On calculations of cosmic relic abundances of extremely weakly interacting particles

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Gauge field dynamics in and out of equilibrium

INT Seattle, April 10, 2012

Outline

- Extremely Weakly Interacting Particles (EWIPs)
- Cosmic Relic Abundances (Th.Relic, Th.Prod.)
- Calculation of the Collision Term (Hard + Soft)
- Phenomenological Implications (T_D, DM, BBN)

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model

Peccei-Quinn Symmetry & Supersymmetry

	Axions $f_a > 10^9$ GeV	Axinos $f_a > 10^9$ GeV	Gravitinos $M_{Pl} = 2.4 \times 10^{18}$ GeV
spin	0	1/2	3/2
mass	<10 meV	?	eV-TeV
int.	$\propto (p/f_a)^n$	$\propto (p/f_a)^n$	$\propto (p/M_{Pl})^n$

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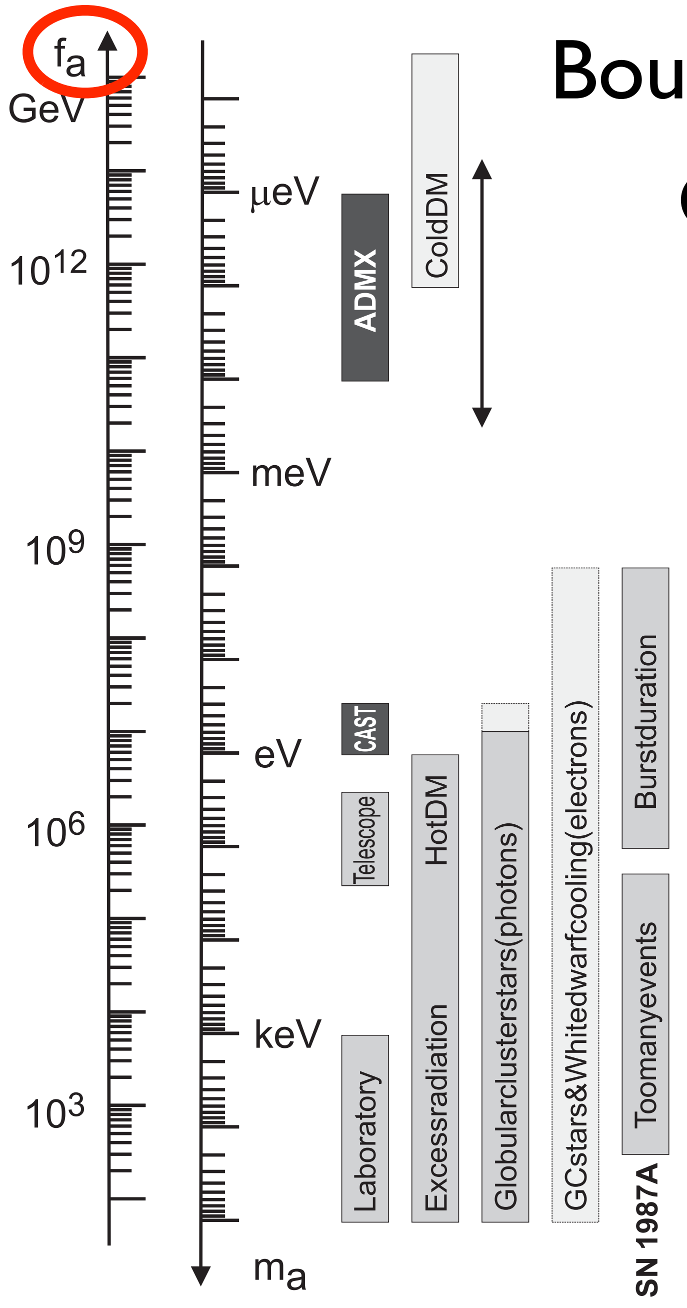
[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



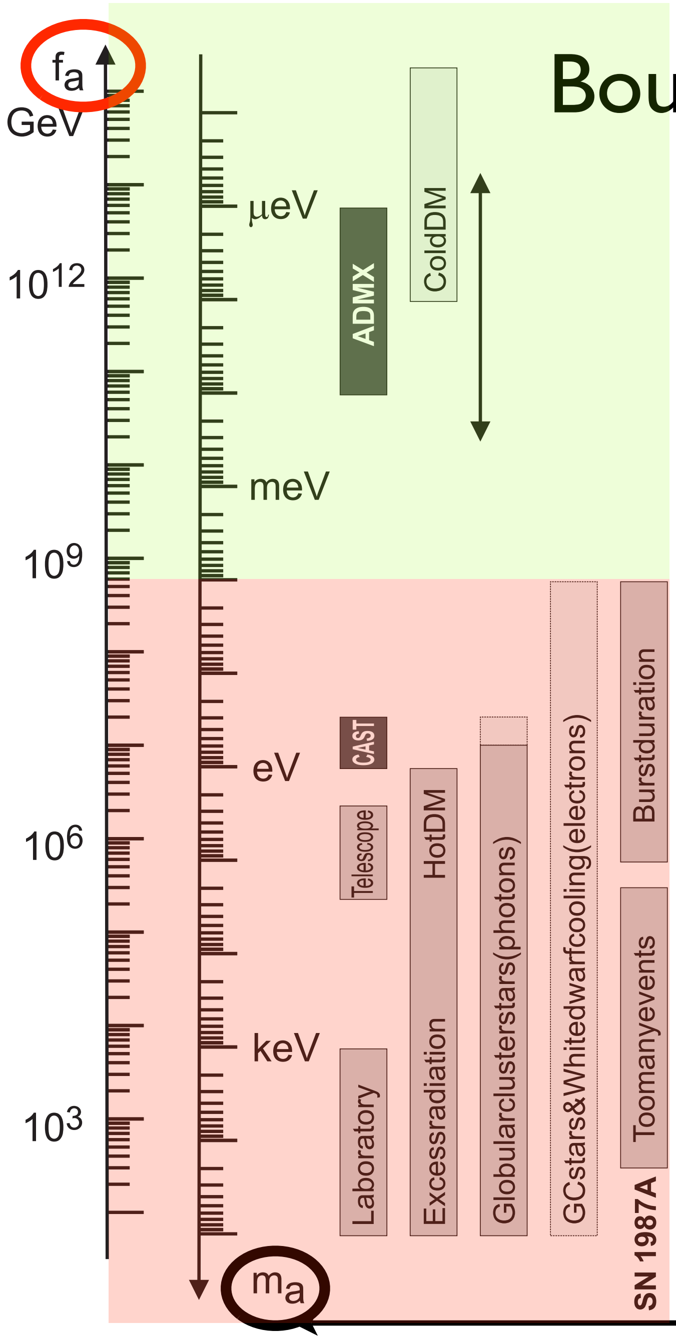
Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

Peccei-Quinn Scale

$$f_a \gtrsim 6 \times 10^8\,\mathrm{GeV}$$

Axion Mass

$$m_a \simeq 0.6\ \mathrm{meV}\,(10^{10}\,\mathrm{GeV}/f_{\mathrm{PQ}})$$

Axion Interactions

- with gluons
  model independent

$$\mathcal{L}_{agg} = \frac{g_s^2}{32\pi^2 f_a}\, a\, G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

- with photons
  model dependent

$$\mathcal{L}_{a\gamma\gamma} = \frac{e^2 C_{a\gamma\gamma}}{32\pi^2 f_a}\, a\, F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

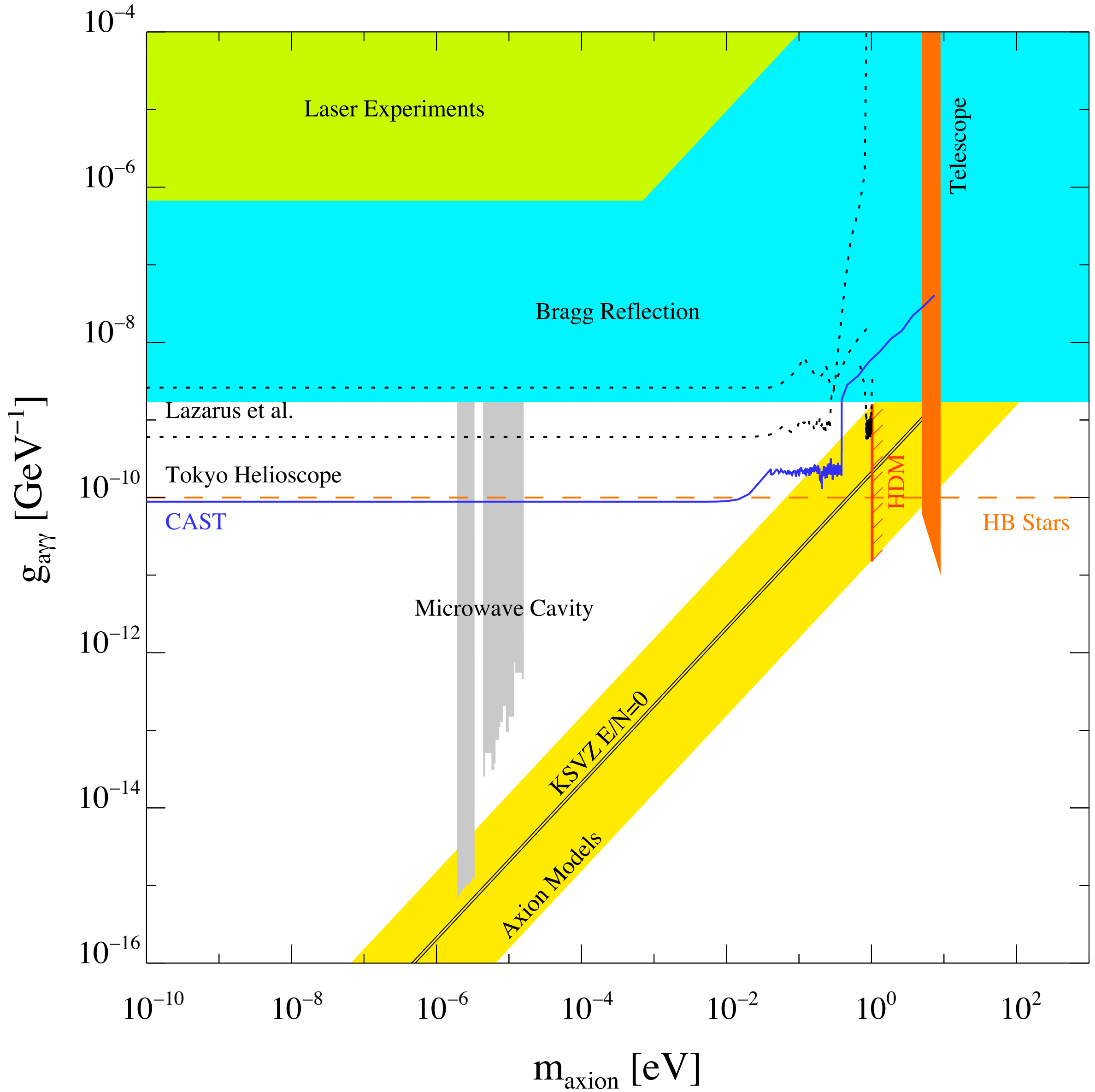
(or $\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$)

↓

but crucial for axion searches

and governs the axion lifetime $\tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{g^2_{a\gamma\gamma} m_a^3}$

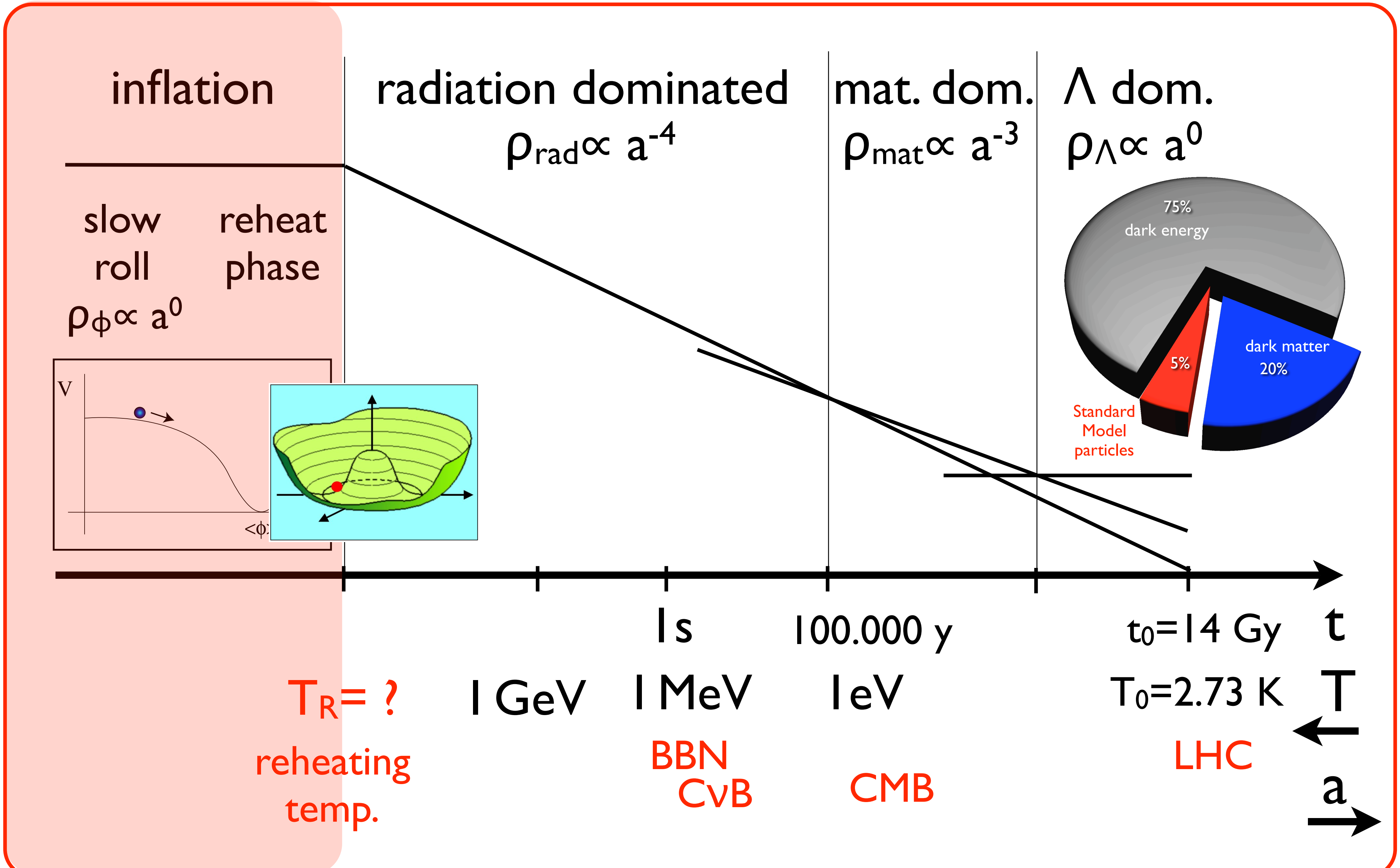
Axion Searches



Updated figure provided by M. Kuster for [FDS, 0811.3347]

see also [Battesti et al., 0705.0015]

Axion Dark Matter



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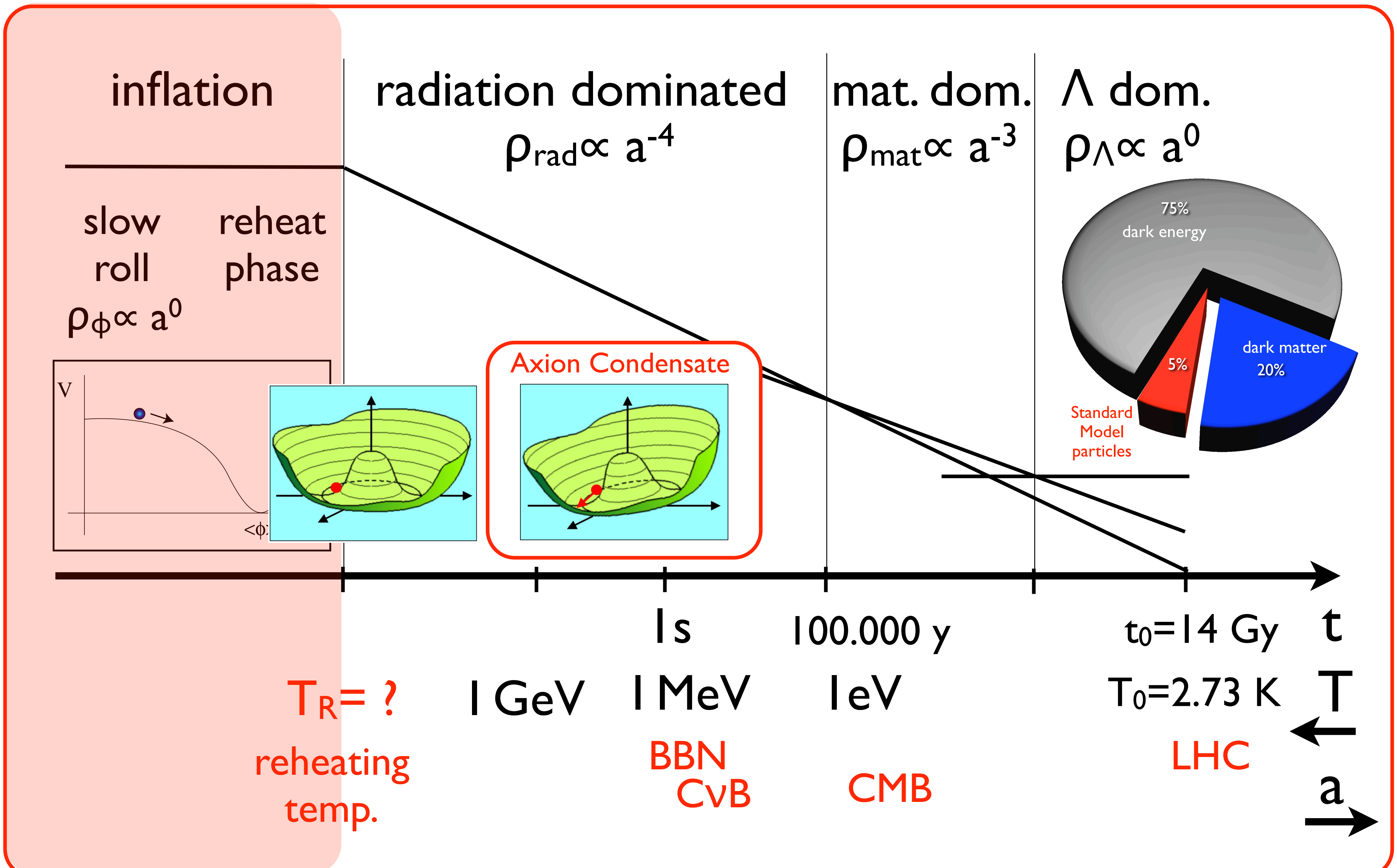

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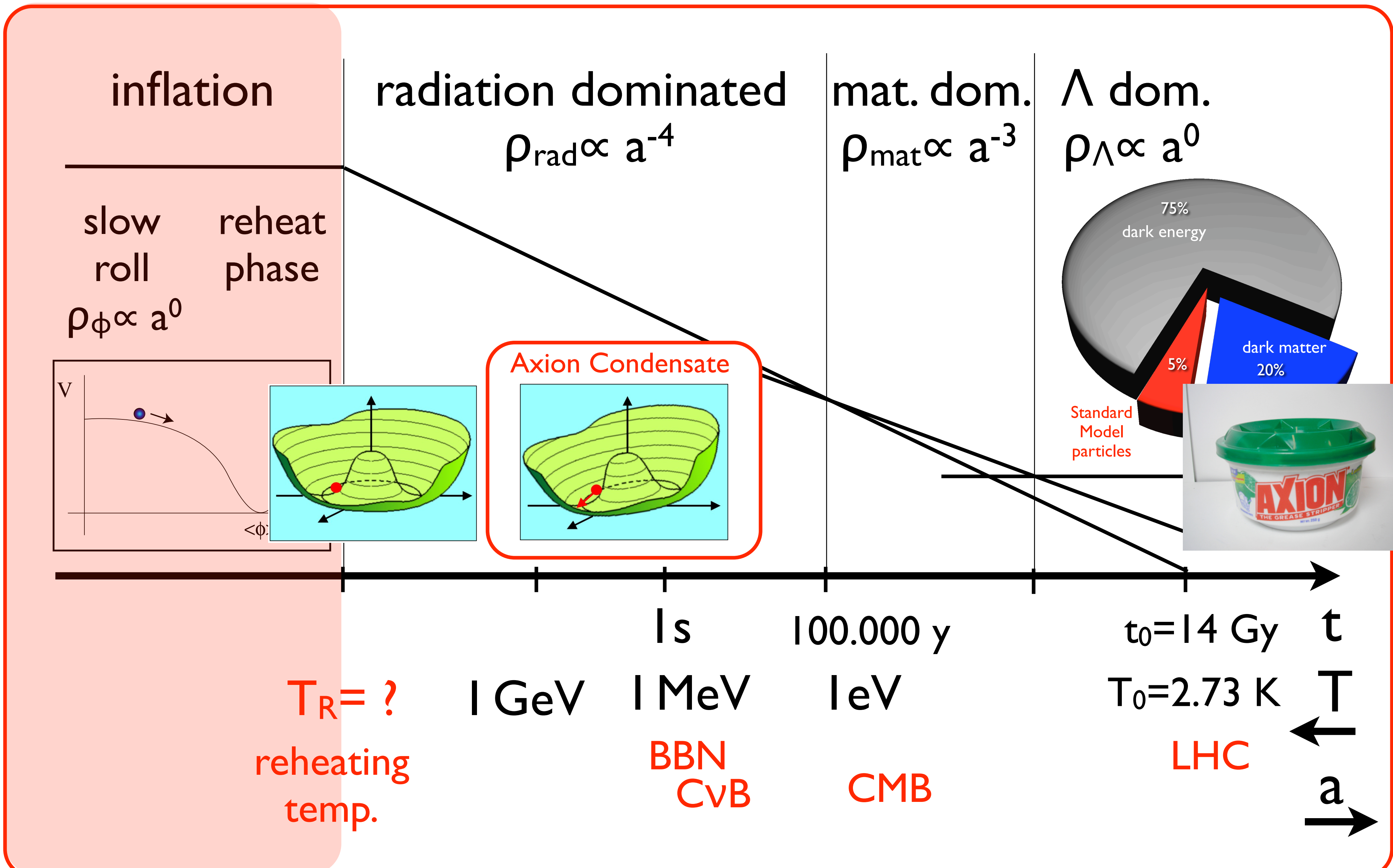

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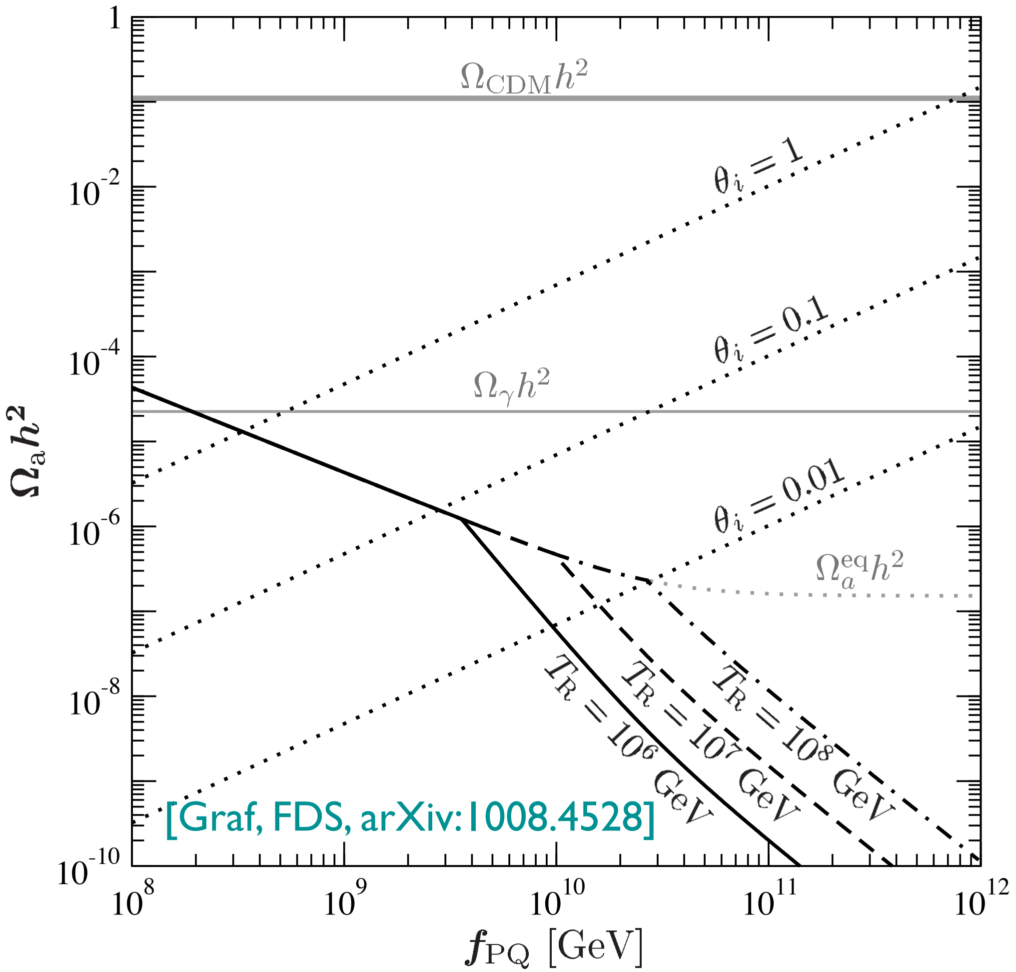

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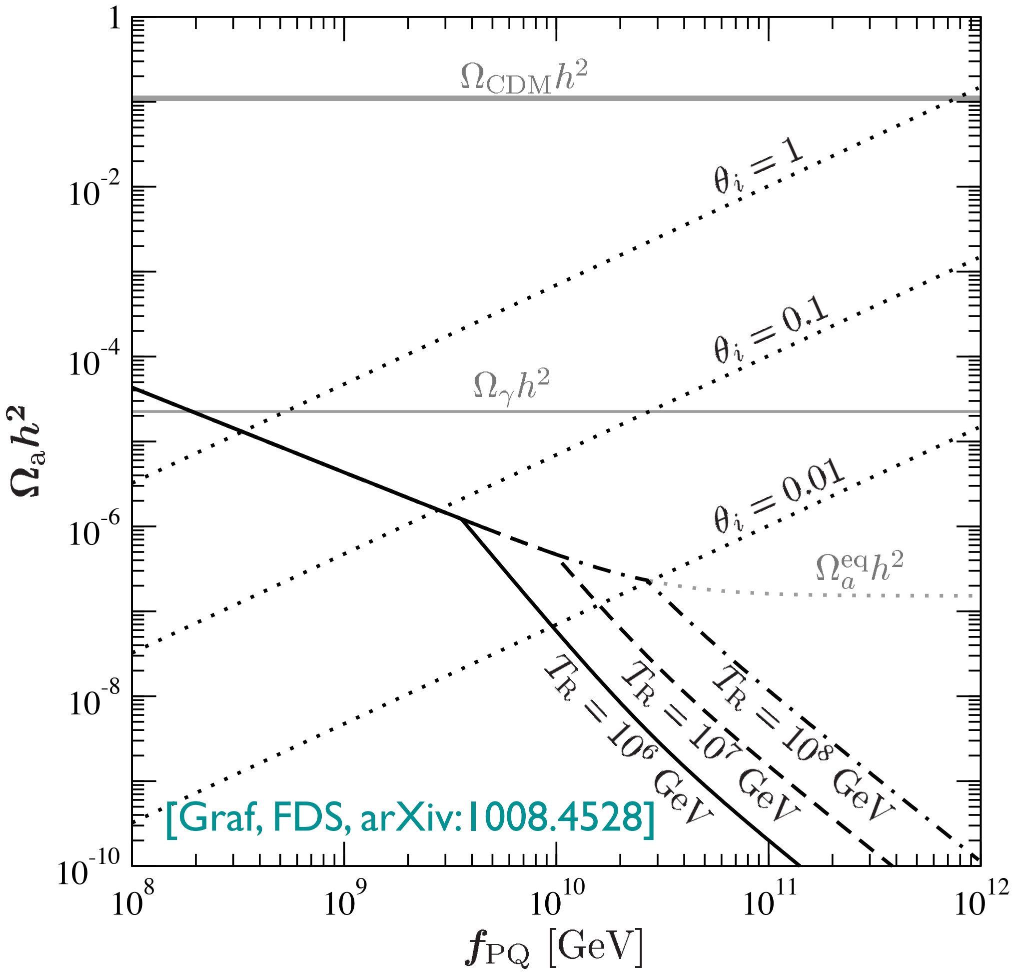

Axion Condensate: CDM

$$\Omega_a^{\rm MIS}h^2 \sim 0.15\,\theta_i^2(f_{\rm PQ}/10^{12}\,{\rm GeV})^{7/6}$$

[... , Sikivie, '08; Kim, Carosi, '08, ...]

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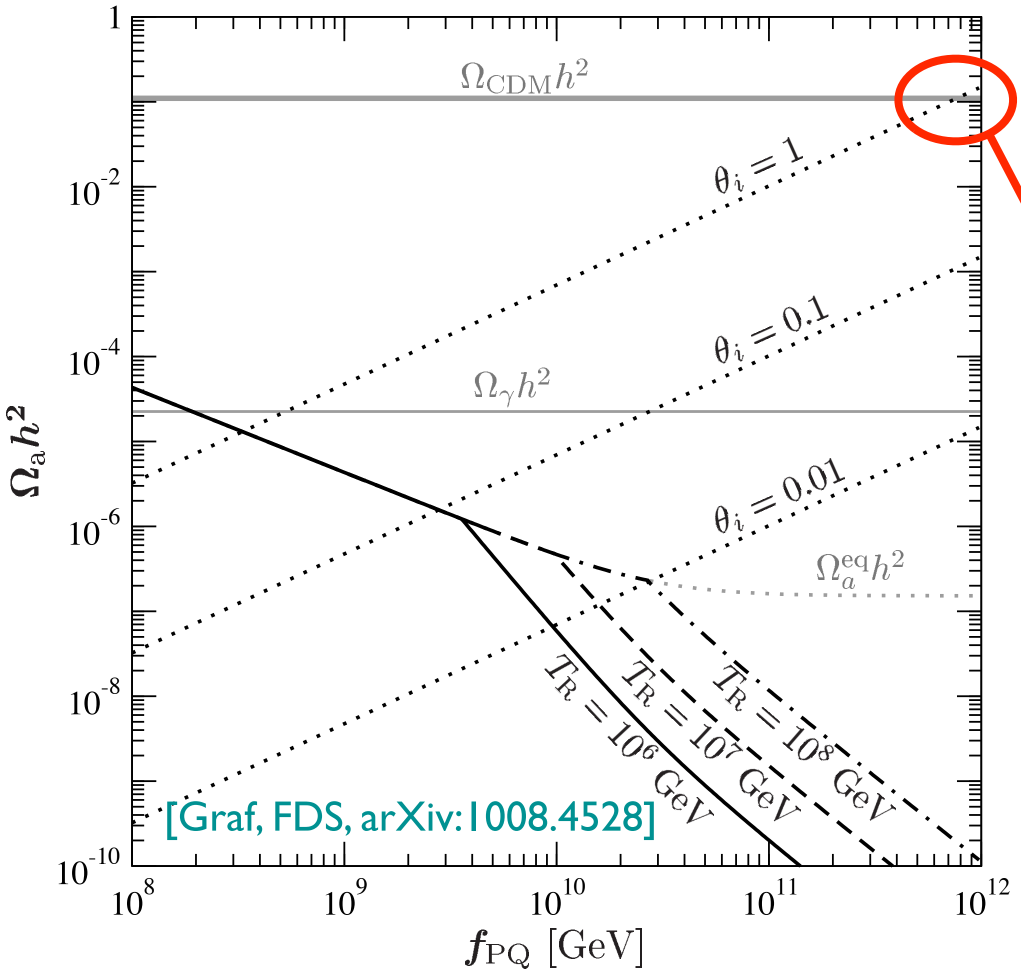

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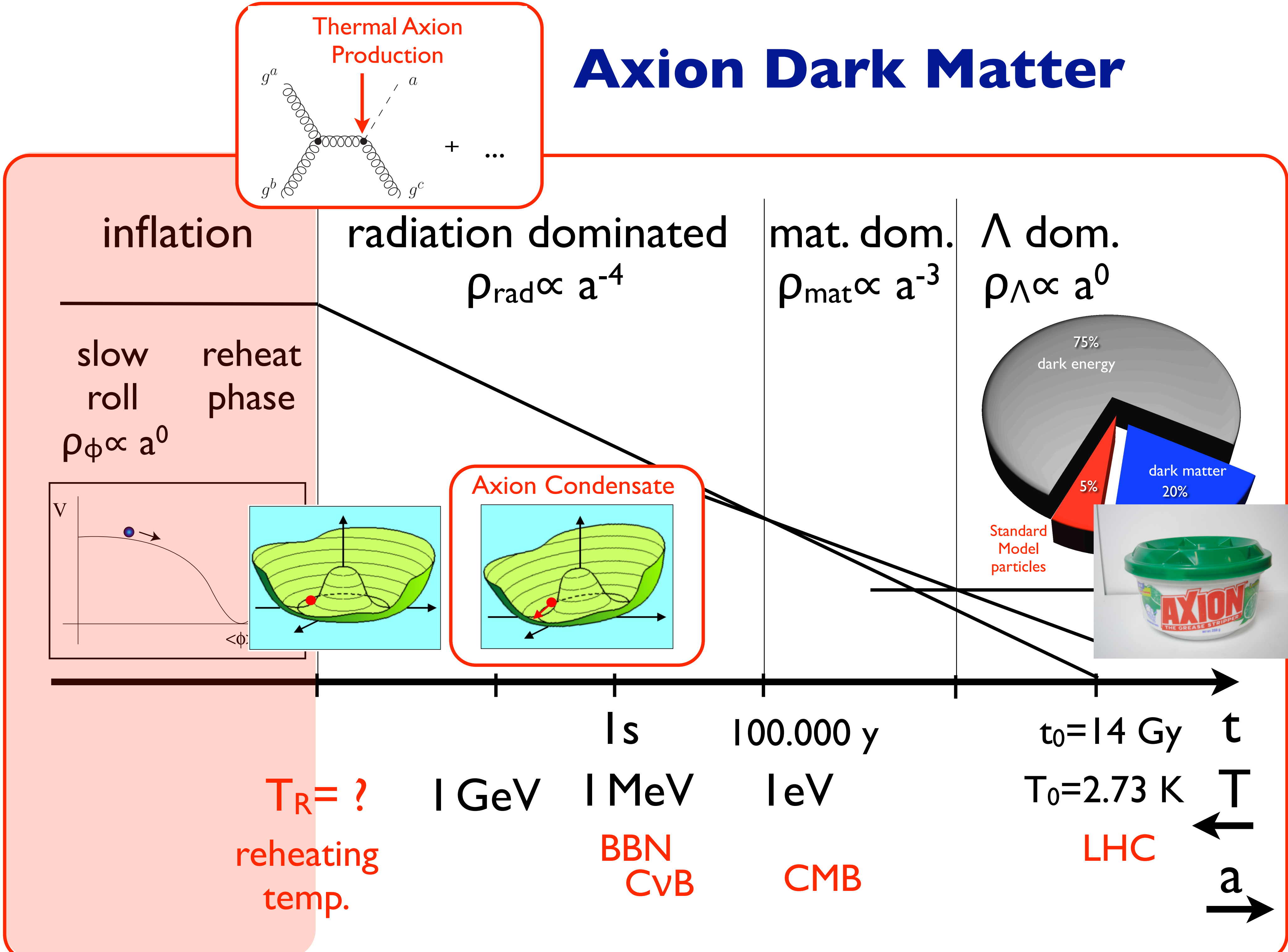
Axions can provide CDM

Axion Dark Matter



Cosmic Relic Abundances

[details → blackboard]

reheating temp. ↓ (T_R) — decoupling temp. of X ↙ (T_D)

- $T_R > T_D$: $1+2 \rightleftarrows 3+X$

$T > T_D$: X in thermal eq. with the primordial plasma
$T \sim T_D$: X decouples as a **hot thermal relic**

- $T_R > T_D$: $1+2 \longrightarrow 3+X$

$T_D >> T$: X is never in th. eq. with the prim. plasma
but **thermally produced** ⟶ Boltzmann eq.

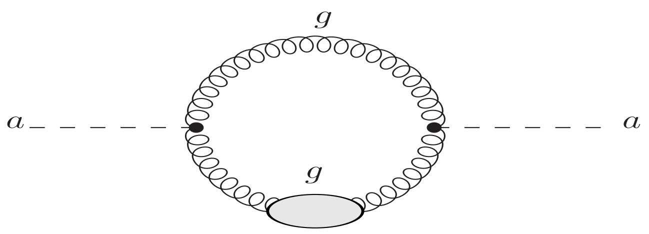
↑ **collision term**

Calculation of the Collsion Term

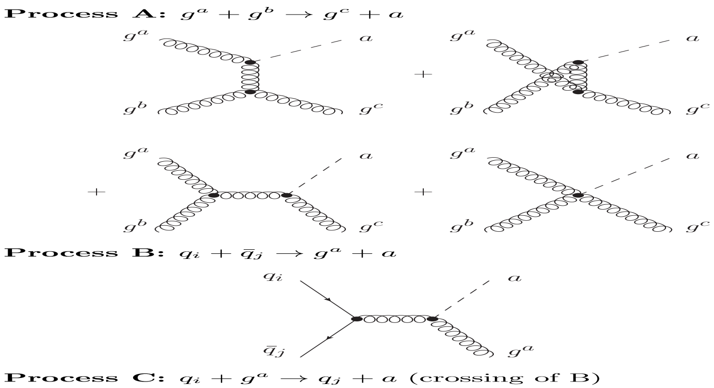
[cf. Braaten, Yuan, '91]

- Thermal Production Rate of X

- Soft Part: $k < k_{cut}$



- Hard Part: $k > k_{cut}$

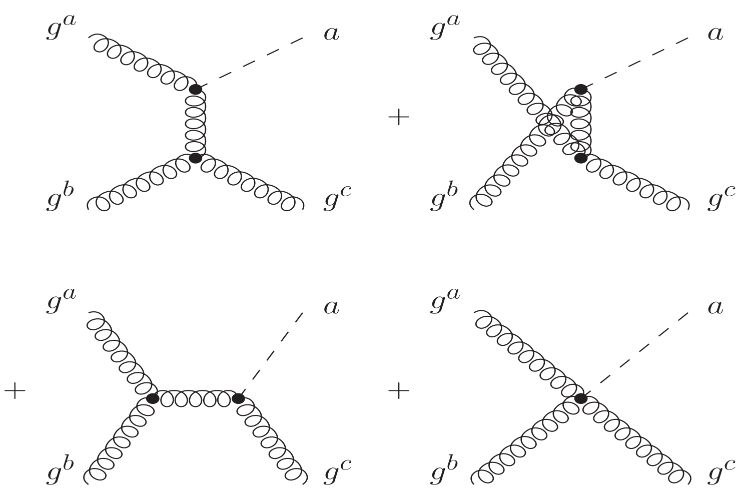


- Hard Thermal Loop (HTL) Resummation

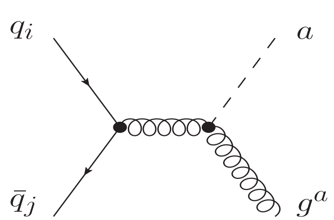
[details → blackboard]

Thermal Axion Production in the Hot QGP

Process A: $g^a + g^b \rightarrow g^c + a$



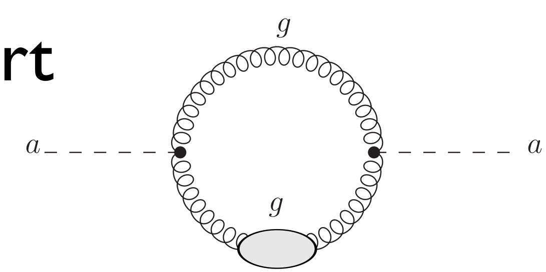
Process B: $q_i + \bar{q}_j \rightarrow g^a + a$



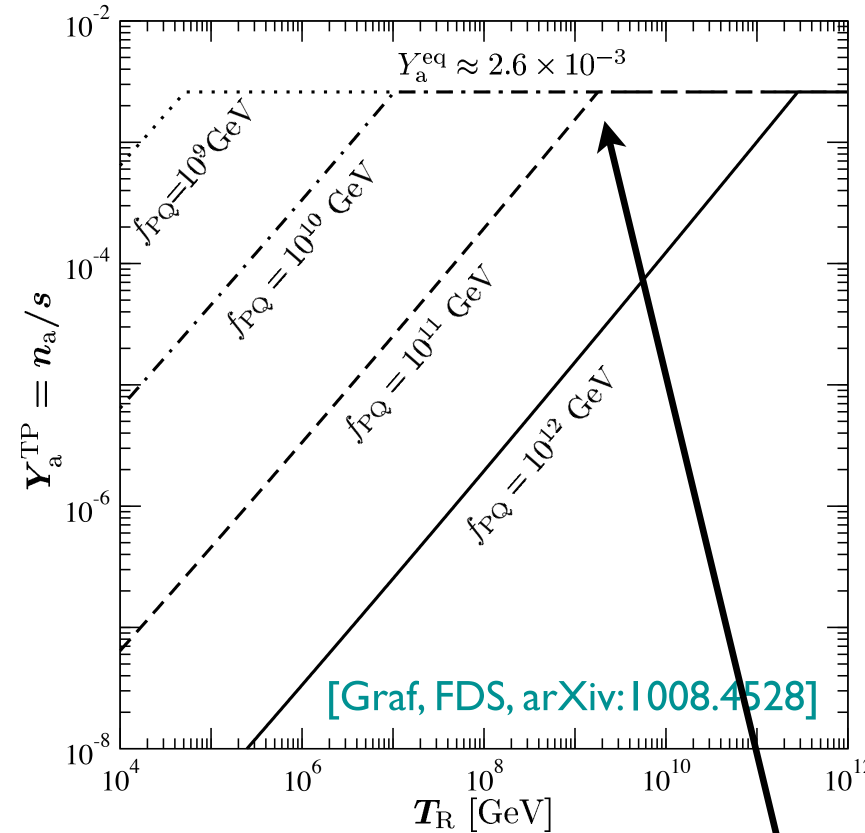
Process C: $q_i + g^a \rightarrow q_j + a$ (crossing of B)

Hard Part

Soft Part



Axion Yield

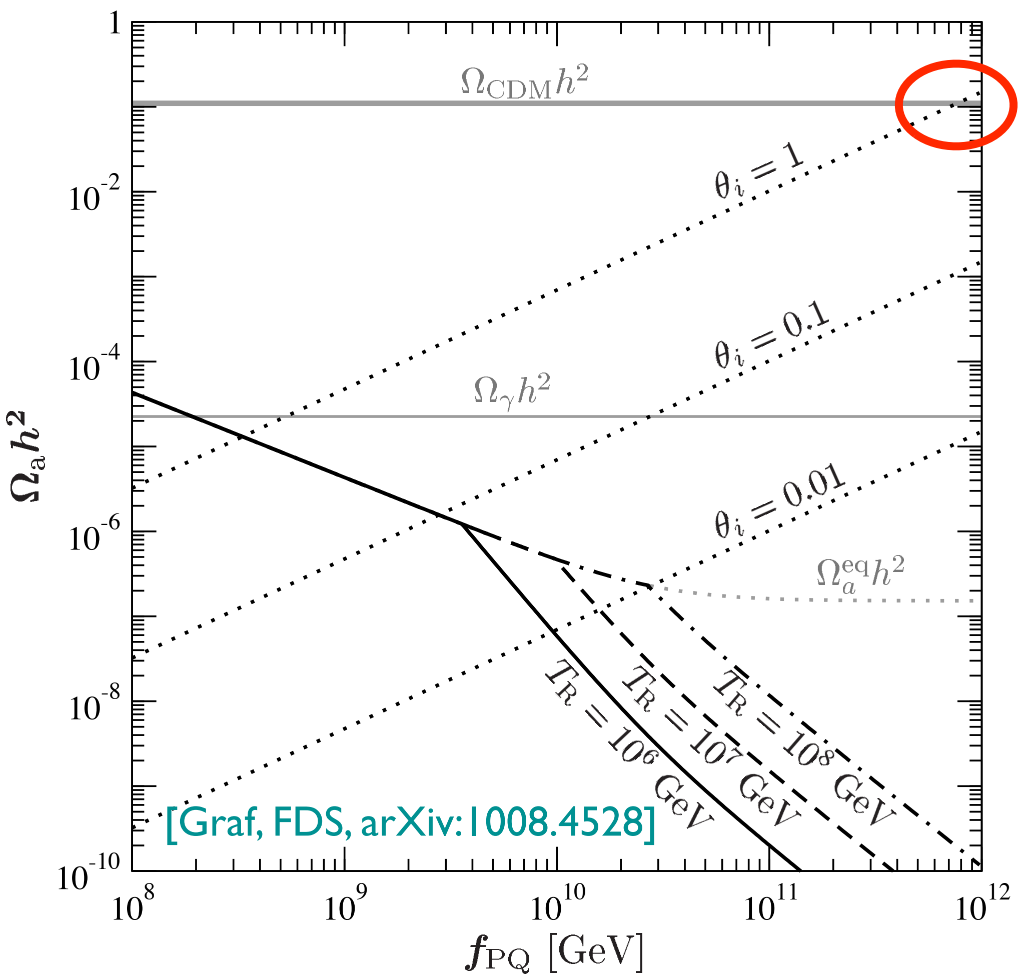


Axion Decoupling Temperature

$$T_D \approx 9.6 \times 10^6\,\mathrm{GeV} \left(\frac{f_{PQ}}{10^{10}\,\mathrm{GeV}} \right)^{2.246}$$

[Masso et al., '02; Sikivie, '08; Graf, FDS, '10]

Axion Dark Matter



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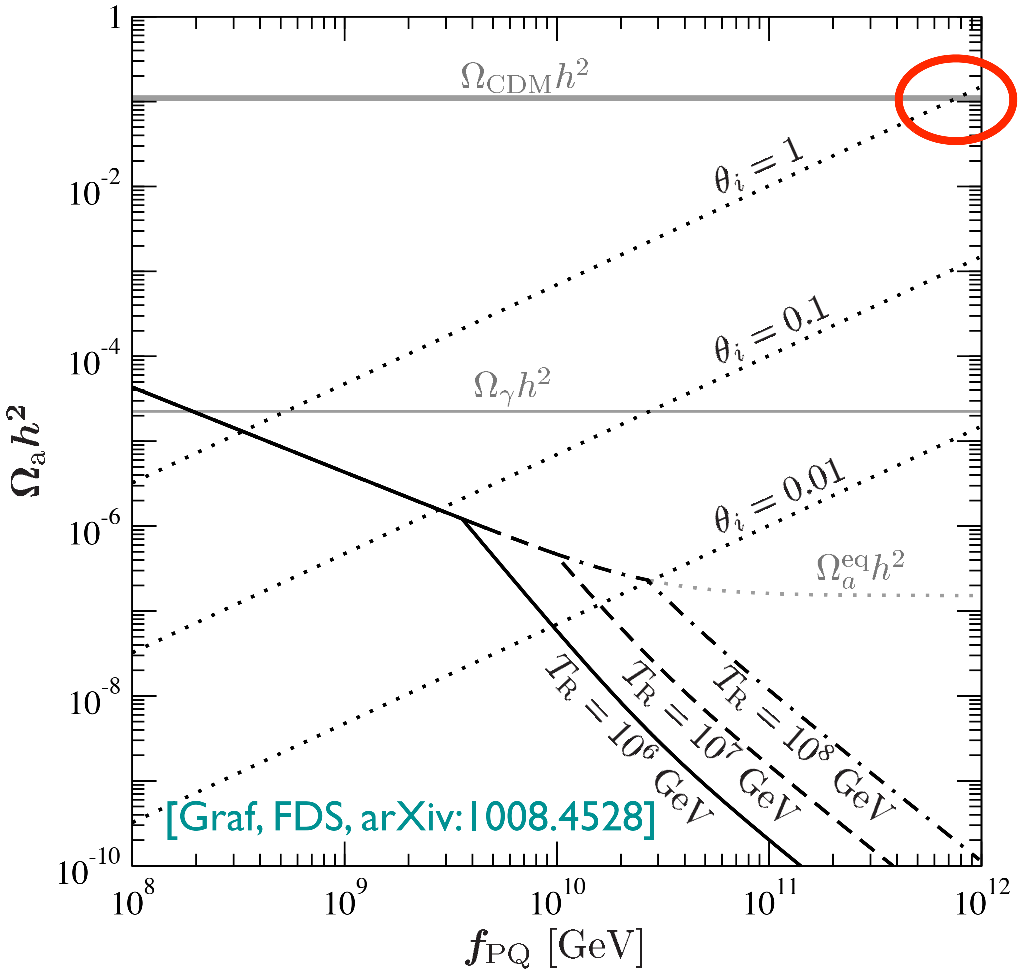

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Thermal Axions: WDM/HDM

$$\Omega_a^{\rm TP/eq} h^2 \simeq \sqrt{\langle p_{a,0}\rangle^2 + m_a^2}\, Y_a^{\rm TP/eq}\, s(T_0) h^2/\rho_c$$

$$18.6 g_s^6 \ln\left(\frac{1.501}{g_s}\right)\left(\frac{10^{10}\,{\rm GeV}}{f_{\rm PQ}}\right)^2\left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right)$$

[Graf, FDS, arXiv:1008.4528]

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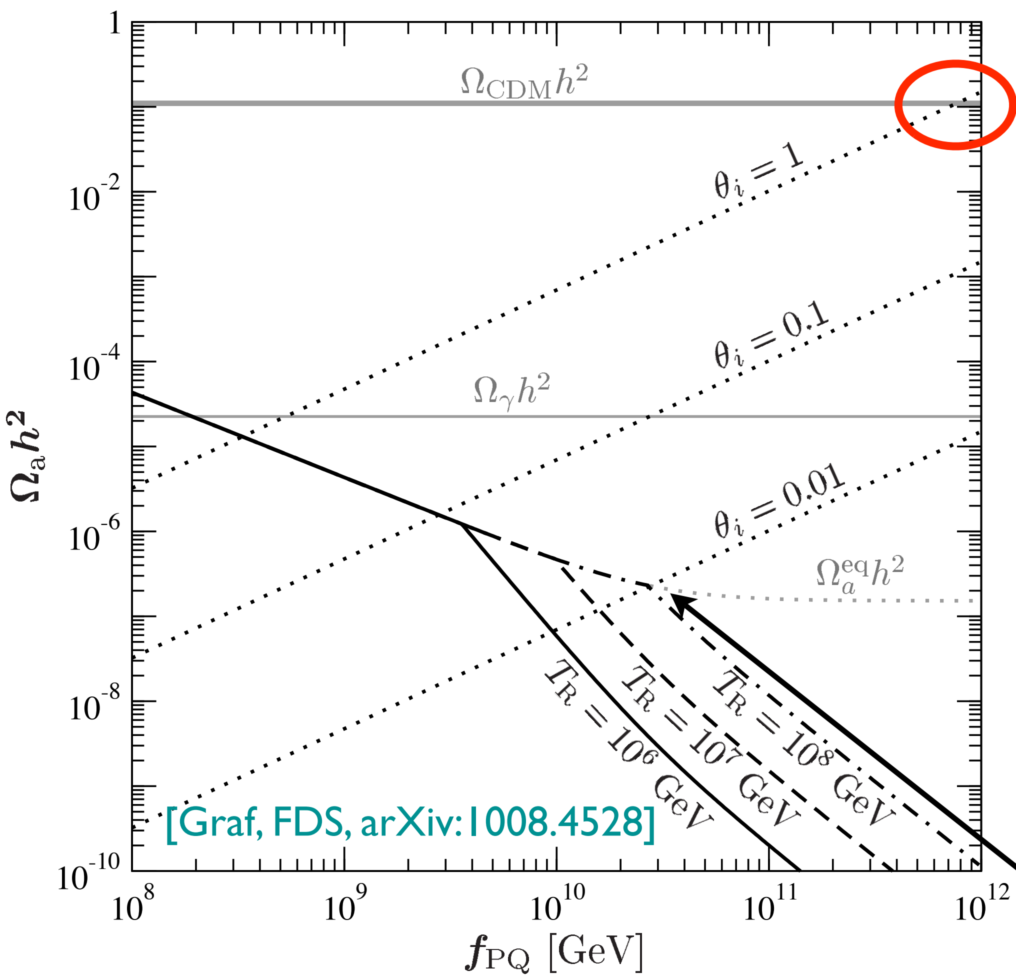

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Axino Interactions

- with gluons and gluinos — model independent

$$\mathcal{L}_{\widetilde{a}\widetilde{g}g} = i\,\frac{g_{\mathrm{s}}^2}{64\pi^2 f_a}\,\bar{\widetilde{a}}\,\gamma_5\,[\gamma^\mu,\gamma^\nu]\,\widetilde{g}^a\,G^a_{\mu\nu}$$

- with photons/Z-bosons and binos — model dependent

$$\mathcal{L}_{\widetilde{a}\widetilde{B}\gamma/Z} = i\,\frac{\alpha_{\mathrm{Y}} C_{\mathrm{aYY}}}{16\pi f_a}\,\bar{\widetilde{a}}\,\gamma_5\,[\gamma_\mu,\gamma_\nu]\,\widetilde{B}\,(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu})$$

but crucial for axino searches

[Brandenburg, FDS, '04]

Thermal Production of

Axino Dark Matter

in the Early Universe

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 $a(p_1) + b(p_2) \to c(p_3) + \tilde{a}(p)$: $(C_{a+b\to c+\tilde{a}} \in C_{\tilde{a}})$

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

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

[Kim, '79; Shifman, Vainshtein, Zakharov, '80]

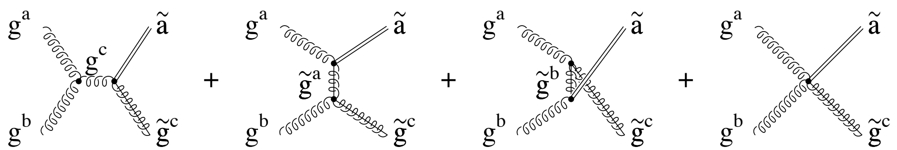
Axino Interactions $\longleftarrow$ Hadronic (KSVZ) Axion Models

- axino–gluino–gluon interaction:

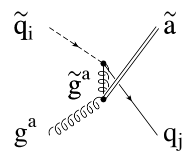
$$\mathcal{L}_{\tilde{a}\tilde{g}g} = i\,\frac{\alpha_{\mathrm{s}}}{16\pi(f_a/N)}\,\bar{\tilde{a}}\,\gamma_5\,[\gamma^\mu,\gamma^\nu]\,\tilde{g}^a\,G^a_{\mu\nu}$$

Thermal Axino Production in SUSY QCD

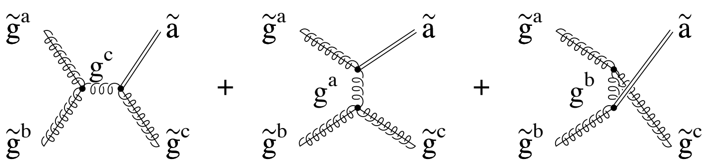
- A: $g^a + g^b \to \tilde{g}^c + \tilde{a}$



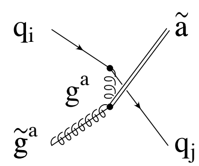
- B: $g^a + \tilde{g}^b \to g^c + \tilde{a}$ (crossing of A)
- C: $\tilde{q}_i + g^a \to \tilde{q}_j + \tilde{a}$



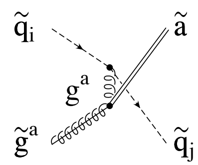
- D: $g^a + q_i \to \tilde{q}_j + \tilde{a}$ (crossing of C)
- E: $\bar{\tilde{q}}_i + q_j \to g^a + \tilde{a}$ (crossing of C)
- F: $\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{a}$



- 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)

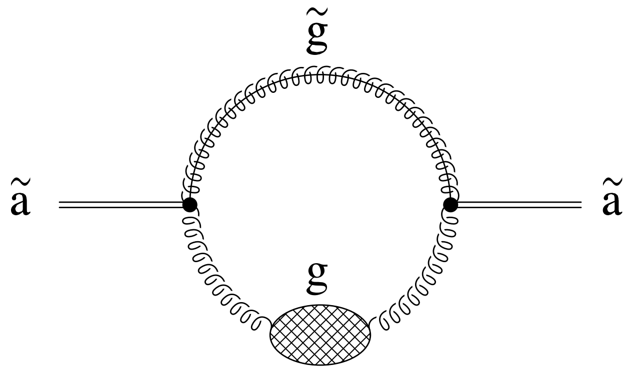
Axino Production in 2 → 2 Processes

	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

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

- Soft Part: Axino Self-Energy

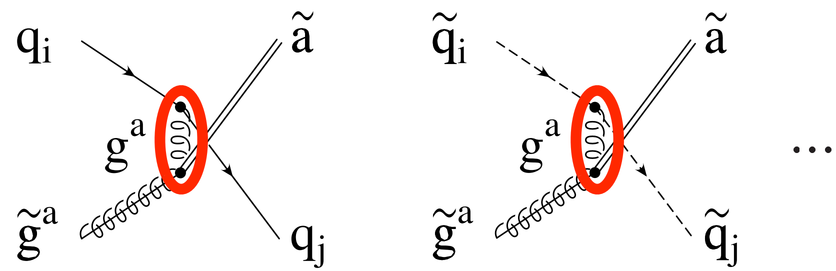


$\rightarrow$ eff. HTL resummed propagator

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

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

- Hard Part: Relativ. Kin. Theory



$\rightarrow$ bare propagator

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

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

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

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

The Collision Term to Leading Order in the Coupling g

- Collision Term: $$C_{\tilde{a}}(T) = \int d^3p \left(\left.\frac{d\Gamma_{\tilde{a}}}{d^3p}\right|_{\text{soft}} + \left.\frac{d\Gamma_{\tilde{a}}}{d^3p}\right|_{\text{hard}} \right)$$

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

- Thermal Gluon Mass in the "QGSGP":

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

- Running of the Strong Coupling in the MSSM:

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

Solving the Boltzmann Equation → Axino Abundance

- Boltzmann equation

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

- conservation of entropy

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

- yield → 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

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

- Axino Yield from Thermal Production

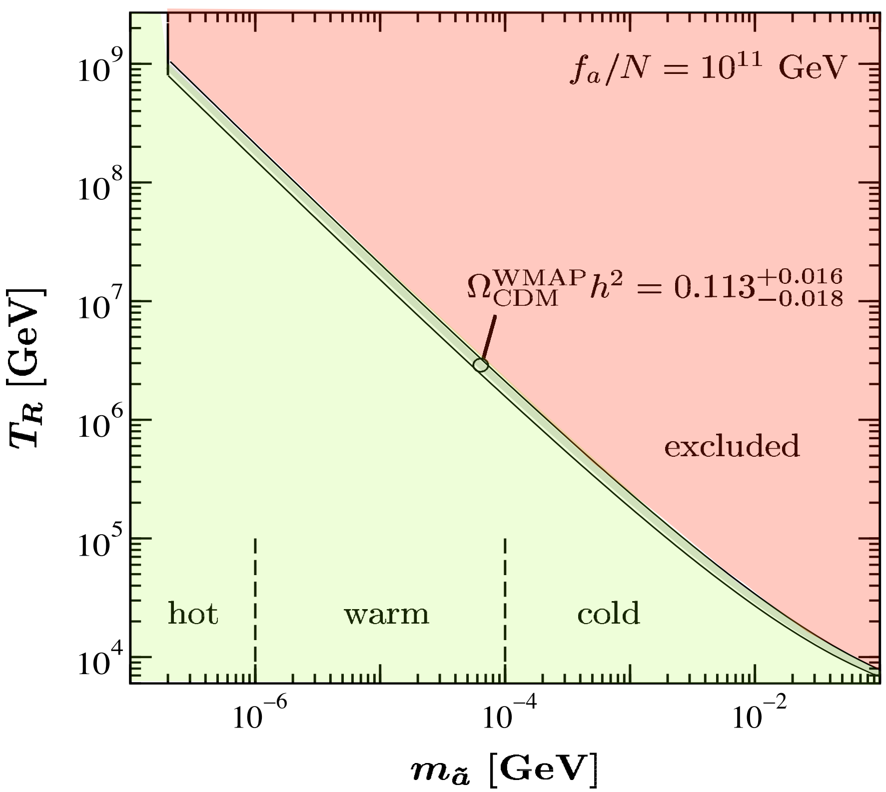
$$Y_{\tilde{a}} \approx \frac{C_{\tilde{a}}(T_R)}{s(T_R)H(T_R)} = 2.0 \times 10^{-7} g^6 \ln\left(\frac{1.108}{g}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a/N}\right)^2\left(\frac{T_R}{10^4\,\mathrm{GeV}}\right)$$

- 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 LSP Case

Thermal $\tilde{a}$ Production



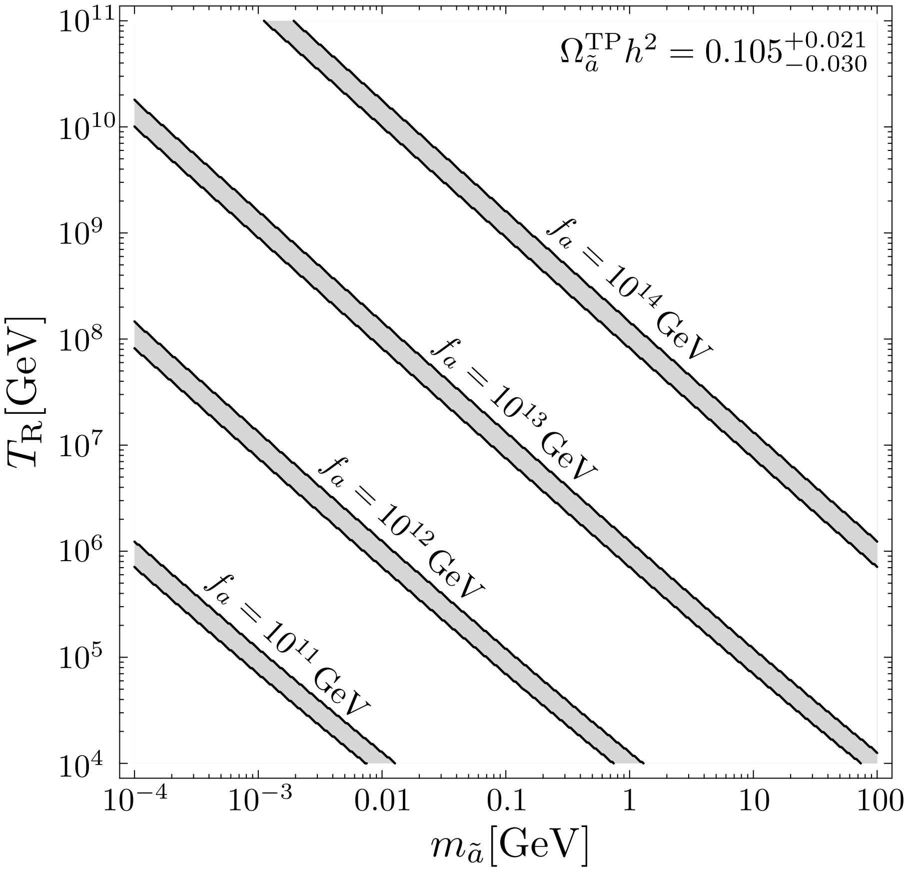
[Brandenburg, FDS, '04]

see also [Covi et al., '01]

and [Strumia, '10]

Axino LSP Case

Thermal $\tilde{a}$ Production



[Freitas, FDS, Tajuddin, Wyler, '09]

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model

Peccei-Quinn Symmetry & Supersymmetry

	Axions $f_a > 10^9$ GeV	Axinos $f_a > 10^9$ GeV	Gravitinos $M_{Pl} = 2.4 \times 10^{18}$ GeV
spin	0	1/2	3/2
mass	<10 meV	?	eV-TeV
int.	$\propto (p/f_a)^n$	$\propto (p/f_a)^n$	$\propto (p/M_{Pl})^n$

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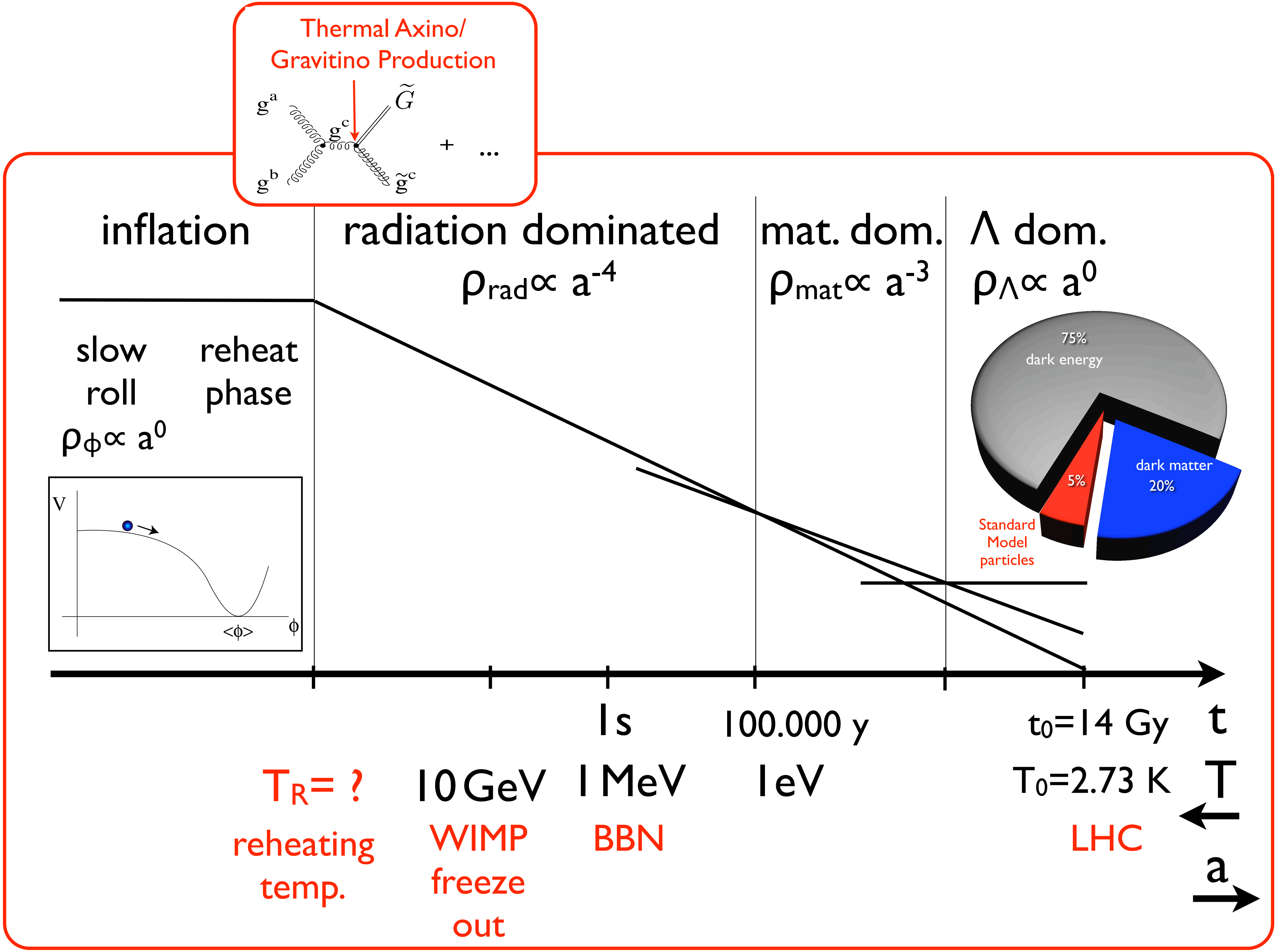
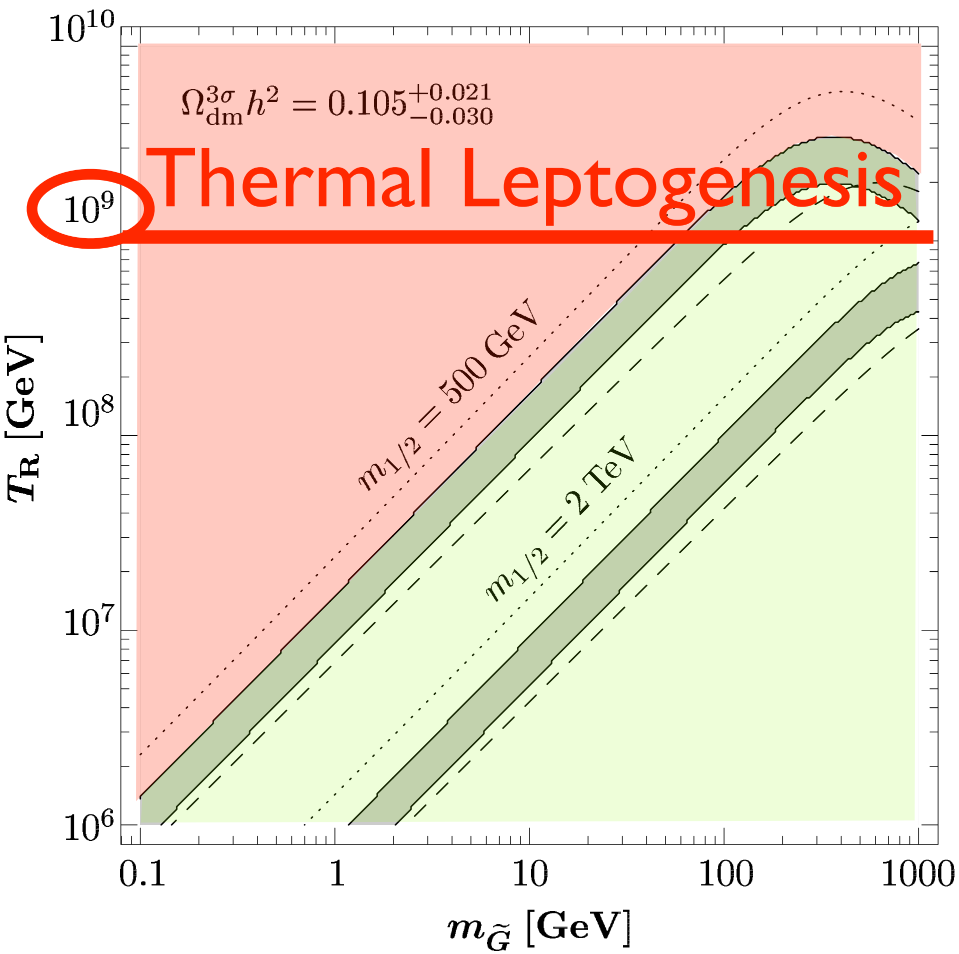

Thermal Axino/
Gravitino Production
g^a
g^b
g^c
$\tilde{G}$
$\tilde{g}^c$
+ ...
inflation
radiation dominated
$\rho_{rad} \propto a^{-4}$
mat. dom.
$\rho_{mat} \propto a^{-3}$
Λ dom.
$\rho_{\Lambda} \propto a^{0}$
slow
roll
$\rho_{\phi} \propto a^{0}$
reheat
phase
V
ϕ
<ϕ>
75%
dark energy
dark matter
20%
5%
Standard
Model
particles
1 s
100.000 y
t_0=14 Gy
t
T_R= ?
10 GeV
1 MeV
1 eV
T_0=2.73 K
T
reheating
temp.
WIMP
freeze
out
BBN
LHC
a

Thermal $\widetilde{G}$ Production



[Pradler, FDS, '07]

see also [Moroi, Murayama, Yamguchi, '93, Asaka, Hamaguchi, Suzuki, '00, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Rychkov, Strumia, '07]

$$\Omega^{\rm TP}_{\widetilde{G}} h^2 = m_{\widetilde{G}}\, Y^{\rm TP}_{\widetilde{G}}(T_0)\, s(T_0)\, h^2/\rho_c$$
$$= \sum_{i=1}^{3} \omega_i\, g_i^2(T_{\rm R}) \left(1 + \frac{M_i^2(T_{\rm R})}{3 m^2_{\widetilde{G}}}\right) \ln\left(\frac{k_i}{g_i(T_{\rm R})}\right)$$
$$\times \left(\frac{m_{\widetilde{G}}}{100\ \mathrm{GeV}}\right)\left(\frac{T_{\rm R}}{10^{10}\ \mathrm{GeV}}\right)$$

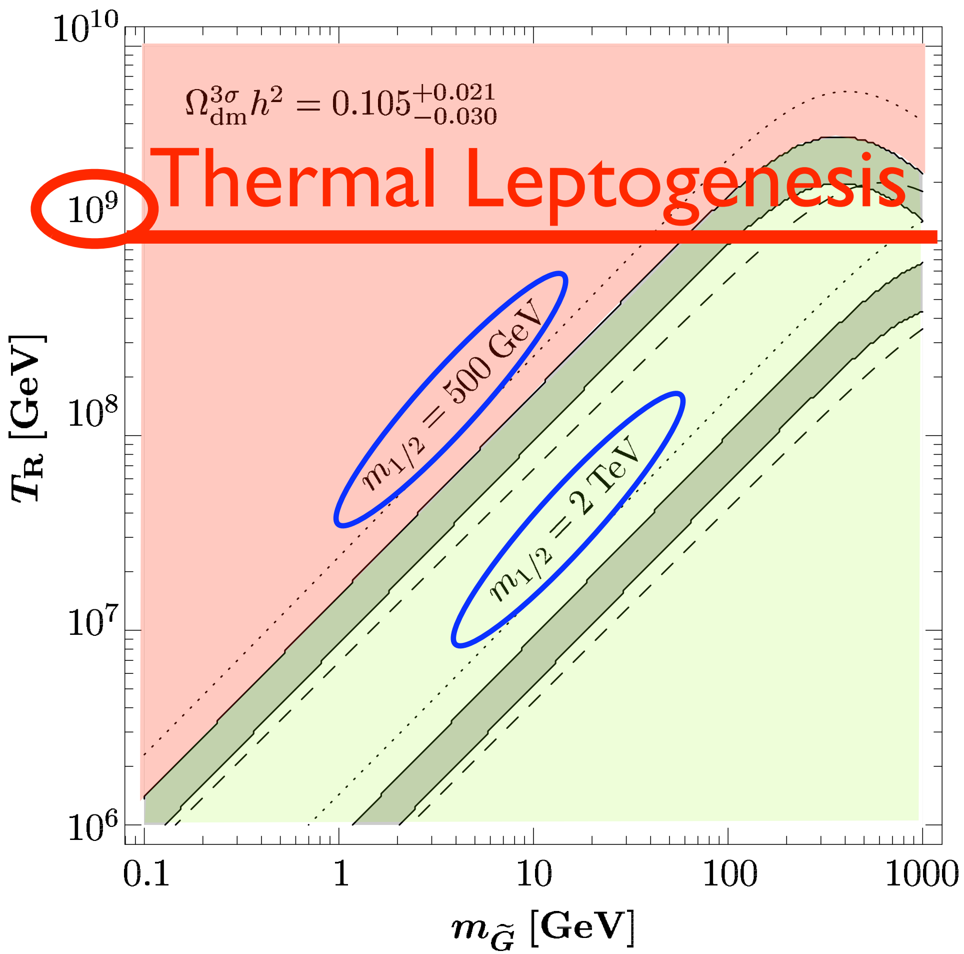
The dark matter density

$$\Omega^{3\sigma}_{\rm dm} h^2 = 0.105^{+0.021}_{-0.030}$$

probes

the reheating temperature

Thermal $\widetilde{G}$ Production



[Pradler, FDS, '07]

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↕

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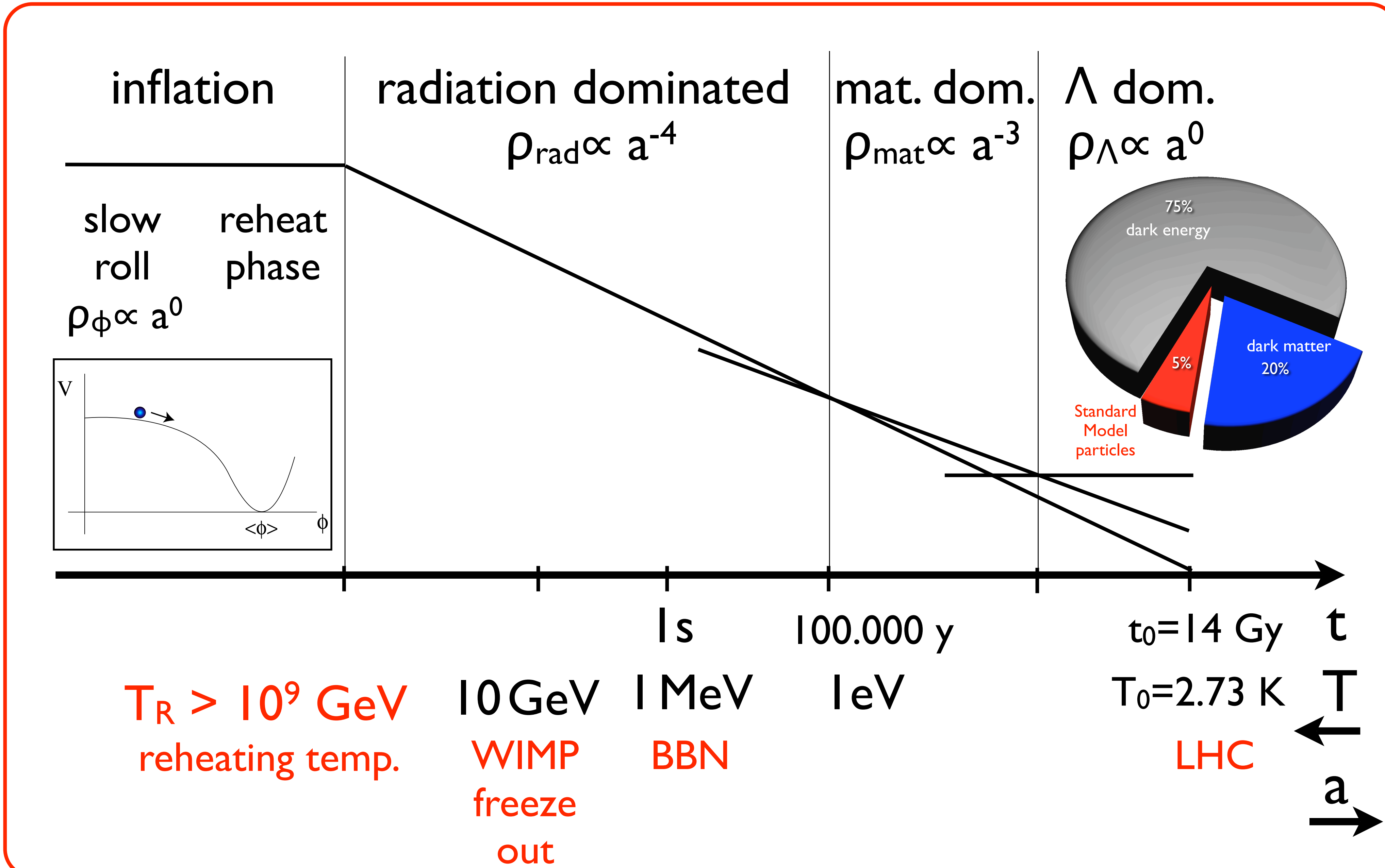
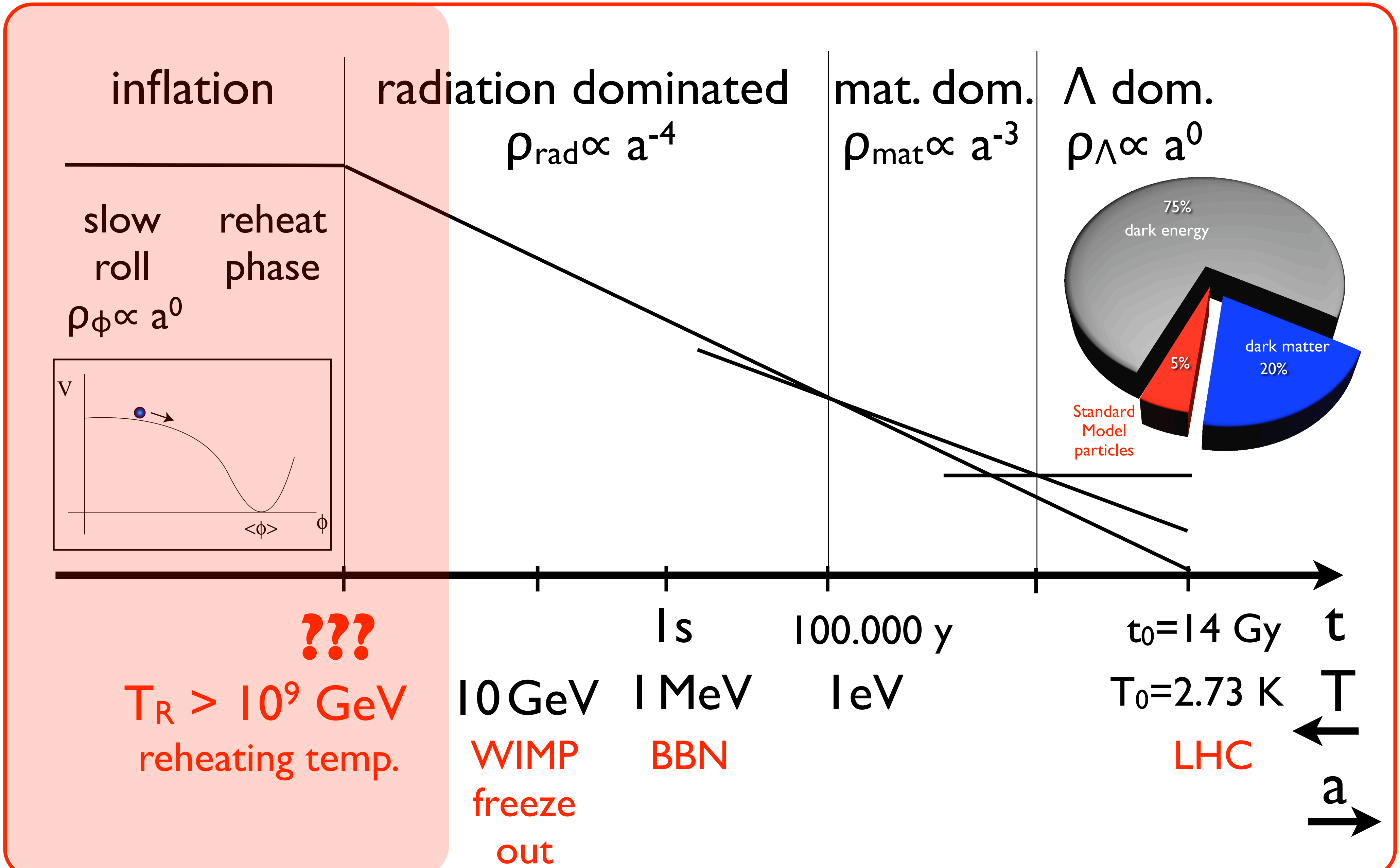
Thermal Leptogenesis



Thermal Leptogenesis



The gravitino can become a problem ...

Thermal Gravitino Production

gauge-field of local SUSY (supergravity)

Stable Gravitino

gravitino LSP

↓

- gravitino DM
- late NLSP decays
- NLSP bound states

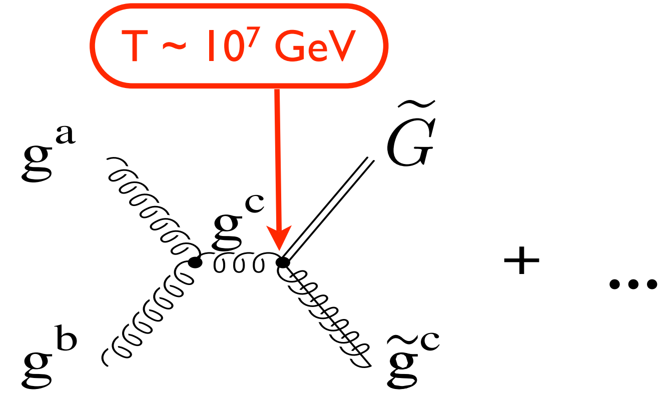
Unstable Gravitino

neutralino LSP

- neutralino DM
- late gravitino decays

BBN constraints

Very Hot Early Universe



gauge-invariant treatment
(hard thermal loop resummation)

SUSY QCD
[Bolz, Brandenburg, Buchmüller, '01]

+ electroweak contributions
[Pradler, Steffen, '06 & '07]

Upper Limits on the Reheating Temperature

Neutralino LSP

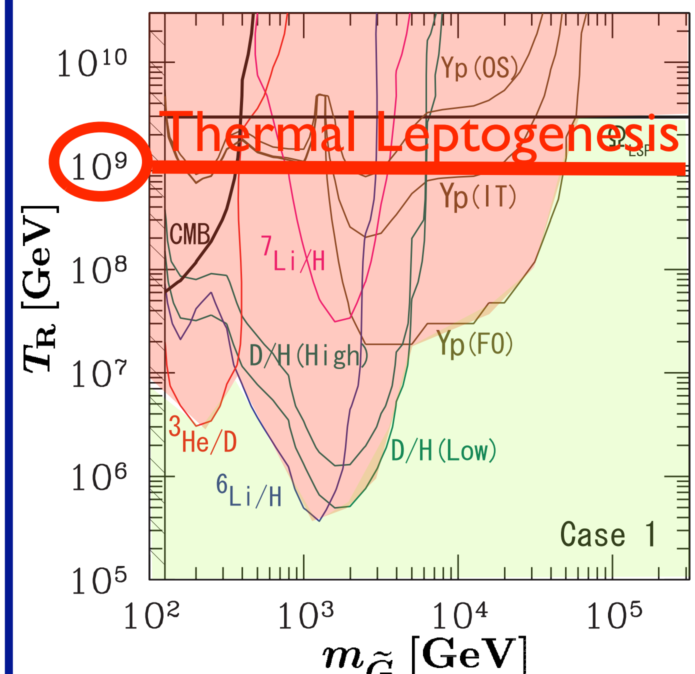
Late Decaying Gravitinos from Thermal Production

$$Y_{\widetilde{G}}^{\mathrm{TP}}(T_{\mathrm{low}}) \equiv \frac{n_{\widetilde{G}}^{\mathrm{TP}}(T_{\mathrm{low}})}{s(T_{\mathrm{low}})} \approx \frac{C_{\widetilde{G}}(T_{\mathrm{R}})}{s(T_{\mathrm{R}})H(T_{\mathrm{R}})}$$

$$= \sum_{i=1}^{3} y_i g_i^2(T_{\mathrm{R}}) \left(1 + \frac{M_i^2(T_{\mathrm{R}})}{3m_{\widetilde{G}}^2}\right) \times \ln\left(\frac{k_i}{g_i(T_{\mathrm{R}})}\right)\left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right),$$

[Pradler, FDS, ’07]

Unstable Gravitino



BBN constraints

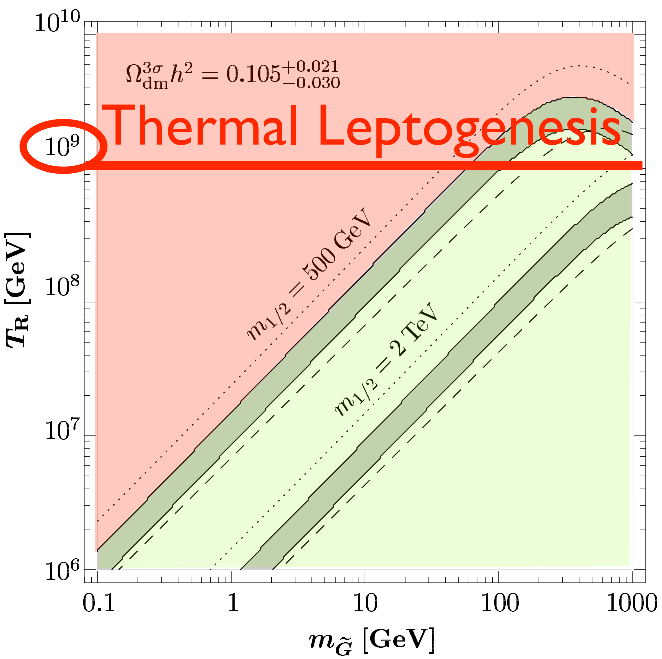
+ Ω_{DM} constraint for neutralino DM

[Kohri, Moroi, Yotsuyanagi, ’05]

Thermal Leptogenesis requires T >10^9 GeV

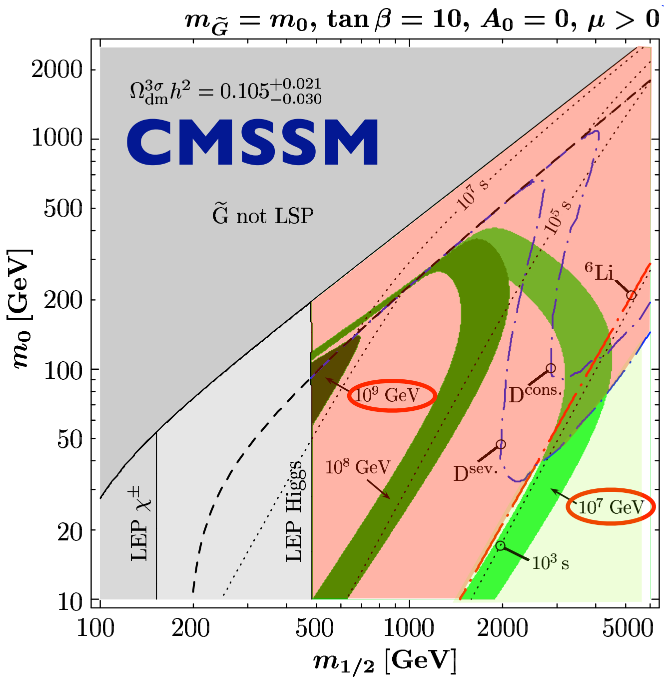
Upper Limits on the Reheating Temperature

Stable Gravitino LSP



Ω_{DM} constraint for gravitino DM

[Pradler, FDS, '07]

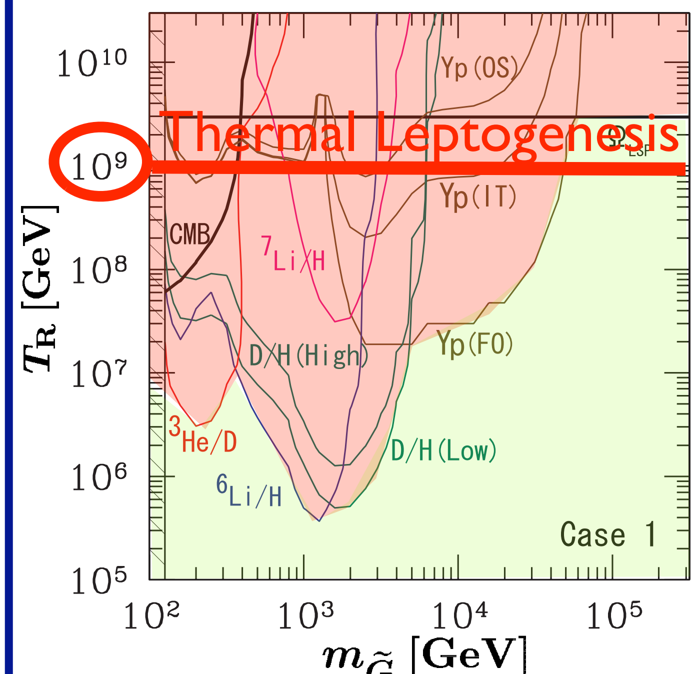


+ BBN constraints

$$T_R \lesssim 4.9 \times 10^7 \text{ GeV} \left(\frac{m_{\widetilde{G}}}{10 \text{ GeV}}\right)^{1/5}$$

[Pradler, FDS, arXiv:0710.2213]

Unstable Gravitino



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Conclusion

Refined calculations of the thermal production of extremely weakly interacting particles (EWIPs) are worth pursuing