COSMOLOGY OF SUSY AXION MODELS

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March 6, 2013

OUTLINE

- Introduction
- Saxion cosmology
- Axino cosmology
- Summary and Implications

FINE-TUNING IN SM

Gauge Hierarchy Problem:

In the SM,

$$m_h^2 \ll \Lambda^2 \ (\sim M_{\rm GUT}^2 \text{ or } M_{\rm Planck}^2)$$

Quantum correction on Higgs mass is quadratically divergent,

$$m_h^2 = m_0^2 - \frac{3\lambda_t^2}{8\pi^2}\Lambda^2 + \cdots$$

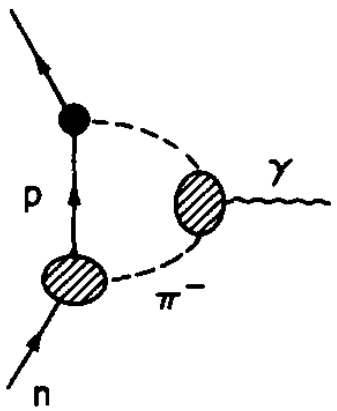
Introducing SUSY,

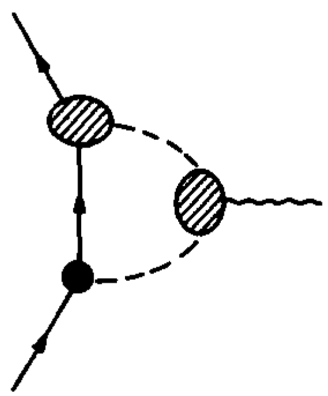
$$m_h^2 = m_{\rm soft}\left(1 - \frac{3\lambda_t^2}{8\pi^2}\ln\frac{\Lambda^2}{m_{\rm soft}} + \cdots\right)$$

Strong CP problem:

QCD θ-term, $\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$

generating CP-violating interaction,





$$D_n = 5.2 \times 10^{-16}\theta \; e \; cm$$

Crewther et al. (1979)

Experiment:

$$D_n < 2.9 \times 10^{-26} \; e \; cm \quad \Rightarrow \quad \theta \lesssim 10^{-11}$$

Introducing anomalous U(1) PQ symmetry,

$$\mathcal{L} \ni \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Dynamical relaxation of θ,

$$\left\langle \frac{a}{f_a} + \theta \right\rangle = 0$$

Peccei and Quinn

Combining SUSY & PQ naturally solves GH & strong CP prob.

SUSY AXION

Axion supermultiplet contains

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 \mathcal{F}_A$$

saxion, axion and axino.

Interactions: $v_{PQ} = f_a/\sqrt{2}$

$$\mathcal{L} = \frac{\xi}{2v_{PQ}} \int d^4\theta A^\dagger A A + \text{h.c.} \quad ; \quad s \to aa, \tilde{a}\tilde{a}$$

$$\mathcal{L} = -\frac{\alpha_s}{8\pi^2 v_{PQ}} \int d^2\theta A W^a W^a + \text{h.c.} \quad \text{for KSVZ} \quad ; \quad s \to gg, \tilde{g}\tilde{g}, \quad \tilde{a} \to \tilde{g}g$$

$$\mathcal{L} = -\frac{\mu}{v_{PQ}} \int d^2\theta A H_u H_d + \text{h.c.} \quad \text{for DFSZ} \quad ; \quad s \to hh, \quad \tilde{a} \to \tilde{\chi}h$$

Typical axion window: $10^9 \text{ GeV} \lesssim v_{PQ} \lesssim 10^{12} \text{ GeV}$

(But larger $v_{PQ} \sim 10^{16}$ GeV if $\theta_i << 1$)

$\Rightarrow$ tiny interactions, long life-time

Negligible for LHC, but important for Cosmology

SAXION COSMOLOGY

Mass of Saxion:

SUSY (holomorphicity) complexifies U(1):
Saxion mass from SUSY breaking, $m_s \sim m_{3/2} \sim m_{\rm soft} \sim \rm TeV$

For GMSB, saxion mass is generated by higher loops, $m_s \ll m_{\rm soft} \sim \rm TeV$

Production of Saxion:

by thermal scattering (KSVZ): DFSZ $\propto \mu$

$$\frac{\rho_s^{TP}}{s} \simeq 1.33 \times 10^{-5} g_s^6 \ln\left(\frac{1.01}{g_s}\right)\left(\frac{10^{12}\ \rm GeV}{f_a}\right)^2\left(\frac{T_R}{10^8\ \rm GeV}\right) m_s$$

Graf and Steffen

by coherent oscillation:

$$\frac{\rho_s^{TP}}{s} \simeq 1.9 \times 10^{-5}\ {\rm GeV}\left(\frac{\min\left[T_R, T_s\right]}{10^8\ \rm GeV}\right)\left(\frac{f_a}{10^{12}\ \rm GeV}\right)^2\left(\frac{s_0}{f_a}\right)^2$$

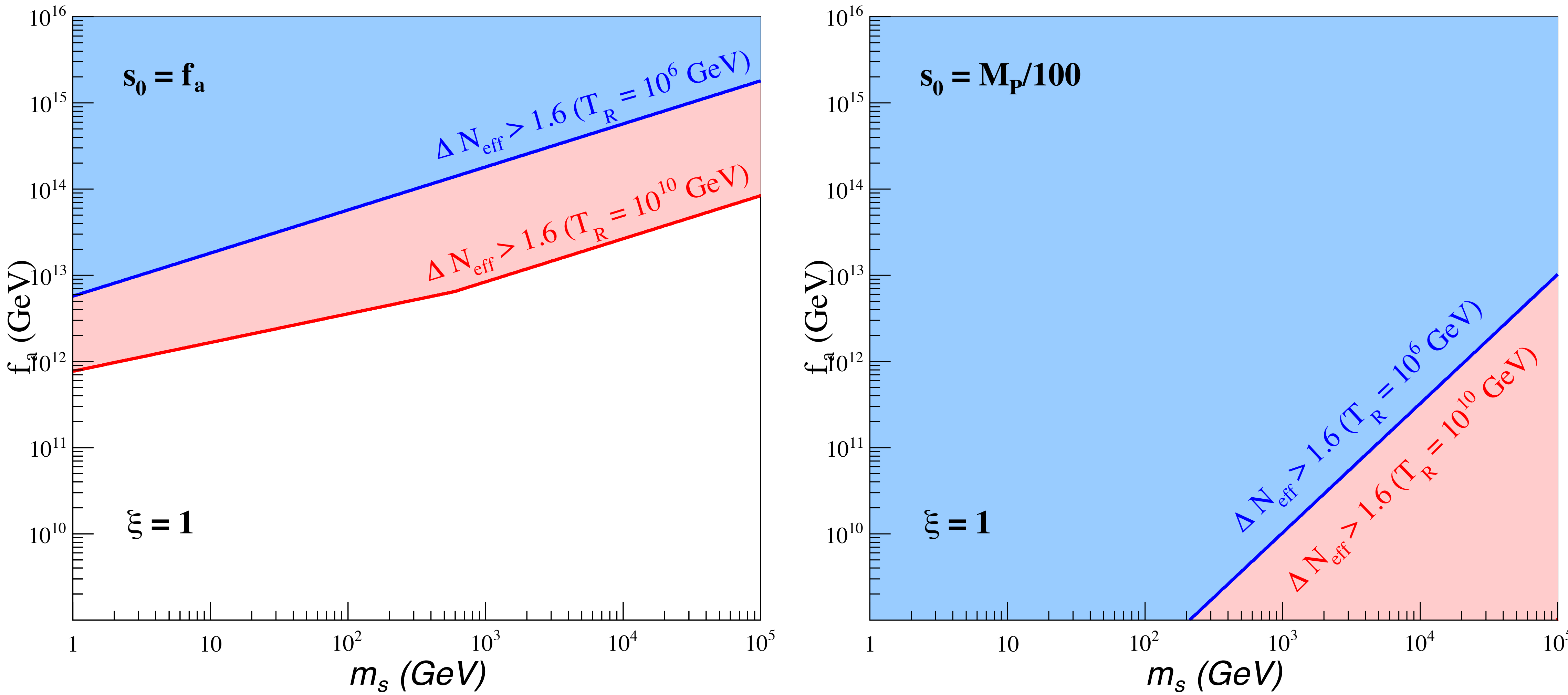
Decay of Saxion:

Ichikawa, Kawasaki, Nakayama, Senami, Takahashi; Moroi, Takimoto; Choi, Choi, Shin; KJB, Baer, Lessa; Jeong, Takahashi; Graf, Steffen

If the dominant mode is $s \to aa$

$\Rightarrow$ provides the dark radiation, constrained by CMB data.

$$\Delta N_\nu \lesssim 1.6$$



KJB, Baer, Lessa

Similar to axion CDM, $f_a \lesssim 10^{12}\ \mathrm{GeV} - 10^{13}\ \mathrm{GeV}$

If the dominant mode is $s \to gg(\gamma\gamma)$

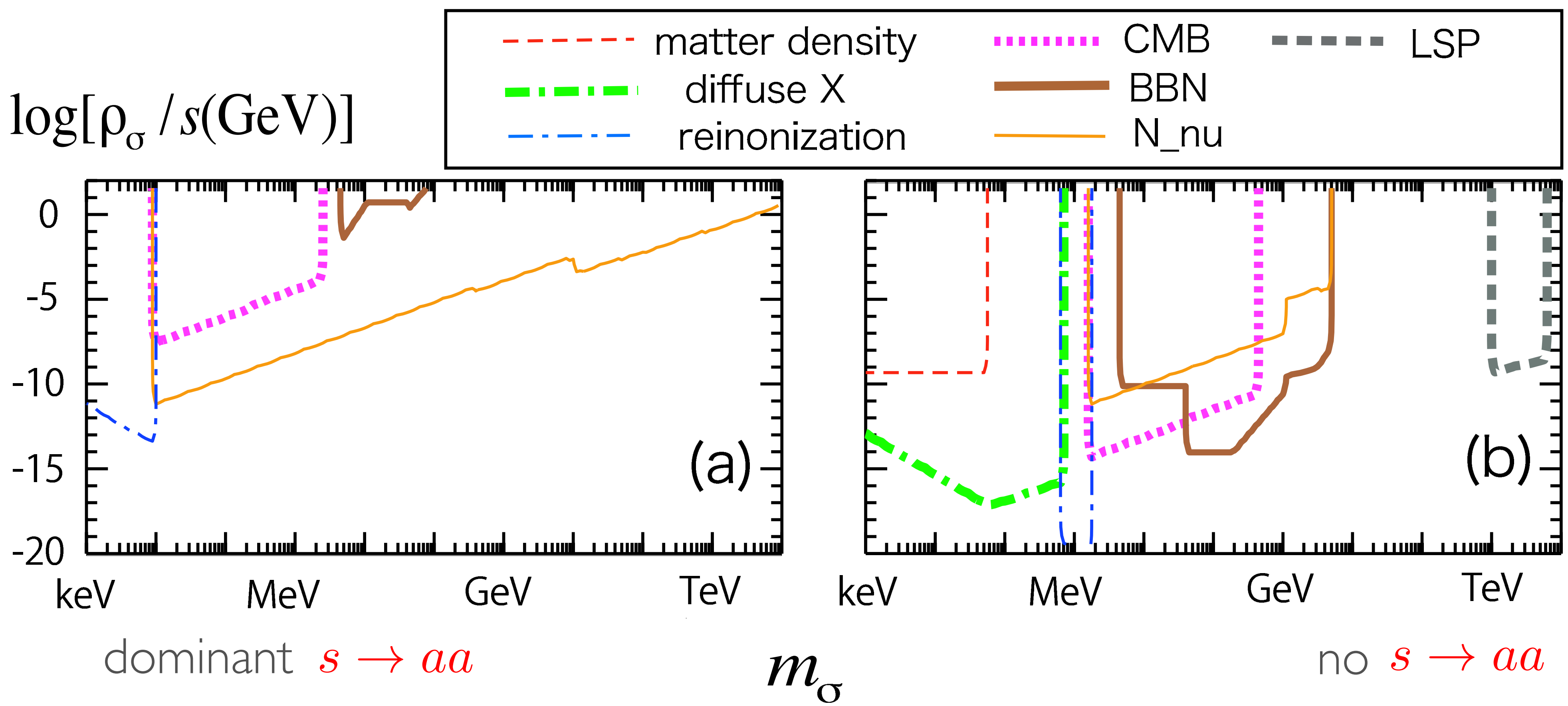
$\Rightarrow$ produces large amount of entropy, dilutes existing relics

For, $1\ \mathrm{MeV} \lesssim T_D \lesssim 1\ \mathrm{GeV}$, CO axion is diluted.

$\Rightarrow$ large PQ scale is allowed, $f_a \lesssim 10^{15}\ \mathrm{GeV}$ (for $\theta_i \sim 1$)

Lazarides, Schaefer, Seckel, Shafi; Kawasaki, Moroi, Yanagida

For longer life-time, important constraints are



Kawasaki, Nakayama, Senami

If saxion is heavy enough to decay into sparticles, it also contributes neutralino abundance.

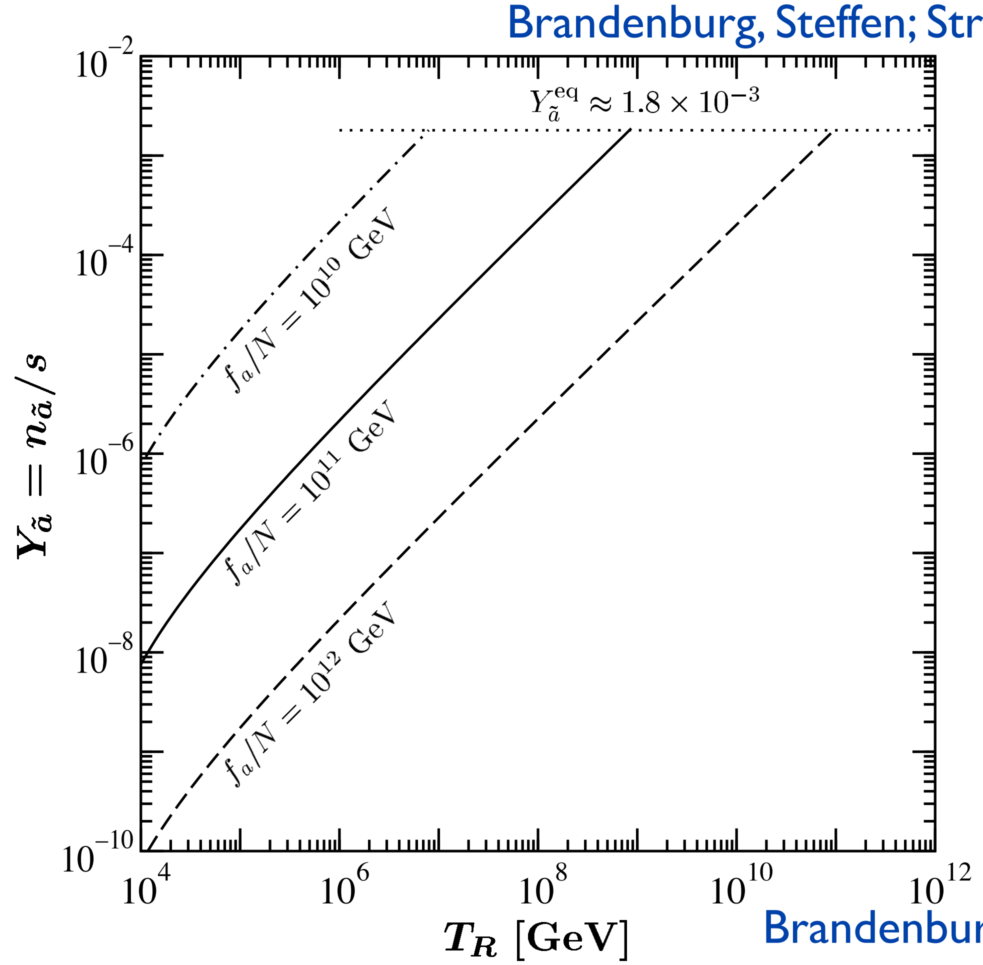
AXINO COSMOLOGY

Production of Axino:

by thermal scattering (KSVZ):

$$\frac{\rho_{\tilde a}}{s} \simeq 0.9\times 10^{-5} g_s^6 \ln\left(\frac{3}{g_s}\right) \times \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^8\ \mathrm{GeV}}\right) m_{\tilde a}$$

Covi, Kim, Kim, Roszkowski; Brandenburg, Steffen; Strumia

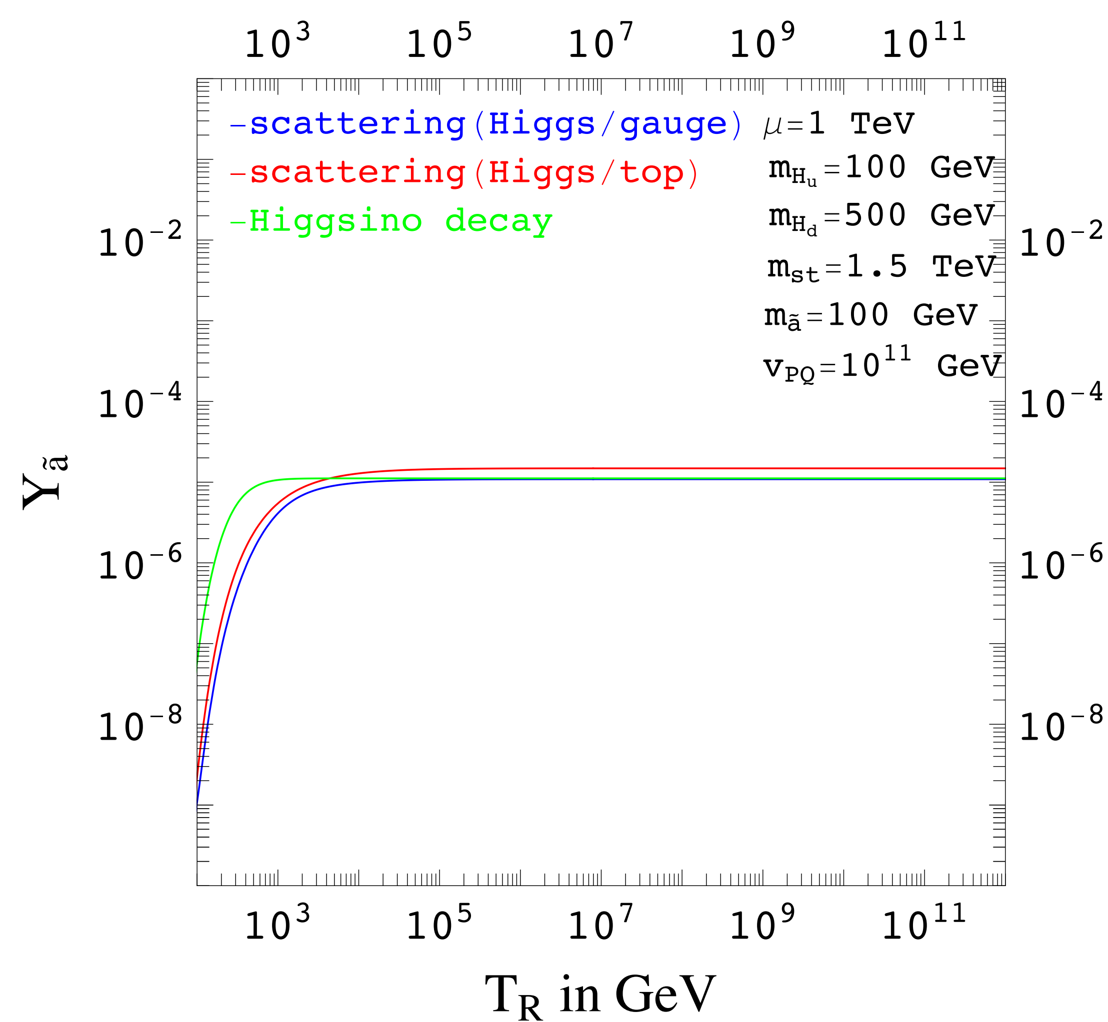


Brandenburg, Steffen

by thermal scattering and decay (or inverse decay) (DFSZ):

$$\frac{\rho_{\tilde a}}{s} \sim 10^{-5}\left(\frac{10^{11}\ \mathrm{GeV}}{f_a}\right)^2 \left(\frac{\mu}{1\ \mathrm{TeV}}\right)^2 m_{\tilde a}$$

Chun; KJB, Choi, Im; KJB, Chun, Im



Non-thermal production from out-of-equilibrium decay

e.g. $s \to \tilde{a}\tilde{a}, \quad \tilde{\chi} \to \gamma\tilde{a}$

Mass of Axino:

mass generated by SUSY breaking, $m_{\tilde{a}} \sim m_{3/2}$

It is highly model-dependent, and can be as light as keV or lighter.

Chun, Kim, Nilles

LSP Axino:

(hot/warm/cold) DM,
NLSP decay modifies cosmological observables (like saxion),
SuperWIMP scenario

Rajagopal, Turner, Wilczek; Covi, Kim, Roszkowski; Feng, Rajaraman, Takayama; Kawasaki, Kohri, Moroi; Jedamzik, Lemoine, Moultaka; Baer, Box, Summy; Choi, Choi, Shin

non-LSP Axino:

decay after LSP freeze-out
feeds neutralino abundance:
PQ augmented DM,
possible entropy production

Choi, Kim, Lee, Seto; Baer, Lessa, Sreethawong; Chun; KJB, Chun, Im

In any case, CO axion can be a (dominant) part of DM.

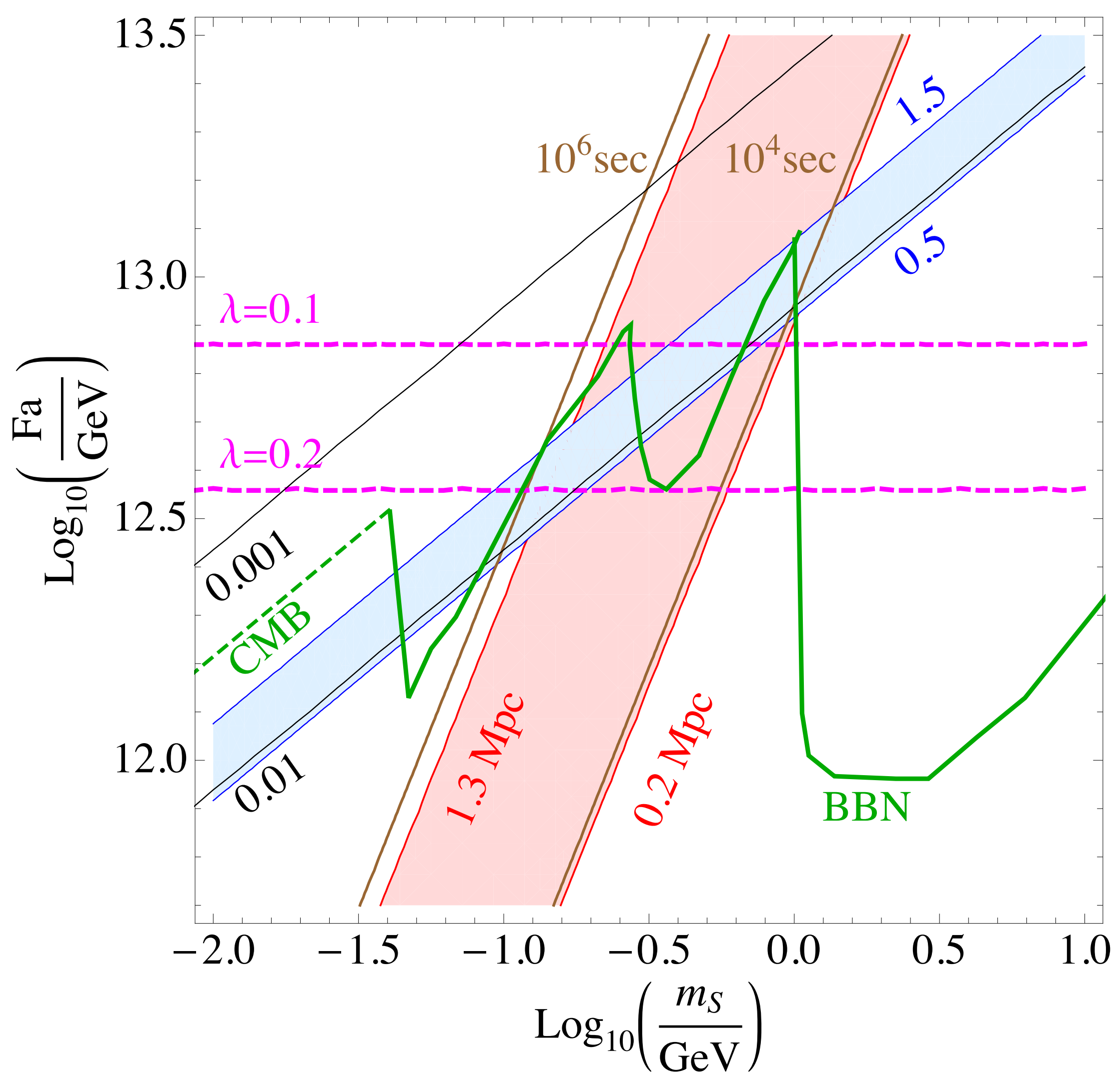
Axino DM:

Choi, Choi, Shin

Produced by late decay of saxion

Axino contributes to the warm dark matter, i.e. $\lambda_{\rm FS} = 0.2 - 1.3$ MPc

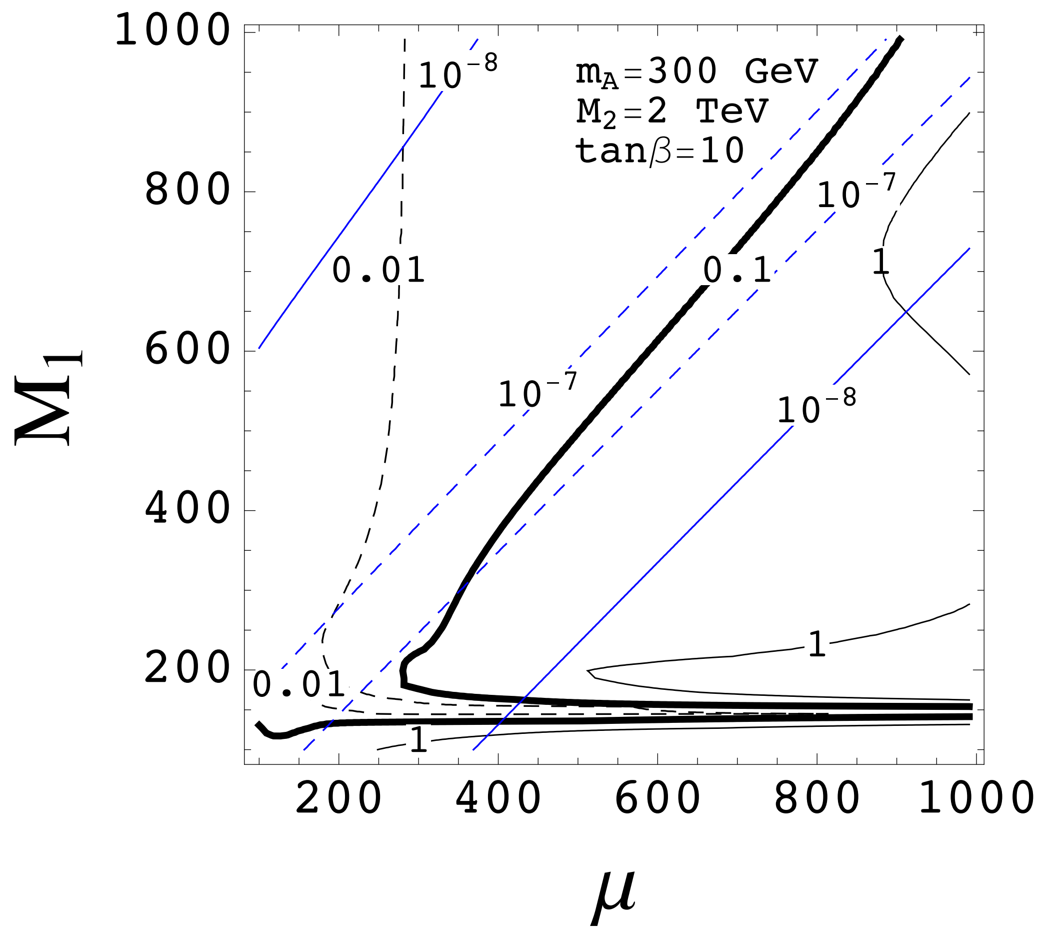
$m_{\tilde{a}} = 0.25 m_s$



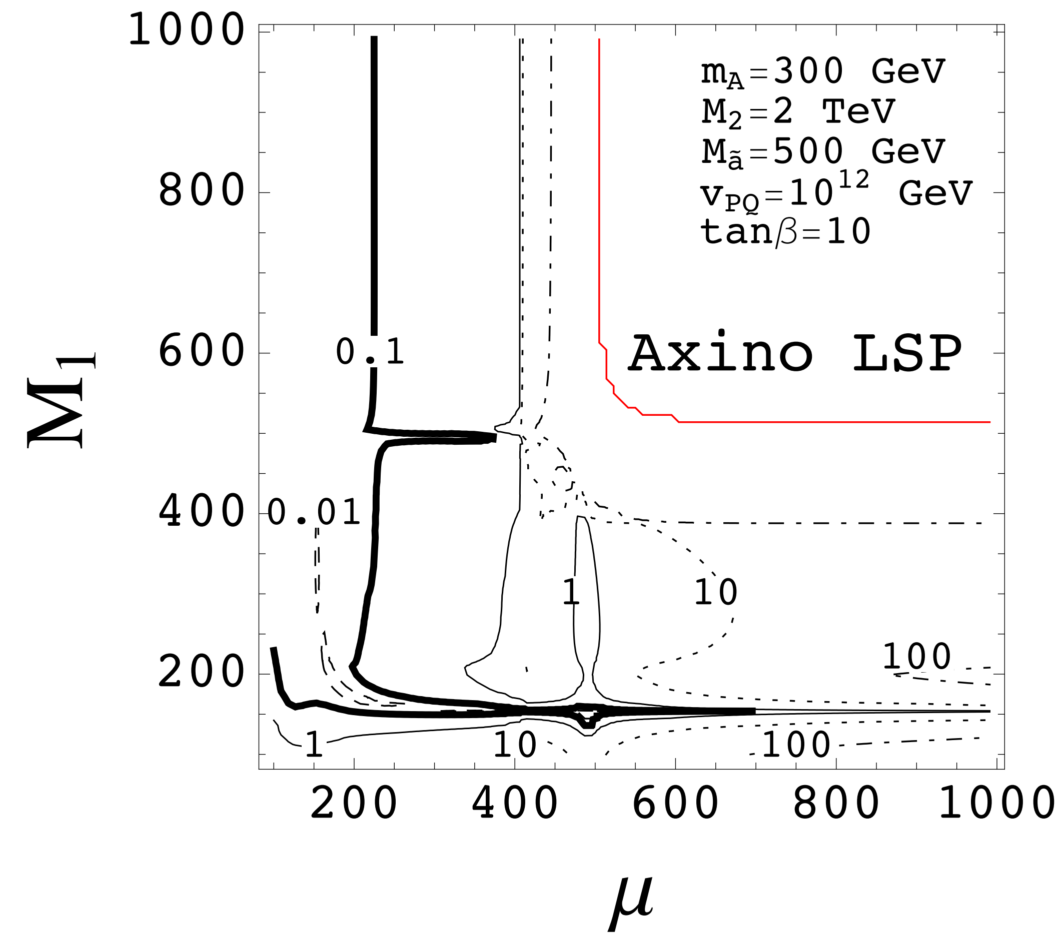
Decaying Axino:

Axino decay after neutralino freeze-out enhance DM abundance.

without axino decay



with axino decay



KJB, Chun, Im

SUMMARY & IMPLICATIONS

- SUSY axion solves both GH & strong CP prob.
- Due to the suppressed interactions, saxion & axino are long-lived and affect cosmological observations (BBN, CMB, etc.).
- Late decay of saxion can provide a source of DR as well as large amount of entropy (visible energy). It can also produce extra neutralinos.
- Axino can be either DM or decaying particle. Stable axino can be a good WDM while Decaying axino feeds neutralino DM abundance.

Implications for future research:

- SUSY models with standard underabundance can provide the right amount of DM (mostly neutralino or neutralino/axion admixture)
- SUSY models with standard overabundance are possibly viable if neutralino decays into light axino (SWIMP) or it is diluted by saxion decay.
- Large PQ scale region, $10^{12}\ \mathrm{GeV} < f_a < 10^{16}\ \mathrm{GeV}$ can be viable, experimental method for high PQ scale would be investigated. (e.g. molecular interferometry) Graham and Rajendran