Axino Dark Matter from Thermal Production in the Early Universe

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Dark Matter in the Universe: Evidence & Candidates

? Solar Neighborhood

  * Planetary Motions

□ Spiral Galaxies

  * Rotation Curves

□ (Super-) Clusters of Galaxies

  * Weak Gravitational Lensing
  * Strong Gravitational Lensing

□ Large Scale Structure

  * Structure Formation

□ CMB Anisotropy: WMAP, ...

  * $\Omega_{\mathrm{M}} = 0.27 \pm 0.016$
  * $\Omega_{\mathrm{Tot}} = 1.02 \pm 0.02$

□ Dark Baryons

  * MACHO's

□ Neutrinos

  * Neutrino Oscillations

□ Axion

  * Strong CP Problem

□ Lightest SUSY Particle (LSP)

  ? Neutralino χ

  ? Gravitino $\tilde{G}$ $\leftarrow$ SUGRA

  ? Axino $\tilde{a}$ $\leftarrow$ SUSY + PQ-Symm.

□ ... ?

Top 10 Puzzle: What is the Nature of Cold Dark Matter?

[Nilles, Raby, '82; Tamvakis, Wyler, '82; Kim, Nilles, '84]

Axinos $\longleftarrow$ SM + Peccei-Quinn Symmetry + Supersymmetry

• strong CP problem → PQ Mechanism   • hierarchy problem → Supersymmetry

↘   ↙

axion supermultiplet: $\Phi = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\tilde{a}\theta + F_\Phi \theta\theta$

saxion   axion   axino

- □ Color Neutral and Electrically Neutral
- □ Interactions are suppressed by the PQ Scale

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

- □ Masses after Breaking of PQ Symmetry and SUSY

  saxion: $m_s = \mathcal{O}(\mathrm{TeV}) \leftarrow$ soft-mass term

  axion: $m_a = \Lambda^2_{\mathrm{QCD}}/f_a \propto 10^{-2} - 10^{-5}\,\mathrm{eV} \leftarrow$ chiral anomaly

  axino: $\mathrm{e}V \lesssim m_{\tilde{a}} \lesssim \mathrm{GeV}$ $\leftarrow$ model dependent

Axino can be Lightest SUSY Particle $\longrightarrow$ Cold Dark Matter

Axinos $\stackrel{?}{=}$ Dominant Part of Cold Dark Matter

□ Assumption: Axino = LSP & stable ← R-parity conservation

? Relic Axino Abundance ← Cosmic Scenario & Production Mechanisms

$$\Omega_{\tilde{a}} h^2 = \rho_{\tilde{a}} h^2/\rho_c = m_{\tilde{a}} n_{\tilde{a}} h^2/\rho_c \qquad \stackrel{?}{\longleftrightarrow} \qquad \Omega_{\rm CDM}^{\rm WMAP} h^2 = 0.113^{+0.016}_{-0.018}$$

? Axino Mass ← SUSY Breaking & Superpotential

$$m_{\tilde{a}} \gtrsim 100\,{\rm keV} \to {\rm cold}\ , \quad 100\,{\rm keV} \gtrsim m_{\tilde{a}} \gtrsim 1\,{\rm keV} \to {\rm warm}\ , \quad 1\,{\rm keV} \gtrsim m_{\tilde{a}} \to {\rm hot}$$

? Nucleosynthesis (BBN) Constraints ← Abundances of D, ^{3}He, ^{4}He, Li

– increase of energy density during BBN

– NLSP Decays: photons & hadronic showers

Inflationary Universe: Relic Axino Density $\stackrel{?}{=}$ WMAP results

Axino Production in the Early Universe

- Inflation $\leftarrow$ flatness, horizont problem, unwanted relics, homog. & isotropy
  - slow roll: exponential expansion $\longrightarrow$ dilution $\longrightarrow$ $n_{\tilde{a}}^{\text{primordial}} = 0$
  - inflaton decay: reheating ($\rightarrow$ model depend. non-thermal production)
- Reheating Temperature T_R
  - $T_R > f_a$: PQ symmetry restored

    [Rajagopal, Turner, Wilczek, 1991]
  - $T_R > T_D$: $\tilde{a}$ in thermal equilibrium $\longrightarrow$ $n_{\tilde{a}} = n_{\tilde{a}}^{\text{eq}} = 3\zeta(3)T^3/(2\pi^2)$
  - $T_D > T_R$: $\tilde{a}$ out of thermal equilibrium [Covi et al., '99, '01, '02, '04]
    - $T_R > 10^4$ GeV: thermal production: hot MSSM plasma $\longrightarrow$ $n_{\tilde{a}}^{\text{TP}}$
    - $T_R < 10^4$ GeV: non-thermal production: NLSP decays, ... $\longrightarrow$ $n_{\tilde{a}}^{\text{NTP}}$

$\longrightarrow$ $f_a > T_D > T_R \gtrsim 10^4$ GeV: Thermal Production

Axino Number Density for $f_a > T_D > T_R \gtrsim 10^4$ GeV

- Boltzmann equation: time evolution of axino density $n_{\tilde{a}}$ in the thermal bath

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = C_{\tilde{a}} = \int d^3p \, \frac{d\Gamma_{\tilde{a}}}{d^3p} \quad \longleftarrow \quad \text{generation of } \tilde{a} - \text{annihilation of } \tilde{a}$$

- collision term for $a(p_1) + b(p_2) \to c(p_3) + \tilde{a}(p)$: $\quad (C_{a+b\to c+\tilde{a}} \in C_{\tilde{a}})$

$$C_{a+b\to c+\tilde{a}} = \int \frac{d^3p}{(2\pi)^3 2E} \int \left[\prod_{i=1}^{3} \frac{d^3p_i}{(2\pi)^3 2E_i}\right] (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p)$$
$$\times \left[|M_{a+b\to c+\tilde{a}}|^2 f_a f_b (1 \pm f_c)(1 - f_{\tilde{a}}) - |M_{c+\tilde{a}\to a+b}|^2 f_c f_{\tilde{a}} (1 \pm f_a)(1 \pm f_b)\right]$$

- phase space densities: $f_i \quad \longrightarrow \quad$ number densities: $n_i = \int \frac{d^3p_i}{(2\pi)^3 2E_i} g_i f_i(E_i)$

a, b, and c: $f_i = f_i^{\text{eq}} = f_{B/F} = \frac{1}{\exp(E_i/T) \mp 1}$, $\qquad$ axino: $f_{\tilde{a}} \approx 0$

Axino Interactions $\longrightarrow$ SUSY QCD

- axino-gluino-gluon interaction:

$$\mathcal{L}_{\tilde{a}\tilde{g}g} = \frac{\alpha_s}{8\pi(f_a/N)}\,\bar{\tilde{a}}\,\gamma_5\,\frac{i}{2}[\gamma^\mu,\gamma^\nu]\;\tilde{g}^a\,G^a_{\mu\nu}$$

- axion-gluon interaction:

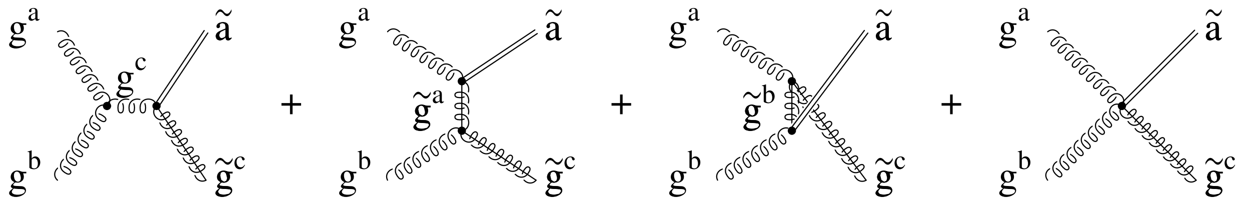
$$\mathcal{L}_{agg} = \frac{\alpha_s}{8\pi(f_a/N)}\,a\,G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

KSVZ model: $N = 1$

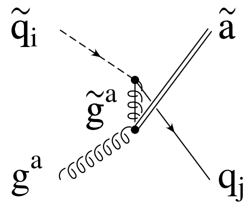
DSFZ model: $N = 6$

Thermal Axino Production in SUSY QCD

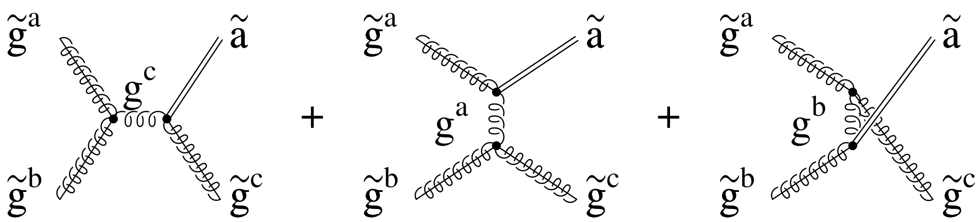
- A: $g^a + g^b \to \tilde{g}^c + \tilde{a}$



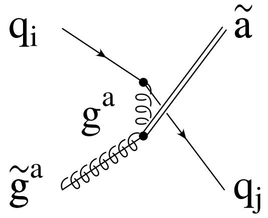
- B: $g^a + \tilde{g}^b \to g^c + \tilde{a}$ (crossing of A)
- C: $\tilde{q}_i + g^a \to \tilde{q}_j + \tilde{a}$



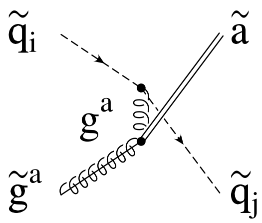
- D: $g^a + q_i \to \tilde{q}_j + \tilde{a}$ (crossing of C)
- E: $\bar{\tilde{q}}_i + q_j \to g^a + \tilde{a}$ (crossing of C)
- F: $\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{a}$



- 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)

Axino Production in $2 \to 2$ Processes

	process i	$\lvert\mathcal{M}_i\rvert^2 / \frac{g^6}{128\pi^4 (f_a/N)^2}$
A	$g^a + g^b \to \tilde{g}^c + \tilde{a}$	$4(s + 2t + 2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \to g^c + \tilde{a}$	$-4(t + 2s + 2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \to q_j + \tilde{a}$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \to \tilde{q}_j + \tilde{a}$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \to g^a + \tilde{a}$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{a}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \to q_j + \tilde{a}$	$-4(s + \frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \to \tilde{q}_j + \tilde{a}$	$-2(\frac{t}{2} + 2s + 2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar{q}_j \to \tilde{g}^a + \tilde{a}$	$-4(t + \frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \to \tilde{g}^a + \tilde{a}$	$2(\frac{s}{2} + 2t + 2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

B, F, G, & H: Logarithmic IR Singularity

Logarithmic Collinear Singularity $\longleftarrow$ Gluon in the t-Channel

- Cut-Off Methods
  - angular cut around forward direction $\longrightarrow$ Collider Phenomenology
  - finite gluon mass: $m_g \propto gT$ $\longleftarrow$ Debye Sceening in the Plasma

[Braaten, Pisarski, 1990]

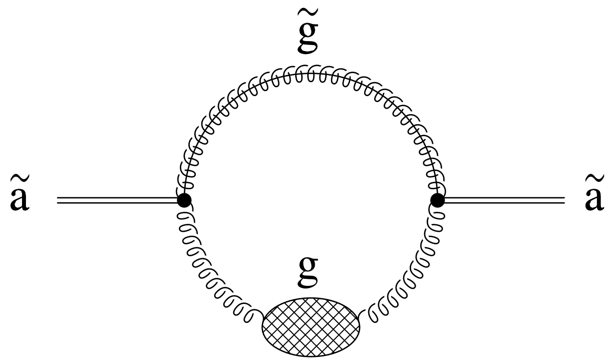
- Improved Eff. Pert. Theory $\longleftarrow$ Hard Thermal Loop Resummation
  - * soft gluons: effective HTL resummed propagator
  - * Debye screening $\longrightarrow$ thermal gluon mass: m_g
  - * independent of "ad hoc" cut-off parameters
  - * gauge invariant
  - * systematic expansion in the coupling
  - ! weak coupling limit: $g \ll 1$
  - ! no static magnetic screening

Systematic Treatment: HTL Resummation Technique

Thermal Axino Production Rate ← HTL Resummation

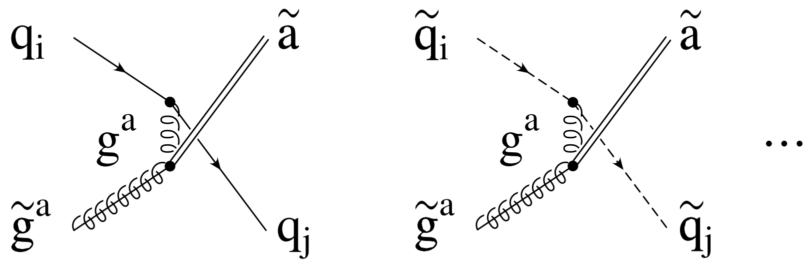
- Separation of Scales: $gT \ll \Lambda \ll T \quad \leftarrow \quad g \ll 1$ [Braaten, Yuan, 1991]

- Soft Part: Axino Self-Energy



→ eff. HTL resummed propagator

- Hard Part: Relativ. Kin. Theory



→ bare propagator

$$E\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{soft}} = -f_F(E)\frac{\text{Im}\Sigma(E+i\epsilon,\mathbf{p})}{(2\pi)^3}\bigg|_{|\mathbf{p}_1-\mathbf{p}_3|<\Lambda}$$

$$= A_{\text{soft}} + B\ln\left[\frac{\Lambda}{gT}\right]$$

$$E\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{hard}} = \frac{1}{2}\int\prod_{i=1}^{3}...|M|^2\Theta(|\mathbf{p}_1-\mathbf{p}_3|-\Lambda)$$

$$= A_{\text{hard}} + B\ln\left[\frac{T}{\Lambda}\right]$$

- Thermal Production Rate: ∗ complete to LO in g , ∗ finite , ∗ indep. of Λ

$$E\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{LO in }g} = E\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{soft}} + E\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{hard}} = A_{\text{soft}} + A_{\text{hard}} + B\ln\left[\frac{1}{g}\right]$$

The Collision Term to Leading Order in the Coupling g

- Collision Term:

$$C_{\tilde{a}}(T) \;=\; \int d^3p \left(\left.\frac{d\Gamma_{\tilde{a}}}{d^3p}\right|_{\mathrm{soft}} + \left.\frac{d\Gamma_{\tilde{a}}}{d^3p}\right|_{\mathrm{hard}} \right)$$

$$C_{\tilde{a}}(T) = \frac{(N_c^2-1)}{(f_a/N)^2}\,\frac{3\zeta(3)g^6T^6}{4096\pi^7}\left[\ln\left(\frac{1.380\,T^2}{m_g^2}\right)(N_c+n_f)+0.4336\,n_f\right]$$

- Thermal Gluon Mass in the “QGSGP”:

$$m_g^2 = \frac{g^2T^2}{6}(N_c+n_f) \quad \text{with} \quad N_c = 3 \quad \text{and} \quad n_f = 6$$

- Running of the Strong Coupling in the MSSM:

$$g(T) = \left(g^{-2}(M_Z) + \frac{3}{8\pi^2}\ln\left[\frac{T}{M_Z}\right]\right)^{-1/2} \longrightarrow \quad 0.85 \text{ for } T \approx 10^{10}\,\mathrm{GeV}$$

Solving the Boltzmann Equation $\rightarrow$ Axino Abundance

- Boltzmann equation

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = C_{\tilde{a}}$$

- conservation of entropy

$$sR^3 = \text{const.}$$

- yield $\rightarrow$ scale out expansion

$$Y_{\tilde{a}} = \frac{n_{\tilde{a}}}{s}$$

- Boltzmann equation

$$\frac{d}{dt}Y_{\tilde{a}} = \frac{C_{\tilde{a}}}{s}$$

- radiation dominated epoch

$$dt = -\frac{dT}{H(T)T}\,, \quad H(T) = \sqrt{\frac{g_*(T)\pi^2}{90}}\frac{T^2}{\mathrm{M_{Pl}}}$$

- entropy density MSSM

$$s(T) = \frac{2\pi^2}{45}g_{*S}(T)T^3\,, \qquad g_{*S} = g_* = \frac{915}{4}$$

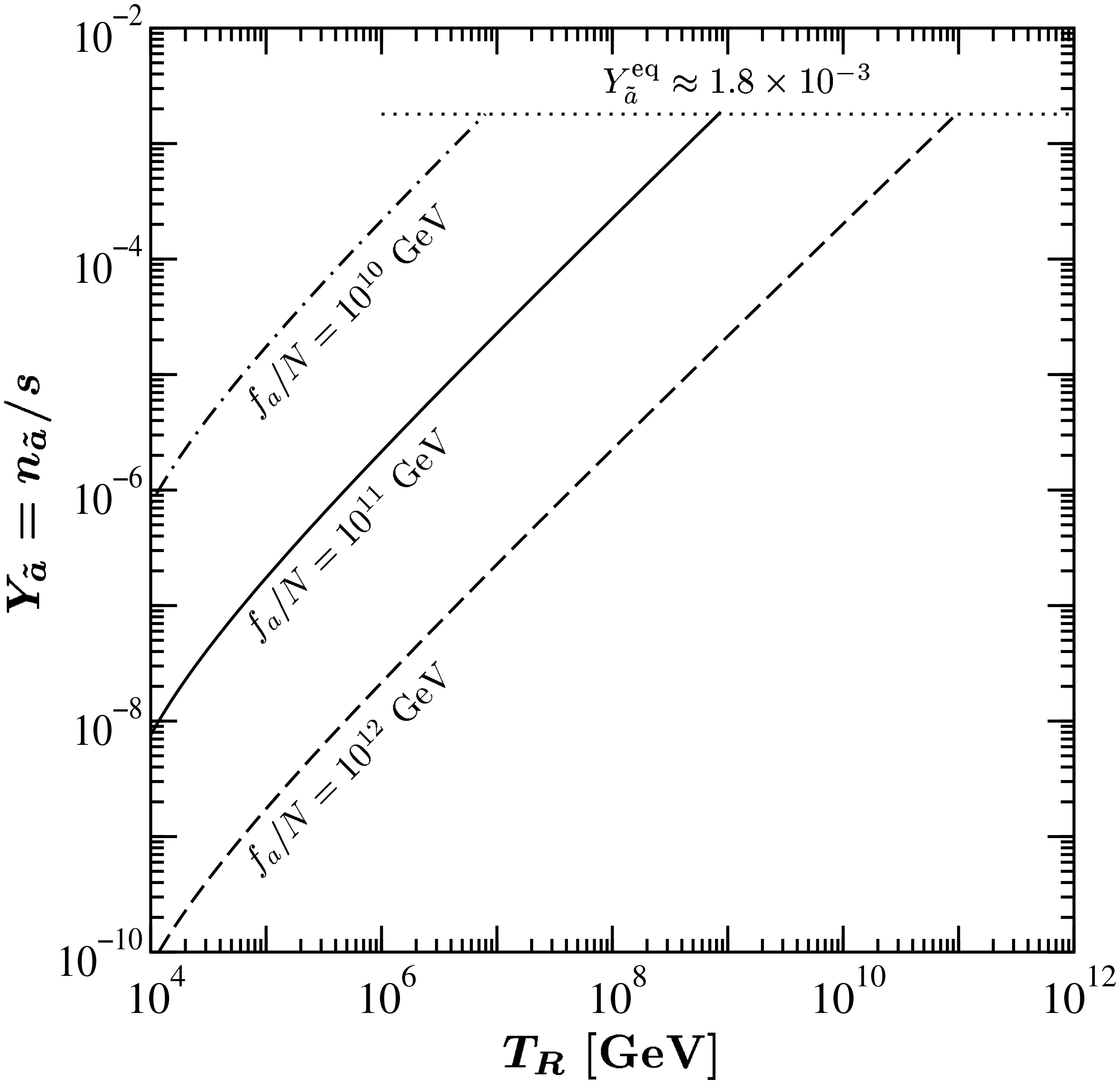
- Axino Yield from Thermal Production

$$Y_{\tilde{a}} \approx \frac{C_{\tilde{a}}(T_R)}{s(T_R)H(T_R)} = 2.0\times 10^{-7}\,g^6 \ln\left(\frac{1.108}{g}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a/N}\right)^2\left(\frac{T_R}{10^4\,\mathrm{GeV}}\right)$$

- Axino Density from Thermal Production

$$\Omega_{\tilde{a}}h^2 = m_{\tilde{a}}Y_{\tilde{a}}s(T_0)h^2/\rho_c = 5.5\,g^6 \ln\left(\frac{1.108}{g}\right)\left(\frac{m_{\tilde{a}}}{0.1\,\mathrm{GeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a/N}\right)^2\left(\frac{T_R}{10^4\,\mathrm{GeV}}\right)$$

Axino Yield from Thermal Production



- Weak Coupling Result: $g \ll 1 \quad \rightarrow \quad T_R > 10^4$ GeV

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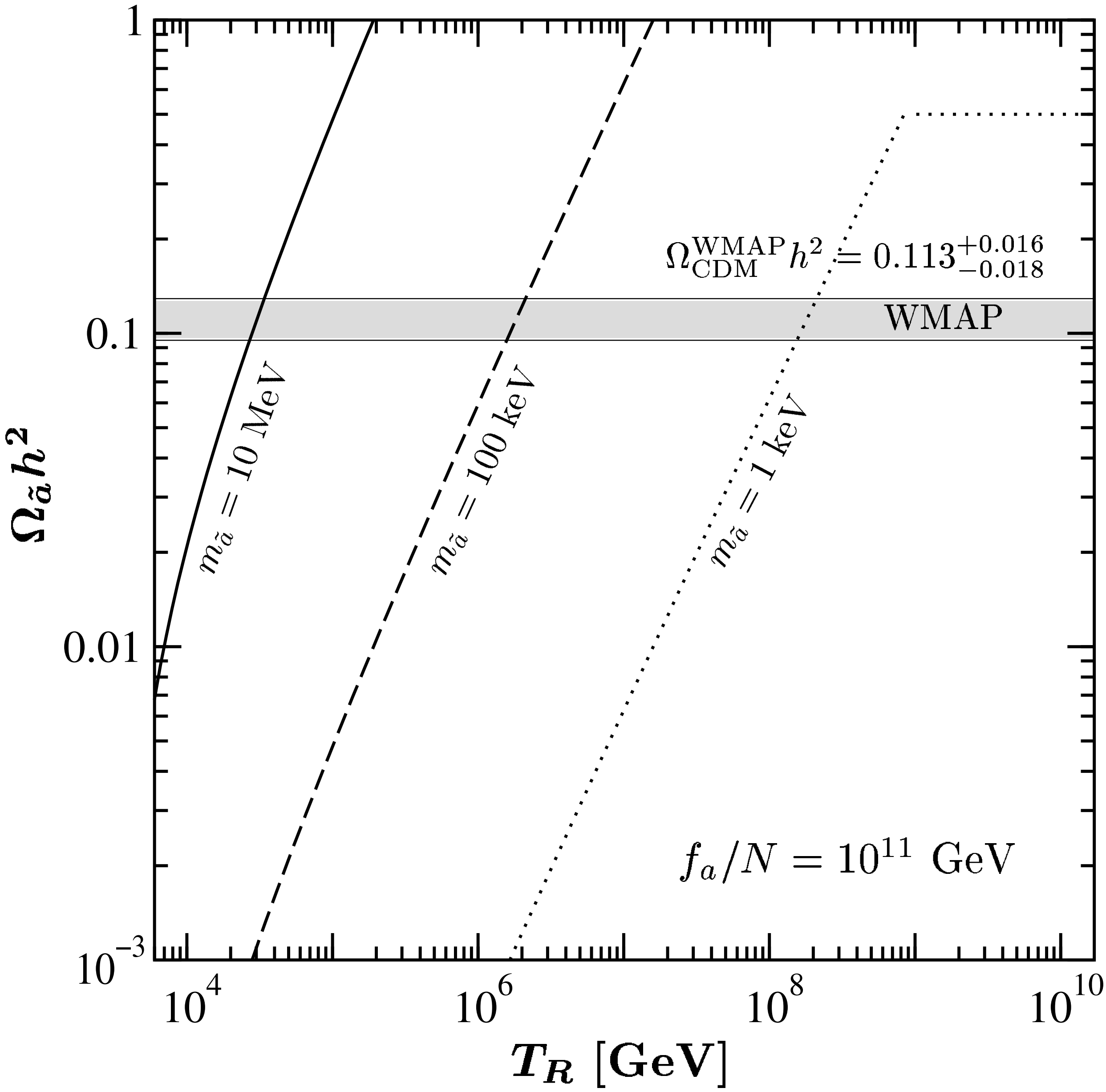
- Strong Coupling: Running in the MSSM

$$g(T_R) = \left(g^{-2}(M_Z) + \frac{3}{8\pi^2}\ln\left[\frac{T_R}{M_Z}\right]\right)^{-1/2}$$

Axino Density from Thermal Production



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Constraints from Nucleosynthesis $\to$ BBN Constraints

- production of energetic axinos shortly before BBN $\to$ energy density $\nearrow$

  $\to$ $H \nearrow$ $\to$ earlier freeze out $\to$ n_p/n_n changes $\to$ D, ^{3}He, ^{4}He, Li

$*$ thermal production at $T > 10^4\,\mathrm{GeV}$ $\longleftarrow$ long before BBN at $T \approx 1\,\mathrm{MeV}$

- photons from NLSP decays: $\chi \longrightarrow \tilde{a} + \gamma$ [Covi et al., '99]

$*$ thermalization: QED plasma & CMBR photons $\longrightarrow$ $\tau_\chi \lesssim 10^4\,\mathrm{sec}$

[Covi et al., '01]

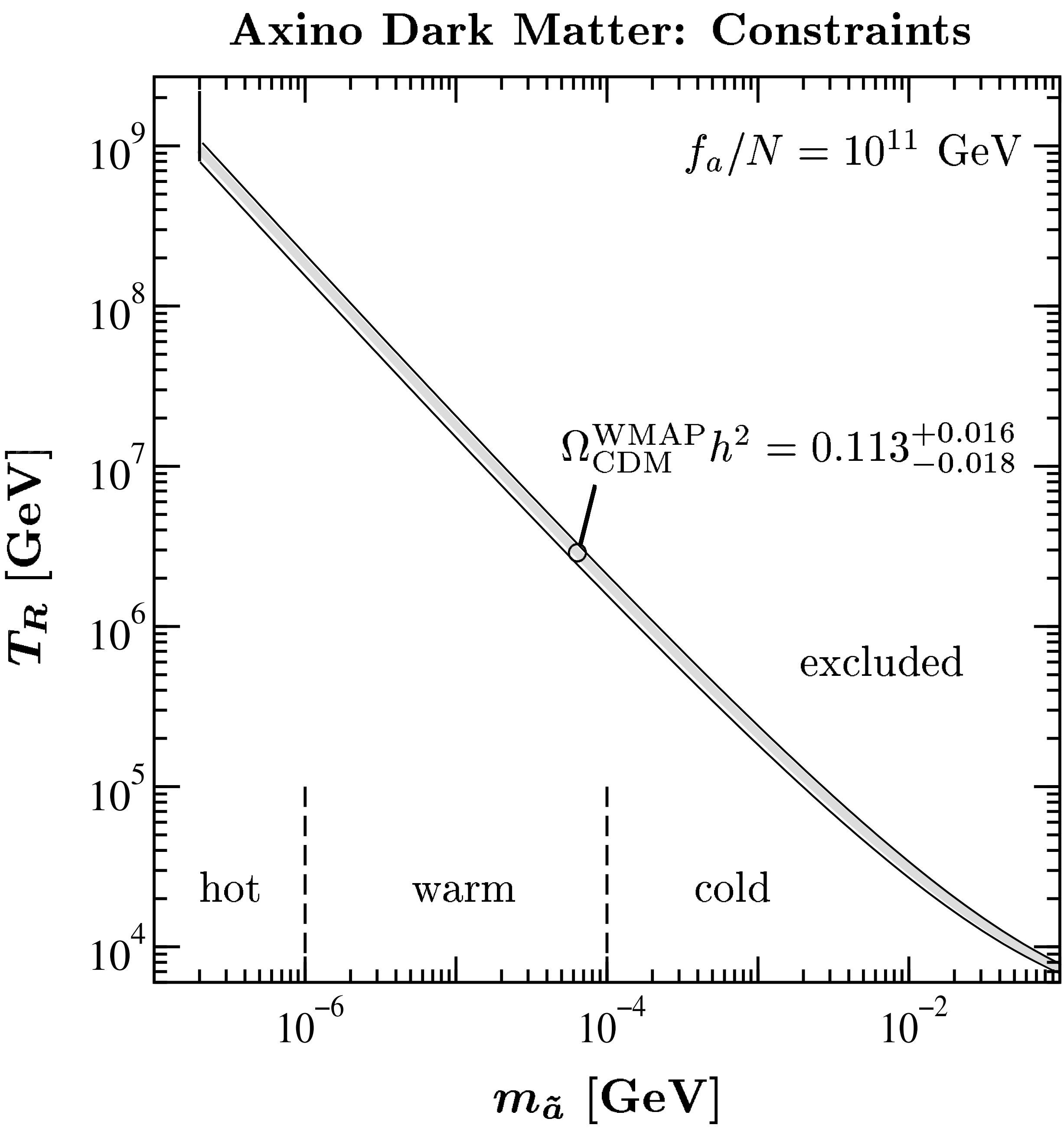
- hadronic showers from NLSP decays: $\chi \longrightarrow \tilde{a} + Z/\gamma \longrightarrow \tilde{a} + q\bar{q}$

! additional $m_{\tilde{a}}$ limits possible $\leftarrow$ strongly sensitive to m_χ & composition of χ

$f_a \ll \mathrm{M_{Pl}}$ $\to$ axino LSP less problematic than gravitino LSP

Axinos $\stackrel{?}{=}$ Dominant Component of CDM

Yes $\longrightarrow$ $T_R \approx 10^6$ GeV and $m_{\tilde{a}} \approx 100\,\mathrm{keV}$



Result from HTL Resummation:

$T_R^{\rm max} \nearrow$ by a factor of 10

compared to result of [Covi et. al. '01]