Based on arxiv: 2406.15939 ; 2011.12848 ; 2003.01662 ; 2002.05554

Dark matter in GUT-scale constrained NMSSM

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Outline

- Introduction to Supersymmetry
- Overview of GUT-scale constrained NMSSM
- Singlino and Higgsino Dark matter
- Results and Discussion
- Conclusion

The Standard Model

- **The Standard Model (SM) has been confirmed.**
- However, it cannot be the ultimate theory in particle physics.
- **Challenges Faced by the SM：**
    1. **Evidence of Limitations**: Dark matter； Neutrino mass； Baryon asymmetry
    2. **Theoretical Challenges:** Hierarchy problem； Strong CP problem
    3. **Aesthetic Issues:** Lack of gauge coupling unification； Too many parameters
- **Exploring New Physics Beyond the SM!**

Why Supersymmetry?

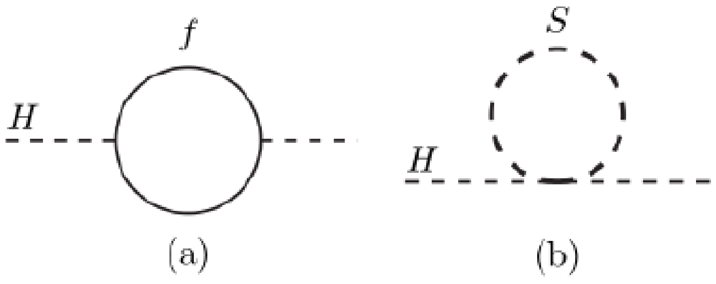
- **Why Do We Still Believe in Supersymmetry?**

1. **Generalized Symmetry:** Supersymmetry extends the Poincaré Algebra, representing the most general symmetry of the S-matrix.
2. **Incorporates Gravity:** Local supersymmetry can includes gravity naturally, leading to supergravity theories.
3. **Solves Hierarchy Problem:** Supersymmetry offers a natural solution to the gauge hierarchy problem, stabilizing the mass of the Higgs boson against quantum corrections.

The Supersymmetric Standard Models

- **Key Benefits of the Supersymmetric Standard Models :**

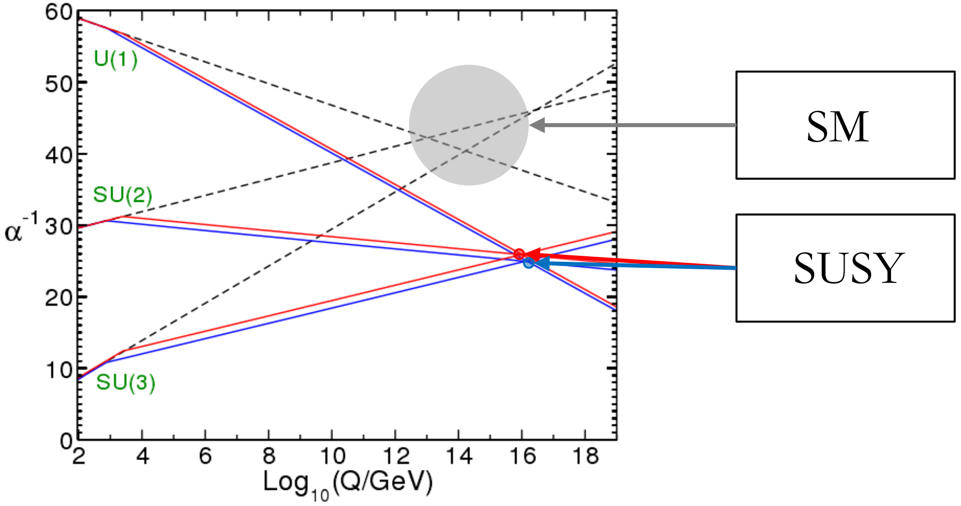
  1. Solves Gauge Hierarchy Problem
  2. Gauge Coupling Unification
  3. Natural Dark Matter Candidates
  4. Radiatively Electroweak Symmetry Breaking
  5. Electroweak Baryogenesis



Martin, arXiv:9709356

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots .$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \ln(\Lambda_{\rm UV}/m_S) + \ldots\right.$$



Our Previous Works

- **Minimal Supersymmetric Standard Model (MSSM)**
  - Unified Soft SUSY Breaking Terms: Constrained MSSM (CMSSM)
    - Status: Excluded
  - Non-Unified Gaugino Mass: Non-Universal Gaugino Mass (NUGM-MSSM)
    - Status: Satisfied all constraints (e.g., muon g-2)
- **Next-to-Minimal Supersymmetric Standard Model (NMSSM)**
  - Unified Soft SUSY Breaking Terms: Constrained NMSSM (CNMSSM)
    - Status: No 125 GeV Higgs with muon g-2 compatibility
  - Non-Unified Higgs Sector: Non-Universal Higgs Mass (NUHM-NMSSM)
    - Status: Features a 95 GeV Higgs and meets all constraints

NMSSM

- **Introduction to NMSSM:**

Addressing the μ-Problem: NMSSM introduces an additional complex singlet superfield, $\hat{S}$, to resolve the " μ-problem" found in the MSSM.

- **Superpotential of NMSSM:**

$$W_{\text{NMSSM}} = y_u \hat{Q} \cdot \hat{H}_u \hat{u}^c + y_d \hat{Q} \cdot \hat{H}_d \hat{d}^c + y_u \hat{L} \cdot \hat{H}_d \hat{e}^c + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- **Effective μ-term:**

$$\mu_{\text{eff}} = \lambda v_s$$

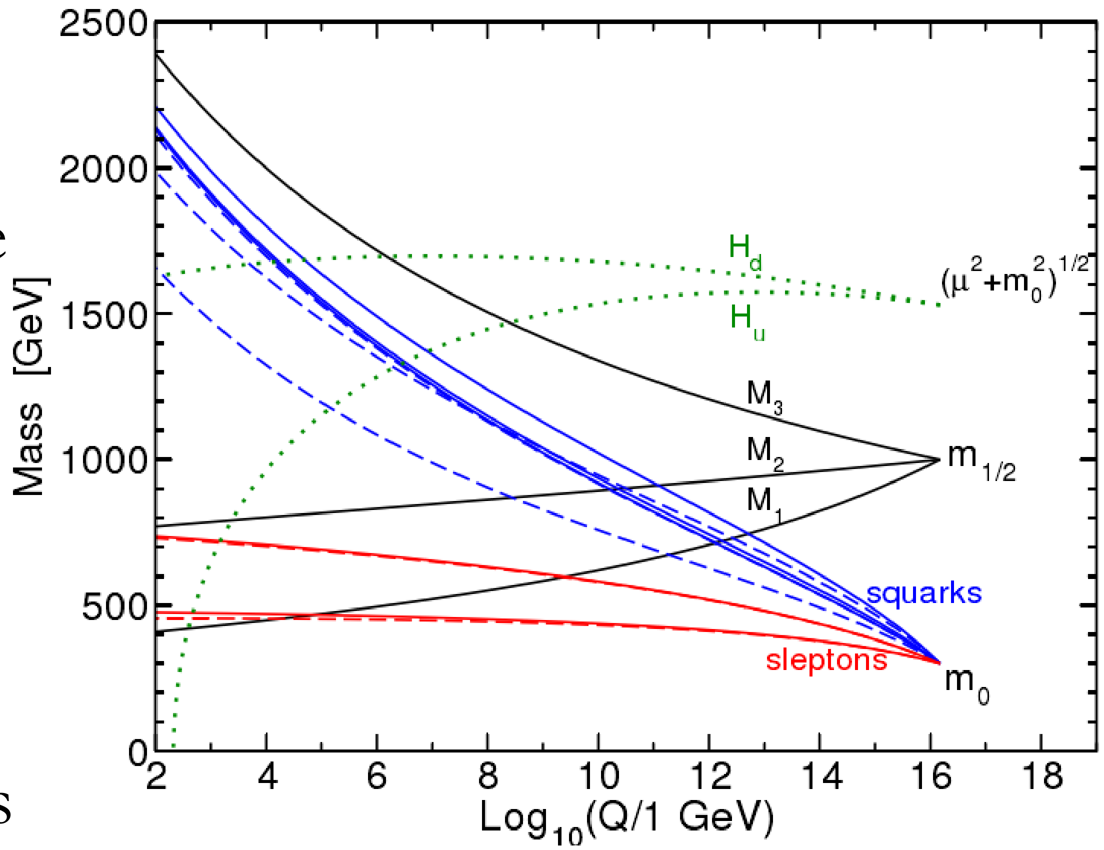
- **Soft Breaking Terms:**

$$-\mathcal{L}^{\text{soft}}_{\text{NMSSM}} = -\mathcal{L}^{\text{soft}}_{\text{MSSM}}|_{\mu=0} + m_S^2 |S|^2 + \lambda A_\lambda S H_u \cdot H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.}$$

GUT-scale constrained NMSSM

- **GUT-scale Constrained:** Trilinear coupling constants, gaugino masses, and scalar particle masses are unified.
- **Flexibility in the Higgs Sector:** To meet both theoretical and experimental constraints, the masses and coupling coefficients in the Higgs sector do not require unification.

$$\boxed{\begin{array}{c} m_{H_u}^2,\ m_{H_d}^2,\ \text{and}\ m_S^2\ \text{to differ from}\ M_0^2+\mu^2 \\ A_\lambda\ \text{and}\ A_\kappa\ \text{differ from}\ A_0 \end{array}}$$



- GUT Scale: M_0 , $M_{1/2}$, A_0
- Higgs Sector: $\tan\beta$, A_λ, A_κ
- Effective μ-Term, λ, κ

Higgs & EW Sector in NMSSM

- **Higgs Sector:**

CP-even Higgs

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = S_{ij} \begin{pmatrix} H_1 \\ H_2 \\ S^R \end{pmatrix}$$

CP-odd Higgs

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = P_{ij} \begin{pmatrix} A \\ S^I \end{pmatrix}$$

Charged Higgs

$$H^\pm$$

$$M_1 : M_2 : M_3 = 1 : 2 : 6$$

- **Neutralino Sector:**

LSP

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = N_{ij} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d \\ \tilde{H}_u \\ \tilde{S} \end{pmatrix}$$

M_1 ✓ Bino LSP

M_2

μ ✓ Higgsino LSP

$2\kappa v_s$ ✓ Singlino LSP

$$m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_3^0} < m_{\tilde{\chi}_4^0} < m_{\tilde{\chi}_5^0}$$

- **Chargino Sector:**

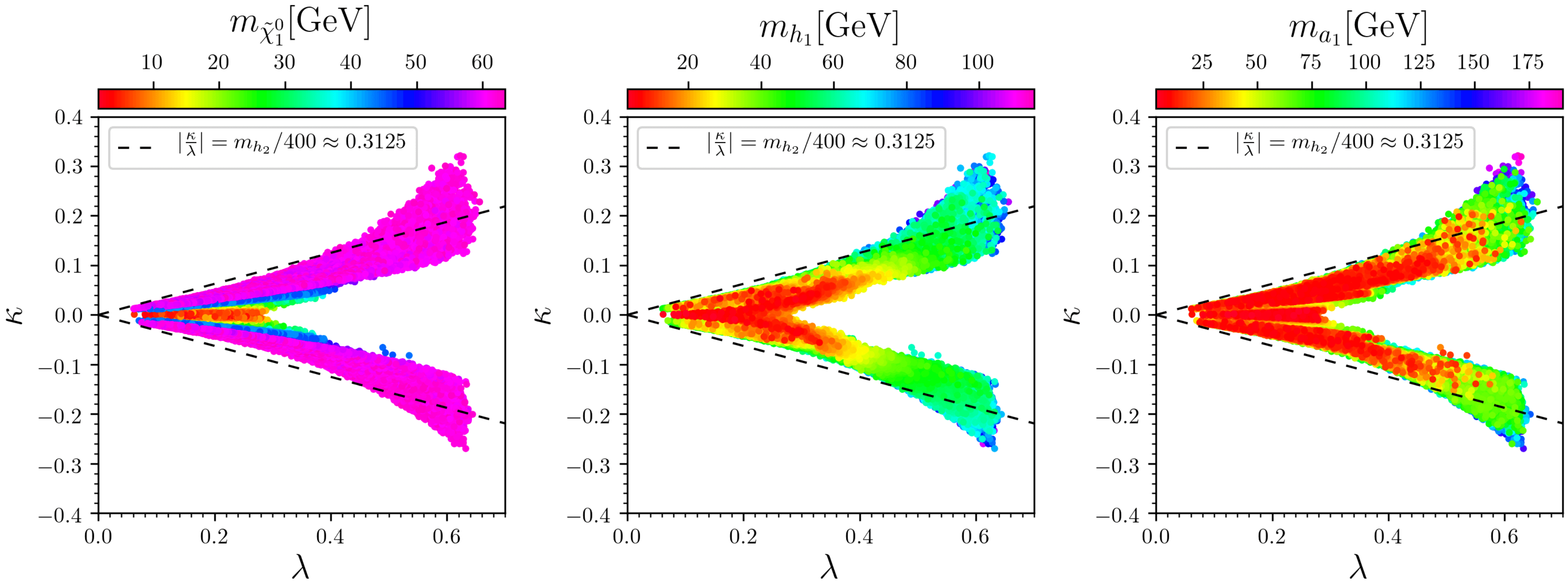
$$\begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix} = V_{ij} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

M_2

μ

$$m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^\pm}$$

Singlino LSP as DM



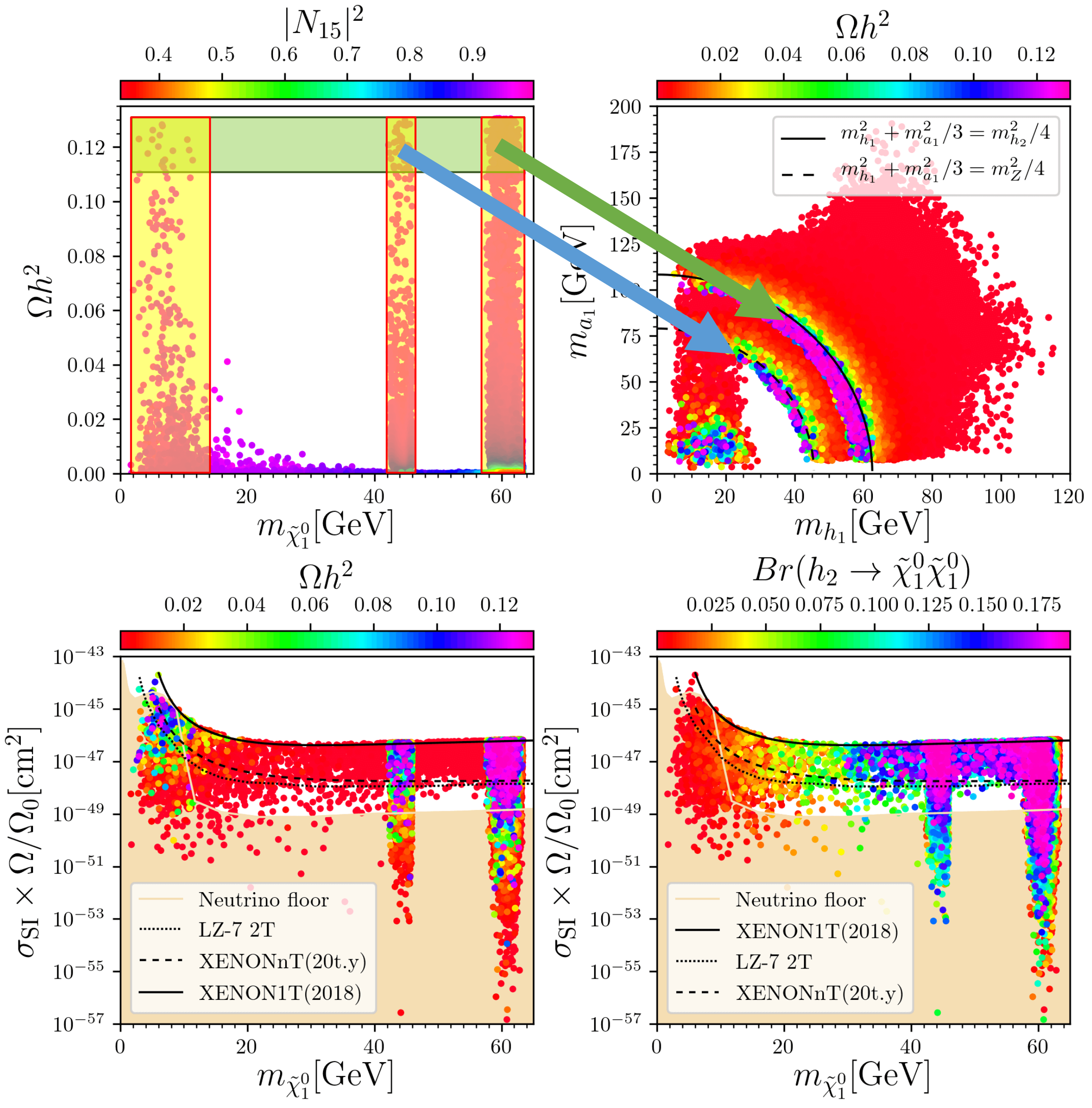
$$m_{\tilde{\chi}_1^0} = 2\kappa v_s = 2\frac{\kappa}{\lambda}\mu \leq m_{h_2}/2$$

Since we need Higgs decay to LSP; range of μ is from 100 to 200 GeV

$$\left[\frac{\kappa}{\lambda}\right]_{\max} \leq \left[\frac{m_{h_2}}{4\mu}\right]_{\min} = \frac{m_{h_2}}{4\times 100} \approx 0.3125$$

- Between the dashed lines, the LSP is primarily singlino.
- The masses of h_1 and a_1 are less than half the mass of h_2.

Singlino LSP Relic Density

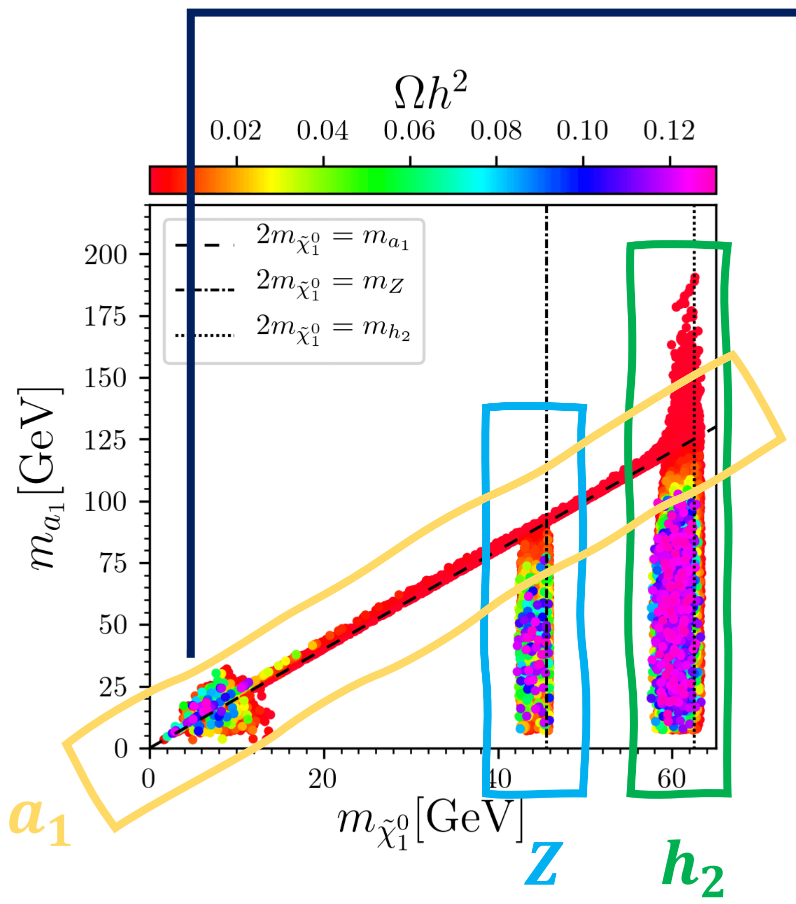


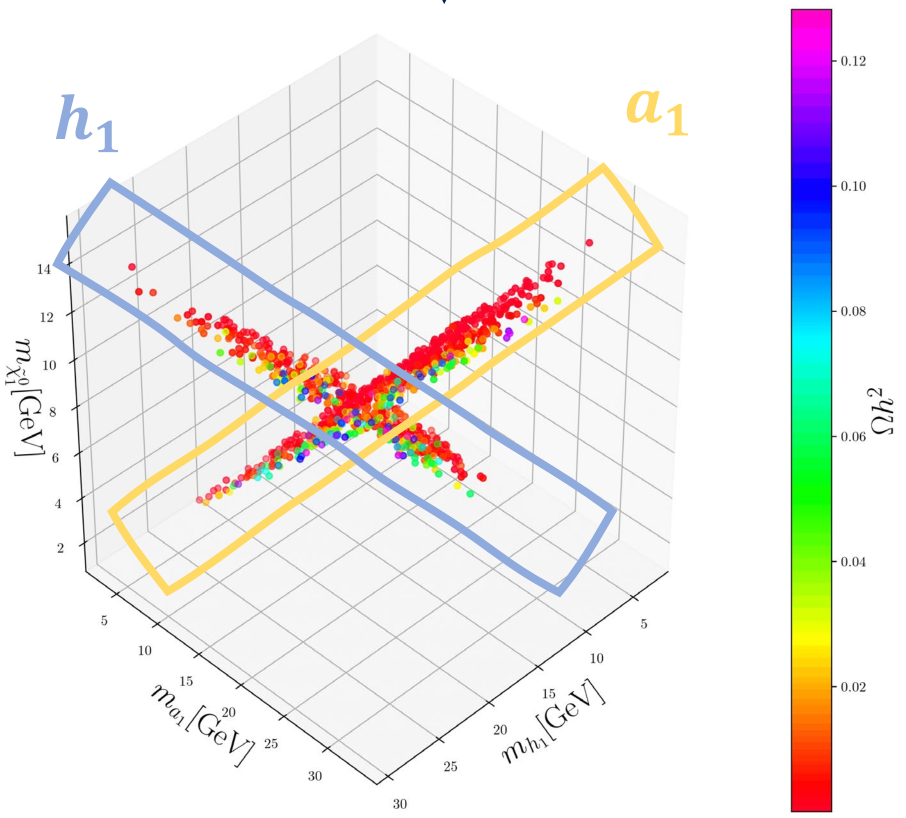
With small λ , κ , large tan β :

$$m_{\tilde{\chi}_1^0}^2 \approx m_{h_1}^2 + \frac{1}{3}m_{a_1}^2$$

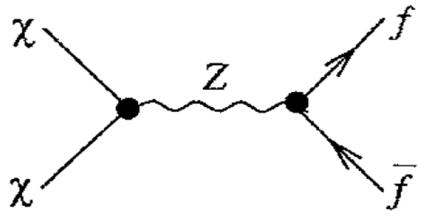
- Accoding to the mass of LSP, there are 3 case.
- The LSP with right DM relic density is highly singlino domainted.
- Lots of samples can be tested on the future DM experiments (LZ, XENONnT).
- When the mass of LSP is larger than 30GeV , Higgs invisible decay is large.

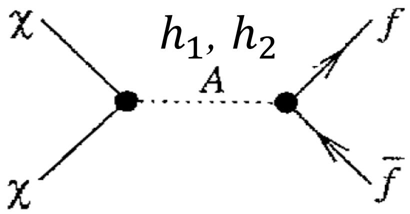
Singlino LSP Annihilation Mechanisms



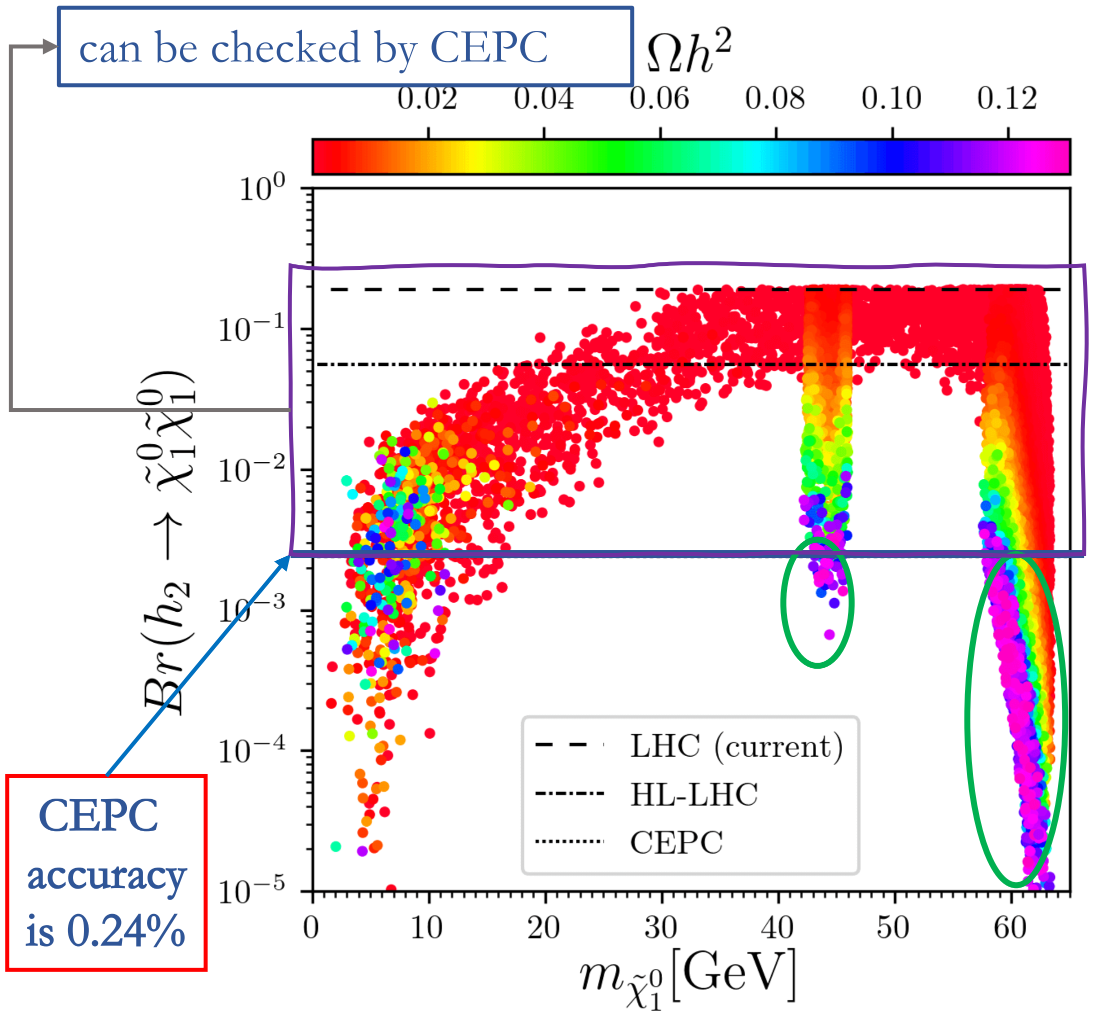


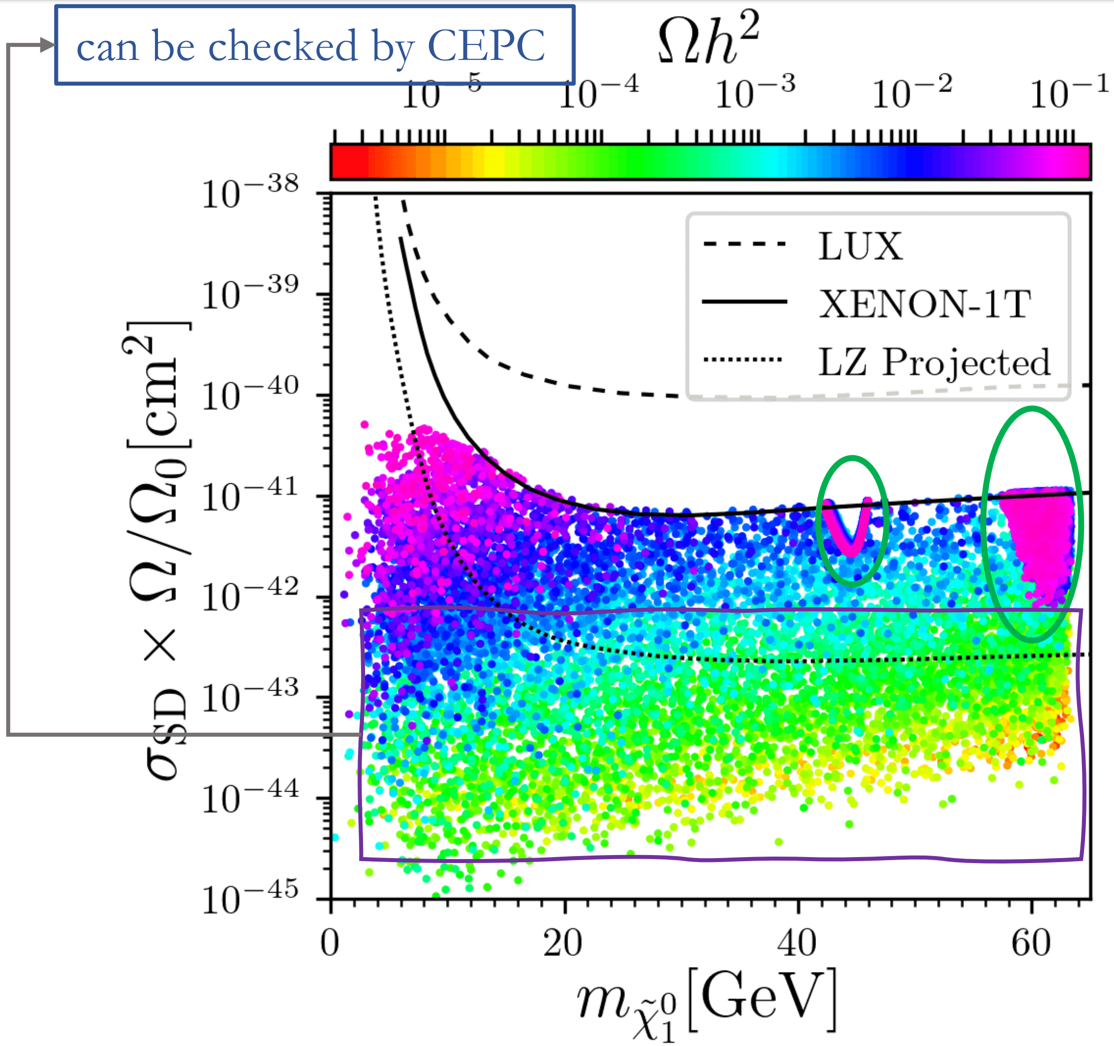
4 funnel-annihilation mechanisms





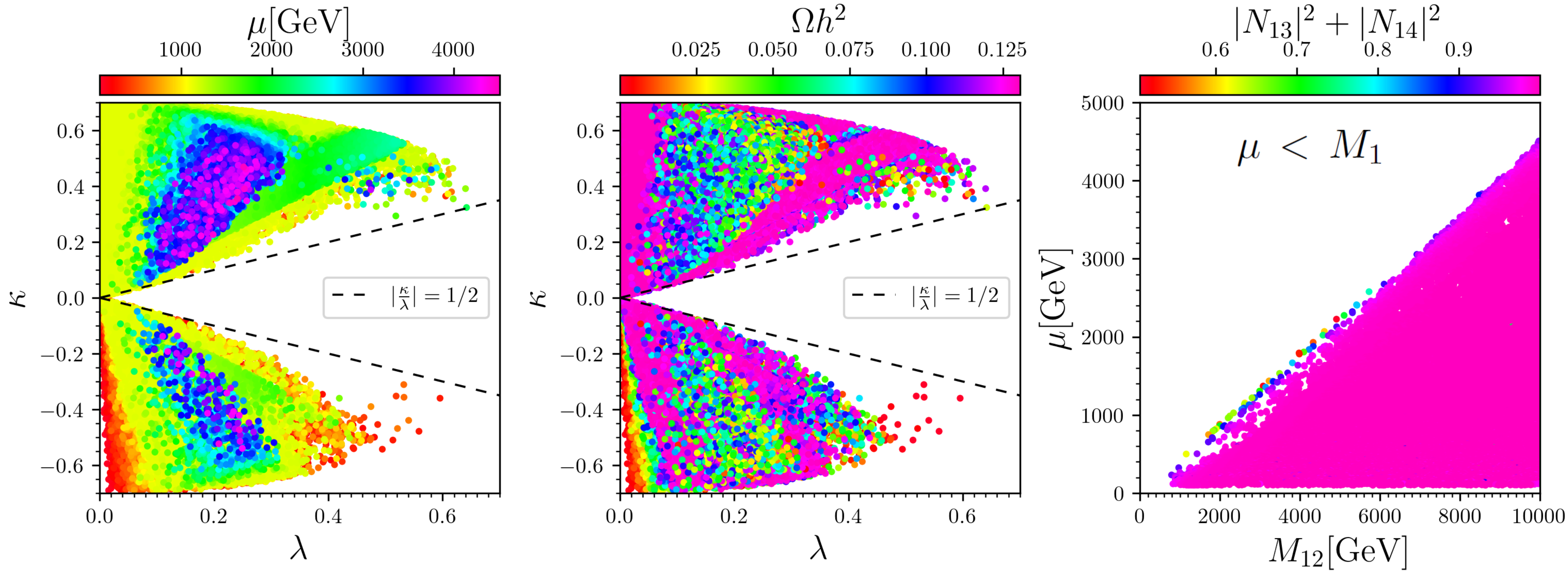
Higgs decay to Singlino LSP





- For LSP with right DM relic density, it can be checked by SD experiment
- For LSP without right DM relic density it can be checked by CEPC.

Higgsino LSP as DM

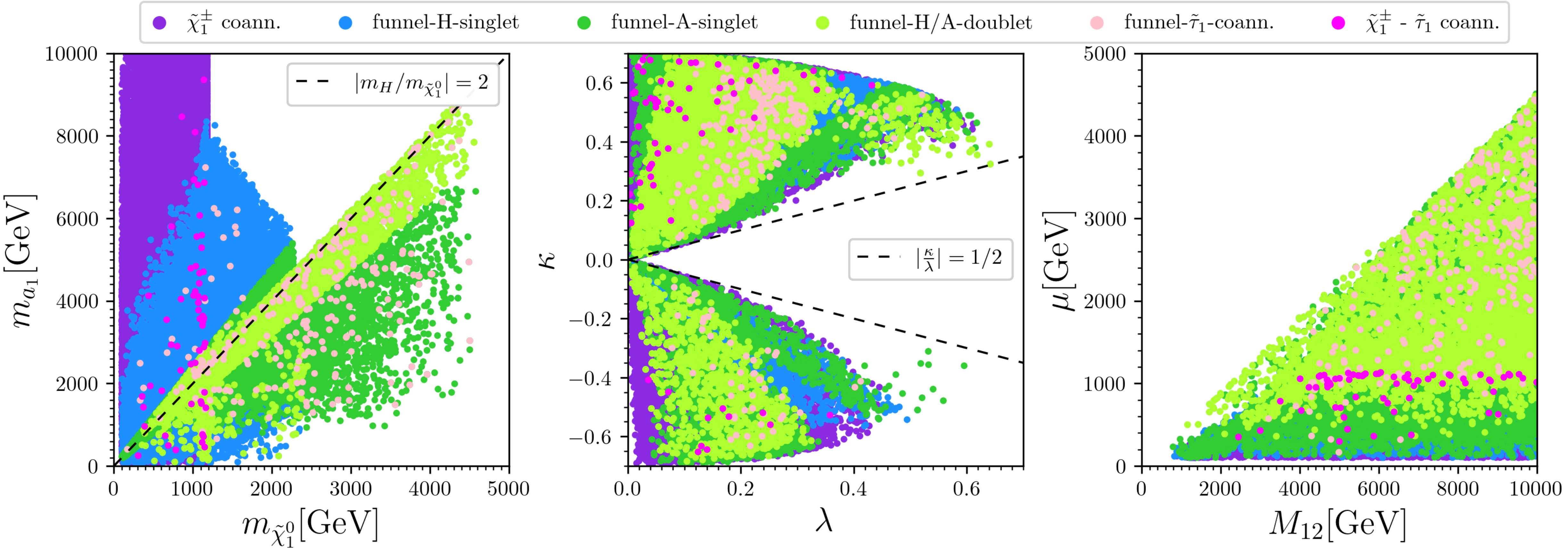


Higgsino LSP:

$$2\kappa v_s = 2\kappa\frac{\mu}{\lambda} > \mu$$

- Higgsino LSP are mainly outside the dotted line;
- $M_{1/2}$ constrains the upper bound of higgsino LSP

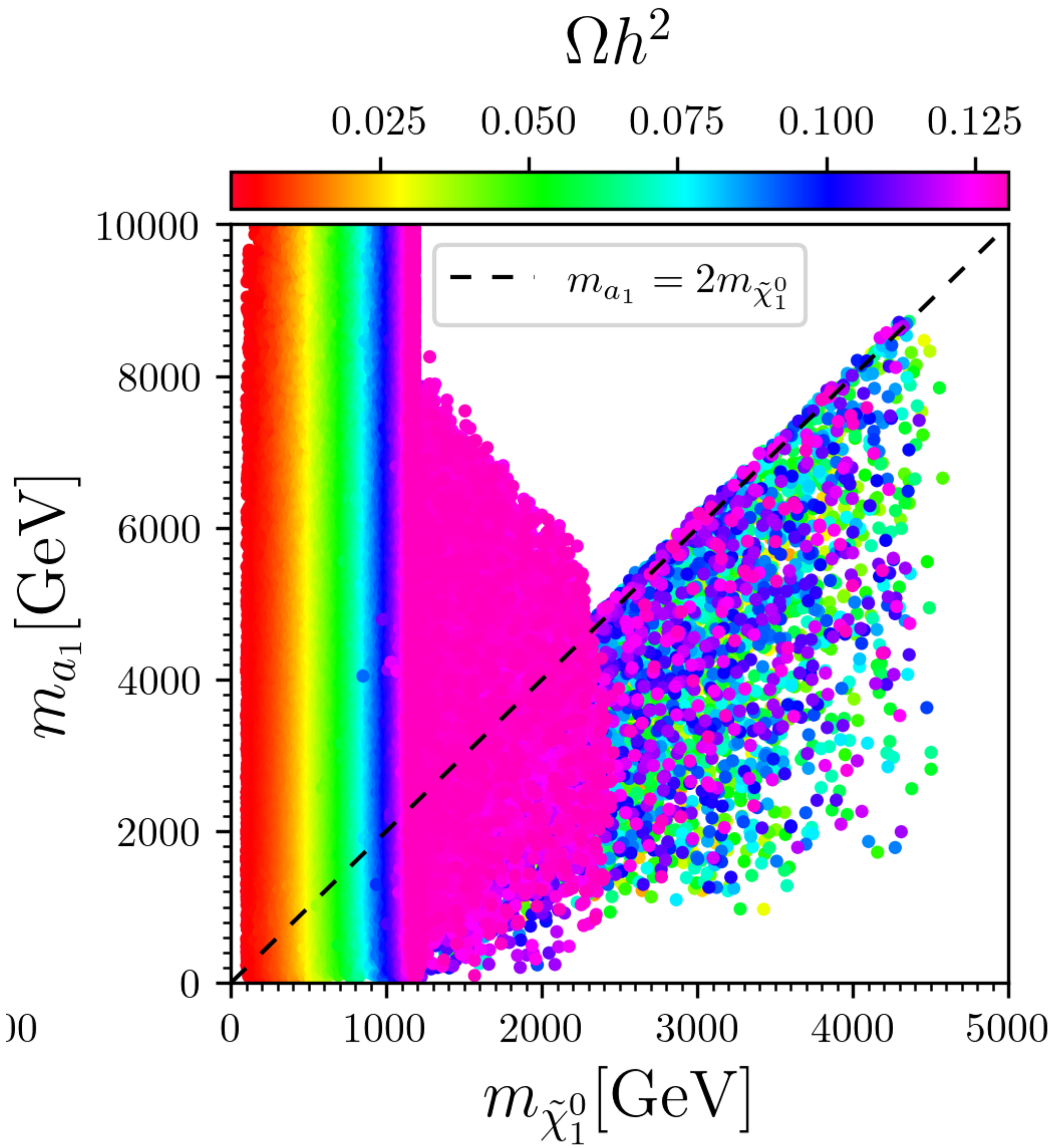
Higgsino LSP Annihilation Mechanisms



$$\tilde{\chi}_1^\pm \text{ coannihilation}: \quad \left(\frac{m_{\tilde{\chi}_1^\pm}}{m_{\tilde{\chi}_1^0}} - 1\right) < 0.1\,, \qquad \tilde{t}_1 \text{ coannihilation}: \quad \left(\frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}_1^0}}\right) - 1 < 0.2\,,$$

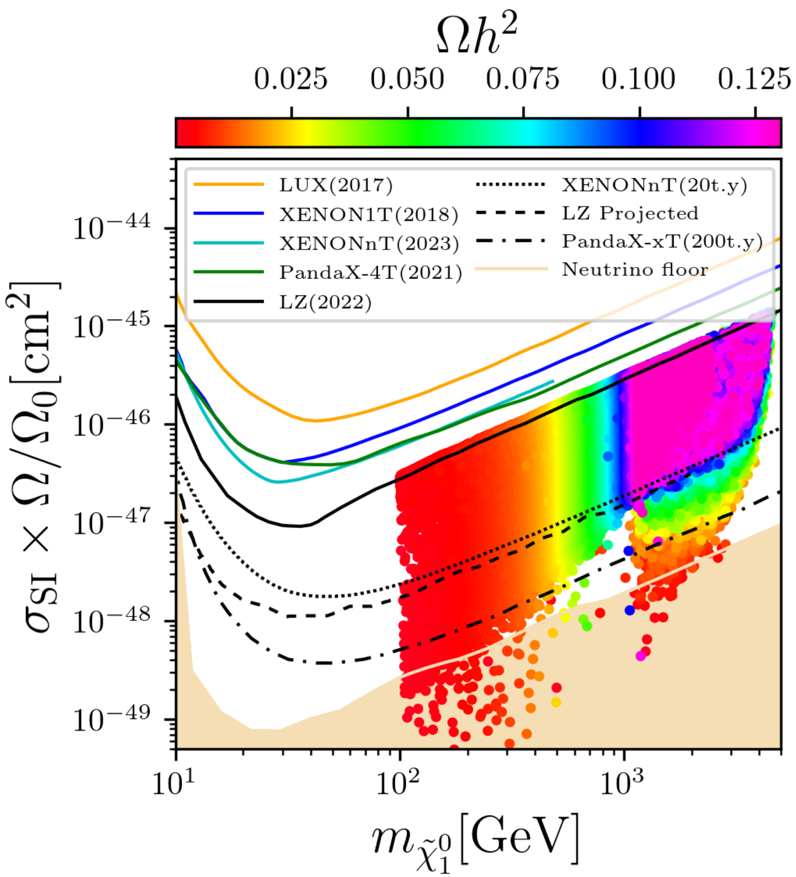
$$\tilde{\tau}_1 \text{ coannihilation}: \quad \left(\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1\right) < 0.15, \qquad A/H \text{ funnel}: \quad \left|\frac{m_{A/H}}{m_{\tilde{\chi}_1^0}} - 2\right| < 0.4\,.$$

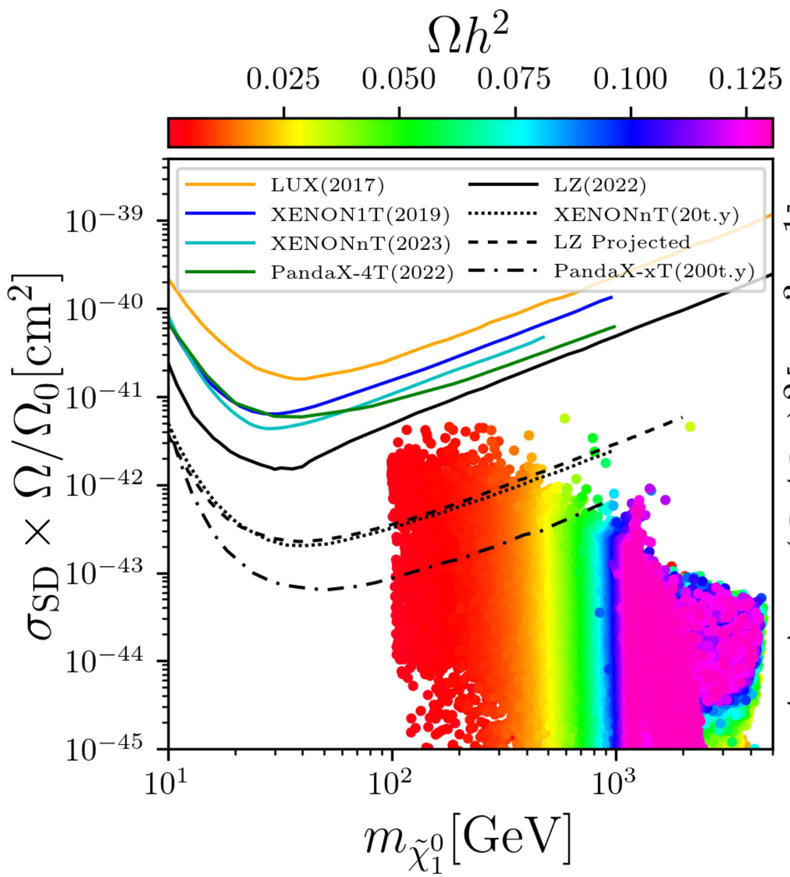
Higgsino LSP Relic Density

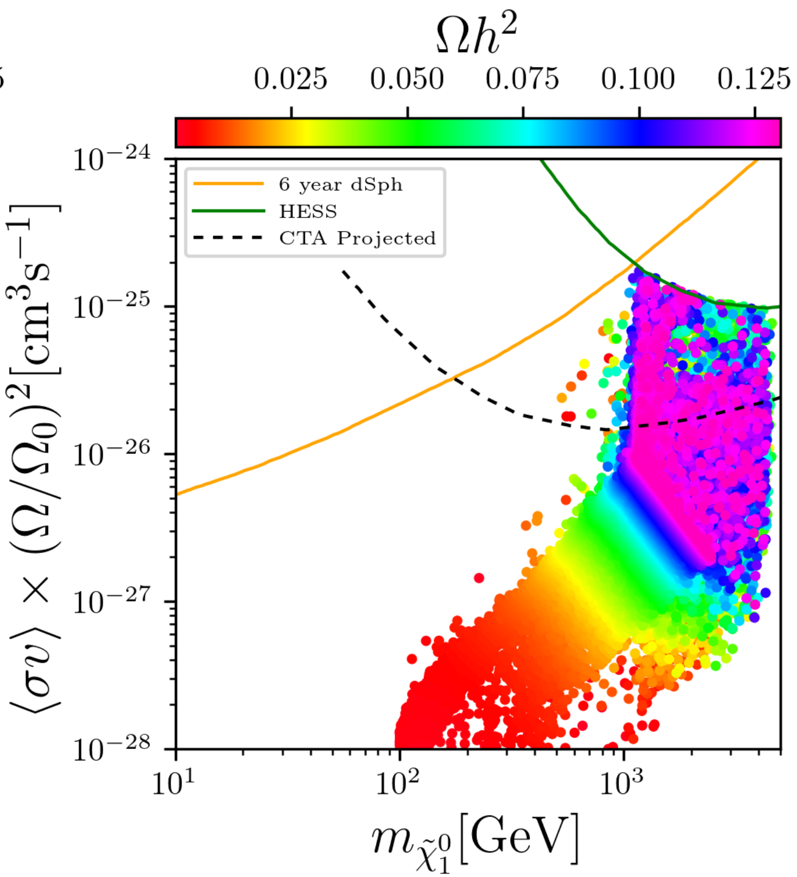


- A distinct region region where higgsino-dominated LSP mass is less than 1300 GeV;
- When the LSP mass is low, the coannihilation process is more efficient, leading to easier annihilation of DM and resulting in an insufficient DM relic density.
- When the LSP mass exceeds 1300 GeV, leading to an excess of DM. At this point, additional funnel annihilation mechanisms are needed to assist in DM annihilation.

Higgsino LSP SI and SD scattering

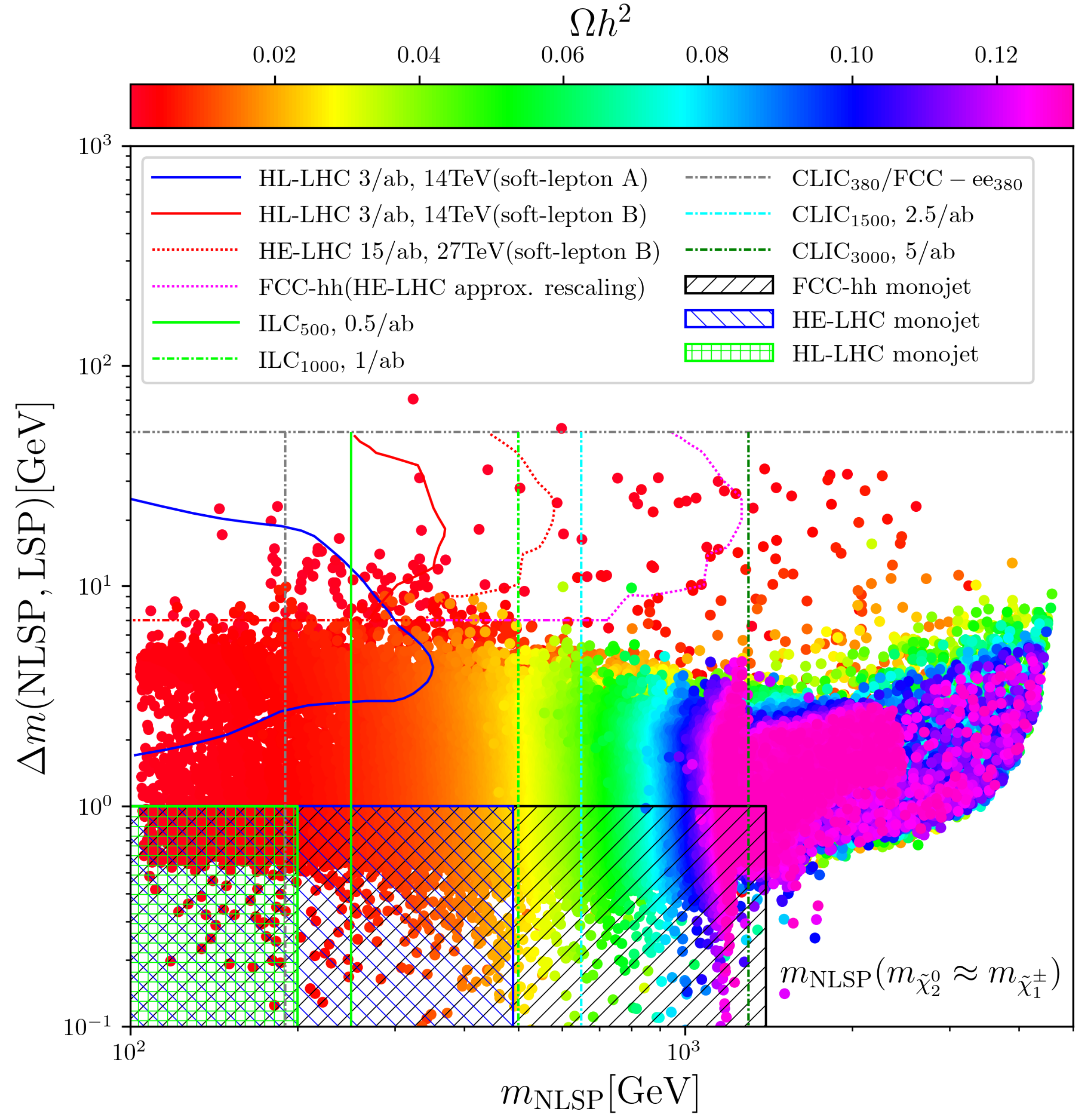


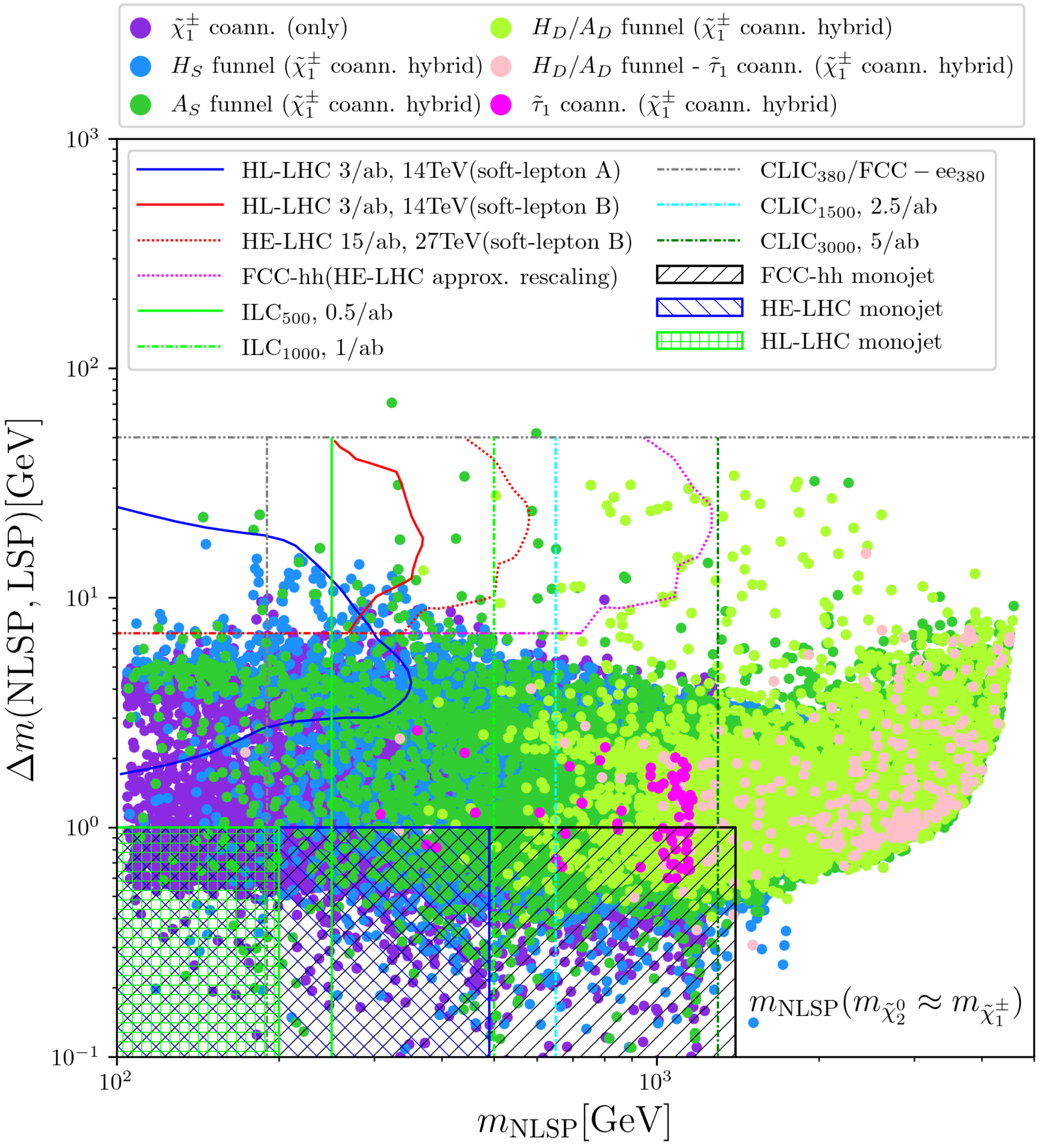




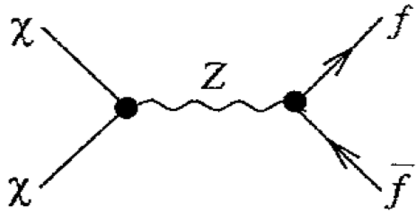
- Samples more easily escape SD constraints; because the higgsino LSP has a very small higgsino asymmetry(SD is proportional to the square of this asymmetry);
- XENONnT (20t.y) and LUX-ZEPLIN (LZ) (1000 day) are expected to cover all samples with the correct DM relic density, PandaXxT(200t.y) will cover nearly all samples.

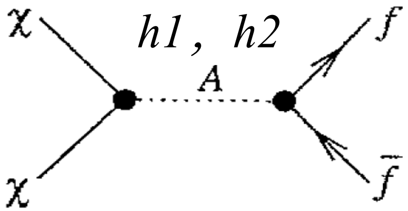
Higgsino LSP at Future Collider





Conclusion





- Singlino LSP :
  - There are 4 funnel-annihilation mechanisms
  - For LSP with right DM relic density, it can be checked by SD experiment
  - For LSP without right DM relic density, it can be checked by CEPC.

- Higgsino LSP:
  - There are 3 mainly annihilation mechanisms：
    - Sole $\chi_1^{\pm}$coannihilation;
    - Higgs funnel annihilation mechanisms alongside $\chi_1^{\pm}$coannihilation
    - $\tilde{\tau}$ coannihilation alongside $\chi_1^{\pm}$coannihilation
  - For LSP with right DM relic density, it can be checked by the upcoming SD experiments, such as XENONnT, LZ (1000 days), and PandaX-xT
  - For LSP without right DM relic density, it can be checked by the CLIC at 3000 GeV.