Double Axino Production

[Based on the work with Hyun Min Lee, 2018]

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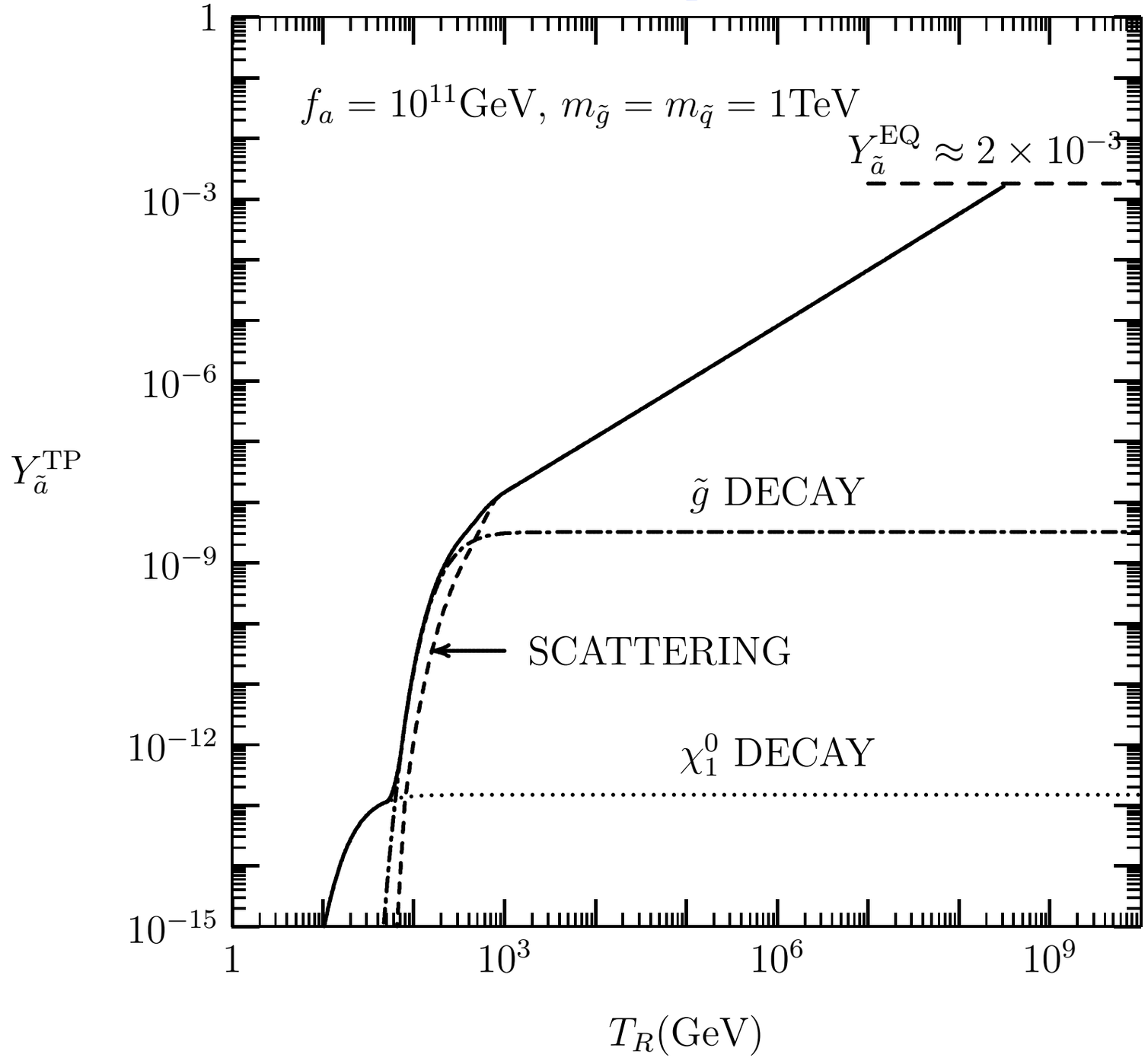
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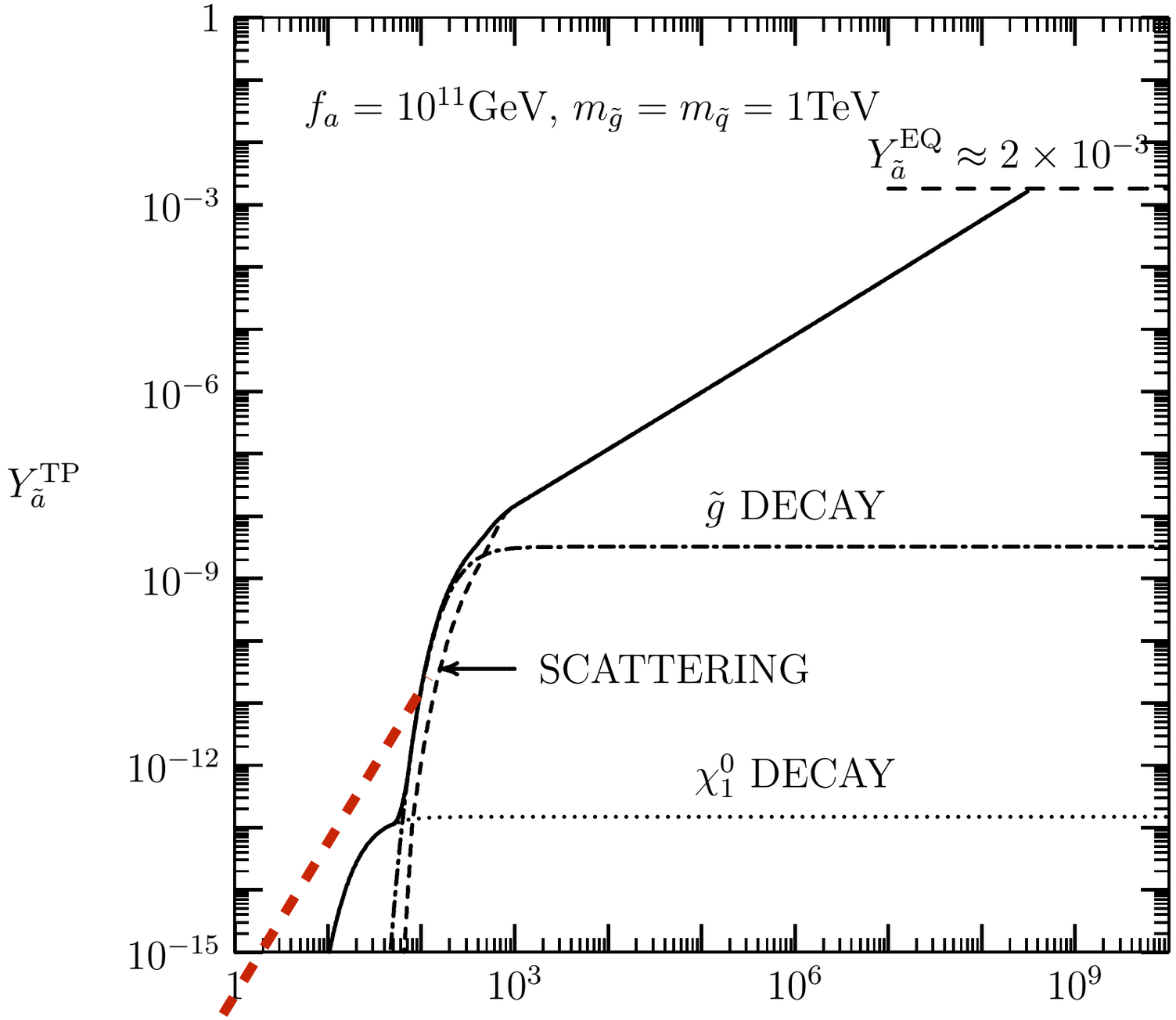
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Single Axino at KSVZ

[Covi, Kim, Kim, Roszkowski, 2001]



Single Axino at KSVZ



Double axino production

Double Axino Production

All the SUSY particles are heavier than the temperature of reheating and the maximum temperature:

- Low-reheating temperature
- High-scale supersymmetry

All the SUSY particles are heavier than the temperature of reheating and the maximum temperature:

$$m_{\tilde{a}} < \ T_{\rm reh} < T_{\rm max} < m_{\rm SUSY}$$

Only the axinos can be produced below reheating temperature by pair.

$$\mathrm{SM} + \mathrm{SM} \rightarrow \tilde{a} + \tilde{a}$$

Axino

axion

$$\mathcal{L} = \frac{g^2}{32\pi^2 f_a} a F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

$$10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

$$6\times 10^{-3}\,\mathrm{eV} \gtrsim m_a \gtrsim 6\times 10^{-6}\,\mathrm{eV}$$

Stellar energy-loss limit
[Raffelt '06, PDG review '07]

Cosmic axion population

$$\Omega_a h^2 \simeq 0.3 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$

$$m_a = \frac{\sqrt{z}}{1+z}\frac{m_\pi f_\pi}{f_a} = 6\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)\,\mathrm{eV}$$

$$z = \frac{m_u}{m_d} = 0.3 - 0.6$$

SUSY

axino

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

$$W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a}\Phi_a W^\alpha W_\alpha$$

- Axino mass
  : strongly model dependent
  -> free parameter
- Axino couplings
  : determined by axion models,
  suppressed by PQ scale, f_a
- Freeze-out temperature :

$$T_f = 10^9\,\mathrm{GeV}\left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^2\left(\frac{\alpha_S}{0.1}\right)^{-3}$$

Axion and Axino models

KSVZ

[Kim 1979] [Shifman, Veinstein, Zakharov 1980]

$$W_{\rm KSVZ} = W_{\rm PQ} + f_Q Q_L \overline{Q}_R S_1$$

$Q_L,\ \bar{Q}_R$ are heavy quarks

$$m_Q = f_A V_a$$

SM fields are not charged under $U(1)_{PQ}$

DFSZ

[Dine, Fischler, Srednicki 1981] [Zhitnitskii 1980]

$$W_{\rm DFSZ} = W_{\rm PQ} + \frac{f_s}{M_{\rm P}} S_1^2 H_d H_u$$

$H_d,\ H_u$ are Higgs multiplets

$$\frac{f_s}{M_P} V_a^2 = \mu$$ mu-term (Kim-Nilles)

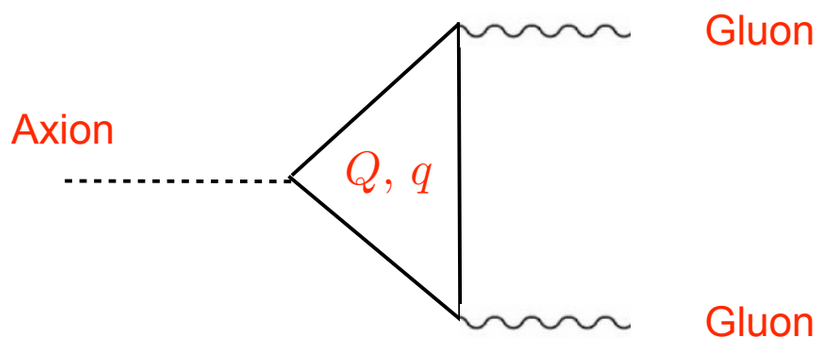
SM fields are charged under $U(1)_{PQ}$

Peccei-Quinn symmetry breaking

$$W_{\rm PQ} = f_Z Z(S_1 S_2 - V_a^2),$$

$$\langle S_1 \rangle = \langle S_2 \rangle = V_a$$

At low-energy,



Effective Lagrangian of axino

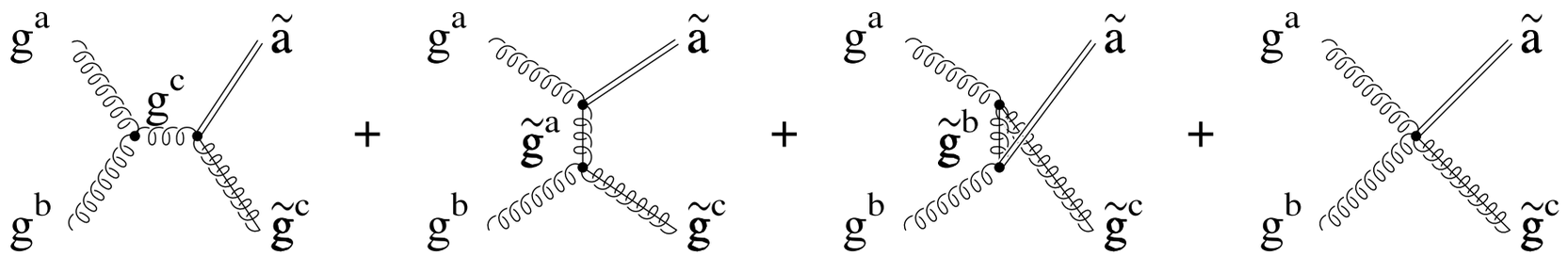
$$\mathcal{L}^{\text{eff}} = -\sum_V \frac{\alpha_V\, C_{aVV}}{2\sqrt{2}\pi f_a} \int A\,\text{Tr}\,[V_a V^a] + \text{h.c.},$$

includes

$$\begin{aligned}
\mathcal{L}^{\text{eff}}_{\tilde{a}} &= i\frac{\alpha_s}{16\pi f_a}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{G}^b G^b_{\mu\nu} + \frac{\alpha_s}{4\pi f_a}\bar{\tilde{a}}\tilde{g}^a \sum_{\tilde{q}} g_s \tilde{q}^* T^a \tilde{q} \\
&+ i\frac{\alpha_2 C_{aWW}}{16\pi f_a}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{W}^b W^b_{\mu\nu} + \frac{\alpha_2}{4\pi f_a}\bar{\tilde{a}}\tilde{W}^a \sum_{\tilde{f}_D} g_2 \tilde{f}^*_D T^a \tilde{f}_L \\
&+ i\frac{\alpha_Y C_{aYY}}{16\pi f_a}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{Y} Y_{\mu\nu} + \frac{\alpha_Y}{4\pi f_a}\bar{\tilde{a}}\tilde{Y} \sum_{\tilde{f}} g_Y \tilde{f}^* Q_Y \tilde{f},
\end{aligned}$$

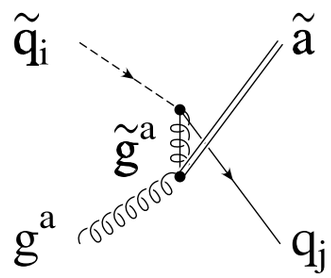
Axino production

- A: $g^a + g^b \to \tilde{g}^c + \tilde{a}$



- B: $g^a + \tilde{g}^b \to g^c + \tilde{a}$ (crossing of A)

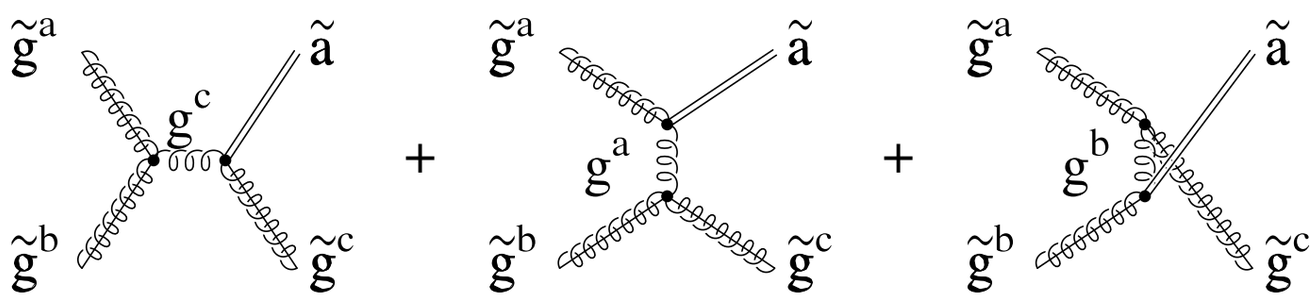
- C: $\tilde{q}_i + g^a \to \tilde{q}_j + \tilde{a}$



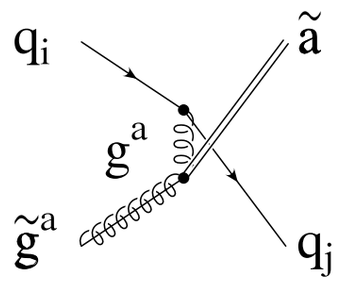
- D: $g^a + q_i \to \tilde{q}_j + \tilde{a}$ (crossing of C)

- E: $\bar{\tilde{q}}_i + q_j \to g^a + \tilde{a}$ (crossing of C)

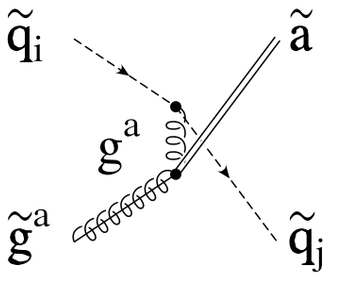
- F: $\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{a}$



- G: $q_i + \tilde{g}^a \to q_j + \tilde{a}$



- H: $\tilde{q}_i + \tilde{g}^a \to \tilde{q}_j + \tilde{a}$



- I: $q_i + \bar{q}_j \to \tilde{g}^a + \tilde{a}$ (crossing of G)
- J: $\tilde{q}_i + \bar{\tilde{q}}_j \to \tilde{g}^a + \tilde{a}$ (crossing of H)

Decoupling temperature of axino

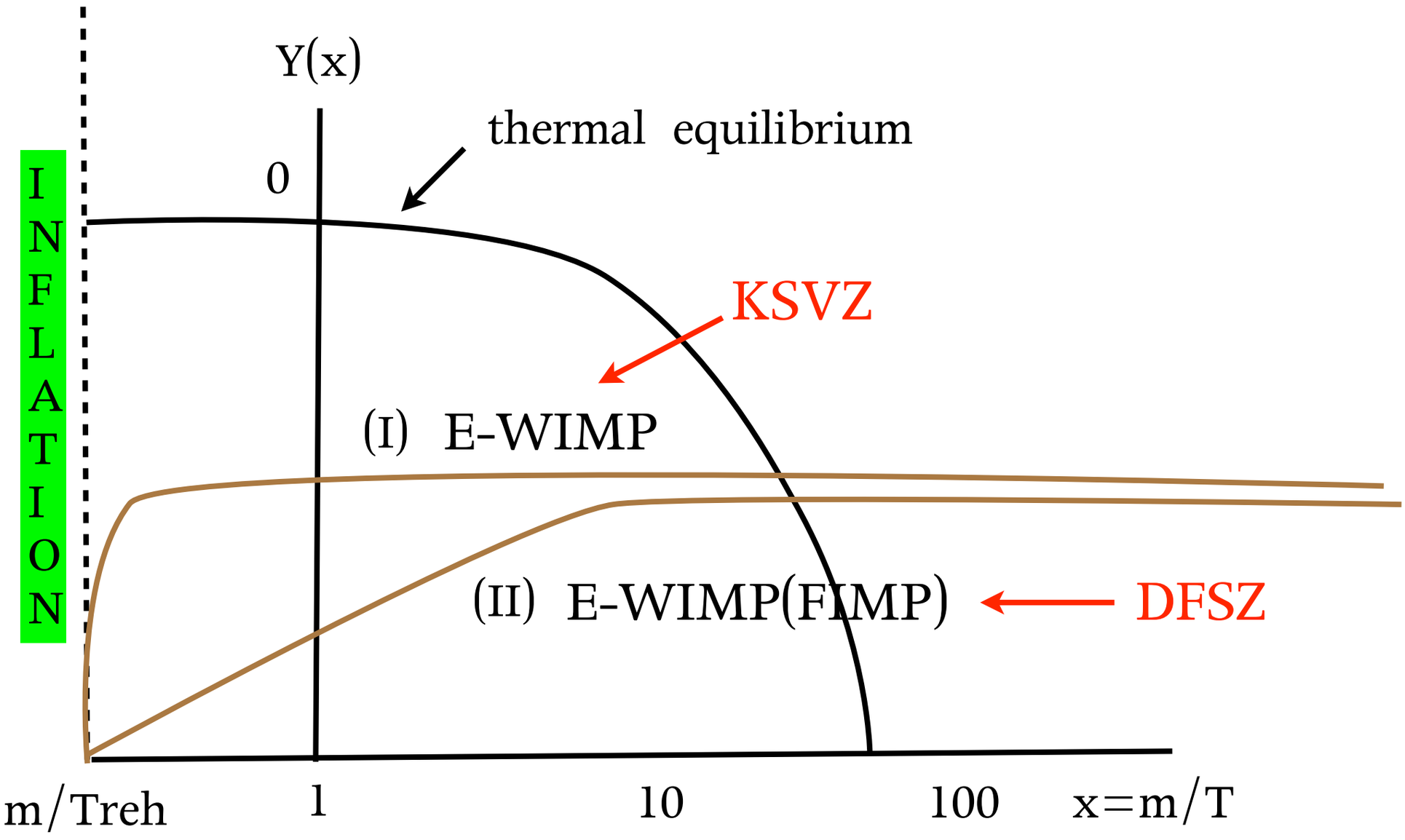
$$T_{\rm dec} = 10^{11}\ {\rm GeV} \left(\frac{f_a}{10^{12}\ {\rm GeV}} \right)^2 \left(\frac{0.1}{\alpha_s} \right)^3$$

For $T_{\rm reh} > T_{\rm dec}$ axinos can be warm dark matter

$$\Omega_{\tilde{a}} h^2 \simeq \frac{m_{\tilde{a}}}{2\ {\rm keV}}$$

However such a large reheating temperature may produce too many gravitinos and make conflicts (Gravitino problem).

When the reheating temperature is lower than decoupling temp,



(I) depends on the reheating temperature
and we can get the same amount of abundance for dark matter.

(II) does not depend on the reheating temperature and we can get the same amount of abundance for dark matter.

(I) depends on the reheating temperature
and we can get the same amount of abundance for dark matter.

For example, Gravitino Axino

$$M_P \sim 10^{18}\,\mathrm{GeV} \qquad f_a \sim 10^{11}\,\mathrm{GeV}$$

They are decoupled already from the thermal plasma,
however can be produced from thermal scatterings or decays

$$\Rightarrow \quad \sigma \sim \frac{1}{M_P^2}, \quad \frac{1}{f_a^2}$$

$$Y(T_0) = \int_{T_0}^{T_{\rm reh}} \frac{\langle \sigma v \rangle n_{eq}^2}{s(T)H(T)T} dT \propto M_P \frac{T_{\rm reh}}{M_P^2}, \quad M_P \frac{T_{\rm reh}}{f_a^2}$$

Relic Abundance $\propto$ Reheating Temperature $T_{\rm reh}$

Roughly, the relic density of axino proportional to the reheating temperature

$$Y_{\tilde{a}}^{\mathrm{TP}}(\mathrm{KSVZ}) \simeq 2 \times 10^{-7} g_s^6 \ln\left(\frac{1.108}{g_s}\right) \frac{T_{\mathrm{reh}}}{10^4\ \mathrm{GeV}} \left(\frac{10^{11}\ \mathrm{GeV}}{f_a}\right)^2$$

[Brandenburg, Steffen, 2014]

(II) does not depend on the reheating temperature and we can get the same amount of abundance for dark matter.

scattering

$$Y(T_0) = \int_{T_0}^{T_{\rm reh}} \frac{\langle\sigma v\rangle n_{eq}^2}{s(T)H(T)T} dT \propto \left. \frac{m_{soft}^2}{f_a^2} \frac{1}{T} \right|_{T\sim m_{soft}}$$

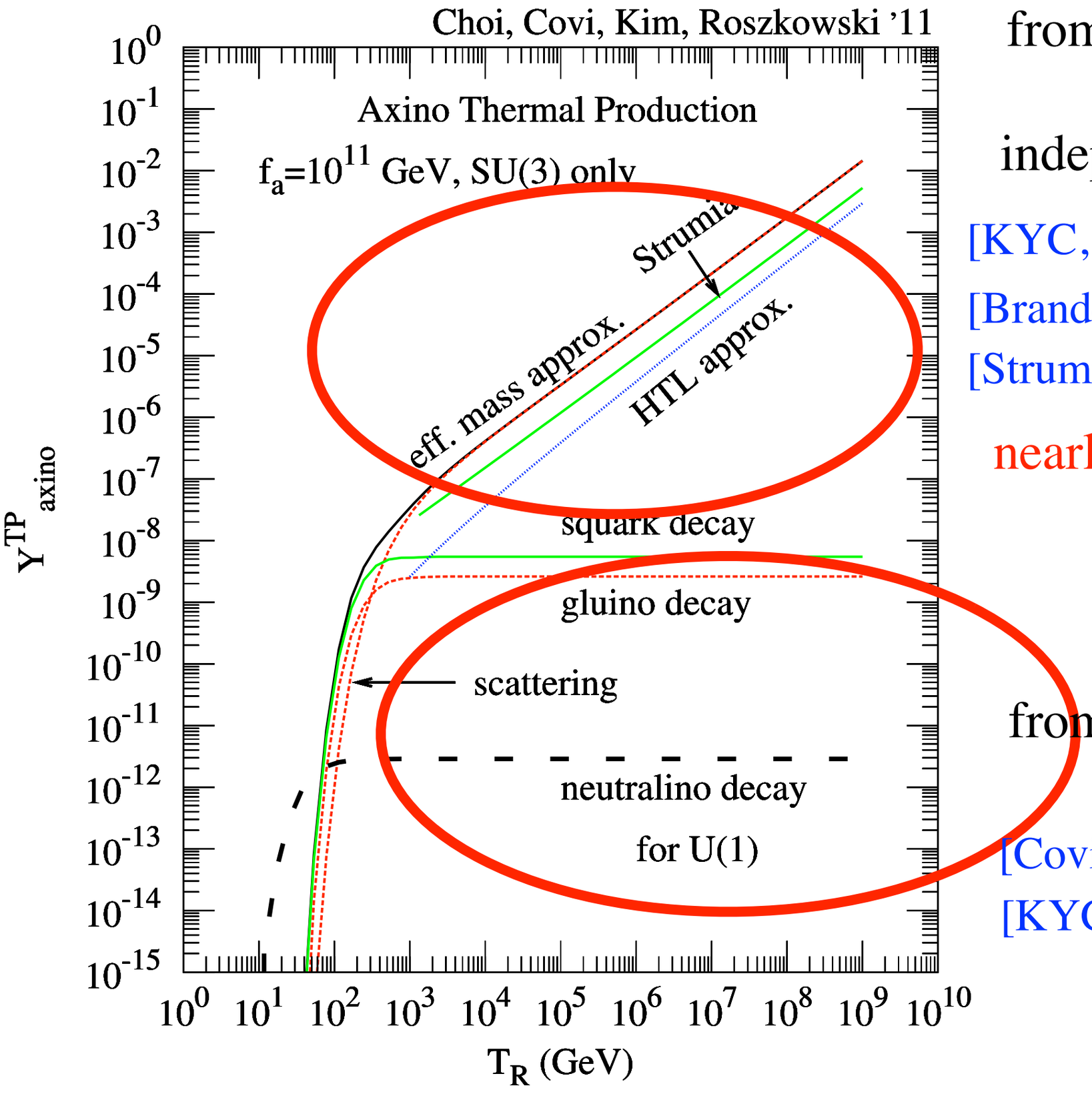
$$\sigma \sim \frac{m_{soft}^2}{f_a^2} \frac{1}{s} \qquad \text{with} \qquad s \propto T^2$$

decay

$$Y(T_0) \simeq \frac{405\sqrt{10}\zeta(5) M_P}{8\pi^4 g_*^{3/2}} \frac{\Gamma}{M^2}.$$

No dependence on the reheating temperature.

Axino thermal production



from anomaly interactions
: depend on Treh,
independent on axino mass

[KYC, Covi, Kim, Roszkowki, 2011]

[Brandenberger, Steffen, 2004]

[Strumia, 2010]

nearly equal but factor 5-10 differences

from decay of thermal particles
: constant for high Treh

[Covi, Kim, Kim, Roszkowski, 2001]

[KYC, Covi, Kim, Roszkowki, 2011]

Axino production in the DFSZ model

[Chun, 2011]
[Bae, Choi, Im, 2011]
[KYC, Covi, Kim, Roszkowki, 2011]

$$Y_{\tilde{a}}^{\rm TP}({\rm DFSZ}) \simeq 10^{-5}\zeta_{\tilde{a}}\left(\frac{\mu}{\rm TeV}\right)^2\left(\frac{10^{11}\ {\rm GeV}}{f_a}\right)^2,$$

from Yukawa interaction in DFSZ model

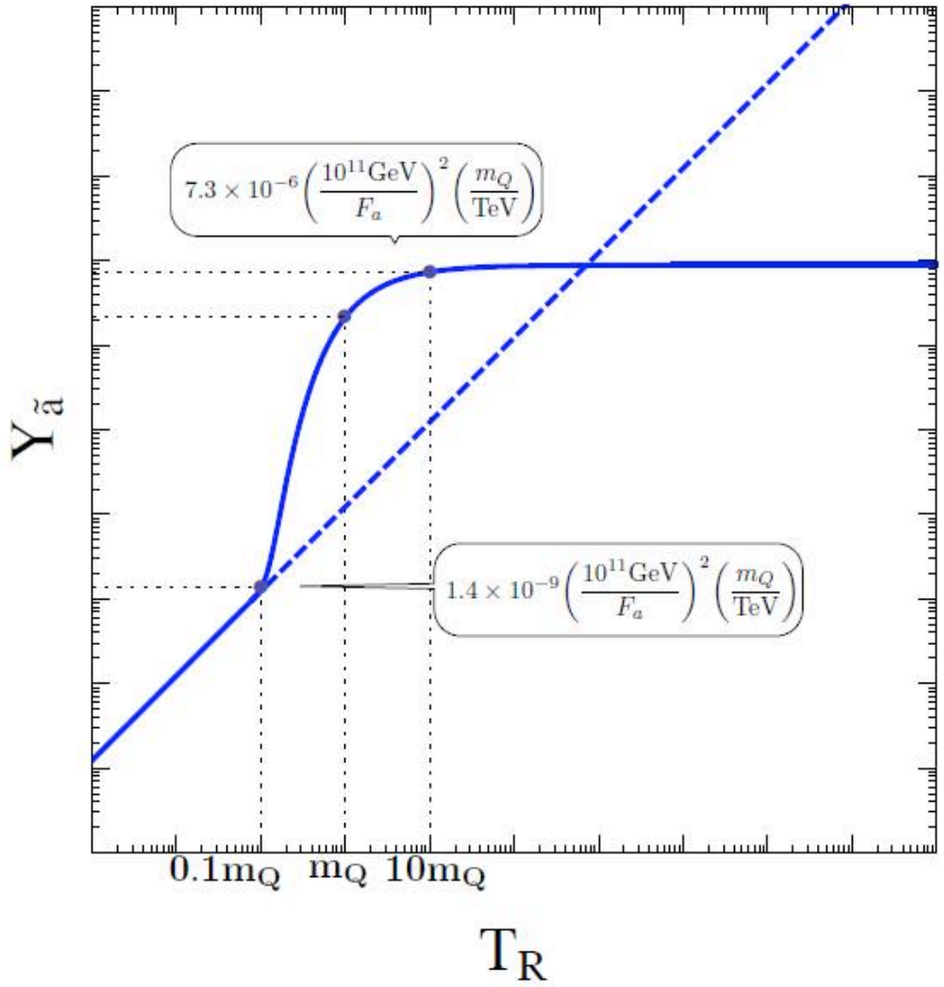
$$\mathcal{L}^{\rm DFSZ} \ni c_H\frac{\mu}{f_a}\tilde{a}[\tilde{H}_d H_u + \tilde{H}_u H_d] + {\rm h.c.}$$

Suppression of axino anomaly interaction [Bae, Choi, Im, 2011]

1PI axino-gluino-gluon amplitude has momentum dependence,

$$\mathcal{A}_{1\mathrm{PI}}[\tilde{a}(k), g(p), \tilde{g}(q)] = \frac{C_{1\mathrm{PI}}}{32\pi^2 F_a}\delta^4(k+p+q)\bar{\tilde{a}}(k)\sigma_{\mu\nu}\gamma_5\tilde{g}(q)\epsilon^\mu p^\nu$$

$$C_{1\mathrm{PI}} = \begin{cases} \mathcal{O}\left(m_Q^2/p^2\right) & \text{for} \quad m_Q < p < F_a \\ nN_Q + \mathcal{O}\left(p^2/m_Q^2\right) & \text{for} \quad p < m_Q \end{cases}$$



T_R = reheat temperature

m_Q = Higgsino mass in DFSZ model
(exotic quark mass in KSVZ model)

For $T_{\mathrm{reh}} > m_Q$

Axino thermal production is suppressed.

Issues with IR regularization with gluon t-channel ⟶ Full Thermal Field Theory

Double Axino Production

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- Low-reheating temperature
- High-scale supersymmetry

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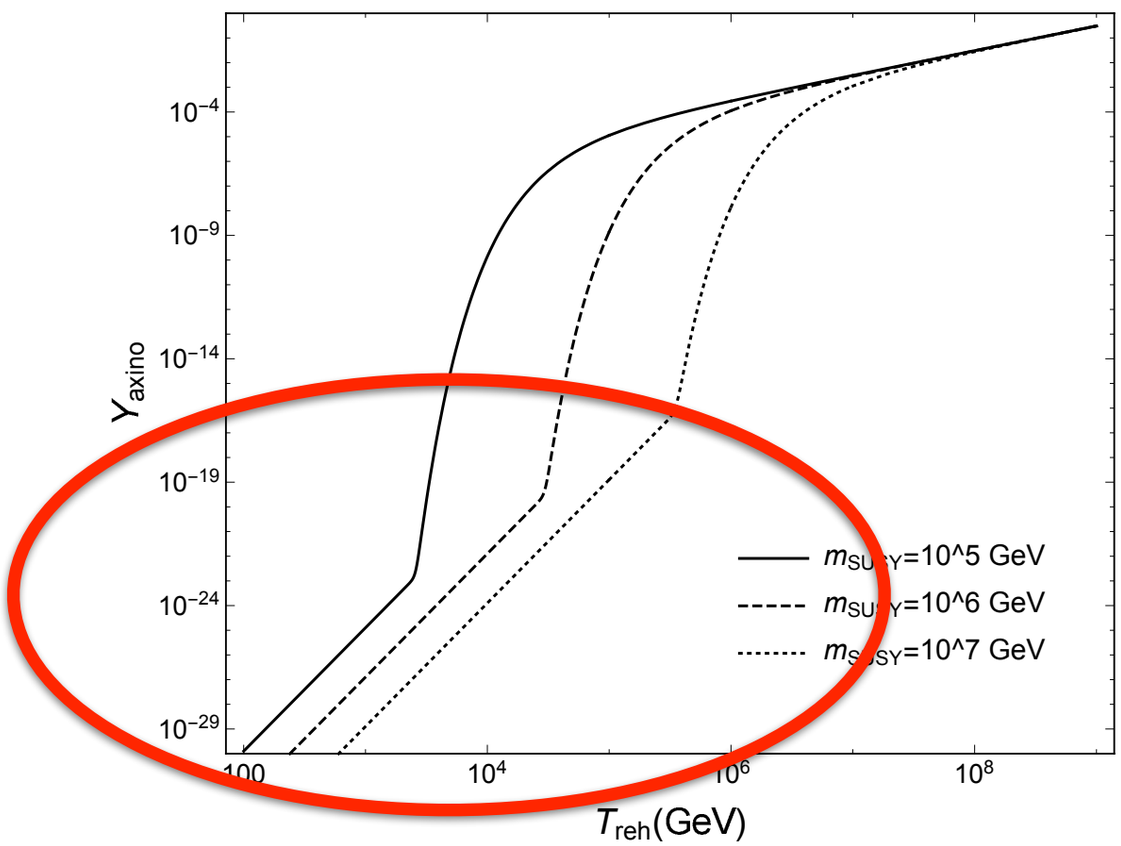
$$\mathrm{SM} + \mathrm{SM} \rightarrow \tilde{a} + \tilde{a}$$

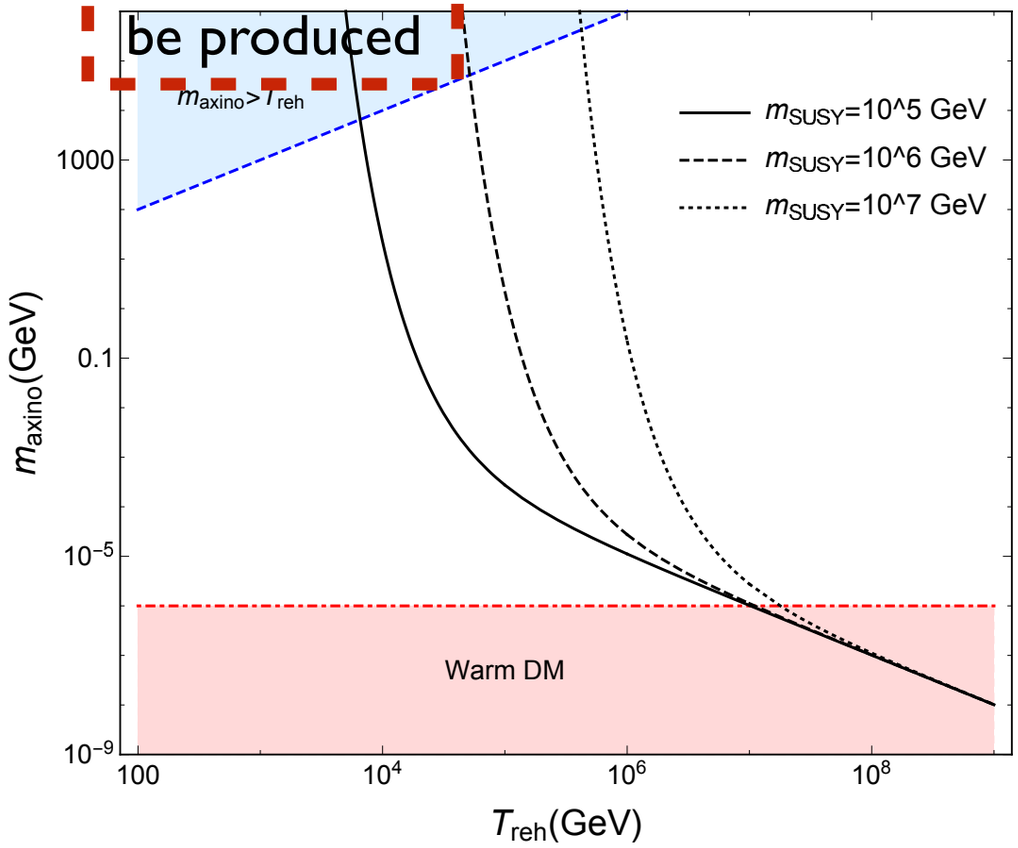
Double Axinos at KSVZ

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After integrating out the gluino, we can obtain the two axinos and two gluons effective interaction:

$$\mathcal{L}_{\rm eff}^{\tilde{g}} = \frac{2\alpha_s^2}{(16\pi f_a)^2 m_{\tilde{g}}}\,\overline{\tilde{a}}\sigma^{\mu\nu}\sigma^{\rho\sigma}\tilde{a}G^b_{\mu\nu}G^b_{\rho\sigma} \equiv \frac{1}{\Lambda_g^3}\,\overline{\tilde{a}}\sigma^{\mu\nu}\sigma^{\rho\sigma}\tilde{a}G^b_{\mu\nu}G^b_{\rho\sigma}$$



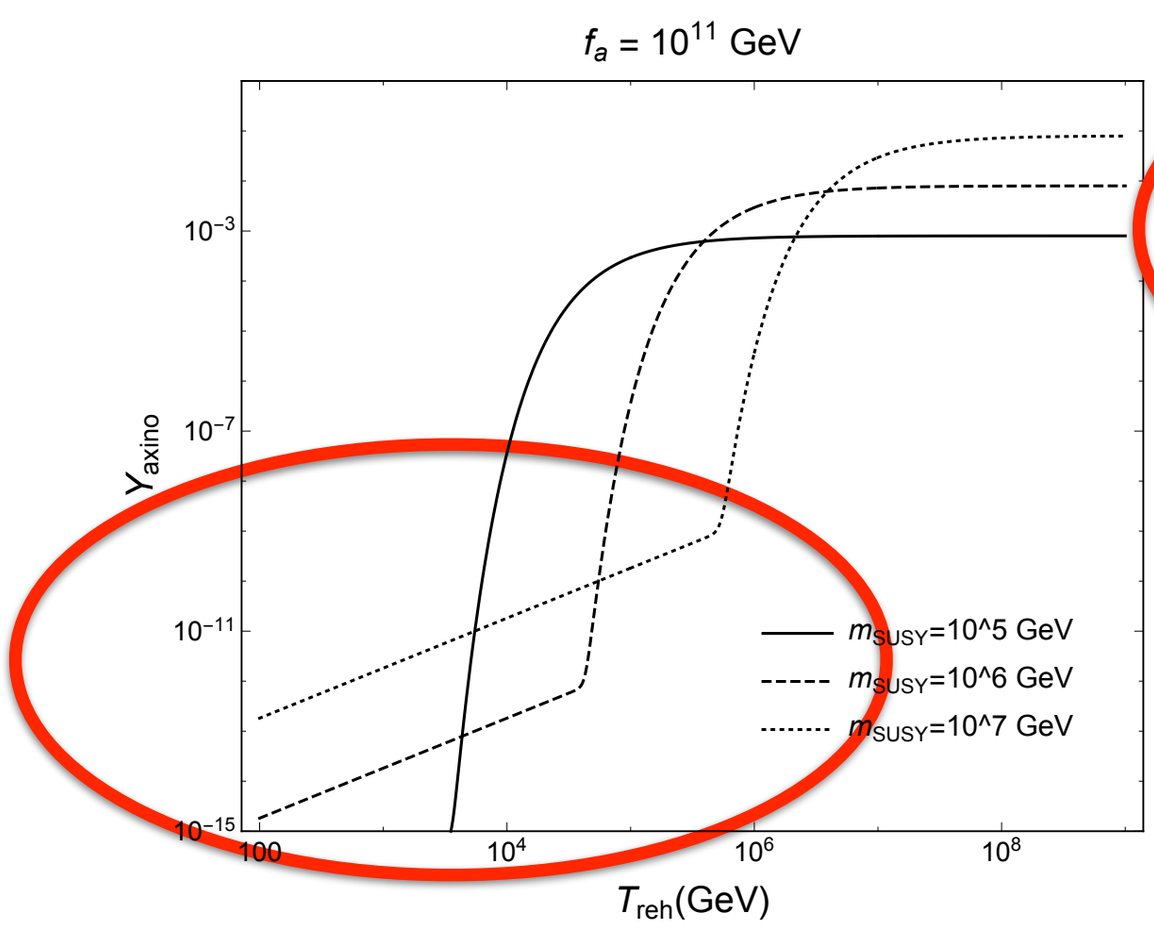


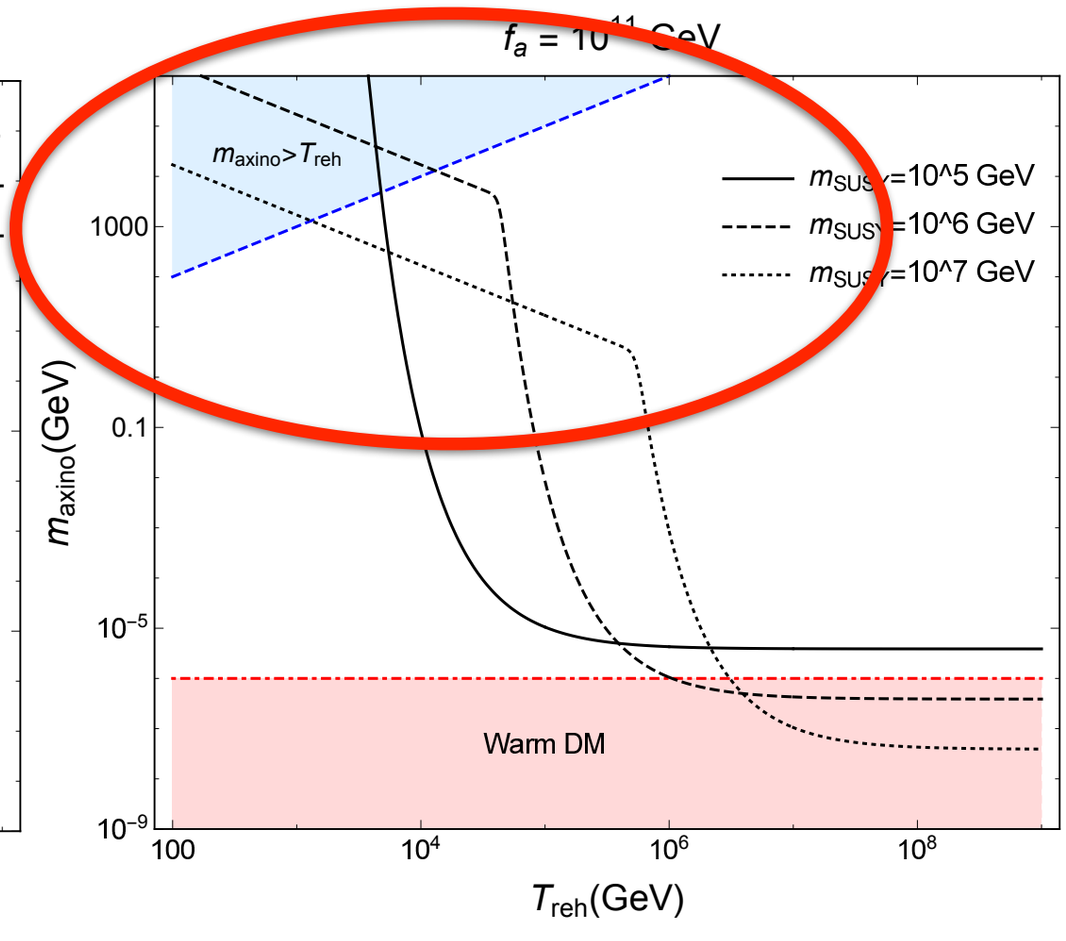
Axino pair at DFSZ

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After integrating out the Higgsino, we can obtain the two axinos and two Higgs effective interaction:

$$\mathcal{L}_{\rm eff}^{\tilde{H}} = \frac{c_H^2 \mu}{2 f_a^2}\, \tilde{a}\tilde{a} H_u H_d + \text{h.c.}.$$





Conclusion

- In the low-reheating temperature or high-scale SUSY, where SUSY particles are heavier than the reheating temperature, the axinos can be produced as a pair.

- The single axino production is suppressed and dominated by the double axino production.

- For reheating temperature between 10^4-10^6 GeV, there is a modification of axino relic density for the mass between 1GeV - 1 TeV.

Thank You!

Ki-Young Choi, Sungkyunkwan University, Korea