DARK MATTER IN SUSY DFSZ AXION MODEL

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based on
KJB, Baer, Chun 1309.0515, 1309.5365
KJB, Baer, Lessa, Serce, in progress

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OVERVIEW

SUSY & PQ

Fine-tuning problems in SM:

- quadratic divergence: $\Delta m_h^2 = \Lambda^2_{\text{cut-off}} + \cdots$ removed by SUSY
- Strong CP problem: $\bar{\theta} G\widetilde{G} \Rightarrow \left(\bar{\theta} + \frac{a}{f_a}\right) G\widetilde{G} \Rightarrow \langle \frac{a}{f_a} \rangle = -\bar{\theta}$ axion

SUSY axion

SUSY partner saxion, axino:

- thermal production: scattering, decay & inverse decay
- late decay: might decay after neutralino freeze-out

affects the neutralino density $\longrightarrow$ augmented WIMP density

also axion CDM

two DM scenario

DFSZ AXION MODEL

Effective Interaction:

$$W = Z(XY - v_{PQ}^2) + \frac{X^2}{M_P} H_u H_d$$

$$X = (v_{PQ} + \rho_1) e^{A/v_{PQ}}, \quad Y = (v_{PQ} + \rho_1) e^{-A/v_{PQ}}, \quad Z = \rho_2$$

$$\Downarrow$$

$$W_{\rm eff} = \mu e^{2A/v_{PQ}} H_u H_d \qquad \mu \sim v_{PQ}^2 / M_P$$

Kim-Nilles mechanism

Interactions via Higgs sector:

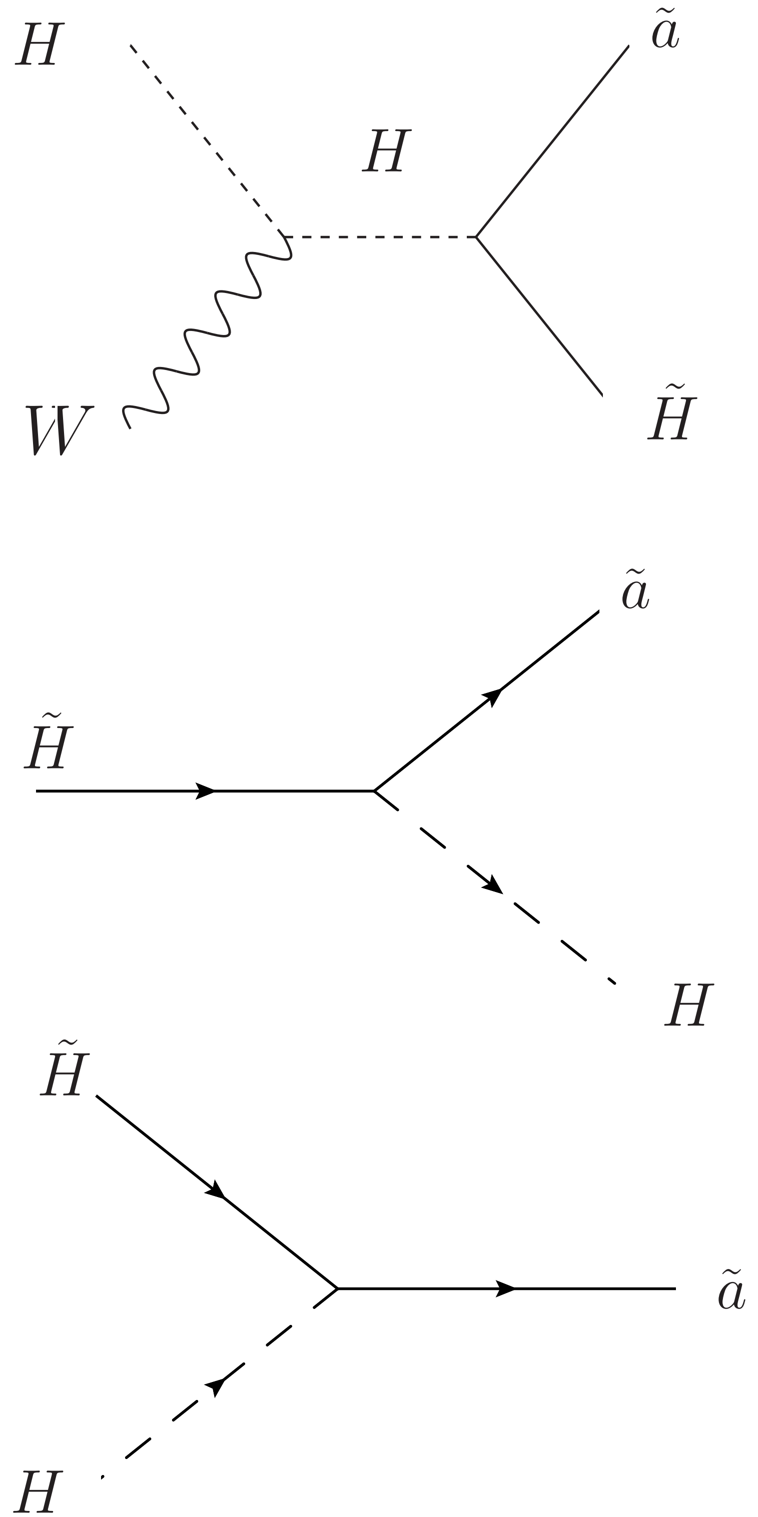
- AHH trilinear int.
- mixing with higgs & higgsino

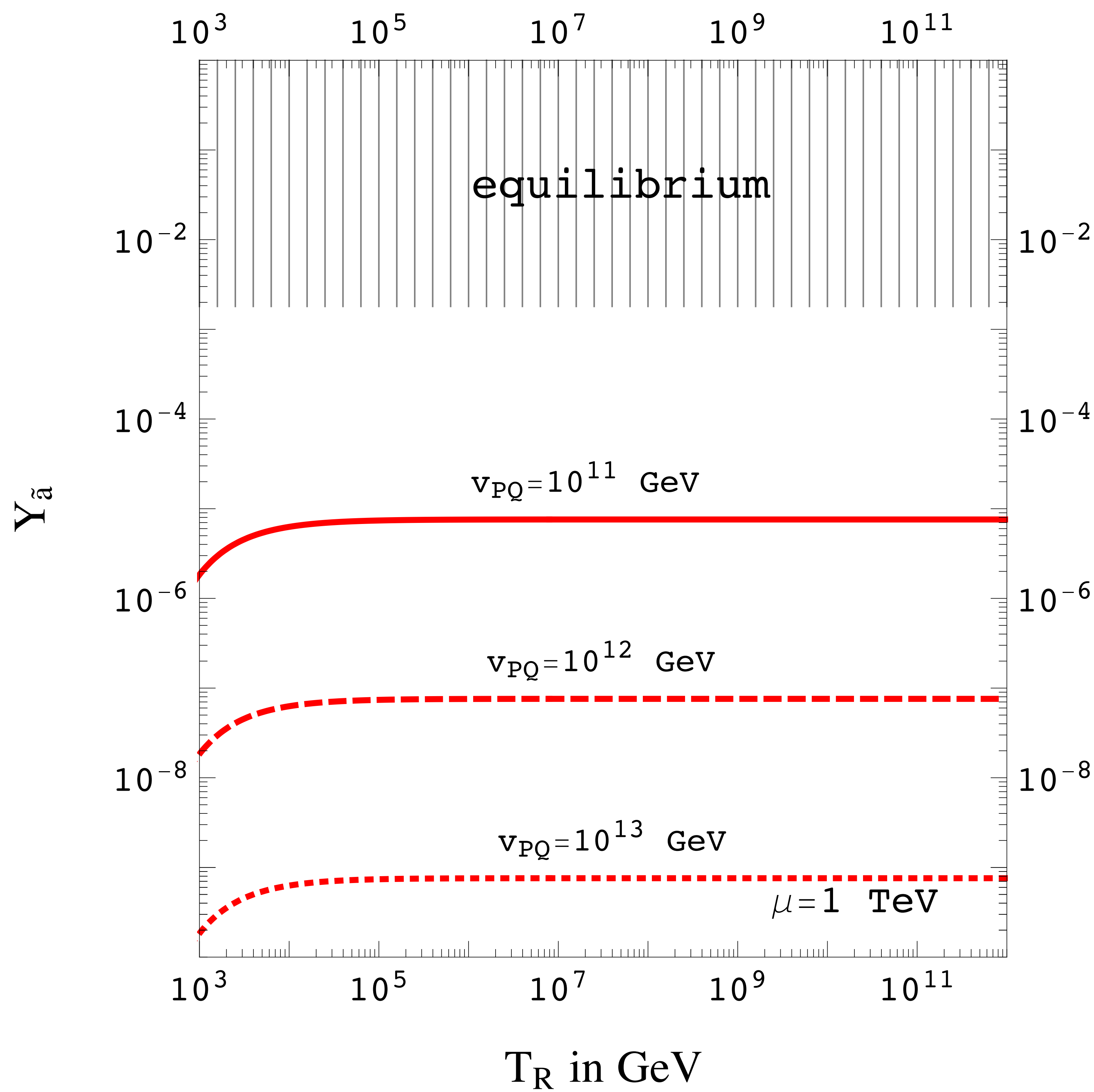
Production of axino/saxion:

scattering/decay/inverse-decay of particles in thermal equilibrium:

“Freeze-In”

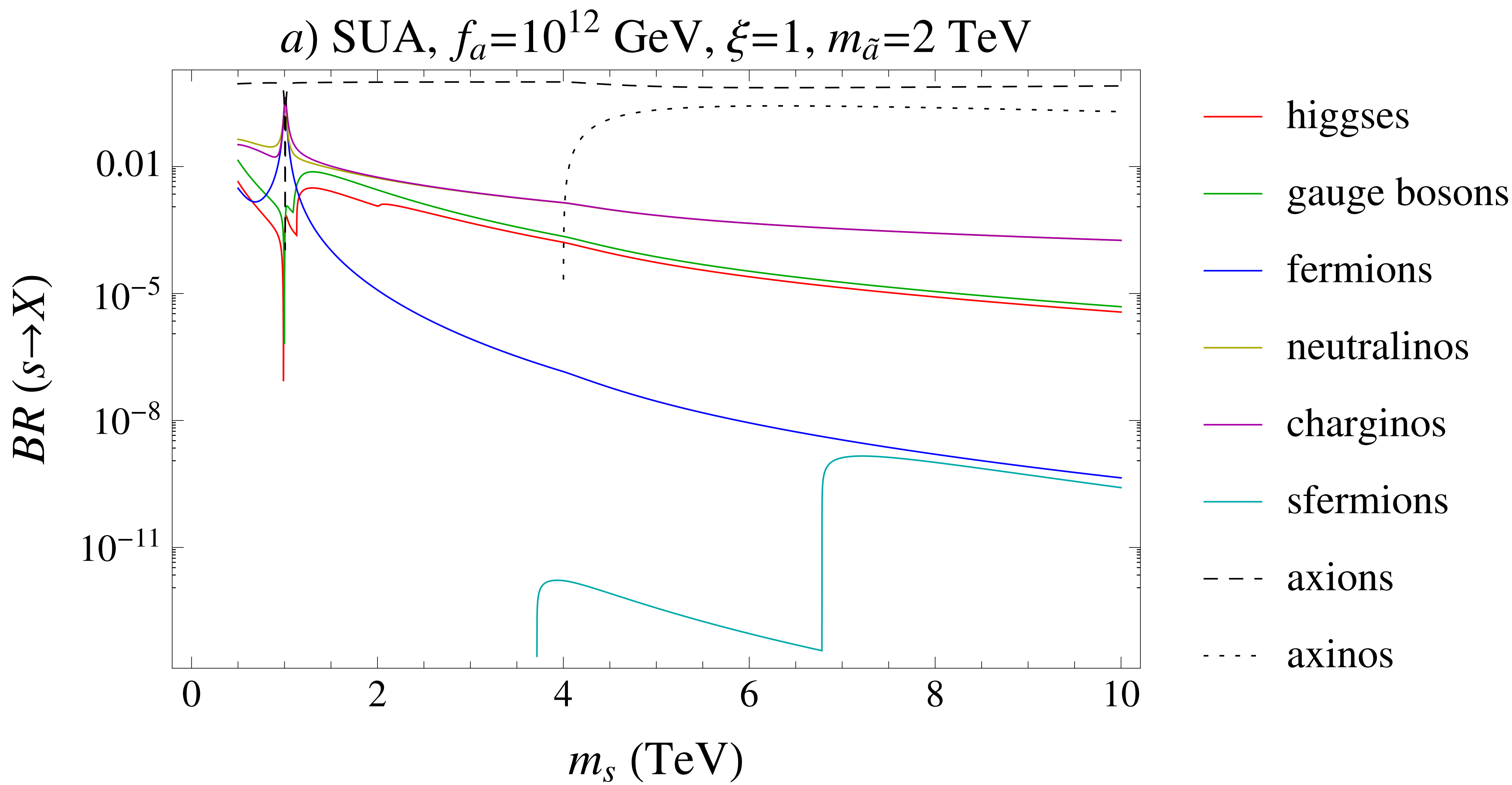
Chun; KJB, Choi, Im; KJB, Chun, Im



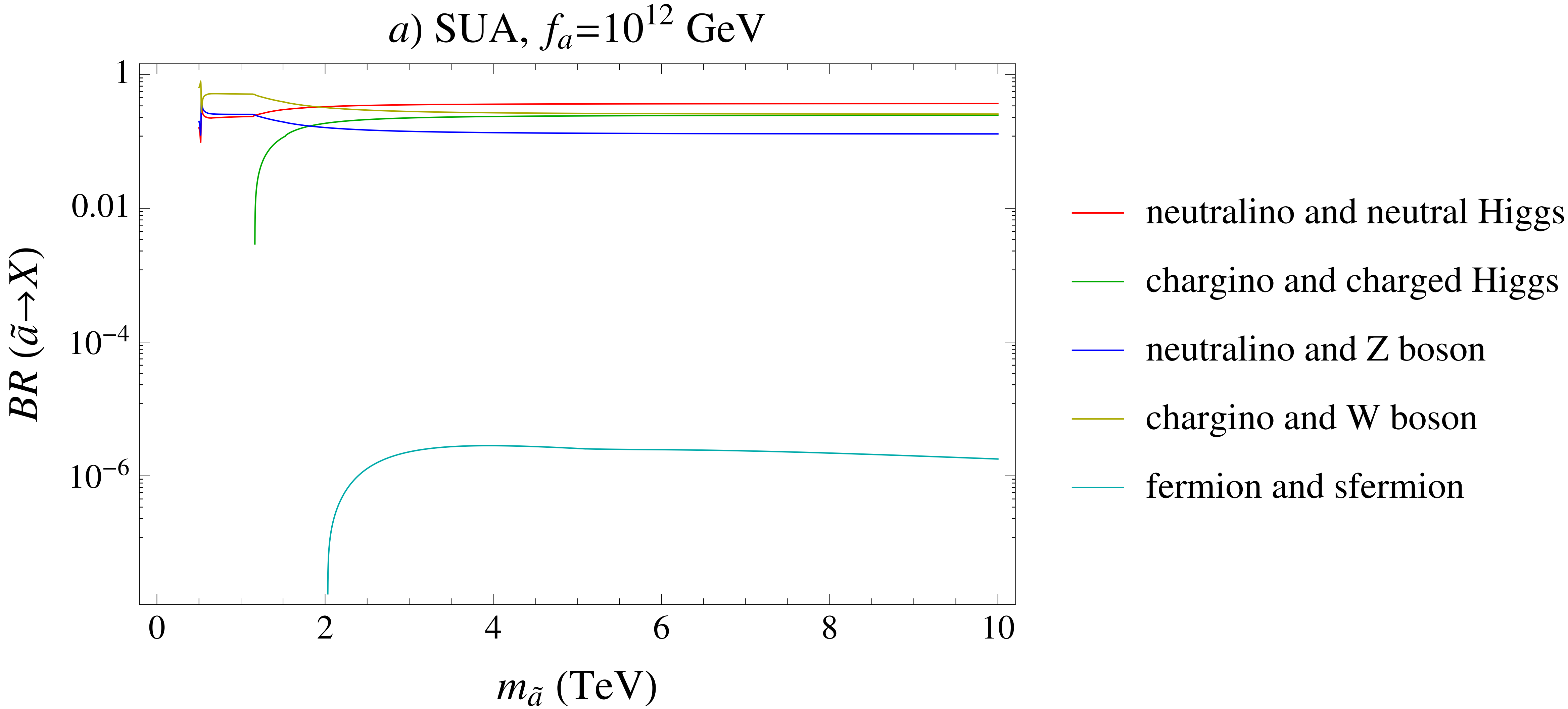


Decay of saxion: $T_D^s = \mathcal{O}(10^{-4}) - \mathcal{O}(10^4)$ GeV

KJB, Baer, Chun



Decay of axino: $T_D^{\tilde{a}} = \mathcal{O}(10^{-4}) - \mathcal{O}(10^{4})$ GeV



BOLTZMANN EQS.

8 Coupled Boltzmann eqs:

1) rad
2) neutralino
3) axion TP
4) axion CO
5) saxion TP
6) saxion CO
7) axino
8) gravitino

$$\frac{dn_i}{dt} + 3Hn_i = \langle \sigma v \rangle (\bar{n}_i^2 - n_i^2)$$
$$- \Gamma_i m_i \frac{n_i}{\rho_i} \left(n_i - \bar{n}_i \sum_{i \to \cdots} B_{ab\cdots} \frac{n_a n_b \cdots}{\bar{n}_a \bar{n}_b \cdots} \right)$$
$$+ \sum_a \Gamma_a B_i m_a \frac{n_a}{\rho_a} \left(n_a - \bar{n}_a \sum_{a \to i \cdots} \frac{B_{ib\cdots}}{B_i} \frac{n_i n_b \cdots}{\bar{n}_i \bar{n}_b \cdots} \right)$$

BOLTZMANN EQS.

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6) saxion CO
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8) gravitino

$$
\begin{aligned}
\frac{dn_i}{dt} + 3Hn_i = &\boxed{\langle\sigma v\rangle(\bar{n}_i^2 - n_i^2)} \\
&- \Gamma_i m_i \frac{n_i}{\rho_i}\left(n_i - \bar{n}_i \sum_{i\to\cdots} B_{ab\cdots} \frac{n_a n_b \cdots}{\bar{n}_a \bar{n}_b \cdots}\right) \\
&+ \sum_a \Gamma_a B_i m_a \frac{n_a}{\rho_a}\left(n_a - \bar{n}_a \sum_{a\to i\cdots} \frac{B_{ib\cdots}}{B_i} \frac{n_i n_b \cdots}{\bar{n}_i \bar{n}_b \cdots}\right)
\end{aligned}
$$

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$$+ \sum_a \Gamma_a B_i m_a \frac{n_a}{\rho_a}\left(n_a - \bar{n}_a \sum_{a\to i\cdots} \frac{B_{ib\cdots}}{B_i}\frac{n_i n_b \cdots}{\bar{n}_i \bar{n}_b \cdots}\right)$$

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BOLTZMANN EQS.

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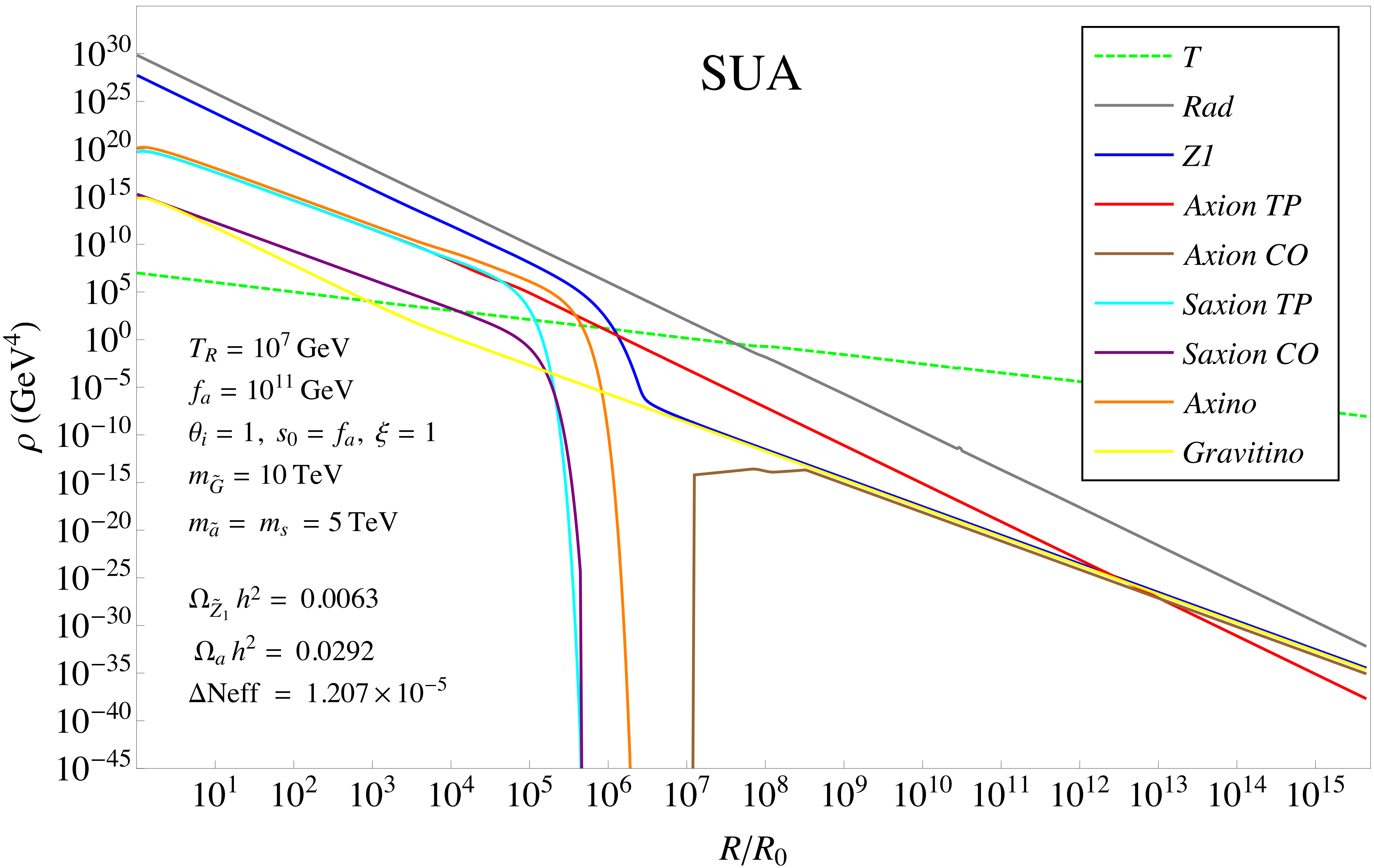
6) saxion CO
7) axino
8) gravitino

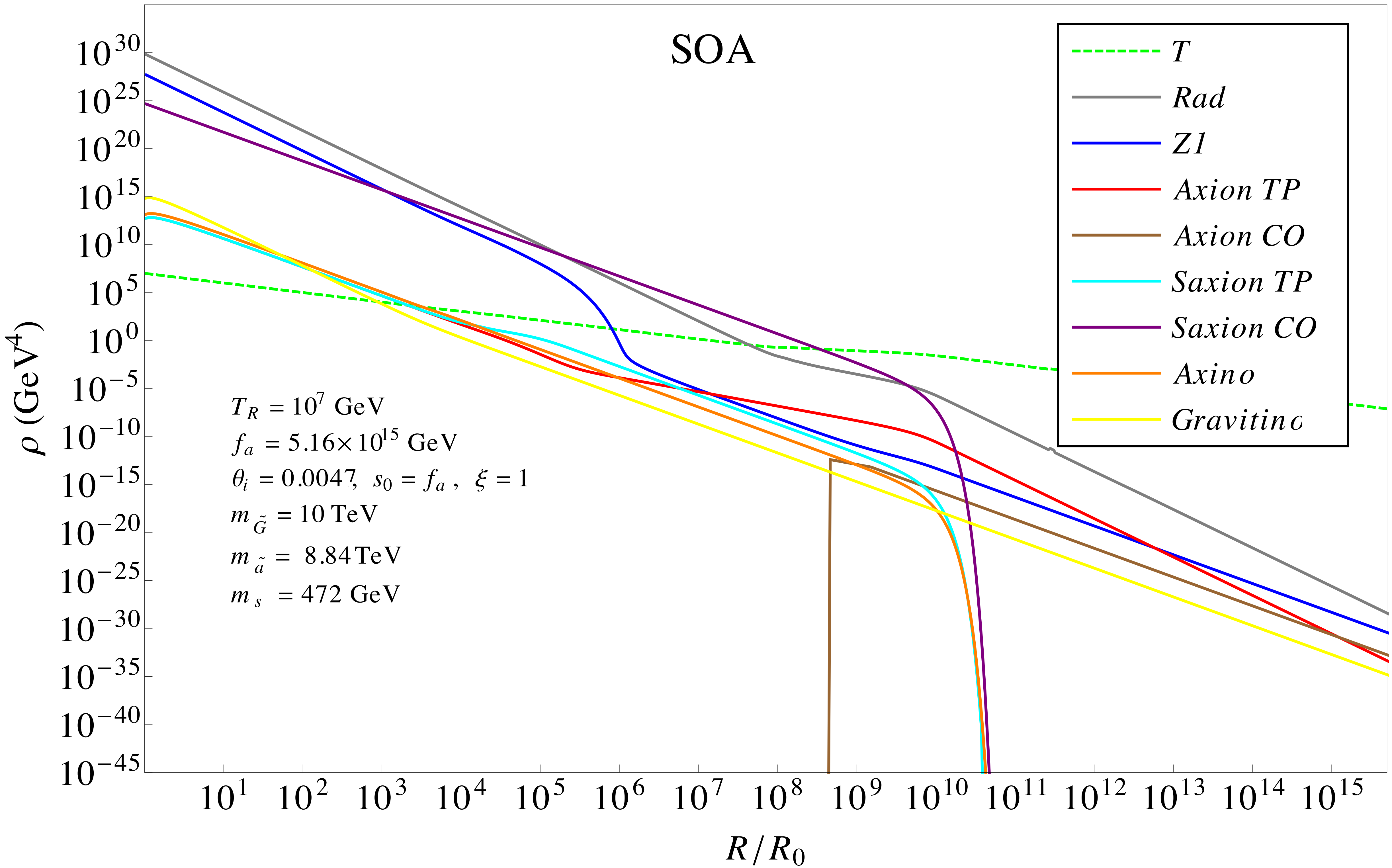
$$\frac{dn_i}{dt} + 3Hn_i = \langle\sigma v\rangle(\bar{n}_i^2 - n_i^2) - \Gamma_i m_i \frac{n_i}{\rho_i}\left(n_i - \bar{n}_i \sum_{i\to\cdots} B_{ab\cdots}\frac{n_a n_b\cdots}{\bar{n}_a\bar{n}_b\cdots}\right) + \sum_a \Gamma_a B_i m_a \frac{n_a}{\rho_a}\left(n_a - \bar{n}_a \sum_{a\to i\cdots}\frac{B_{ib\cdots}}{B_i}\frac{n_i n_b\cdots}{\bar{n}_i\bar{n}_b\cdots}\right)$$

$$\frac{d\rho_i}{dt} + 3H(\rho_i + P_i) = \langle\sigma v\rangle\frac{\rho_i}{n_i}(\bar{n}_i^2 - n_i^2) - \Gamma_i m_i\left(n_i - \bar{n}_i \sum_{i\to\cdots} B_{ab\cdots}\frac{n_a n_b\cdots}{\bar{n}_a\bar{n}_b\cdots}\right) + \sum_a \Gamma_a B_i \frac{m_a}{2}\left(n_a - \bar{n}_a \sum_{a\to i\cdots}\frac{B_{ib\cdots}}{B_i}\frac{n_i n_b\cdots}{\bar{n}_i\bar{n}_b\cdots}\right)$$

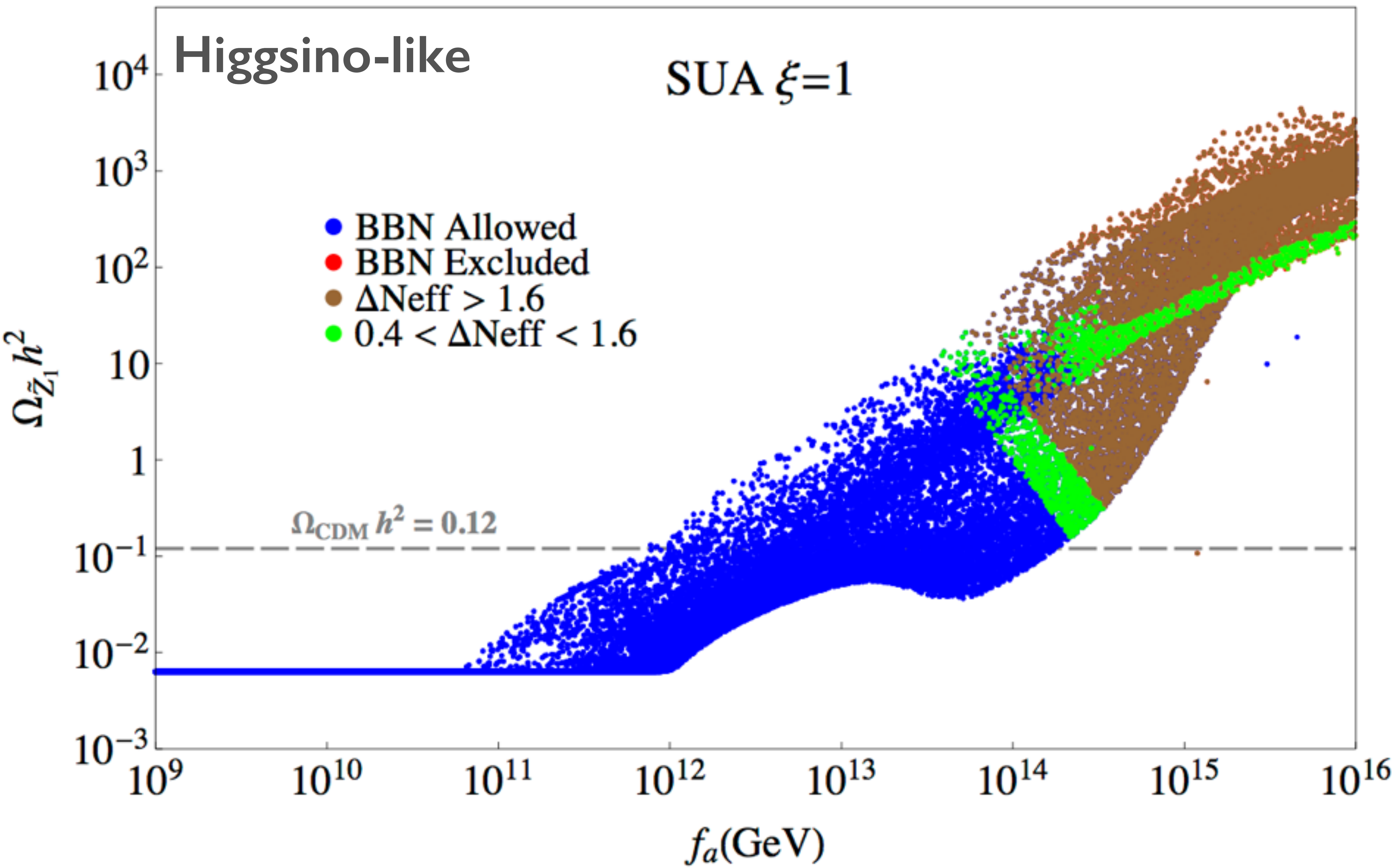
EVOLUTION


SUA
T
Rad
Z1
Axion TP
Axion CO
Saxion TP
Saxion CO
Axino
Gravitino
$T_R = 10^7$ GeV
$f_a = 10^{11}$ GeV
$\theta_i = 1,\ s_0 = f_a,\ \xi = 1$
$m_{\tilde{G}} = 10$ TeV
$m_{\tilde{a}} = m_s = 5$ TeV
$\Omega_{\tilde{Z}_1} h^2 = 0.0063$
$\Omega_a h^2 = 0.0292$
ΔNeff $= 1.207 \times 10^{-5}$
ρ (GeV^4)
R/R_0
10^{30} 10^{25} 10^{20} 10^{15} 10^{10} 10^{5} 10^{0} 10^{-5} 10^{-10} 10^{-15} 10^{-20} 10^{-25} 10^{-30} 10^{-35} 10^{-40} 10^{-45}
10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}

EVOLUTION

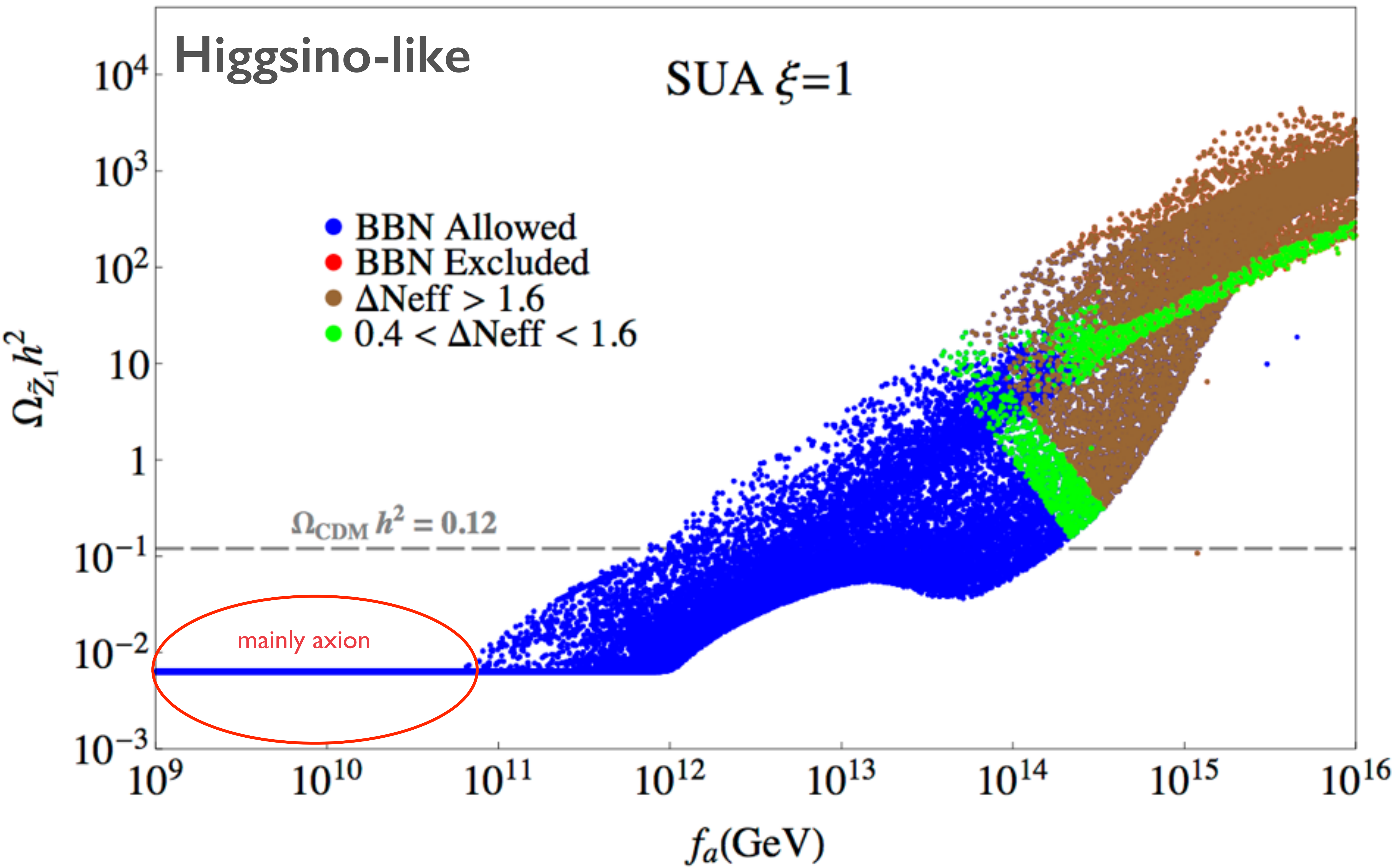

SOA
T
Rad
Z1
Axion TP
Axion CO
Saxion TP
Saxion CO
Axino
Gravitino
$T_R = 10^7$ GeV
$f_a = 5.16\times10^{15}$ GeV
$\theta_i = 0.0047,\ s_0 = f_a,\ \xi = 1$
$m_{\tilde{G}} = 10$ TeV
$m_{\tilde{a}} = 8.84$ TeV
$m_s = 472$ GeV
ρ (GeV^4)
R/R_0

RESULTS



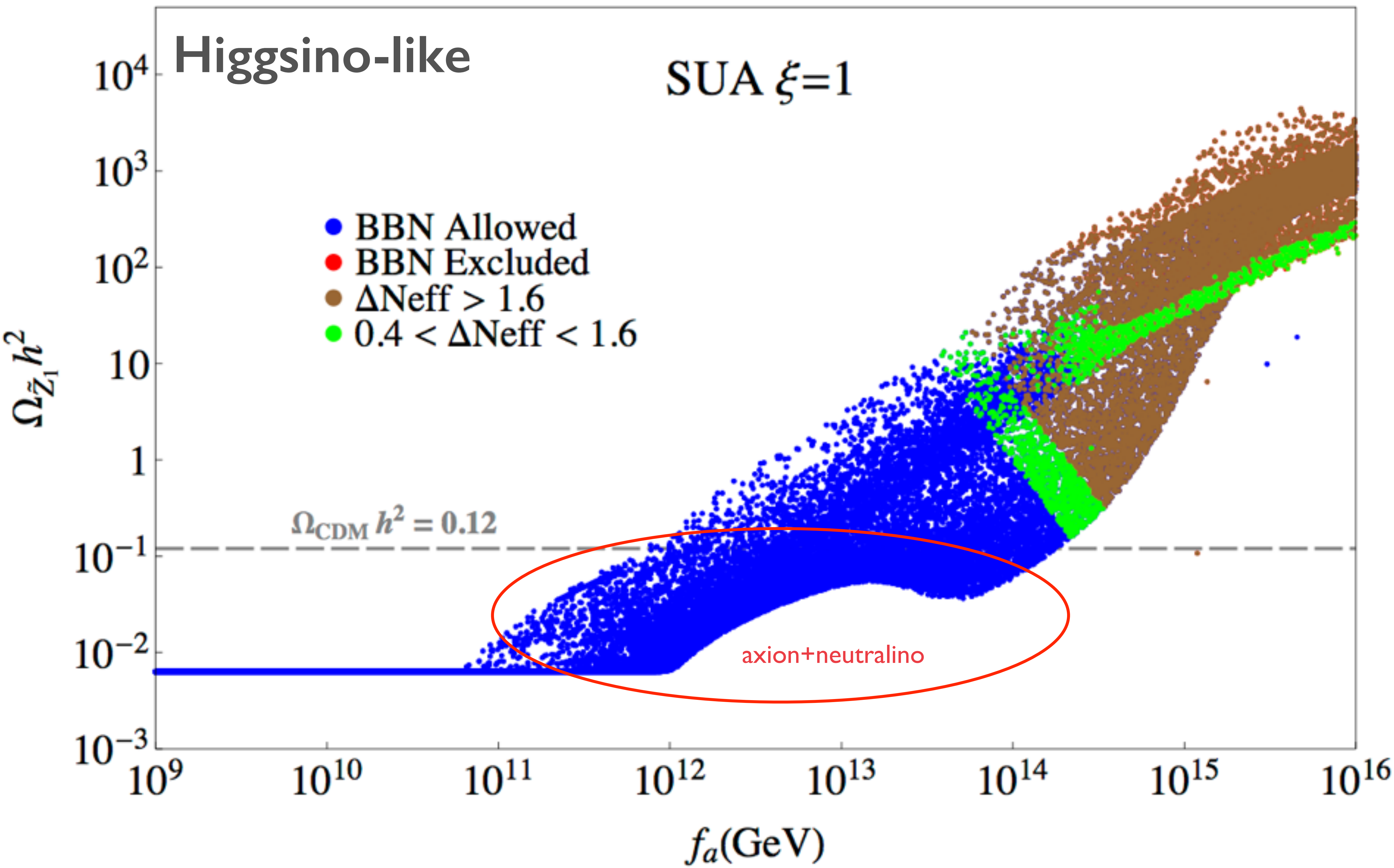
Higgsino-like
SUA ξ=1
BBN Allowed
BBN Excluded
ΔNeff > 1.6
0.4 < ΔNeff < 1.6
$\Omega_{CDM} h^2 = 0.12$
$\Omega_{\tilde{Z}_1} h^2$
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
f_a(GeV)

RESULTS

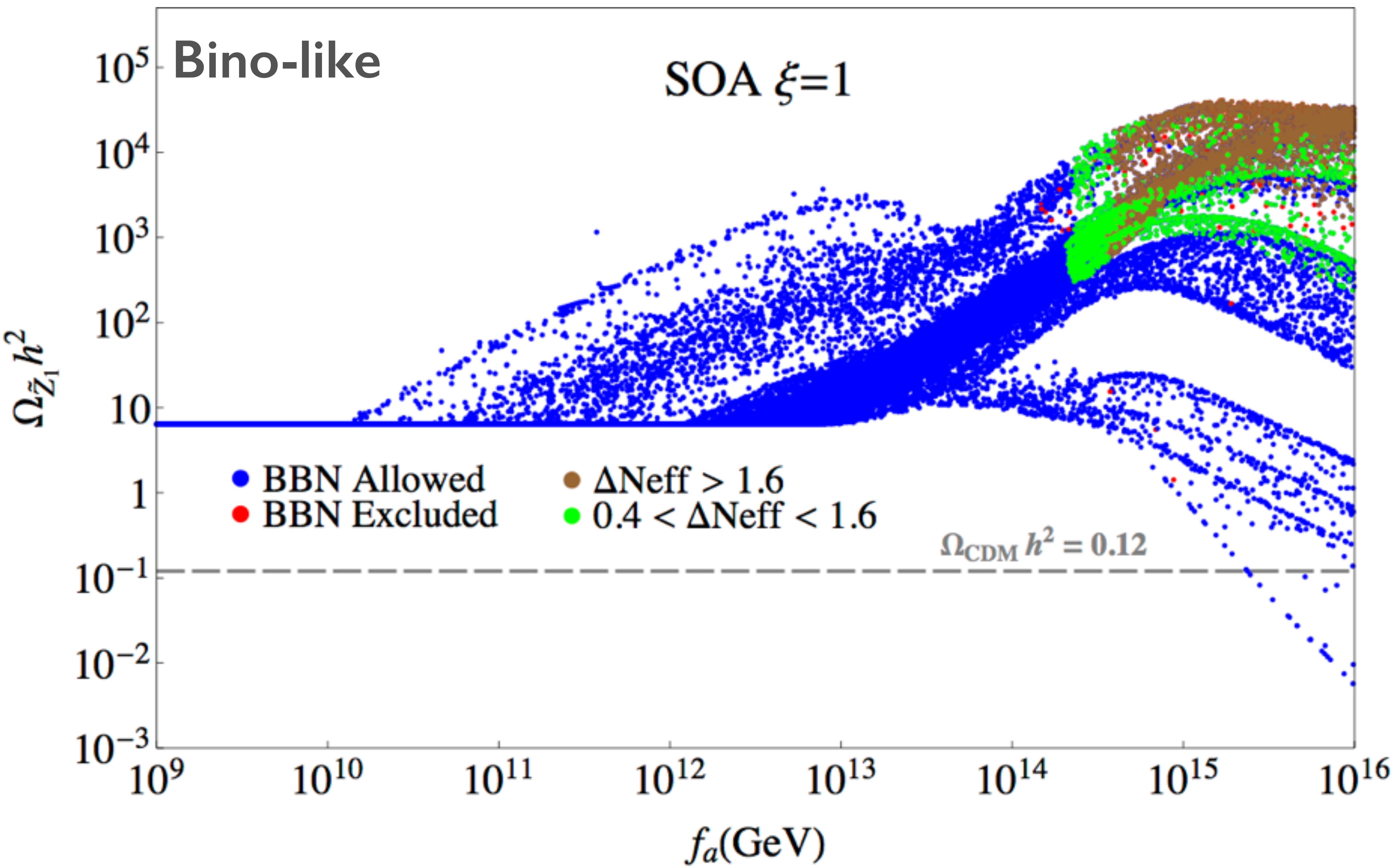


Higgsino-like
SUA ξ=1
BBN Allowed
BBN Excluded
ΔNeff > 1.6
0.4 < ΔNeff < 1.6
$\Omega_{CDM} h^2 = 0.12$
mainly axion
$\Omega_{\tilde{Z}_1} h^2$
f_a(GeV)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}

RESULTS


Higgsino-like
SUA ξ=1
BBN Allowed
BBN Excluded
ΔNeff > 1.6
0.4 < ΔNeff < 1.6
$\Omega_{CDM} h^2 = 0.12$
axion+neutralino
$\Omega_{\tilde{Z}_1} h^2$
f_a(GeV)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}

RESULTS



Bino-like
SOA ξ=1
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
$\Omega_{\tilde{Z}_1} h^2$
BBN Allowed
BBN Excluded
ΔNeff > 1.6
0.4 < ΔNeff < 1.6
$\Omega_{CDM} h^2 = 0.12$
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
f_a(GeV)

COMMENTS ON BICEP2

BICEP2 result:

r~0.16 with $H_I \sim 10^{14}$ GeV implies

1) PQ broken during & after inflation ($f_a > H_I$):

Marsh, Grin, Hlozek, Ferreira; Visinelli, Gondolo

massless axion $\longrightarrow$ isocurvature perturb.

$$\mathcal{P}_a \sim 4\left(\frac{\Omega_a}{\Omega_{CDM}}\right)^2\left(\frac{H_I}{2\pi f_a \theta_i}\right)^2 \lesssim 0.04\mathcal{P}_{\mathcal{R}}$$

Planck 2013

$$f_a \gtrsim 10^{28}\ \mathrm{GeV} \times \left(\frac{\Omega_a h^2}{0.12}\right)^{1.22}$$

2) PQ restored after inflation ($f_a < H_I$):

no isocurvature perturb.

domain wall problem arises, $N_{DW}=6$ for DFSZ

Possoble solutions:

1) Explicit PQ breaking during inflation: Higaki, Jeong, Takahashi

massive axion $\longrightarrow$ no isocurvature perturb.

$$m_a^2(t = t_I) \sim H_I^2$$

2) PQ scale during inflation : $f_a(t_I) \gg f_a(t_0)$ Choi, Jeong, Seo; Chun

$$f_a(t_I) \sim (H_I M_P^n)^{1/(n+1)}$$

$$\frac{\mathcal{P}_a}{\mathcal{P}_\mathcal{R}} \sim \left(\frac{H_I}{2\pi f_a(t_I)}\right)^2 \ll \left(\frac{H_I}{2\pi f_a(t_0)}\right)^2$$

SUMMARY

- SUSY axion models solves 2 fine-tuning problems in SM.
- DFSZ realization provides mu-term solution and effective interactions of axion sector.
- For small f_a<10^{11} GeV, axion is dominant DM, while for f_a>10^{11} GeV, DM is a mixture of axion & neutralino.
- BICEP2 constrains DFSZ axion models but can be avoided in the extension of PQ sector.