SUSY μ term from Radiative Breaking of Peccei-Quinn Symmetry

→ *Natural Little Hierarchy*

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based on the paper : "*Natural Little Hierarchy for SUSY from radiative breaking of the Peccei-Quinn symmetry" Phys. Rev. D 91, 015003 (2015) with Kyu Jung Bae and Howard Baer* **(arxiv:1410.7500).**

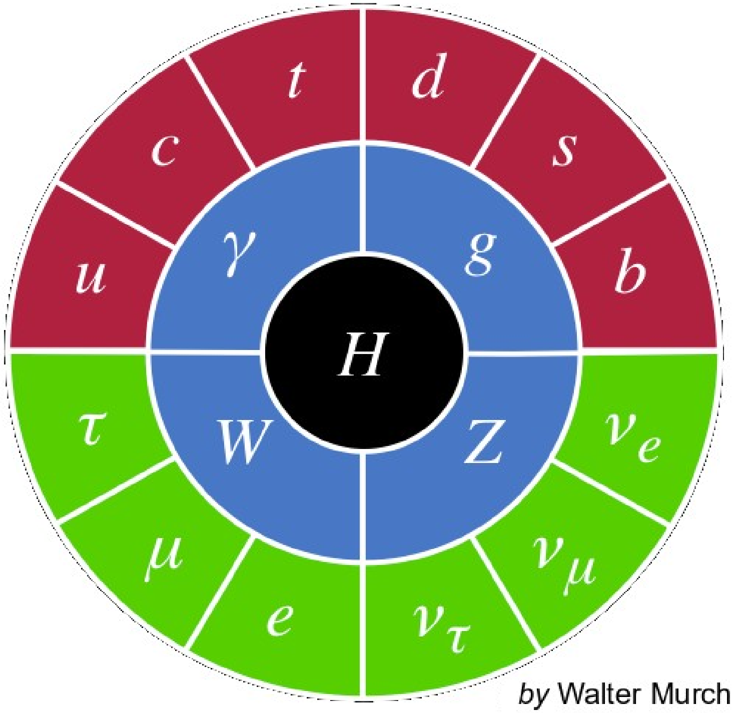
Standard Model *and beyond*

$m_h \sim 125$ GeV → SM ✔ & SUSY 🏋

... but no sign of SUSY at the LHC (yet).

$m_{sparticles} \geq$ TeV where $m_{sparticles} \sim m_{3/2}$ (in gravity mediation)

$\sim m^2_{hidden} / M_P$



by Walter Murch & Kyle Kranmer

In spite of large m_h and LHC sparticle limits, SUSY can still be *natural:*

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$
$$\simeq -m_{H_u}^2 - \mu^2$$

→ m^2_{Hu} driven to $\sim (-m^2_Z)$

→ $\mu \sim$ 100-200 GeV and $m_{sparticles} \sim$ TeV

apparent Little Hierarchy:

$\mu \ll m_{3/2} \sim$ multi-TeV (LHC bounds)

SUSY μ Problem

- the problem:

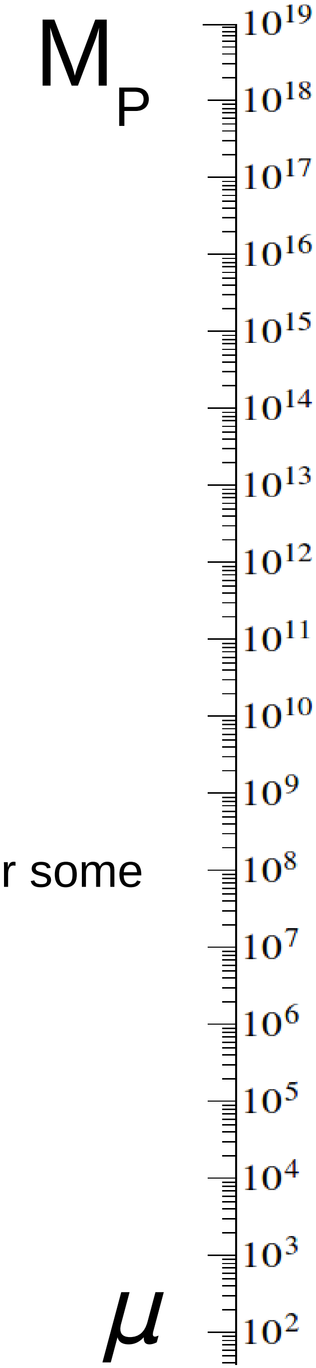
  μ is supersymmetric so one expects it to be at the order of Planck scale

  $$W_{MSSM} \ni \mu H_u H_d \rightarrow \mu \sim M_P$$

  But phenomenology ($m^2_Z \sim -2\mu - 2m^2_{Hu}$) requires $\mu \sim$ 100-200 GeV.

- the solution:

  Step 1: Forbid μ via some symmetry.
  Step 2: Regenerate μ via coupling to some field which acquires a vev under some symmetry breaking.



Solutions to μ Problem:

1. NMSSM

$$W_{\text{NMSSM}} \ni \lambda_S S H_u H_d$$

superfield, S develops vev <S> ~ $m_{3/2}$ → $\mu \sim \lambda_S m_{3/2}$
problem with gauge singlets (see Supersymmetry Primer by S.P. Martin).

2. Guidice-Masiero

$\mu \sim m_{3/2}$

Some (unknown) symmetry forbids μ but Higgs doublets coupled to a hidden sector field, h :

$$K \ni \lambda h H_u H_d / M_P$$

field h develops vev <h> ~ m^2_{hidden} where m^2_{hidden} is hidden sector mass parameter with $m^2_{hidden} \sim m_{3/2} \times M_{Pl}$ → $\mu \sim \lambda\, m_{3/2}$

3. Kim-Nilles (SUSY DFSZ)

PQ symmetry forbids μ but Higgs doublets carry PQ charges and coupled to a PQ charged superfield P*:*

$$W_{DFSZ} = \lambda_H (P^2/M_P) H_u H_d, \qquad W_{PQ} = \lambda_S S(PQ - v^2_{PQ}/2) H_u H_d$$

under PQ symmetry breaking P and Q receives a vev ~ $v_{PQ}/\sqrt{2}$ → $\mu = \lambda_H v^2_{PQ}/2M_P$

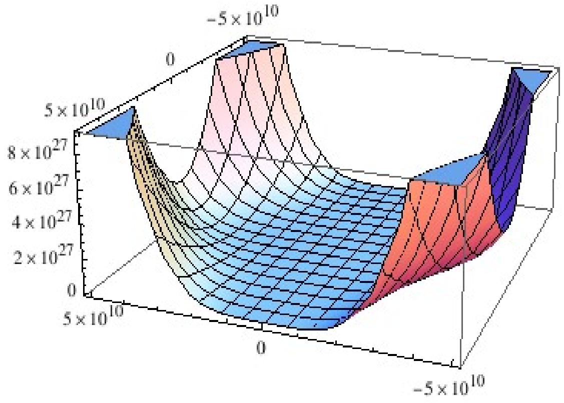
MSY Model

H. Murayama, H. Suzuki and T. Yanagida
Phys.Lett. B291 (1992) 418-425

→ a DFSZ-like SUSY axion model with radiatively broken PQ Symmetry.

augment MSSM superpotential with PQ charged fields X, Y :

$$\hat{f}' = \frac{1}{2}h_{ij}\hat{X}\hat{N}_i^c\hat{N}_j^c + \frac{f}{M_P}\hat{X}^3\hat{Y} + \frac{g}{M_P}\hat{X}\hat{Y}\hat{H}_u\hat{H}_d$$



the relevant part of scalar potential is: $V_F \ni \frac{|f|^2}{M_P^2}|\phi_X^3|^2 + \frac{9|f|^2}{M_P^2}|\phi_X^2\phi_Y|^2$

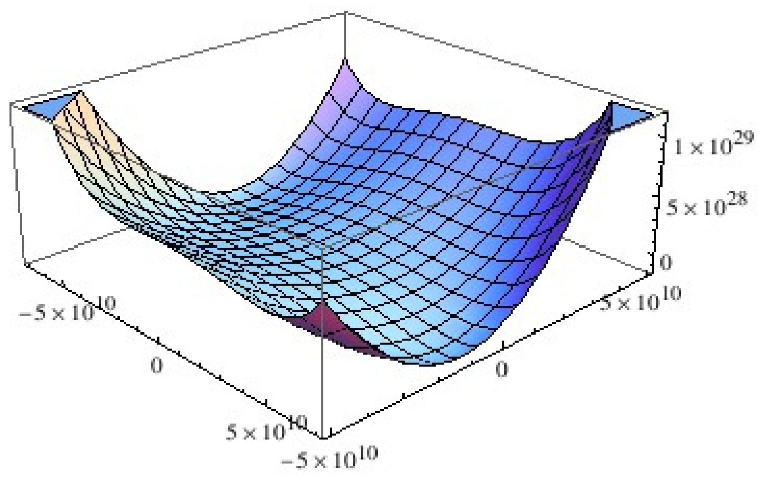
(very flat)

corresponding soft SUSY breaking terms are given by :

$$\begin{aligned} V_{\rm soft} &= m_X^2|\phi_X|^2 + m_Y^2|\phi_Y|^2 + m_{N_i^c}^2|\phi_{N_i^c}|^2 \\ &+ \left(\frac{1}{2}h_i A_i \phi_{N_i^c}^2\phi_X + \frac{f}{M_P}A_f\phi_X^3\phi_Y + \frac{g}{M_P}A_g H_u H_d \phi_X\phi_Y + h.c.\right) \end{aligned}$$

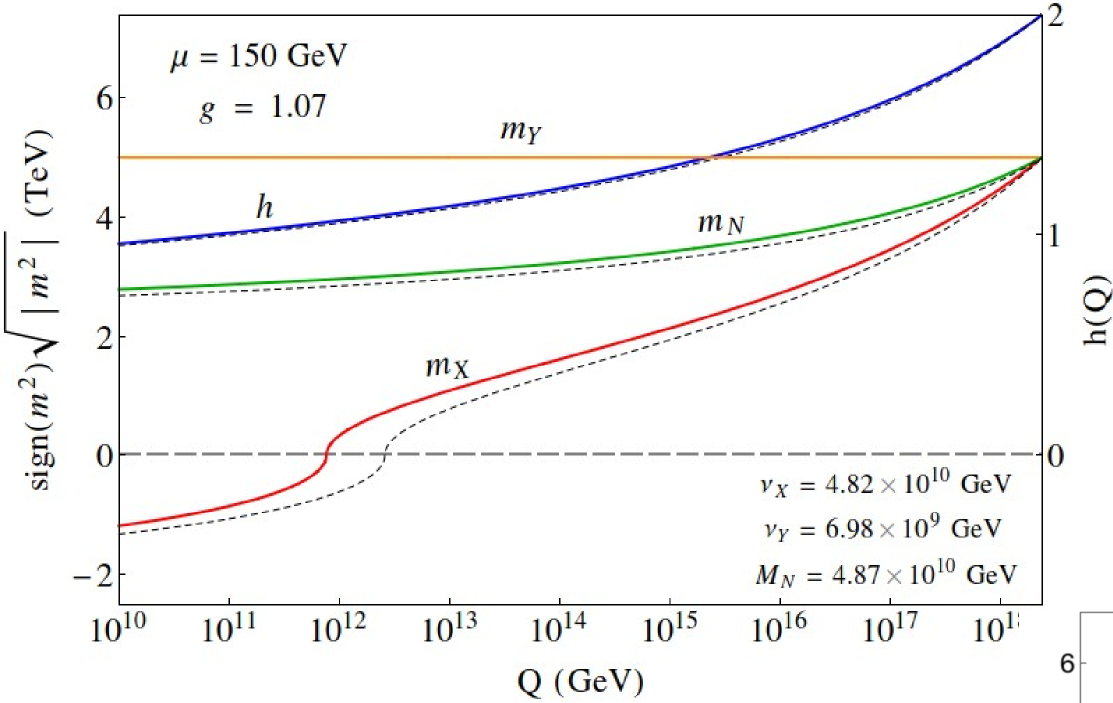
minimize V at a scale Q = v_{PQ} to find vevs of Φ_X and Φ_Y

$$\begin{aligned} 0 &= \frac{9|f|^2}{M_P^2}|v_X^2|^2 v_Y + f^*\frac{A_f^*}{M_P}v_X^{*3} + m_Y^2 v_Y \\ 0 &= \frac{3|f|^2}{M_P^2}|v_X^2|^2 v_X + \frac{18|f|^2}{M_P^2}|v_X|^2|v_Y|^2 v_X + 3f^*\frac{A_f^*}{M_P}v_X^{*2}v_Y^* + m_X^2 v_X \end{aligned}$$



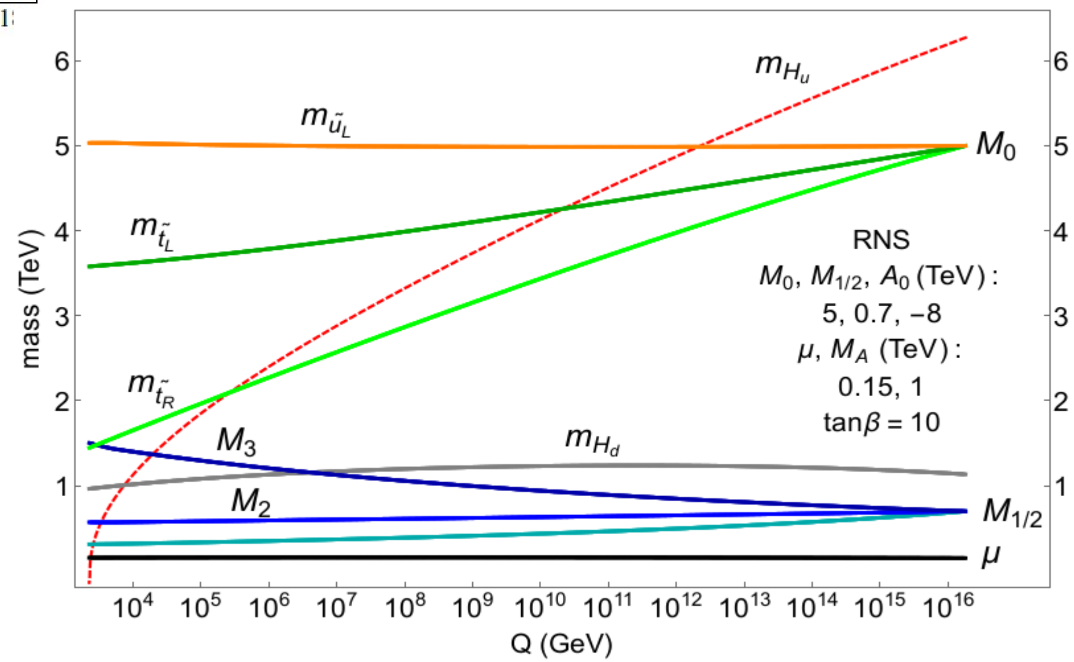
Phys. Rev. D 91, 015003 (2015)
(K.J.Bae,H.Baer,H.**Serce**)

Breaking Symmetry *Radiatively*



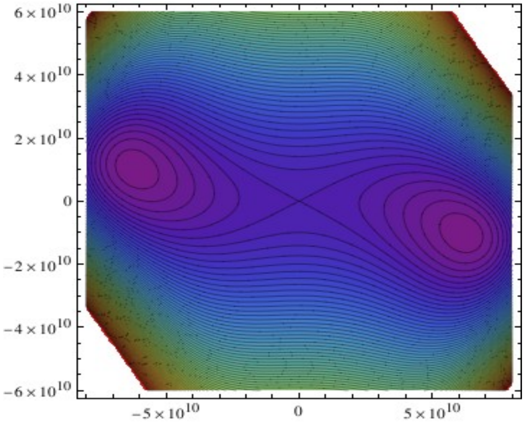
Breaking PQ Symmetry (MSY)

EW Symmetry Breaking



Breaking PQ Symmetry (MSY)

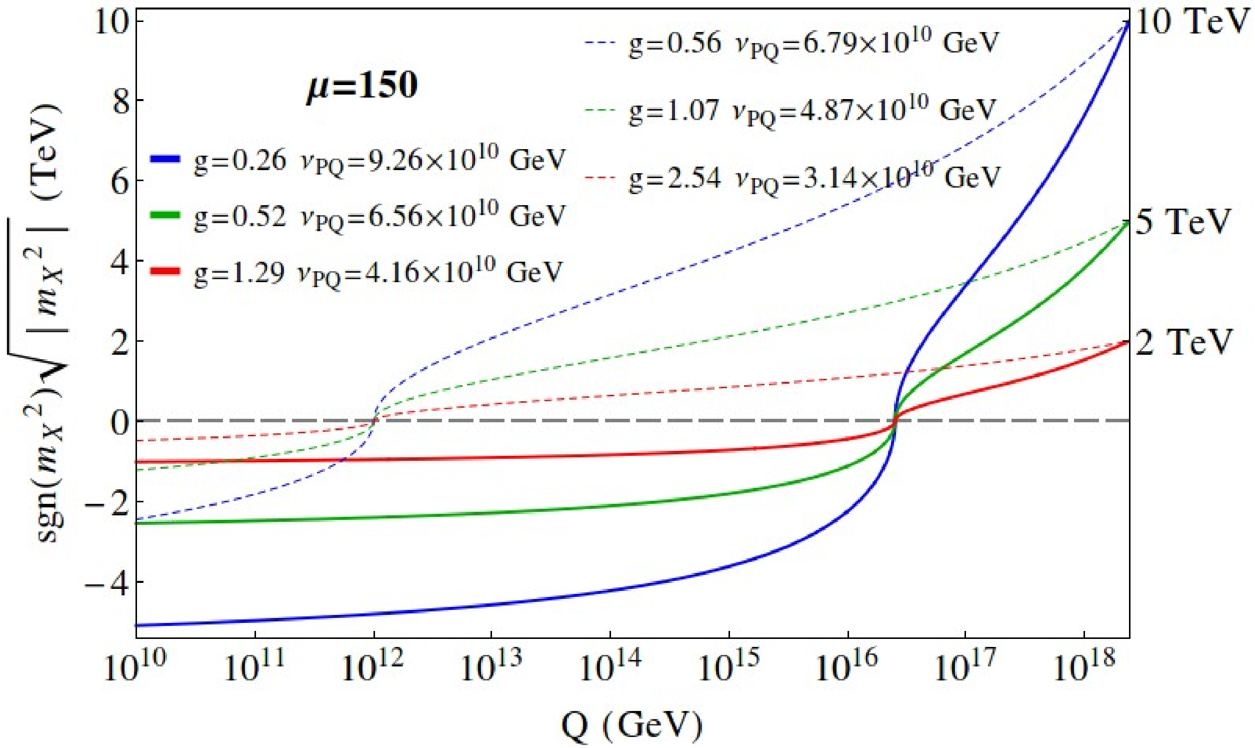
The potential has 2 minima on ν_X - ν_Y plane symmetrically located with respect to origin. Majorana neutrino mass term and SUSY μ term generated upon symmetry breaking:



$$\mu = g\frac{v_X v_Y}{M_P} \qquad M_{N_i^c} = v_X\, h_i|_{Q=v_X}$$

what to expect for the scale of g ?

→ unity: g ~ 1 for $m_{3/2}$ ~ TeV and μ ~100-200 GeV as required by naturalness so that Little Hierarchy μ << $m_{3/2}$ emerges from MSY.



Phys. Rev. D 91, 015003 (2015)
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h_i vs $m_{3/2}$ Plane

$$\hat{f}' = \frac{1}{2} h_{ij} \hat{X} \hat{N}_i^c \hat{N}_j^c + \frac{f}{M_P} \hat{X}^3 \hat{Y} + \frac{g}{M_P} \hat{X} \hat{Y} \hat{H}_u \hat{H}_d$$

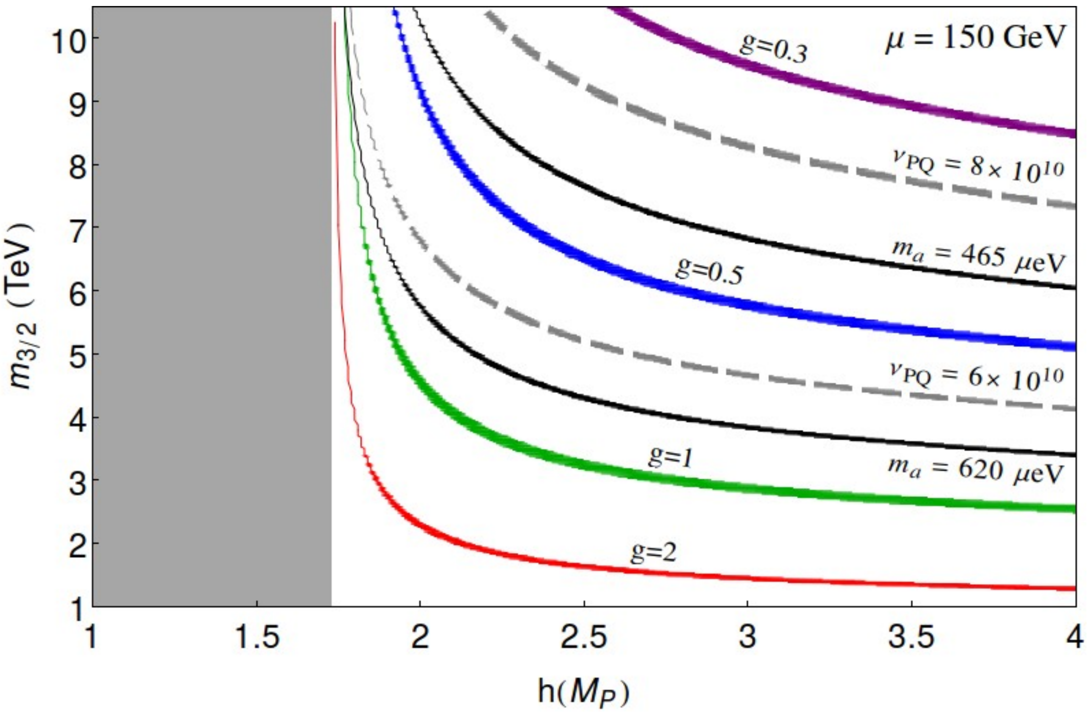
$$M_{N_i^c} = v_X \, h_i|_{Q=v_X} \qquad \mu = g \frac{v_X v_Y}{M_P}$$

$f_a = \sqrt{(v_x^2 + 9v_y^2)} \rightarrow 3.7\times10^{10} \leq f_a \leq 1.1\times10^{11}$

$v_{PQ} = \sqrt{(v_x^2 + v_y^2)} \rightarrow 3.4\times10^{10} \leq v_{PQ} \leq 9.4\times10^{10}$

$M_N \sim 10^{10\text{-}11}$ GeV

$m_a \sim 620\mu\text{eV}\,(10^{10}\ \text{GeV}/(f_a/N_{DW}))$



- Since f_a determines axion mass, m_a related to higgsino mass !

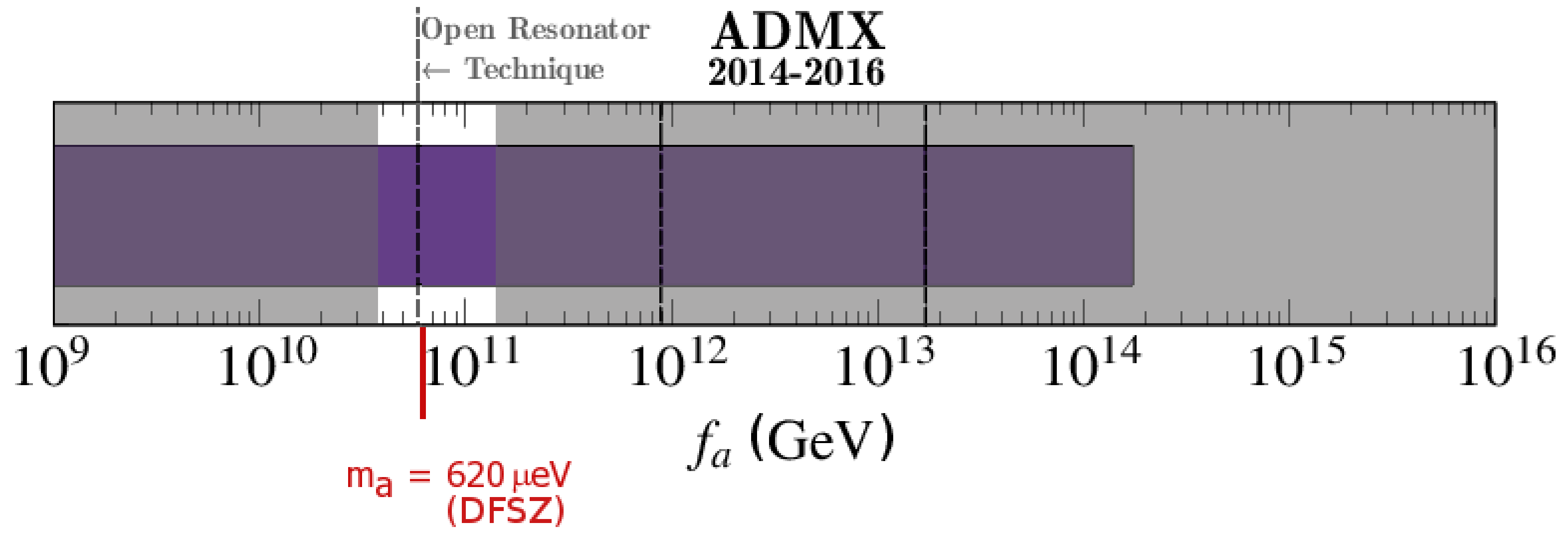
- Large values of g > 1 are required for rather low values of $m_{3/2}$ ~ 2 TeV.

- For higher values of $m_{3/2} \geq 5$ TeV as favored by gravitino problem, then typically g ~ 0.5 is required to generate the Little Hierarchy.

Axion Search - ADMX II

ADMX-II 2016 reach: m_a ~ 40 μeV [1]

Open resonator technique expected sensitivity: m_a ~ 700 μeV [2]



[1] Status of the Axion Dark Matter Experiment (ADMX) L. Rosenberg Talk at the Patras Workshop at CERN (2014)

[2] Phys. Rev. D. 91, 011701(R) (2015) (G.Rybka, A.Wagner, K.Patel, R.Percival, K.Ramos)

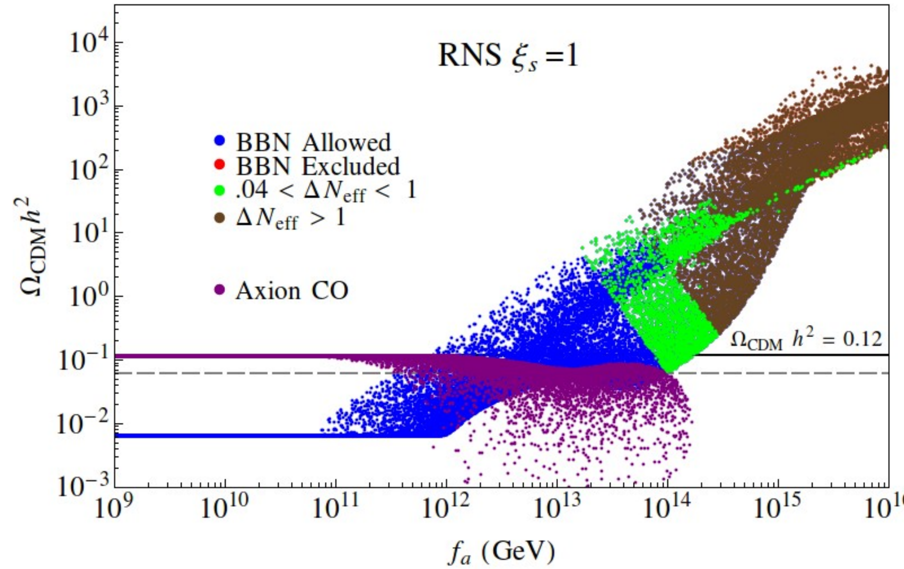
DM from EW and QCD Naturalness

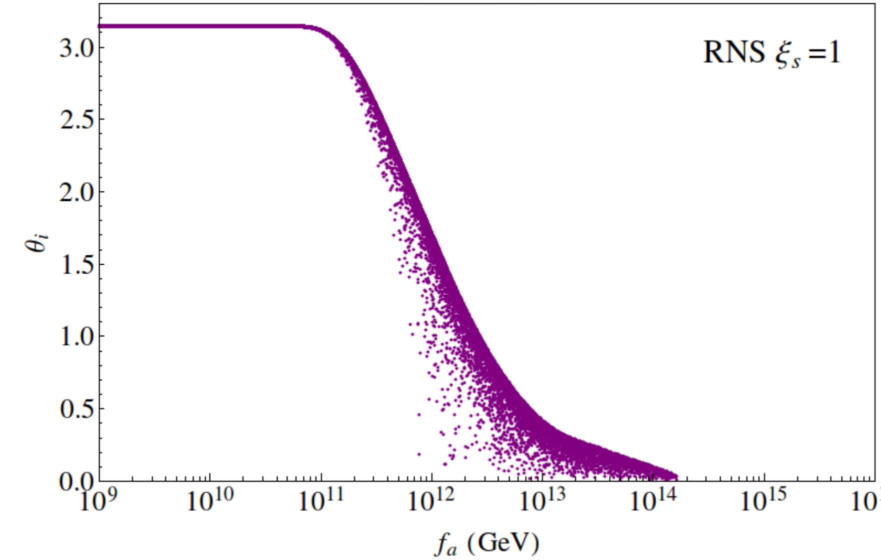
axion-higgsino mixture !

Coupled Boltmann computation of mixed axion-WIMP DM in SUSY DFSZ model with RNS benchmark point by keeping track of energy density and number densities of neutralinos, gravitinos, saxions, axinos, axions and radiation.

→ mainly axion CDM (~ 90%), 10% higgsino-like WIMPS unless $f_a \geq 10^{13}$-10^{14} GeV

→ large $f_a \geq 10^{14}$ GeV too much WIMP DM from saxion oscillation / decay





JCAP 1410 (2014) 10, 082 (**arxiv:1406.4138**)
(K.J.Bae,H.Baer,A.Lessa,H.**Serce**)

Conclusions

- Given multi TeV values of $m_{3/2}$, a class of models typified by MSY give rise to radiatively-driven PQ symmetry breaking and generates a weak scale value of μ (~100-200 GeV) and produces intermediate scale Majorana masses for right-hand neutrinos
- Little Hierarchy characterized by $\mu << m_{3/2}$ emerges quite naturally and is indeed a feature expected from naturalness and LHC bounds.
- $\mu << m_{3/2}$ is a consequence of $v_{PQ} << m_{hidden}$.
- SUSY DFSZ/MSY axion model solves Big Hierarchy, strong CP and μ problem and Little Hierarchy (EW naturalness $\mu \sim m_Z$) hence we get mixed axion-higgsino dark matter.