AXINO DARK MATTER IN SUPERSYMMETRIC CLOCKWORK MODEL

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AXION AND SUSY

Axion: a good solution to the strong CP problem

$$\rightarrow \quad \sim \frac{\alpha}{f} a G \tilde{G} \qquad 10^9 \text{ GeV} \lesssim f \lesssim 10^{12} \text{ GeV}$$

"invisible" axion is a good DM candidate

SUSY: a good solution to the gauge hierarchy problem

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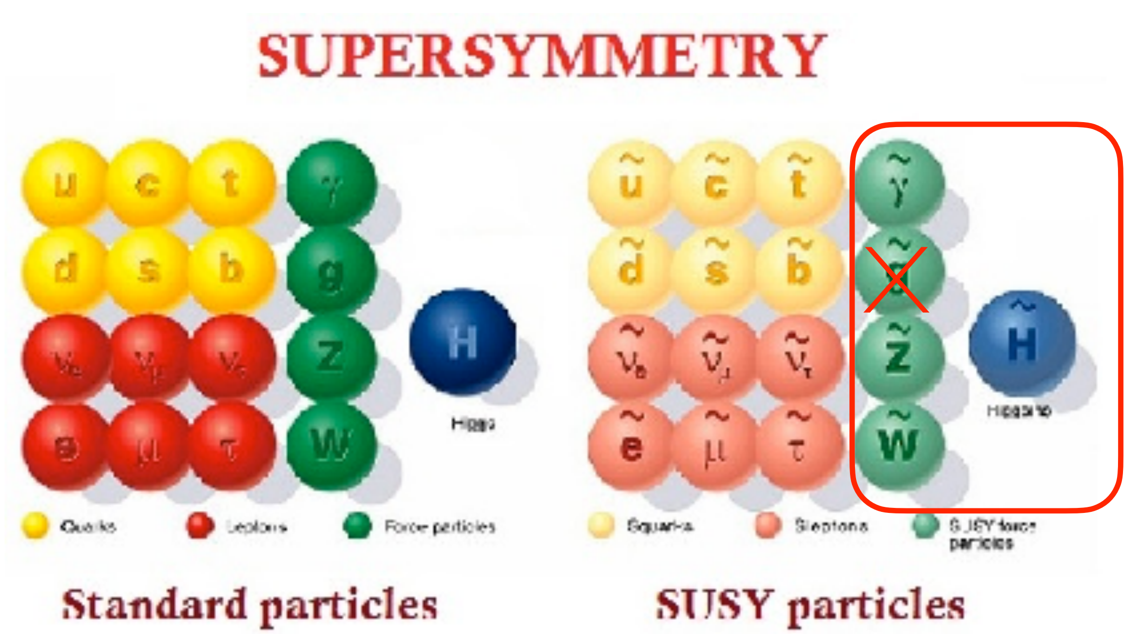


weak scale DM

AXINO

SUSY+Axion: another DM candidate

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

Axino: fermion partner of axion

- massive component due to SUSY breaking

  (highly model-dependent)

- inherits feeble couplings from the axion

$$\sim \frac{\alpha}{f} a G\tilde{G} \longrightarrow \sim \frac{\alpha}{f}\int d^2\theta A W W \sim \frac{\alpha}{f} G^b_{\mu\nu}\bar{\tilde{a}}\sigma^{\mu\nu}\gamma^5\tilde{g}^b$$

$$10^9 \ \mathrm{GeV} \lesssim f$$

CLOCKWORK AXION

a chain of N+1 pNGBs

Choi, Kim, Yun; Choi, Im; Kaplan, Rattazzi

$$\phi_0 \;\overset{1/q}{\text{———}}\; \phi_1 \;\overset{1/q}{\text{———}}\; \phi_2 \;\overset{1/q}{\text{———}}\; \cdots \;\overset{1/q}{\text{———}}\; \phi_N \;\overset{\alpha/v}{\text{———}}\; G\tilde{G}$$

The lightest one

$$a_0 \simeq \phi_0 \qquad \phi_0 \;\overset{\alpha/q^N v}{\text{———}}\; G\tilde{G}$$

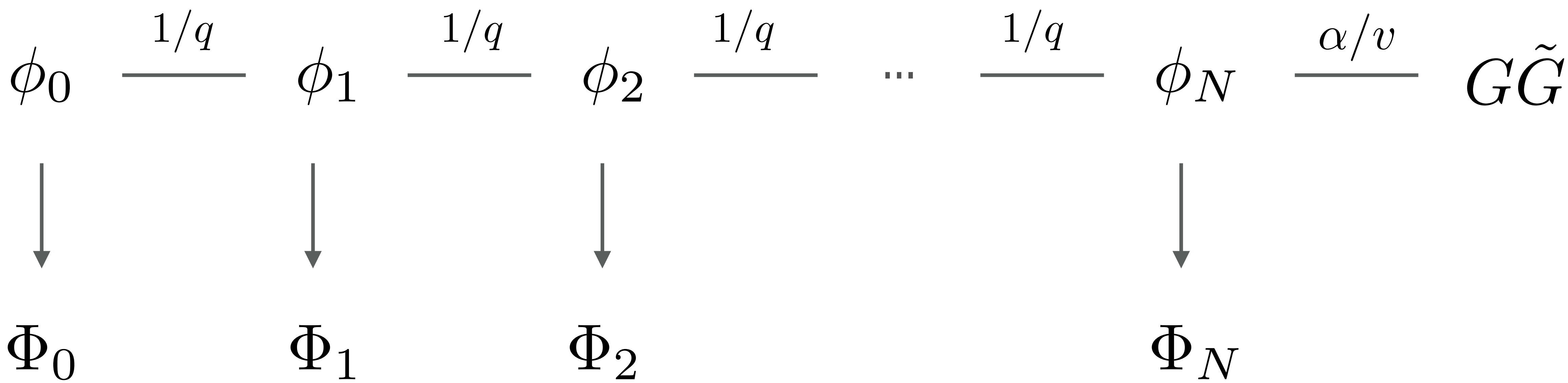
Feeble couplings may originate from the clockwork $f \sim q^N v$

e.g. $v = 1 \text{ TeV} \quad q = 2 \quad N = 20$

$$\longrightarrow \quad f \sim 10^9 \text{ GeV}$$

AXINO DM IN CW MODEL

All gears become SUSY multiplets



All multiplets have pNGBs, scalars, and fermions

with the clockwork structure

$$\Phi_j = \frac{1}{\sqrt{2}}(\sigma_j + i\phi_j) + \sqrt{2}\theta\psi_j + \theta^2 F_j$$

COSMOLOGY

Axions: lightest a_0 $\longrightarrow$ QCD axion, possibly DM candidate

heavy $a_1, \cdots, a_N$ $\quad \sim \dfrac{\alpha}{v} a_j G\tilde{G}$

$\longrightarrow$ decay before BBN

Saxions: all heavy due to SUSY breaking

$\longrightarrow$ decay before BBN

For a review,
Kawasaki, Nakayama, Senami (2008)

Axinos: heavy axinos abundantly produced $\quad \sim \dfrac{\alpha}{v} \bar{\tilde{a}} G_{\mu\nu} \sigma^{\mu\nu} \gamma^5 \tilde{g}$

subsequent decay into lightest axino

$\longrightarrow$ enhancing the axino density

OUTLINE

1. Introduction
2. Axino production
3. Clockwork axion model
4. Axino dark matter in clockwork axion model
5. Conclusion

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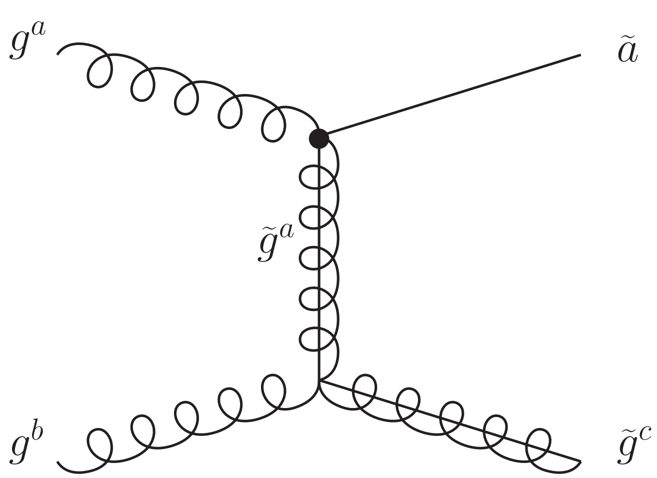
AXINO PRODUCTION

SUSY axion interaction (KSVZ-type model)

$$\frac{\sqrt{2}\alpha_s}{8f}\int d^2\theta A W^b W^b \sim \frac{\alpha_s}{8f}\bar{\tilde{a}}\sigma^{\mu\nu}\gamma^5\tilde{g}^b G^b_{\mu\nu}$$

thermally produced via



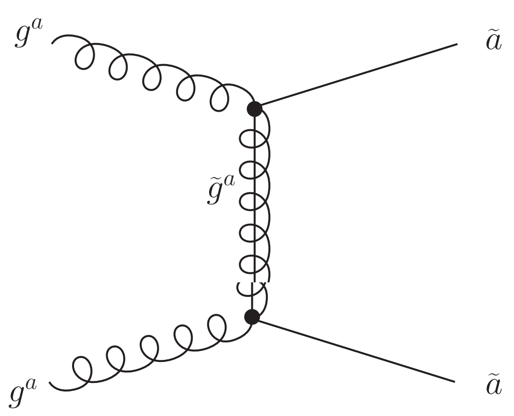
for $T_R > m_{\rm SUSY}$

$$\Omega_{\tilde{a}}h^2 \sim 0.1\left(\frac{m_{\tilde{a}}}{2\ \mathrm{keV}}\right)\left(\frac{10^{10}\ \mathrm{GeV}}{f}\right)^2\left(\frac{T_R}{10^5\ \mathrm{GeV}}\right)$$

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

AXINO PRODUCTION

For high-scale SUSY, $T_R < m_{\rm SUSY}$



$$\sim \frac{2\alpha^2}{(16\pi f)^2 m_{\tilde{g}}} \bar{\tilde{a}} \sigma^{\mu\nu} \sigma^{\rho\sigma} \tilde{a} G^b_{\mu\nu} G^b_{\rho\sigma}$$

$$\Omega_{\tilde{a}} h^2 \sim 10^{-16} \left(\frac{m_{\tilde{a}}}{\rm keV}\right) \left(\frac{10^{10}\ \rm GeV}{f}\right)^4 \left(\frac{10^7\ \rm GeV}{m_{\tilde{g}}}\right)^2 \left(\frac{T_R}{10^5\ \rm GeV}\right)^5$$

Choi, Lee (2018)

highly suppressed due to double power of 1/f and gluino mass

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SUSY CW AXION MODEL

Choi, Im; Kaplan, Rattazzi

KJB, Im

Kähler potential and superpotential

$$K = \sum_{j=0}^{N} \left(X_j^\dagger X_j + Y_j^\dagger Y_j + Z_j^\dagger Z_j \right)$$

$$W = \sum_{j=0}^{N} \kappa Z_j \left(X_j Y_j - v^2 \right) + \frac{1}{v^{q-1}} \sum_{j=0}^{N-1} \left(m X_j Y_{j+1}^q + m' Y_j X_{j+1}^q \right)$$

For $m, \; m' \to 0$

N+1 U(1) symmetries are preserved

	Z_j	X_j	Y_j
charge	0	1	-1

corresponding flat directions $X_j Y_j = v^2$

$$X_j = x \; e^{\Phi_j / v_0}, \quad Y_j = y \; e^{-\Phi_j / v_0} \qquad \Phi_j = \frac{1}{\sqrt{2}} (\sigma_j + i \phi_j) + \sqrt{2} \theta \psi_j + \theta^2 F_j$$

$$v_0 = \sqrt{x^2 + y^2}$$

SUSY CW AXION MODEL

When m, m' are turned on, flat directions develop potentials

$$\langle Z_j \rangle = -\frac{q+1}{\kappa}\sqrt{mm'}, \quad \langle X_j \rangle = x, \quad \langle Y_j \rangle = y \qquad xy = v^2, \quad x = \left(\frac{m}{m'}\right)^{\frac{1}{2(q-1)}} v$$

$$\longrightarrow \quad K_{\text{eff}} = v_0^2 \sum_{j=0}^{N} \left[\cosh\left(\frac{\Phi_j + \Phi_j^\dagger}{v_0}\right) + \xi \sinh\left(\frac{\Phi_j + \Phi_j^\dagger}{v_0}\right)\right]$$

$$\xi = (x^2 - y^2)/v_0^2$$

$$W_{\text{eff}} = m_\Phi v_0^2 \sum_{j=0}^{N-1} \cosh\left(\frac{\Phi_j - q\Phi_{j+1}}{v_0}\right)$$

$$m_\Phi \equiv 2\sqrt{mm'}\left(\frac{v}{v_0}\right)^2$$

N U(1)'s are broken by m, m' > 0

One U(1) remains unbroken

$$\Phi_j \to \Phi_j + q^{-j}\alpha$$

$\longrightarrow$ Clockwork structure appears

SUSY CW AXION MODEL

Effective superpotential in quadratic order

$$W_{\rm eff} = \frac{1}{2} m_\Phi M_{{\rm CW}ij} \Phi_i \Phi_j + \cdots$$

$$\mathbf{M}_{\rm CW} = \begin{pmatrix} 1 & -q & 0 & \cdots & & 0 \\ -q & 1+q^2 & -q & \cdots & & 0 \\ 0 & -q & 1+q^2 & \cdots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \cdots & -q & q^2 \end{pmatrix}$$

Supersymmetric mass with CW structure

SUSY BREAKING

KJB, Im

SUSY breaking in the superpotential

$$\mathcal{L} = \int d\theta^2 (1 + m_s \theta^2) W + \text{h.c.}$$

$$\to V = -m_\Phi |m_s| v_0^2$$

$$\times \sum_{j=0}^{N-1} \left[e^{(\sigma_j - q\sigma_{j+1})/\sqrt{2}v_0} \cos\left(\frac{\phi_j - q\phi_{j+1}}{\sqrt{2}v_0} + \delta_s \right) + e^{-(\sigma_j - q\sigma_{j+1})/\sqrt{2}v_0} \cos\left(\frac{\phi_j - q\phi_{j+1}}{\sqrt{2}v_0} - \delta_s \right) \right]$$

leads to SUSY breaking masses for pNGBs and scalars

$$V_\sigma \simeq -2m_\Phi |m_s| v_0^2 \cos\delta_s \sum_{j=0}^{N-1} \cosh\left(\frac{\sigma_j - q\sigma_{j+1}}{\sqrt{2}v_0} \right) \longrightarrow -m_{\rm sb}^2 \mathbf{M}_{\rm CW}$$

$$V_\phi \simeq -2m_\Phi |m_s| v_0^2 \cos\delta_s \sum_{j=0}^{N-1} \cos\left(\frac{\phi_j - q\phi_{j+1}}{\sqrt{2}v_0} \right) \longrightarrow +m_{\rm sb}^2 \mathbf{M}_{\rm CW}$$

SUSY breaking masses with CW structure

MASS SPECTRUM

KJB, Im

SUSY breaking in Kähler potental

⟶ universal masses for scalars $(m_\sigma^K)^2\mathbf{I}$ and fermions $m_\psi^K\mathbf{I}$

Mass matrices are

$$\mathbf{M}_\phi^2 = m_\Phi^2\mathbf{M}_{\rm CW}^2 + m_{\rm sb}^2\mathbf{M}_{\rm CW},$$
$$\mathbf{M}_\sigma^2 = m_\Phi^2\mathbf{M}_{\rm CW}^2 - m_{\rm sb}^2\mathbf{M}_{\rm CW} + \left(m_\sigma^K\right)^2\mathbf{I}$$
$$\mathbf{M}_\psi = m_\Phi\mathbf{M}_{\rm CW} + m_\psi^K\mathbf{I}.$$

simultaneously diagonalized by

$$\mathbf{O}^T\mathbf{M}_{\rm CW}\mathbf{O} = {\rm diag}(\lambda_0,\cdots,\lambda_k)$$

$\phi_j = \mathbf{O}_{jk}a_k,$ axions

$\sigma_j = \mathbf{O}_{jk}s_k,$ saxions

$\psi_j = \mathbf{O}_{jk}\tilde{a}_k,$ axinos

$$\lambda_0 = 0, \quad \lambda_k = q^2 + 1 - 2q\cos\left(\frac{k\pi}{N+1}\right),$$

$$\mathbf{O}_{j0} = \frac{\mathcal{N}_0}{q^j}, \mathbf{O}_{jk} = \mathcal{N}_k\left[q\sin\frac{jk\pi}{N+1} - \sin\frac{(j+1)k\pi}{N+1}\right]$$
$$\text{for} \quad j = 0,\cdots,N; \quad k = 1,\cdots,N\ ,$$

$$\mathcal{N}_0 = \sqrt{\frac{q^2-1}{q^2-q^{-2N}}}, \quad \mathcal{N}_k = \sqrt{\frac{2}{(N+1)\lambda_k}}.$$

AXINO INTERACTIONS

KJB, Im

1) gluon-gluino-axino vertices

$$\frac{\alpha_s}{8v_0}\int d^2\theta \Phi_N W^b W^b$$

$$\longrightarrow \mathcal{L}_{\rm axn}= \frac{1}{\sqrt{2}v_0}\left(\frac{\mathcal{N}_0}{q^N}\bar{\tilde{a}}_0-\sum_{k=1}^{N}(-1)^k\mathcal{N}_k q\sin\frac{k\pi}{N+1}\bar{\tilde{a}}_k\right)\frac{g_s^2 C_{aGG}}{32\pi^2}G^b_{\mu\nu}\sigma^{\mu\nu}\gamma^5\tilde{g}^b$$

responsible for axino production

2) axion-axino-axino vertices

$$K\supset\frac{\xi}{3!}v_0^2\sum_{j=0}^{N}\left(\frac{\Phi_j+\Phi_j^\dagger}{v_0}\right)^3$$

$$\to \mathcal{L}_{nml}=\frac{\xi}{\sqrt{2}v_0}\sum_j^N \mathbf{O}_{jn}\mathbf{O}_{jm}\mathbf{O}_{jl}\times[\,+is_n\bar{\tilde{a}}_m\gamma^\mu\partial_\mu\tilde{a}_l-(\partial_\mu a_n)\bar{\tilde{a}}_m\gamma^5\gamma^\mu\tilde{a}_l]$$

responsible for axino decay

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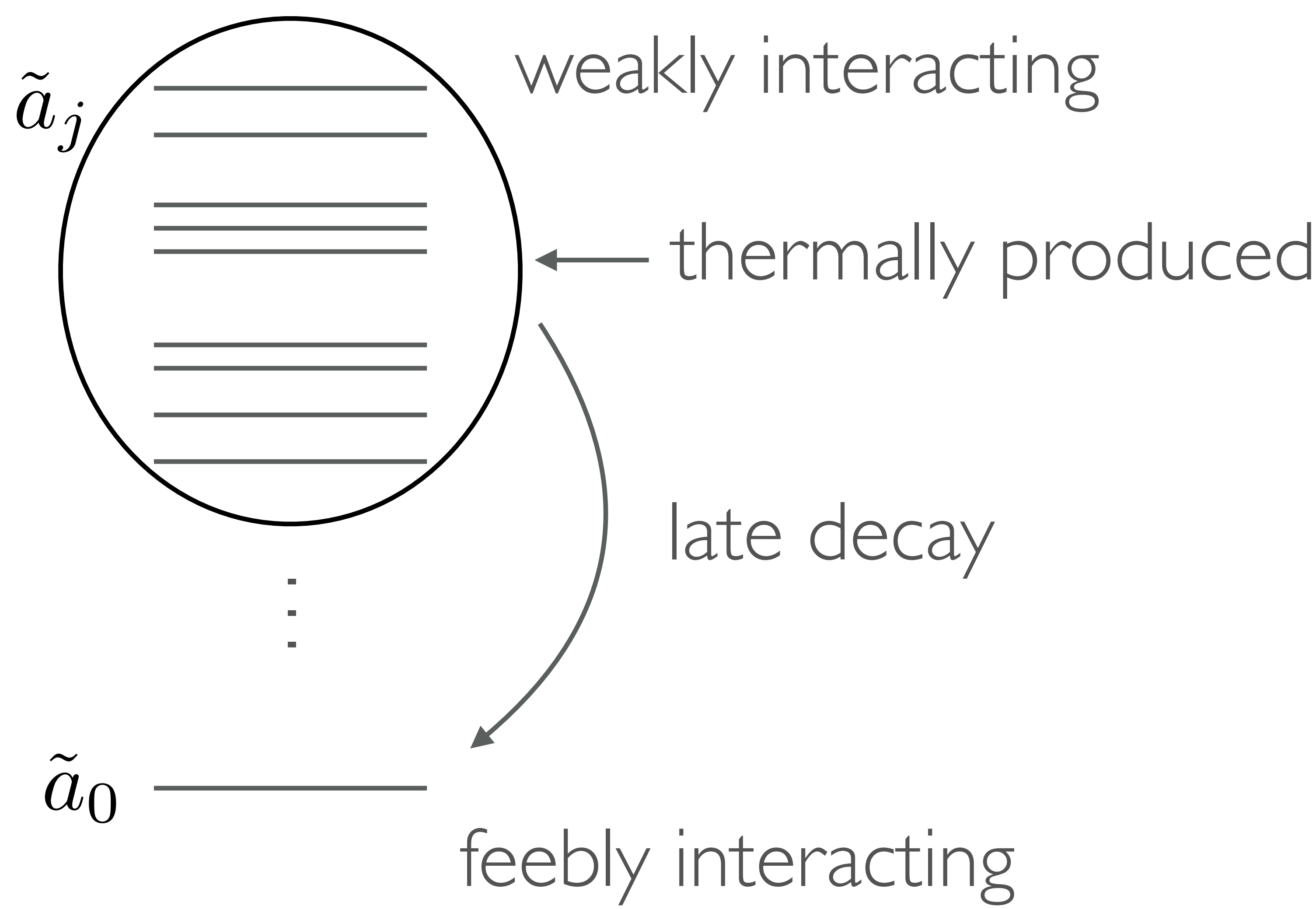
SECLUDED SPECTRUM

KJB, Im

Assumption $m_{\tilde{g}} \gg T_R \gg m_{s,a} \gg m_{\tilde{a}}$

Normal mass ordering of axinos $m_{\psi}^{K} > 0$

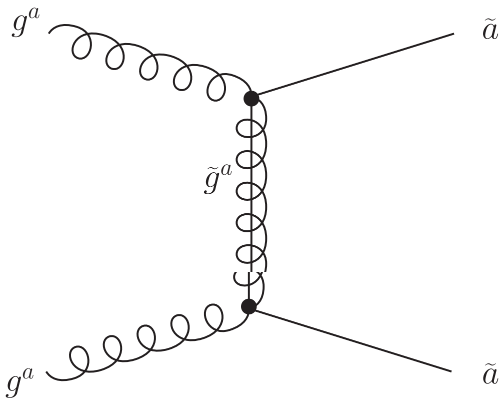


THERMAL PRODUCTION

KJB, Im

1) gluino-mediated processes

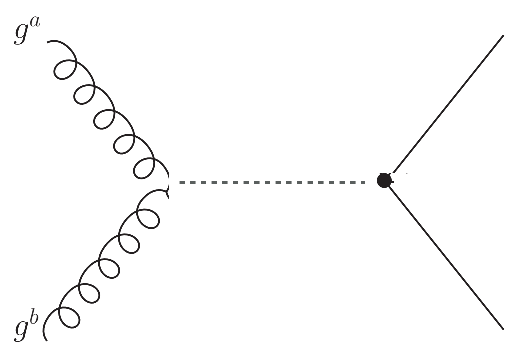
$$\mathcal{L}_{gg\tilde{a}\tilde{a}} = -\frac{\alpha_s^2 C_{aGG}^2}{1024\pi^2 v_0^2 m_{\tilde{g}}} \mathbf{O}_{Nn}\mathbf{O}_{Nm}\,\bar{\tilde{a}}_n[\gamma^\mu,\gamma^\nu][\gamma^\rho,\gamma^\sigma]\tilde{a}_m G^b_{\mu\nu}G^b_{\rho\sigma}$$



dominant

2) saxion/axion-mediated processes

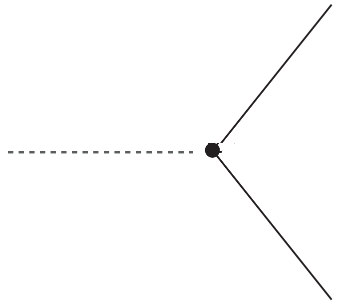
$$\mathcal{L}_{nml} = \frac{\xi}{\sqrt{2}v_0}\sum_j^N \mathbf{O}_{jn}\mathbf{O}_{jm}\mathbf{O}_{jl}\times[\,+is_n\bar{\tilde{a}}_m\gamma^\mu\partial_\mu\tilde{a}_l - (\partial_\mu a_n)\bar{\tilde{a}}_m\gamma^5\gamma^\mu\tilde{a}_l]$$



subdominant

3) saxion/axion decays

subdominant



THERMAL PRODUCTION

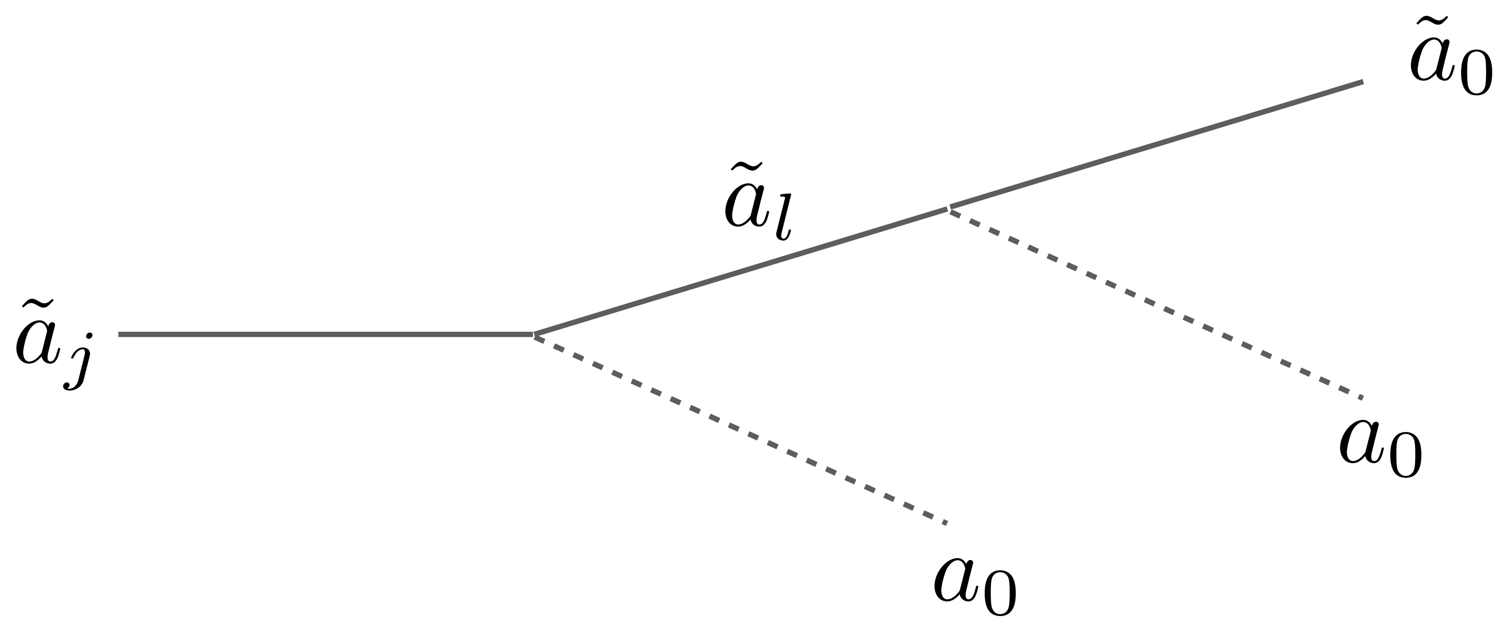
KJB, Im

Time-averaged cross section

$$\langle \sigma v \rangle_{nm} \simeq \frac{6\alpha_s^4 C_{aGG}^4 T^4}{\pi^5 [\zeta(3)]^2 v_0^4 m_{\tilde{g}}^2} \left| \mathbf{O}_{Nn} \mathbf{O}_{Nm} \right|^2 \Delta_{nm}$$

$\Delta_{nm} = 1 \ (1/2)$ for $n \neq m$ $(n = m)$

All heavy axinos eventually decay into the lightest axino



THERMAL PRODUCTION

KJB, Im

Total yield $Y_{\tilde{a}} \propto \sum_{n,m} |O_{Nn} O_{Nm}|^2 = 1$

independent of clockwork gears, decay paths, ...

Axino dark matter density

$$\begin{aligned}\Omega_{\tilde{a}} h^2 &\simeq 2.8 \times 10^5 \times Y_{\tilde{a}}^{\rm DM} \left(\frac{m_{\tilde{a}}}{\rm MeV}\right) \\ &\simeq 0.13 \times \left(\frac{C_{aGG}}{1}\right)^4 \left(\frac{\rm TeV}{v_0}\right)^4 \left(\frac{10~\rm TeV}{m_{\tilde{g}}}\right)^2 \\ &\times \left(\frac{T_R}{40~\rm GeV}\right)^5 \left(\frac{m_{\tilde{a}}}{10~\rm keV}\right),\end{aligned}$$

cf) single axino for $f = 10^{10}$ GeV

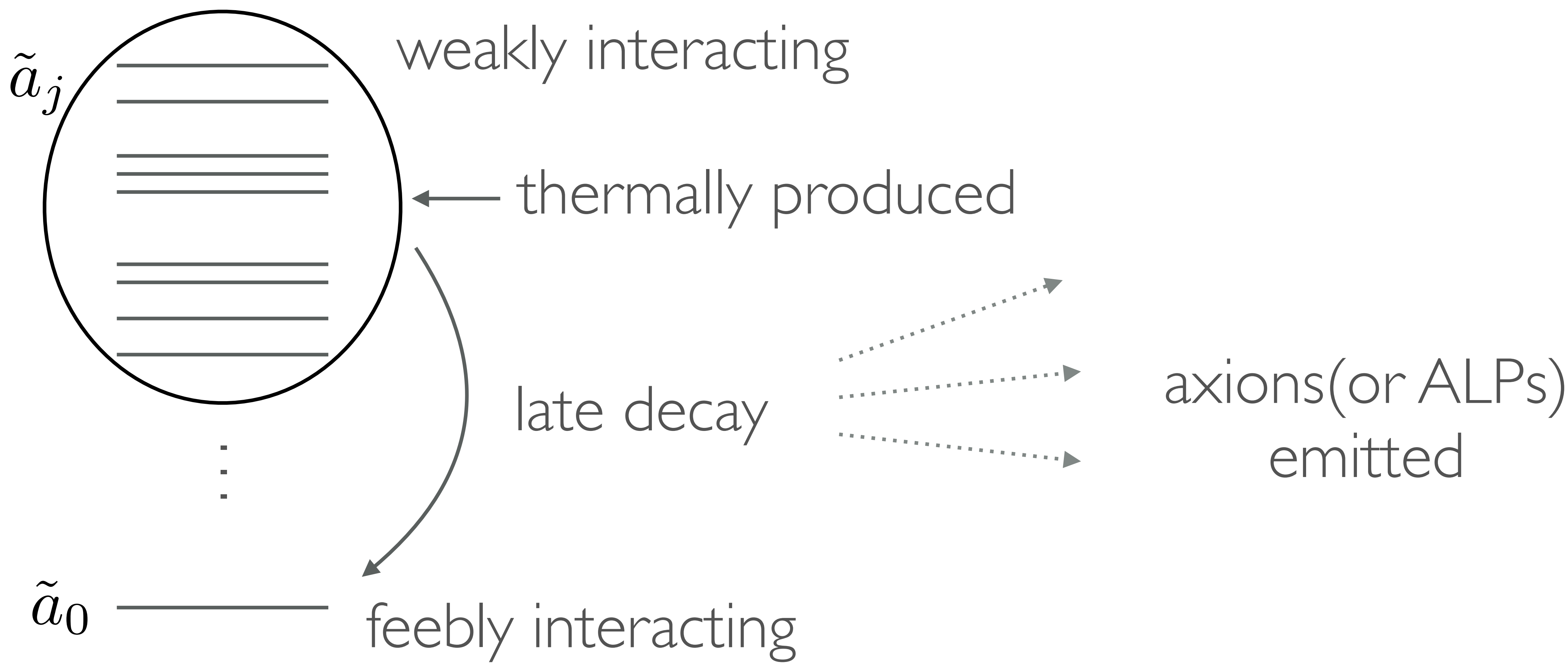
$\Omega h^2 \sim 10^{-25}$

- regardless of the DM coupling, abundance is enhanced due to the heavy mode decays

PHASE SPACE DISTRIBUTION

KJB, Kost (in preparation)

Normal mass ordering of axinos $m_\psi^K > 0$



lightest state: dominantly from decays (th. prod. is negligible)

- ⟶ nonthermal dist.
- ⟶ matter power spectrum (observable: e.g., Ly-alpha forest)
- ⟶ signals from emitted axions

INELASTIC DM

KJB, Kim (in preparation)

$\mathbf{M}_\psi = m_\Phi \mathbf{M}_{\rm CW} + m_\psi^K \mathbf{I}.$ $\quad |m_\psi| \gg m_\Phi$ opposite sign

"inverted" ordering

feebly interacting

weakly interacting

lightest state: dominantly thermal production & distribution

small mass gap ==> inelastic scattering off the nuclei/electron

SUMMARY

- Axino is a feebly-interacting DM candidate in SUSY axion model.
- Feeble interaction may originate from clockwork mechanism
    - a tower of axino states with CW structure
    - one feebly-interacting (the lightest axino),
      N weakly-interacting (heavy axinos)
- Heavy axinos are abundantly produced, then decay to the lightest one.
- Axino DM abundance is enhanced and independent of the details of the CW gears and decay paths.