Shedding Light on Light SUSY DM

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IMSC@60 celebration!

HAPPY BIRTHDAY IMSC

- What is DM

- What is SUSY DM? The Lightest Supersymemtric Particle : LSP

- Low mass DM in SUSy : mostly $m_{LSP} < m_{h_{SM}}/2$.

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. Sengupta light DM in pMSSM, 2207.06238

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

Dark Matter is Literally Matter that does not shine!

In other words matter that does not interact with light.

Postulated by Zwicky in 1933, solid evidence established by Vera Rubin in 1970.

Over the past decades the evidence for its existence at all distance scales in the Universe has grown!

Its effects have been seen at all distance scales : Kiloparsec, Megaparsec and Gigaparsec. 1 parsec = 3.3 light years. As a calibration light takes 8 minutes from sun to earth and about 43 minutes to Jupiter!

DM 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!

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

2)Calculations of the expected relic density is 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 be non relativistic when it decouples from radiation in the early universe. This depends on the mass and the interactions that the DM particle has! 'Cold Dark Matter' : CDM . The weakly interacting massive particle (WIMP) paradigm ruled for a long time. But it is under tension!

We have found a light Higgs boson at the LHC!

'lightness of the Higgs' sort of nicely explained by SUSY .

As a bonus SUSY has ready made DM candidates.

For this reason and many others SUSY was the most attractive BSM for decades.

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.

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 $\tilde{\chi}_1^0$

LSP: Two candidates: the sneutrino (supersymmetric partner of the neutrino) : $\tilde{\nu}_L$ and the neutralino $\tilde{\chi}_1^0$: a combination of supersyemmetric partners of the Higgs higgsinos and the W/Z bosons electroweakinos.

$\tilde{\nu}_L$ 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 $\tilde{\chi}_1^0$.

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

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

It is usually difficult to exclude conclusively regions in SUSY parameter space. We believe we have shown that certain values of a light neutralino mass are (almost)ruled out if we demand consistency with a number of different measurements!

In general for theoretical reasons one expected the neutralinos to be among the lightest supersymmetric particles! The master told us!

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 Eweakinos can be lightest part of the SUSY spectrum under certain conditions.

Planck measurements of the anisotropies in the cosmic microwave background radiation tell us

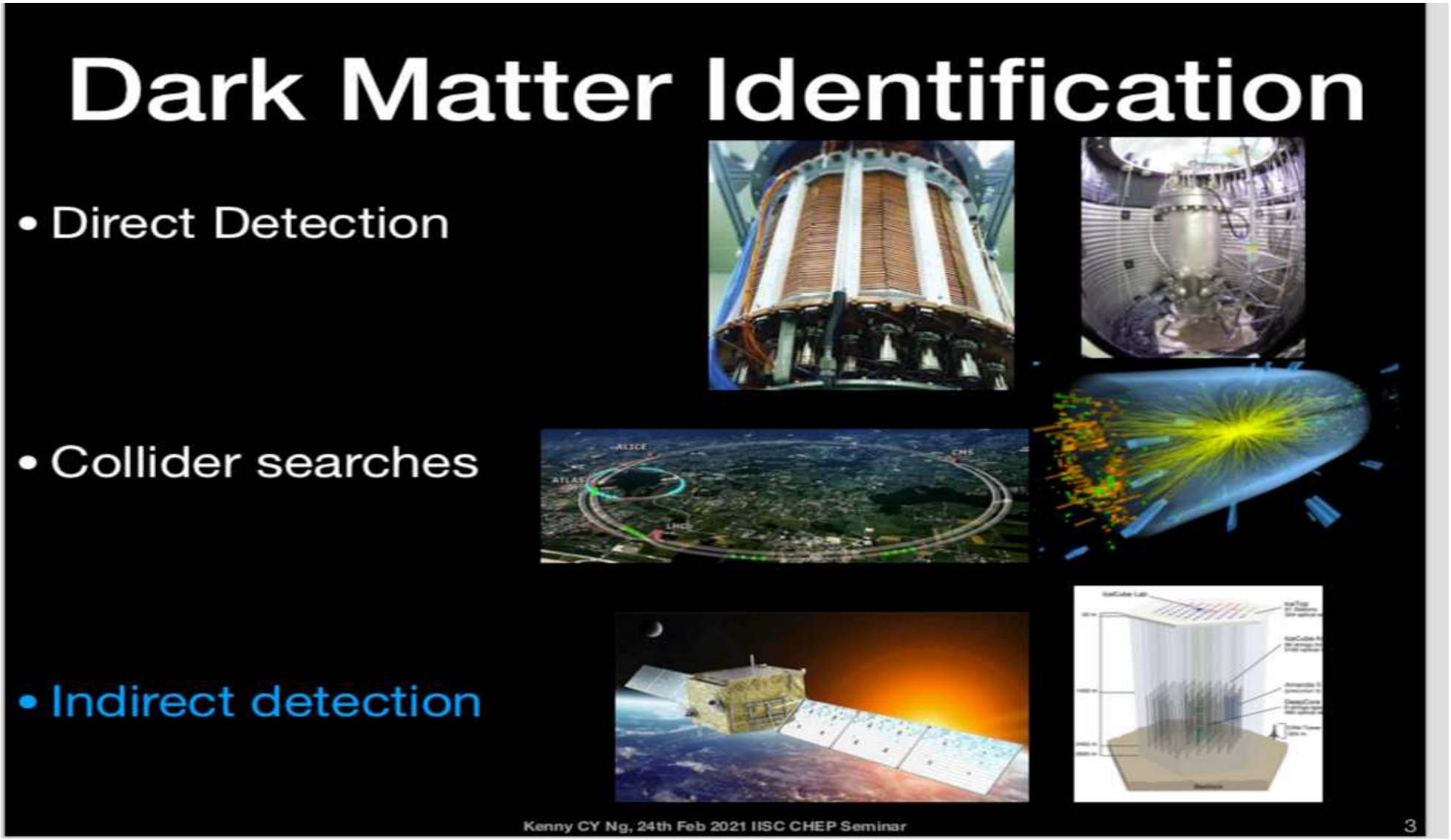
$\Omega_{DM}h^2 = 0.120 \pm 0.001$

In a model the predicted relic :

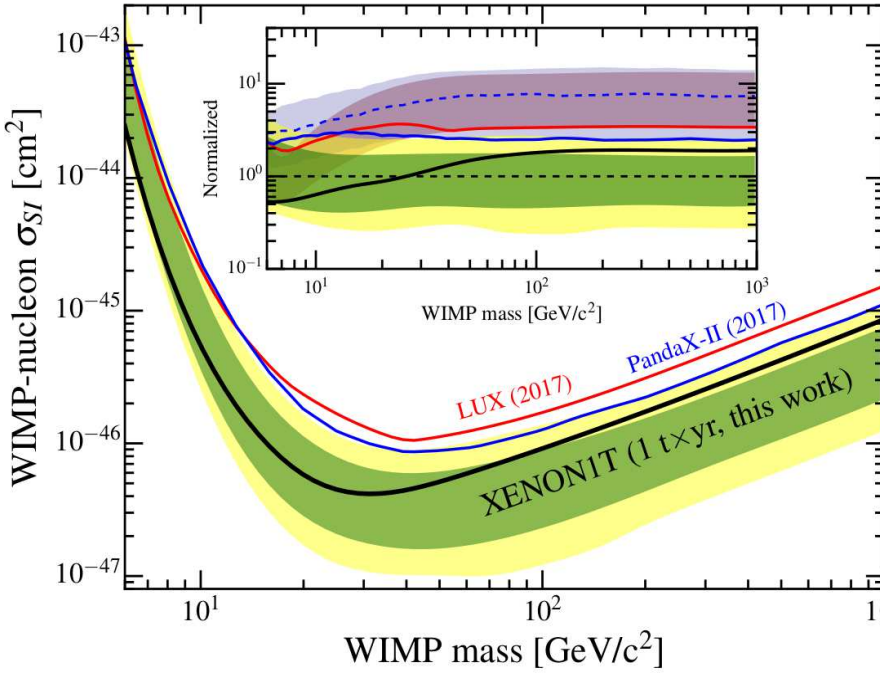
$\Omega_{\tilde{\chi}}h^2 = \frac{m_{\tilde{\chi}}n_{\tilde{\chi}}}{\rho_c} \simeq \frac{3\times10^{-27}\mathrm{cm}^3s^{-1}}{\langle\sigma_{ann}v\rangle}$,

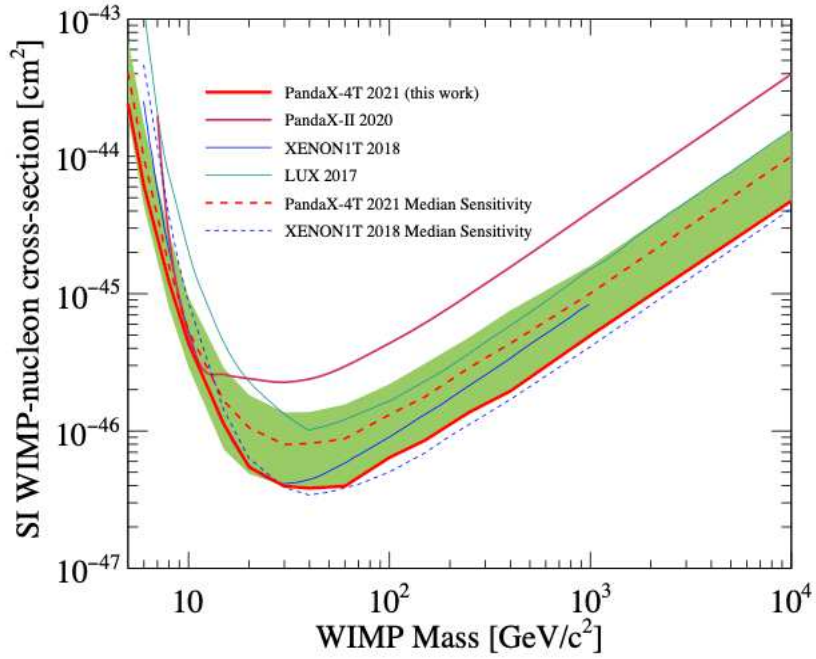
σ_{ann} decided by the couplings of the DM particle which in turn will depend on the model. $\sigma_{ann} \propto \frac{g_{\tilde{\chi}}^4}{m_{\tilde{\chi}}^2}$. As theorists we can compute this.

If computed Ωh^2 is bigger than the measured one theory is inconsistent with the observed flat nature of the Universe!

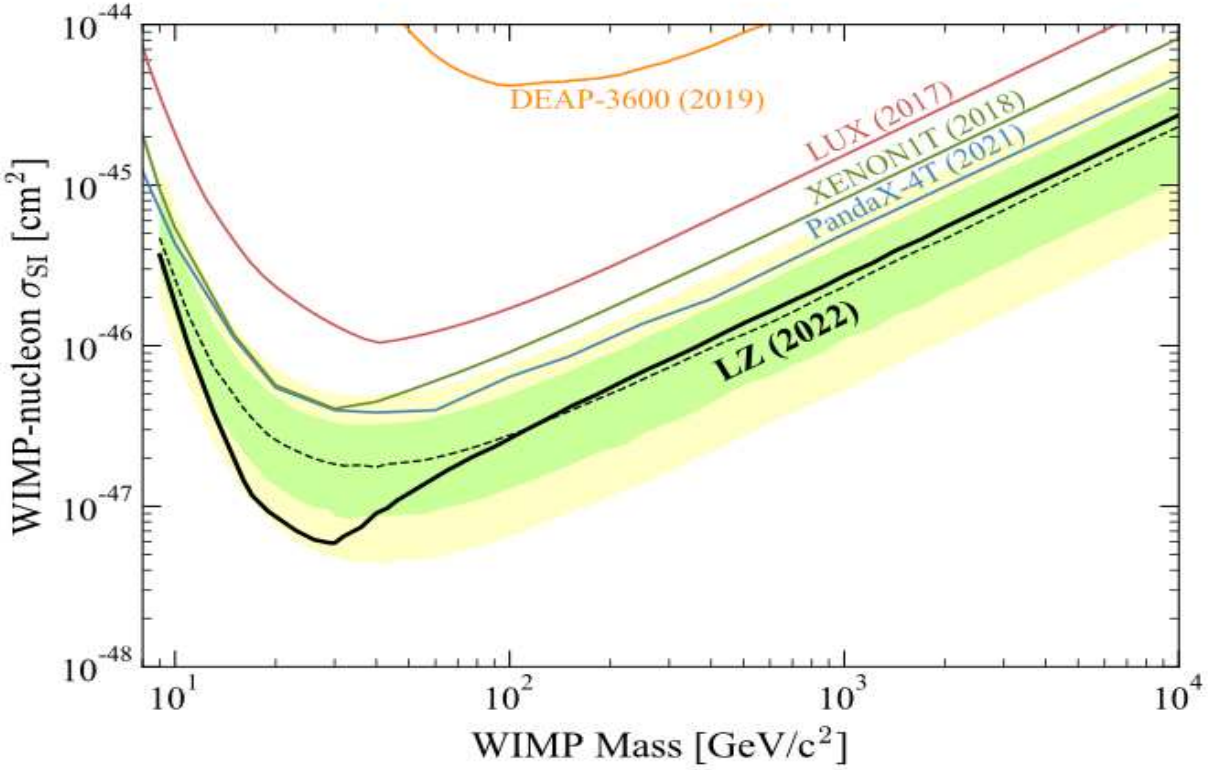

Dark Matter Identification
• Direct Detection
• Collider searches
• Indirect detection
Kenny CY Ng, 24th Feb 2021 IISC CHEP Seminar
3

The current status of the best limits from Direct Detection, straining the WIMP paradigm! Changing landscape of sightings of light DM in direct/indirect detection expts!





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.

"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 predict a value for relic density which is at least smaller than the observed, assuming standard thermal history of the Universe. Will make some comments about non standard cosmology and non thermal case as well in the end

- Should be allowed the Direct/Indirect detection constraints.

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 .

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

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

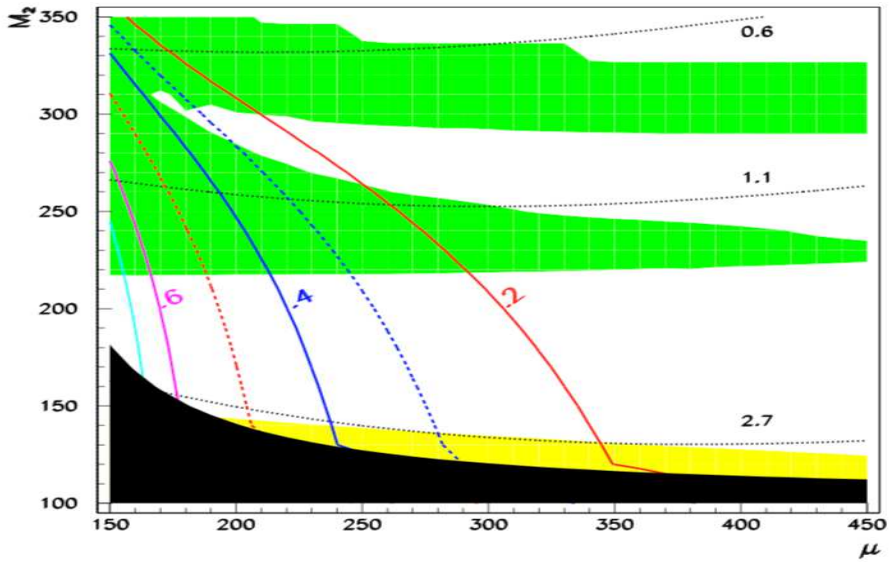
For case of $\tilde{\nu}_R$ LSP additional Yukawa couplings may come into play.

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 $\sim 13\%$.ATLAS-CONF-2020-008 and $\sim 14.5\%$ 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.

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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.

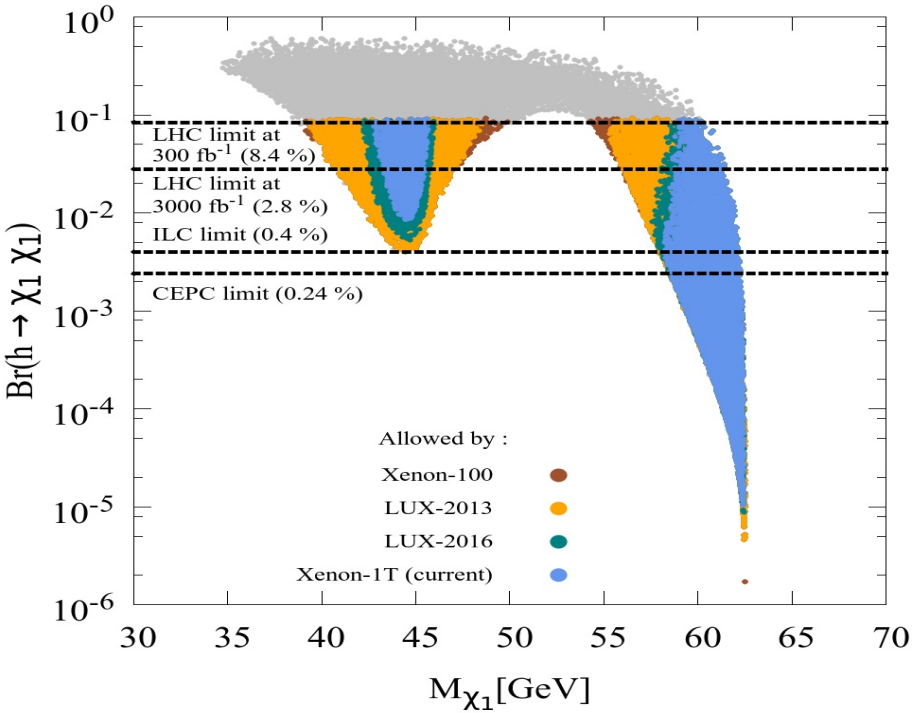
2)Calculate the invisible branching ratio for the Higgs.

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

4) Calculate the relic density for the given point.

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

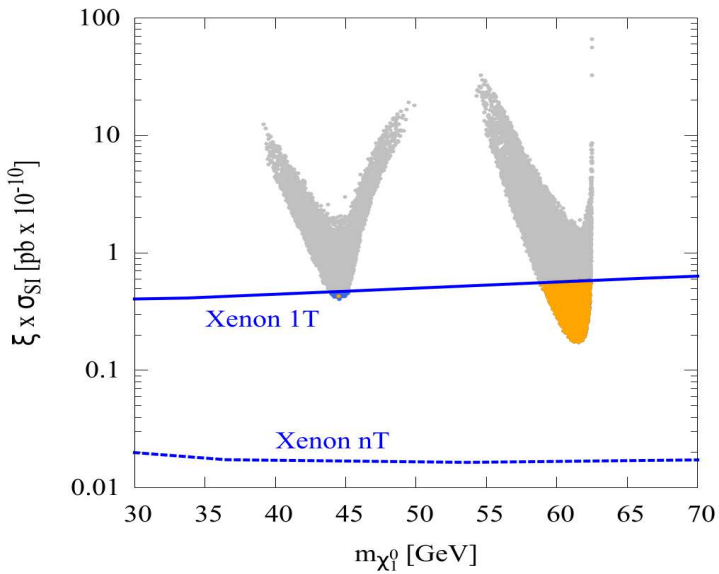
$\xi \leq 1$: Thermal DM



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.

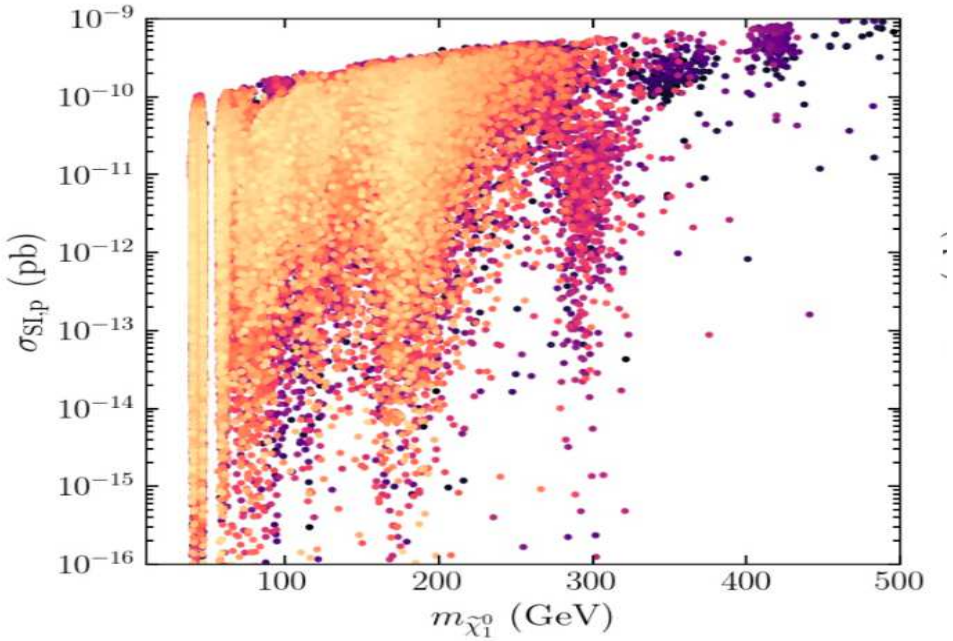


R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Eur.Phys.J.ST 229 (2020) 21, 3159-3185

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

Production of electro weakino pairs which decay through mediation of WZ or Wh . WZ mediated 3l + MET or dilepton + MET searches and Wh_{125} mediated 1l + 2b + MET searches. HL/LHC can cover most of the region still allowed by the current electro-weakino searches and DD.

Situation for -ve μ slightly different.(B., Bhattacharjee, R. K. Barman, G. Belanger, R. Godbole and R. Sengupta, 2207.06238.)

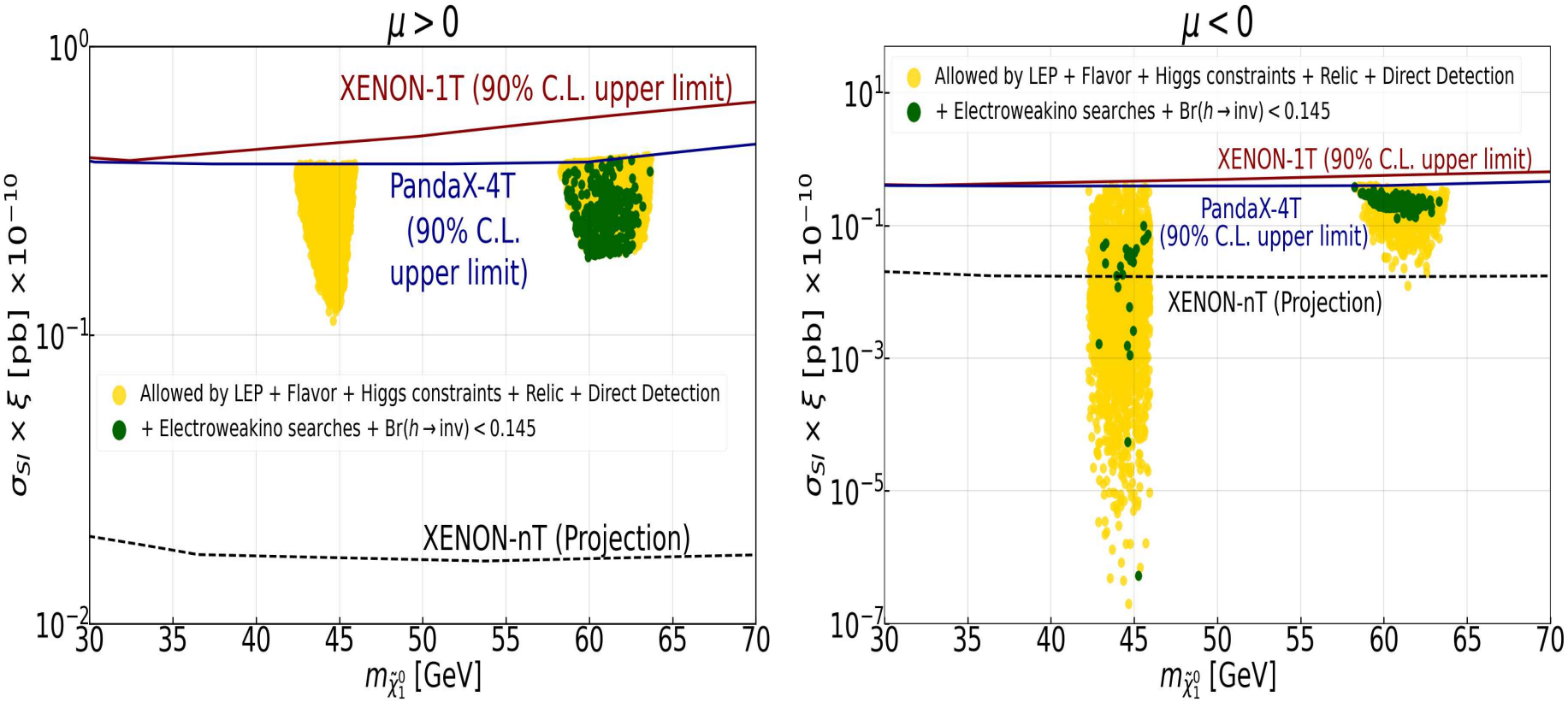


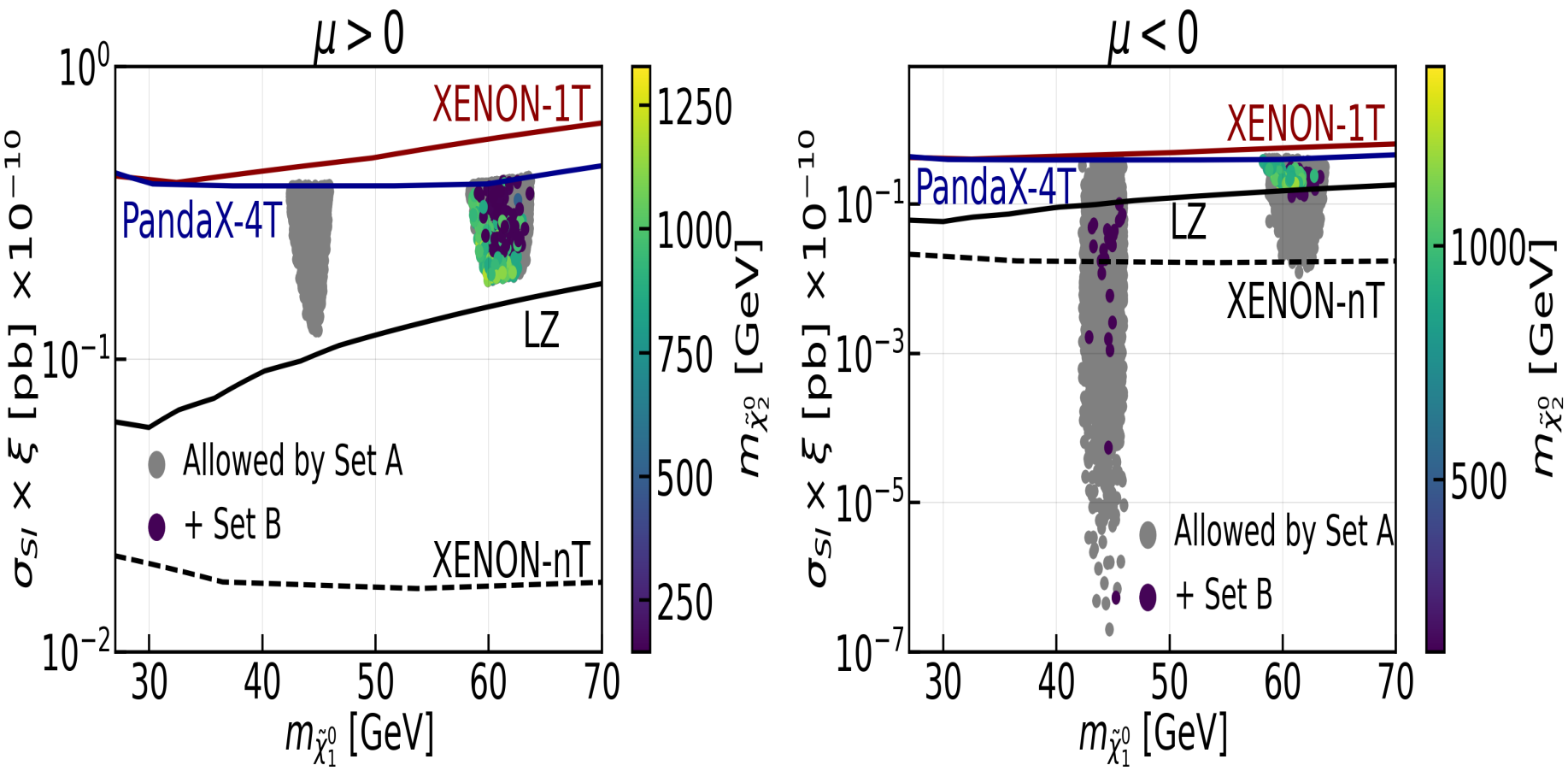
As said before we do need more scrutiny of the region $m_{\tilde{\chi}_1^0} \sim m_Z/2$.

A recent analysis by Melissa Van Beekveld and collaborators (hep-ph/2104.03245) does have allowed points in this mass range.

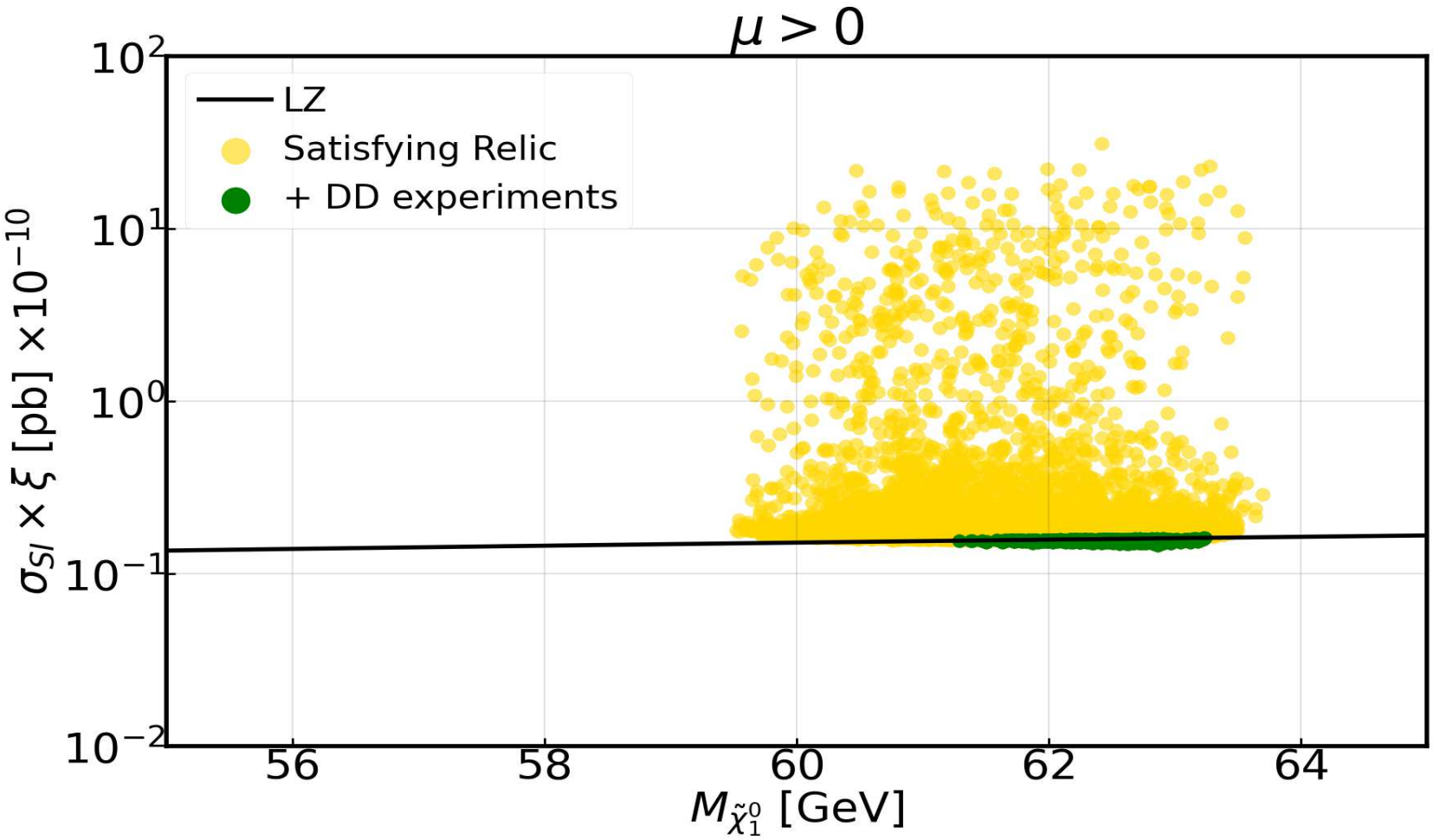
This analysis looks at PMSSM allowed spectra in light of current data and (g-2). The Δ_{EW} smallest if LSP is lighter than 100 GeV.

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.)





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


$\mu > 0$
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]

In next to minimal MSSM (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 in the full NMSSM parameter space!

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

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, but will be tested by upcoming LHC and/or DD experiments!

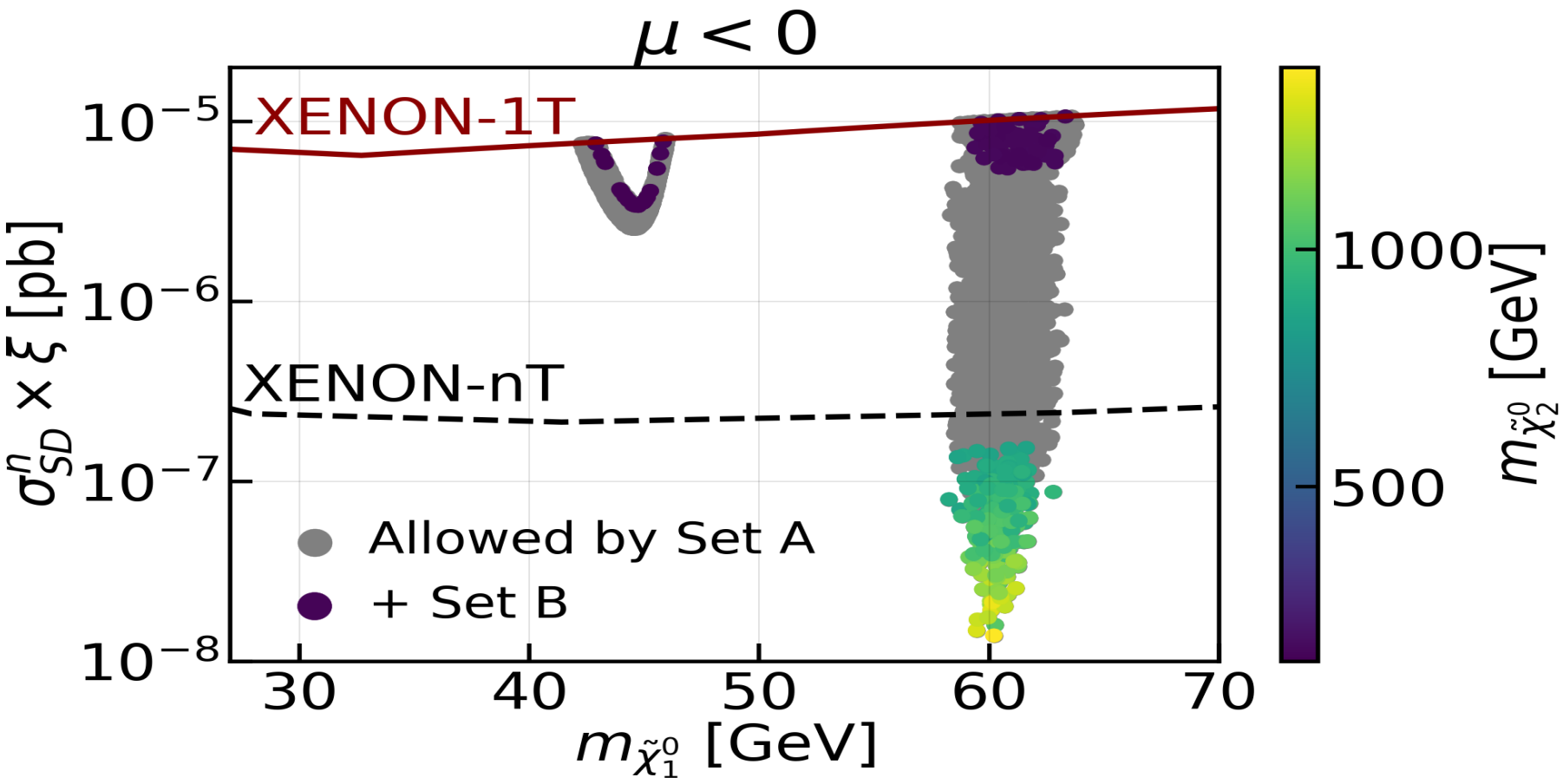
Case different for NMSSM. Investigations on going!

I did not discuss: For pMSSM light LSP as DM allowed for non thermal scenario but it can be tested completely at the High Luminosity (HL) LHC!

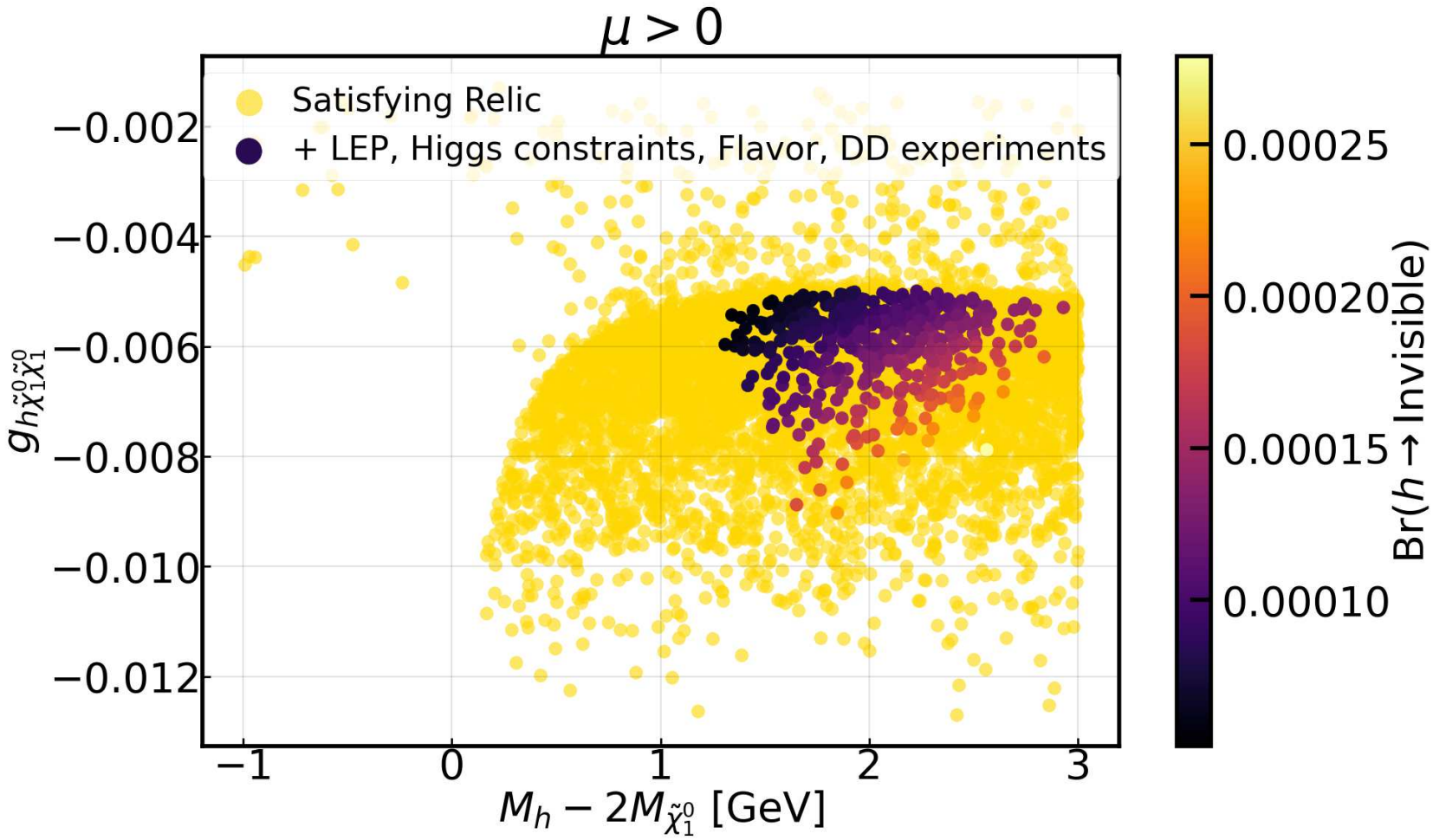
pMSSM extended with a $\tilde{\nu}_R$: a light $\tilde{\nu}_R$ still possible. Characteristic signals. Discussed in a White paper "Unveiling Hidden Physics at the LHC - Whitepaper", Bruce Mellado and Oliver Fischer. arXiv/hep-ph/ 2109.06065

All scenarios can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

Additional Slides



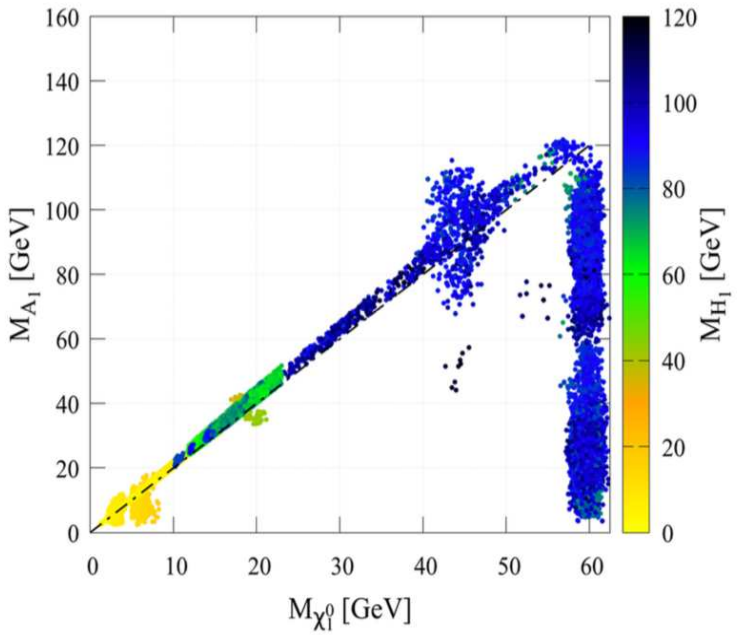
2207.06238 : R.K. Barman, G. Belanger, Biplob Bhattacharjee, R.G., Rhitaja Sengupta


$\mu > 0$
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
Br($h \to$ Invisible)

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.



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.

Light $\tilde{\nu}_R$ 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