Axion / Axino Dark Matter
BBN constraints and LHC phenomenology

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Excellence Cluster Universe

Vistas in Axion Physics

INT Seattle, April 25, 2012

Outline

- Axion DM
  - Lee-Weinberg curve
  - decoupling temperature T_D
- Axino DM scenarios with long-lived staus
  - BBN constraints: new f_{PQ} limits
  - LHC phenomenology: probing f_{PQ}

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
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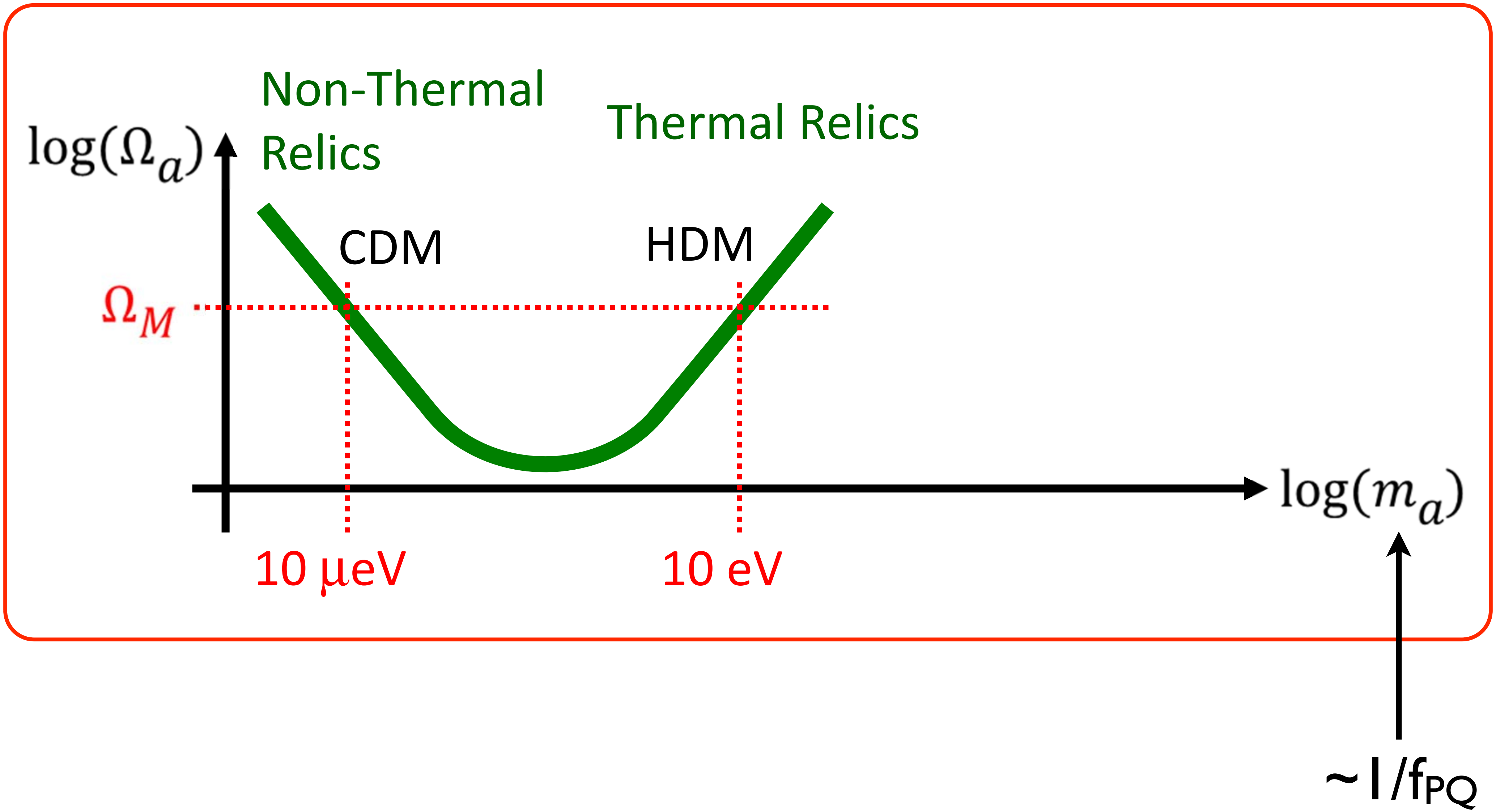
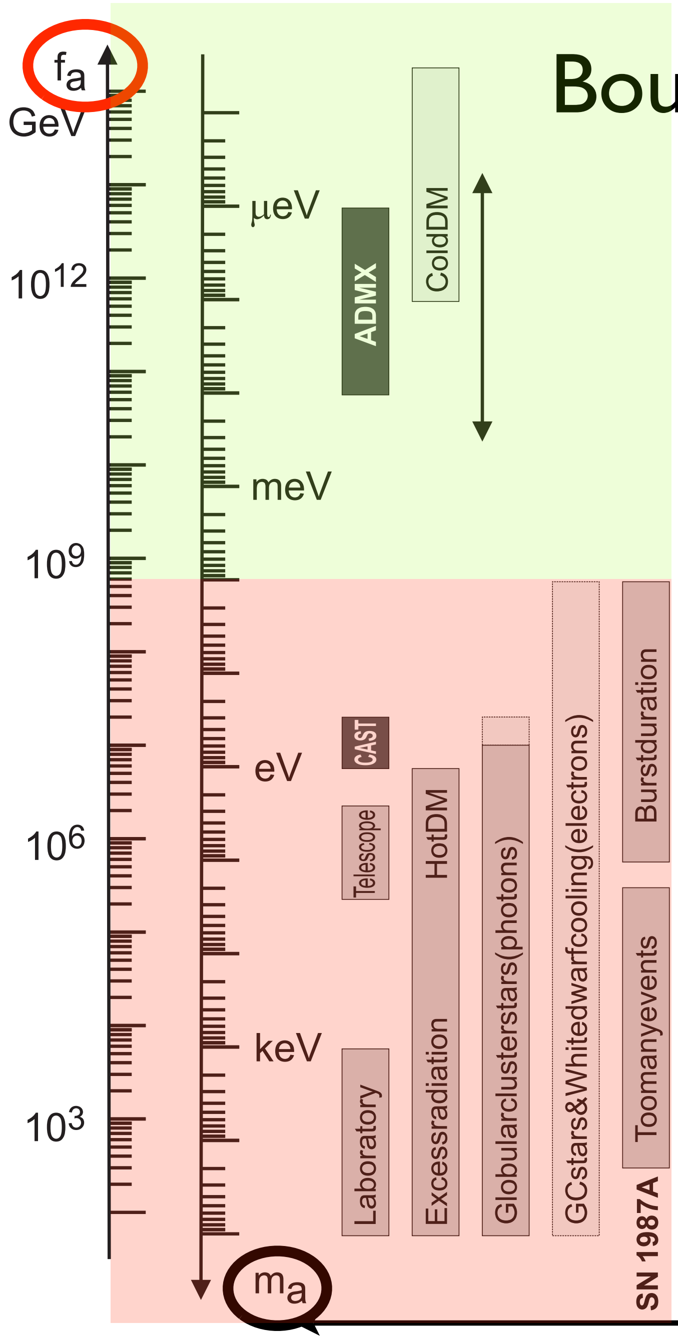
[Talk by Georg Raffelt]

Lee-Weinberg Curve for Axions



Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

Peccei-Quinn Scale

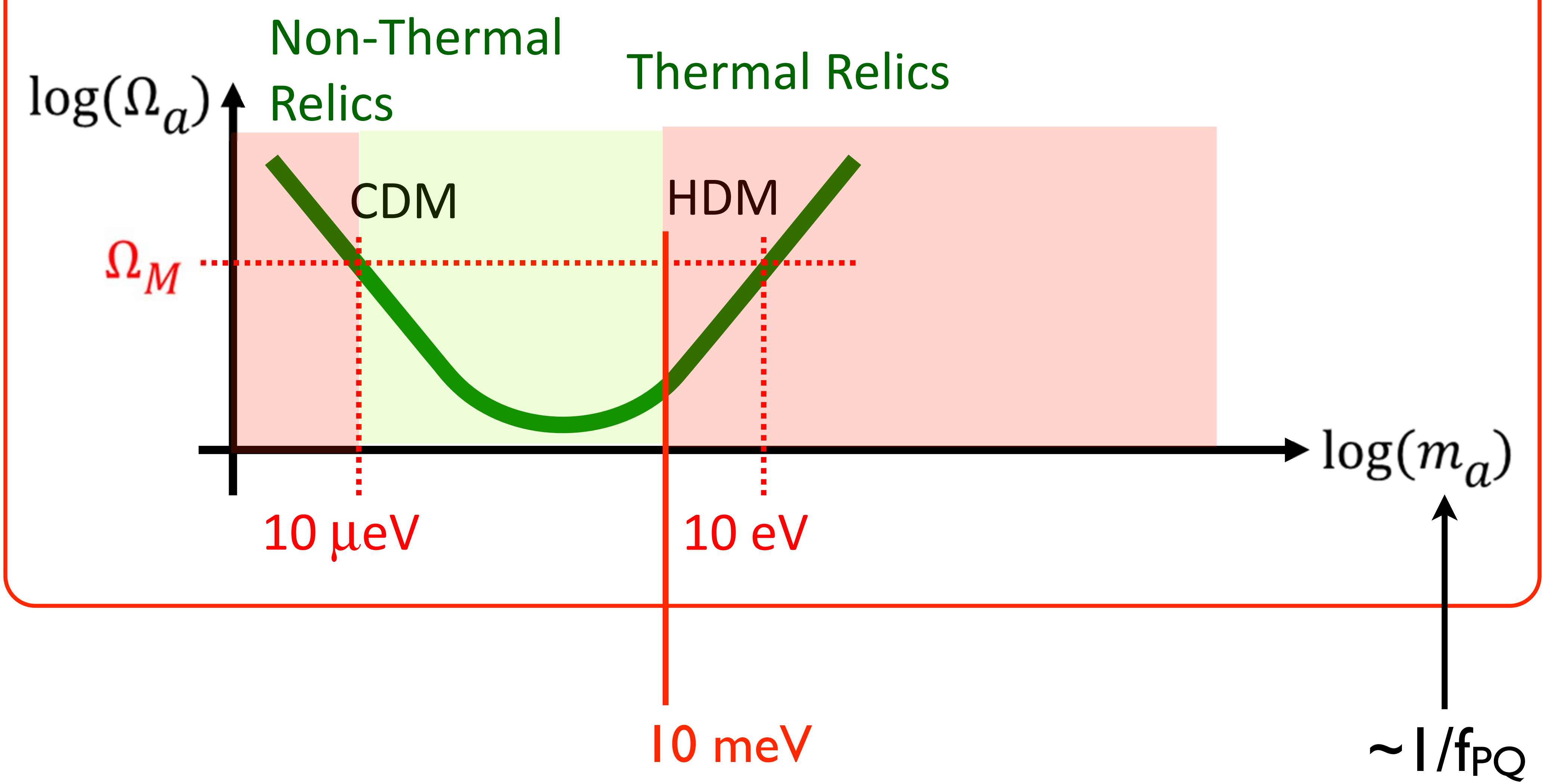
$$f_a \gtrsim 6 \times 10^8 \, \mathrm{GeV}$$

Axion Mass

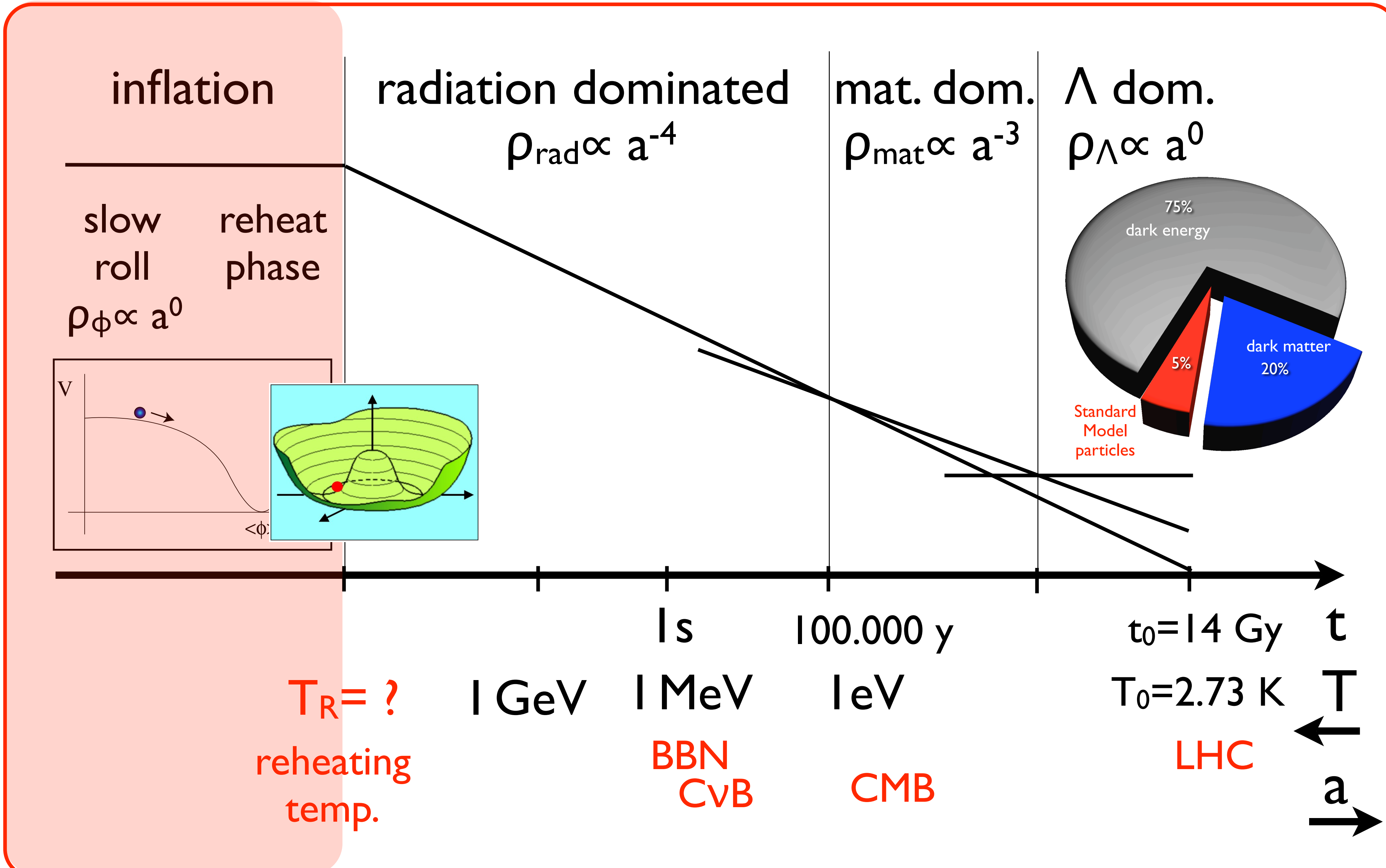
$$m_a \simeq 0.6 \ \mathrm{meV} \, (10^{10} \, \mathrm{GeV} / f_{\mathrm{PQ}})$$

[Talk by Georg Raffelt]

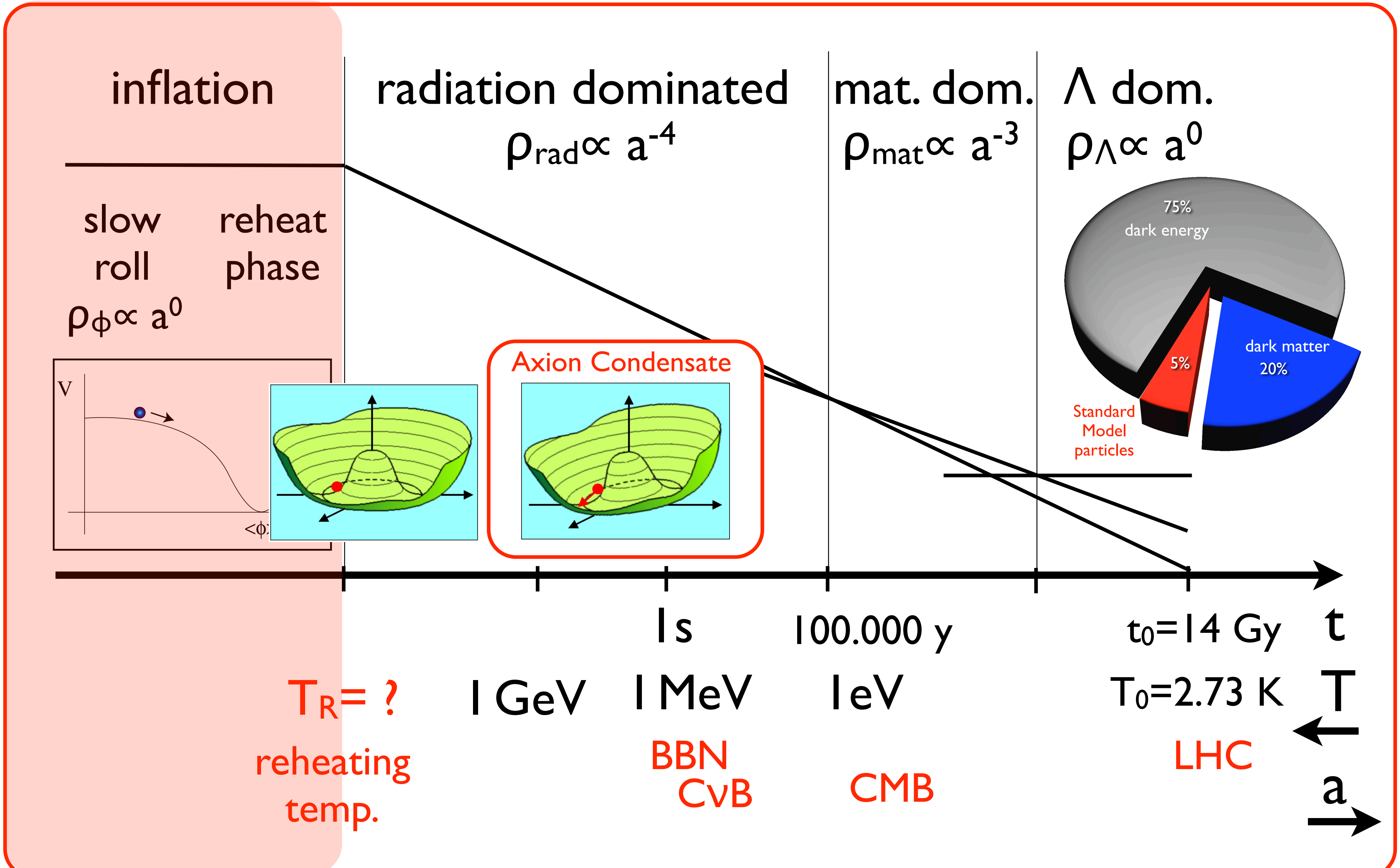
Lee-Weinberg Curve for Axions



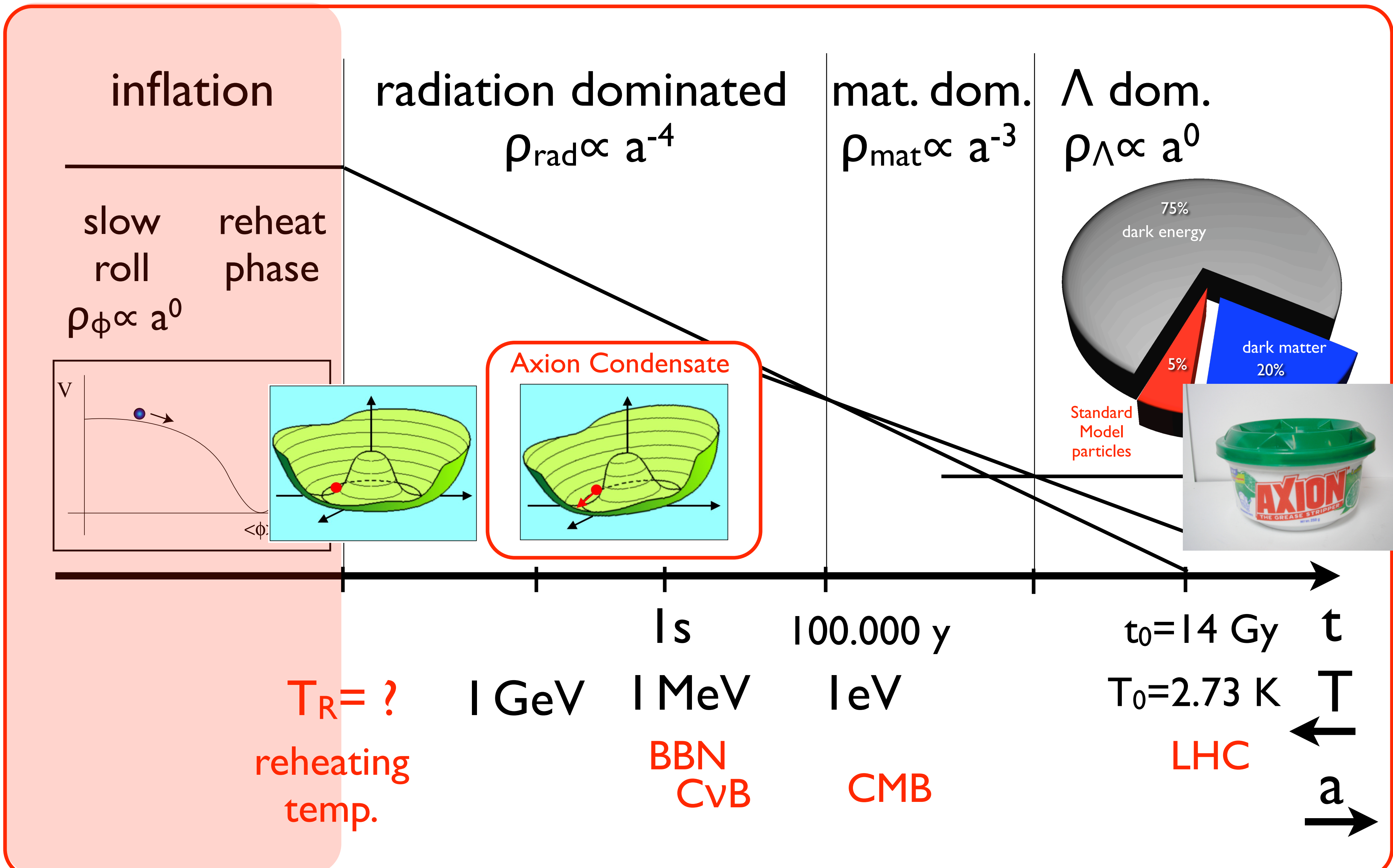
Axion Dark Matter



Axion Dark Matter

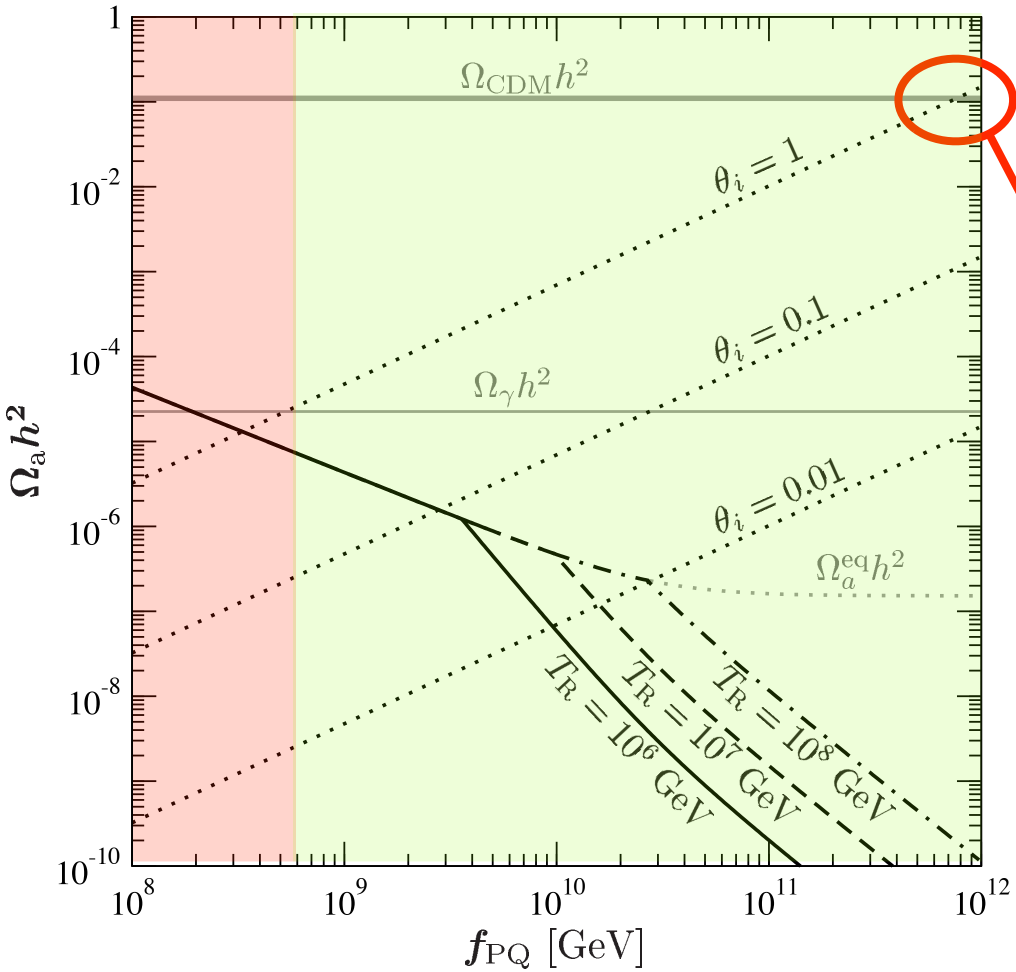


Axion Dark Matter



[Graf, Steffen, '11]

Lee-Weinberg Curve for Axions



Axion Condensate: CDM

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

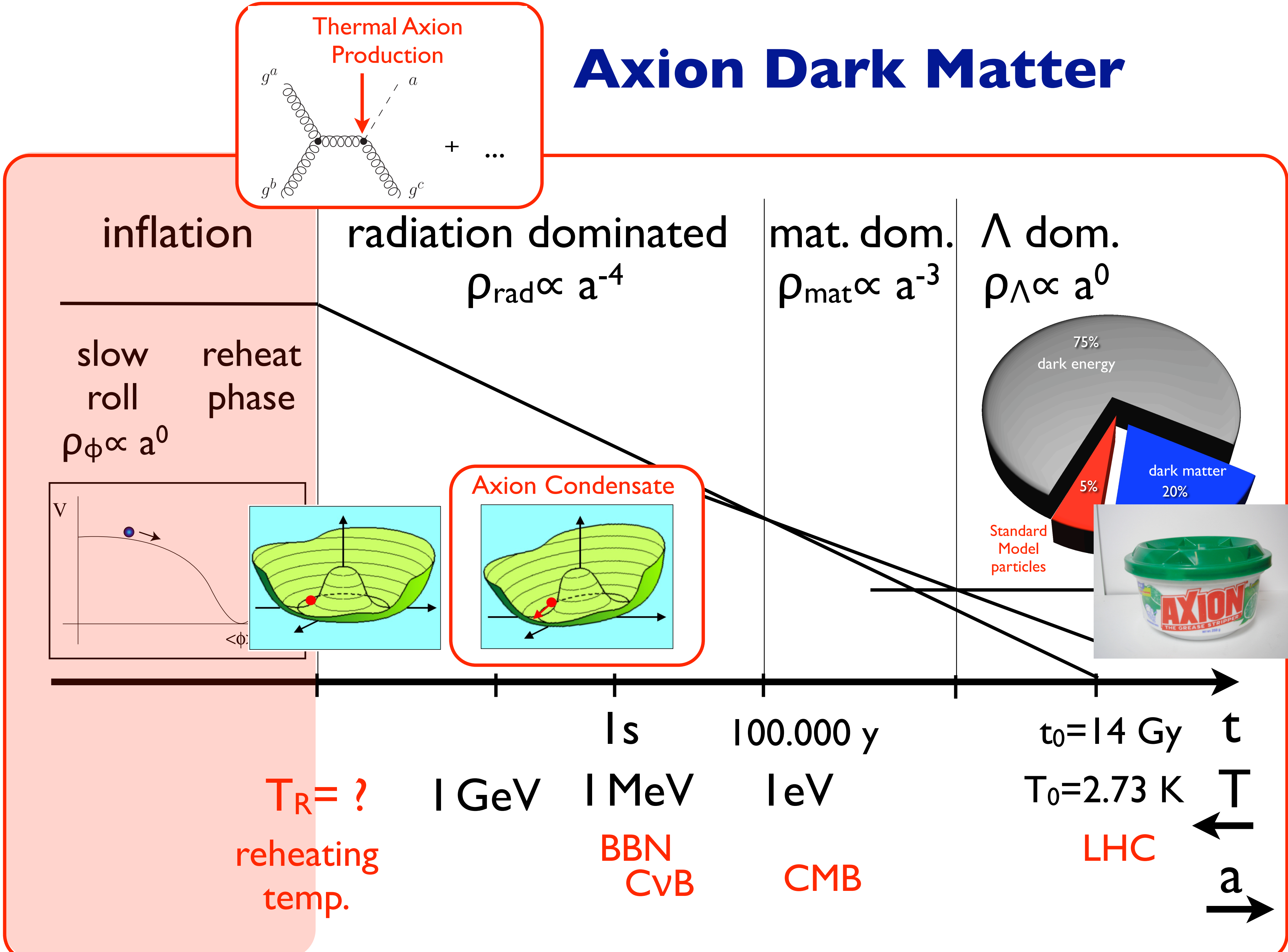
[... ; Sikivie, '08; Kim, Carosi, '08; ...]

Axions can provide CDM

Axion Mass

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

Axion Dark Matter



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 Decoupling Temperature

reheating temp.

decoupling temp.

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

$T > T_D$: axion in thermal eq. with the primordial plasma

$T \sim T_D$: axion decouples as a **hot thermal relic**

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

$T_D >> T$: axion is never in th. eq. with the prim. plasma

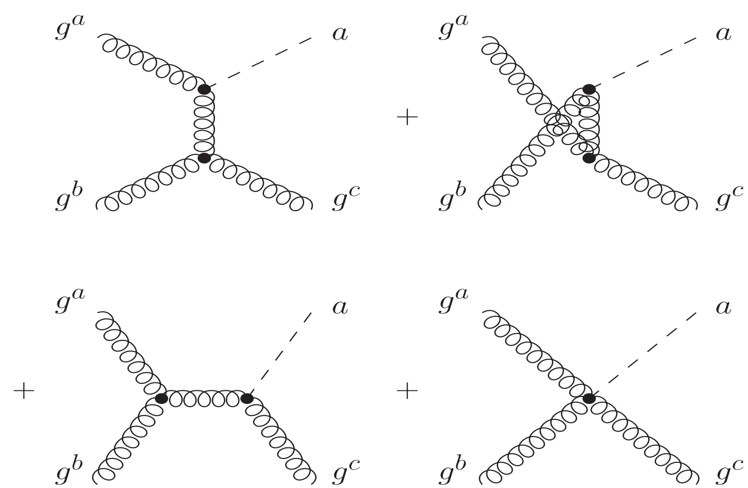
but **thermally produced** $\longrightarrow$ Boltzmann eq.

collision term

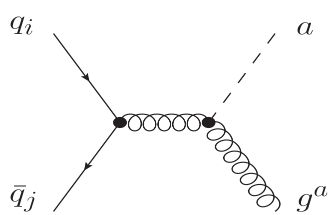
[Graf, Steffen, '11]

Thermal Axion Production in the Hot QGP

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



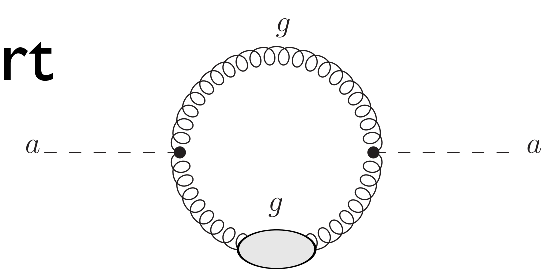
Process B: $q_i + \bar{q}_j \to g^a + a$



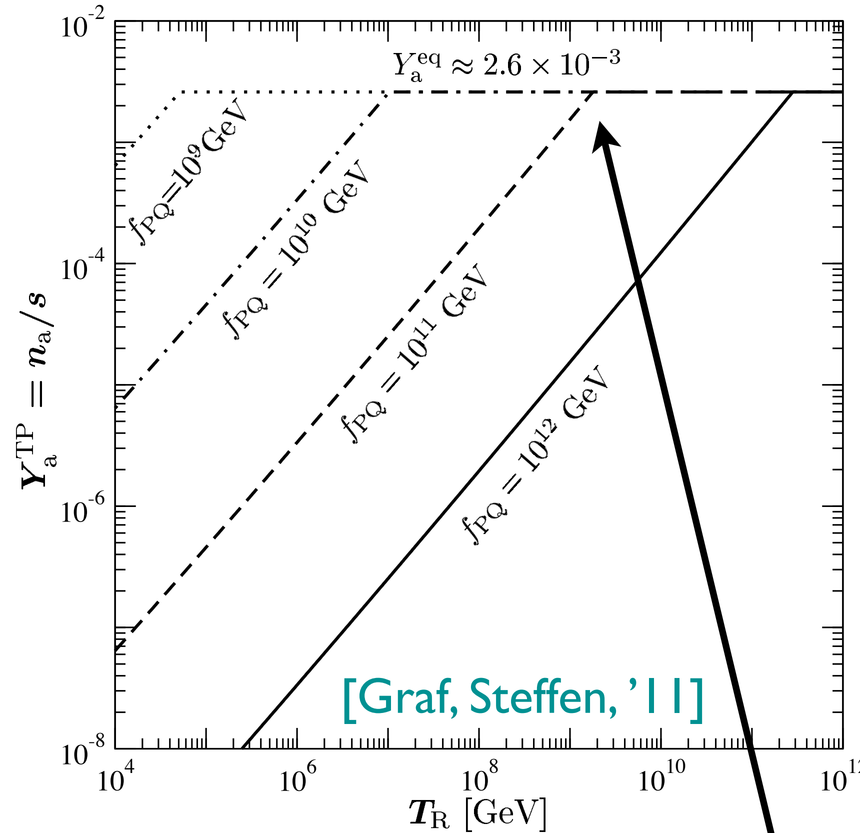
Process C: $q_i + g^a \to q_j + a$ (crossing of B)

Hard Part

Soft Part



Axion Yield



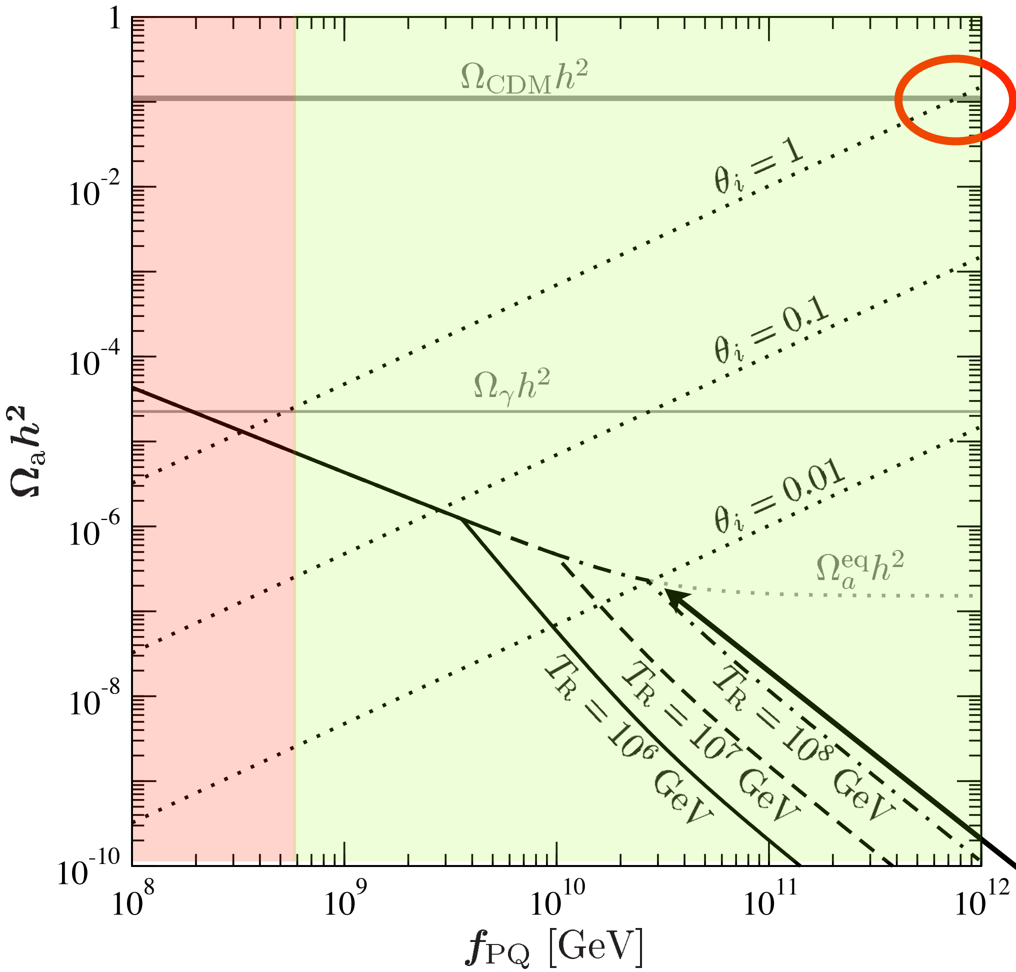
Axion Decoupling Temperature

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

[Masso et al.,'02; Sikivie,'08; Graf, Steffen, '11]

[Graf, Steffen, '11]

Lee-Weinberg Curve for Axions



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

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

Thermal Axions: WDM/HDM

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

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

Axion Decoupling Temperature

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

Axion Mass

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

Conclusions - Part I

- Lee-Weinberg curve for axions
- two guaranteed axion populations
- axions from the misalignm. mech. may provide all or only a fraction of Ω_{dm} - depending on f_{PQ} & θ_i
- thermal relic or thermally produced axions will be present as a HDM with $(\Omega_a)^{th} < \Omega_\gamma << \Omega_{dm}$

extremely challenging to detect experimentally

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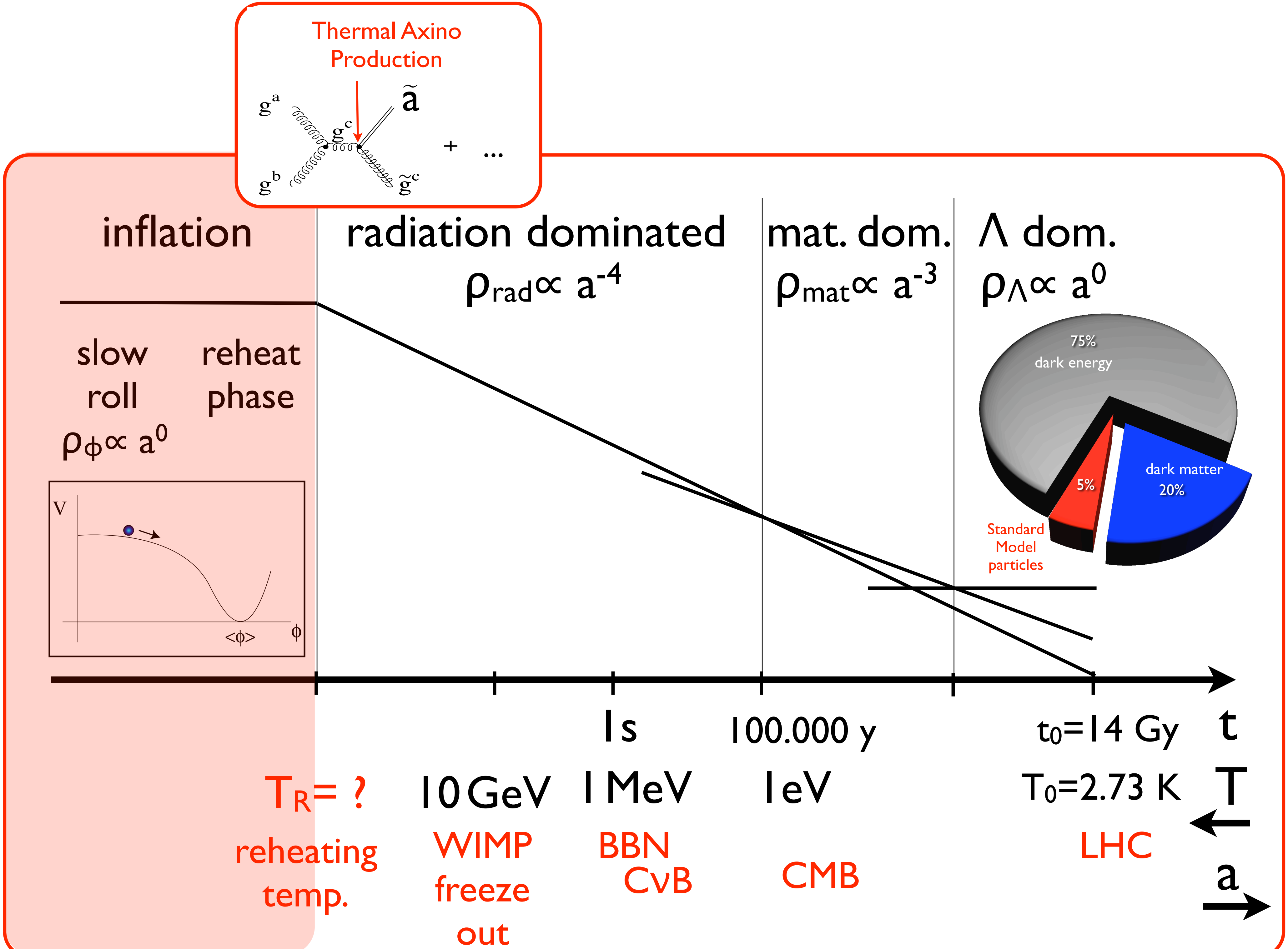
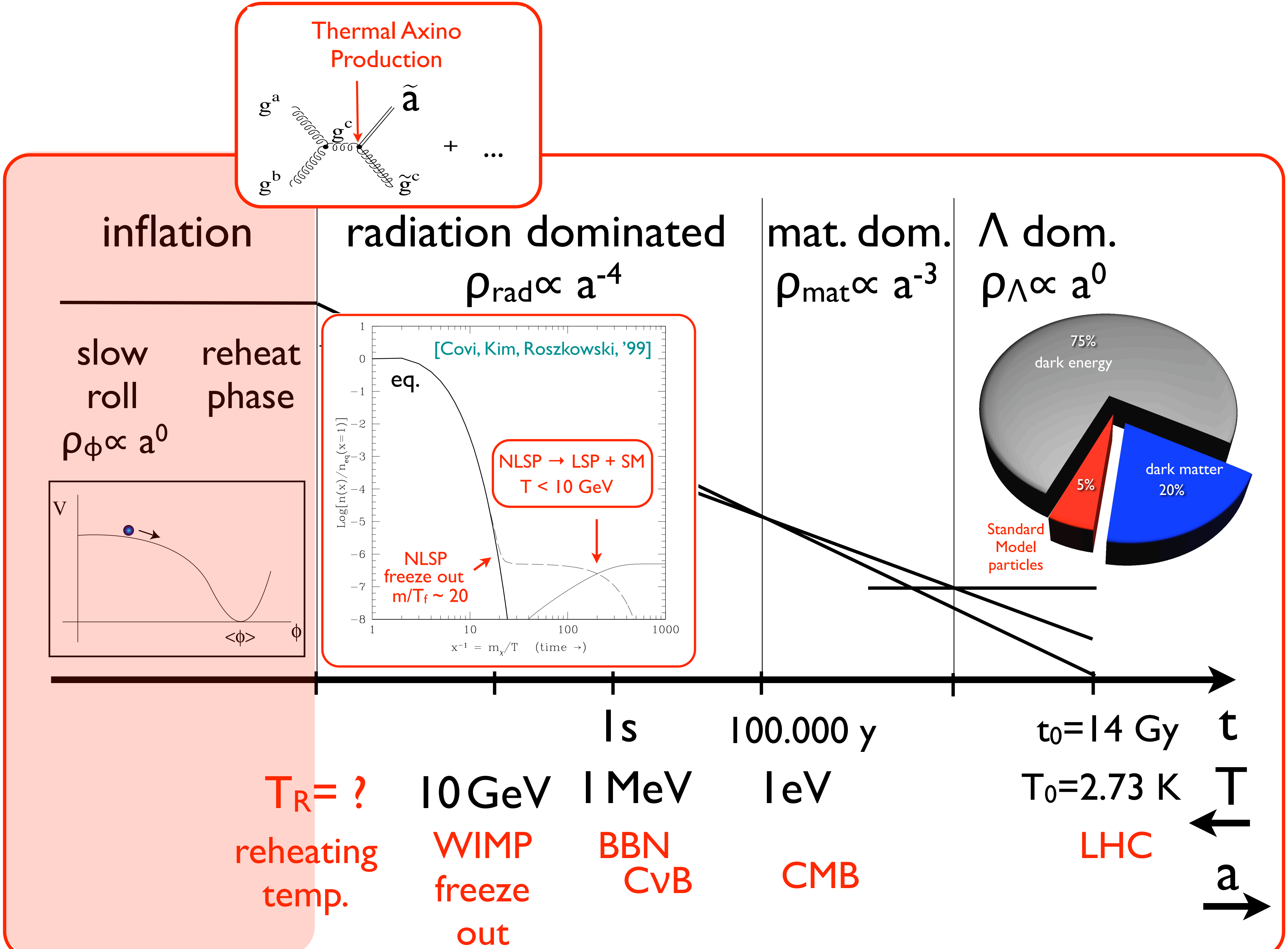
[see also talk by Howard Baer]



Thermal Axino Production
g^a
g^b
g^c
ã
g̃^c
+ ...
inflation
slow roll
reheat phase
ρ_φ ∝ a^0
V
φ
<φ>
radiation dominated
ρ_rad ∝ a^-4
mat. dom.
ρ_mat ∝ a^-3
Λ dom.
ρ_Λ ∝ a^0
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
CνB
CMB
LHC
a


Thermal Axino Production
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$\rho_{rad} \propto a^{-4}$
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$\rho_{\phi} \propto a^{0}$
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V
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[Covi, Kim, Roszkowski, '99]
eq.
NLSP → LSP + SM
T < 10 GeV
NLSP freeze out
$m/T_f \sim 20$
$x^{-1} = m_\chi/T$ (time →)
Log[n(x)/n_eq(x=1)]
75% dark energy
dark matter 20%
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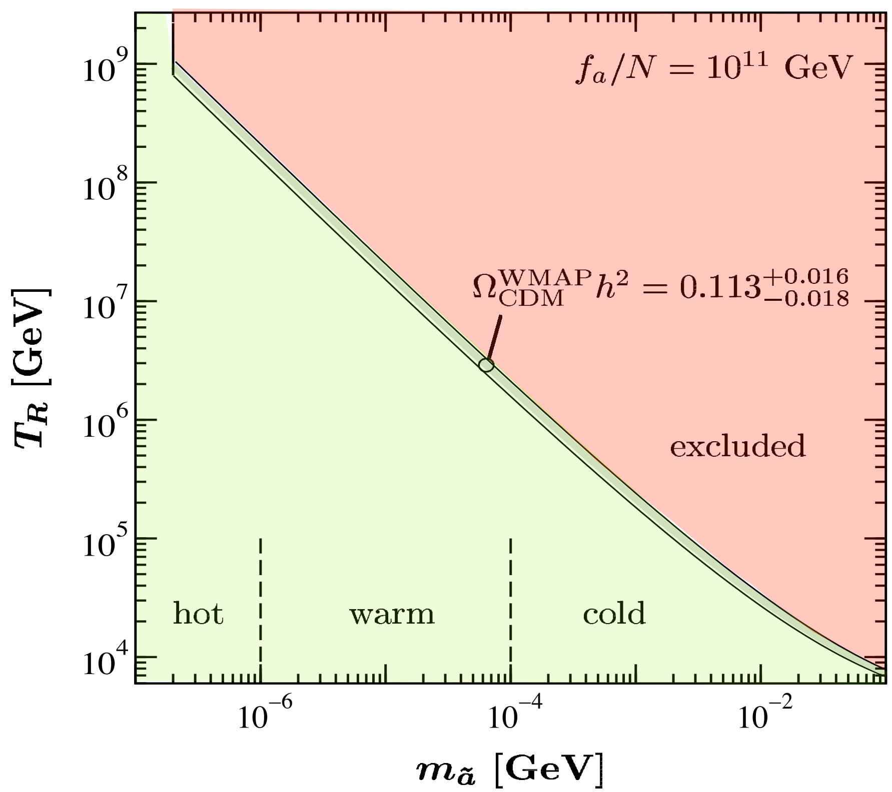
Axino LSP Case

Thermal $\tilde{a}$ Production

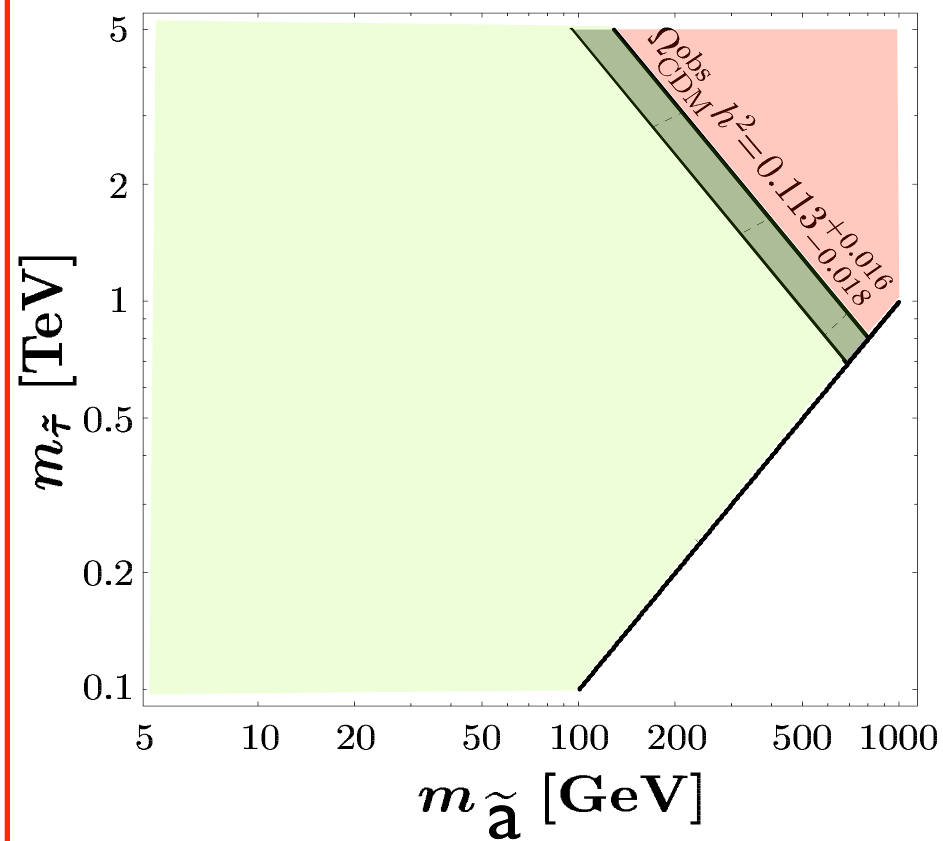


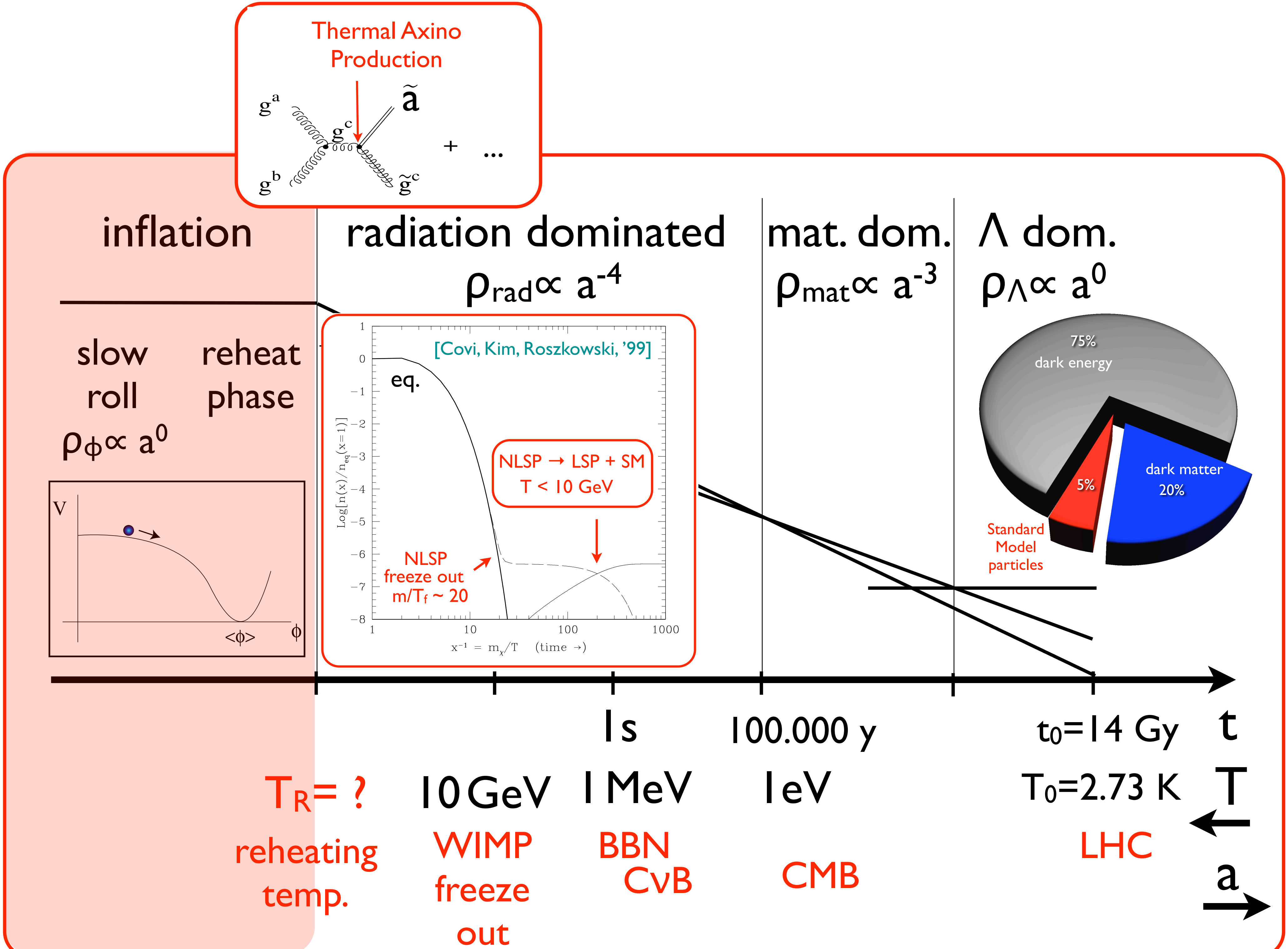
[Brandenburg, FDS, '04]

see also [Covi et al., '01]

and [Strumia, '10]

$\tilde{\tau}$ NLSP $\longrightarrow$ $\tilde{a} + \tau$





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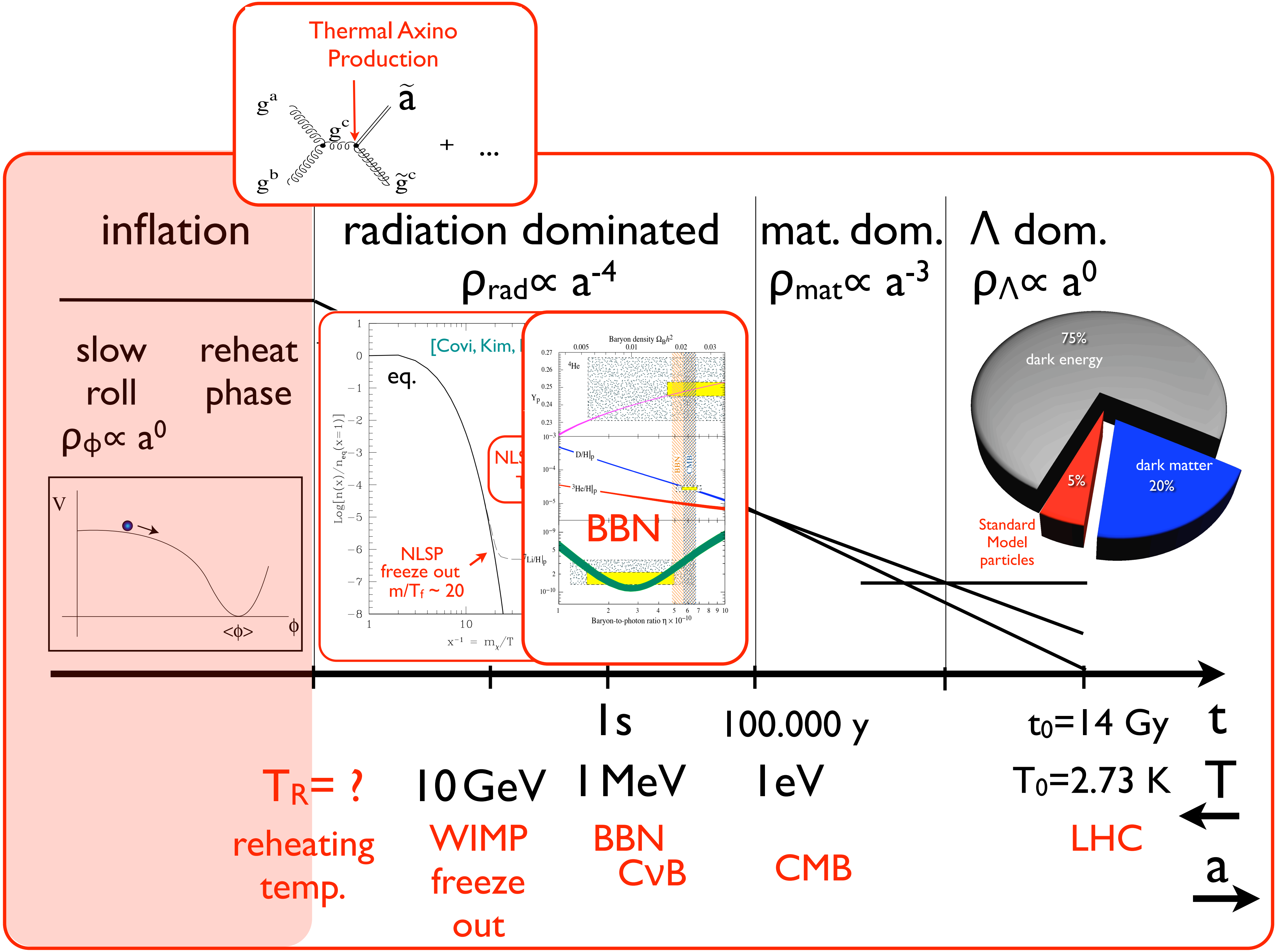

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V
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φ
[Covi, Kim,
eq.
NLSP freeze out m/Tf ~ 20
x-1 = mχ/T
Log[n(x)/neq(x=1)]
Baryon density ΩBh2
Baryon-to-photon ratio η × 10-10
4He
D/H|p
3He/H|p
7Li/H|p
BBN
CMB
BBN
75% dark energy
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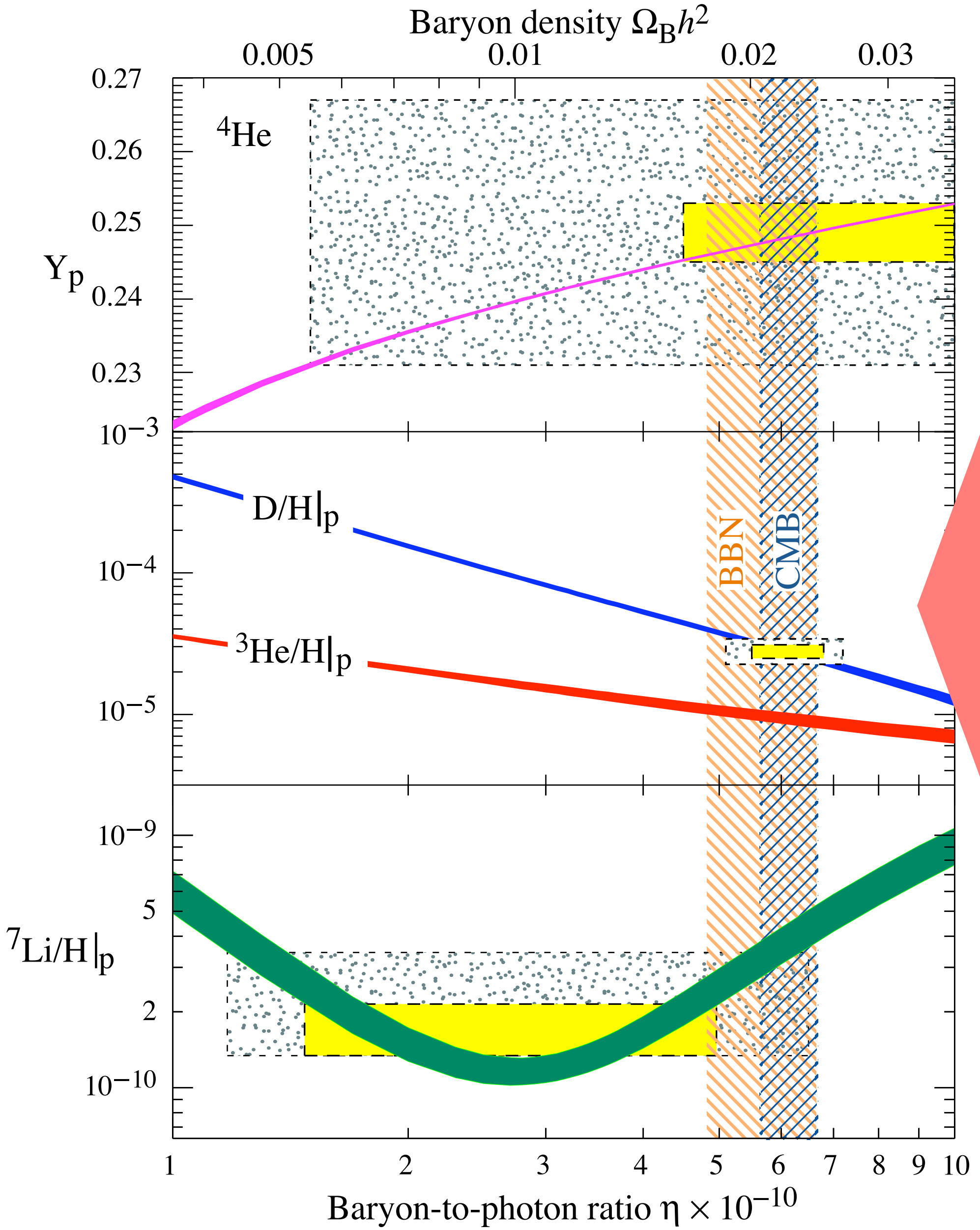
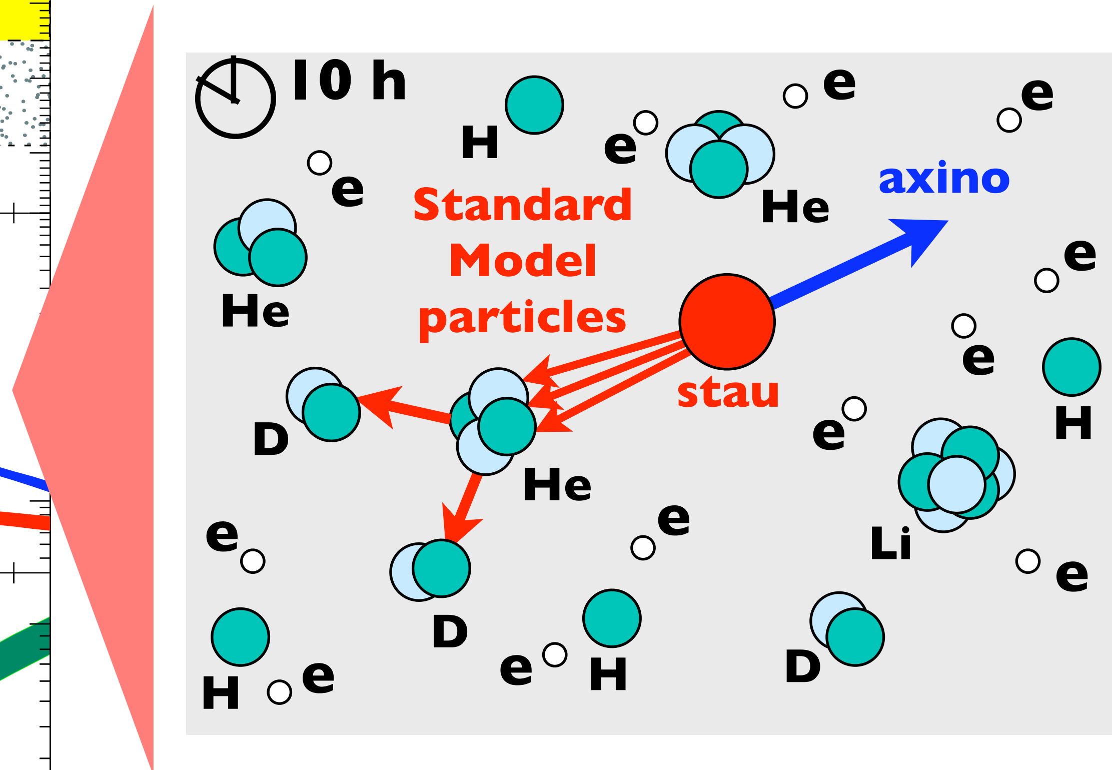
Big-Bang Nucleosynthesis

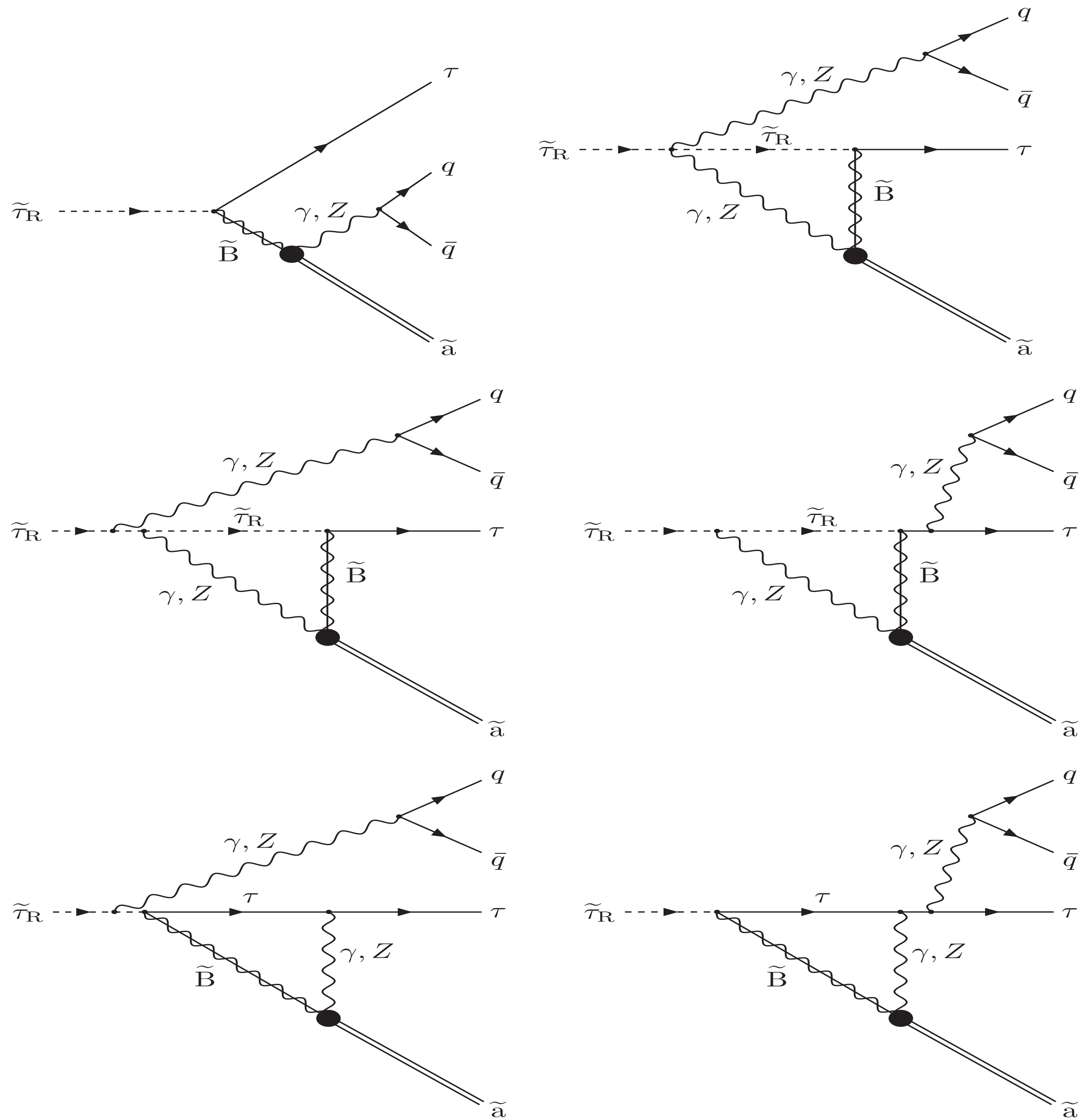


[Particle Data Book 2006]

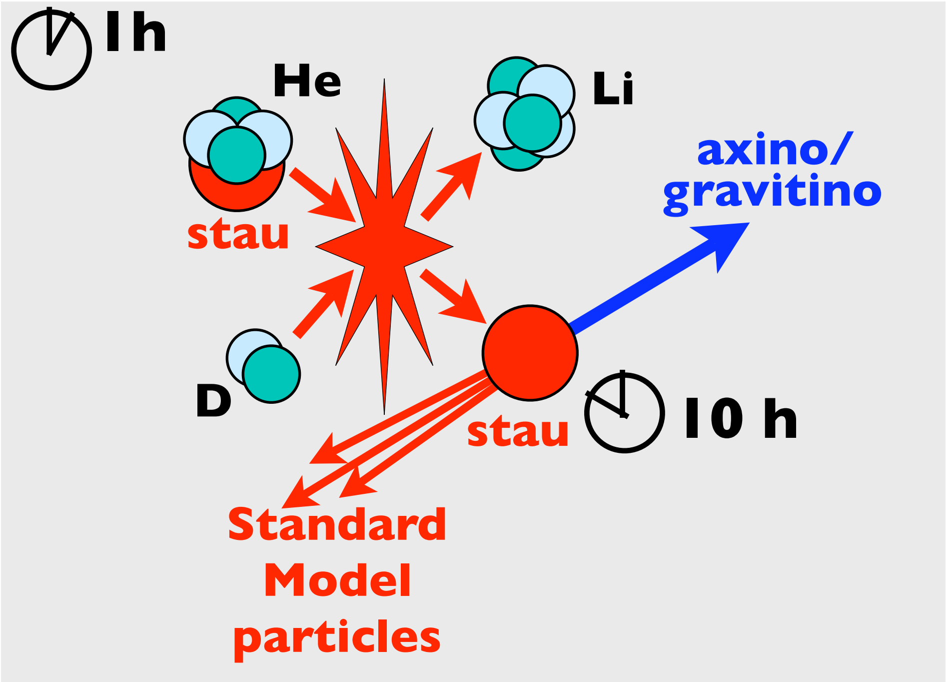


[Freitas, FDS, Tajuddin, Wyler, '09]

Late Hadronic Energy Injection



Catalyzed BBN [Pospelov, '06]

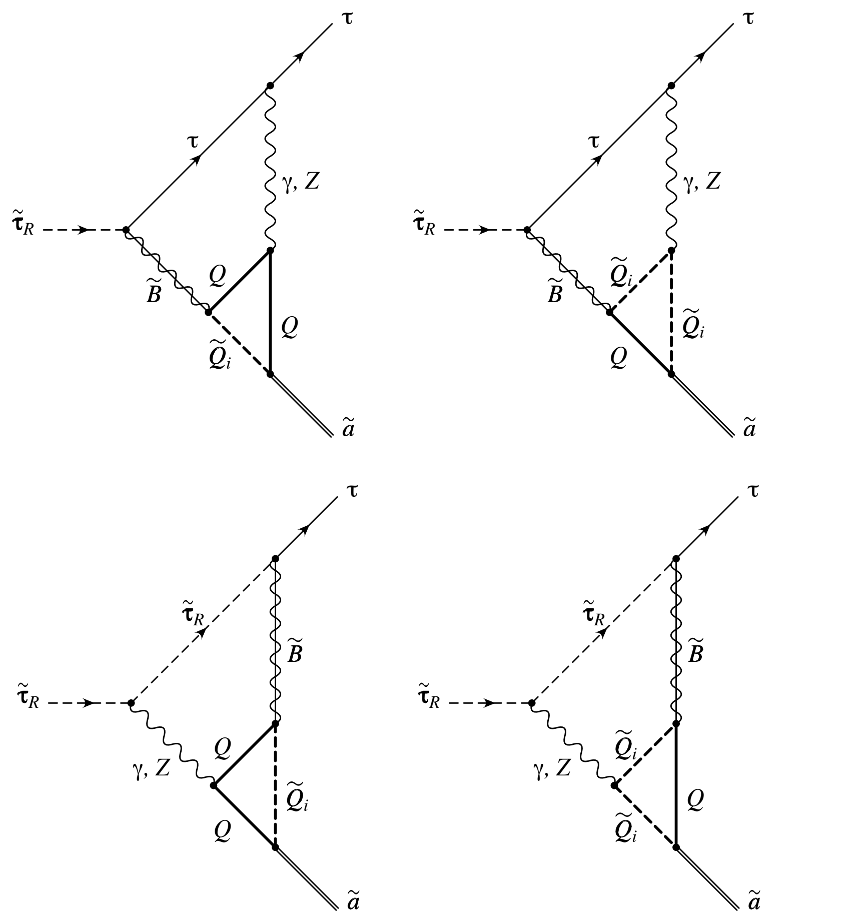


[Cyburt et al., '06; FDS, '06; Pradler, FDS, '07; Hamaguchi et al., '07; Kawasaki, Kohri, Moroi, '07; Takayama, '07; Jedamzik, '07; Pradler, FDS, '08]

CBBN of ^{9}Be: [Pospelov, '07; Pospelov, Pradler, FDS, '08]

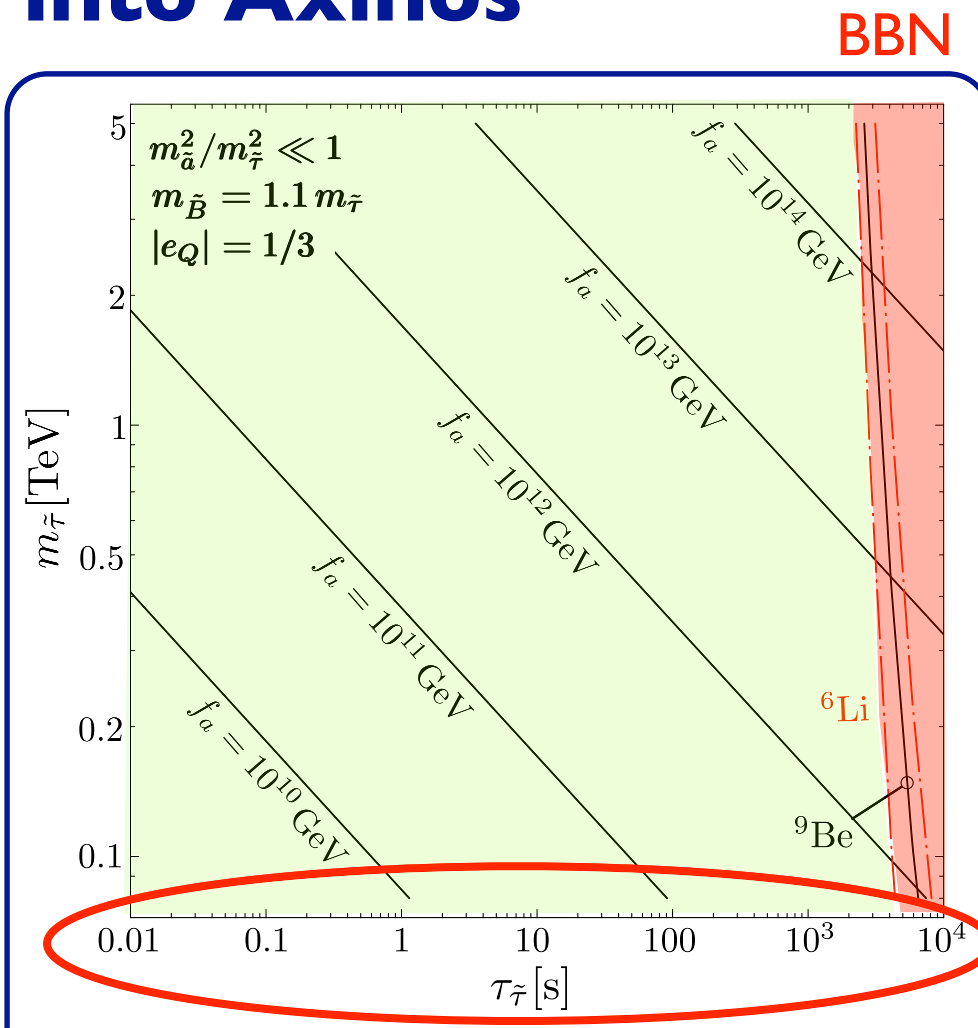
[Freitas, Tajuddin, FDS, Wyler, '09]

Stau Decays into Axinos



$W_{PQ} = y \Phi Q_1 Q_2 \qquad M_{\tilde{Q}_{1,2}} = M_Q = y\langle\phi\rangle = y f_a/\sqrt{2}$

Chiral multiplet	$U(1)_{PQ}$	$(SU(3)_c, SU(2)_L)_Y$
$\Phi = \phi + \sqrt{2}\chi\theta + F_\phi\theta\theta$	$+1$	$(\mathbf{1},\mathbf{1})_0$
$Q_1 = \tilde{Q}_1 + \sqrt{2}q_1\theta + F_1\theta\theta$	$-1/2$	$(\mathbf{3},\mathbf{1})_{+e_Q}$
$Q_2 = \tilde{Q}_2 + \sqrt{2}q_2\theta + F_2\theta\theta$	$-1/2$	$(\mathbf{3}^*,\mathbf{1})_{-e_Q}$

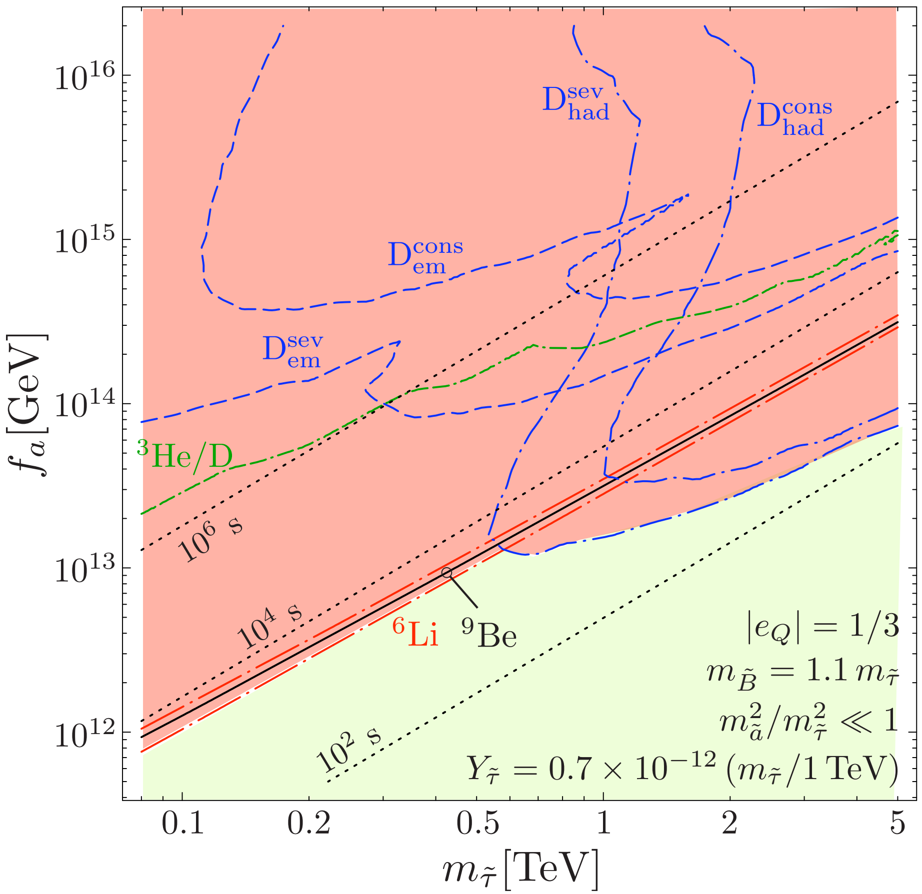


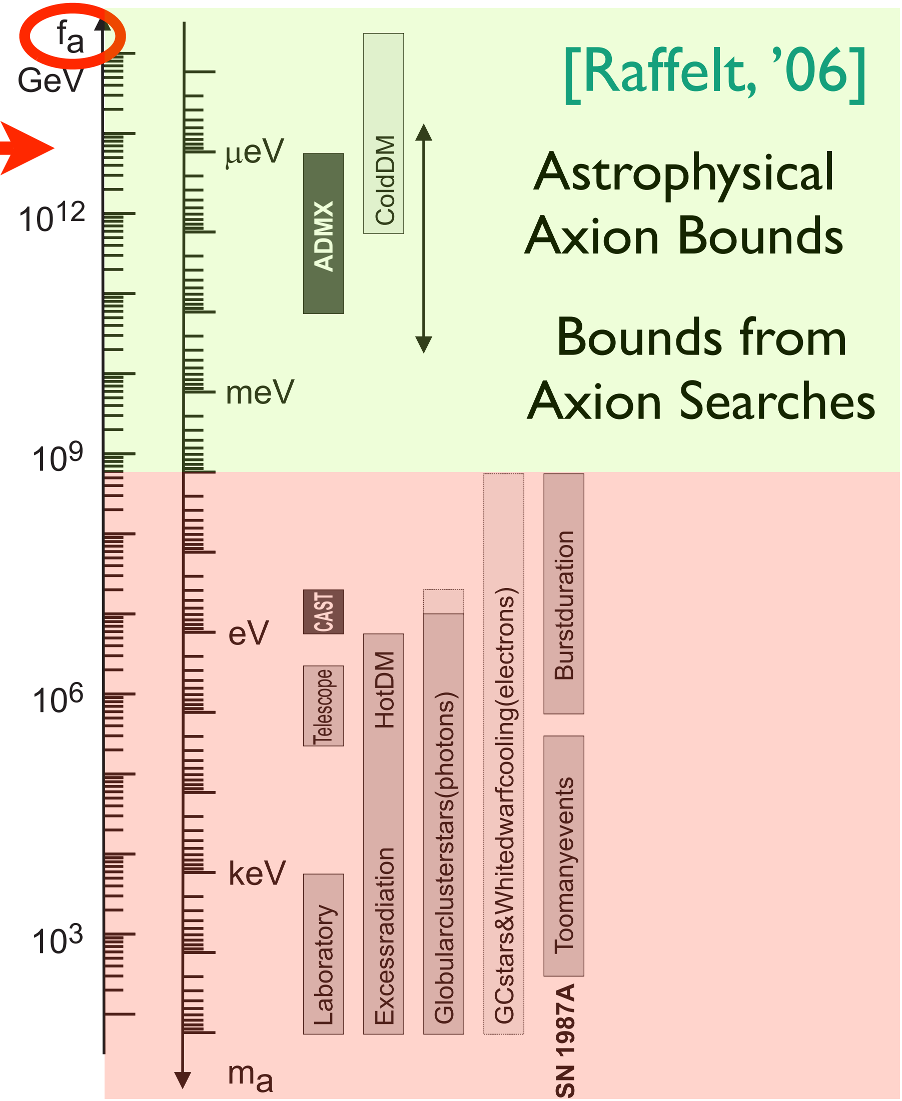
$$\Gamma_{\rm tot}^{\tilde{\tau}_R} \approx \Gamma(\tilde{\tau}_R \to \tau\tilde{a})_{LL}$$

$$= \frac{81\alpha^4 e_Q^4}{128\pi^5\cos^8\theta_W}\,\frac{m_{\tilde{\tau}} m_{\tilde{B}}^2}{f_a^2}\left(1-\frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}}^2}\right)^2 \ln^2\!\left(\frac{y f_a}{\sqrt{2}m_{\tilde{\tau}}}\right)$$

[Freitas, FDS, Tajuddin, Wyler, 0909.3293]

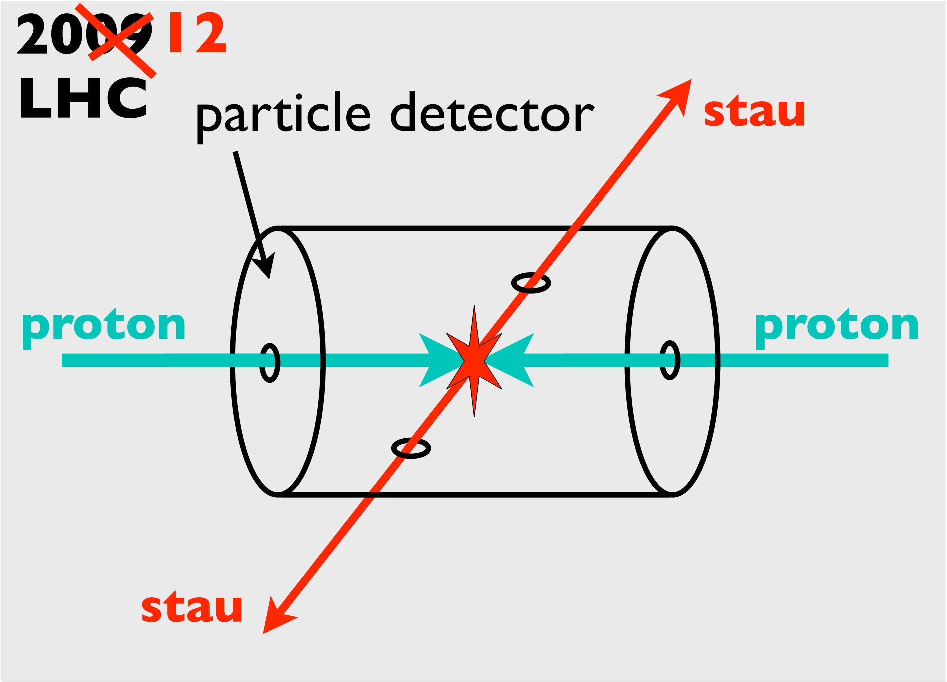
Axino LSP Case with a Charged Slepton NLSP





Upper Limits on the Peccei-Quinn Scale

Axino DM @ LHC ⟵ Stau NLSP



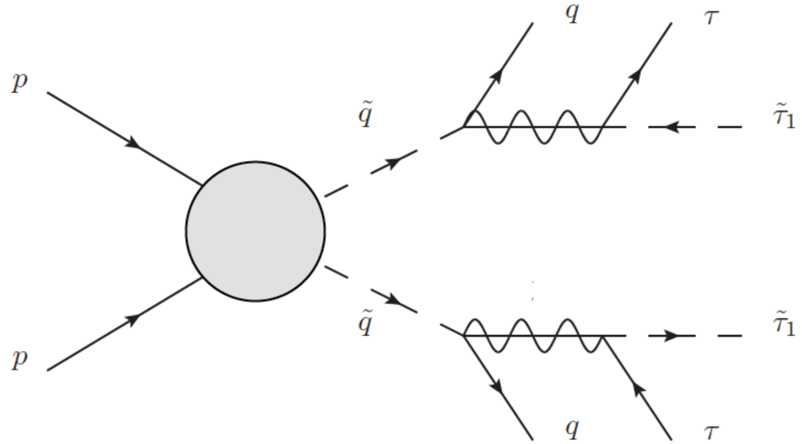
The signal:
jets + leptons

+ 2 “stable”
charged particles

Very different from the large E_T^{miss} signal of Neutralino DM

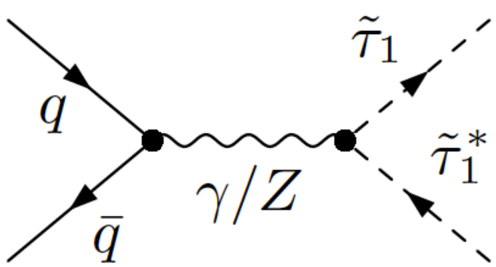
Stau Production @ LHC

- Production in cascade decays



determined by
squark + gluino production
(& BRs)

- Direct production

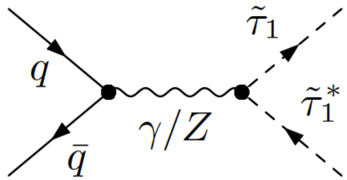


Drell-Yan
(known @ NLO (S)QCD
[Benakker, Klasen, Krämer, Plehn, Spira; '99]
and @ NLL [Bozzi, Fuks, Klasen; '06])

[Lindert, Steffen, Trenkel, '11]

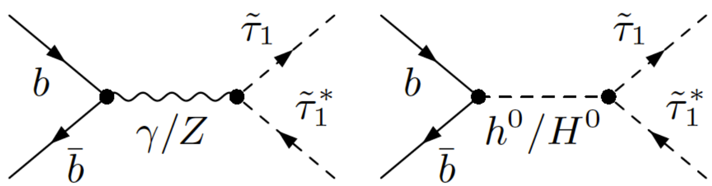
Direct Stau Production at Hadron Colliders

Drell-Yan production



$O(\alpha^2)$ & NLO (S)QCD $O(\alpha_s^2\alpha^2)$

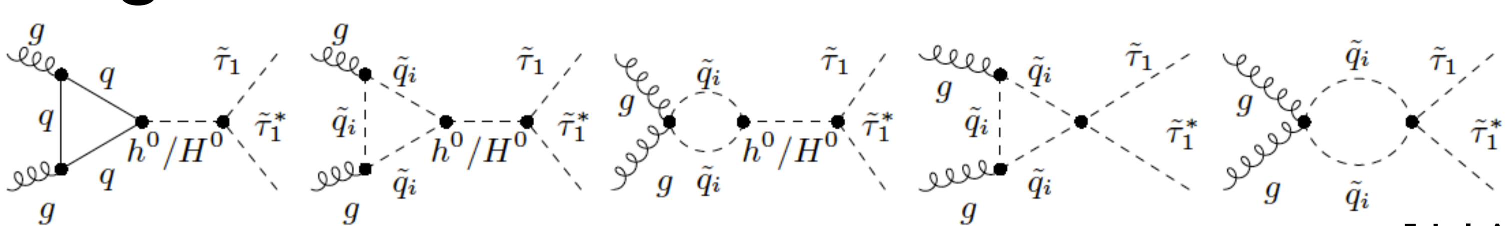
$b\bar{b}$ annihilation



$O(\alpha^2)$ + bottom PDFs

[del Aguila, Ametller; '91; Bisset, Raychaudhuri; '96]

gluon fusion

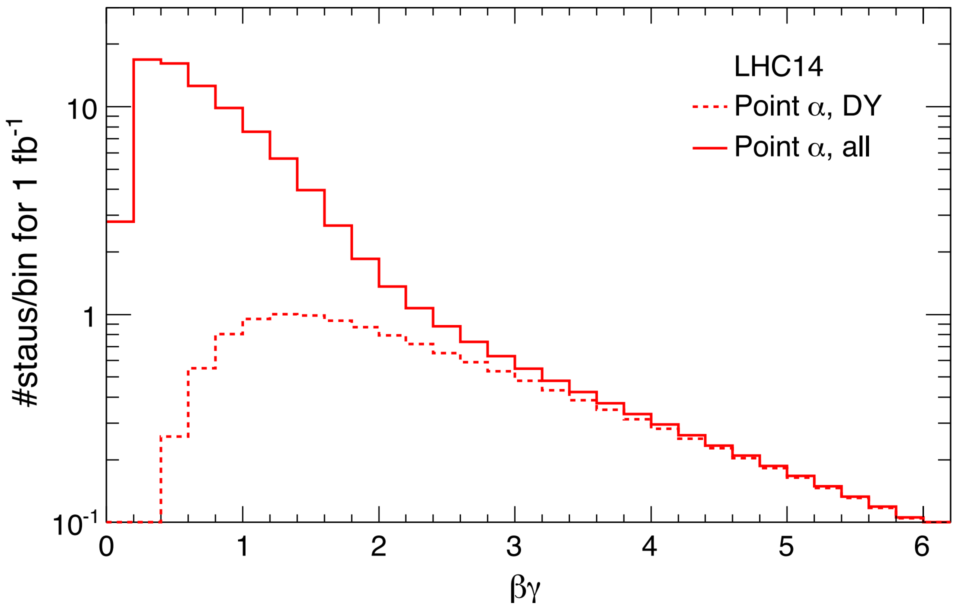


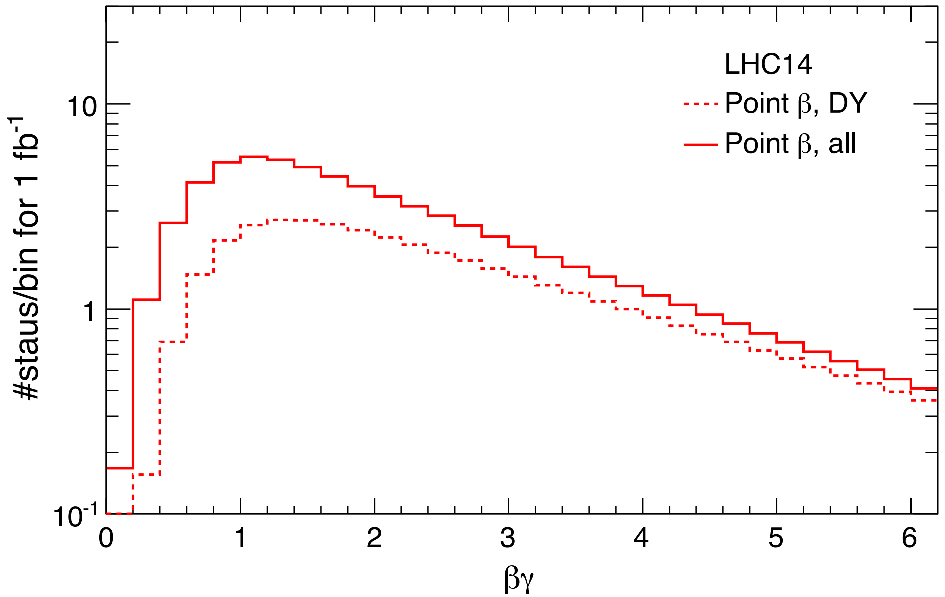
$O(\alpha_s^2\alpha^2)$

[del Aguila, Ametller; '91; Borzumati, Hagiwara; '09]

on-shell: $\dfrac{1}{p^2 - m_{H^0}^2} \longrightarrow \dfrac{1}{p^2 - m_{H^0}^2 + i m_{H^0}\Gamma_{H^0}}$

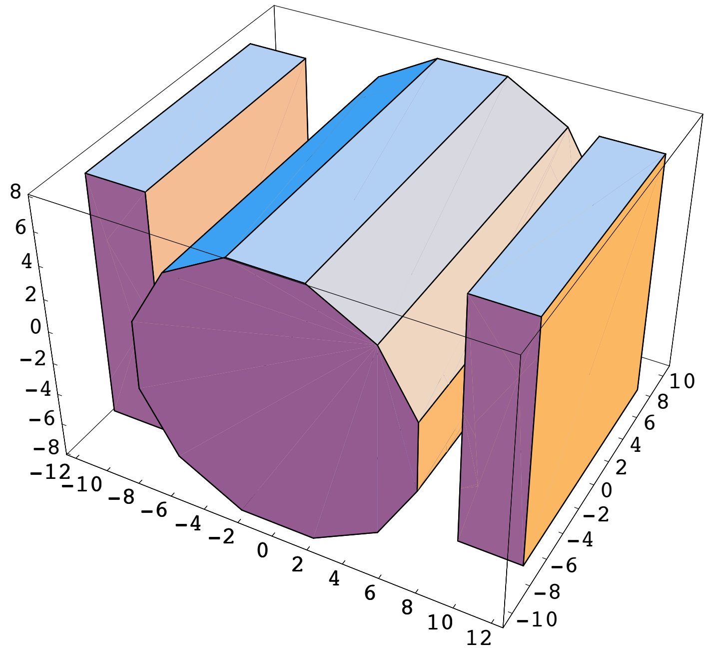
Stopping of long-lived staus

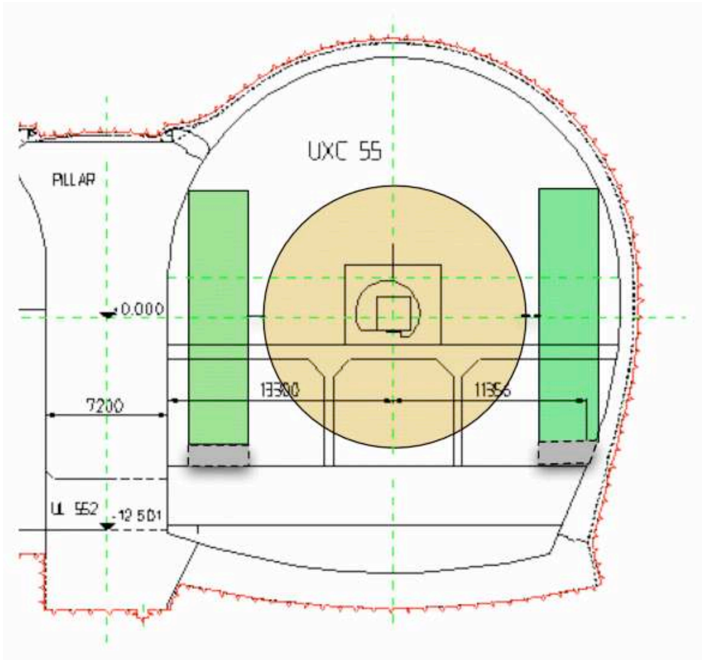




$\tilde{\tau}_1$ are stopped for: $\beta\gamma \lesssim 0.45$

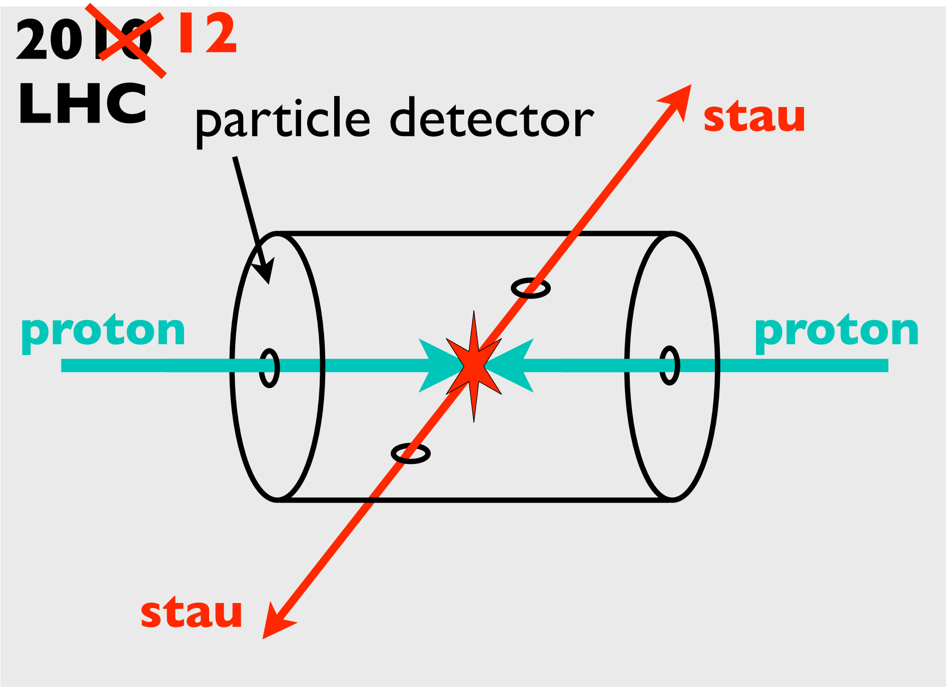
Stopping of long-lived staus @ CMS

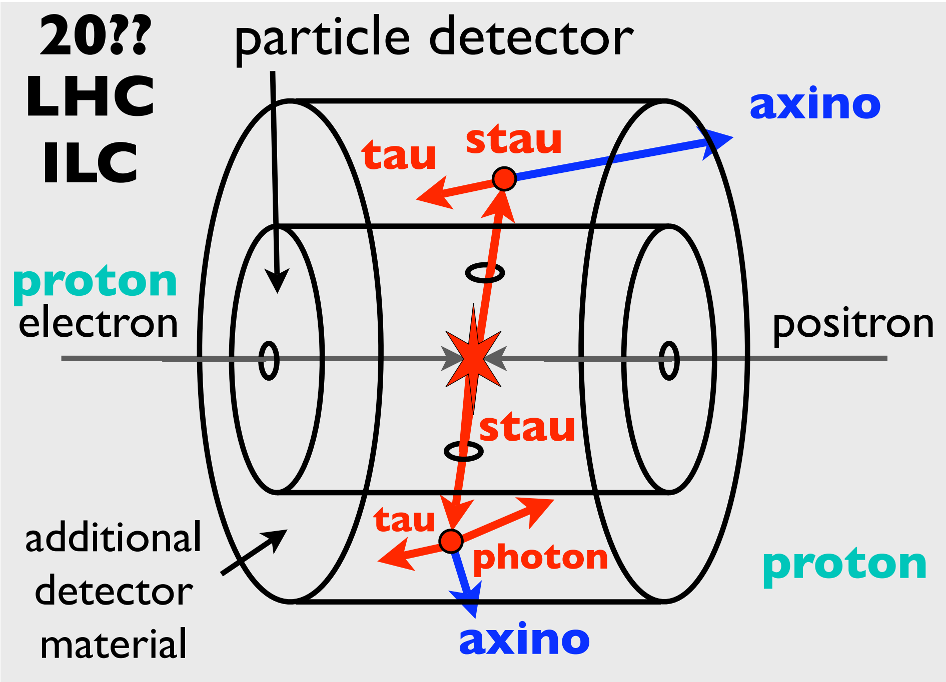




[Hamaguchi, Nojiri, de Roeck, '07]

Stopping of long-lived staus





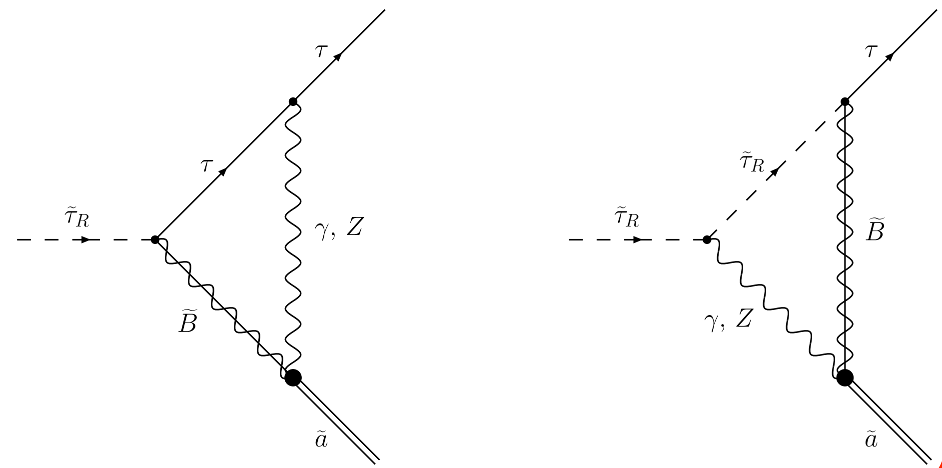
Probing f_a @ Colliders

[Brandenburg et al., '05]

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

$\tilde{a}$ LSP $\rightarrow$ Peccei–Quinn Scale f_a & Axino Mass $m_{\tilde{a}}$

hadronic (KSVZ) axion model



□ Assumption: $\widetilde{\tau}_R$ NLSP & $\widetilde{\chi}^0 \simeq \widetilde{B}$

- 2-Body Decay $\widetilde{\tau}_R \rightarrow \tau + \tilde{a}$

$$\Gamma(\widetilde{\tau}_{\mathrm{R}} \rightarrow \tau \widetilde{a}) \simeq \xi^2 \, (25 \, \mathrm{sec})^{-1} C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\tilde{a}}^2}{m_{\widetilde{\tau}}^2}\right) \left(\frac{m_{\widetilde{\tau}}}{100 \, \mathrm{GeV}}\right) \left(\frac{10^{11} \, \mathrm{GeV}}{f_a}\right)^2 \left(\frac{m_{\tilde{B}}}{100 \, \mathrm{GeV}}\right)^2$$

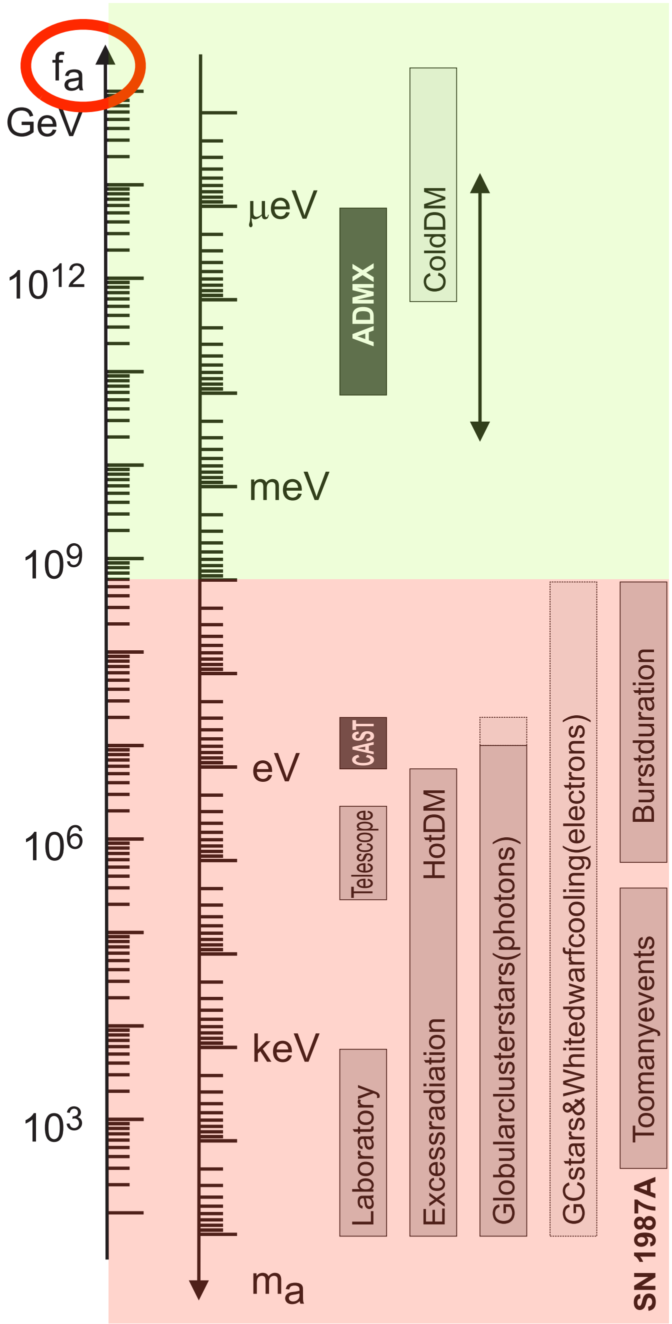
- Peccei–Quinn Scale f_a $\longleftarrow$ NLSP Lifetime $\tau_{\widetilde{\tau}} \approx 1/\Gamma(\widetilde{\tau}_R \rightarrow \tau \, \tilde{a})$

$$f_a^2 \simeq \left(\frac{\tau_{\widetilde{\tau}}}{25 \, \mathrm{sec}}\right) \xi^2 \, C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\tilde{a}}^2}{m_{\widetilde{\tau}}^2}\right) \left(\frac{m_{\widetilde{\tau}}}{100 \, \mathrm{GeV}}\right) \left(\frac{m_{\tilde{B}}}{100 \, \mathrm{GeV}}\right)^2 (10^{11} \, \mathrm{GeV})^2$$

- Axino Mass $m_{\tilde{a}} = \sqrt{m_{\widetilde{\tau}}^2 + m_{\tau}^2 - 2 m_{\widetilde{\tau}} E_{\tau}}$ $\longleftarrow$ Kinematics

[Raffelt, ’06]

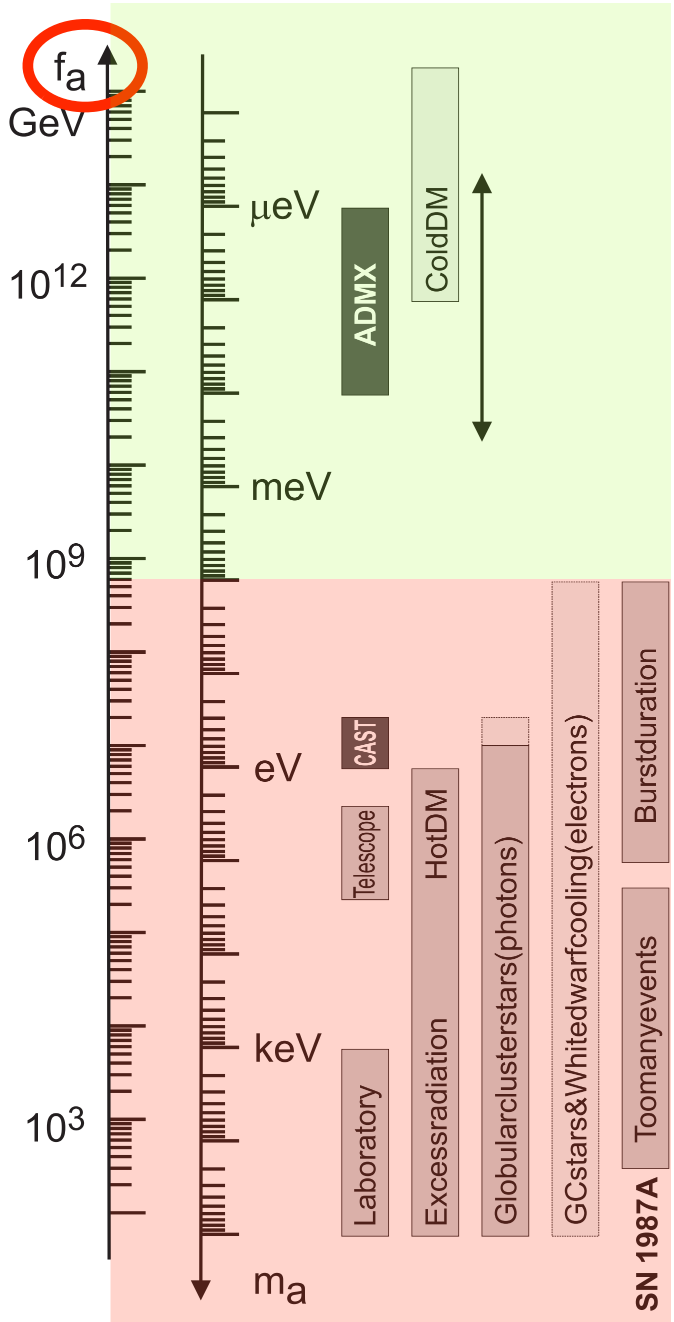
Bounds on the Peccei-Quinn Scale



Is the value of the Peccei-Quinn scale inferred from axino searches consistent with astrophysical axion bounds and results from axion searches?

[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



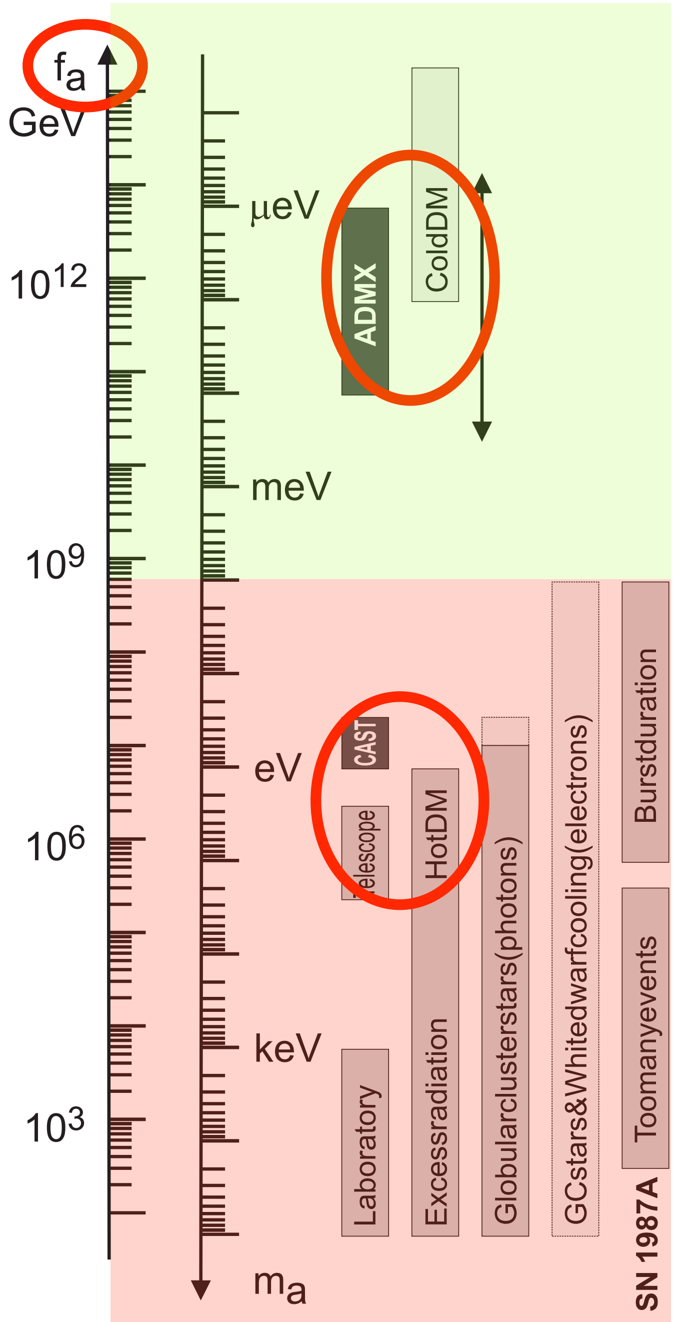
Agreement between Axion & Axino Searches

↓

Strong Hint for the Axino LSP

[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



Agreement between Axion & Axino Searches

↓

Strong Hint for the Axino LSP

Axion DM & Axino DM might coexist!

Conclusions - Part II

- axino LSP is possible if PQ mech. & SUSY exist

- axinos from therm. prod. and NLSP decays may provide (a fraction of) Ω_{dm} - dep. on f_{PQ}, T_R, m_{stau}

- stau NLSP is possible - CHAMP signal @ LHC

- BBN constraints - new m_{stau}-dep. upper limits on f_{PQ}

- LHC pheno - prod. & stopping of staus - probing f_{PQ}

↑

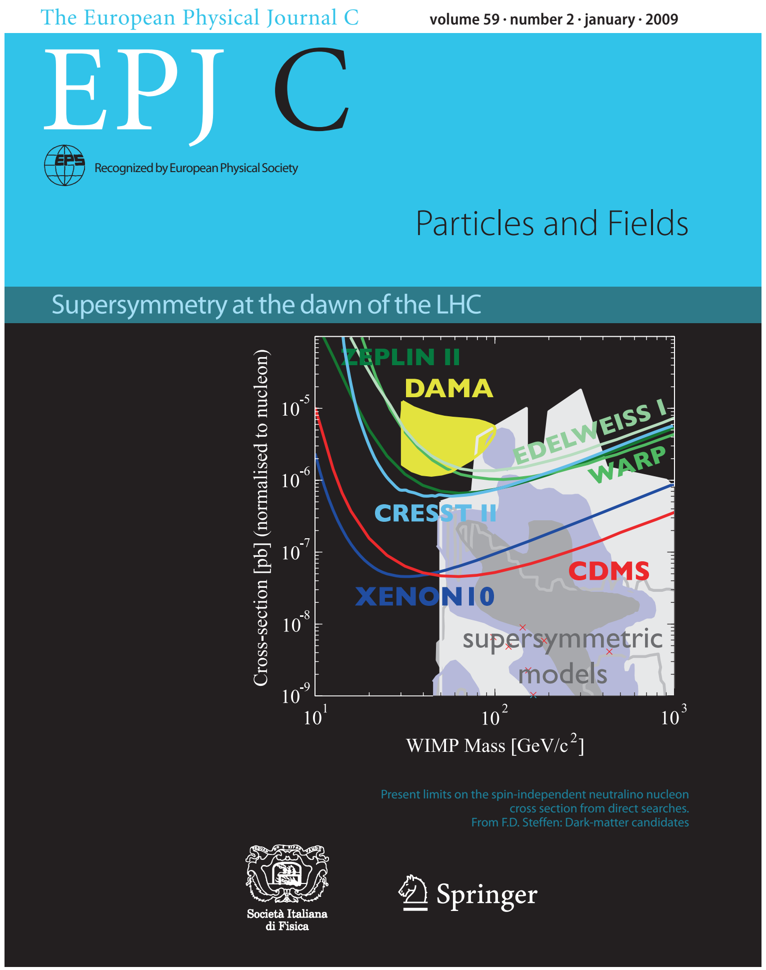
complementary to f_{PQ} determ. in axion searches

For a review (including an extensive list of references),

see

[FDS, *Dark Matter Candidates*, Eur. Phys. J. C59 (2009) 557, arXiv:0811.3347]

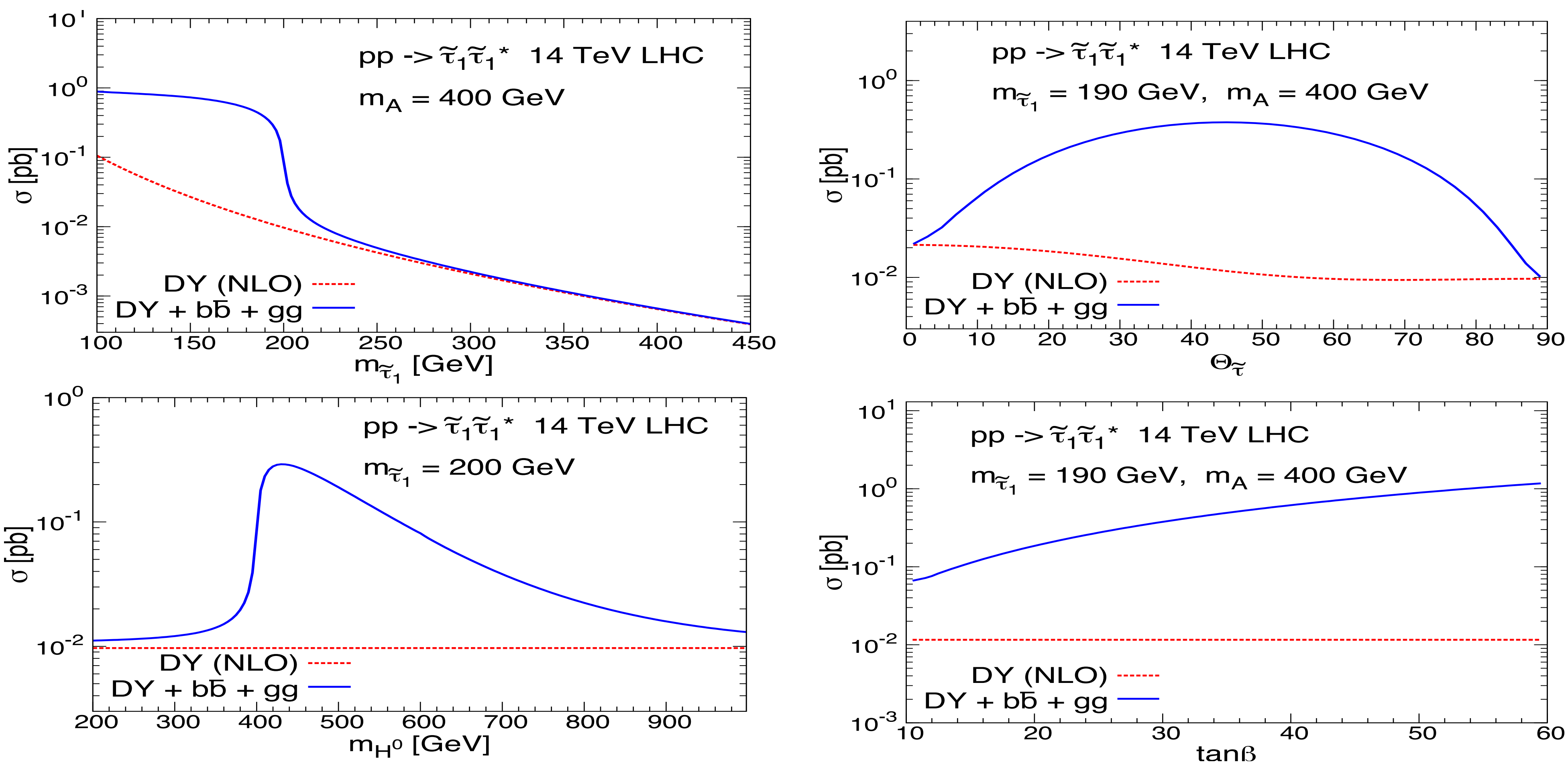
in



Bonus slides

[Lindert, FDS, Trenkel, '11]

Direct Stau Production @ LHC



$$\theta_{\tilde{\tau}} = 45^\circ, \qquad m_{\tilde{\tau}_1} = 200\ \text{GeV},$$

$$\tan\beta = 30, \qquad \mu = 500\ \text{GeV}, \qquad m_A = 400\ \text{GeV}.$$

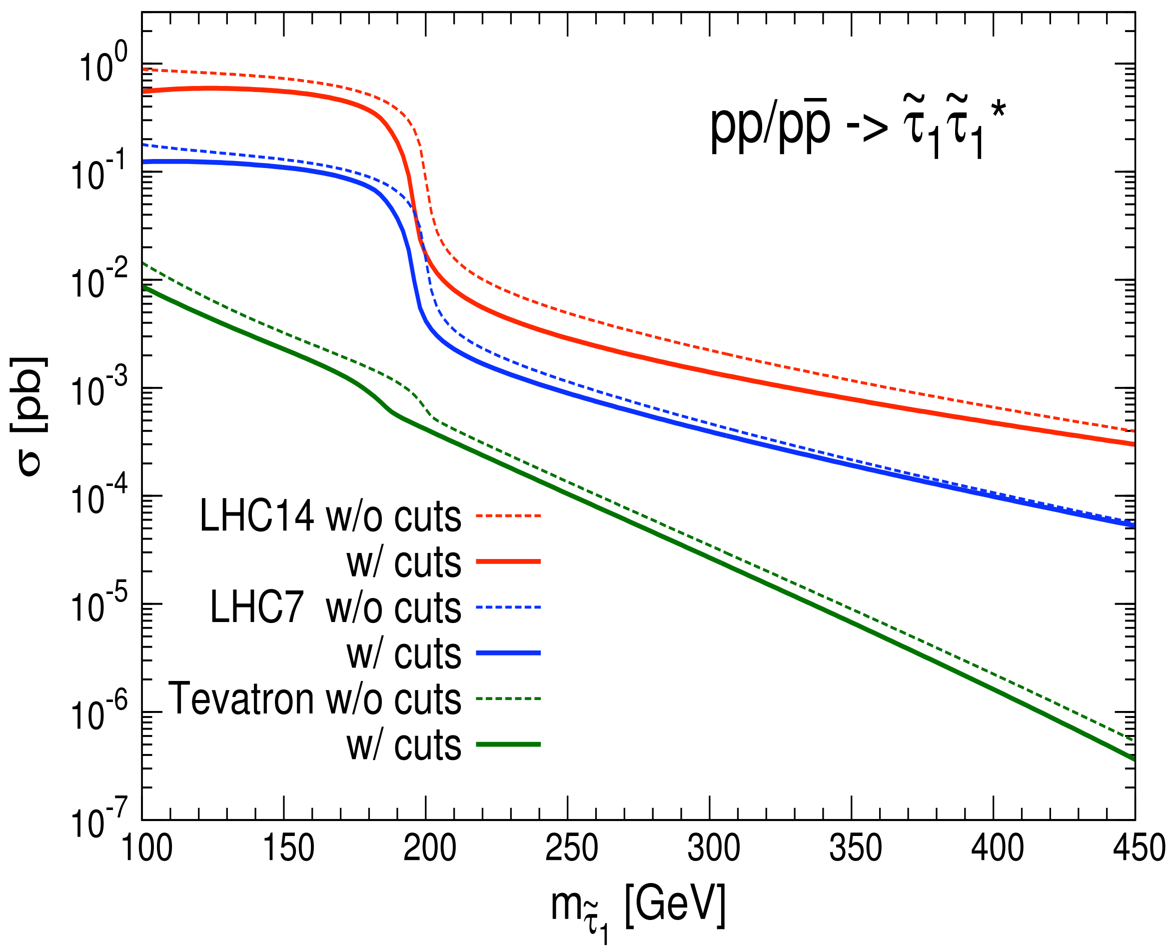
$$M_1 = M_2 = M_3 = 1.2\ \text{TeV}, \qquad A_t = A_b = A_\tau = 600\ \text{GeV},$$

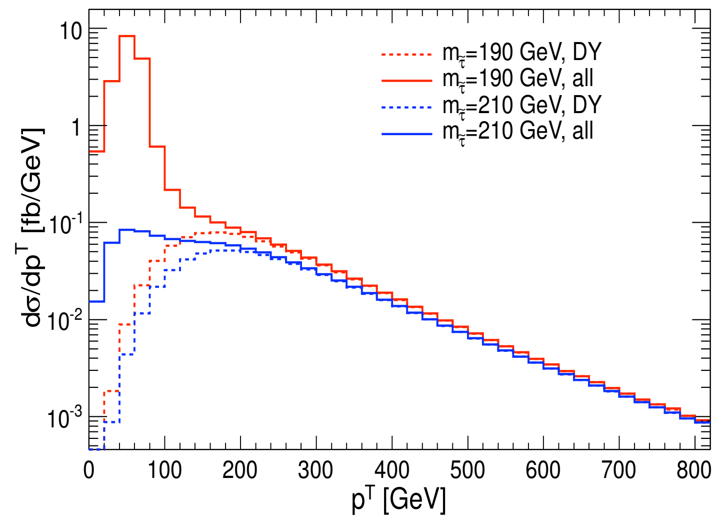
$$m_{\tilde{Q}_i} = m_{\tilde{U}_i} = m_{\tilde{D}_i} = 1\ \text{TeV}, \qquad m_{\tilde{L}_{1/2}} = m_{\tilde{E}_{1/2}} = 500\ \text{GeV}$$

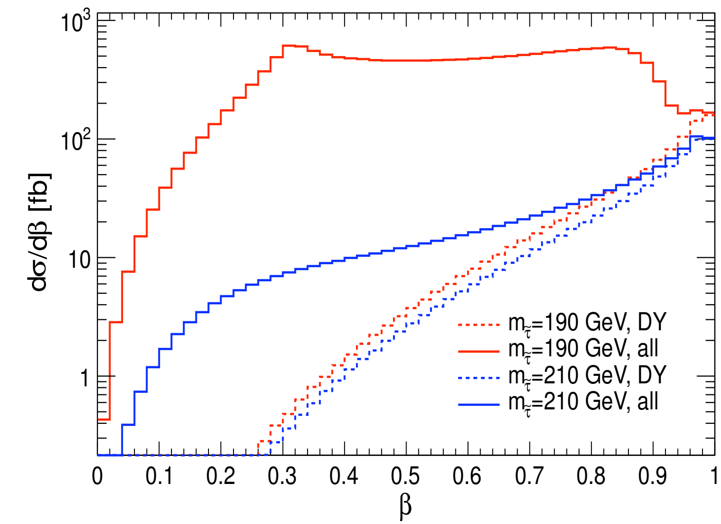
[Lindert, FDS, Trenkel, '11]

Kinematical Cuts

$$p^{\mathrm{T}} > 40 \text{ GeV}, \qquad 0.4 < \beta < 0.9,$$
$$|\eta| < 0.7 \text{ (Tevatron)} \qquad |\eta| < 2.4 \text{ (LHC)}$$







[Lindert, FDS, Trenkel, '11]

Direct Production vs. Cascade Decays

Benchmark point		α	β	γ	ϵ
LHC 7 TeV					
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\rm DY}$	[fb]	3.2 (2.3)	12.5 (7.3)	9.0 (5.6)	7.95 (5.00)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{b\bar{b}}$	[fb]	9.8 (5.1)	0.03 (0.02)	19.2 (16.5)	0.07 (0.06)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\rm gg}$	[fb]	0.1 (0.1)	3.3 (2.4)	0.32 (0.25)	0.01 (0.01)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\rm all}$	[fb]	13.1 (7.5)	15.8 (9.7)	28.5 (22.4)	8.03 (5.07)
$\sigma(\tilde{g}\tilde{g})$	[fb]	0.05	10^{-6}	0.06	2.57
$\sigma(\tilde{g}\tilde{q})$	[fb]	0.63	4×10^{-4}	0.99	37.36
$\sigma(\tilde{q}\tilde{q})$	[fb]	1.18	0.006	2.41	77.25
$\sigma(\tilde{\chi}\tilde{q})+\sigma(\tilde{\chi}\tilde{g})$	[fb]	0.481	0.007	0.72	12.77
$\sigma(\tilde{\chi}\tilde{\chi})$	[fb]	20.4	0.29	19.8	91.78
LHC 14 TeV					
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\rm DY}$	[fb]	11.2 (5.64)	37.5 (15.9)	28.0 (12.4)	24.7 (11.2)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{b\bar{b}}$	[fb]	58.4 (27.0)	0.7 (0.2)	113.3 (87.1)	0.5 (0.4)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\rm gg}$	[fb]	0.7 (0.4)	17.4 (11.1)	1.8 (1.3)	0.07 (0.05)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\rm all}$	[fb]	70.3 (33.1)	55.6 (27.2)	143.1 (100.8)	25.3 (11.6)
$\sigma(\tilde{g}\tilde{g})$	[fb]	20.2	0.12	20.8	232.19
$\sigma(\tilde{g}\tilde{q})$	[fb]	104.4	2.46	133.2	1328.4
$\sigma(\tilde{q}\tilde{q})$	[fb]	92.5	6.46	139.0	1301.1
$\sigma(\tilde{\chi}\tilde{q})+\sigma(\tilde{\chi}\tilde{g})$	[fb]	16.9	1.08	22.4	175.12
$\sigma(\tilde{\chi}\tilde{\chi})$	[fb]	134.5	6.40	131.1	422.2

Benchmark point		α	β	γ	ϵ
$m_{1/2}$	[GeV]	600	1050	600	440
m_0	[GeV]	800	30	600	20
$\tan\beta$		55	55	55	15
A_0	[GeV]	1600	60	1200	−250
$m_{\tilde{\tau}_1}$	[GeV]	193	136	148	153
$\theta_{\tilde{\tau}}$		81°	73°	77°	76°
m_{H^0}	[GeV]	402	763	413	613
Γ_{H^0}	[GeV]	15	26	16	2.2
$m_{\tilde{g}}$	[GeV]	1397	2276	1385	1028
avg. $m_{\tilde{q}}$	[GeV]	1370	1943	1287	894
μ	[GeV]	667	1166	648	562
A_τ	[GeV]	515	−143	351	−275
BR($b \to s\gamma$)	[10^{-4}]	3.08	3.03	2.94	3.00
BR($B_s^0 \to \mu^+\mu^-$)	[10^{-8}]	1.65	1.04	2.44	0.30
a_μ	[10^{-10}]	13.2	11.5	16.8	18.7
CCB [108]		✓	—	✓	✓
$Y_{\tilde{\tau}_1}$	[10^{-15}]	3.5	2.5	37.7	164

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

m_{axino}, $m_{\text{gravitino}}$ < m_{stau}