O(1) GeV DM in SUSY and a very light pseudoscalar at the LHC

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in collaboration with
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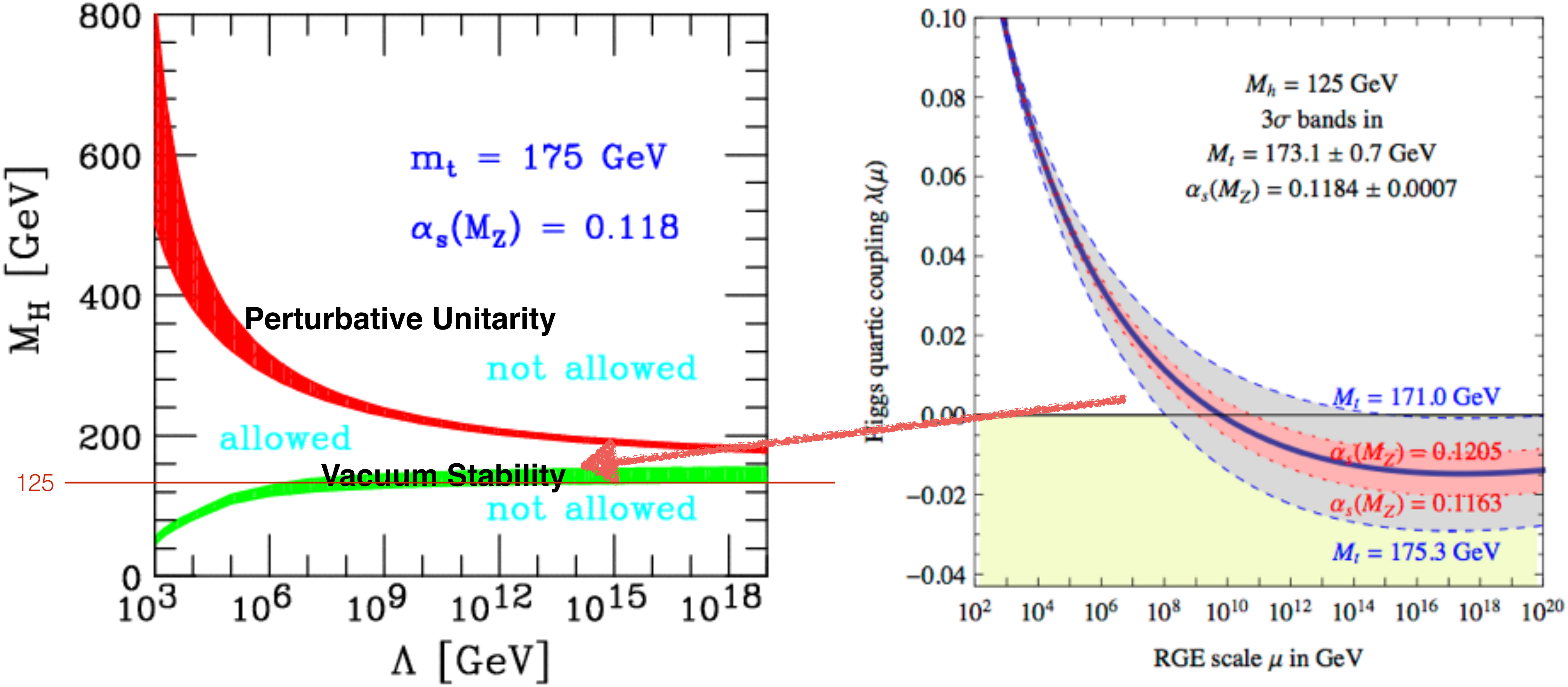
Higgs is found. Then what else?



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- 125 GeV is quite a safe mass if we consider SM as the effective theory below 100 ~ 1000 TeV.

- And LHC has so far seen no remarkable observation to be regarded as a new physics signal.

- But still we keep our positions and waiting for some news.

Higgs is found. Then what else?

- Attempts to survey the structure of our vacuum or universe are going on.
- Hierarchy Problem - SUSY, Composite Higgs, Twin Higgs, Extra D, etc.
- Dark Matter
- Neutrino Oscillation (Nobel Prize 2015)
- Other Precision measurements: B-physics, neutron EDM, muon g-2, etc.

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SUSY Model of SM particles

- Theoretically sound and predictive model
- Rich in phenomenological implications:
  3 neutral Higgs, DM candidate (LSP neutralino with R-parity)
- However, no evidence at all in the LHC Run I.
- Because m_h^2 requires a large radiative correction from the stops, and it implies m_{soft} ~ TeV or X_t (A_t) ~ multi TeV.

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- Large fine-tuning between $m_{H_i}^2, \mu$ and M_Z .

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

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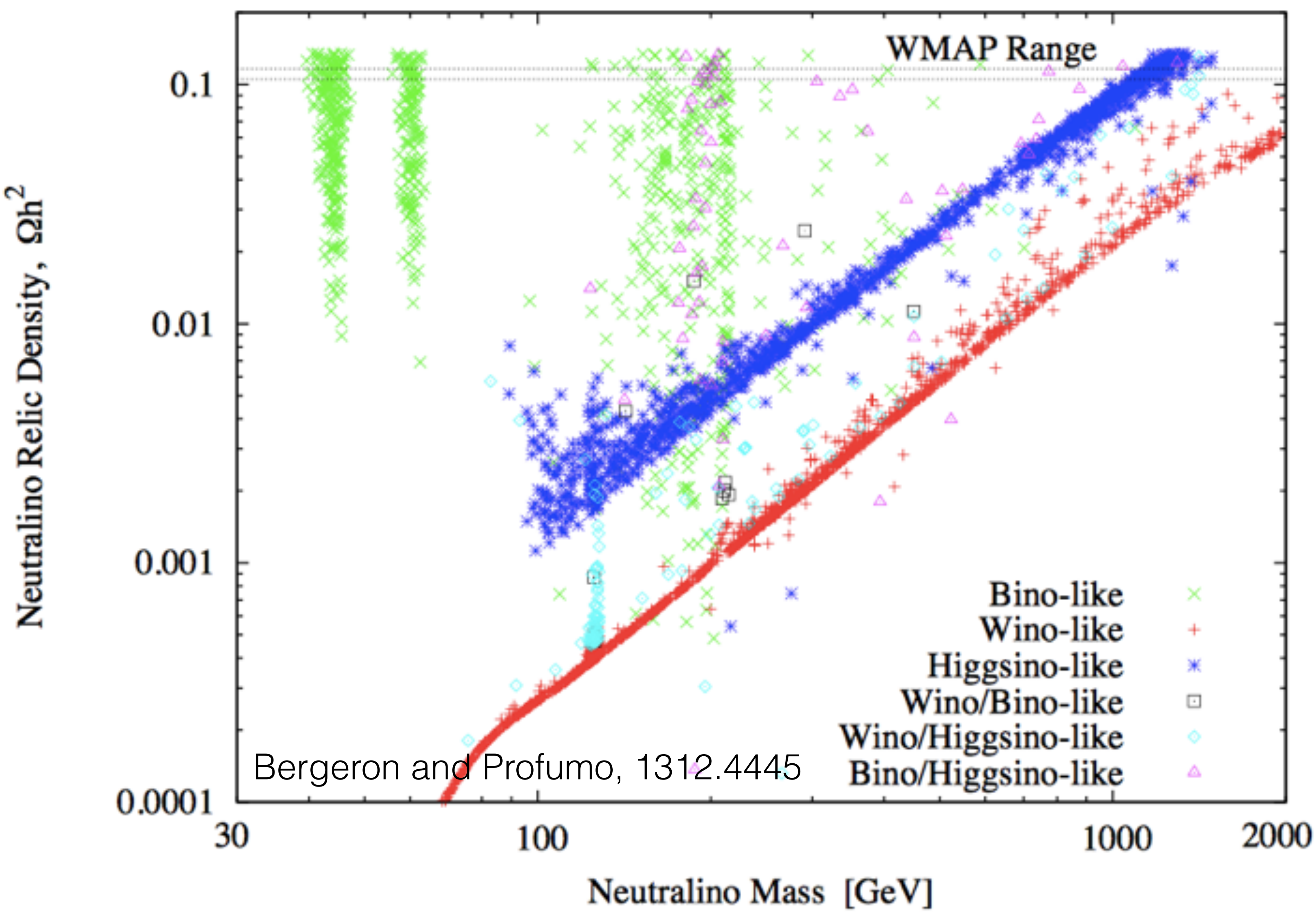
- Large fine-tuning between $m_{H_i}^2, \mu$ and M_Z .
- What are the issues in the Dark Matter side?

DM might be just around the corner of Higgs

- SUSY suggests a good DM candidate (LSP with R-Parity).

DM might be just around the corner of Higgs

- MSSM neutralino covers a large range of DM mass.



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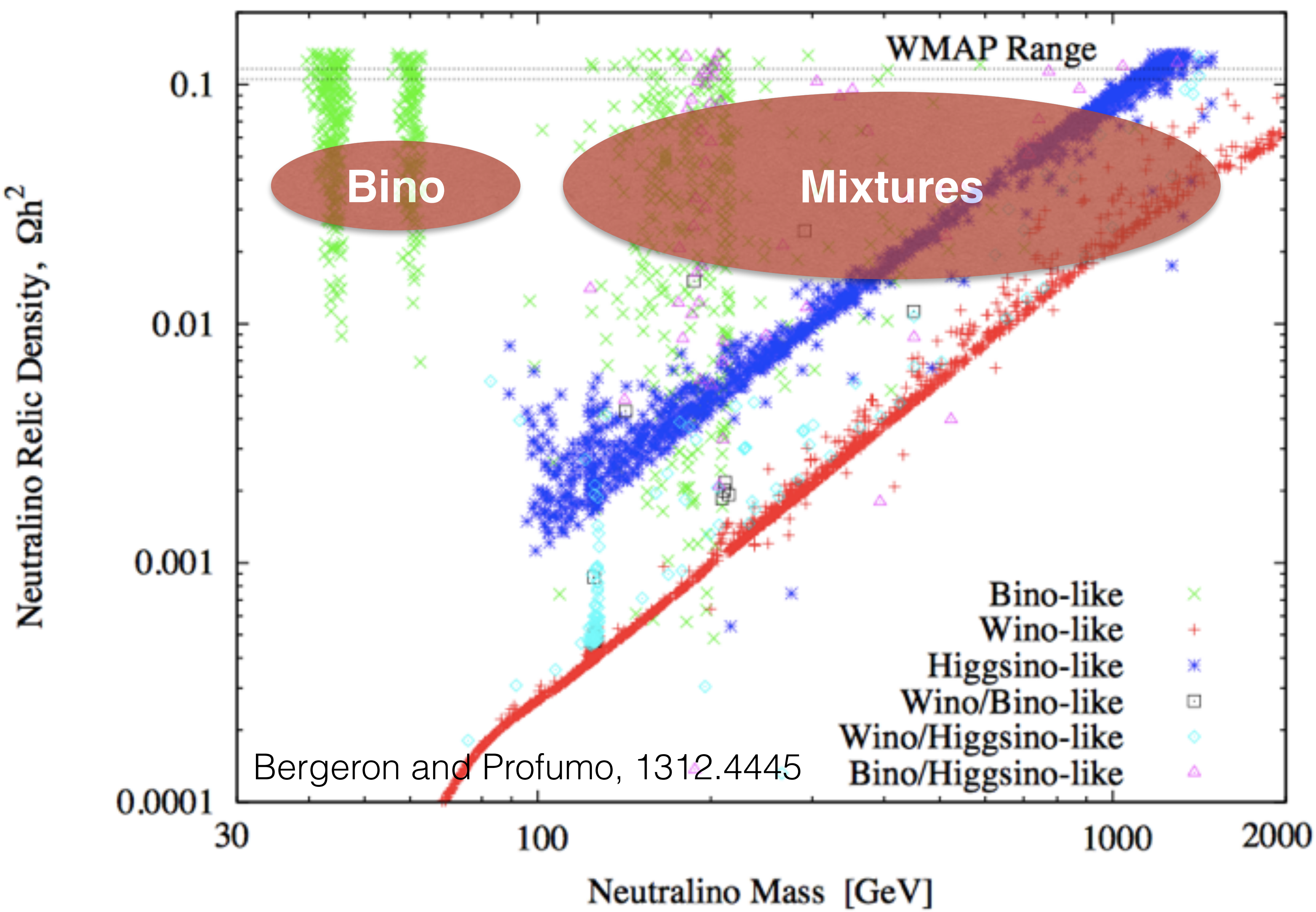


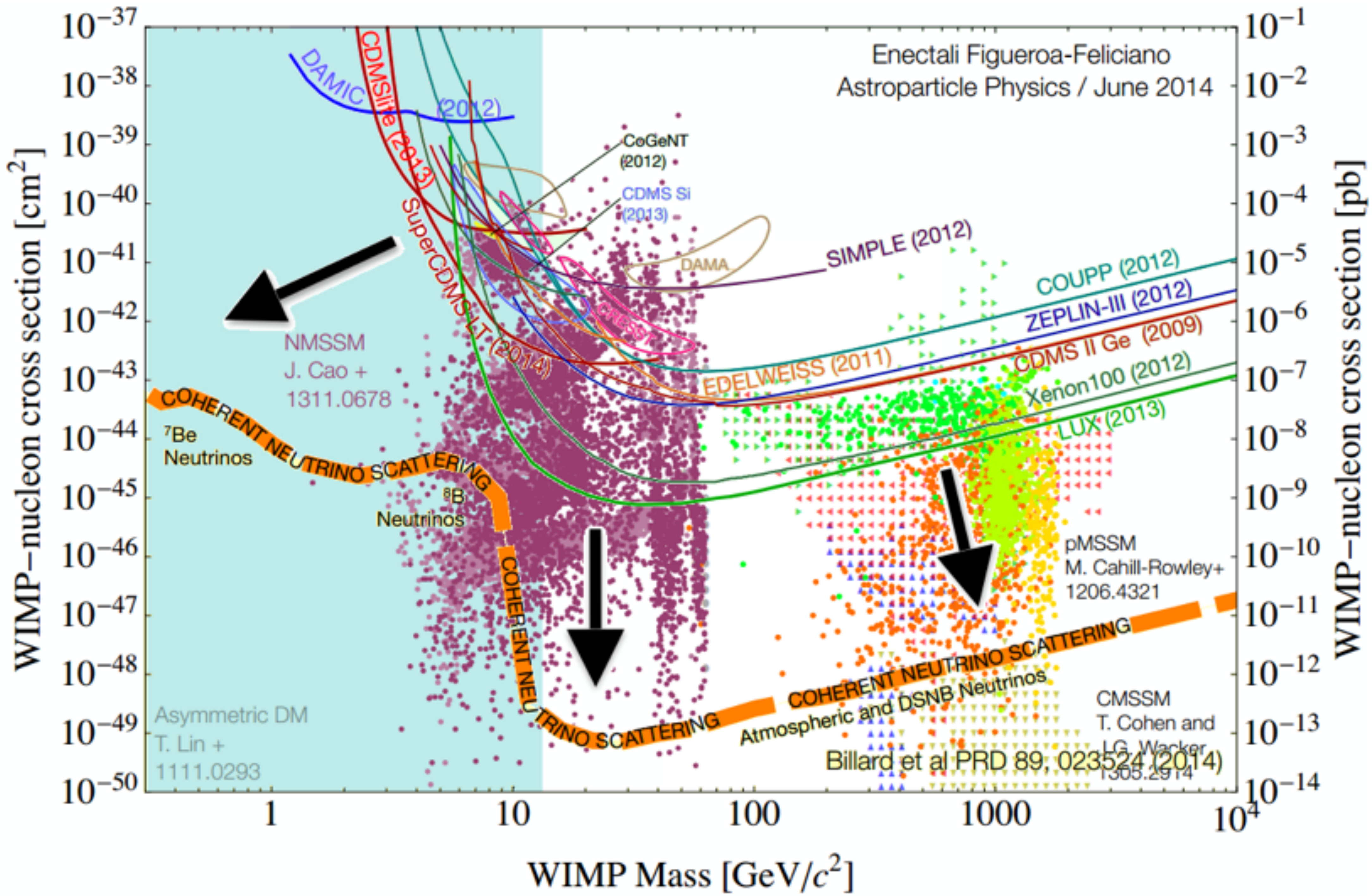
DM might be just around the corner of Higgs

- SUSY suggests a good DM candidate (LSP with R-Parity).
- If we consider the relic abundance measured in PLANCK exp., an MSSM wino-higgsino mixture is promising in a wide mass range.
- Bino DM is also possible when it annihilates resonantly via some mediators such as Z’, Higgs, etc.
- Or we can suggest a more complicated model to prevent our universe from over-closure. (Bino is an NLSP and we have lighter one such as axino DM.)
- From MSSM, it is hard to accommodate the neutralino DM below 10 GeV mass range.

DM might be just around the corner of Higgs

- SUSY suggests a good DM candidate (LSP with R-Parity).
- But the DM search is getting challenged more.

DM might be just around the corner of Higgs



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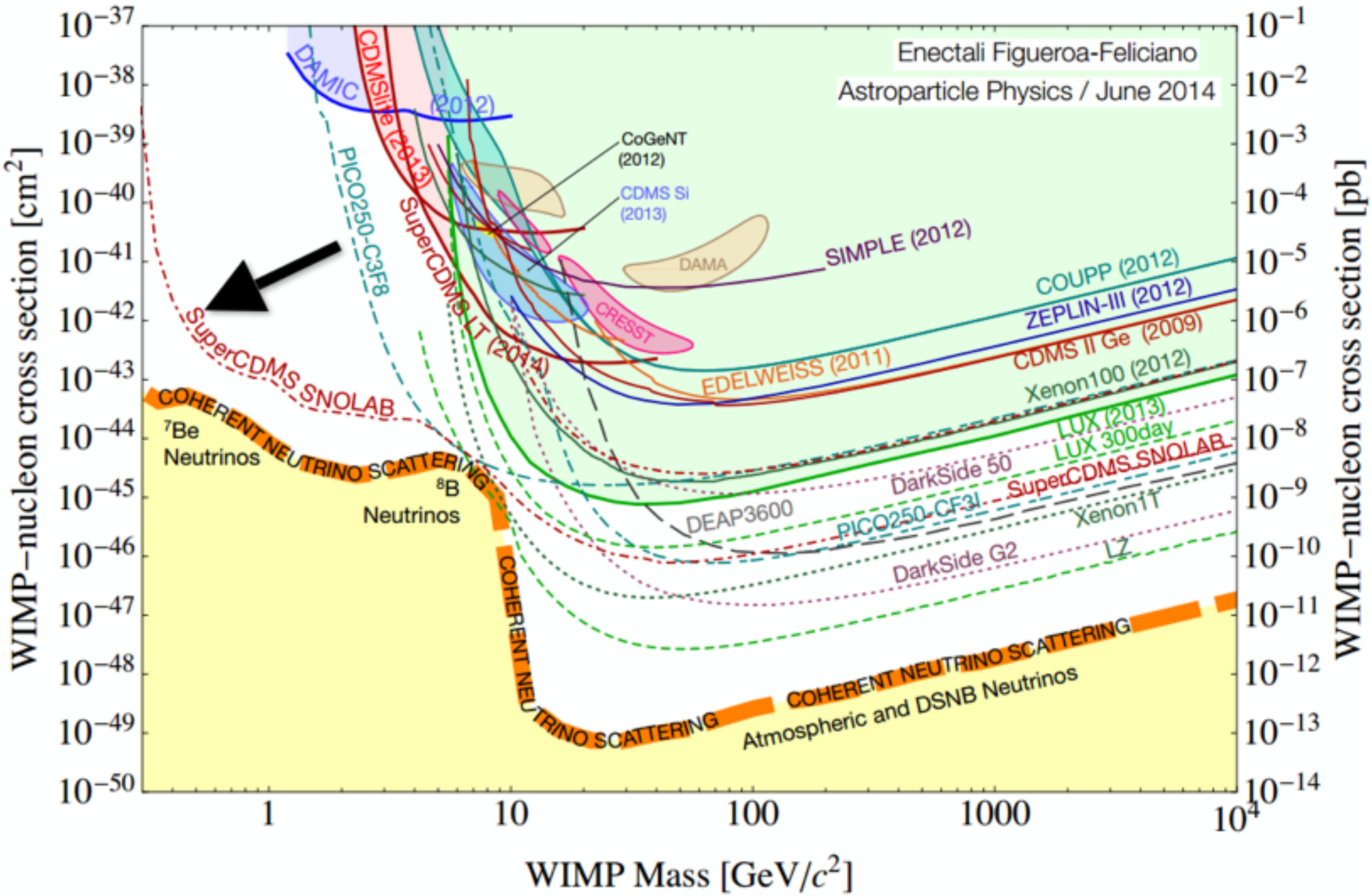

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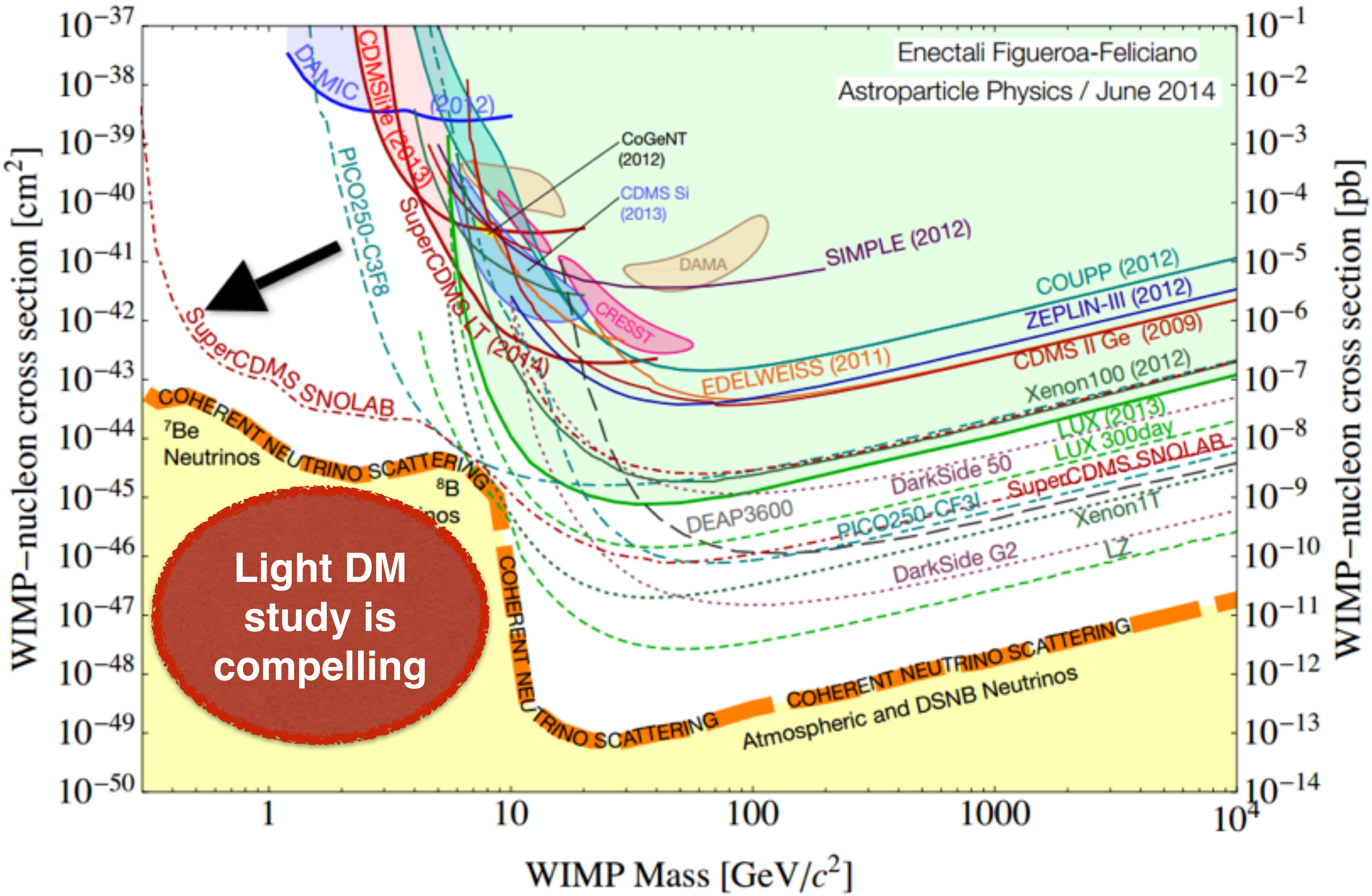
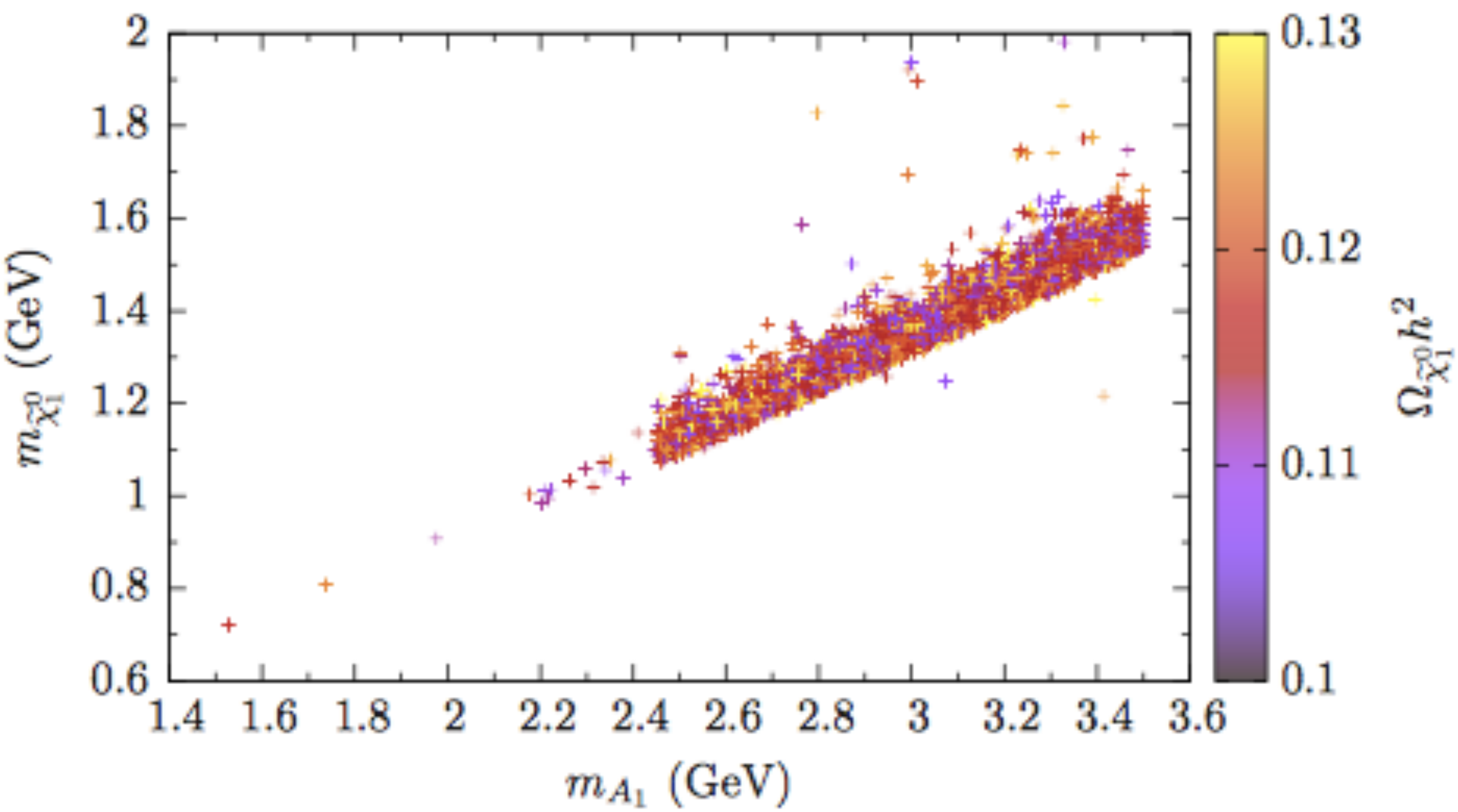


How to realize light DM in SUSY

- It is difficult to realize an O(1) GeV DM in the MSSM
  -> But in the NMSSM, it is possible. (1504.05085)



NMSSM setup for singlino DM

- Next-to-Minimal Supersymmetric extension of the Standard Model

- Introduces a SM singlet superfield to reduce the fine-tuning of the Higgs mass. And all mass scales are introduced at the SUSY breaking scale.

$$\begin{array}{c} W \supset \mu H_u H_d \\ V \supset B\mu h_u h_d \end{array} \xrightarrow[\text{NMSSM}]{\text{MSSM}} \begin{array}{c} W \supset \lambda S H_u H_d + \frac{\kappa}{3} S^3 \\ V \supset \lambda A_\lambda S h_u h_d \end{array}$$

- SM Higgs mass is lifted up at tree level by a sizable interaction with singlet sector.

$$m_{H_{1,2}}^2 \simeq \frac{1}{2} \Big\{ m_Z^2 + 4(\kappa s)^2 - \kappa s A_\kappa \mp \sqrt{[m_Z^2 - 4(\kappa s)^2 - \kappa s A_\kappa]^2 + 4\lambda^2 v^2 [2\lambda s - (A_\lambda + \kappa s) \sin 2\beta]^2} \Big\}$$

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- Light singlino-like DM is decoupled from the higgsino states. ($\kappa s \ll \mu_{\text{eff}}$)

$$\begin{array}{c} \begin{array}{ccc} m_{\tilde{B},\tilde{W}} & m_{\tilde{H}_{u,d}} & m_{\tilde{S}} \end{array} \\ \begin{pmatrix} \cdots & & & \\ & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & -\mu_{\text{eff}} & 0 & -\lambda v_d \\ & -\lambda v_u & -\lambda v_d & 2\kappa s \end{pmatrix} \end{array}$$

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- Strong mass correlation between $m_{\tilde{\chi}_1^0}$ and $m_{A_1^0}$ (~ κs) for a large $\tan\beta$.

$$m_{A_1^0}^2 \simeq \lambda(A_\lambda + 4\kappa s)\frac{v^2 \boxed{\sin^2 2\beta}}{2s} - \boxed{3\kappa s A_\kappa}$$

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- Light singlino-like DM is decoupled from the higgsino states. ($\kappa s \ll \mu_{\rm eff}$)

- Strong mass correlation between $m_{\tilde{\chi}_1^0}$ and $m_{A_1^0}$ (~ κs) for a large $\tan\beta$.
  ⇨ Light singlino and light pseudo-scalar can be easily realized.

Parameter Scan and Benchmark Points

- Relic abundance consistent with PLANCK 2015 data.
  ⇨ Necessity to enhance the annihilation channel of LSP
  ⇨ Resonant s-channel process: $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to A_1^0 \to f\bar{f}$
  H_1^0: p-wave suppressed
  $2m_{\tilde{\chi}_1^0} = m_{A_1^0}$ ~ 3 GeV

- Rare B meson decay constraints.

- LEP Electroweak Precision Test.

- Etc.

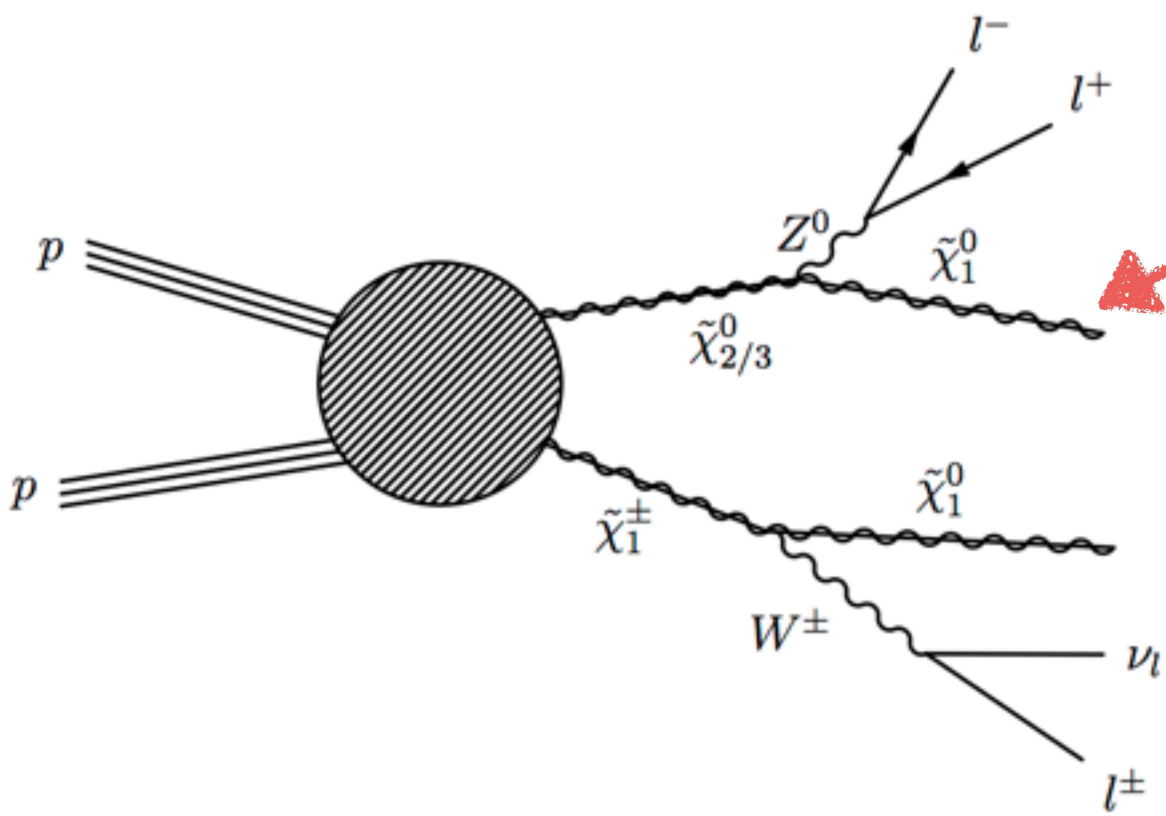
Parameter Scan and Benchmark Points

- Parameter sets we have found interesting

	BP1	BP2
Model parameters		
M_0 (GeV)	1951.1	1826.0
$M_{1/2}$ (GeV)	892.24	929.2
A_0 (GeV)	2462.2	2626.2
μ_{eff} (GeV)	191.34	164.52
$\tan\beta$	14.056	19.785
λ	0.0814	0.3102
κ	0.0002	0.0008
A_λ (GeV)	4080.2	3596.7
A_κ (GeV)	-3.6681	-6.8466

LHC search

- How to optimally survey BPs in the collider:
  BP1 and 2 have distinguishable features at the LHC (300/fb).



	BP1	BP2
Masses		
$m_{\tilde{\chi}_1^0}$ (GeV)	1.0025	1.4081
$m_{\tilde{\chi}_2^0}$ (GeV)	189.09	170.13
$m_{\tilde{\chi}_3^0}$ (GeV)	−201.67	−182.27
$m_{\tilde{\chi}_1^\pm}$ (GeV)	194.97	167.72
m_{A_1} (GeV)	2.1776	2.9856
m_{H_2} (GeV)	124.12	125.79
Branching Ratios		
$BR(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)$	0.634	0.603
$BR(\tilde{\chi}_2^0 \to A_1\tilde{\chi}_1^0)$	0.004	0.089
$BR(\tilde{\chi}_3^0 \to Z\tilde{\chi}_1^0)$	0.736	0.704
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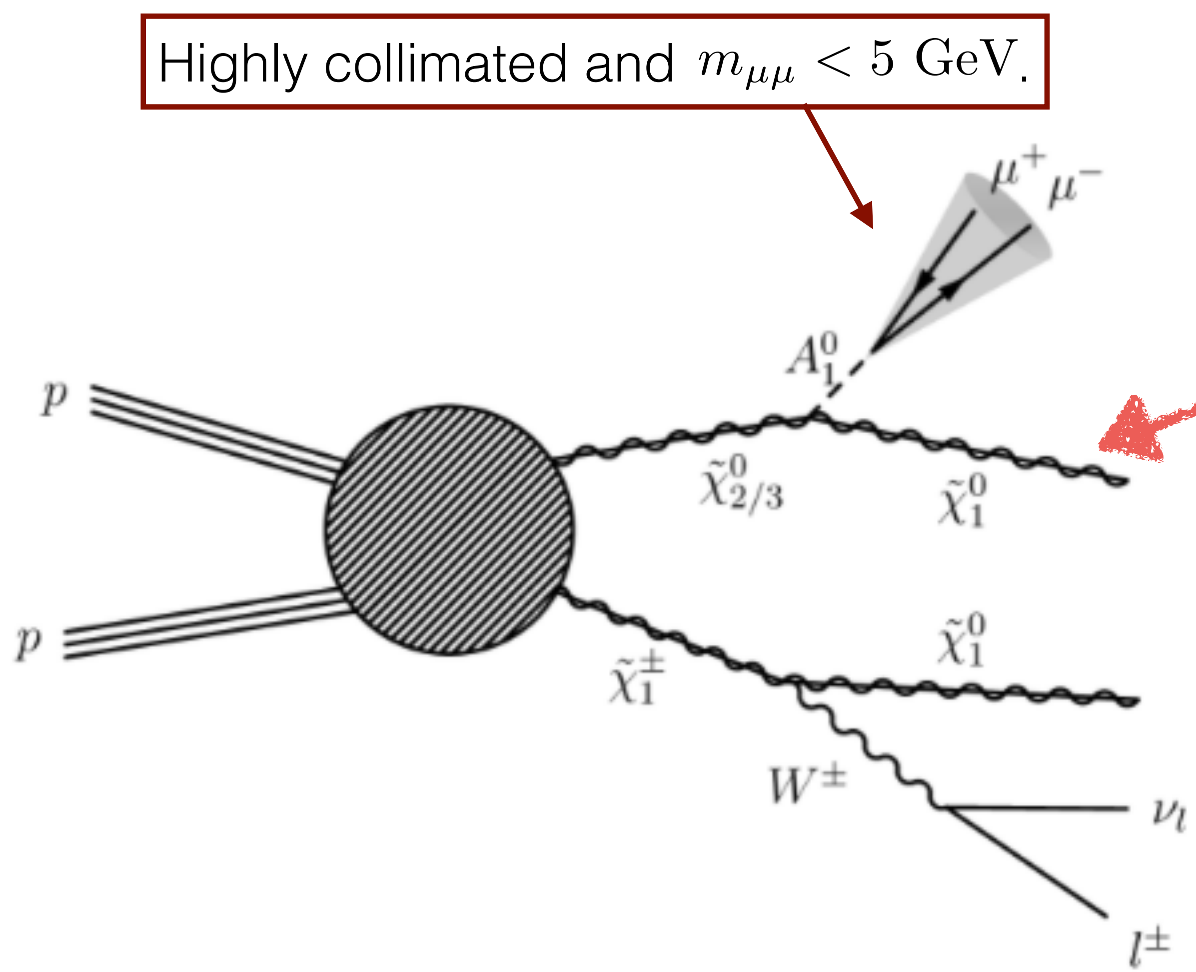

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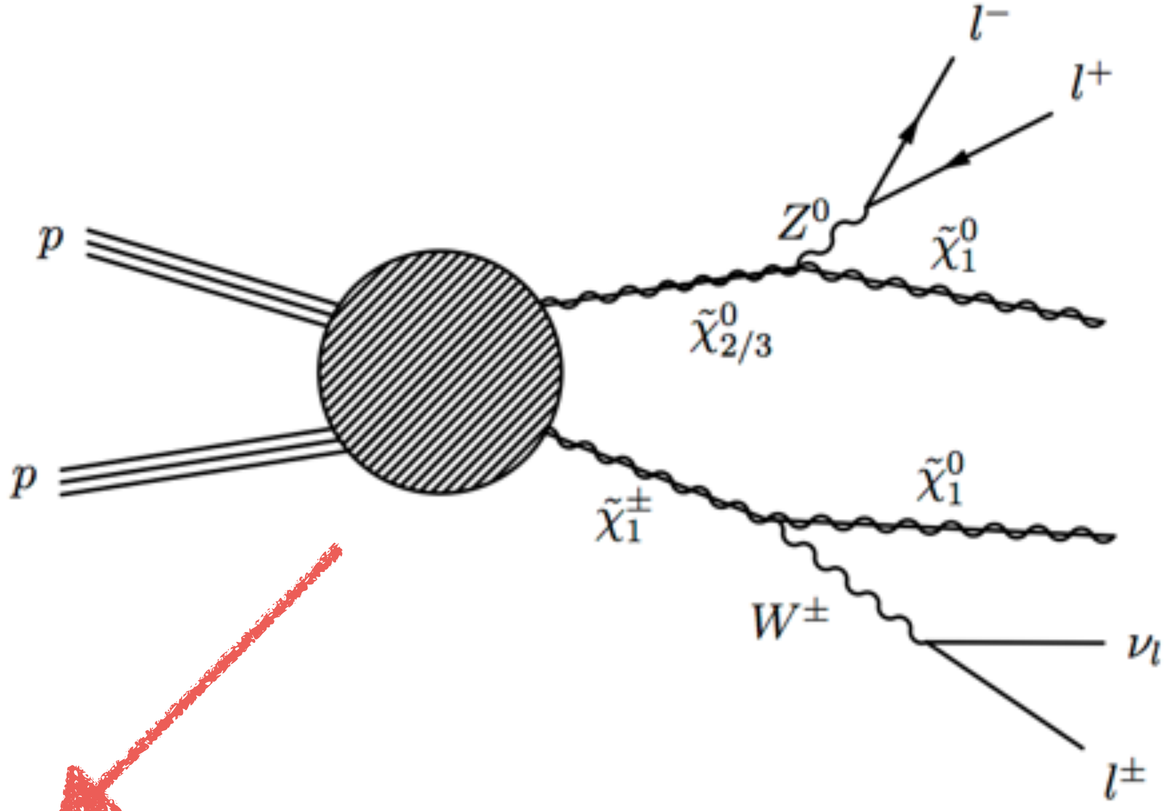
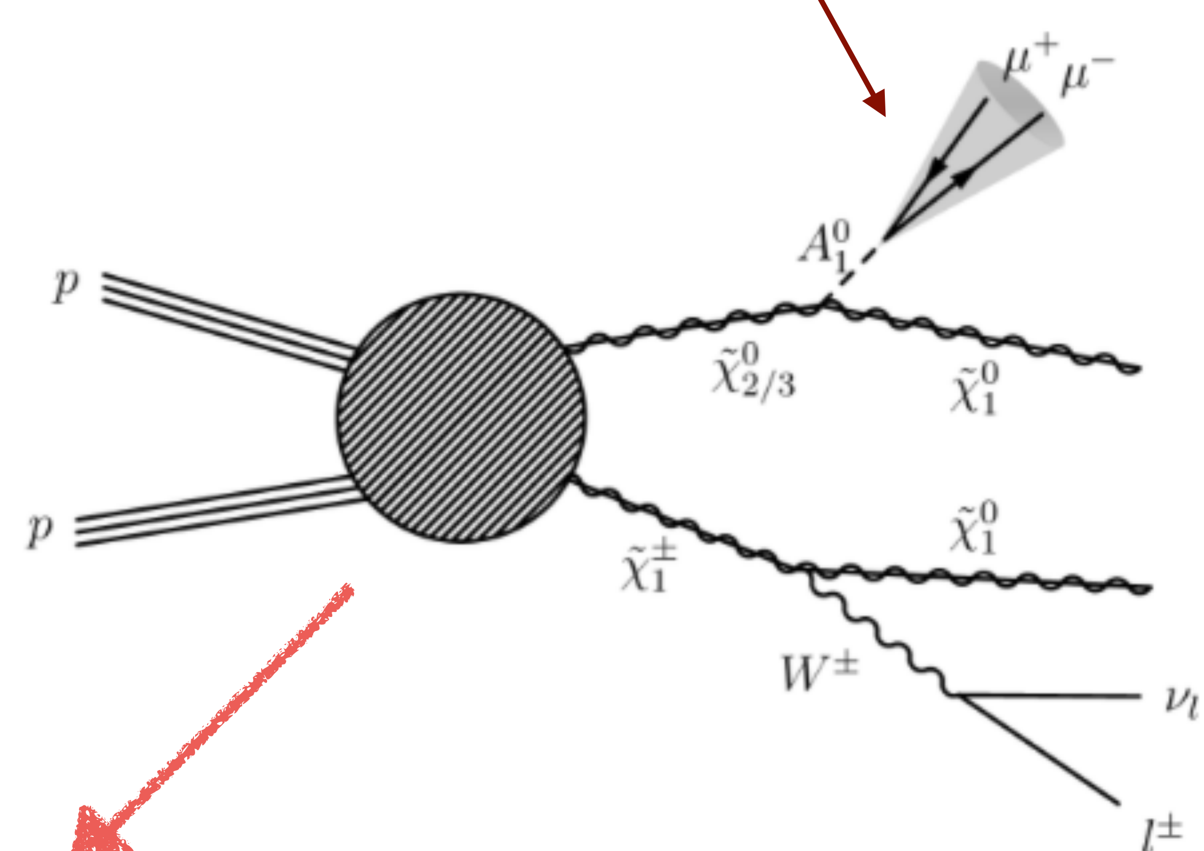
Highly collimated and $m_{\mu\mu} < 5\ \mathrm{GeV}$.





2.7σ significance level expected at the LHC Run II

S/B ~ 15 expected at the LHC Run II

Summary

- Higgs mass implies that the simplest implementation of SUSY still requires a fine-tuning. NMSSM may help to ameliorate the tension.
- DM search calls for back-up by the LHC data.
- NMSSM accommodates O(1) GeV DM via the decoupled singlet sector, and sometimes produces the collimated objects which is easily missed out.
- A proper treatment for them may catch priceless events at the LHC Run II.
- Especially, a collimated soft final states are useful for the model with a compressed mass spectrum. [1502.03734]
- Thank you.

BACKUP SLIDES

LHC search

- Similar to and Motivated by the lepton-jet object.

- Define a collimated muon system as a single detector object.
  1. Require the transverse momentum > 10 GeV for each muon.
     Invariant mass of the muon pair < 5 GeV
  2. Scalar sum of transverse momenta of all additional charged tracks inside the jet cone size $\Delta R = 0.4$, less than 3 GeV.

- Main Backgrounds, containing two collinear muons along with a third lepton and MET, include $W(\to l^{\pm}\nu)\gamma^*$ and $Z(\to l^+l^-)\gamma^*$.

LHC search

- Final Result

	BP1	$W\gamma^*$	$Z\gamma^*$	$Wb\bar{b}$
Cross section (fb)	0.178	246.9	10.0	3770.0
Cut efficiency	0.123	2.15×10^{-4}	6×10^{-5}	1×10^{-6}
Effective cross section (fb)	0.022	0.053	0.0006	0.003
No. of events	6.6	15.9	0.18	0.9

	BP2	$W\gamma^*$	$Z\gamma^*$	$Wb\bar{b}$
Cross section (fb)	3.93	246.9	10.0	3770.0
Cut efficiency	0.050	5.3×10^{-5}	3×10^{-5}	1×10^{-6}
Effective cross section (fb)	0.197	0.013	0.0003	0.003
No. of events	59.1	3.9	0.09	0.9

Point	S/B in analysis		$\mathcal{Z}$ (σ) in analysis	
	3ℓ (SRZc region)	μ_{col}	3ℓ (SRZc region)	μ_{col}
BP1	0.591	0.42	2.7	1.2
BP2	0.436	15	2.0	27