Dark Matter in the Kim-Nilles Mechanism

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Outline

- Strong CP problem and axion
- KSVZ and DFSZ axion models
- Supersymmetric axion models & μ problem
- Axino couplings, mass & cosmic abundance
- Natural SUSY & Kim-Nilles mechanism
- Mixed Higgsino-axion dark matter
- Conclusion

Strong CP problem

- Gauge-invariance allows QCD θ term:

$$\mathcal{L}_\theta = \theta \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- It is a CP-odd E·B term inducing nucleon EDM.

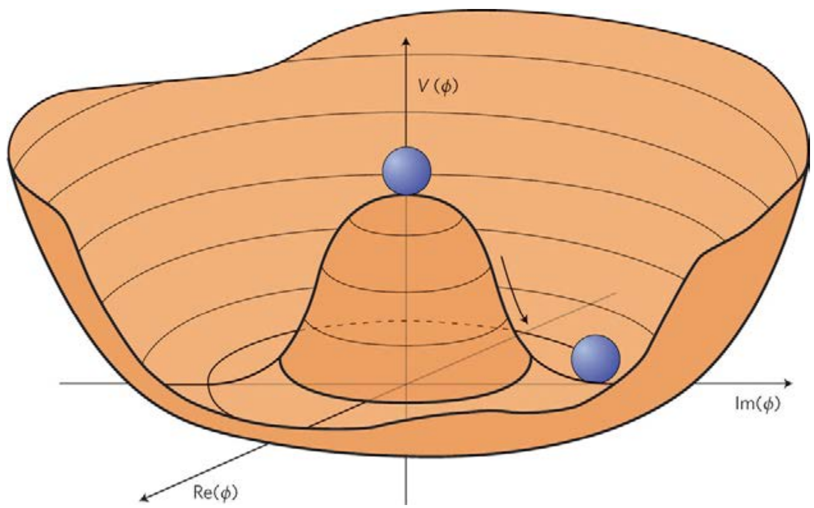
$$d_n \sim e\theta m_q / m_N^2 < 10^{-26} ecm \Rightarrow \theta < 10^{-11}$$

- Why is θ so small?
- Cf) Hierarchies of fundamental parametrs in SM:

  $y_t \sim 1$, $y_e \sim 10^{-6}$; $y_\nu^D \sim 10^{-12}$.

Axion

- Peccei-Quinn introduced an QCD-anomalous global U(1) symmetry broken spontaneously at F_a to produce a pseudo-scalar boson = Axion.



Axion solution

- QCD anomaly induces a-G-G coupling:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + (\theta + c_G \frac{a}{F_a}) \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\Rightarrow \bar{\theta} \equiv \theta + c_G \frac{a}{F_a}$$

- QCD phase transition generates axion potential:

$$V \sim \Lambda^4_{QCD} (1 - \cos\bar{\theta}) \Rightarrow \langle \bar{\theta} \rangle = 0$$

- Axion is super-light:

$$m_a \sim \frac{\Lambda^2_{QCD}}{F_a} \sim 10^{-3} \left(\frac{10^{10}\mathrm{GeV}}{F_a} \right) \mathrm{eV}$$

Axion models

- **K**im-**S**hifman-**V**ainshtein-**Z**akharov:

$$\mathcal{L}_{KSVZ} = \lambda_Q S Q Q^c + h.c.$$

- **D**ine-**F**ischler-**S**rednicki-**Z**hitinitski:

$$\mathcal{L}_{DFSZ} = y_u q u^c H_u + y_d q d^c H_d + \lambda_H S H_u H_d + h.c.$$

- PQ charges (QCD-anomalous):

$$\begin{array}{llllllll} S; & Q, & Q^c; & q, & u^c, & d^c, & H_u, & H_d \\ 2; & -1, & -1; & 1/2, & 1/2, & 1/2, & -1, & -1 \end{array}$$

- After the PQ symmetry breaking:

$$S = F_a e^{2ia/F_a}$$

Constraints on F_a

- Lower bound from star cooling: low F_a → efficient axion emission → fast star cooling.
- Upper bound from axion dark matter density: axion potential after Λ_{QCD} drives a coherent axion oscillation → $\Omega_a \sim F_a^{7/6}$.

$$10^{10}\mathrm{GeV} \leq F_a \leq 10^{12}\mathrm{GeV}$$

Supersymmetric Standard Model

- Gauge-invariant superpotential terms:

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

- μ as a fundamental parameter: What do you choose for the scale of μ?
- "μ problem":

m_Z= 90 GeV , m_h = 125 GeV

→ μ ~ 100 GeV << M_P ??

Supersymmetric axion models

- KSVZ: $W_{\rm KSVZ} = \lambda_Q S Q Q^c$

- DFSZ: $W_{\rm DFSZ} = \lambda_H \frac{S^2}{M_P} H_u H_d$ Kim-Nilles, 1984

  Solves the μ problem: $\mu = \lambda_H F_a^2 / M_P$

- Supersymmetric axion multiplet -- axion accompanied by saxion and axino:

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

Axino mass

- SUSY and PQ symmetry breaking model dependent:

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

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

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

- Axino mass is typically at TeV but can be much lighter.

EJC, Kim, Nilles, 1992
EJC, Lukas, 1995

Axino couplings

- KSVZ below the heavy quark mass scale (~F_a):

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

- DFSZ:

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

($\tilde{a}$-$\tilde{H}$ mixing)

Cosmic axino production

- Axinos are too weakly interacting to be in thermal equilibrium.
- Still, axinos are produced copiously by their couplings to gluon(ino)s, (s)quarks and Higgs(ino)s in thermal equilibrium.

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

KSVZ axino abundance

- Driven by supersymmetric QCD coupling in a simple case:

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 axino is stable, DM constraint requires $\Rightarrow m_{\tilde{a}} < 40\ {\rm MeV} \left(\frac{\rm TeV}{T_R}\right) \left(\frac{F_a}{10^{11}{\rm GeV}}\right)^2$

DFSZ axino abundance

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

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

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

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

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

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

Implication of heavy (unstable) axino

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

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

- $T_D > T_f$: 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.

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

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

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

DM from DFSZ axino decay

- DFSZ axino decay into Higgsino:

EJC, 1104.2219
Bae, EJC, Im, 1111.5962

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

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

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

$$> x_f \sim 23$$

$$\Rightarrow \Omega_{DM} \propto \frac{x_D}{\langle \sigma_A v \rangle}$$

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 needs1-loop correction:

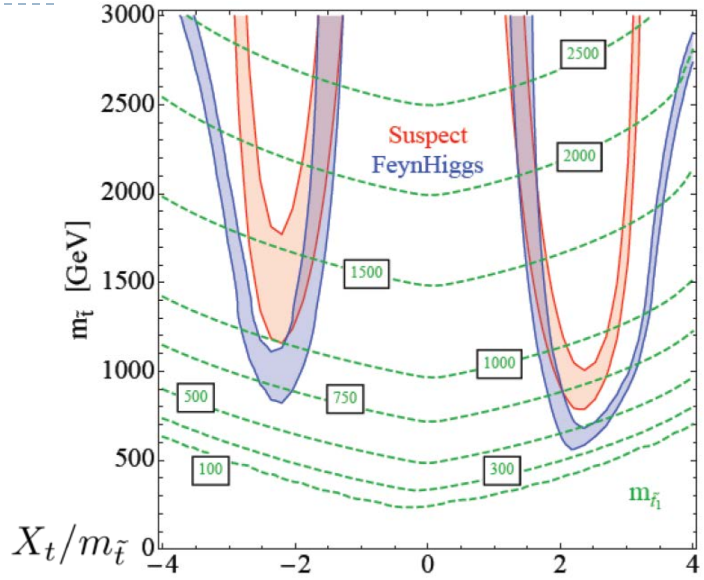
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{1}{12}\frac{X_t^2}{m_{\tilde{t}}^2}\right)\right]$$

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

Natural SUSY?

- LHC pushes up gluino/squark masses above 1000 GeV.
- 125 GeV Higgs requires stop mass above ~ 1000 GeV.

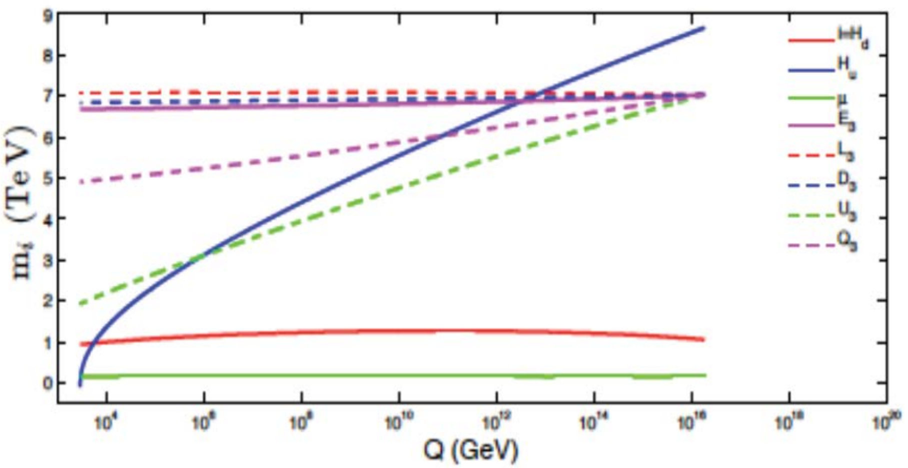
Hall, et.al., 2012



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

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

Baer, et.al., 2012



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
$m_{\tilde{Z}_1}$	135.4
$\Omega^{\rm std}_{\tilde{Z}_1} h^2$	0.01
$\sigma^{\rm SI}(\tilde{Z}_1 p)$ pb	1.7×10^{-8}

- Higgsino LSP
- underabundant

DM candidates

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

  *Re-annihilation due to saxion/axino decay may enhance the abaundance.

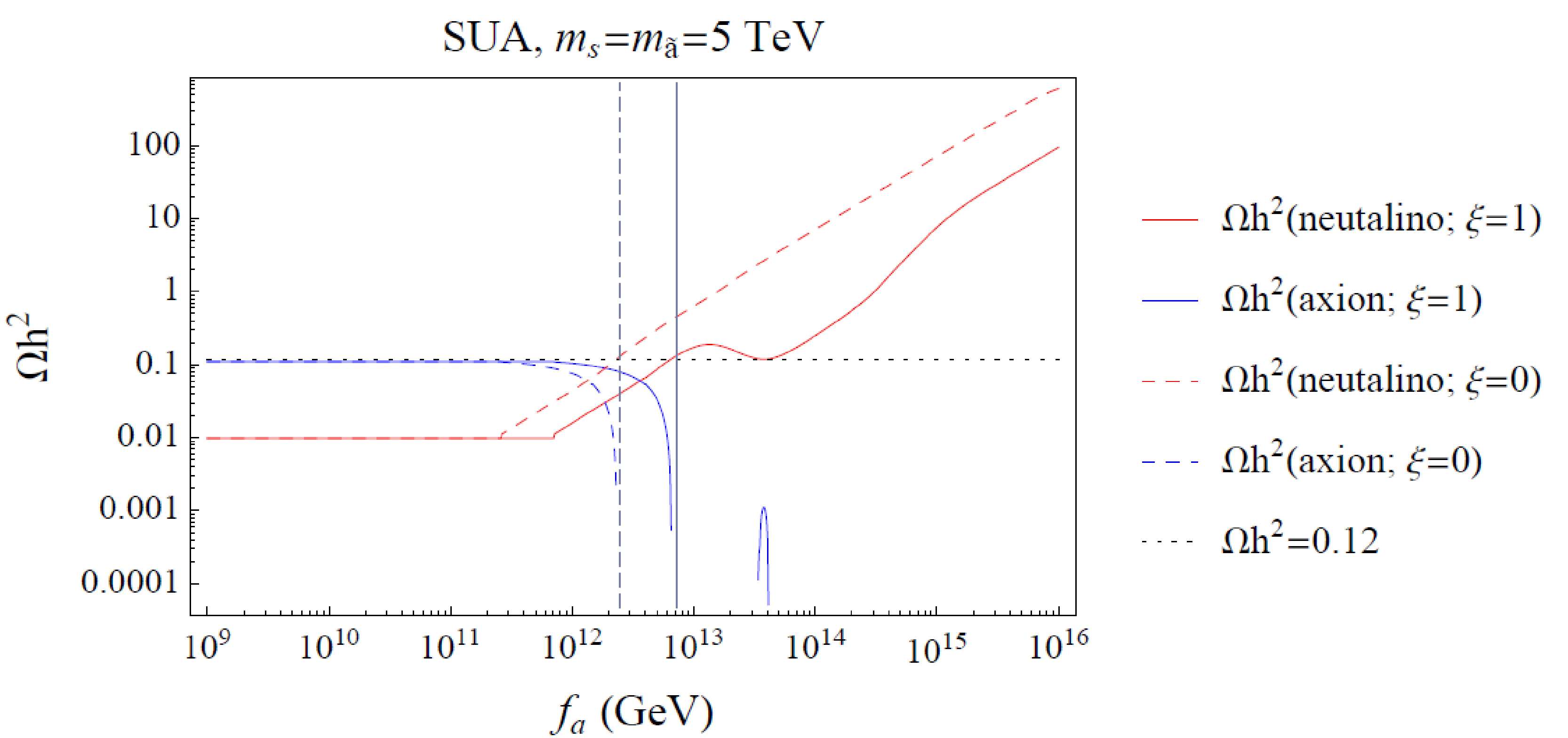
$$\Omega_{\tilde{H}} \approx 0.1 \frac{x_D}{x_f} \left(\frac{\mu}{1\mathrm{TeV}}\right)^2$$

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

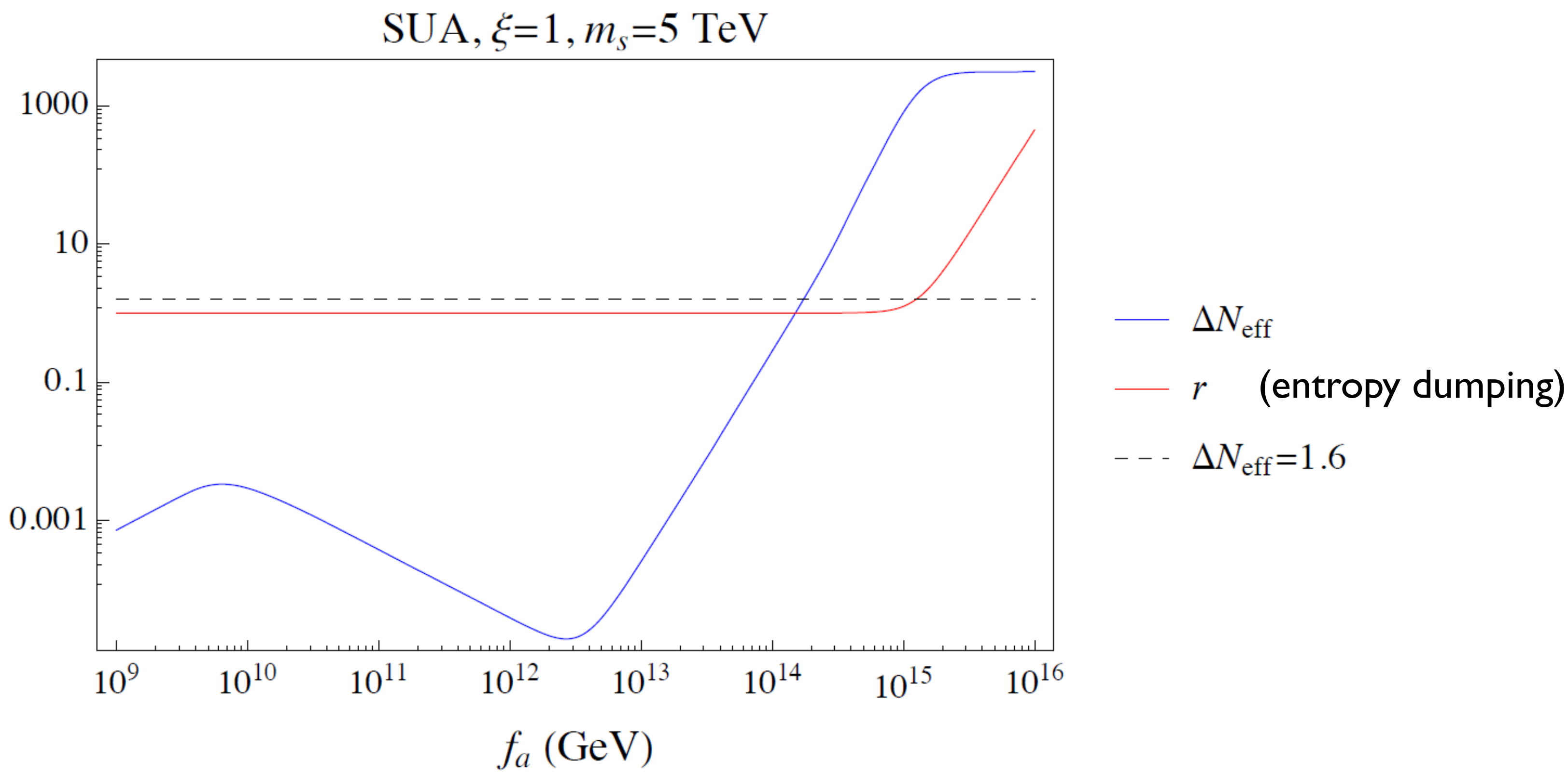
$$\Omega_{\tilde{a}} h^2 \approx 0.18\, \theta_1^2 \left(\frac{F_a}{10^{12}\mathrm{Gev}}\right)^{1.19} \left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right)$$

- Axino if very light (<MeV).

Dark Matter composition



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%)

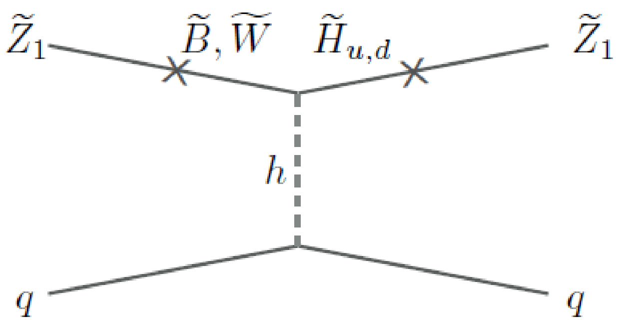
- High F_a region: $10^{13} - 10^{16}$ GeV.

  Overclosing neutralinos even after re-annihilation

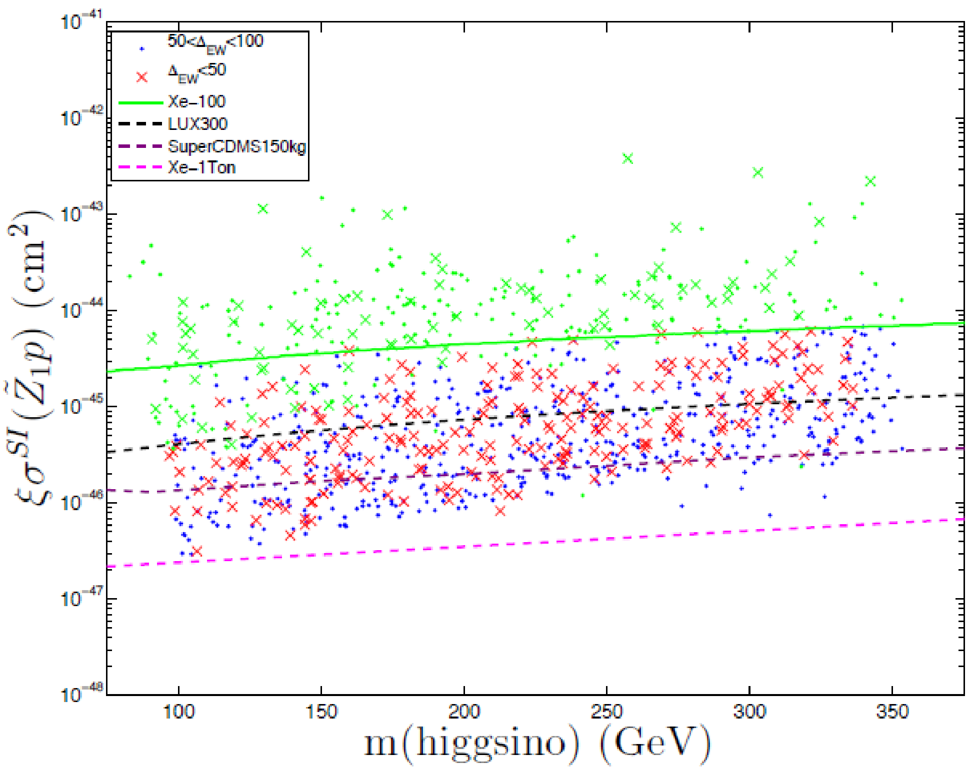
  Saxion oscillation produces sizable dark radiation (axion)

Neutralino detection

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

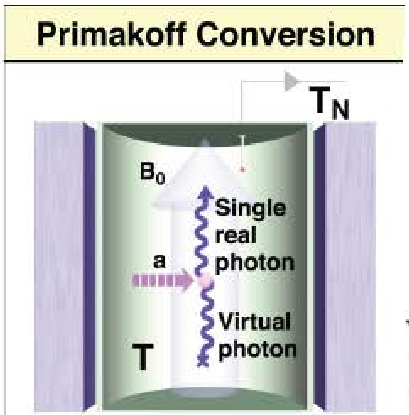


$$\xi \equiv \frac{\Omega_{\tilde{Z}_1} h^2}{0.12}$$

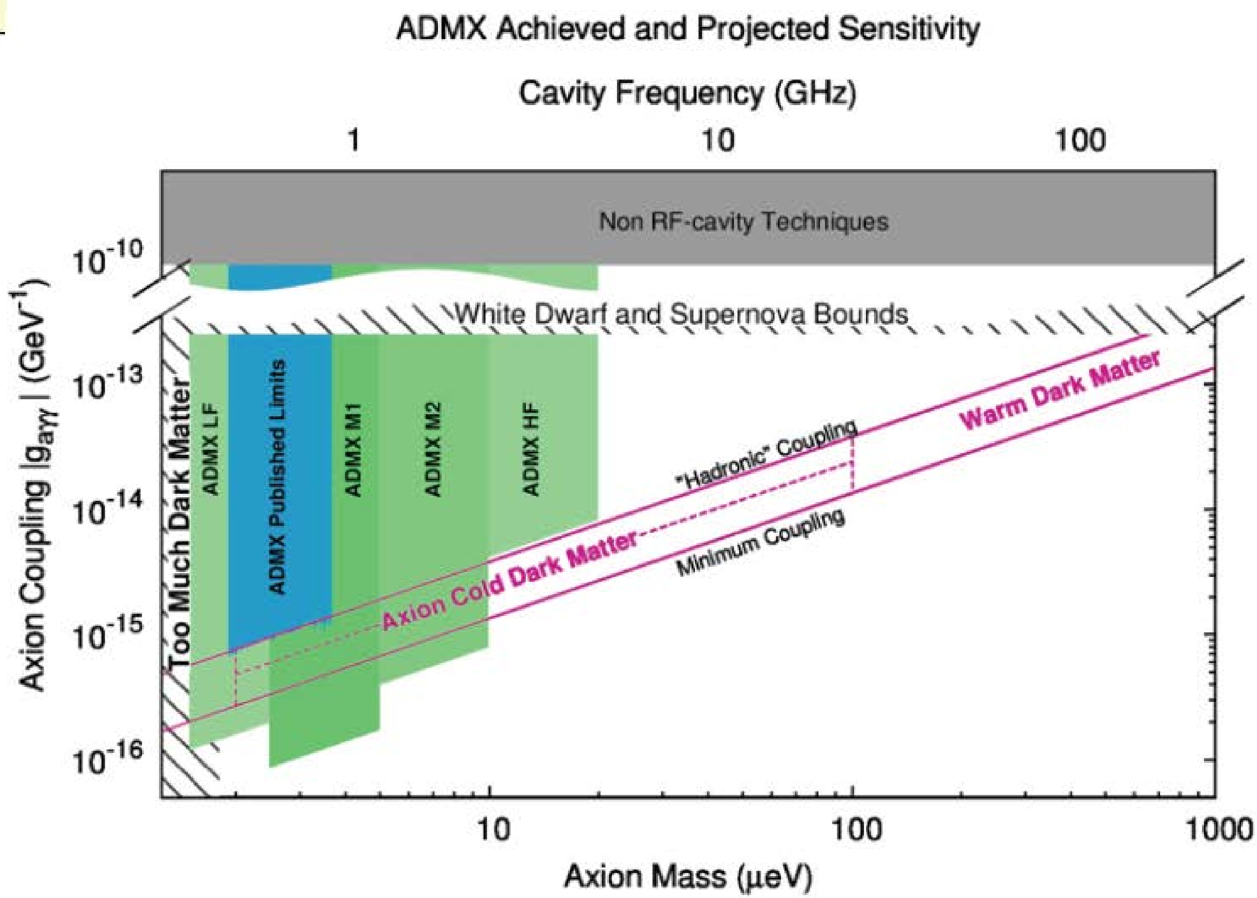


Baer, Barger, Mickelson

Axion detection



Rybka's Talk at Cosmic Frontier 2013



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

Conclusion

- Resolution of the mu, 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?