Exploring the Dark Sector, KIAS, 16-20 Mar.. 2015

Mixed Axion/Higgsino Dark Matter

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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Outline

- Natural SUSY & DFSZ axion.
- Cosmology of the axion superfield:

  Saxion/axino production and decay.

  Neutralino re-annihilation, axion as dark radiation, entropy dumping.
- Cold dark matter: mixed axion & Higgsino.
- Conclusion.

EJC, 1104.2219
Bae, EJC, Im, 1111.5962
Bae, Baer, EJC, 1309.0519; 1309.5365

EWSB and Higgs mass in SUSY

- 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:

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

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

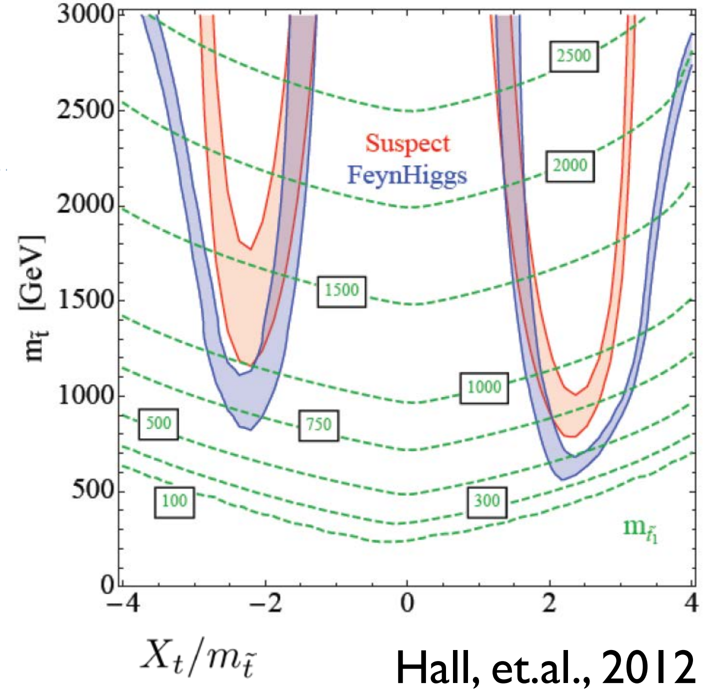
- Higgs mass at 1-loop:

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{1}{12}\frac{X_t^2}{m_{\tilde{t}}^2}\right)\right]$$

$125^2 = 91^2 + 86^2$

Natural SUSY?

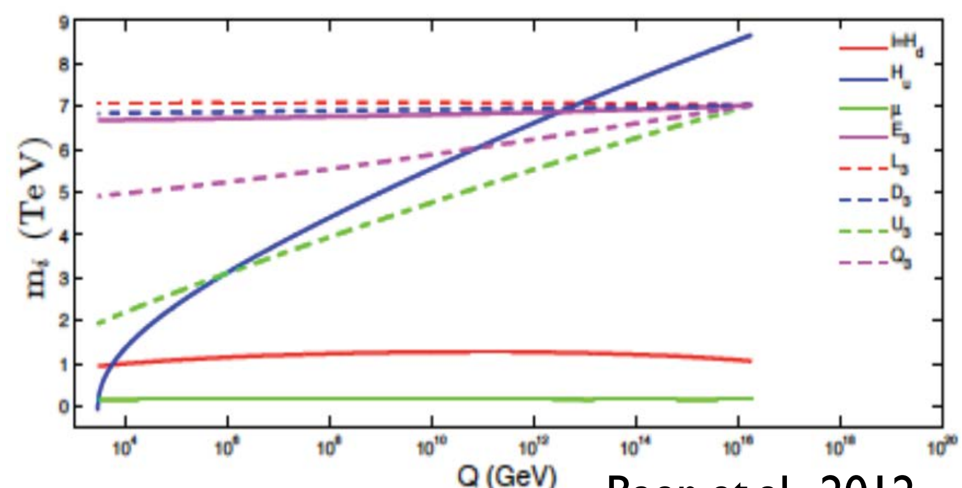
- LHC pushes up gluino/squark masses above multi TeV.
- 125 GeV Higgs requires stop mass above TeV in general.



Hall, et.al., 2012

- Still EWSB can be made "natural" with both radiatively driven m_{Hu} and tree μ at around 100 GeV → Higgsino LSP.

$$\frac{1}{2}M_Z^2 \approx -m_{H_u}^2 - \mu^2$$



Baer, et.al., 2012

Strong CP problem & axion

- QCD θ parameter allowed in SM:

$$\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \;\Rightarrow\; \theta\, \mathbf{E} \cdot \mathbf{B}$$

- EDM constraint: $d_n = 5.2 \times 10^{-16} \theta ecm \;\Rightarrow\; \theta < 10^{-11}$
- Weak CP ~ 1 vs. Strong CP $< 10^{-11}$??
- Peccei-Quinn mechanism: a spontaneously broken QCD-anomalous global U(1) symmetry → axion.

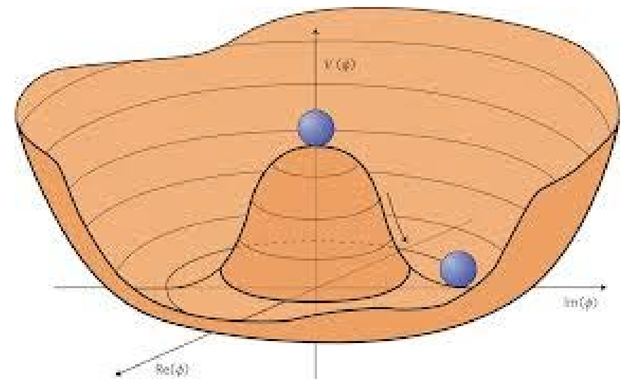
$$\mathcal{L} = \left(\frac{a}{F_a} + \theta \right) \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\mathcal{L} = \Lambda^4_{\rm QCD} \left[1 - \cos\left(\frac{a}{F_a} + \theta \right) \right] \;\Rightarrow\; \langle \frac{a}{F_a} + \theta \rangle = 0$$

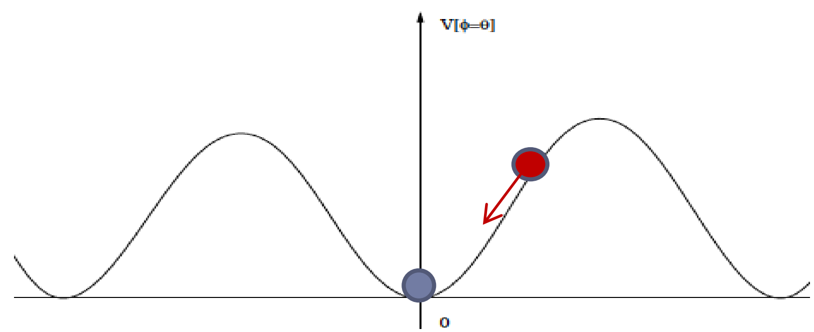
- Star cooling → $F_a > 10^{9\text{-}10}$ GeV.

Axion Cold Dark Matter

- Being a Goldstone boson, axion has no potential after the PQ symmetry breaking at F_a .
- As the axion potential develops at the QCD phase transition, θ oscillates starting from its mis-aligned value θ_0 → a stable oscillating scalar field forms cold dark matter.
- Axion DM → $F_a < 10^{12}$ GeV.



$$\theta \equiv a/F_a = [0, 2\pi N_{\rm DW}]$$



Supersymmetric axion models

- Two ways to realize PQ symmetry (QCD-anomaly).
- 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:

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

1 -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 μ problems"

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

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.
- Saxion & axino play important roles in cosmology including dark matter physics.
- DFSZ saxion/axino couplings:

$$\mathcal{L}_{\rm DFSZ} = c_H \frac{\mu}{F_a} \left\{ \tilde{a}[H_u \tilde{H}_d + \tilde{H}_u H_d] + s \tilde{H}_u \tilde{H}_d + a_h s h h \right\}$$
$$+ c_t \frac{m_t}{F_a} \{ \tilde{a}[t \tilde{t}^c + \tilde{t} t^c] + s t t^c + a_t s \tilde{t} \tilde{t}^c \} + h.c.$$

DM candidates

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

  *Re-annihilation due to saxion/axino decay may enhance the abundance: $\Omega_{\tilde{H}} h^2 \approx 0.1 \frac{x_D}{x_f} \left(\frac{\mu}{1\text{TeV}}\right)^2$

- Axion – CDM from standard coherent oscillation with initial misalignment θ_1:

$$\Omega_a h^2 \approx 0.18\, \theta_1^2 f(\theta_1) \left(\frac{F_a}{10^{12}\text{Gev}}\right)^{7/6} \left(\frac{\Lambda_{\text{QCD}}}{400\text{MeV}}\right)$$

$$f(\theta_1) = \left[\ln \frac{e}{1-\theta_1^2/\pi^2}\right]^{7/6}$$

- Axino if very light (<MeV).

Axino/saxion 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

- Axino mass is typically $m_{3/2}$ but can be much lighter.
- Saxion mass is around $m_{3/2}$.

Cosmic axino/saxion production

- Axino/saxion are too weakly interacting to be in thermal equilibrium.
- Still, copious axino/saxion are generated by their couplings to gluon(ino)s, (s)quarks and Higgs(ino)s in thermal equilibrium.

$$\boxed{\frac{dY_{s,\tilde{a}}}{dT} = -\frac{\gamma}{sHT}} \qquad \gamma \sim \begin{cases} T^6/F_a^2 & \text{KSVZ} \\ \lambda^2 T^4 & \text{DFSZ} \end{cases}$$

DFSZ axino abundance

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

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

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

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

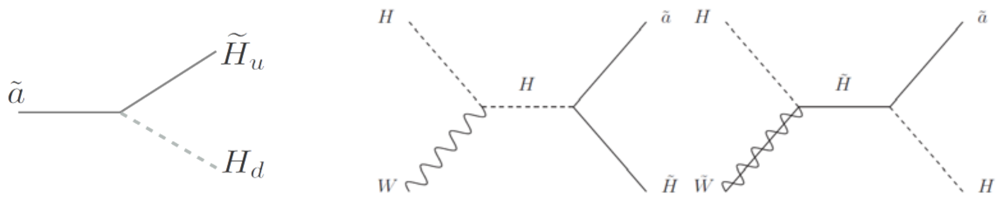
If stable

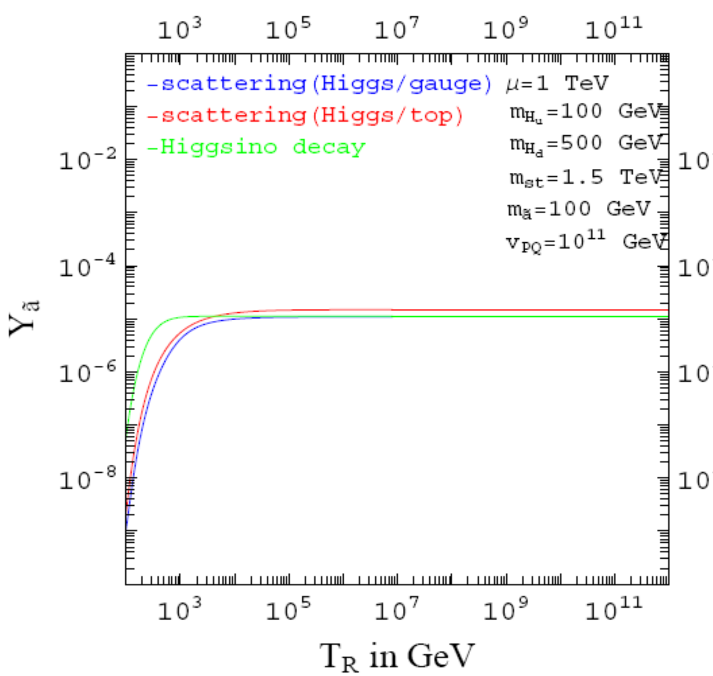
$$\Rightarrow\; m_{\tilde{a}} < 40\,{\rm keV}\left(\frac{m_H}{\rm TeV}\right)\left(\frac{\rm TeV}{\mu}\right)^2\left(\frac{F_a}{10^{11}\rm GeV}\right)^2$$

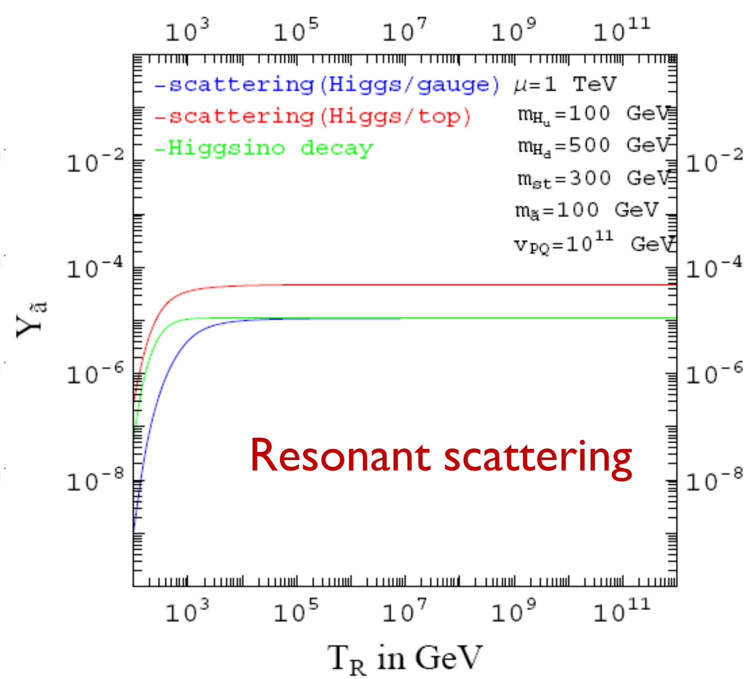
- For $T_R < m_{H,\,stop}$: Boltzmann suppressed → larger mass allowed.

DFSZ axino abundance

- Decay/inverse-decay & scattering:

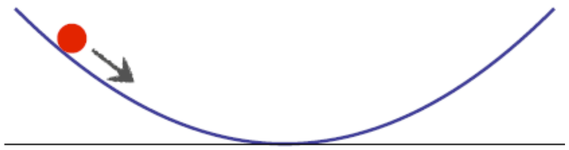






Cosmic saxion production

- Production from thermal scattering: same as for the axino.
- Coherent oscillation with initial amplitude $s_0 = F_a$:



$$3H(T_s) = m_s \Rightarrow T_s \sim 10^{10}\mathrm{GeV}$$

$$Y_s \sim 10^{-7}\left(\frac{\min[T_R, T_s]}{10^8\mathrm{GeV}}\right)\left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^2\left(\frac{100\mathrm{GeV}}{m_s}\right)$$

Saxion/axino decays

- Saxion has generically order-one couplings to axions/axinos: $\xi = \sum_i q_i^3 v_i^2 / F_a^2$ EJC, Lukas, '95

$$\Gamma(s \to aa) = \frac{\xi^2 m_s^3}{64\pi F_a^2}$$

$$\Gamma(s \to \tilde{a}\tilde{a}) = \frac{\xi^2}{8\pi} \frac{m_{\tilde{a}}^2 m_s}{F_a^2} \left(1 - 4\frac{m_{\tilde{a}}^2}{m_s^2}\right)^{3/2}$$

- Saxion to Higgs/Higgsinos:

$$\Gamma(s \to hh) \approx \frac{c_H^2}{16\pi} \frac{m_A^4 \cos^4\beta}{F_a^2 m_s}$$

$$\Gamma(s \to \tilde{H}\tilde{H}) \approx \frac{c_H^2}{16\pi} \frac{\mu^2}{F_a^2} m_s$$

- Axino to Higgs and Higgsino: $\Gamma(\tilde{a} \to h\tilde{H}) \approx \dfrac{c_H^2}{16\pi} \dfrac{\mu^2}{F_a^2} m_{\tilde{a}}$

Implication of saxion/axino decays

- Late decay of overabundant axino/saxion may (over)produce neutralino (dark matter), axion (dark radiation), entropy (SM particles):
- Decay temperature:

$$\Gamma_{s,\tilde{a}} \sim \frac{1}{16\pi}\left(\frac{\mu}{F_a}\right)^2 m_{s,\tilde{a}}$$

$$T_D \sim g_*^{-1/4}\sqrt{\Gamma_{s,\tilde{a}} M_P}$$

$$T_D \sim 1\,\mathrm{GeV}\left(\frac{\mu}{200\mathrm{GeV}}\right)\left(\frac{10^{12}\mathrm{GeV}}{F_a}\right)\left(\frac{m_{s,\tilde{a}}}{1\mathrm{TeV}}\right)^{1/2}$$

Impact on neutralino relic density

- Decay of abundant heavy saxion/axino will overproduce the neutralinos ($Y_{WIMP} \sim 10^{-12}$):

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

- $T_D > T_f$: standard freeze-out relic density.
- $T_D < T_f$: strong annihilation can deplete the over-produced DM abundance → Reannhilation of neutralino LSP → Higgsino/wino DM.

$$\frac{dY_{DM}}{dT} = \langle \sigma_A v \rangle Y_{DM}^2 \frac{s}{HT}$$

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

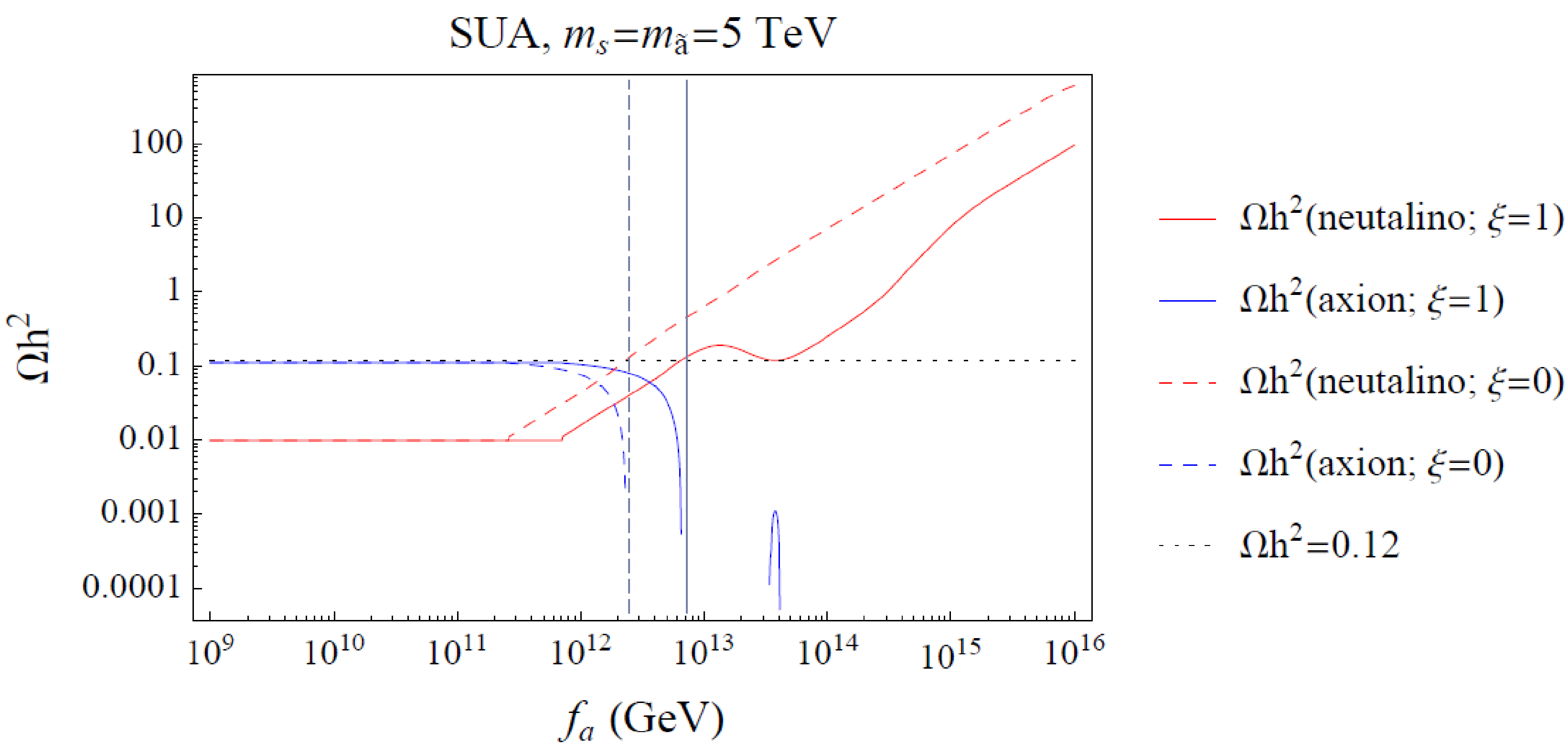
$$\Rightarrow \Omega_{DM} \propto \frac{x_D}{\langle \sigma_A v \rangle} \quad (x_D > x_f)$$

Benchmark for radiative natural SUSY

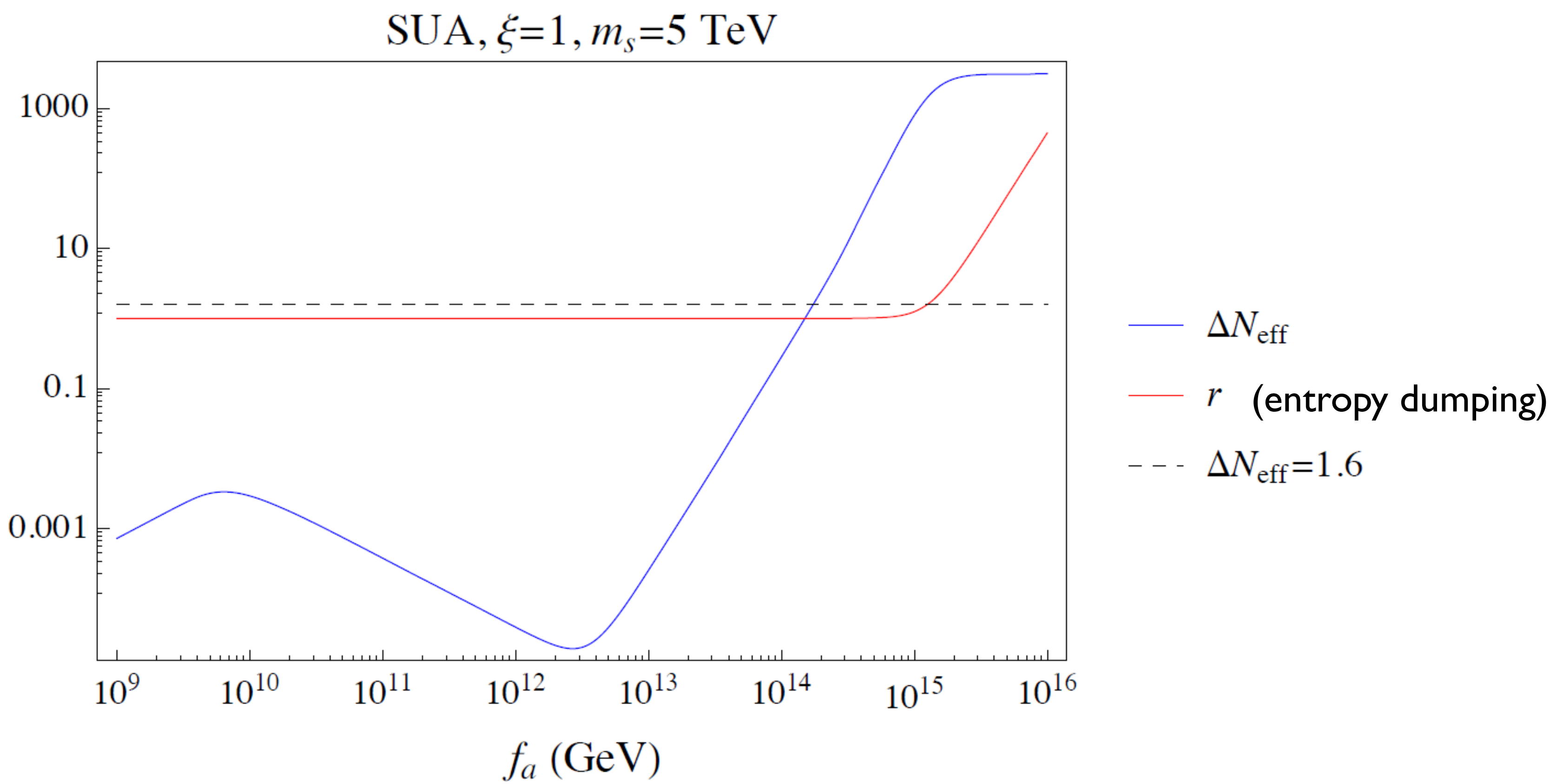
	SUA (RNS2)
m_0	7025
$m_{1/2}$	568.3
A_0	-11426.6
$\tan\beta$	8.55
μ	150
m_A	1000
m_h	125.0
$m_{\tilde{g}}$	1562
$m_{\tilde{u}}$	7021
$m_{\tilde{t}_1}$	1860
$m_{\widetilde{Z}_1}$	135.4
$\Omega^{\rm std}_{\widetilde{Z}_1} h^2$	0.01
$\sigma^{\rm SI}(\widetilde{Z}_1 p)$ pb	1.7×10^{-8}

- Higgsino LSP
- underabundant

Dark Matter composition



Dark radiation from s→aa



Characteristics depending on F_a

- Low F_a region: $10^{10} – 10^{12}$ GeV.

  Saxion/axino decay before neutralino freeze-out

  Standard neutralino density (10%)+axion density (90%)

- Intermediate F_a region: $10^{12} – 10^{13}$ GeV.

  Saxion/axino decay after neutralino freeze-out

  Augmented neutralino (10-100%) + axion (90-0%)

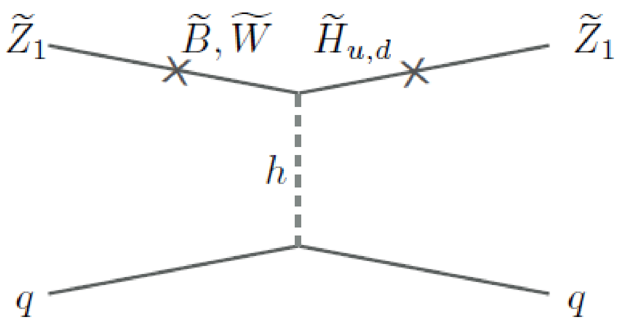
- High F_a region: $10^{13} – 10^{16}$ GeV.

  Overclosing neutralinos even after re-annihilation

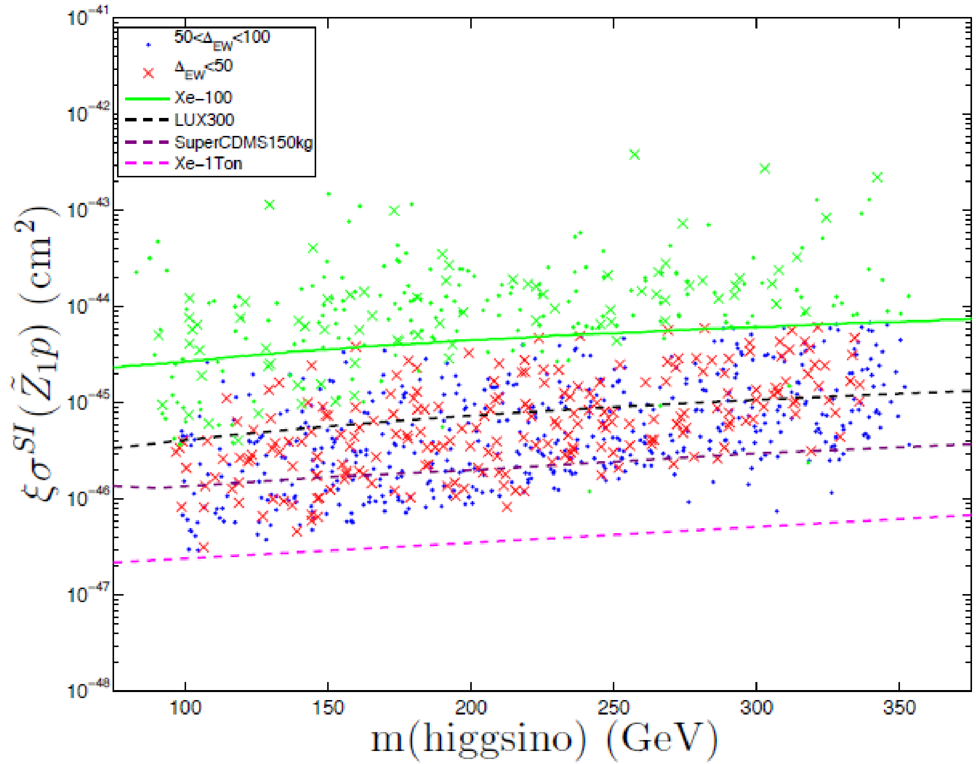
  Saxion oscillation produces sizable dark radiation (axion)

Neutralino detection

- Higgsino-like DM: SI scattering from Higgsino-gaugino mixing

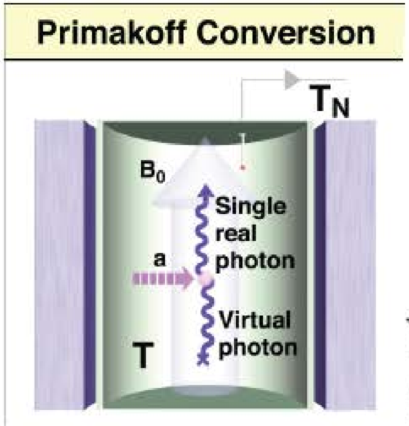


$$\xi \equiv \frac{\Omega_{\tilde{Z}_1} h^2}{0.12}$$

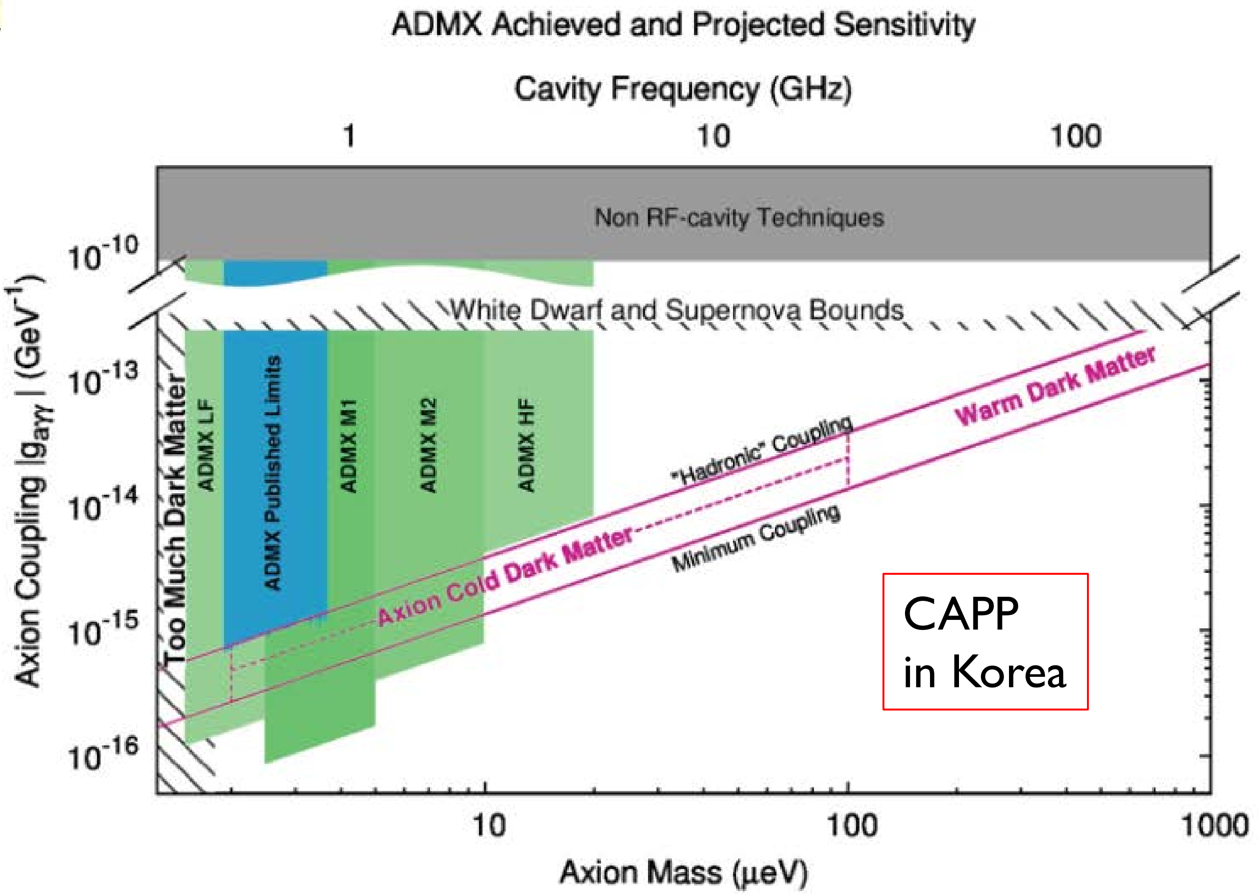


Baer, Barger, Mickelson

Axion detection



Rybka's Talk at
Cosmic Frontier
2013



$F_a(\mathrm{GeV}) \approx 10^{12}$ $\quad 10^{11} \quad 10^{10}$

Conclusion

- Resolution of the mu scale, strong CP and the Higgs fine-tuning problems leads to "Natural SUSY+DFSZ axion".
- Long-lived saxion & axino are produced a lot via thermal generation/coherent oscillation.
- Their late decays may produce significant amounts of neutralino, dark radiation, & entropy to change DM cosmology.
- Mixed neutralino/axion DM realized for $F_a = 10^{10} - 10^{13}$ GeV → Signals in LUX/Zenon+ADMX/CAPP?