# SM-like 125 GeV Higgs Boson and Dark Matter in Peccei-Quinn NMSSM

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## Outline

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in the minimal PQ-NMSSM

# Introduction and motivation

Combining SUSY with PQ symmetry has many attractive features:

*** It solves the gauge hierarchy problem and the strong CP problem.**

*** It can solve the mu-problem:** Kim & Nilles (1984)

There can be a close connection between the PQ scale and SUSY breaking scale.

Intermediate PQ scale generated by an interplay between SUSY breaking effects and supersymmetric but Planck-scale (or GUT-scale) suppressed effects:

Murayama, Suzuki & Yanagida (1992)

$$\mathrm{V} = -\mathrm{m}_{\mathrm{soft}}^2 |\mathrm{X}|^2 + \frac{|\mathrm{X}|^6}{\mathrm{M}_{\mathrm{Planck}}^2} \quad \Rightarrow \quad \mathrm{v}_{\mathrm{PQ}} \equiv \langle \mathrm{X} \rangle \sim \sqrt{\mathrm{m}_{\mathrm{soft}} \mathrm{M}_{\mathrm{Planck}}}$$

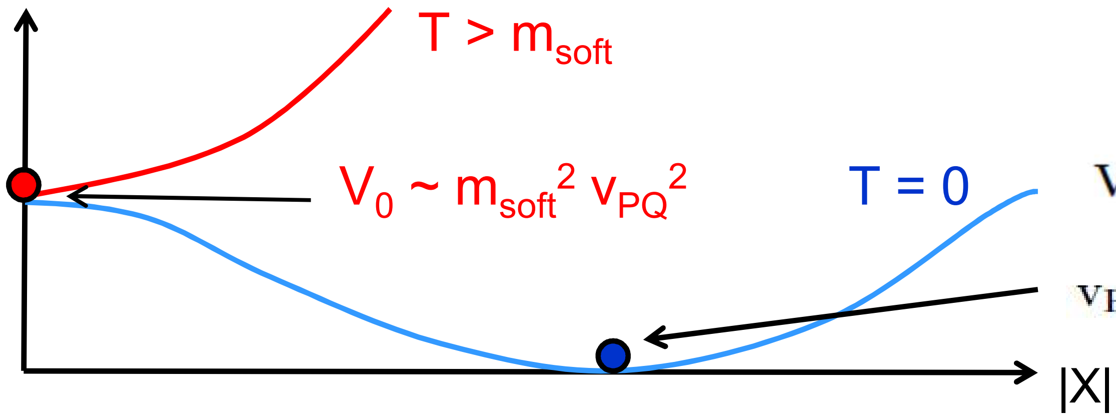
$U(1)_{PQ}$ forbids a bare mu-term, but a correct size of mu can be generated as a consequence of spontaneous PQ breaking:

$$\Delta \mathrm{W} = \frac{\mathrm{X}^2}{\mathrm{M}_{\mathrm{Planck}}} \mathrm{H}_u \mathrm{H}_d \quad \Rightarrow \quad \mu \sim \frac{\mathrm{v}_{\mathrm{PQ}}^2}{\mathrm{M}_{\mathrm{Planck}}} \sim \mathrm{m}_{\mathrm{soft}}$$

* **It provides a natural setup to realize a late thermal inflation which would solve the cosmological moduli problem.**

Lyth & Stewart (1996); KC, Chun & Kim (1997)

Thermal inflation before the PQ phase transition at $\mathbf{T_{PQ} \sim m_{soft}}$




$$V = -m_{soft}^2 |X|^2 + \frac{|X|^6}{M_{Planck}^2}$$

$$v_{PQ} \equiv \langle X \rangle \sim \sqrt{m_{soft} M_{Planck}}$$

* **Rich dark matter candidates: neutralino, axino, axion**

Diverse mechanisms for DM production:

1) Freeze-out of thermal neutralinos

2) Misalignment of axion

3) Dilution or production of DM by out of equilibrium decays of saxions

# PQ-NMSSM

Recent LHC data indicates a SM-like Higgs boson with $m_{higgs}$ ~ 125 GeV.

Although such SM-like Higgs boson can be explained within the MSSM (with multi-TeV stop masses or maximal stop mixing), an interesting alternative is to have an additional singlet S (NMSSM) with

$$\Delta W = \lambda S H_u H_d \quad \rightarrow \quad \Delta V = \lambda^2 |H_u H_d|^2 \quad \rightarrow \quad \Delta m^2_{higgs} = \frac{2\lambda^2 \sin^2 2\beta}{g_1^2 + g_2^2} M_Z^2$$

which is sizable when $\lambda$ is close to its perturbativity bound $\lambda$ = 0.7 - 0.8 , and $\tan\beta$ is small (< 3) .

## PQ-NMSSM:

Models with $\Delta W = \lambda S H_u H_d$ and a PQ symmetry

$$U(1)_{PQ}: \ H_u H_d \to e^{-i\alpha} H_u H_d, \ \ S \to e^{i\alpha} S, \ldots$$

spontaneously broken at $v_{PQ} \sim \sqrt{m_{soft} M_{Planck}}$ (or $(m_{soft} M^n_{Planck})^{1/(n+1)}$) by an interplay between SUSY breaking effects and Planck-scale suppressed effects.

## Low energy effective theory of general PQ-NMSSM:

$$\mathrm{U(1)_{PQ}}: \ \mathrm{A} \to \mathrm{A} + \mathrm{i}\alpha \mathrm{v_{PQ}}, \ \ \mathrm{H_u H_d} \to \mathrm{e}^{-\mathrm{i}\alpha}\mathrm{H_u H_d}, \ \ \mathrm{S} \to \mathrm{e}^{\mathrm{i}\alpha}\mathrm{S}, \ldots$$

$$( \ \mathrm{A} \equiv \text{axion superfield} = \sigma + \mathrm{ia} + \theta\tilde{\mathrm{a}} + \theta^2 \mathrm{F^A} \ )$$

$$\mathrm{K} = \mathrm{K_0}(\mathrm{A} + \mathrm{A}^\dagger) + \sum_\Phi \mathrm{Z}_\Phi(\mathrm{A} + \mathrm{A}^\dagger)\Phi^\dagger\Phi + \Delta\mathrm{K}$$

$$\Delta\mathrm{K} = \tilde{\mu}_4 \mathrm{e}^{\mathrm{A}^\dagger/\mathrm{v_{PQ}}}\mathrm{S} + \kappa_2 \mathrm{e}^{2\mathrm{A}^\dagger/\mathrm{v_{PQ}}}\mathrm{S}^2 + \kappa_3 \mathrm{e}^{-2\mathrm{A}^\dagger/\mathrm{v_{PQ}}}\mathrm{H_u H_d} + \ldots + \mathrm{h.c.}$$

$$\mathrm{W} = \lambda \mathrm{S H_u H_d} + \mathrm{y_U H_u Q U^c} + \mathrm{y_D H_d Q D^c} + \mathrm{y_L H_d L E^c} + \Delta\mathrm{W}$$

$$\Delta\mathrm{W} = \tilde{\mu}_\mathrm{i}^2 \mathrm{e}^{-\mathrm{A}/\mathrm{v_{PQ}}}\mathrm{S} + \tilde{\mu}_2 \mathrm{e}^{-2\mathrm{A}/\mathrm{v_{PQ}}}\mathrm{S}^2 + \tilde{\mu}_3 \mathrm{e}^{2\mathrm{A}/\mathrm{v_{PQ}}}\mathrm{H_u H_d} + \kappa_1 \mathrm{e}^{-3\mathrm{A}/\mathrm{v_{PQ}}}\mathrm{S}^3 + \ldots$$

Generically $\tilde{\mu}_\mathrm{i} \sim \mathrm{v_{PQ}}\left(\frac{\mathrm{v_{PQ}}}{\mathrm{M_{Planck}}}\right)^{\mathrm{n_i}}, \qquad \kappa_\mathrm{i} \sim \left(\frac{\mathrm{v_{PQ}}}{\mathrm{M_{Planck}}}\right)^{\mathrm{k_i}} \qquad (\mathrm{n_i}, \mathrm{k_i} \geq 1)$

➔ $|\kappa_\mathrm{i}| \sim 0$

$\mathrm{Max}\,(\tilde{\mu}_\mathrm{i}) \sim \mathrm{m_{soft}}$

For low energy particle phenomenology, one can replace the axion-superfield by its VEV: $A = \langle A \rangle = \mathcal{O}(m_{soft} v_{PQ} \theta^2)$

After an appropriate field redefinition $S \to S + \mu_0 + b_0 \theta^2$ , low energy effective theory of general PQ-NMSSM (with $A = \langle A \rangle$) takes the form:

$$K_{eff} = \sum_{\Phi} (1 - m_\Phi^2 \theta^2 \bar{\theta}^2) \Phi^\dagger \Phi$$

$$\begin{aligned} W_{eff} &= \lambda (1 + A_\lambda \theta^2) S H_u H_d + \mu_1^2 (1 + B_1 \theta^2) S + \frac{1}{2} \mu_2 (1 + B_2 \theta^2) S^2 \\ &+ y_U (1 + A_U \theta^2) H_u Q U^c + y_D (1 + A_D \theta^2) H_d Q D^c + y_L (1 + A_L \theta^2) H_d L E^c \end{aligned}$$

Three possibilities:

1) $\mu_1 \sim m_{soft}, \quad \mu_2 \sim m_{soft} (v_{PQ}/M_{Planck})^k \sim 0$

(nMSSM: Panagiotakopoulos & Tamvakis; Panagiotakopoulos & Pilaftsis; Dedes et al; Menon et al; Kang et al; Barger et al; Balazs et. al, … )

2) $\mu_1 \sim \mu_2 \sim m_{soft}$ (S-MSSM: Delgado et al )

3) $\mu_2 \sim m_{soft}, \quad \mu_1 \sim m_{soft} (v_{PQ}/M_{Planck})^k \sim 0$

It is straightforward to construct an explicit PQ sector which gives each of these models in the low energy limit, but the following model giving the first type low energy theory (nMSSM) is the simplest.

(Other models require more PQ-sector fields and/or additional symmetry.)

**Minimal PQ-NMSSM:**

* PQ charges: $(S, H_uH_d, X, Y) = (1, -1, 1/2, -1/6)$

* PQ-invariant Kahler potential and superpotential:

$$K = \sum_\Phi \Phi^*\Phi + \frac{1}{M_{\rm Planck}} X^2 S^* + \frac{1}{M_{\rm Planck}^4} X^4 S^{*2} + \ldots$$

$$W = \lambda S H_u H_d + \frac{1}{M_{\rm Planck}} X^2 H_u H_d + \frac{1}{M_{\rm Planck}} X Y^3 + \ldots$$

➔ $$v_{PQ} \sim \langle X \rangle \sim \langle Y \rangle \sim \sqrt{m_{\rm soft} M_{\rm Planck}} \quad , \quad \frac{F^X}{X} \sim \frac{F^Y}{Y} \sim m_{\rm soft}$$

➔ $$W_{\rm eff} = \lambda S H_u H_d + \mu_1^2 S + \frac{1}{2}\mu_2 S^2 + \ldots$$

$$\mu_1 \sim \frac{v_{PQ}^2}{M_{\rm Planck}} \sim m_{\rm soft} \qquad \mu_2 \sim m_{\rm soft}\left(\frac{v_{PQ}}{M_{\rm Planck}}\right)^4 \sim 0$$

(Similar models: Jeong, Shoji & Yamaguchi, arXiv:1112.101; Kim, Nilles & Seo, arXiv:1201.6547)

## SM-like 125 GeV Higgs boson and DM in the minimal PQ-NMSSM:

Effective theory for low energy particle physics (= nMSSM)

$$K_{\rm eff} = \sum_{\Phi}(1 - m_{\Phi}^2\theta^2\bar{\theta}^2)\Phi^*\Phi$$

$$W_{\rm eff} = \lambda(1 + A_\lambda\theta^2)SH_uH_d + \mu_1^2(1 + B_1\theta^2)S + \ldots$$

(The axion multiplet (= axino, saxion, axion) can play an important role in cosmology, e.g. for the DM aspects of the model.)

EWSB: $\frac{1}{2}M_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} - \mu_{\rm eff}^2 \qquad \sin 2\beta = \frac{2b_{\rm eff}}{2\mu_{\rm eff}^2 + m_{H_u}^2 + m_{H_d}^2 + \lambda^2 v^2}$

$$\langle S\rangle = \frac{\lambda A_\lambda v^2 \sin 2\beta + 2\mu_1^2 B_1}{2(m_S^2 + \lambda^2 v^2)}$$

$$v = \sqrt{v_u^2 + v_d^2} = 174\ {\rm GeV}, \quad \tan\beta = v_u/v_d$$

$$\mu_{\rm eff} = \lambda\langle S\rangle, \quad b_{\rm eff} = \mu_{\rm eff}A_\lambda + \lambda\mu_1^2$$

An important feature of the model: light singlino-like neutralino

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix}$$

➔

$$\mathrm{m}_{\tilde{\chi}^0_1} = \frac{\lambda^2 \mathrm{v}^2 \mu_{\rm eff} \sin 2\beta}{\mu_{\rm eff}^2 + \lambda^2 \mathrm{v}^2} - \mathcal{O}\left(\frac{\mathrm{g}^2 \mathrm{v}^2 \lambda^2 \mathrm{v}^2 \cos^2 2\beta}{\mu_{\rm eff}^2 \mathrm{M}_{\tilde{\mathrm{B}},\tilde{\mathrm{W}}}}\right)$$

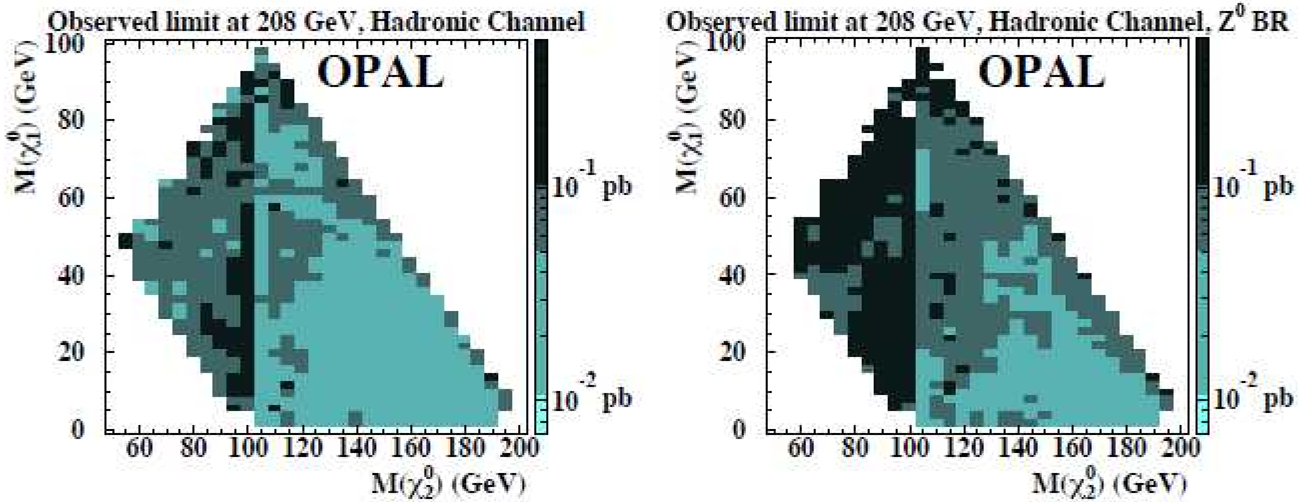
$$< \lambda \mathrm{v} \cos\beta = 86 \left(\frac{\lambda}{0.7}\right) \left(\frac{2}{1+\tan^2\beta}\right)^{1/2} \mathrm{GeV}$$

➔ Under the perturbativity bound $\lambda \leq 0.7 - 0.8$ (perturbative at least up to $\mathbf{v_{PQ}}$ ), the lightest neutralino mass is lighter than $\frac{1}{2}\mathrm{m}_{\rm higgs} \simeq 62\ \mathrm{GeV}$ in most of the parameter space.

(Lightest neutralino can be heavier than 62 GeV only for a narrow range of small $\tan\beta \leq 1.5 - 1.7$ and relatively light $\mu_{\rm eff}$.)

## Phenomenological constraints on light neutralinos:

* $m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} < 208\ \mathrm{GeV}: \quad \sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0) < \mathcal{O}(10-100)\ \mathrm{fb}$




(a) $\chi_2 \to q\bar{q}\chi_1$ (b) $\chi_2 \to Z^*\chi_1$

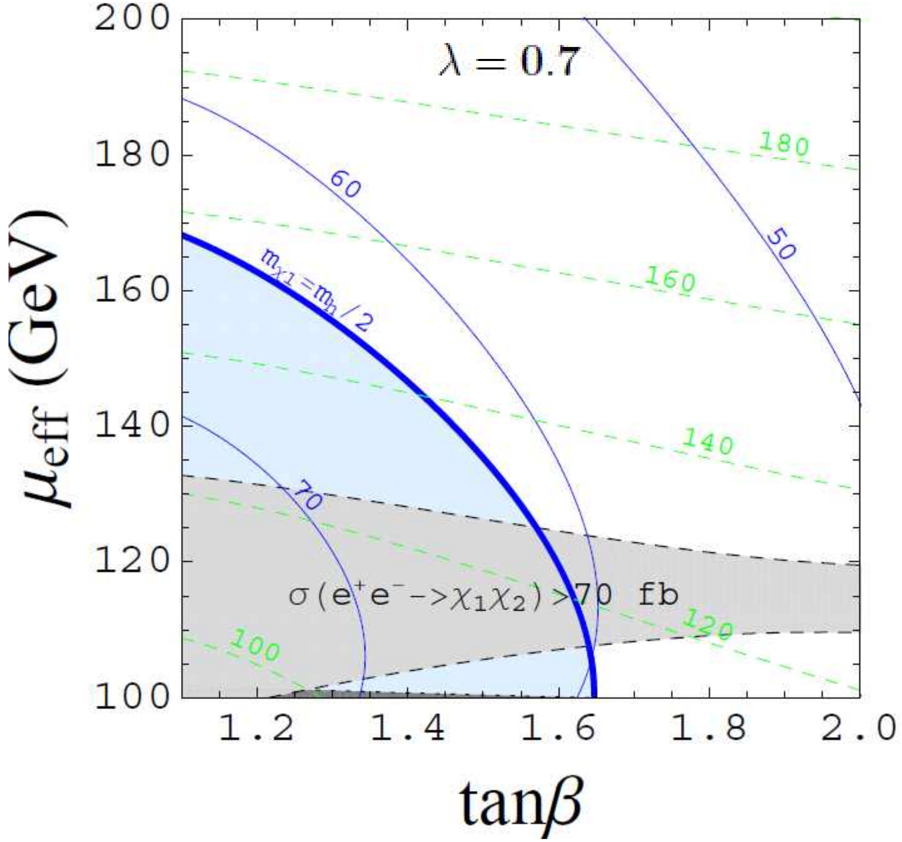
* $m_{\tilde{\chi}_1^0} < \frac{m_{\mathrm{higgs}}}{2} \simeq 62\ \mathrm{GeV}: \quad g_{h_1\tilde{\chi}_1\tilde{\chi}_1} \simeq 0$ for $h_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ to be a subdominant decay mode.

* $m_{\tilde{\chi}_1^0} < \frac{M_Z}{2}: \quad \Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 3\ \mathrm{MeV}$

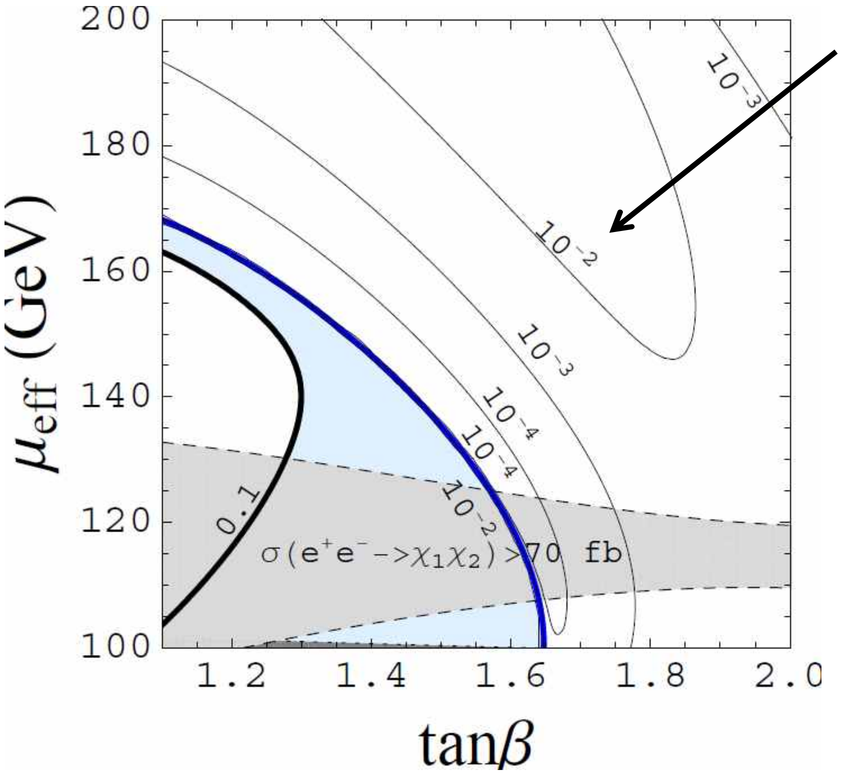
**A) Lightest neutralino heavier than** $\frac{1}{2}\mathrm{m_{higgs}} \simeq 62\ \mathrm{GeV}$

$$\frac{\mathrm{m_{higgs}}}{2} < \mathrm{m}_{\tilde{\chi}_1^0} < 86\left(\frac{\lambda}{0.7}\right)\left(\frac{2}{1+\tan^2\beta}\right)^{1/2}\mathrm{GeV}$$

Possible only for small $\tan\beta \leq 1.5 - 1.7$ and relatively light $\mu_{\mathrm{eff}}$ .



Relic mass density of thermal LSP neutralino for $m_{\tilde{\chi}_1^0} > \frac{1}{2} m_{\rm higgs} \simeq 62\ \mathrm{GeV}$




$\Omega_\chi h^2$

* Lightest neutralino can be a good DM candidate:

Sizable Higgsino component, so has a direct detection cross section close to the present bound (XENON 100):

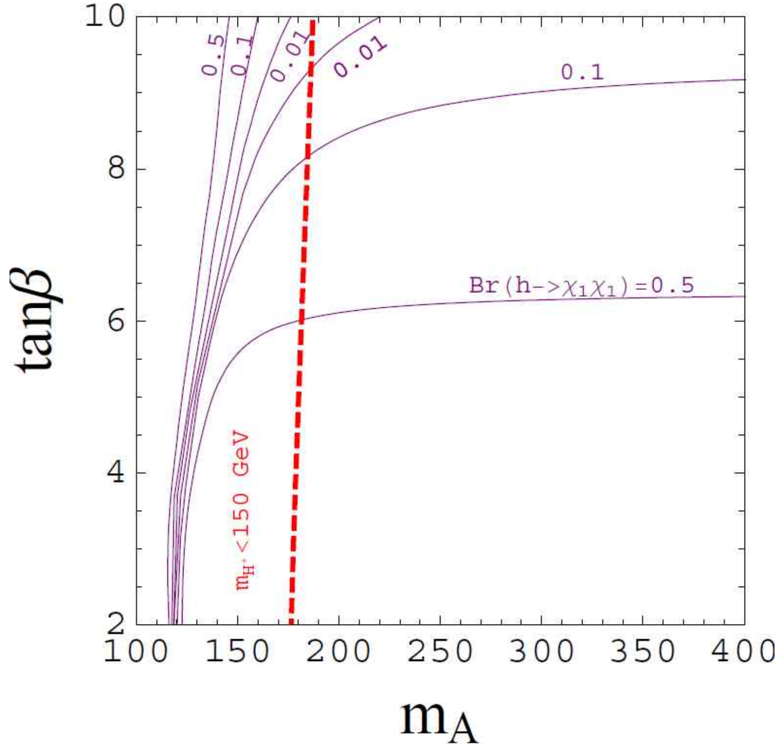
$$\tilde{\chi}_1^0 \simeq 0.8\tilde{S} + 0.5\tilde{H}_u + 0.2\tilde{H}_d$$

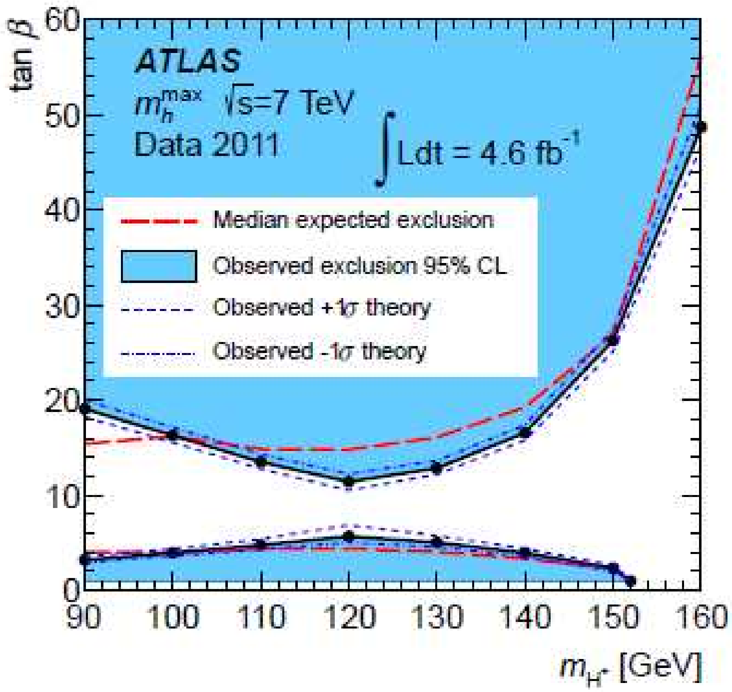
$$\sigma_{N\tilde{\chi}_1} \sim 10^{-8}\ \mathrm{pb}$$

* $\Omega_{\rm DM} h^2 \simeq 0.1$ can be achieved for the whole light blue colored region with axion DM and/or by out of equilibrium decays of saxion (or axino) into neutralinos.

**B)** $m_{\tilde{\chi}_1^0}$ **<** $\frac{1}{2}m_{higgs} \simeq 62\ \mathrm{GeV}$**, but still** $\tan\beta$ **< 3 and** $\lambda \simeq 0.7 - 0.8$ **,**

**so** $\Delta m^2_{higgs} = \frac{2\lambda^2 \sin^2 2\beta}{g_1^2 + g_2^2} M_Z^2$ **is sizable.**




Either a too large $\mathrm{Br}(h_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ or a too light charged Higgs boson.

C) $m_{\tilde{\chi}_1^0}$ << $\frac{1}{2} m_{\rm higgs} \simeq 62$ GeV

To suppress $\mathrm{Br}(h_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ without an unnatural cancellation, we need a relatively light $m_{\tilde{\chi}_1^0}$ < 5 GeV, which can be obtained naturally in the limit

$$\lambda \ll 1 \quad \text{and/or} \quad \tan\beta \gg 1 \quad \text{and/or} \quad \mu_{\rm eff} \gg M_Z$$

$$\Rightarrow \quad m_{\tilde{\chi}_1^0} \simeq \frac{2\lambda^2 v^2}{\mu_{\rm eff}} \frac{1}{\tan\beta}, \qquad g_{h_1 \tilde{\chi}_1 \tilde{\chi}_1} = \mathcal{O}\left(\frac{m_{\tilde{\chi}_1^0}}{v}\right), \qquad g_{Z \tilde{\chi}_1 \tilde{\chi}_1} \simeq \frac{g \tan\beta}{4 \cos\theta_W} \left(\frac{m_{\tilde{\chi}_1^0}}{\mu_{\rm eff}}\right)$$

In this limit, $\Delta m^2_{\rm higgs} = \frac{2\lambda^2 \sin^2 2\beta}{g_1^2 + g_2^2} M_Z^2$ is negligible, but a very light neutralino LSP can have an interesting implication for collider signatures:

SUSY events with softer MET and longer cascade decays,

displaced vertex, …

In this case, major constraint comes from the relic neutralino mass density which is too large for 100 eV << $m_{\tilde{\chi}_1^0}$ < 5 GeV:

Cold relic: $\Omega_\chi^{TH} h^2 \sim 20 \left(\frac{5\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^2 \left(\frac{0.05}{g_{Z\tilde{\chi}_1\tilde{\chi}_1}}\right)^2 \quad \mathrm{for}\ m_{\tilde{\chi}_1^0} \gg 10^2\ \mathrm{MeV}$

Hot relic: $\Omega_\chi^{TH} h^2 \sim 0.1 \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{eV}}\right) \left(\frac{100}{g_*(T_f)}\right) \quad \mathrm{for}\ m_{\tilde{\chi}_1^0} \ll 10^2\ \mathrm{MeV}$

**Several options to avoid a too large DM density:**

1) Very light $m_{\tilde{\chi}_1^0} \leq \mathcal{O}(100)\ \mathrm{eV}$ with $\lambda \leq 10^{-4}$

2) For $m_{\tilde{\chi}_1^0} \leq \mathcal{O}(10)\ \mathrm{MeV}$, $\Omega_\chi^{TH}$ (and $\Omega_a$ also) can be diluted enough by out of equilibrium decays of saxions with

$$T_{TH} \sim 700 \left(\frac{m_\sigma}{300\ \mathrm{GeV}}\right)^{3/2} \left(\frac{10^{12}\ \mathrm{GeV}}{v_{PQ}}\right) \mathrm{MeV} < \mathrm{O}(100)\ \mathrm{MeV}.$$

$$10\ \mathrm{MeV} < T_{RH} < \mathcal{O}(100)\ \mathrm{MeV} \quad \mathrm{for}\ v_{PQ} = 10^{13} - 14\ \mathrm{GeV}$$

$$v_{PQ} \sim (m_{soft} M_{Planck}^n)^{1/(n+1)} \sim 10^{13} - 10^{14}\ \mathrm{GeV} \quad \mathrm{for}\ n = 2$$

There are a variety of ways to get

$$\Omega_{\mathrm{DM}}\mathrm{h}^2 = \Omega_\chi^{\mathrm{TH}}\mathrm{h}^2 + \Omega_\chi^{\mathrm{NTH}}\mathrm{h}^2 + \Omega_{\mathrm{a}}\mathrm{h}^2 \simeq 0.1$$

with

$$\Omega_\chi^{\mathrm{TH}}\mathrm{h}^2 \sim 3\times10^{-2}\left(\frac{\mathrm{m}_{\tilde{\chi}_1^0}}{10\ \mathrm{MeV}}\right)\left(\frac{1\ \mathrm{GeV}}{\mathrm{T_f}}\right)^5\left(\frac{\mathrm{T_{RH}}}{100\ \mathrm{MeV}}\right)^5$$

$$(\ \mathrm{T_f} \geq 1\ \mathrm{GeV} \quad \text{for } \mathrm{m}_{\tilde{\chi}_1^0} < 10\ \mathrm{MeV}\ )$$

$$\Omega_\chi^{\mathrm{NTH}}\mathrm{h}^2 \sim 8\times10^{-3}\left(\frac{300\ \mathrm{GeV}}{\mathrm{m}_\sigma}\right)^5\left(\frac{\mathrm{m}_{\tilde{\chi}_1^0}}{10\ \mathrm{MeV}}\right)^3\left(\frac{\mathrm{T_{RH}}}{100\ \mathrm{MeV}}\right)$$

$$\Omega_{\mathrm{a}}\mathrm{h}^2 \sim 3\times10^{-2}\left(\frac{\mathrm{T_{RH}}}{100\ \mathrm{MeV}}\right)^2\left(\frac{\mathrm{v_{PQ}}}{10^{12}\ \mathrm{GeV}}\right)^{1.5}\delta\theta^2$$

## Summary

1) PQ-NMSSM is an attractive extension of the MSSM:

* It can solve the many problems altogether: gauge hierarchy problem, strong CP problem, mu-problem, cosmological moduli problem.
* It involves rich DM candidates, and can realize diverse DM production mechanism.
* There is additional source of the Higgs boson mass which might be useful to have $m_{higgs}$ ~ 125 GeV.

2) Minimal PQ-NMSSM provides a simple UV completion of nMSSM, and can accommodate a SM-like 125 GeV Higgs boson with correct amount of DM in the two interesting corners of the parameter space:

(a) $\tan\beta \sim 1.3 - 1.5, \quad \mu_{\rm eff} \sim 130 - 150 \ {\rm GeV}, \quad \lambda \sim 0.7$

➔ Mixed singlino-Higgsino DM with $\mathrm{m}_{\tilde{\chi}_1^0} \sim 65 \ \mathrm{GeV}, \quad \sigma_{\mathrm{N}\tilde{\chi}_1} \sim 10^{-8} \, \mathrm{pb}$

(b) Very light singlino LSP with $\mathrm{m}_{\tilde{\chi}_1^0} \leq \mathcal{O}(10) \ \mathrm{MeV}$