Light LSP DM in SUSY

Rohini M. Godbole

Centre for High Energy Physics, IISc, Bangalore, India

Presented at:

Physics Department, Shiv Nadar University.

- Introduction.

- Low mass (mostly $m_{LSP} < m_{h_{SM}}/2$) DM in SUSY.

1 $\tilde{\chi}_1^0$ LSP: pMSSM, NMSSM

2 $\tilde{\nu}_R$: cMSSM,pMSSM,NMSSM (work by others)

Based on:

1)R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838;

2)R. K. Barman, G. ,Belanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata,2006.07854, Phys. Rev. D 103, (2021) 015029;

3)R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Invited Review :Eur.Phys.J.ST 229 (2020) 21, 3159-3185,

4)R. K. Barman, G. Belanger, B. Bhattacharjee, R. Godbole and R. Senguptalight DM in pMSSM, 2207.06238

These papers focus on $2m_{\tilde{\chi}_1^0} \leq m_h(125)$.

An analytic continuation of sorts of work which I had started around 2000/2001.

- G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000) [hep-ph/0002039]

- G. Belanger, F. Boudjema, A. Cottrant, R. M. Godbole and A. Semenov, Phys. Lett. B **519**, 93 (2001) [hep-ph/0106275]

- D. Albornoz Vasquez, G. Belanger, R. M. Godbole and A. Pukhov, Phys. Rev. D **85** (2012) 115013,[arXiv:1112.2200 [hep-ph]].

- G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole, S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013) [arXiv:1308.3735 [hep-ph]]

It forms 26.8% of the energy budget of the Universe.

DM velocities now are about 200 km/sec.

Direct experimental evidence exists ONLY for their gravitational interactions.

It is electromagnetically neutral and HAS got to be stable on the scale of life time of the Universe i.e. few billion years!

The DM provided the attraction to bind matter together to form stars/galaxies and all the structures! this is called structure formation.

1)Astrophysical evidence is strong. These are relics left over from the early universe.

2)The expected relic density predictions are determined by the theoretical understanding of early universe and particle content of the particles in the early universe and their interactions. **Truly astro-particle physics object!**

3)Strictly speaking we do not have any observational information which will constrain its mass.

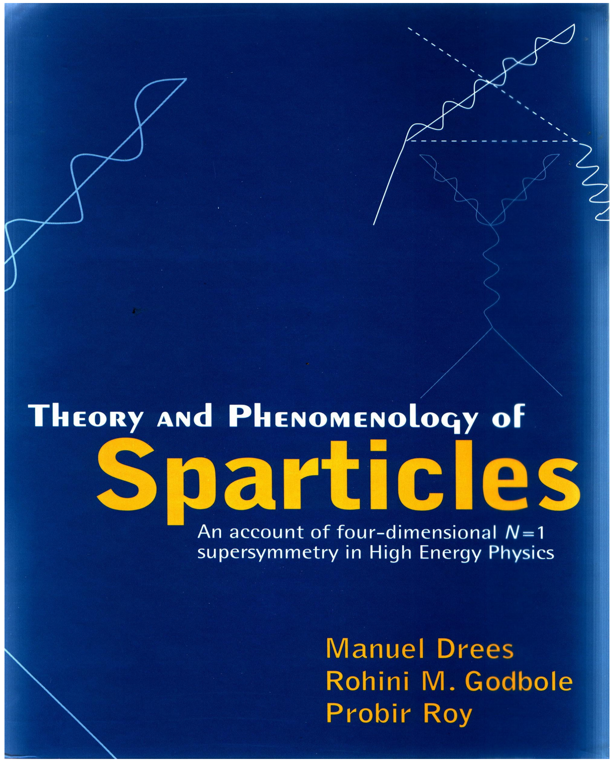
4)Has implications for structure formation in the Universe and hence is constrained by that. What is 'liked' is a particle which would fall out of thermal equilibrium with radiation in the early universe when it is non relativistic. 'Cold Dark Matter' : CDM . The weakly interacting massive particle (WIMP) paradigm ruled for a long time. But it is under tension!

Solution to Keep the higgs light! Associated with every particle there is a supersymmetric partner!

For the symmetry to solve the aesthetic problems of the SM we need the partners of t quarks to have a mass M with $Mc^2 < 1000$ GeV. Looking for them at LHC was one way to probe the BSM! But we have not found any evidence of those partners so far at the LHC!

At the same time the theory has some ready made DM candidate particles.

Looking for this DM candidate at the LHC can be also a window for SUSY at the LHC.



Most of us grew up in the period where SUSY was the 'standard BSM' and the Lightest Supersymmetric Particle (LSP) was the most attractive, Weakly Interacting Massive Particle as the candidate for the DM.

But LHC results have put the idea of 'natural' SUSY under stress and the XENON-1T, PandaX (4T), LZ results have put the WIMP paradigm under stress.

LSP: Two candidates: the sneutrino (supersymmetric partner of neutrino) $\tilde{\nu}_L$ and the neutralino $\tilde{\chi}_1^0$ (supersymmetric partners of W, Z (gauginos) and of the Higgs (Higgsinos).

$\tilde{\nu}_L$ has full strength gauge couplings to SM matter. A light $\tilde{\nu}_L$ can not be a good DM candidate and also ruled out by Direct Detection(DD) experiments.

The weakest LHC constraints from non observation are on the mass of the $\tilde{\chi}_1^0$.

Focus on $\tilde{\chi}_1^0$.

Not discussing light gravitino here.

Experimental constraints on masses of various sparticles from the LHC

These translate into constraints on SUSY parameters.

Many are constrained to have very high values.

One that is still allowed to be 'light' is the lightest neutralino $\tilde{\chi}_1^0$

Critically evaluate the case of a light LSP (in general light EW sector).
That is the subject of my talk: A light LSP ($2m_{\tilde{\chi}_1^0} < m_{h125}$)

Look at phenomenological minimal supersymmetric extension of the Standard Model (PMSSM).

The small mass of the observed Higgs 'smells' of SUSY

But its mass close to the upper limit of 132 GeV in MSSM implies larger values of M_S!

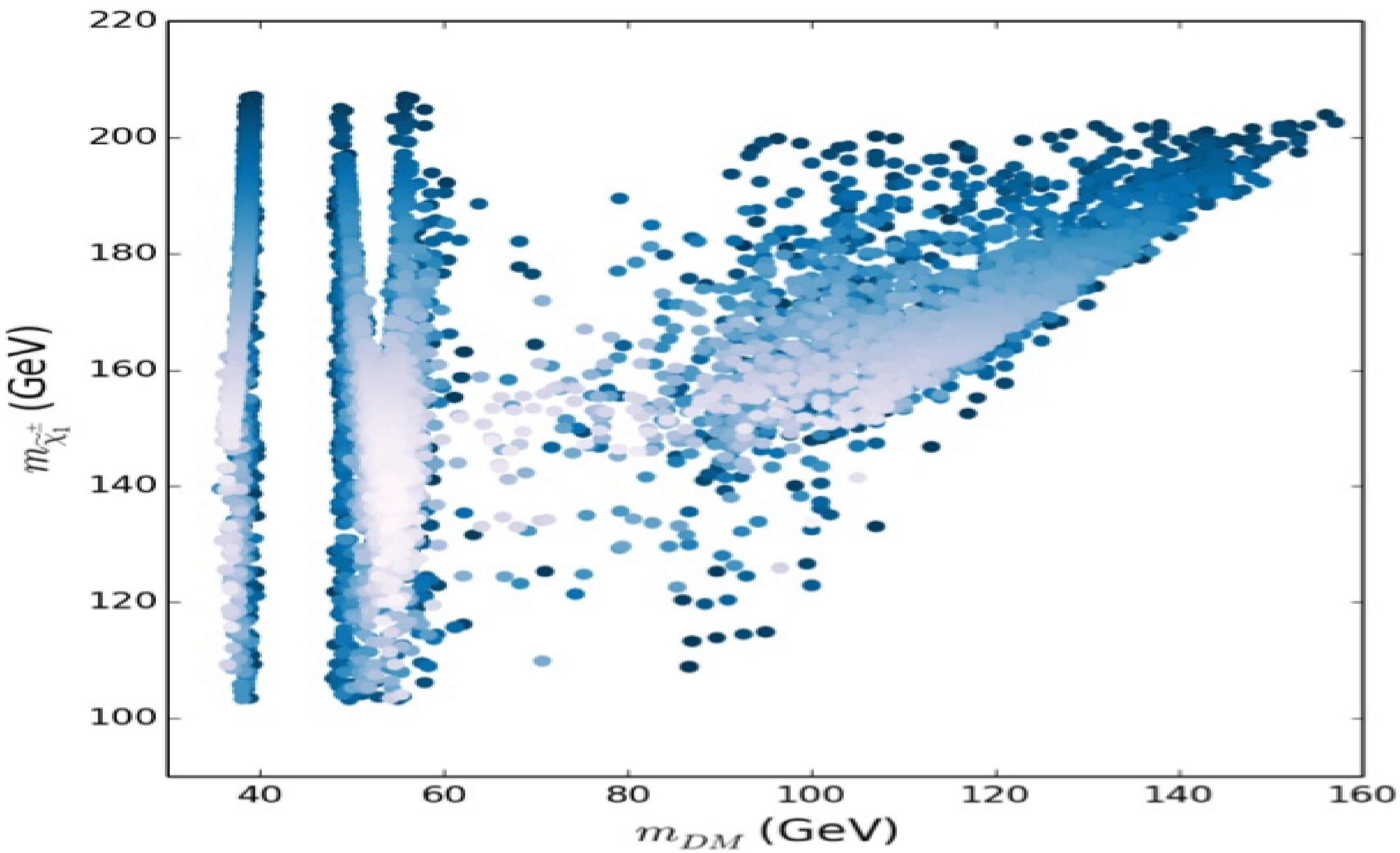
For many people this indicates 'unnaturalness' ! For example Dine: "Naturalness Under Stress"......

(On a lighter note: who are we to tell 'Nature' what is 'natural!')

More seriously, Tata et al suggested a new measure of 'naturalness' Δ_{EW} which can be small even if the Δ_{BG} is large.

1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Austri: a light LSP is 'natural' in this sense in the PMSSM. More recent JHEP 01 (2020) 147 analysis shows similar results.

1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Ruiz de Austri. light to dark, Δ varies from 4 to 10.



VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

Upper Bound on Gauge-Fermion Masses

Steven Weinberg
Department of Physics, University of Texas, Austin, Texas 78712
(Received 22 November 1982)

A large class of broken supersymmetry theories is shown to imply the existence of fermions $\lambda^{\pm}$ and λ^0, lighter than or nearly degenerate with the $W^{\pm}$ and Z^0 gauge bosons, and with vanishing baryon and lepton number. If the $\lambda^{\pm}$ is appreciably lighter than the $W^{\pm}$ it can be readily produced in $W^{\pm}$ decay, as well as in e^+-e^- collisions.

PACS numbers: 11.30.Pb, 14.80.Er, 14.80. Pb

Weinberg was the first one to point out that the Electroweakinos can be lightest part of the SUSY spectrum under certain conditions.

1)SUSY breaking happened through supergravity interactions in the hidden sector (Lykken, Weinberg, Hall, PRD 27, 1983)

2) Minimal Kinetic terms for the Yang Mills Superfields.

Is there a cosmological limit on how light a CDM particle can be?

C. Boehm et al. J. Phys. G, 30:279–286, 2004. arXiv: astro-ph/0208458; C. Boehm, T.A. Ensslin, and J. Silk, J. Phys. G, 30:279–286, 2004, C. Boehm et al. JCAP, 08:041, 2013. arXiv: 1303.6270

Using PLANCK limit on N_{eff} ; effective number of ν species: masses for CDM as small as $\sim$ MeV and less than a few GeV $\tilde{\chi}_1^0$ (neutralino in SUSY) can be allowed.

In SUSY the $\tilde{\chi}_1^0$ is a mixture of Higgsino and Gauginos. The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with matter and also on the Higgs boson. These couplings are related to the couplings of the $h/Z/W$ with matter particles and gauge bosons in the SM.

$$g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = \frac{g}{2\cos\theta_W}\left(|N_{13}|^2 - |N_{14}|^2\right) \quad (1)$$

$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = g\,(N_{11} - \tan\theta_W N_{12})\,(\sin\alpha\; N_{13} + \cos\alpha\; N_{14}) \quad (2)$$

g is the SU(2) coupling, α is the Higgs mixing angle, and N_{1j} are elements of the neutralino mixing matrix .

Masses of LSP and the N_{ij} both decided by M_1, M_2, μ and $\tan\beta$.

"Status of low mass LSP in SUSY"

Eur. Phys. J. ST **229**, no.21, 3159-3185 (2020), [arXiv:2010.11674 [hep-ph]] and references therein

Question to ask:

How light can a SUSY LSP candidate be and still be a viable DM candidate?

What is meant by that?

- It should not over close the Universe.(If we assume standard cosmology and hence thermal relic) (Will make some comments about non thermal case as well in the end)

- Should be allowed the Direct/Indirect detection constraints.

Planck measurements and the anisotropies tell us

$\Omega_{DM}h^2 = 0.120 \pm 0.001$

Major part of the discussion will talk about usual thermal relic.

Recall:

Possibilities with freeze in and freeze out also exist.

Further late time entropy injection can also make the relic consistent with observed relic.

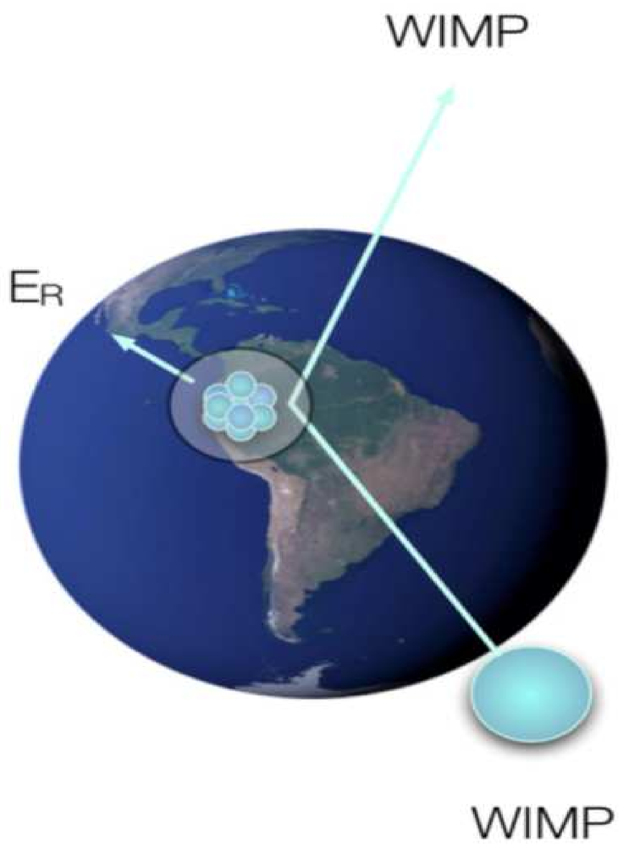
In a model the predicted relic :

$$\Omega_{\tilde{\chi}} h^2 = \frac{m_{\tilde{\chi}} n_{\tilde{\chi}}}{\rho_c} \simeq \frac{3 \times 10^{-27} \mathrm{c}m^3 s^{-1}}{\langle \sigma_{ann} v \rangle},$$

The couplings of the DM particle which decides σ_{ann} will then decide relic density which in turn will depend on the model. $\sigma_{ann} \propto \frac{g_{\tilde{\chi}}^4}{m_{\tilde{\chi}}^2}$. Combinations of $g_{\tilde{\chi}}$ and $m_{\tilde{\chi}}$ will produce the right relic.

This expression above is for thermal relic, ie. the species abundance is decided by the temperature at which it falls out of thermal equilibrium, ie. freezes out.

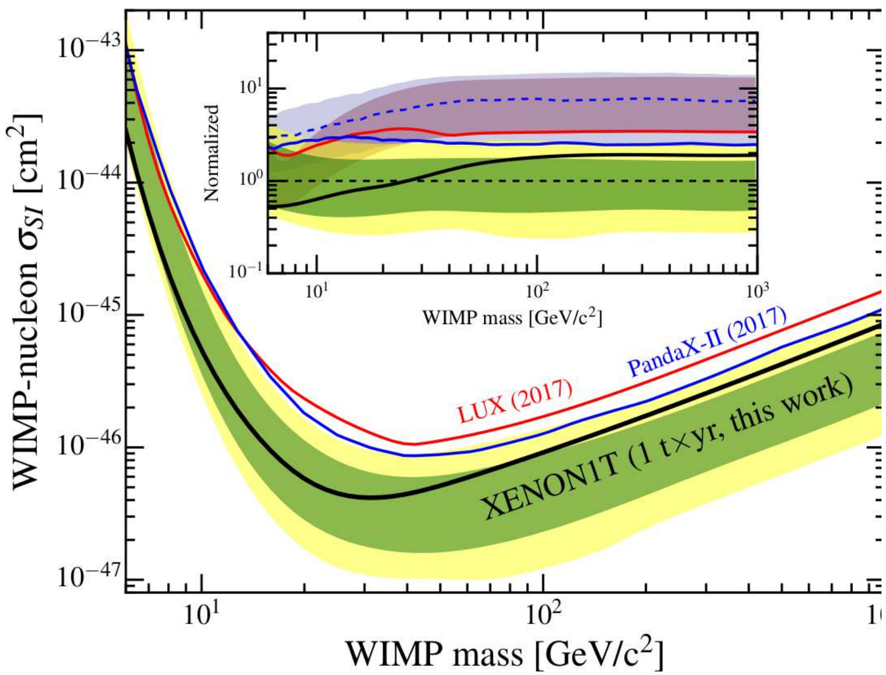
How can we detect it on earth?

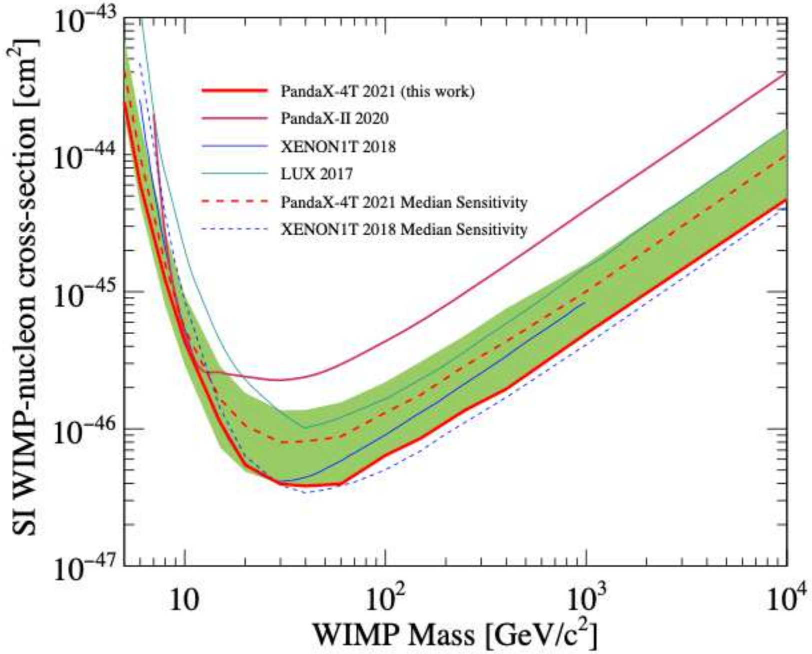


Works for DM particle mass in the range 10 to 1000 times heavier than proton. Use a heavy nucleus Xenon. It will recoil in collision. Measure the recoil velocity. Expected typical recoil energies: upto 100 KeV. Difficult experiment.

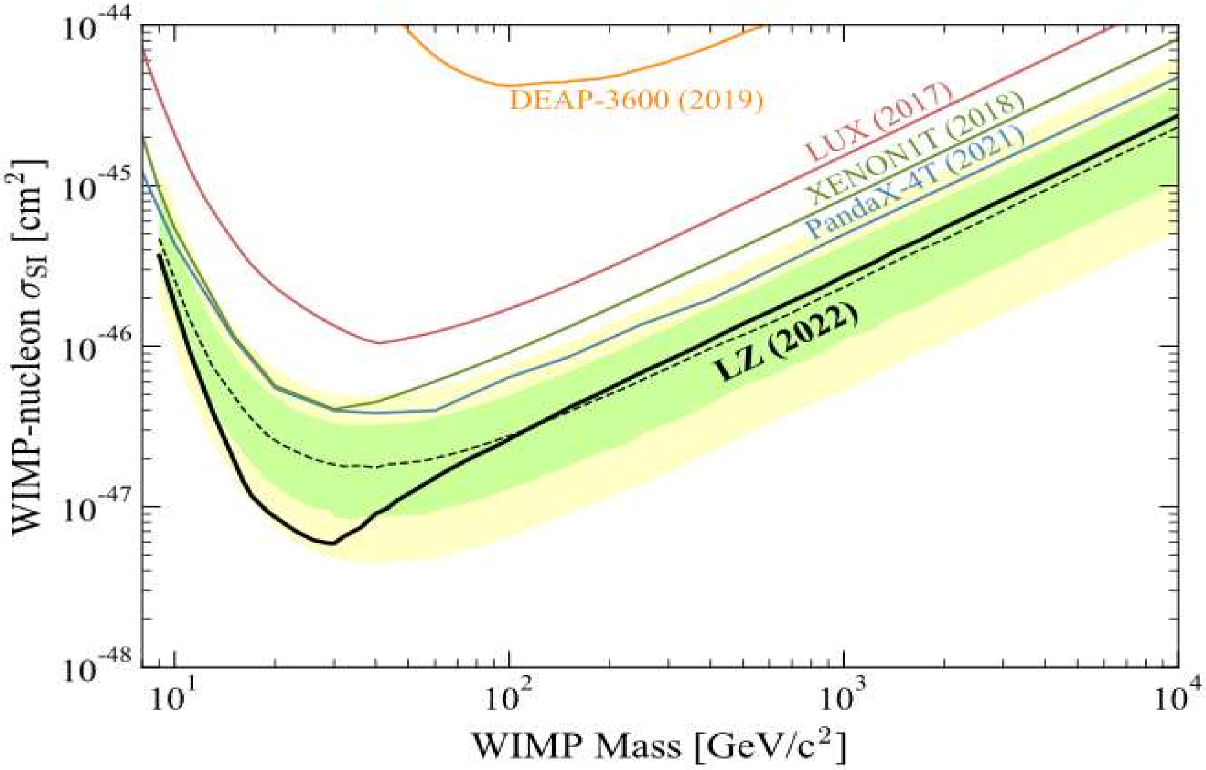
Modifications of detection techniques for 'light'er DM particles! Lot of developments!

The current status of the best limits from Direct Detection, straining the WIMP paradigm!





Xenon-1T(PRL, 111302 (2018)) PandaX-4T (PRL, 127, 261802, (2021))



This is data from only the first 60 days of exposure. The most stringent limit is set for spin-independent scattering at 30 GeV, excluding cross sections above$5.9 \times 10^{-48} cm^2$ at the 90% confidence level.

The relic density calculations and also the DM detection cross-sections in a model will depend on the couplings of the DM with the SM particles!

In pMSSM the $\tilde{\chi}_1^0$ is a mixture of Higgsino and Gauginos .

For NMSSM it is a mixture of higgsinos and gauginos as well as a singlino. The additional scalars are also doublet-singlet mixtures.

For case of $\tilde{\nu}_R$ LSP additional Yukawa couplings may come into play.

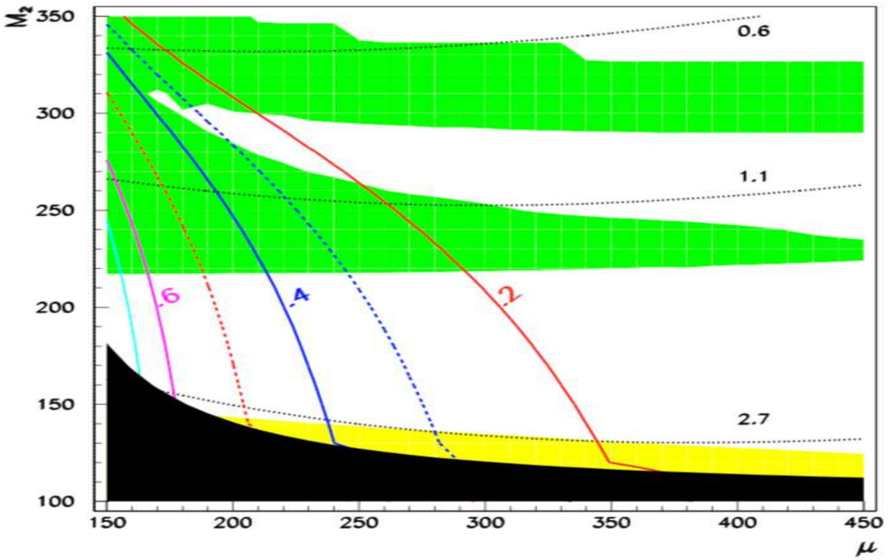
The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with all the SM and (N)MSSM particles.

A Wino like or Higgsino like $\tilde{\chi}_1^0$ will have to be heavy ($\sim$ TeV) to explain the observed relic due to the high cross-sections. How a model can produce a wino like LSP is a different question.

A bino-like $\tilde{\chi}_1^0$ means too high a relic density unless additional annihilation possibilities exist because of its smaller couplings!

t-channel light slepton OR a resonant annihilation via Higgs/A/Z. The Z exchange requires a nontrivial Higgsino fraction too in the neutralino! The so called 'well tempered neutralino'.

For the Higgsino-Bino well tempered relic, h_{125} **can** have appreciable branching fraction into invisible neutralino pair. In fact this was the focus of our early papers! G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000)



Green : Relic < 0.1, White: $0.1 < $ relic < 0.3, yellow : relic > 0.3

Phys. Lett. B 519 (2001) 93-102 "The MSSM invisible Higgs in the light of dark matter and g-2"

Till the DM detection experiments came in full swing the collider bounds dominated the story. In cMSSM the LEP constraint on $m_{\tilde{\chi}_1^{\pm}}$ and universal gaugino mass would rule out light $\tilde{\chi}_1^0$. So a light $\tilde{\chi}_1^0$ necessarily means non universal gaugino masses. Focus moved to the pMSSM

G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000), Phys. Lett. B 519 (2001) 93-102.

Before Xenon 1T and LHC results, older relic measurements:
Lower limit of 30 GeV on the mass of the $\tilde{\chi}_1^0$.

L. Calibbi, T. Ota, Y. Takanishi, JHEP 07, 013 (2011), D.A. Vasquez, G. Belanger, C. Boehm, Phys. Rev. D 84, 095015 (2011), G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole,S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013)

A light LSP can contribute to the 'invisible' decay of the Higgs.

Invisible decay of the Higgs can also be searched for at the LHC:

E.g. : R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003), Phys. Lett. B **571**; D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, Phys. Lett. B 725, arXiv:1211.7015 [hep-ph] (2013)

Current best limit from the LHC is ĩ3%.ATLAS-CONF-2020-008 and ĩ4.5% ATLAS: submitted to JHEP, 2202.07953

Future for looking for this 'dark' higgs is 'bright'.

LHC can reach 'invisible' BR upto 3.8%

ILC/CLIC/FCC can reach upto 0.2-0.4 %

In the current situation different possibilities to look for light $\tilde{\chi}_1^0$ in SUSY:

1)Look for Mono events or LLP. Not effective for light LSP.

2)Look for invisibly decaying Higgs.

3)Direct production of the heavier Electroweakino states ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ etc) and their decays. WZ mediated and WH mediated decays of heavier charginos and neutralinos.

Now we have

1)precise determination of relic,

2)strong constraints from Direct Detection

3) LEP/LHC searches for electroweakinos

4)**Higgs detection and measurements**

5)precision calculations of the Higgs mass

6) measurements of the invisible width of the Higgs.

What is the situation now?

How low a mass can a viable DM candidate have in SUSY consistent with all the current exclusions? Can the future colliders probe these 'light' LSP's? Ie. can we rule out this region from collider experiments?Using phenomenology of the heavier electro weakinos.

Can models and observed relic density support a light SUSY DM particle if reported in either Direct or Indirect detection experiment? If yes what can the LHC (current,HL/LHC and HE/LHC) say about it?

Will discuss:

i) PMSSM : The weakest LHC constraints from non observation are on the mass of the $\tilde{\chi}_1^0$. The important parameters are μ, M_1, M_2 and $\tan\beta$. Radiative corrections bring in dependence on A_t, m_t. and even M_3. We will discuss this in the context of standard and nonstandard cosmology.

ii) NMSSM (Additional singlet higgs superfield) : In addition to above additional parameters related to this extra field. Additional light (pseudo)scalars. $\kappa, \lambda, A_\kappa, A_\lambda$.

iii) PMSSM + $\tilde{\nu}_R$

iv) NMSSM + $\tilde{\nu}_R$

A 'light' $\tilde{\chi}_1^0$ DM at the collider in pMSSM (2017):

Light $\tilde{\chi}_1^0$: pure Bino, will over close the universe. Mixed bino-higgsino efficient annihilation via Z or h_{125}. Hence a light $\tilde{\chi}_1^0$ in pMSSM has to be necessarily a 'mixed' state.

Consider parameter range consistent with $m_h \simeq 125$ GeV and no SUSY observation:

$$
\begin{aligned}
1 \text{ GeV} < M_1 < 100 \text{ GeV},\ 90 \text{ GeV} < M_2 < 3 \text{ TeV}, \\
1 < \tan\beta < 55,\ 70 \text{ GeV} < \mu < \ 3 \text{ TeV}, \\
800 \text{ GeV} < M_{\tilde{Q}_{3l}} < 10 \text{ TeV}, 800 \text{ GeV} < M_{\tilde{t}_R} < 10 \text{ TeV}, \\
800 \text{ GeV} < M_{\tilde{b}_R} < 10 \text{ TeV}, \\
2 \text{ TeV} < M_3 < 5 \text{ TeV}, -10 \text{ TeV} < A_t < 10 \text{ TeV}
\end{aligned}
$$

Analysis from 2017:

1) Make sure given point is allowed by a variety of current constraints: LHC constraints, LEP constraints, flavour constraints coming from B sector, Higgs sector constraints.

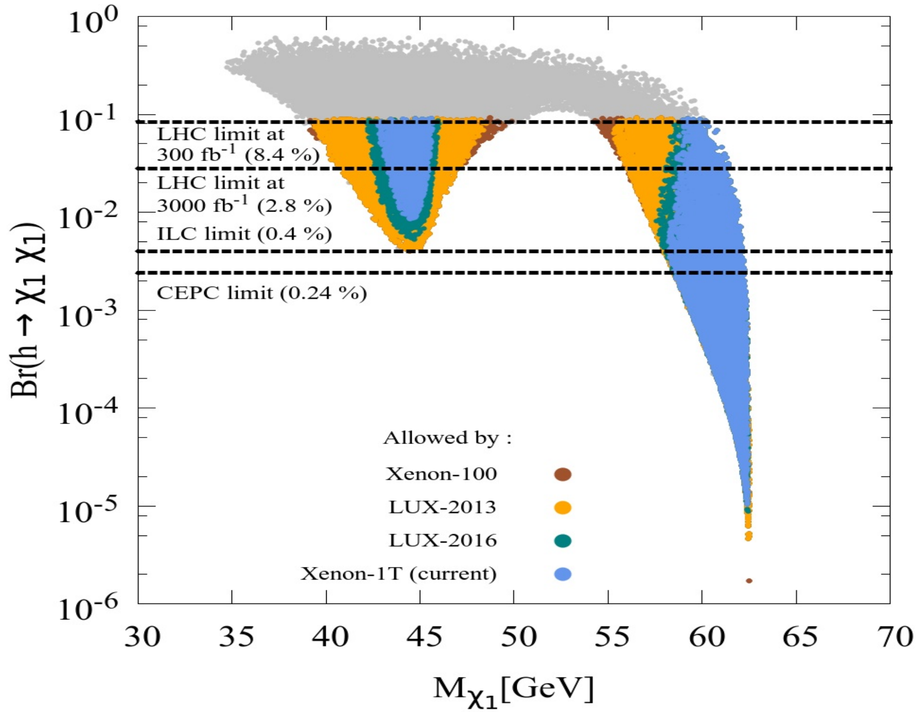
2)Calculate the invisible branching ratio for the Higgs.

3) Calculate the expected 'direct detection cross-sections.

4) Calculate the relic density for the given point.

Calculate $\xi = \Omega_{cal}h^2/\Omega_{obs}h^2 = \Omega_{cal}h^2/0.122$

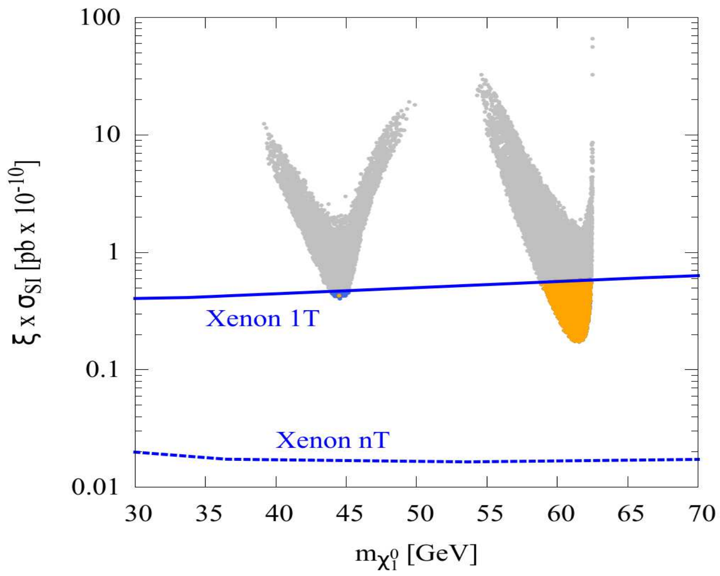
$\xi \leq 1$: Thermal DM



R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838 Projection for 13/14 TeV: 1310.8361 + HL LHC CMS/ATLAS studies:

300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

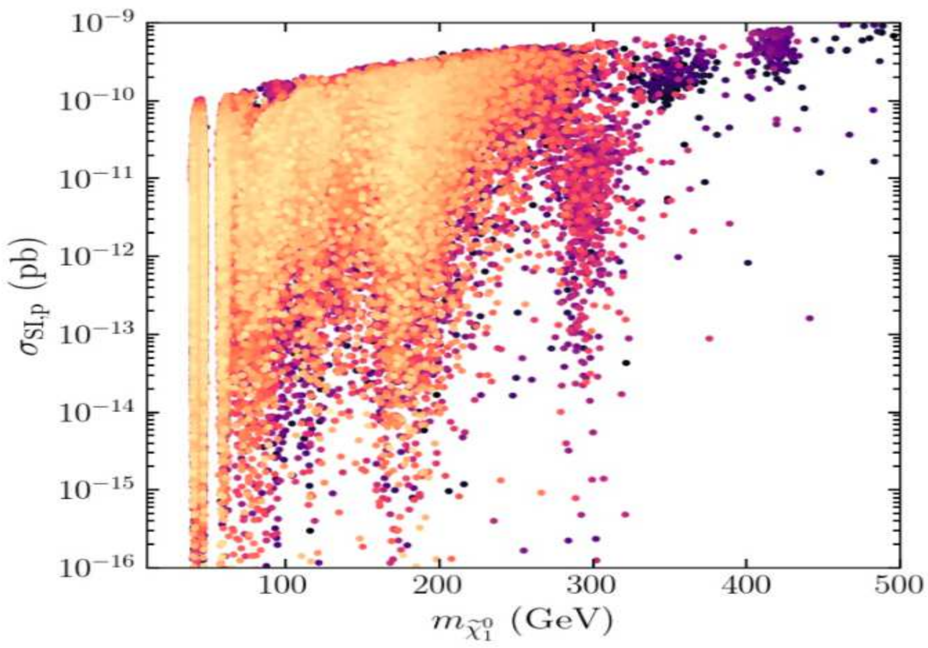
Since then LHC run-II data became available and Xenon 1T came up with its result.



R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Eur.Phys.J.ST 229 (2020) 21, 3159-3185

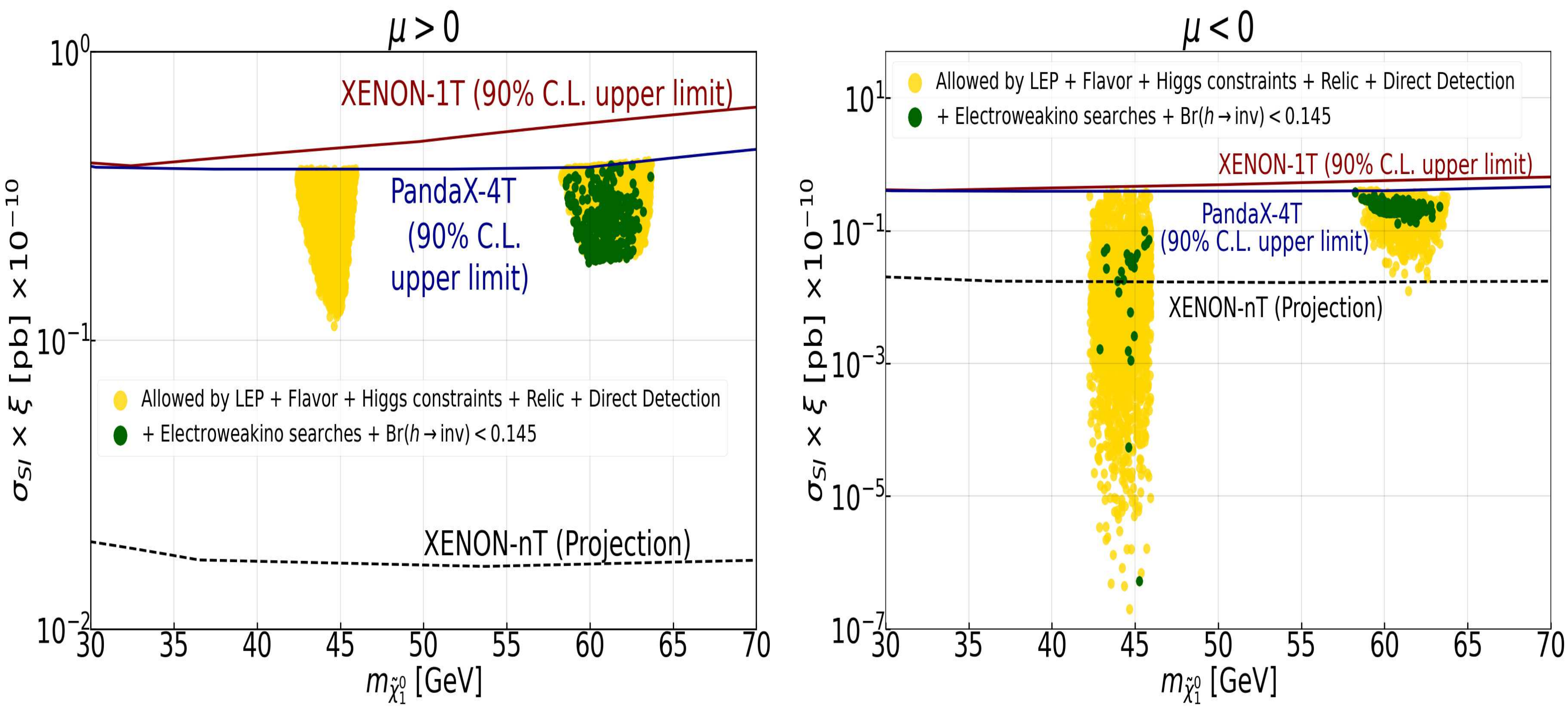
Xenon-1T all but rules out now the Z-funnel region. Points still allowed by current LHC Electro-weakino searches.

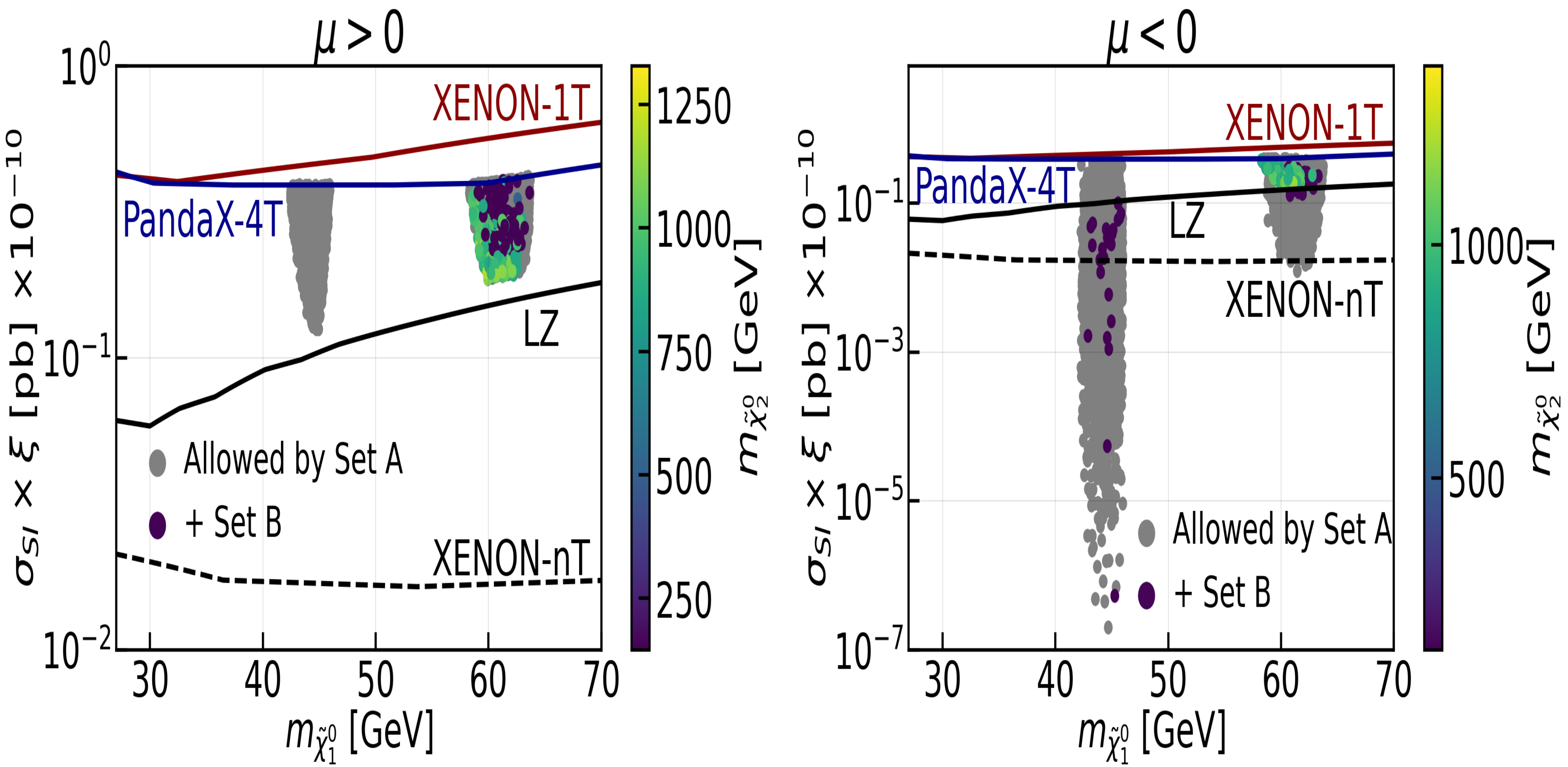
Situation for -ve μ slightly different. Currently investigating. (B., Bhattacharjee, R. K. Barman, G. Belanger, R. Godbole and R. Sengupta.)



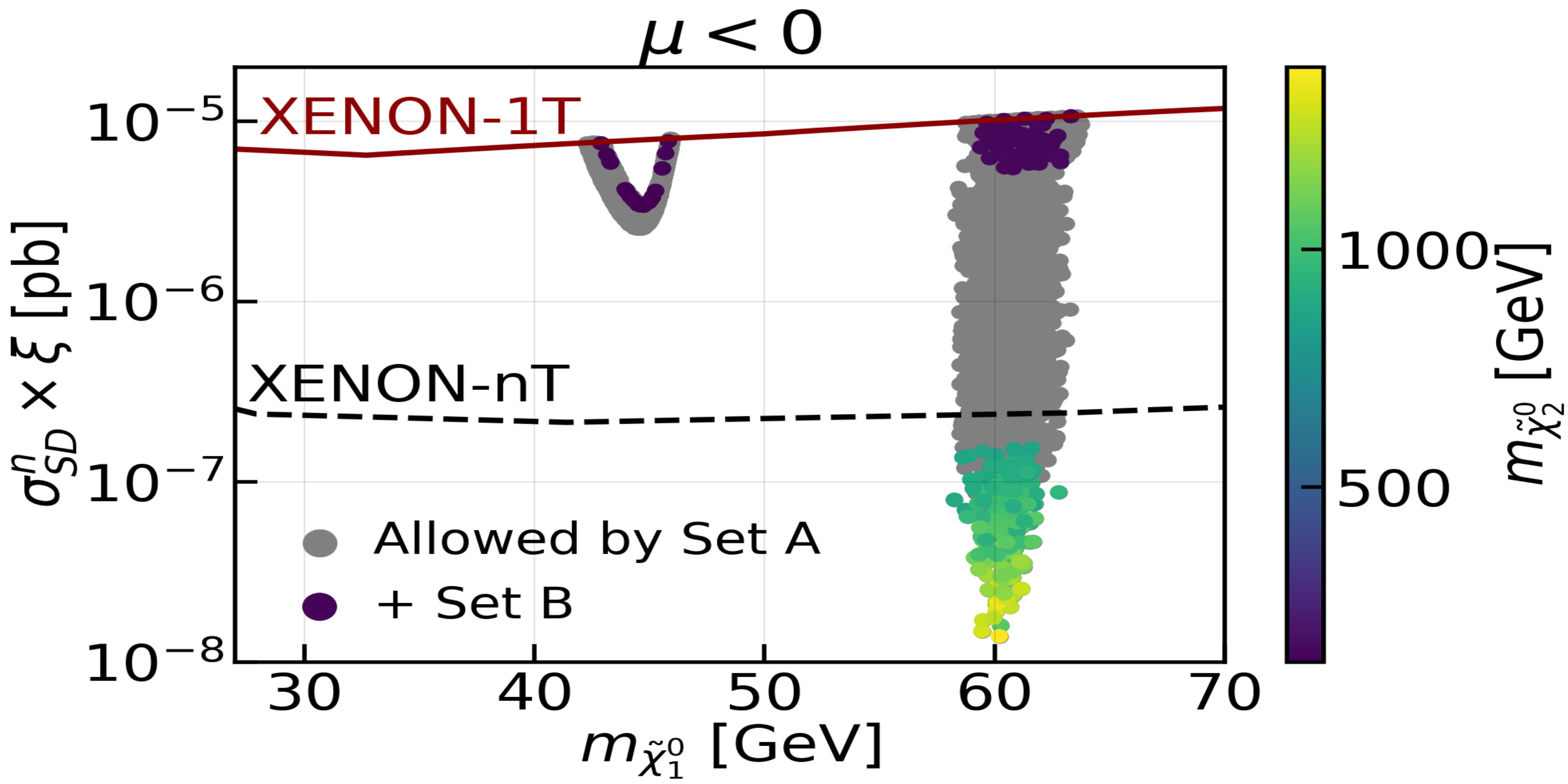
As said before we do need more scrutiny of the region $m_{\tilde{\chi}_1^0} \sim m_Z/2$.
A recent analysis by Melissa Van Beekveld and collaborators (hep-ph/2104.03245) does have allowed points in this mass range.
This analysis looks at PMSSM allowed spectra in light of current data and (g-2). The Δ_{EW} smallest if LSP is lighter than 100 GeV.

We extended the scan region by adding $\mu < 0$, have done more dedicated scanning to focus on light masses, applied the latest collider bounds on electroweakinos using Smodels. (R. Barman, G. Belanger, B. Bhattacharjee, R.G., Rhitaja Sengupta .)

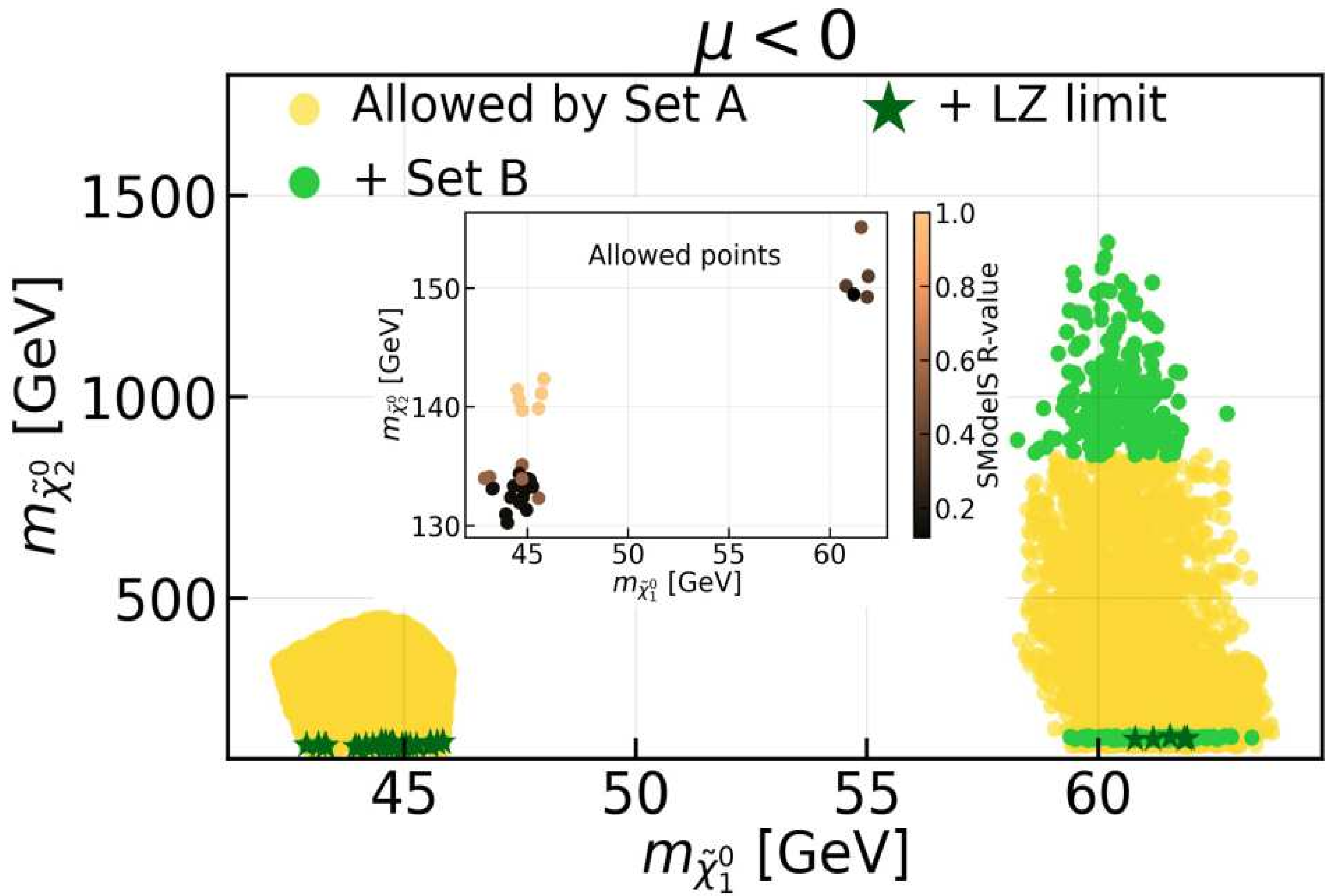




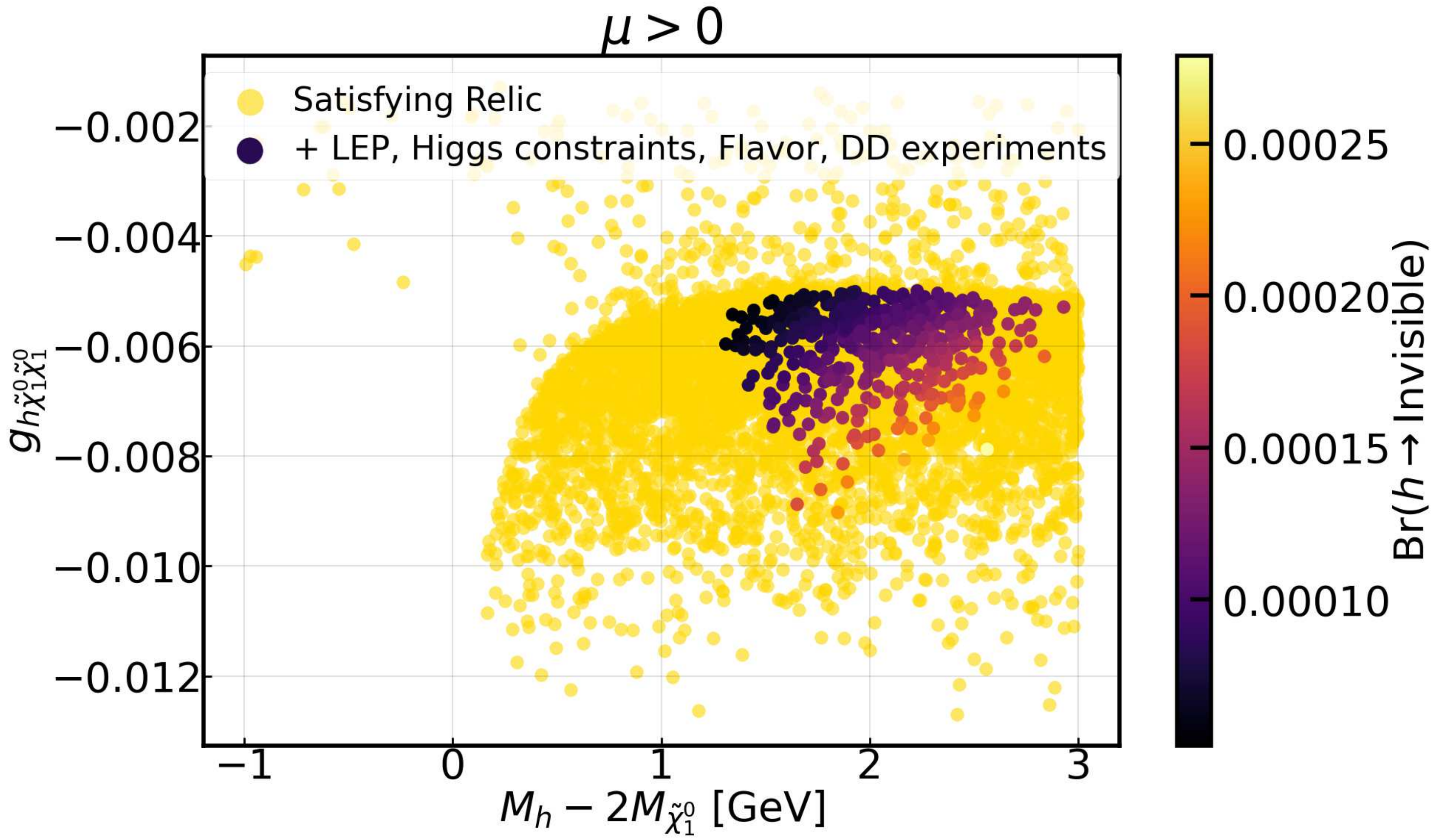
2207.06238 : R.K. Barman, G. Belanger, Biplob Bhattacharjee, R.G., Rhitaja Sengupta. Set A: without LHC EW searches, SET B: with EW searches.

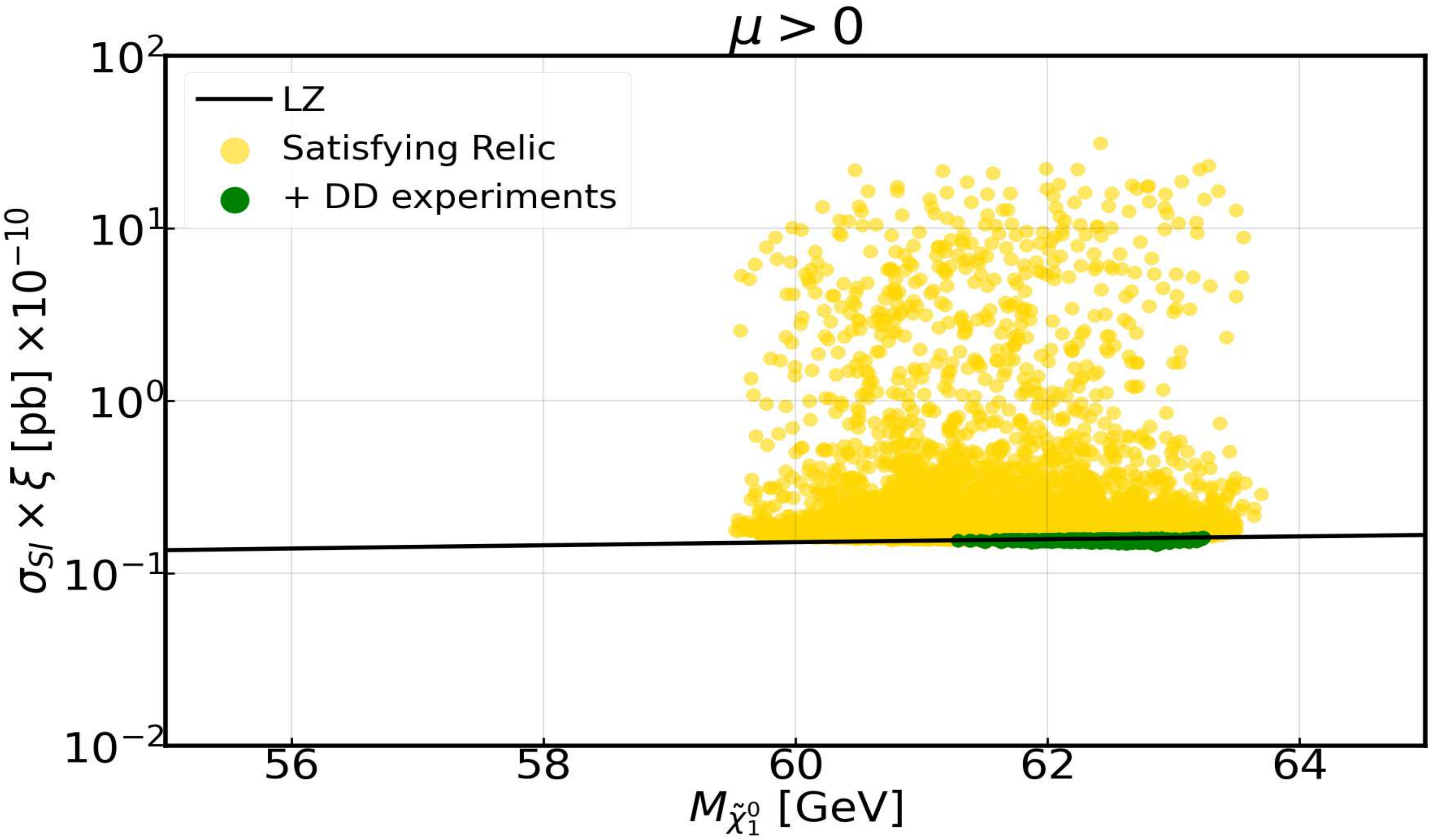


2207.06238 : R.K. Barman, G. Belanger, Biplob Bhattacharjee, R.G., Rhitaja Sengupta


$\mu < 0$
Allowed by Set A
+ Set B
+ LZ limit
1500
1000
500
$m_{\tilde{\chi}_2^0}$ [GeV]
45
50
55
60
$m_{\tilde{\chi}_1^0}$ [GeV]
Allowed points
150
140
130
1.0
0.8
0.6
0.4
0.2
SModelS R-value

2207.06238


$\mu > 0$
Satisfying Relic
+ LEP, Higgs constraints, Flavor, DD experiments
$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$
−0.002
−0.004
−0.006
−0.008
−0.010
−0.012
−1
0
1
2
3
$M_h - 2M_{\tilde{\chi}_1^0}$ [GeV]
0.00025
0.00020
0.00015
0.00010
$\mathrm{Br}(h \to \mathrm{Invisible})$


$\mu > 0$
LZ
Satisfying Relic
+ DD experiments
10^2
10^1
10^0
10^{-1}
10^{-2}
$\sigma_{SI} \times \xi$ [pb] $\times 10^{-10}$
56
58
60
62
64
$M_{\tilde{\chi}_1^0}$ [GeV]

NMSSM superpotential extended from MSSM by adding terms $\lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$

Now the neutralino mass matrix is five dimensional. There is one more neutral fermion : the singlino. The LSP is a superposition of all the five.

Has one more pseudoscalar and scalar in addition to the MSSM Higgses. Thus in principle two 'lighter states A_1, H_1 become available for resonant annihilation. Thus additional annihilation channels become possible.

Much studied subject. Our focus was looking in detail at the low mass LSP region in light of all the current constraints and connection with invisible width of the Higgs. See if (small) LSP masses other than those approximately $M_Z/2$ or $M_{h125}/2$ are allowed

We focussed on the light LSP region and in the full NMSSM.

$$0.01 < \lambda < 0.7,\ 10^{-5} < \kappa < 0.05,\ 3 < \tan\beta < 40$$
$$100 \text{ GeV} < \mu < 1 \text{ TeV},\ 1.5 \text{ TeV} < M_3 < 10 \text{ TeV}$$
$$2 \text{ TeV} < A_\lambda < 10.5 \text{ TeV},\ -150 \text{ GeV} < A_\kappa < 100 \text{ GeV} \quad (3)$$
$$M_1 = 2 \text{ TeV},\ 70 \text{ GeV} < M_2 < 2 \text{ TeV}$$
$$A_t = 2 \text{ TeV},\ A_{b,\tilde{\tau}} = 0,\ M_{U_R^3}, M_{D_R^3}, M_{Q_L^3} = 2 \text{ TeV},\ M_{e_L^3}, M_{e_R^3} = 3 \text{ TeV}$$

The $\tilde{\chi}_1^0$ is a linear combination of singlino, bino and higgsino/wino.

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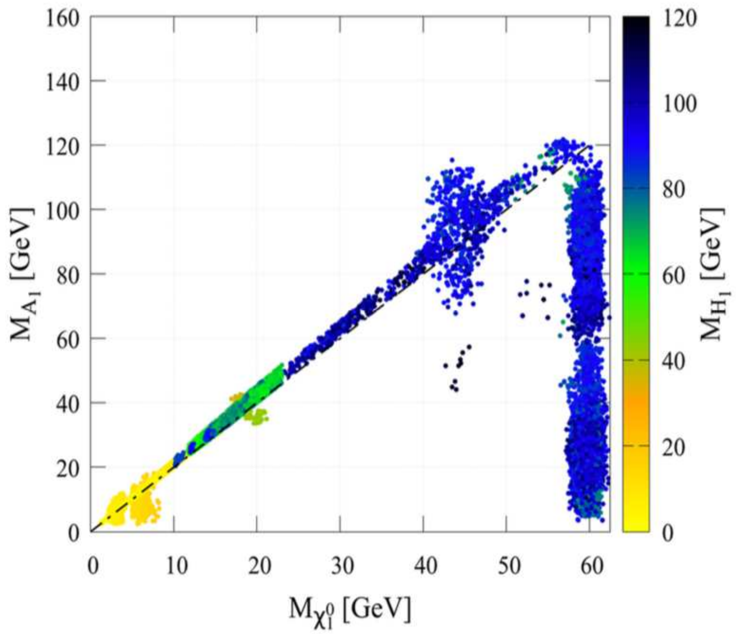
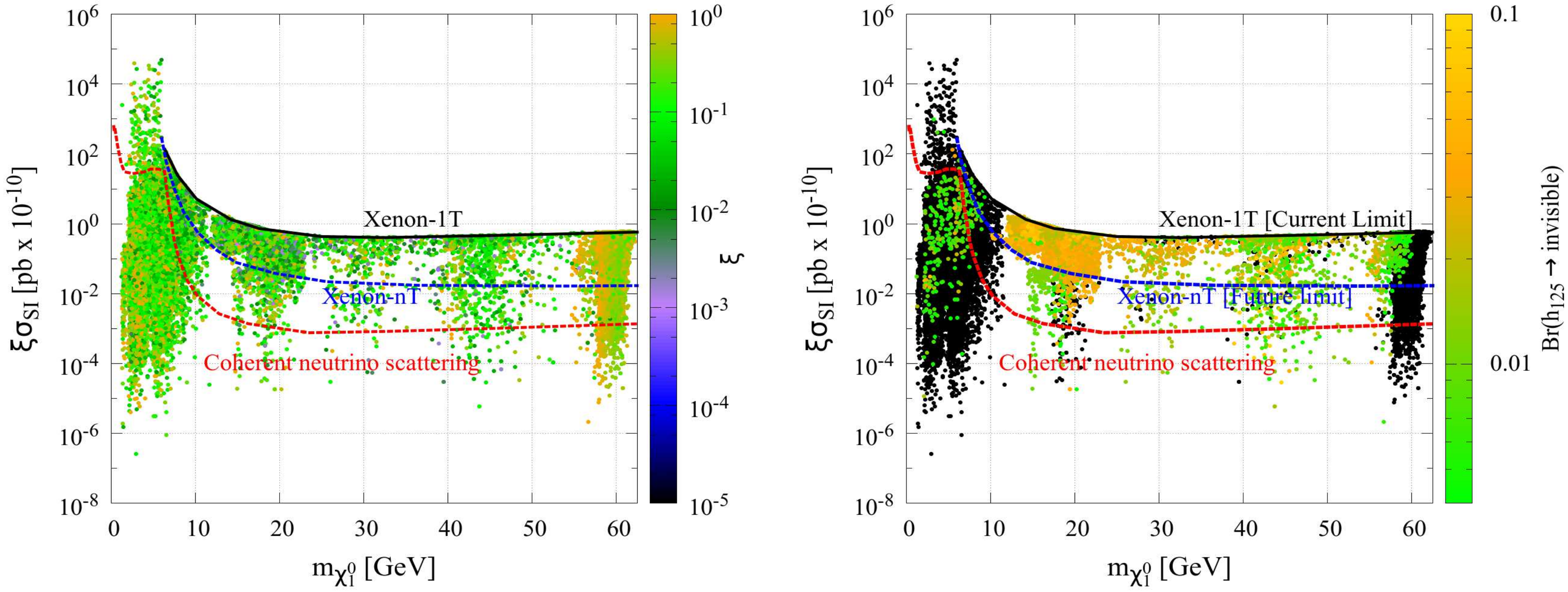


h_2 identified with the observed SM -like Higgs. Possibility of a light singlet dominated h_1, a_1 lighter than 122 GeV.

$\tilde{\chi}_1^0$ Singlino or Bino dominated. Annihilations through a_1, h_1 provide the right relic No co-annihilations for our choice . Only resonance annihilations.

Along the line $2M_{\tilde{\chi}_1^0} = m_{a_1}$. Away from this it is the h_1 which provides efficient annihilation.



R. K. Barman, G. Bélanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata, Phys. Rev. D **103**, no.1, 015029 (2021)

Annihilation through A_1, H_1 gives allowable relic.

Low mass LSP regions allowed by DD as well as relic. Black points not reachable even by CEPC in the invisible channel.

How can they be probed at HL/LHC or HE/LHC? Again through WZ mediated and WH mediated EWeakino signals as well as light Higgses!

So in NMSSM a light LSP is easily accommodated.

Question: Light A_1, H_1 obtained with low values of κ, λ. Is that natural?

Our LSP is mostly singlino. Difficulty to search for a mixed, light LSP region.

Plan to do first a simplified model analysis and then perhaps go back to NMSSM again to understand it.

Light partner of the right handed neutrino, $\tilde{\nu}_R$ can be LSP. Avoid DD constraints by small Yukawa couplings of the $\tilde{\nu}_R$ (pMMSM,cMSSM). Have an NLSP $\tilde{\tau}_1$. Correct relic by a freeze in mechanism or Decay of long lived $\tilde{\tau}_1$. Interesting phenomenology at the LHC. $\tilde{\nu}_R \sim 30-40$ GeV. S. Banerjee et al. JHEP, 07:095, 2016. arXiv: 1603.08834, S. Banerjee et al. JHEP, 09:143, 2018. arXiv: 1806.04488.

Light $\tilde{\nu}_R$ can be LSP in NMSSM. Interactions of $\tilde{\nu}_R$ with SM particles through additional Higgses: D. G. Cerdeno et al. Phys. Rev. D, 79:023510, 2009. arXiv: 0807.3029, D.G. Cerdeo et al. JCAP, 08:005, 2014. arXiv: 1404.2572, D.G. Cerdeno et al. Phys. Rev. D, 91(12):123530, 2015. arXiv: 1501.01296.
No recent analysis of this scenario is available. Would be good to have this analysis. The invisible width measurement of the Higgs can constrain this picture.

Some of these scenarios give unusual signatures at the LHC. Discussed in a White paper "Unveiling Hidden Physics at the LHC - Whitepaper", Bruce Mellado and Oliver Fischer. arXiv/hep-ph/ 2109.06065

One can, however, think of various possibilities which will then give a relic different than the thermal case.

Freeze in OR Out of equilibrium decay.

OR

one can think of 'nonstandard cosmology'. The thermal relic might be above the observed relic, but there might be a period of entropy injection which will dilute the relic density to the 'measured' value.

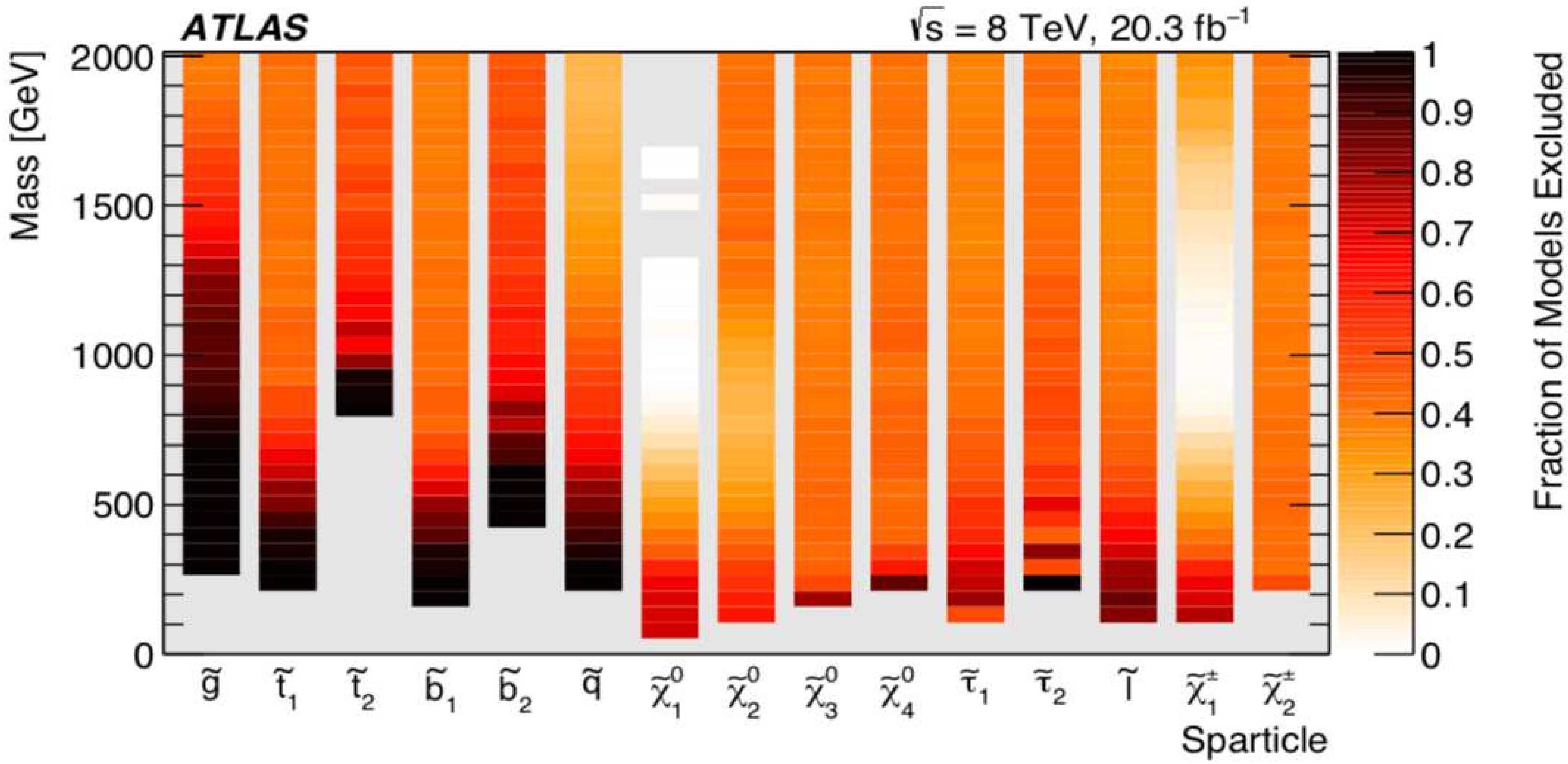
A light LSP in pMSSM is almost ruled out: light $\tilde{\chi}_1^0$. Both the h and Z funnel regions under stress in PMSSM. Allowed points can be probed at the HL/LHC.

In NMSSM a light LSP is allowed. Only thermal scenario studied. Direct detection, LHC searches and invisible branching ratio of the Higgs all offer probes of the scenario.

pMSSM extended with a $\tilde{\nu}_R$: a light $\tilde{\nu}_R$ still possible. Characteristic signals.

We can see that this WIMP paradigm for a light LSP in pMSSM as **thermal** DM is all but ruled out. A very tiny region is allowed. Case different for NMSSM. For pMSSM light LSP as DM allowed happily for non thermal scenario. Both can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

BACKUP



SMS analyses transferred to PMSSM models. A small mass $\tilde{\chi}_1^0$ still allowed in PMSSM! From the PDG

However, for the best fit points of various SUSY analyses LSP has mass a few hundred GeV! (Bagnaschi et al, arXiv: 1610.10084)

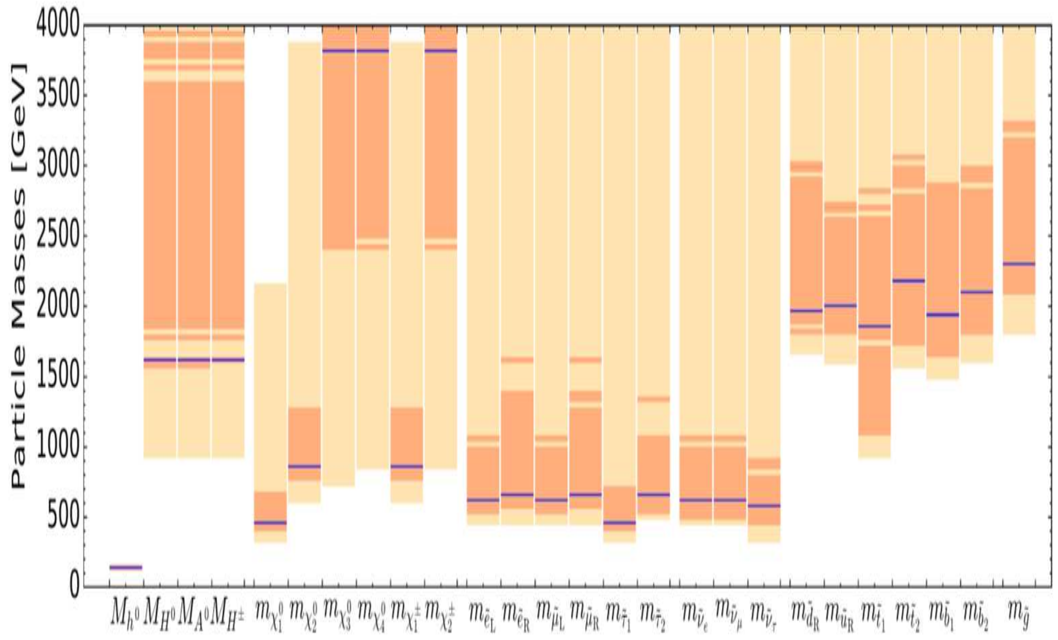
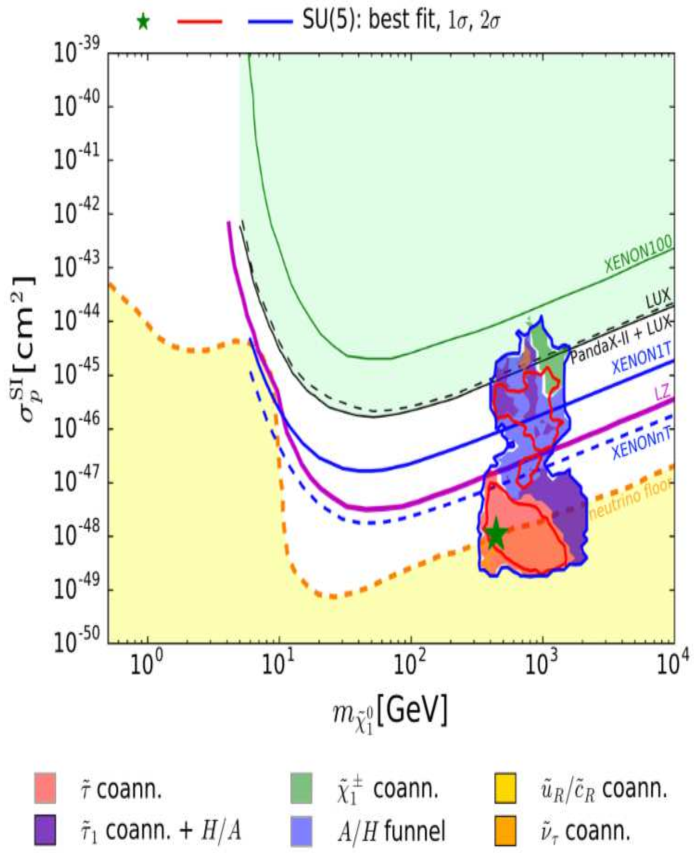


Fig. 12 The one-dimensional 68 and 95% CL ranges of masses we obtain for the current fit in the supersymmetric SU(5) model, shown in dark and light orange, respectively. The best-fit point is represented by blue lines



In general LHC constraints on the Electro Weakinos are the weakest.

Run-II data 35fb^{-1} .

Higgsino upto 390 GeV ruled out. G. Pozzo et al. Phys. Lett. B, 789:582–591, 2019. arXiv: 1807.01476 : Pure Wino upto 650 GeV ruled out (CMS data).

There are newer (and higher) limits from analysis of hadronically decaying boosted bosons ATLAS, Phys. Rev. D, 104 (2021) 112010. with Wino mass limits going upto 1060 GeV (Higgsino upto 900 GeV), for LSP lighter than 400 (200) GeV. Need large mass difference with the LSP. Will comment about the effect of these results in the end

Critically evaluate the case of a light LSP (in general light EW sector). That is the subject of my talk: A light LSP ($2m_{\tilde{\chi}_1^0} < m_{h125}$)

Co-GenT, CRESST, CDMS-SI, DAMA/LIBRA:

C.E. Aalseth et al. Phys. Rev. Lett., 106:131301, 2011. arXiv: 1002.4703. G. Angloher et al. Eur. Phys. J. C, 72:1971, 2012. arXiv: 1109.0702. Z. Ahmed et al. Science, 327:1619–1621, 2010. arXiv: 0912.3592. R. Agnese et al. Phys. Rev. Lett., 111(25):251301, 2013. arXiv: 1304.4279.

R. Bernabei et al. Eur. Phys. J. C, 67:39–49, 2010. arXiv: 1002.1028; R. Bernabei et al. Eur. Phys. J. C, 74(3):2827, 2014. arXiv: 1403.4733.

The DD reports are ruled out by Xenon, LUX

The indirect detection (Fermi-LAT) reports are 'clouded' by astrophysical uncertainties.

L. Goodenough et al. arXiv: 0910.2998. D. Hooper et al. Phys. Lett. B, 697:412–428, 2011. arXiv: 1010.2752, D. Hooper et al. Phys. Rev. D, 84:123005, 2011. aeXiv: 1110.0006, T. Daylan et al. Phys. Dark Univ., 12:1–23, 2016.

This formula is an approximate one. Derived neglecting velocity dependence of the annihilation cross-section.

For the observed relic density, the freeze-out temperature $T_f \simeq m_{\tilde{\chi}}/30$ – $m_{\tilde{\chi}}/20$ I.e. $\tilde{\chi}$ is moving at *non-relativisitc* speeds at the time of freeze out. 'Cold' DM candidate.

Expand the annihilation cross-section as a function of velocity. For s-channel annihilation for Dirac fermions the leading term is independent of velocity. For $\tilde{\chi}$ Majorana (like SUSY) the leading term is proportional to v.

This means that the cross-sections at the freeze out and now can be different in the latter case!

For resonant annihilation additional complications.

In the usual scenario one assumes that the expansion of the Universe is adiabatic. If there is an entropy injection, for example decay of a heavier particle (like a heavy modulus), this can then dilute the relic density of a species.

One can thus think of various possibilities which will then give a relic different than predicted from the Ω^{FO} that I wrote above.

These are options of getting the right relic even if the thermal relic is higher or lower than allowed by the Planck data.

Freeze in:

$$\Omega_{\tilde{\chi}}^{FI} h^2 \simeq \frac{1.09 \times 10^{-27}}{g^{*3/2}} m_{\tilde{\chi}} \sum_i \frac{g_i \Gamma_i}{m_i^2}$$

where g^* is the average number of the effective degrees of freedom contributing to the thermal bath and g_i, Γ_i and m_i are the degrees of freedom, the decay width and the mass of the i^{th} BSM particle.

Out of Equlibrium decay of NLSP:

Another possibility is that the NLSP($\tilde{\chi}_1$) decays on a long time scale, either due to compressed spectra or small couplings, into a final state containing the LSP. In that case this 'out of equilibrium' decay of the NLSP will contribute to the relic density of the LSP.

$$\Omega_{\tilde{\chi}}^{FO} h^2 = \frac{m_{\tilde{\chi}}}{m_{\tilde{\chi}_1}} \Omega_{\tilde{\chi}_1} h^2$$

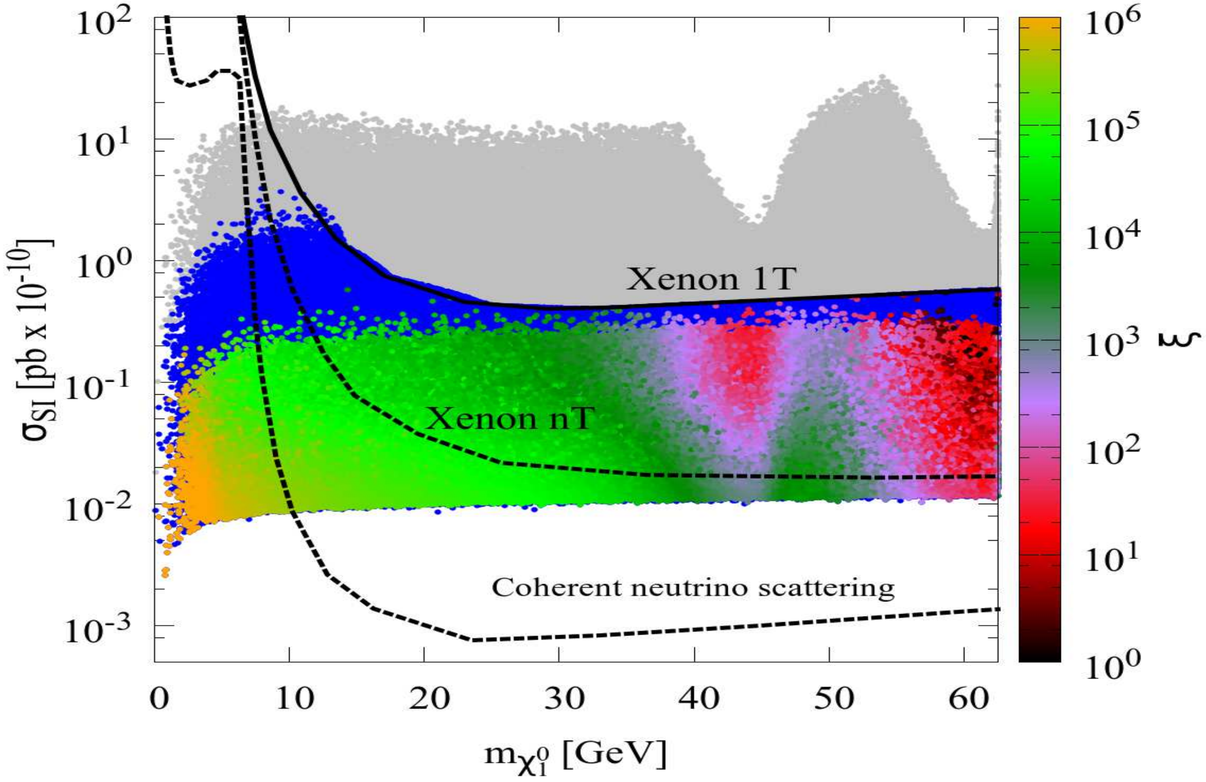
where $\Omega_{\tilde{\chi}_1}$ is the freeze-out relic density of the quasi-stable NLSP.

Calculate $\xi = \Omega_{cal}h^2/\Omega_{obs}h^2 = \Omega_{cal}h^2/0.122$

So far I presented the results for $\xi < 1$.

What happens for $\xi > 1$ (Non thermal) I.e. assume there is a mechanism of (say) entropy injection to reduce Ω_{DM}.

Can this be probed at HL/LHC? As we discussed in a paper in 2015 this gives rise to different interesting search strategies. Not discussing that here. But just the classic trilepton, dilepton with missing E_T signal can work!



R. Kumar Barman, G. Belanger and R. M. Godbole, Eur. Phys. J. ST **229**, no.21, 3159-3185 (2020)

Reach of HL LHC through trilepton, dilepton + MET and 1 l + 2b + MET indicated by blue points. Can not be reached by Xenon nT DD, some even below the Neutrino floor!