IBS-SNU joint workshop on particle physics

2-4 May 2016
Global Convention Plaza, Seoul National University

Axino Phenomenology

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Eung Jin Chun

Outline

- Introduction
- Axino mass and cosmological production
- Axino>Higgsino scenario
- Higgsino>Axino scenario

My Axino Chronicle

- Axino mass, [9205229] E.J. Chun, J.E. Kim, H.P. Nilles
- Dark matters in axino gravitino cosmology [9305208] E.J. Chun, H.B. Kim, J. E. Kim
- Axino mass in supergravity models [9503233] E.J. Chun, A. Lukas

- QuasiGoldstone fermion as a sterile neutrino [9507371] E.J. Chun, A.S. Joshipura, A.Yu. Smirnov
- Axino neutrino mixing in GMSB models [9901220] E.J. Chun
- Nonthermal axino as cool dark matter in SSM without R-parity [9906392] E.J. Chun, H.B. Kim
- Cosmological constraints on a Peccei-Quinn flatino as LSP [0008139] E.J. Chun, H.B. Kim, D.H. Lyth
- Axino as a sterile neutrino and R-parity violation [0101026] K, Choi, E.J. Chun, K. Hwang
- Axino Light Dark Matter and Neutrino Masses with R-parity Violation [0607076] E.J. Chun, H.B. Kim
- Flaxino dark matter and stau decay [0801.4108] E.J. Chun, H.B. Kim, K. Kohri, D.H. Lyth

- Dark matter in the Kim-Nilles mechanism [1104.2219] E.J. Chun
- Cosmology of the DFSZ axino [1111.5961] K.J. Bae, E.J. Chun, S.H. Im
- Mainly axion cold dark matter from natural supersymmetry [1309.0519] K.J. Bae, H. Baer, E.J. Chun
- Mixed axion/neutralino dark matter in the SUSY DFSZ axion model [1309.5365] K.J. Bae, H. Baer, E.J. Chun.
- Implications of an axino LSP for naturalness [1407.1218] G. Barenboim, E.J. Chun, S. Jung, W.I. Park

Naturalness: Axion & SUSY

- Axion dynamically resolves the strong CP problem.
- SUSY naturally solves the hierarchy problem: Axion accompanied by Saxion and Axino.
- Implications of Axion SUSY multiplet in cosmology and collider physics.

Axino mass

Supersymmetric axion models

- KSVZ – introduce extra heavy vector-like quarks:

$$W_{\rm KSVZ} = \lambda_{Q'} S Q' Q'^c \qquad (\mathcal{A}_3 = N_{Q'})$$

1 0 -1

- DFSZ – extend the Higgs bilinear term:

$$W_{DFSZ} = \lambda_H \frac{S^2}{M_P} H_u H_d \qquad (\mathcal{A}_3 = 2N_g)$$

2 -1 -1

$$+ y_u Q U^c H_u + y_d Q D^c H_d + y_e L E^c H_d$$

0 1 -1 0 1 -1 0 1 -1

"Simultaneous resolution of the strong CP and 1 problems"

$$\mu = \lambda \frac{\langle S \rangle^2}{M_P}, \qquad \langle S \rangle = \frac{F_a}{\sqrt{2}}$$

Kim-Nilles, '84

Supersymmetric axion multiplet

- Axion accompanied by its superpartners -- saxion & axino:

$$A = (s + ia, \tilde{a})$$

- Effective theory below F_a : A+MSSM.
- Aaxino & saxion play important roles in cosmology including dark matter physics.
- Characteristically different saxion/axino couplings:

$$\mathcal{L}_{\rm KSVZ} = c_a \frac{g^2}{32\pi^2} \frac{1}{F_a} \left[\tilde{a}\sigma^{\mu\nu}\tilde{g}^a G^a_{\mu\nu} + s G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + h.c. \right]$$

$$\mathcal{L}_{\rm DFSZ} = c_H \frac{\mu}{F_a} \left\{ \tilde{a}[H_u \tilde{H}_d + \tilde{H}_u H_d] + s\tilde{H}_u\tilde{H}_d + a_h shh \right\}$$

$$+ c_t \frac{m_t}{F_a} \{ \tilde{a}[t\tilde{t}^c + \tilde{t}t^c] + stt^c + a_t s\tilde{t}\tilde{t}^c \} + h.c.$$

Axino mass

- SUSY breaking induces axino/saxion mass.
- Model-dependent SUSY and PQ symmetry breaking:

$$W_{PQ} = \lambda X(SS' - F_a^2)$$

$$\Rightarrow m_{\tilde{a}}^{\rm tree} = \lambda \langle X \rangle \text{ where } \langle X \rangle \sim m_{3/2}, m_{3/2}^2/F_a, \cdots$$

$$\Rightarrow m_{\tilde{a}}^{\rm loop} \sim \frac{\lambda^2}{16\pi^2} m_{3/2}$$

EJC, Kim, Nilles, '92
EJC, Lukas, '95

- In SUGRA, axino mass is typically at TeV but can be much lighter.
- In GMSB, it is $\lesssim M_S^2/F_a$.

EJC, 99

Axino Abundance

Cosmic axino/saxion production

- Axinos are too weakly interacting to be in thermal equilibrium.
- Still copiously produced from thermal bath through their (weak) interaction with gluon(ino)s, (s)quarks and Higgs(ino)s.

$$\frac{dY_{s,\tilde{a}}}{dT} = -\frac{\gamma}{sHT} \propto \begin{cases} \dfrac{M_P}{F_a^2} & \text{KSVZ} \\ \dfrac{M_P}{T^2} & \text{DFSZ} \end{cases}$$

KSVZ axino abundance

- For $T_R < Fa = M_Q$:

Covi, Kim, Kim, Roszkovski, 0101009
Brandenburg, Steffen, 0405158
Strumia, 1003.5847

$$\mathcal{L}_{\rm QCD} = c_a \frac{g^2}{32\pi^2} \frac{1}{F_a} \tilde{a}\sigma^{\mu\nu}\tilde{g}^a G^a_{\mu\nu} + h.c.$$

$$\gamma \sim \frac{g_3^4 T^6}{256\pi^7 F_a^2} \cdot 10 \ \Rightarrow \ Y_{\tilde{a}} \sim 10^{-8} \left(\frac{T_R}{\rm TeV}\right) \left(\frac{10^{11} \ {\rm GeV}}{F_a}\right)^2$$

if stable

$$\Rightarrow m_{\tilde{a}} < 40 \ {\rm MeV} \left(\frac{\rm TeV}{T_R}\right) \left(\frac{F_a}{10^{11}{\rm GeV}}\right)^2$$

DFSZ axino abundance

- For $T_R > m_{H,\,\mathrm{stop}}$:

EJC, 1104.2219
Bae, KChoi, Im, 1106.2452
Bae, EJC, Im, 1111.5962

$$\mathcal{L}_{\mathrm{Yuk}} = \frac{\mu}{F_a}\tilde{a}[H_u\tilde{H}_d + \tilde{H}_u H_d] + c_t\frac{m_t}{F_a}\tilde{a}[t\tilde{t}^c + \tilde{t}t^c] + h.c.$$

$$\gamma \sim \frac{1}{16\pi^3}\frac{\mu^2}{F_a^2}T^4 \;\Rightarrow\; Y_{\tilde{a}} \sim 10^{-5}\left(\frac{\mathrm{TeV}}{m_H}\right)\left(\frac{\mu}{\mathrm{TeV}}\right)^2\left(\frac{10^{11}\mathrm{GeV}}{F_a}\right)^2$$

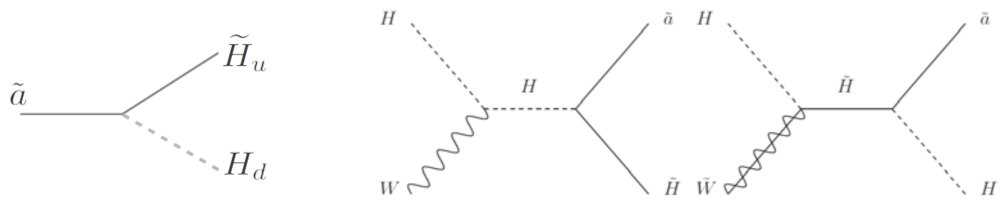
if stable

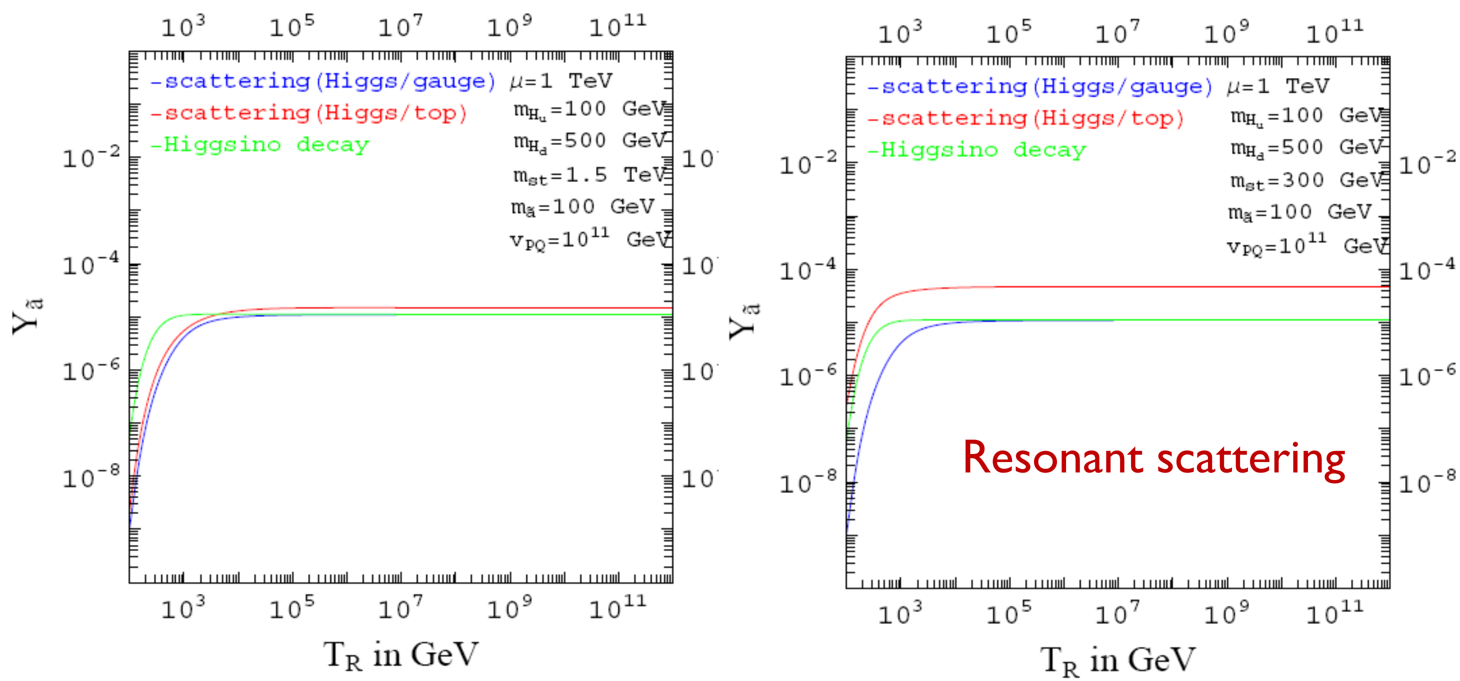
$$\Rightarrow\; m_{\tilde{a}} < 40\,\mathrm{keV}\left(\frac{m_H}{\mathrm{TeV}}\right)\left(\frac{\mathrm{TeV}}{\mu}\right)^2\left(\frac{F_a}{10^{11}\mathrm{GeV}}\right)^2$$

- For $T_R < m_{H,\,\mathrm{stop}}$: Boltzmann suppressed → larger mass allowed.

DFSZ axino abundance

- Decay/inverse-decay & scattering: Bae, EJC, Im, 1111.5962





Higgsino LSP & Heavier Axino

Natural SUSY and Higgsino LSP

- Higgs potential in SUSY:

$$W = y_u Q U^c H_u + y_d Q D^c H_d + y_e L E^c H_d + \mu H_u H_d$$

$$V_H = (m_{H_u}^2 + \mu^2)|H_u|^2 + (m_{H_d}^2 + \mu^2)|H_d|^2 + (B\mu H_u H_d + h.c.) + V_D$$

$$V_D = \frac{1}{8}(g_2^2 + g_1^2)\left[|H_u|^2 - |H_d|^2\right]^2$$

- Minimization conditions:

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

$$\frac{2B\mu}{\sin 2\beta} = m_{H_u}^2 + m_{H_d}^2 + \mu^2$$

- May imply $M_Z \sim \mu \sim m_{H_{u,d}}$

Implication of heavy (unstable) axino

- Decay of abundant heavy axino will overproduce the neutralinos:

$$Y_{\tilde{a}} = 10^{-5}\xi\left(\frac{\mu}{\mathrm{TeV}}\right)^2\left(\frac{10^{11}\mathrm{GeV}}{F_a}\right)^2 \gg Y_{WIMP} \sim 10^{-12}$$

- $T_D > T_f$: the standard freeze-out relic density.
- $T_D < T_f$: the overproduced neutralino abundance can be depleted through strong re-annihilation → light Higgsino DM.

KYChoi, Kim, Lee, Seto, 0801.0491
Baer, et.al., 1103.5413

Higgsino DM after DFSZ axino decay

- DFSZ axino decay into Higgsino:

EJC, 1104.2219
Bae, EJC, Im, 1111.5962

$$\tilde{a} \to \tilde{H} + h/Z, \quad \tilde{H}^{\pm} + W^{\mp}$$

$$T_D \sim g_*^{-1/4} \sqrt{\Gamma_{\tilde{a}} M_P} \qquad \Gamma_{\tilde{a}} \sim \frac{1}{16\pi} \left(\frac{\mu}{F_a} \right)^2 m_{\tilde{a}}$$

$$x_D \sim 30 \left(\frac{g_*}{70} \right)^{1/4} \left(\frac{500\mathrm{GeV}}{m_{\tilde{a}}} \right)^2 \left(\frac{m_{DM}}{\mu} \right) \left(\frac{F_a}{10^{11}\mathrm{GeV}} \right)$$

$$> x_f \sim 23$$

$$\frac{dY_{DM}}{dT} = \langle \sigma_A v \rangle Y_{DM}^2 \frac{s}{HT} \Rightarrow \Omega_{DM} \propto \frac{x_D}{\langle \sigma_A v \rangle} \quad (x_D > x_f)$$

DM candidates

- Higgsino – standard under-abundant, strong direct detection constraint.

  *Re-annihilation due to heavy axino decay may enhance the abundance.

$$\Omega_{\tilde{H}} \approx 0.1 \frac{x_D}{x_f} \left(\frac{\mu}{1\mathrm{TeV}}\right)^2$$

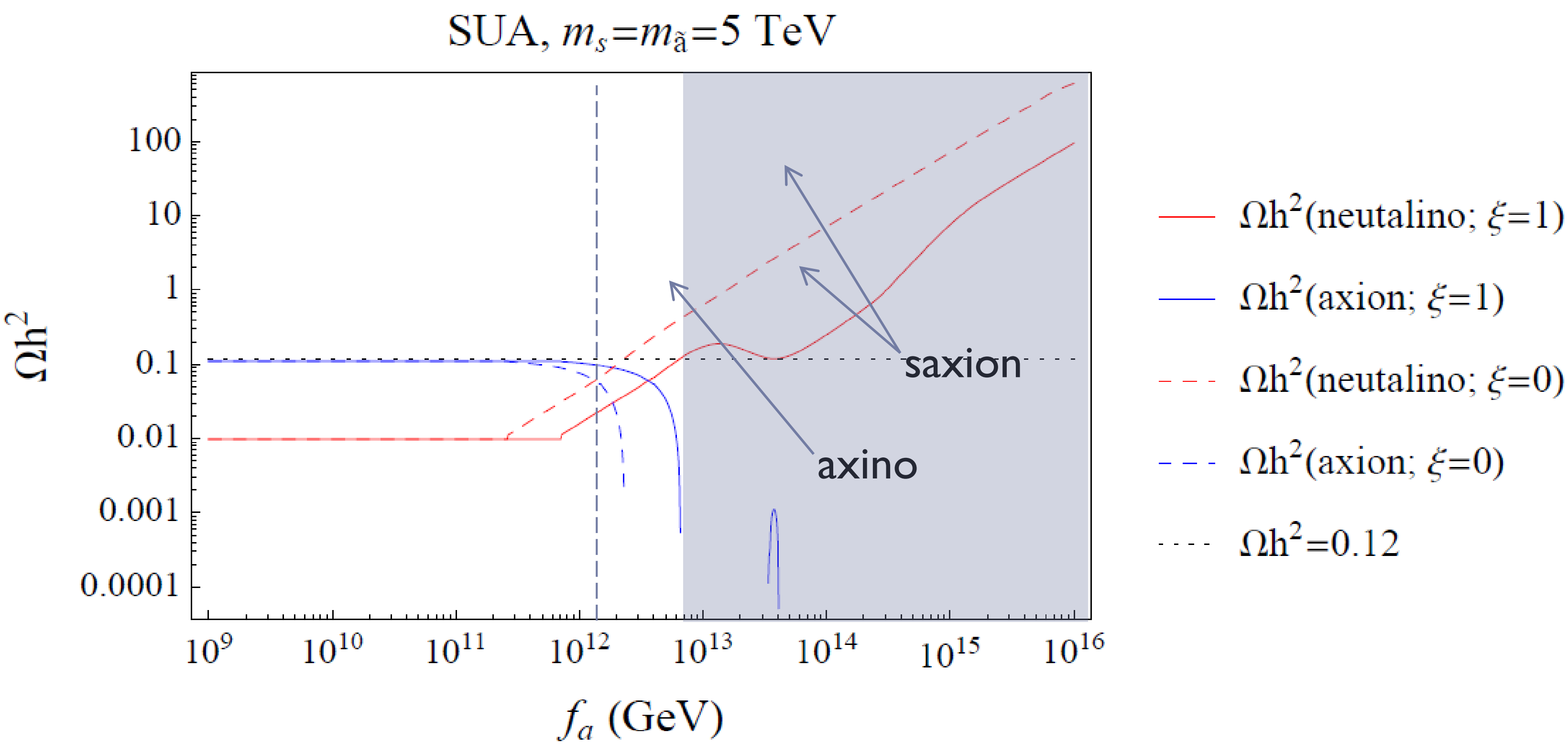
- Axion – CDM from standard coherent oscillation with initial misalignment μ_I:

$$\Omega_{\tilde{a}} h^2 \approx 0.18\, \theta_1^2 \left(\frac{F_a}{10^{12}\mathrm{Gev}}\right)^{1.19} \left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right)$$

- Axino if very light (<MeV).

Dark Matter composition

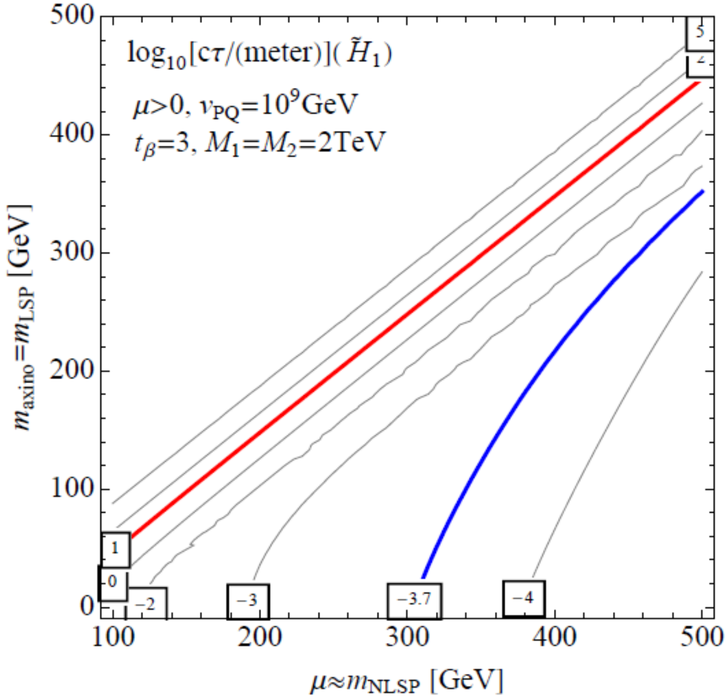
For Higgsino mass ~ 200 GeV
with sizable bino-mixing



Higgsino NLSP & Axino LSP

LHC probe of Higgsino NLSP-Axino LSP

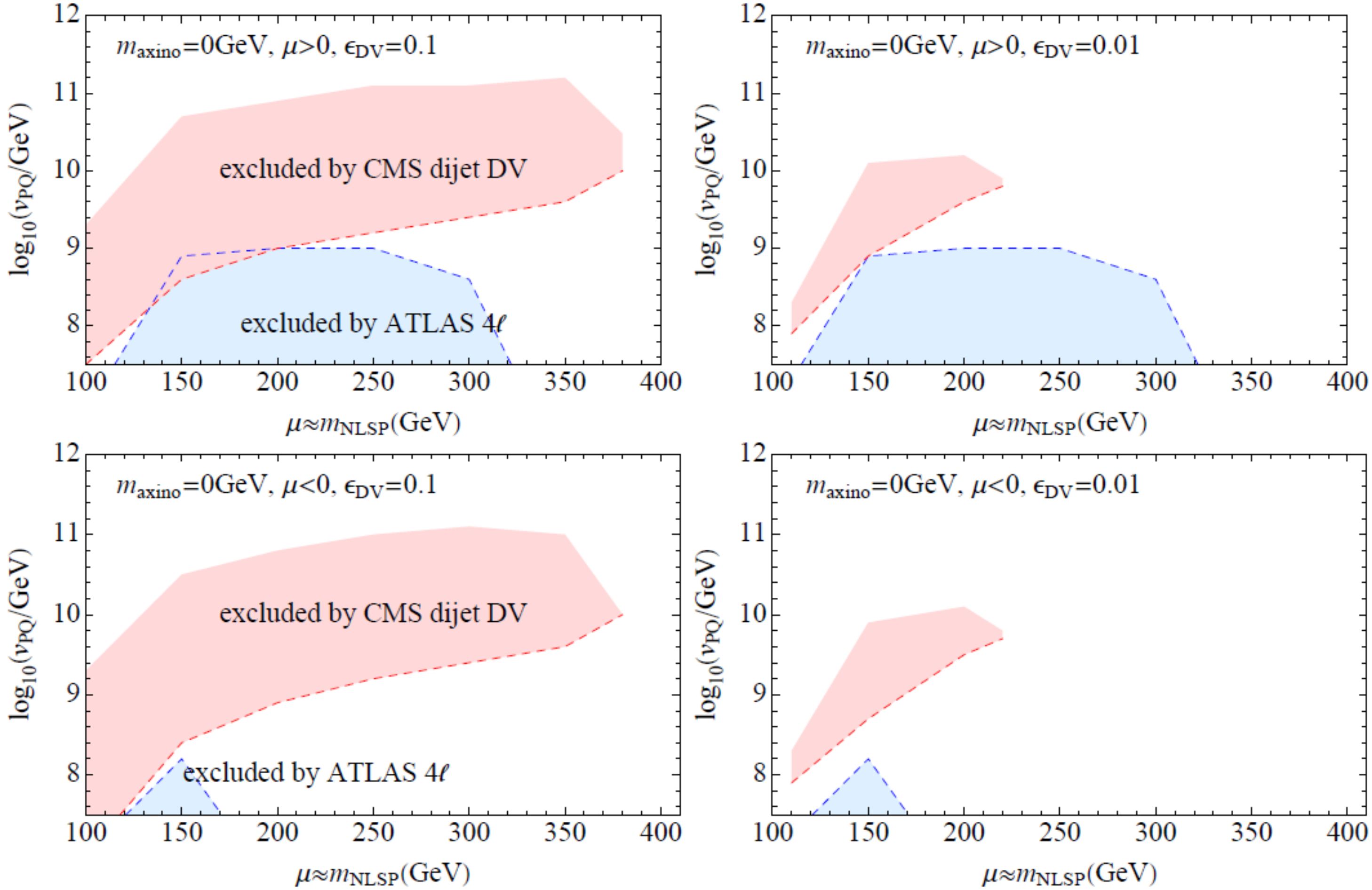
- Higgsino decay $\widetilde{H} \rightarrow h/Z + \tilde{a}$ leaves displaced vertices.



Barenboim, EJC, Jung, Park, 1408.1218

- The current & future (dijet) DV searches probe ^{1} & F_a.

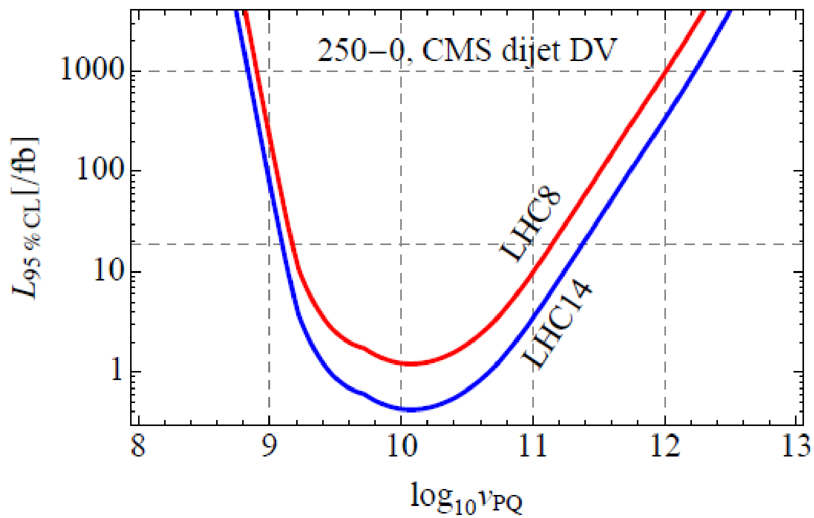
LHC 8 limits

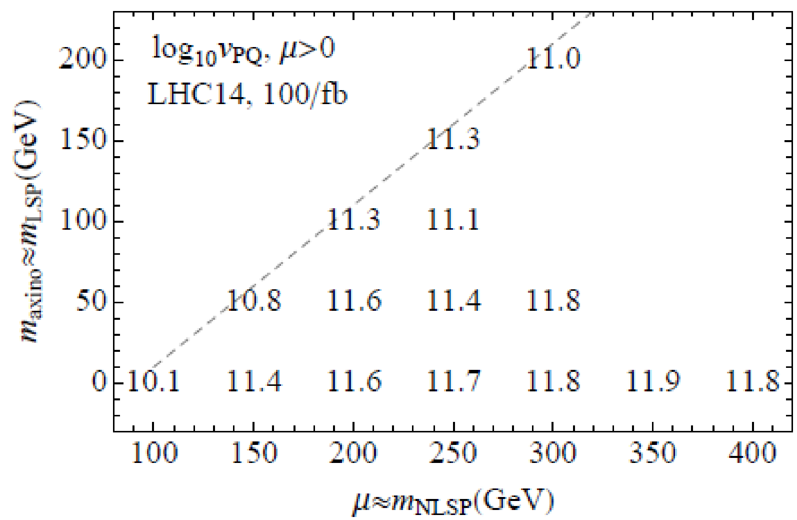


m_{axino}=0GeV, μ>0, ϵ_{DV}=0.1
excluded by CMS dijet DV
excluded by ATLAS 4ℓ
$\log_{10}(v_{PQ}/\text{GeV})$
$\mu \approx m_{NLSP}$(GeV)
m_{axino}=0GeV, μ>0, ϵ_{DV}=0.01
m_{axino}=0GeV, μ<0, ϵ_{DV}=0.1
m_{axino}=0GeV, μ<0, ϵ_{DV}=0.01

LHC14 projection

- Assuming $^2_{DV} = 0.1$:





Conclusion

- Resolution of the mu, strong CP and the Higgs fine-tuning problems leads to "Natural SUSY+DFSZ axion".
- Long-lived axinos can be produced copiously thru thermal generation.
- Heavy unstable axino: late decays may produce significant amounts of Higgsino LSP.
- Mixed Higgsino/axion DM realized for $F_a = 10^{10} - 10^{13}$ GeV → Signals in LUX/Zenon+ADMX/CAPP.
- Axino LSP: Higgsino NLSP decay to h/Z+axino leaves displaced vertices—the current/future dijet DV searches probe F_a up to $10^{11/12}$ GeV.