DARK MATTER IN SUSY AXION MODEL

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HIGGS & DM

- Higgs boson is discovered

$m_h = 125$ GeV   All SM is discovered

If SM is valid up to M_P or M_{GUT}, what determines weak scale?

$m \sim m_h \sim v \sim M_W \sim 100$ GeV

How to solve the hierachy problem? $\delta m_h^2 \sim \frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \cdots$

- Dark Matter Existence

Cosmological & astrophysical evidence for DM

$\Omega h^2 \simeq 0.12$ (26.8% of energy density of the Universe)

cold & non-baryonic $\longrightarrow$ new physics particle(s)?

SUPERSYMMETRY

Symmetry btw fermion and boson

- No quadratic div.

$$\delta m_h^2 \sim \frac{\lambda_f^2}{8\pi^2} m_{\rm soft}^2 \log \Lambda^2$$

- Weak scale SUSY drives the radiative EWSB

$$m_{\rm soft} \sim M_W \sim m_h$$

- Lightest SUSY particle can be DM

$$\widetilde{Z}_1 = N_{1\widetilde{B}}\widetilde{B} + N_{1\widetilde{W}}\widetilde{W} + N_{1\widetilde{H}_d}\widetilde{H}_d + N_{1\widetilde{H}_u}\widetilde{H}_u$$

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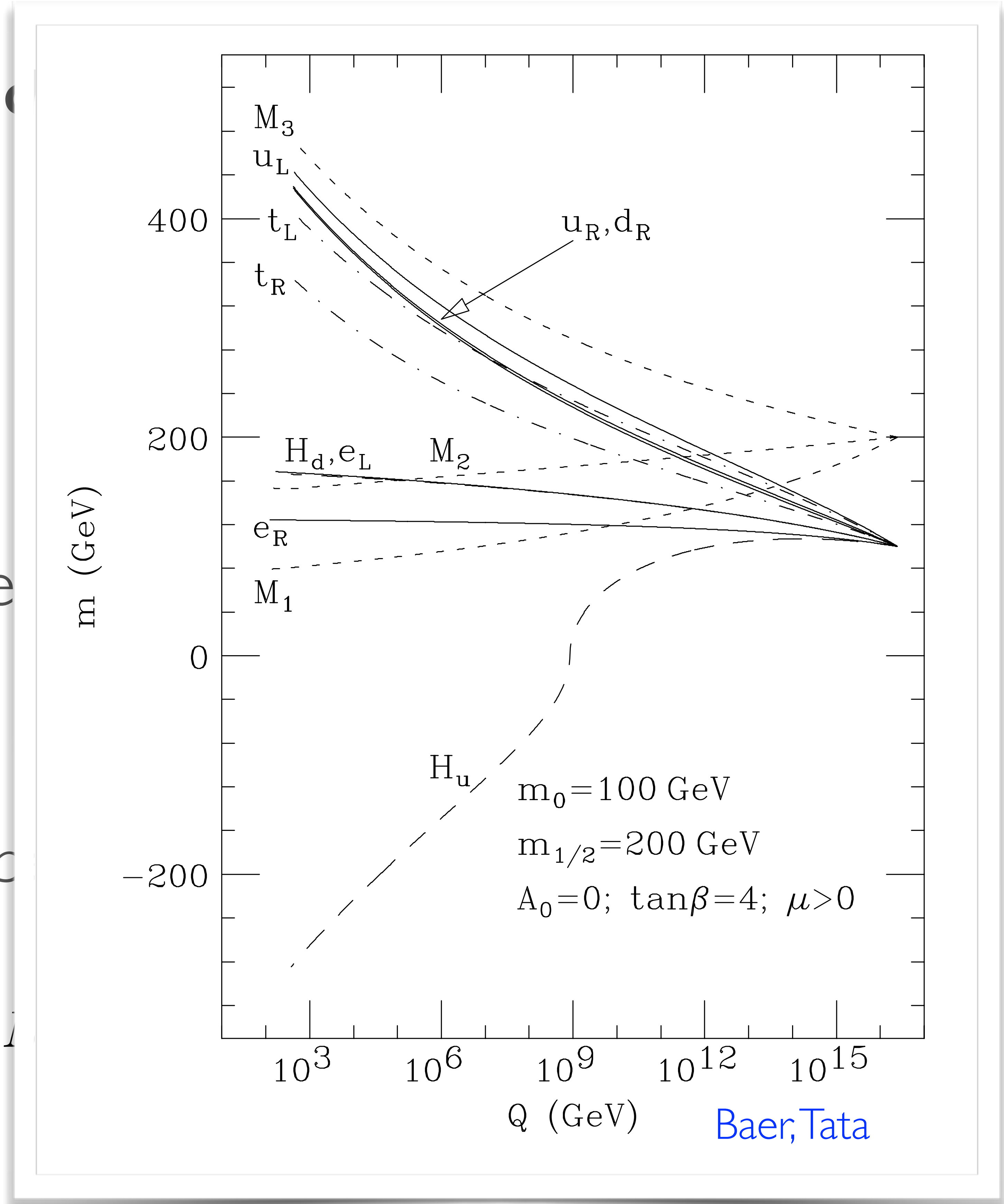
$$\widetilde{Z}_1 = N_{1\widetilde{B}}\widetilde{B} + N_{1\widetilde{W}}\widetilde{W} + $$



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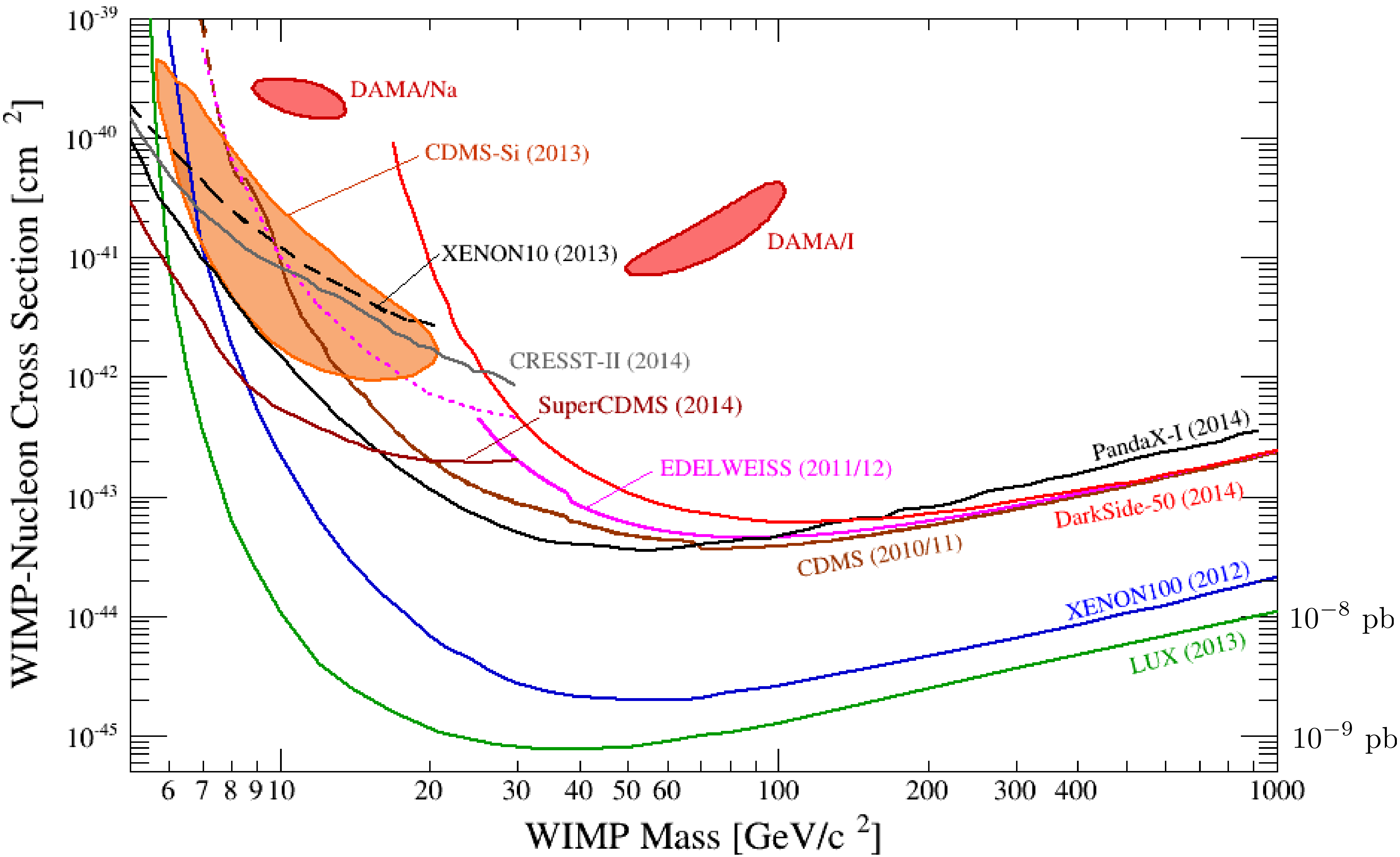
$$\widetilde{Z}_1 = N_{1\widetilde{B}} \widetilde{B} + N_{1\widetilde{W}} \widetilde{W} + N_{1\widetilde{H}_d} \widetilde{H}_d + N_{1\widetilde{H}_u} \widetilde{H}_u$$

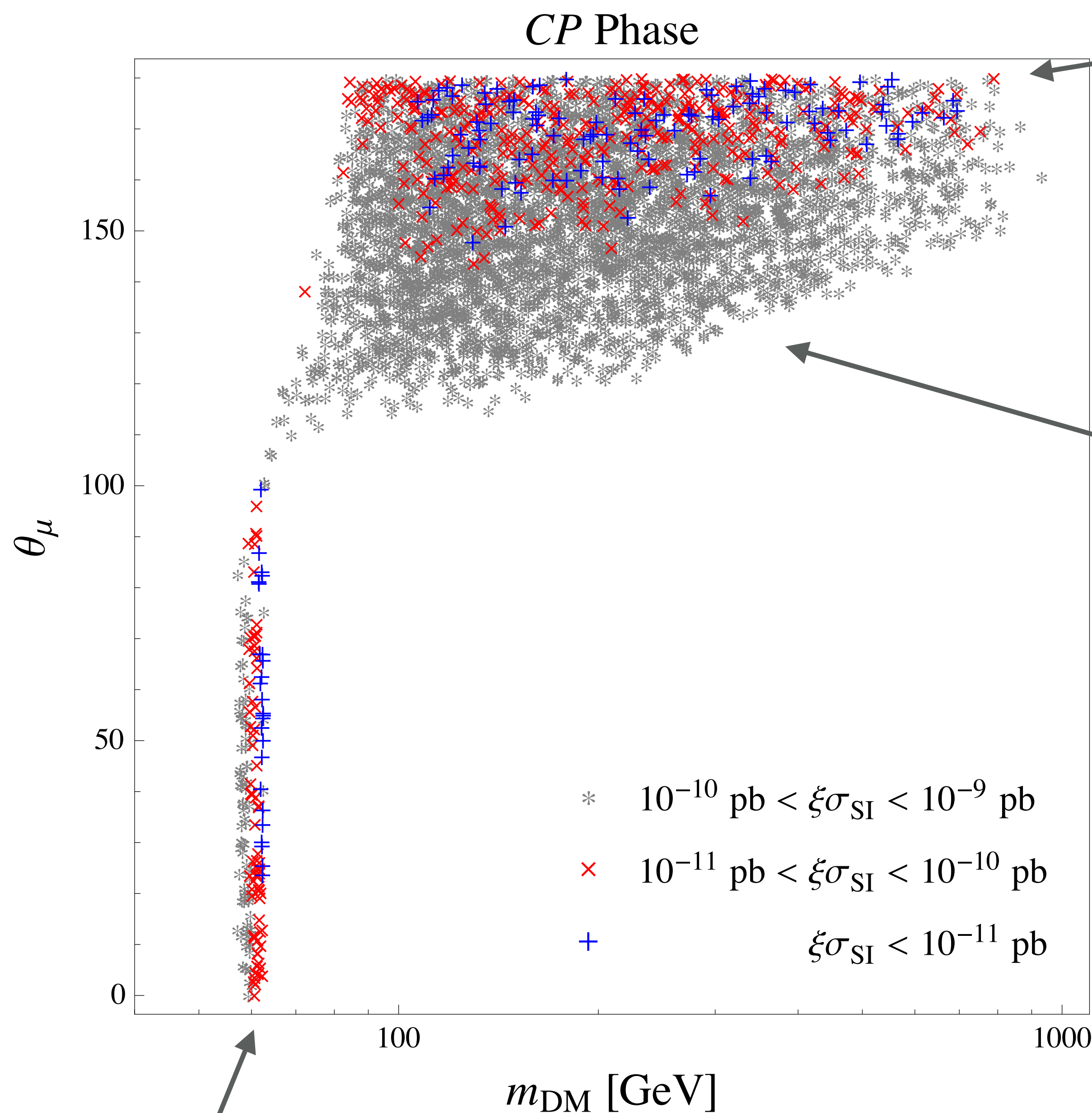
EXPERIMENTAL TEST

Upper limit for $\sigma_{\rm SI}$ is getting smaller

arXiv:1501.01200



Bino-Higgsino neutralino is in the corner



"blind spot"

$$M_1 + \mu \sin 2\beta \to 0$$

Cheung, Hall, Pinner, Ruderman

CPV

$$d_e \sim 10^{-29}\ \mathrm{cm}\cdot e$$

current bound

$$d_e(\mathrm{exp}) < 8.7 \times 10^{-29}\ \mathrm{cm}\cdot e$$

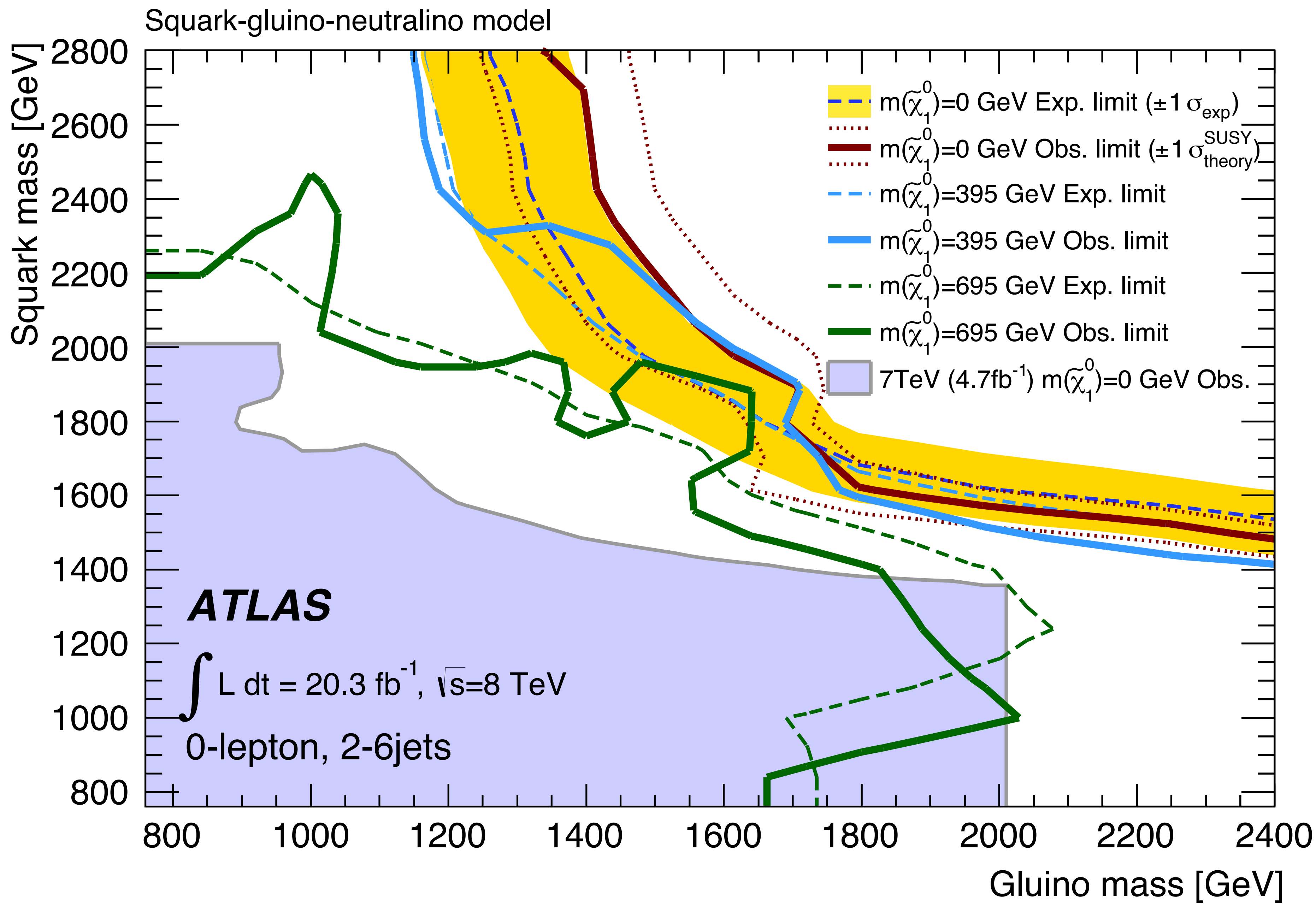
ACME collaboration

KJB, Nagata, Ruderman, Shirai (in progress)

resonance:

$$m_{\widetilde{Z}_1} < m_h/2$$

Scale of “weak scale SUSY” is getting higher



$$m_{\tilde{g}} > 1.2 \text{ TeV}$$
$$m_{\tilde{q}} > 1.4 \text{ TeV}$$

TeV scale SUSY ?

Natural EWSB

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

Natural EWSB requires $\mu^2 \sim M_Z^2$

$\longrightarrow$ $\mu \sim M_Z \ll m_{\rm soft} \sim \mathcal{O}(\rm TeV)$

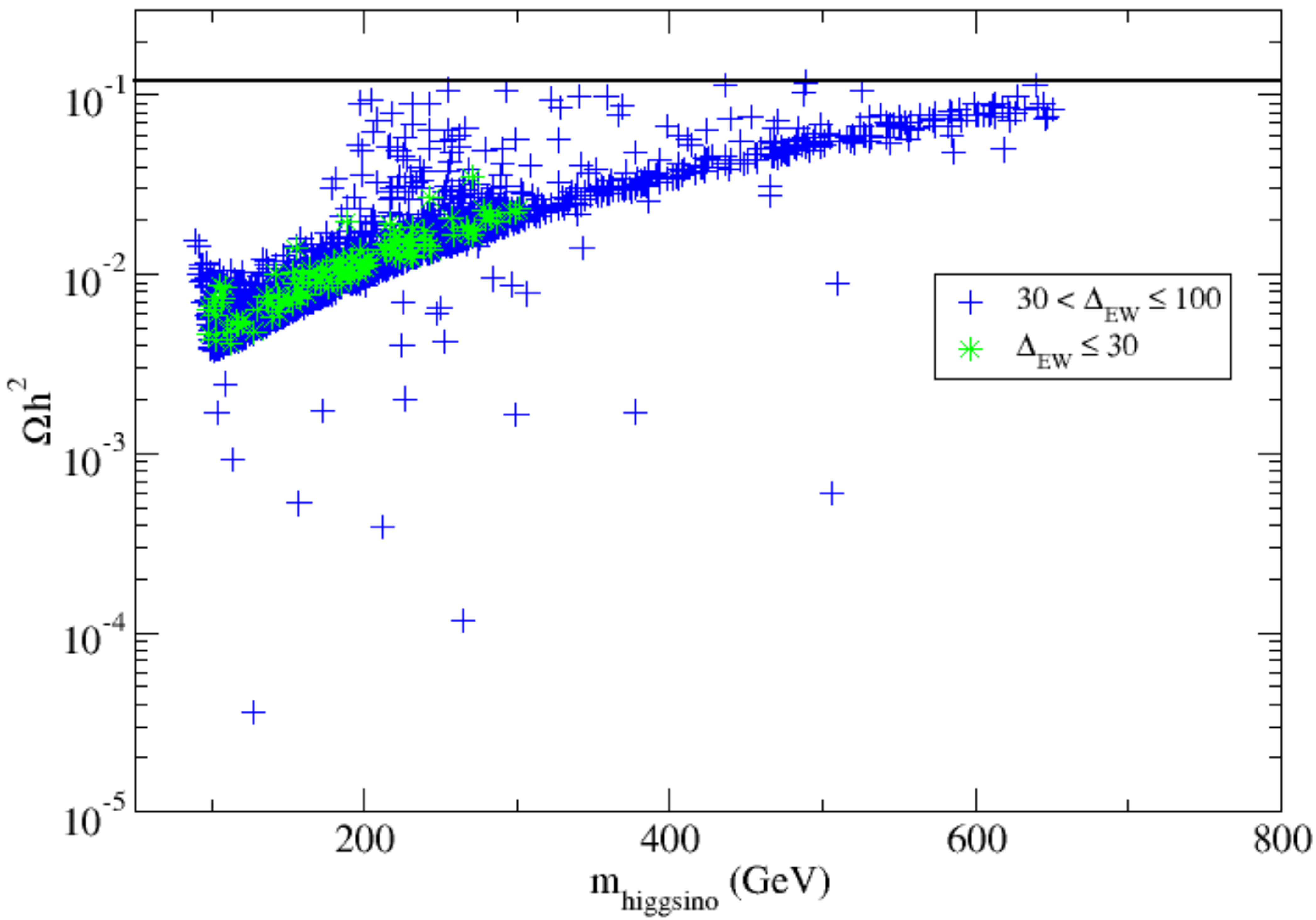
$\longrightarrow$ mostly higgsino-like neutralino

Baer, Barger, Huang, Mickelson, Mustafayev, Tata

Higgsino is generally underabundant

$$\Omega h^2 \simeq 0.1 \left(\frac{\mu}{1\ \rm TeV}\right)^2$$

Underabundant higgsino



Extension for DM

- another DM component(s)?

  → introducing new symm. → new (quasi-)stable particle

- non-thermal production for WIMP?

  → long-lived heavy particle → decay into neutralino

- Super WIMP?

  → neutralino is NLSP → decay into LSP (swimp)

  e.g. gravitino LSP (discussed later)

AXION

- Introducing $U(1)_{PQ}$: broken at $f_a > 10^9$ GeV

- Solution to the strong CP problem

$$\mathcal{L}_{\text{eff}} \supset \frac{g_s^2}{32\pi^2}\left(\frac{a}{f_a} + \bar{\theta}\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} \longrightarrow \langle \frac{a}{f_a} + \theta \rangle = 0$$

- Axion is pseudo-Nambu-Goldstone boson

$$f_a > 10^9 \text{ GeV} \longrightarrow \tau(a \to 2\gamma) \simeq \frac{10^9 t_U}{C^2_{a\gamma\gamma}}\left(\frac{f_a}{10^9 \text{ GeV}}\right)$$

- SUSY partners: axino/saxion

$f_a > 10^9$ GeV $\longrightarrow$ long-lived: T_{dec}~MeV - TeV

We will consider SUSY axion model!

OUTLINE

- Introduction
- Supersymmetric Axion Model
- Dark Matter
- Summary & Future Plan

SUSY AXION MODEL

SUSY AXION MODEL

Peccei-Quinn symm. + SUSY

$\longrightarrow$ MSSM + axion sector (a. k. a. PQMSSM)

supersymmtrizing axion

$$a \longrightarrow A = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

axion couplings

KSVZ: $W \supset m_Q e^{A/f_a} Q Q^c$

DFSZ: $W \supset \mu e^{-2A/f_a} H_u H_d$

$$\longrightarrow \mathcal{L} \supset -\frac{\sqrt{2}\alpha_s}{8\pi(f_a/N)} \int d^2\theta A W^a W^a + \text{h.c.}$$

axion mass: $m_a = 6 \text{ meV} \left(10^9 \text{ GeV}/f_a\right)$

saxion/axino mass is generated by SUSY breaking

AXINO MASS

Goto, Yamaguchi;
Chun, Kim, Nilles;
Chun, Lukas

- No additional zero mode:

$W = Z(XY - f_0^2)$ SUSY VEV: $Z_0 = 0, \; X_0 Y_0 = f_0^2$

$XY = f_0^2$: flat direction in SUSY limit $\longrightarrow$ axion mode!

$$X = f_0 e^{A/f_0}, \; Y = f_0 e^{-A/f_0}$$

$$V_{\rm soft} = m_Z^2 |Z|^2 + m_X^2 |X|^2 + m_Y^2 |Y|^2 + A_Z ZXY - C_Z Z f_0^2$$

soft term scale $\sim m_{3/2}$ $\longrightarrow$ $m_s \sim m_{3/2}$

$m_{\tilde{a}} \sim \langle Z \rangle$ $\longleftarrow$ $\langle F_X/X \rangle \sim \langle F_Y/Y \rangle \sim \langle Z \rangle$

$\langle X \rangle \sim \langle Y \rangle \sim f_0$ $\quad$ $\langle Z \rangle \sim m_{3/2}$ for $A_Z \neq C_Z$

$\langle Z \rangle \sim \mathcal{O}(m_{3/2}^2/f_0)$ for $A_Z = C_Z$

typical axino (saxion) mass is at gravitino mass scale or smaller

AXINO MASS (CONT.)

- Additional zero mode:

Chun, Lukas;
KJB, Baer, Chun, Shin

$$W = S(\lambda_x XY - \lambda_z Z^2) + \lambda_f (Z - f_0)^3$$

⟶ SUSY VEV: $S_0 = 0, \ Z_0 = f_0, \ X_0 Y_0 = (\lambda_z/\lambda_x) f_0^2$

$XY = (\lambda_z/\lambda_x) f_0^2$ axion direction $\dfrac{2X_0}{f_0} X + Z$ additional zero mode!

$$V_{\rm soft} = m_S^2 |S|^2 + m_X^2 |X|^2 + m_Y^2 |Y|^2 + m_Z^2 |Z|^2 + A_x SXY - A_z SZ^2 + A_f Z^3 + B_f Z^2 + C_f Z$$

gravity mediation $m_{\rm soft} \sim m_{3/2}$

$$m_s \sim m_{\tilde{a}} \sim \sqrt{2}\lambda_x \langle S \rangle \sim \left(\lambda_f m_{3/2}^2 f_0\right)^{1/3}$$

$m_{\tilde{a}} \sim m_s >> m_{3/2}$ can be realized!

DARK MATTER

Depending on axino mass

$m_{\tilde{a}} \ll m_{3/2}$ axino/axion DM (not considered here)

$m_{\tilde{a}} \sim m_{3/2} \sim m_{\rm soft}$ neutralino/axion DM

higgsino-like neutralino:

TP and NTP (from axino/saxion decay)

$m_{3/2} \ll m_{\rm soft} \ll m_{\tilde{a}}$ gravitino/axion DM

TP and
NTP (from axino/saxion and neutralino decay)

NEUTRALINO/AXION DM

DM in SUSY axion models: $m_{\rm soft} < m_{\tilde{a},s} < m_{3/2}$

- Axion DM
  - quasi-stable $\tau \gg t_U$
  - bosonic coherent motion at T~1 GeV
  - determined by θ_i:

$$\Omega h^2 \sim 0.1\theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.18}$$

- Neutralino DM
  - stable (assuming *R*-parity)
  - thermal freeze-out at *T*~5-10 GeV

- Saxion/Axino components
  - thermally produced: scattering and (inverse-)decay ("freeze-in")
  - unstable → decay into neutralinos $T_{\rm dec}$~MeV - TeV

⟶ *solving the coupled Boltzmann equations!*

BOLTZMANN EQ.

- Neutralino density:

scattering

$$\frac{dn_{\widetilde{Z}_1}}{dt} + 3Hn_{\widetilde{Z}_1} = \langle \sigma v \rangle (\bar{n}^2_{\widetilde{Z}_1} - n^2_{\widetilde{Z}_1})$$

BOLTZMANN EQ.

- Neutralino density:

scattering

heavy particle decay/inverse decay into/from neutralino

$$\frac{dn_{\widetilde{Z}_1}}{dt} + 3Hn_{\widetilde{Z}_1} = \langle\sigma v\rangle(\bar{n}^2_{\widetilde{Z}_1} - n^2_{\widetilde{Z}_1}) + \sum_{i,k}\Gamma_{i\to\widetilde{Z}_1+k} m_i \frac{n_i}{\rho_i}\left(n_i - \bar{n}_i \frac{n_{\widetilde{Z}_1}}{\bar{n}_{\widetilde{Z}_1}}\frac{n_k}{\bar{n}_k}\right)$$

$i \in \{\tilde{a}, s, \widetilde{G}\}$

BOLTZMANN EQ.

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$i \in \{\tilde{a}, s, \widetilde{G}\}$

- For decaying particles, we need to know $\Gamma_{i\to\widetilde{Z}_1+k},\ n_i,\ \rho_i$

$$\frac{dn_i}{dt} + 3Hn_i = \sum_{j\in\text{MSSM}}\langle\sigma v\rangle_{ij}(\bar{n}_i\bar{n}_j - n_i n_j)$$

scattering

$$-\sum_{j,k}\Gamma_{i\to j+k}m_i\frac{n_i}{\rho_i}\left(n_i - \bar{n}_i\frac{n_j}{\bar{n}_j}\frac{n_k}{\bar{n}_k}\right)$$

$i \in \{\tilde{a}, s, \widetilde{G}\}$ decay/inverse decay into/from light particles

$$+\sum_{j,k}\Gamma_{j\to i+k}m_j\frac{n_j}{\rho_j}\left(n_j - \bar{n}_j\frac{n_i}{\bar{n}_i}\frac{n_k}{\bar{n}_k}\right)$$

heavy particle decay/inverse decay into/from $i \in \{\tilde{a}, s, \widetilde{G}\}$

BOLTZMANN EQ.

- Neutralino density:

scattering

heavy particle decay/inverse decay into/from neutralino

$$\frac{dn_{\widetilde{Z}_1}}{dt} + 3Hn_{\widetilde{Z}_1} = \langle \sigma v \rangle (\bar{n}^2_{\widetilde{Z}_1} - n^2_{\widetilde{Z}_1}) + \sum_{i,k} \Gamma_{i \to \widetilde{Z}_1 + k} m_i \frac{n_i}{\rho_i} \left(n_i - \bar{n}_i \frac{n_{\widetilde{Z}_1}}{\bar{n}_{\widetilde{Z}_1}} \frac{n_k}{\bar{n}_k} \right)$$

$i \in \{\tilde{a}, s, \widetilde{G}\}$

- For decaying particles, we need to know $\Gamma_{i \to \widetilde{Z}_1 + k}, \; n_i, \; \rho_i$

$$\frac{dn_i}{dt} + 3Hn_i = \sum_{j \in \mathrm{MSSM}} \langle \sigma v \rangle_{ij} (\bar{n}_i \bar{n}_j - n_i n_j)$$

scattering

$$- \sum_{j,k} \Gamma_{i \to j + k} m_i \frac{n_i}{\rho_i} \left(n_i - \bar{n}_i \frac{n_j}{\bar{n}_j} \frac{n_k}{\bar{n}_k} \right)$$

$i \in \{\tilde{a}, s, \widetilde{G}\}$ decay/inverse decay into/from light particles

$$+ \sum_{j,k} \Gamma_{j \to i + k} m_j \frac{n_j}{\rho_j} \left(n_j - \bar{n}_j \frac{n_i}{\bar{n}_i} \frac{n_k}{\bar{n}_k} \right)$$

heavy particle decay/inverse decay into/from $i \in \{\tilde{a}, s, \widetilde{G}\}$

- *need to know* $\langle \sigma v \rangle_{ij}$, Γ *to determine production/decay of axino/saxion*

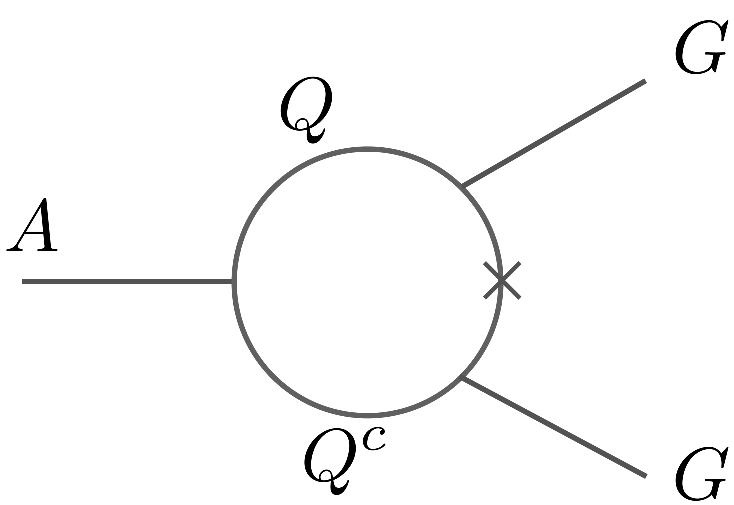
EFFECTIVE INT.

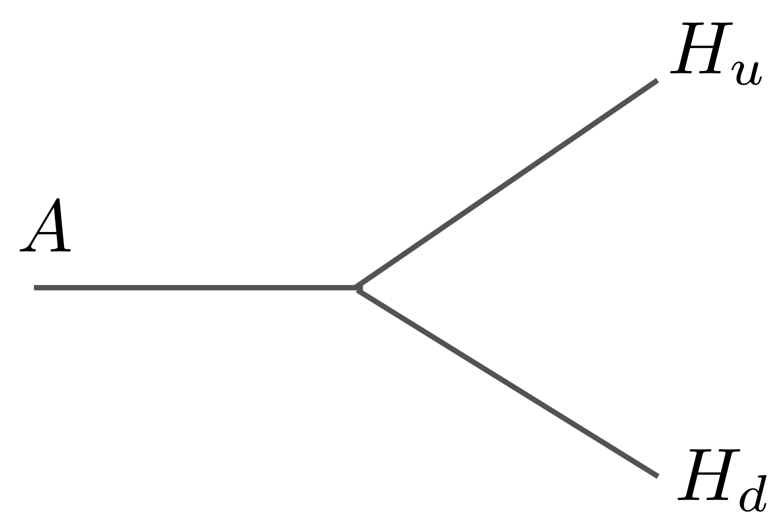
2 types of realization:

$$\int d^2\theta\ m_Q e^{A/f_a} QQ^c \qquad \text{or} \qquad \int d^2\theta\ \mu e^{-2A/f_a} H_u H_d$$

$\Downarrow$ KSVZ-type $\qquad\qquad$ $\Downarrow$ DFSZ-type

Axion multiplet interacts with MSSM via

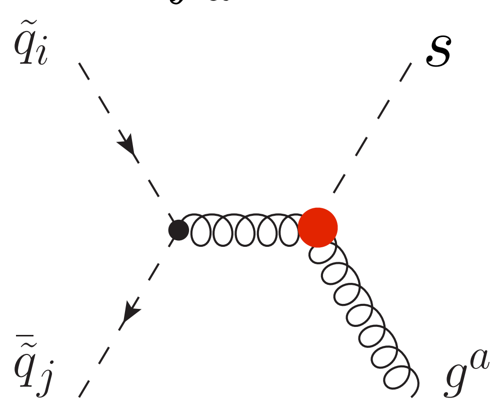




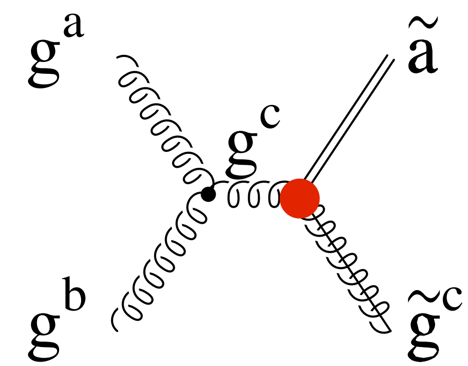
KSVZ model

- Effective interaction:

$$\sim \frac{g_s^2}{32\pi^2}\frac{1}{f_a} s\partial_\mu G_\nu^a \partial^\mu G^{a\nu}$$



$$\sim \frac{g_s^2}{32\pi^2}\frac{1}{f_a} \bar{\tilde{a}}\gamma_5\sigma^{\mu\nu}\partial_\nu G_\nu^a$$



- scattering cross section

saxion: $\langle\sigma v\rangle \sim \frac{9g_s^6}{128\pi^3 f_a^2}$ axino: $\langle\sigma v\rangle \sim \frac{3g_s^6}{64\pi^3 f_a^2}$

$$Y_s^{\rm TP} \sim Y_{\tilde{a}}^{\rm TP} \sim 10^{-5} g_s^6 \left(\frac{10^{12}\ {\rm GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^8\ {\rm GeV}}\right)$$

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

- saxion coherent oscillation

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

KSVZ model (cont.)

- saxion decay

$s \to gg, \gamma\gamma$ $\Rightarrow$ produce entropy $\Rightarrow$ dilutes axion/neutralino
$\Rightarrow$ larger PQ scale can be possible

$s \to aa$ $\Rightarrow$ produce rel. axion $\Rightarrow$ contributes to N_{eff}

$s \to \tilde{a}\tilde{a}, \tilde{g}\tilde{g}$ $\Rightarrow$ feeds neutralino DM

$$\frac{\xi}{f_a} s \left(\partial_\mu a \partial^\mu a + i\bar{\tilde{a}}\gamma^\mu \partial_\mu \tilde{a}\right)$$

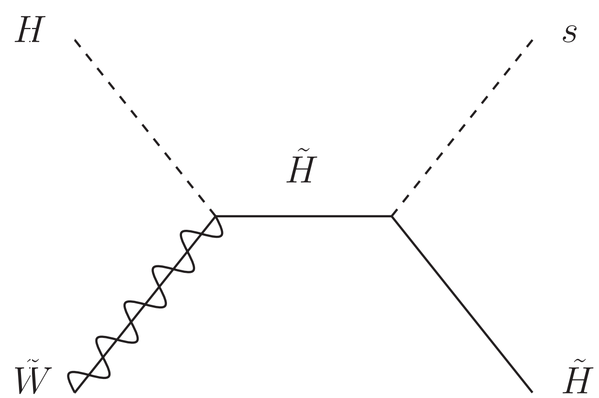
- axino decay

$\tilde{a} \to g\tilde{g}, \gamma\widetilde{Z}$ $\Rightarrow$ feeds neutralino DM and/or entropy

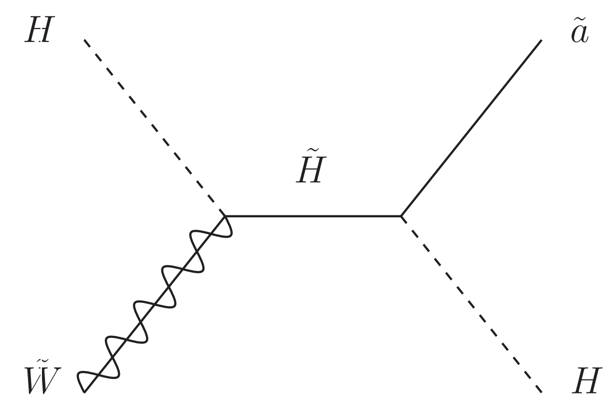
DFSZ model

- Effective interaction:

$$\sim \frac{\mu}{f_a} s\widetilde{H}_u\widetilde{H}_d$$



$$\sim \frac{\mu}{f_a} \tilde{a}\widetilde{H}_u H_d$$



- scattering cross section

$$\langle \sigma v \rangle \sim \left(\frac{\mu}{f_a}\right)^2 \left(\frac{M_{\rm th}^2}{T^4}\right) K_2(M_{\rm th}/T)$$

$$Y_s^{\rm TP} \sim Y_{\tilde{a}}^{\rm TP} \sim 10^{-5} \left(\frac{\mu}{\rm TeV}\right)^2 \left(\frac{10^{11}\ {\rm GeV}}{f_a}\right)^2 \left(\frac{\rm TeV}{M_{\rm th}}\right)$$

No T_R dependence!

KJB, Choi, Im; KJB, Chun, Im

- saxion coherent oscillation also exists

DFSZ model (cont.)

- Decay

  Interactions via Higgs sector:

  AHH trilinear int. → tree-level decay

  mixing with higgs & higgsino → decay into all SM & partners

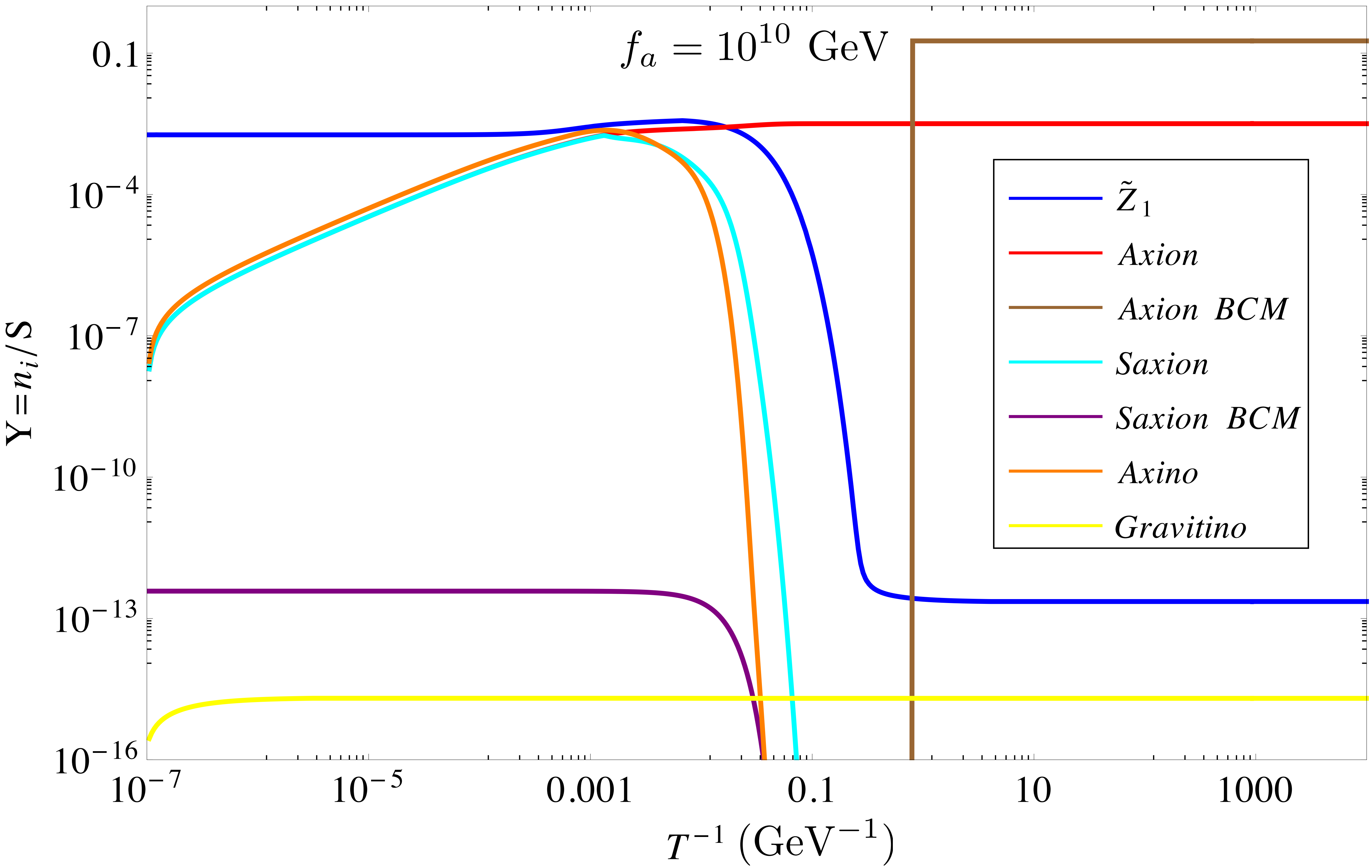
- Larger decay width and shorter life-time

  → Inverse decay is sizable production channel

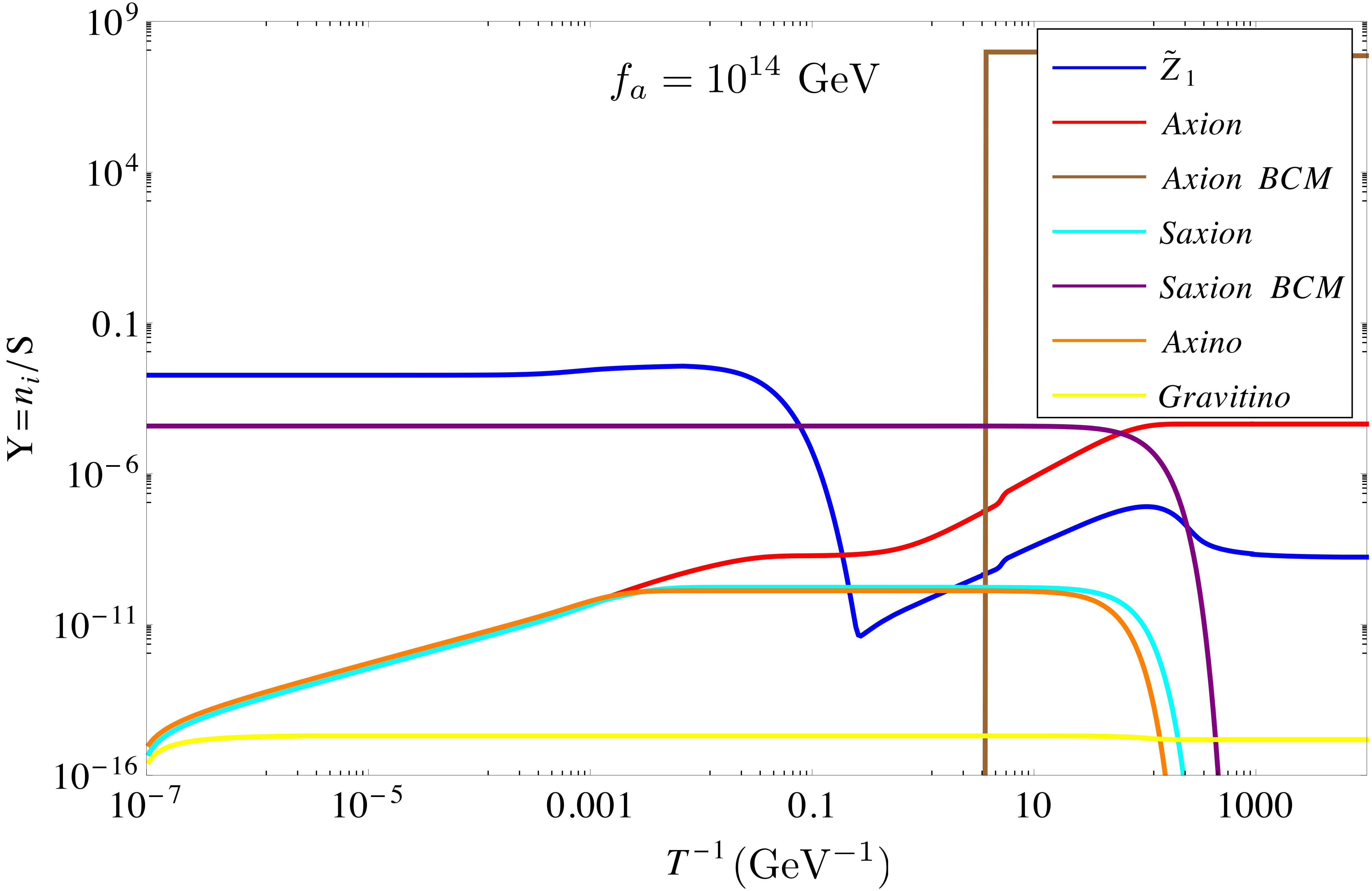
  → Neutralino density tends to be smaller than in KSVZ

$$Y \sim \frac{(90/\pi^2 g_*)^{1/2}}{4\langle\sigma v\rangle T_{\rm dec}}$$

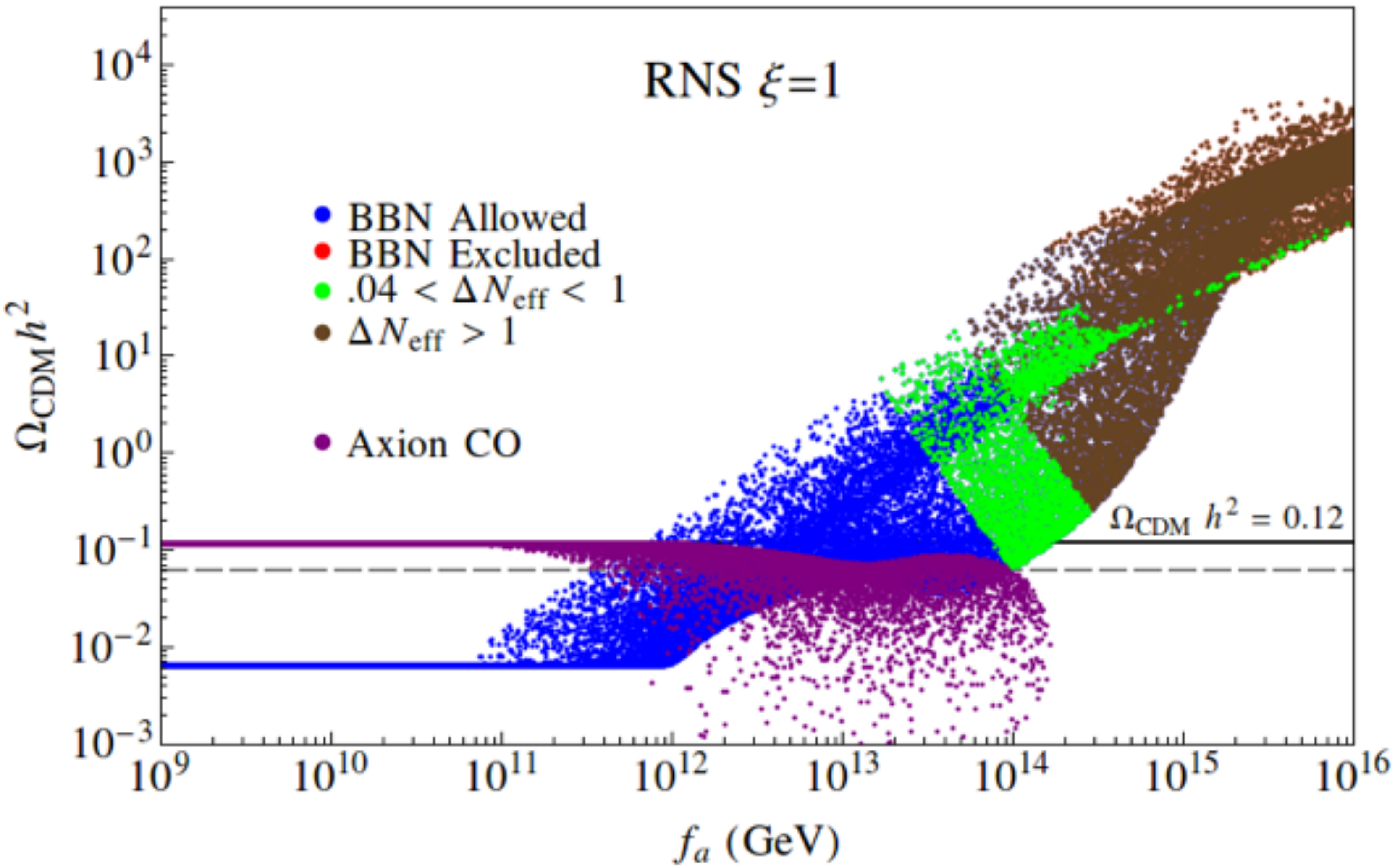
Axino/Saxion decay *before* freeze-out



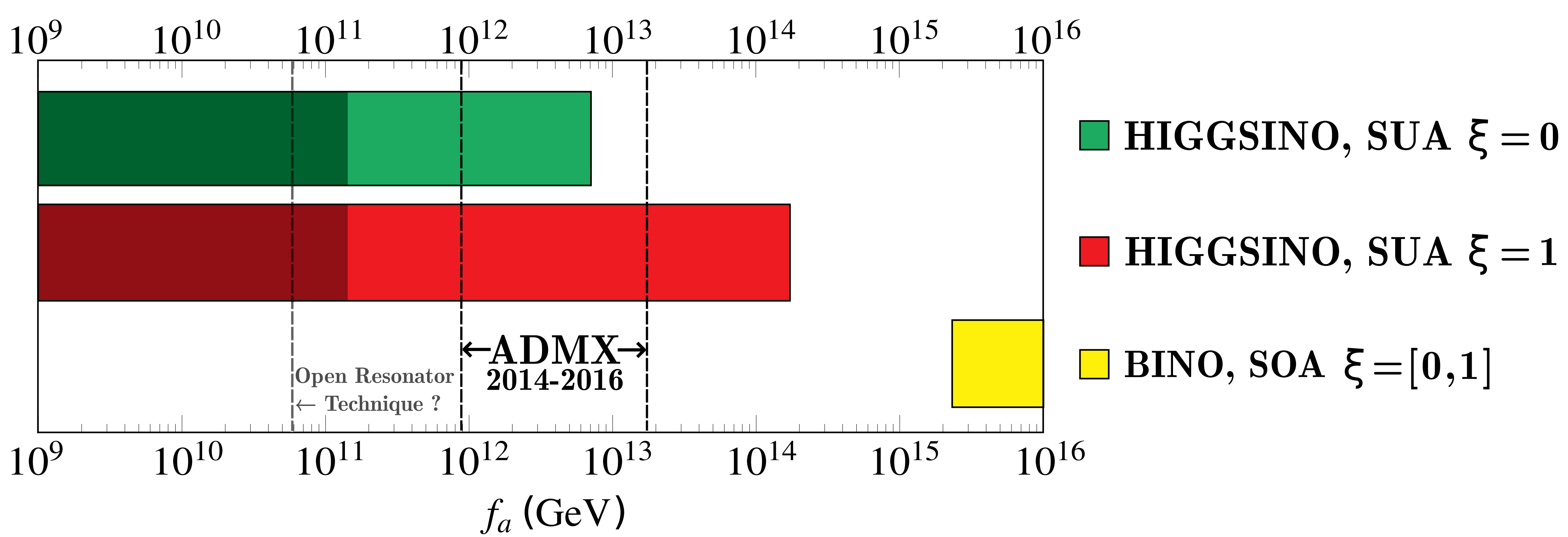
Axino/Saxion decay *after* freeze-out



Result: DFSZ



RNS ξ=1
BBN Allowed
BBN Excluded
$.04 < \Delta N_{\rm eff} < 1$
$\Delta N_{\rm eff} > 1$
Axion CO
$\Omega_{\rm CDM}\, h^2 = 0.12$
$\Omega_{\rm CDM} h^2$
f_a (GeV)



HIGGSINO, SUA $\xi = 0$
HIGGSINO, SUA $\xi = 1$
BINO, SOA $\xi = [0,1]$
ADMX
2014-2016
Open Resonator
← Technique ?
f_a (GeV)

GRAVITINO/AXION DM

Gravitino Dark Matter

- In models with $m_{3/2} \ll m_{\rm soft} \ll m_{\tilde{a},s}$
  - Gravitino DM
    - thermally produced: scattering and decay ("freeze-in")

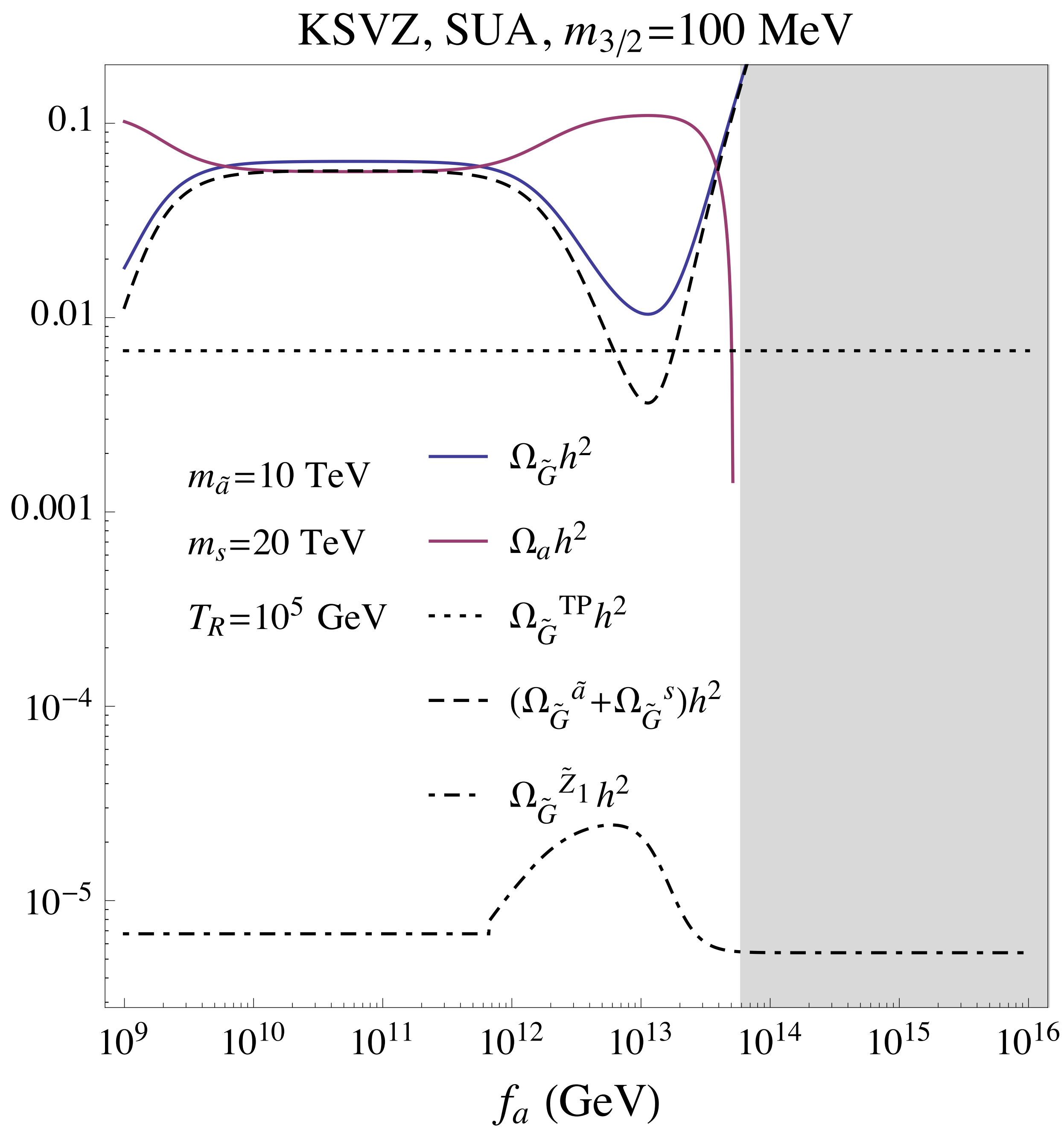
$$\Omega^{\rm TP}_{\widetilde{G}} h^2 = 0.21 \left(\frac{m_{\tilde{g}}}{1~\rm TeV}\right)^2 \left(\frac{1~\rm GeV}{m_{3/2}}\right) \left(\frac{T_R}{10^8~\rm GeV}\right)$$

Bolz, Brandenburg, Buchmuller; Rychkov, Strumia

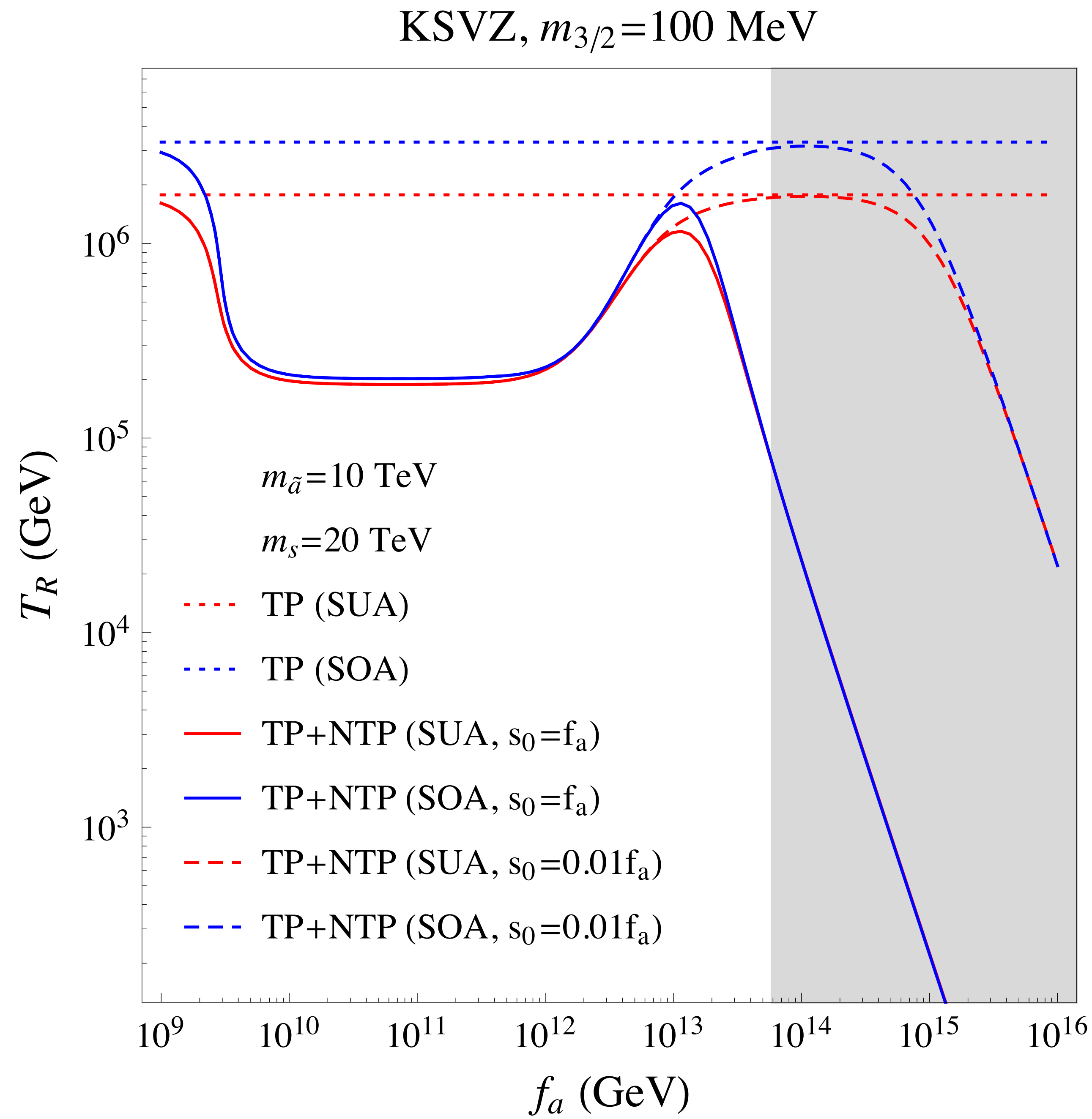
    - one more step for decay chain

$\left\{ \begin{array}{l} \text{axino/saxion} \rightarrow \text{neutralino} \rightarrow \text{re-annihil.} \rightarrow \text{gravitino} \\ \text{axino/saxion} \rightarrow \text{gravitino} \end{array} \right.$

Result



KSVZ, SUA, $m_{3/2}$=100 MeV
0.1
0.01
0.001
10^{-4}
10^{-5}
$m_{\tilde{a}}$=10 TeV
m_s=20 TeV
T_R=10^5 GeV
$\Omega_{\tilde{G}}h^2$
$\Omega_a h^2$
$\Omega_{\tilde{G}}^{TP}h^2$
$(\Omega_{\tilde{G}}^{\tilde{a}}+\Omega_{\tilde{G}}^{s})h^2$
$\Omega_{\tilde{G}}^{\tilde{Z}_1}h^2$
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}
f_a (GeV)



KSVZ, $m_{3/2}$=100 MeV
T_R (GeV)
10^6
10^5
10^4
10^3
$m_{\tilde{a}}$=10 TeV
m_s=20 TeV
TP (SUA)
TP (SOA)
TP+NTP (SUA, $s_0=f_a$)
TP+NTP (SOA, $s_0=f_a$)
TP+NTP (SUA, $s_0=0.01f_a$)
TP+NTP (SOA, $s_0=0.01f_a$)
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}
f_a (GeV)

SUMMARY

- SUSY axion model provide 2 DM as well as thermal and non-thermal production of DM.
- Depending on UV model for PQ breaking, mixed neutralino/axion or gravitino/axion DM is considered.
- To obtain precise DM density, extended Boltzmann eqs. are considered. As their ingredients, $\langle \sigma v \rangle, \ \Gamma$ are calculated.
- $10^{11}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{14}\ \mathrm{GeV}$ is favored in mixed neutralino/axion DM scenario. (similar region can be covered by future axion searches.)
- Mixed gravitino/axion DM depends on T_R, upper limit is obtained.

FUTURE PLAN

AXION & SUSY

Axion and SUSY

PQ & SUSY: solutions to fine-tuning problems

scale of theory: $f_a, \; m_{\rm soft}$ $\longrightarrow$ symmetry breaking!

f_a determines axion interaction

$m_{\rm soft}$ scale of SUSY particles

DM in SUSY axion

DM density is determined by *both* $f_a, \; m_{\rm soft}$

$\longrightarrow$ *interplay* btw PQ & SUSY breaking is the key on DM physics

$\longrightarrow$ implies model building & collider signal

test of the model from observations & experiments!

DARK MATTER

Precision for Axino/Saxion

f_a will be determined by ADMX & CAPP

determines axion DM (mass, density, interaction, ...)

$\longrightarrow$ determines axino/saxion properties (up to masses)

To examine SUSY model we need to calculate precise density of SUSY DM $(\Omega_a + \Omega_{\rm SUSY})h^2 = 0.12$

$\longrightarrow$ *requires precise calculations for general MSSM*

- currently $\langle \sigma v \rangle$ is obtained in SUSY limit or simplified spectrum
- Γ's contain only 2-body decays
- need to develop an automatized tool (including thermal effects)

important for *axino DM* scenario

DARK MATTER (CONT.)

Improving Boltzmann eqs.

- We assumed Maxwellian dist. $\longrightarrow$ eqs. for number density n_i
- easy to obtain DM density & portion (ordinary diff. eqs.)
- hard to extract DM velocity dist.

How cold is DM?

- improving eqs. to address *phase space density* $f(E, t)$

$\longrightarrow$ warm dark matter from heavy particle decay

- important for non-thermal DM from decay

e.g. $\tilde{a} \to \widetilde{G}$ mixed (warm+cold) DM scenario?

- can be examined by structure formation

MODEL BUILDING

Exploring the relation btw ~~PQ~~ & ~~SUSY~~

- *PQ breaking can be triggered by SUSY breaking*
- mu term is generated in DFSZ

Murayama, Suzuki, Yanagida; Choi, Chun, Kim; Martin; KJB, Baer, Serce

SUSY breaking can be mediated by axion sector

- PQ charged field $PQ(X) \neq 0$

$$\langle F_X / X \rangle \sim m_{\tilde{a}} \gg m_{3/2}$$
$$\langle X \rangle \sim f_a$$

⟶ *"axion mediation"*

- ~~PQ~~ & axino mass correlates with SUSY spectrum

⟶ distinctive signals

⟶ may observe nature of DM in collider

COLLIDER STUDY

Direct SUSY search

- SUSY particle production at Collider
- identifying new particle (mass, spin, ...)
- involving DM physics (missing E_T, ...)

Indirect SUSY search

- measurement of couplings (Higgs, gauge, Yukawa, ...)
- new physics contribution via loop & mixing

e.g. loop-induced higgs decay $h \to \gamma\gamma$

triple gauge couplings $\gamma W^+ W-, \ Z W^+ W^-$

work in progress (KJB, Baer, Nagata, Serce)