remain...

- How long was inflation? When did it finish?
- How long did the thermalization took?
- Could relic particles have been generated non-thermally during reheating?
- Is inflation related to particle physics phenomena?

Baryogenesis, Leptogenesis

- What happened???

Particle-Antiparticle Asymmetry

- Where has antimatter gone?
- Are we in a special antimatter-free part of the Universe?
- Need for a Beyond SM scenario
- Sakharov conditions:
 - Baryon number B violation
 - C -symmetry and CP -symmetry violation
 - Interactions out of thermal equilibrium
- Probably related to leptogenesis and/or baryogenesis
- Underlying processes and ingredients unknown
- Relation to Inflation unknown

QCD dominated era

- Quark gluon plasma dominating after EW symmetry breaking
- Quark hadron transition not completely described
- Need for precise calculation of the relativistic degrees of freedom
- Lattice calculations needed for accurate predictions
- More information needed from Heavy Ion Collisions
- Important for accurate relic density calculations

Big Bang Nucleosynthesis (BBN)

- Oldest period for which we have (rather) direct observations
- Well described by current knowledge of nuclear physics
- Good agreement between standard BBN model and observations for hydrogen and helium
- Problem of Lithium: ${}^6\text{Li}$ overabundant, ${}^7\text{Li}$ underabundant
- Still many possibilities for deviation from standard BBN: extra radiation, dark energy effects, late entropy generation, effects of relic particles, modified expansion rate, ...

Nature of dark energy

- Cosmological Constant?
- Vacuum Energy?
- Quintessence, spintessence, K-essence, phantom energy, ...?

Nature of (cold) dark matter

- Produced thermally or not?
- Made of a single type of particles?
- Dark matter profiles in galaxies and clusters?
- Cuspy centers of not?
- Dark galaxy satellites or not?
- Local (near Sun) dark matter density?

Phenomenological MSSM (pMSSM)

The most general MSSM scenario with R -parity, CP conservation and minimal flavour violation

→ 19 independent parameters (20 with gravitino mass)

Two cases: lightest neutralino or gravitino as dark matter

Neutralino types:

- bino-like ($|M_1| \ll |M_2|, |\mu|$)
- wino-like ($|M_2| \ll |M_1|, |\mu|$)
- higgsino-like ($|\mu| \ll |M_1|, |M_2|$)
- or a mixed state

→ Flat scans on the pMSSM parameters

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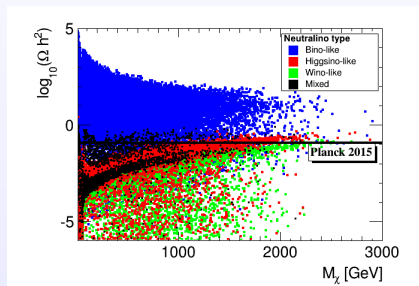
19 (20)-parameter pMSSM with neutralino (gravitino) dark matter

Parameter	Range (in GeV)
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 3000]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 3000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 3000]
$M_{\tilde{\tau}_L}$	[0, 3000]
$M_{\tilde{\tau}_R}$	[0, 3000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 3000]
$M_{\tilde{q}_{3L}}$	[0, 3000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 3000]
$M_{\tilde{t}_R}$	[0, 3000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 3000]
$M_{\tilde{b}_R}$	[0, 3000]
$\tan\beta$	[1, 60]
$(M_{\text{gravitino}})$	$< M_{\tilde{\chi}_1^0}$

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables and Z widths (Superlso)
- Computation of dark matter observables (Superlso Relic, Micromegas)
- Determination of SUSY and Higgs mass limits (Superlso, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higgs, FeynHiggs, SusHi)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino, MadGraph)
- Implementation of ATLAS and/or CMS SUSY and monoX search results
- Determination of detectability with fast detector simulation (Delphes)

Very precise measurements of cold dark matter density by Planck (2015):

$$\Omega_c h^2 = 0.1188 \pm 0.0010$$

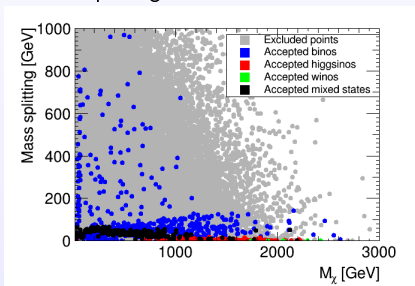
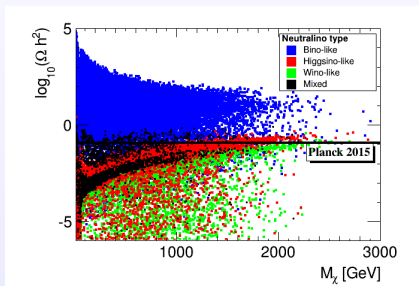


AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

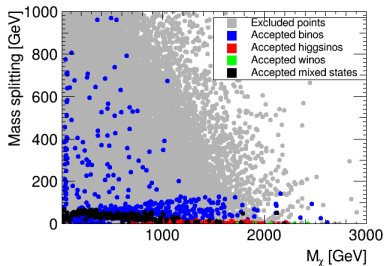
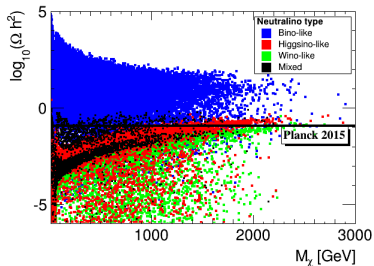
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imposing Planck 2015 limits

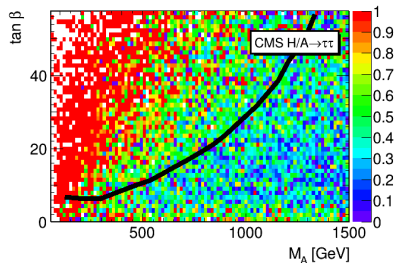
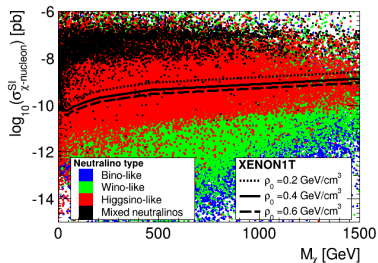


AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426



Theoretical limitations: uncertainties

- QCD equations of state: $\sim 5\%$
- Sommerfeld enhancement (non-perturbative): $\sim 5\text{--}50\%$
- Higher order corrections: $\sim 5\text{--}50\%$
- Multi-component dark matter: lower limit not applicable?
- Early Universe dominated by a dark component: lower limit not applicable?
- Entropy injection in Early Universe: Planck limits not applicable?



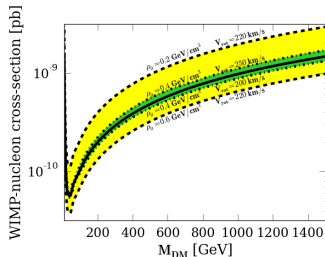
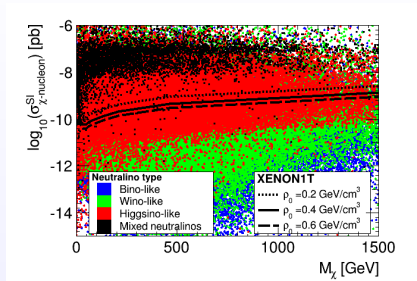
AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Upper limits on the WIMP-nucleon scattering cross sections

Strong constraints on the $(M_A, \tan \beta)$ parameter plane

Higgsino-like neutralinos more strongly probed

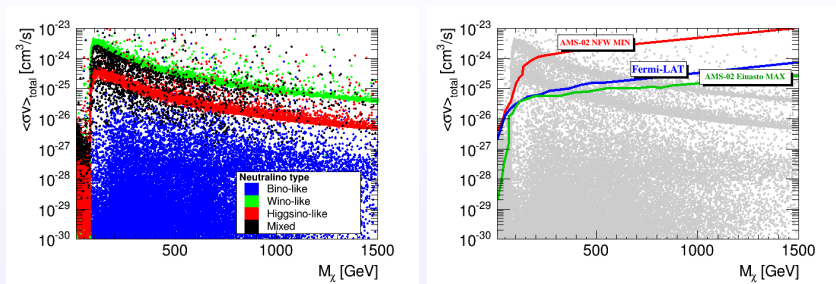
Complementary to $H/A \rightarrow \tau^+\tau^-$ and $B_s \rightarrow \mu^+\mu^-$ searches



AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Theoretical limitations: uncertainties

- Nuclei form factors: $\sim 20\text{-}50\%$
- Velocity of the Solar System: $\sim 20\%$
- Local dark matter density (using halo profiles): roughly factor 2
- Local dark matter density (absolute): limit not applicable
- Multi-component dark matter: limit to be rescaled



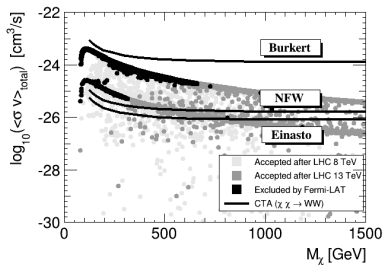
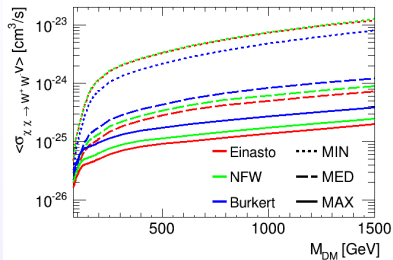
AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Upper limits on annihilation cross sections

AMS-02: anti-proton fluxes

Fermi-LAT: gamma rays from dwarf spheroidal galaxies

Wino-like neutralinos more strongly probed

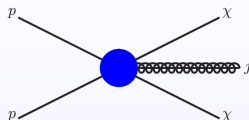


AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Theoretical limitations: uncertainties

- Sommerfeld enhancement: generally $\sim 10 - 50\%$, up to factor ~ 1000
- Propagation model (anti-protons only): roughly factor 10
- Galaxy profiles: roughly factor 2 (much more near galaxy centers)
- Multi-component dark matter: limit to be rescaled
- Astrophysical sources in galactic centers: limit non applicable (positrons...)

Generic monojets in “simple” DM scenarios:



Monojets in the MSSM:

AA, M. Battaglia, F. Mahmoudi, arXiv:1506.02148

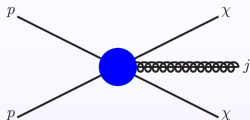
LHC very sensitive to the strongly interacting particles

→ larger monojet cross sections in the MSSM

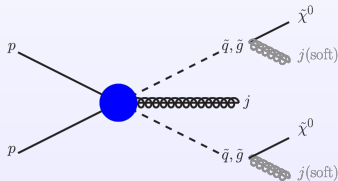
→ particularly relevant when small mass splitting between squark/gluino and neutralino

→ monojet searches in the MSSM do not probe the dark matter sector...

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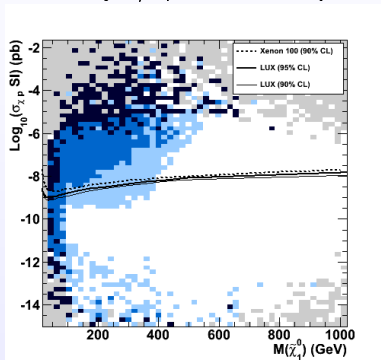
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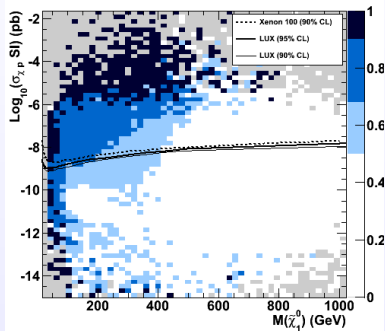
→ monojet searches in the MSSM do not probe the dark matter sector...

In the dark matter direct detection scattering cross section vs. neutralino mass plane:

jets/leptons+MET only



jets/leptons+MET searches and monojet

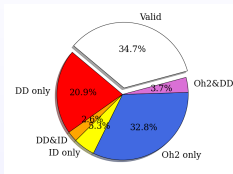


AA, M. Battaglia, F. Mahmoudi, arXiv:1311.7641

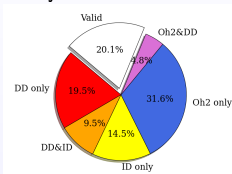
Colour scale: fraction of excluded points

DM direct detection complementary to the LHC searches!

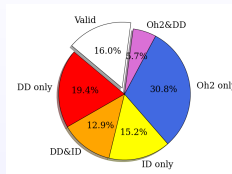
Exclusion by dark matter observables



CONSERVATIVE

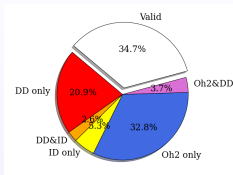


STANDARD

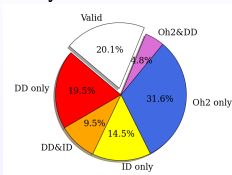


STRINGENT

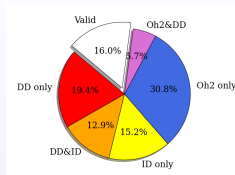
Exclusion by dark matter observables



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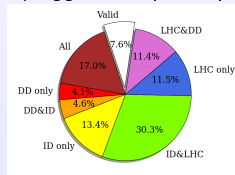
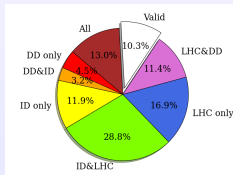
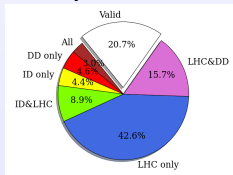


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Exclusion by dark matter observables and LHC searches (Higgs mass pre-imposed)



Study restricted to neutralino NLSP case for comparison with neutralino LSP scenario

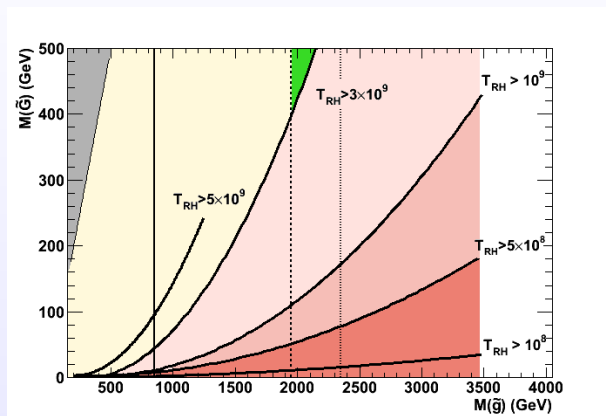
- Gravitino LSP
- Neutralino NLSP short-lived with respect to cosmology
 - Gravitino produced either through NLSP decay or reheating
 - Neutralino lifetime constrained by Big-Bang Nucleosynthesis
- Neutralino NLSP long-lived with respect to collider physics
 - Same collider constraints as for neutralino LSP scenario
- DM composed exclusively of gravitinos
 - Constraints from direct and indirect detection completely escaped (gravitino very elusive!)
 - Constraints from relic density strongly relaxed (in particular because of gravitino production during reheating)

Gravitino LSP scenario much less constrained than the neutralino LSP scenario!

Constraining the reheating temperature with LHC in the MSSM with gravitino DM

Production of gravitino after inflation related to reheat temperature and gaugino masses

→ LHC gluino searches and DM density measurements probe the reheating temperature



AA, M. Battaglia, L. Covi, J. Hasenkamp, F. Mahmoudi, arXiv:1505.04595

Interesting interplay between cosmology and collider physics!

Discussions...