etc.
Axions ~~and defects~~ in the early Universe

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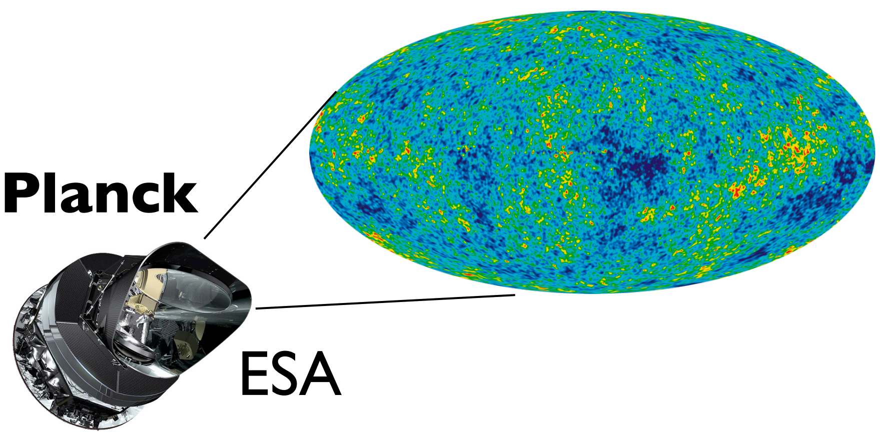
MITP Scientific Program

Jets, particle production and transport properties
in collider and cosmological environments

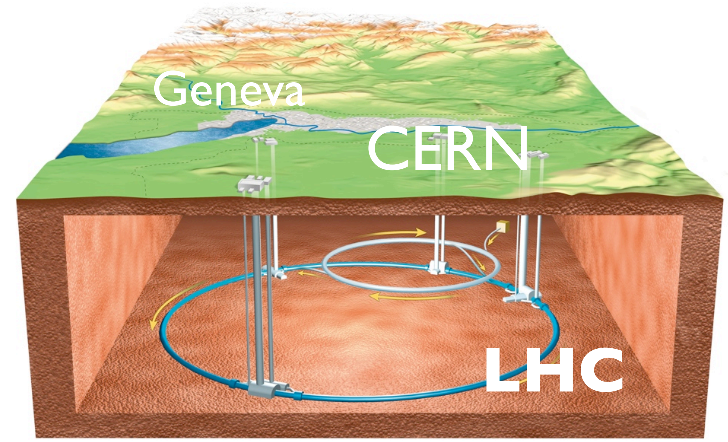
Mainz, July 28, 2014

Astroparticle Physics

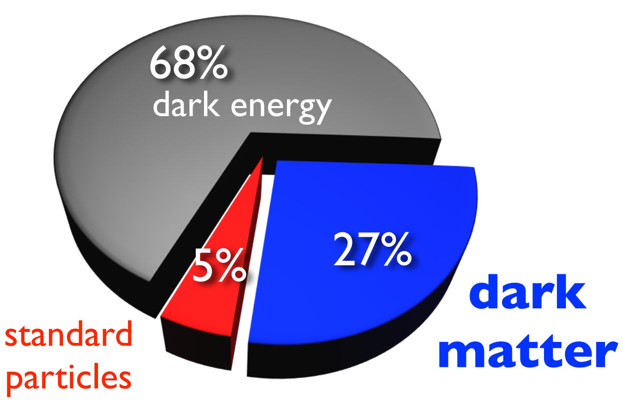
Cosmology
largest scales



Particle Physics
smallest scales



What is the energy budget of the Universe?



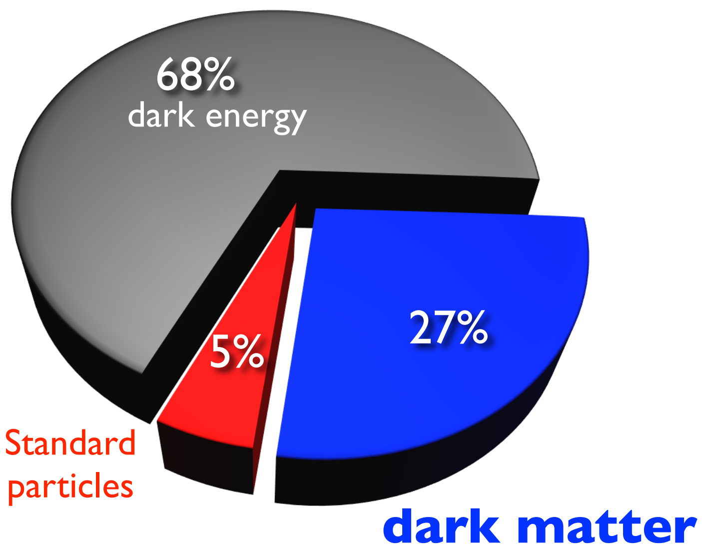
What is the particle identity and origin of dark matter?

What are the fundamental constituents of matter?

Standard Model

Cosmology

- 2013: Planck CMB sky map



- Cosmological puzzles

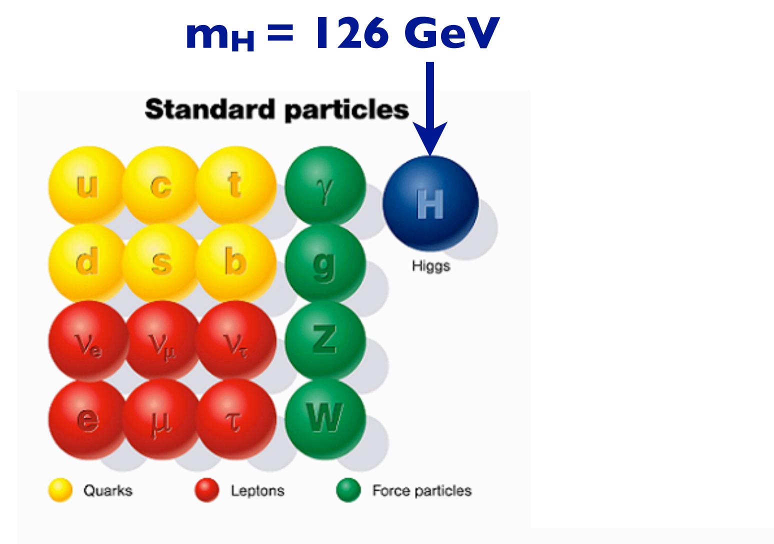
? Matter-Antimatter Asymmetry

? Particle Identity & Origin of Dark Matter

? Dark Energy = Cosmological Constant

Particle Physics

- 2012: LHC Higgs-boson discovery



- Intrinsic fine tuning problems

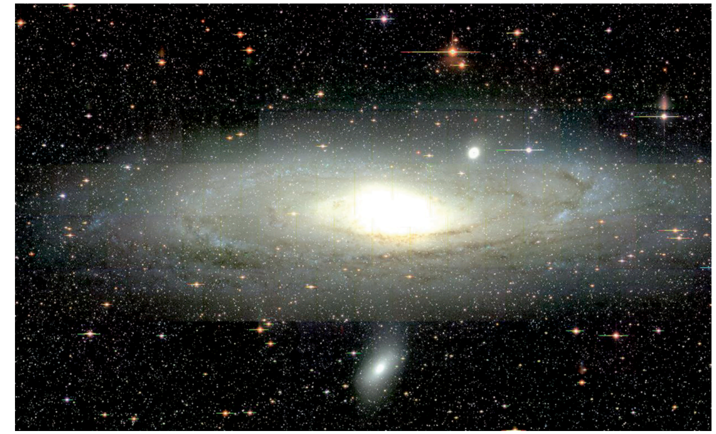
? Hierarchy Problem ($m_H << M_{Planck}$)

? Strong CP Problem ($\Theta_{QCD} << 1$)

? Small Neutrino Masses ($m_\nu << m_H$)

→ Physics beyond the Standard Model

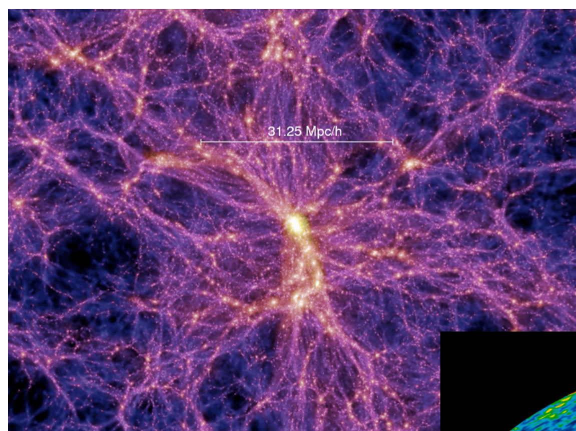
Properties of Dark Matter



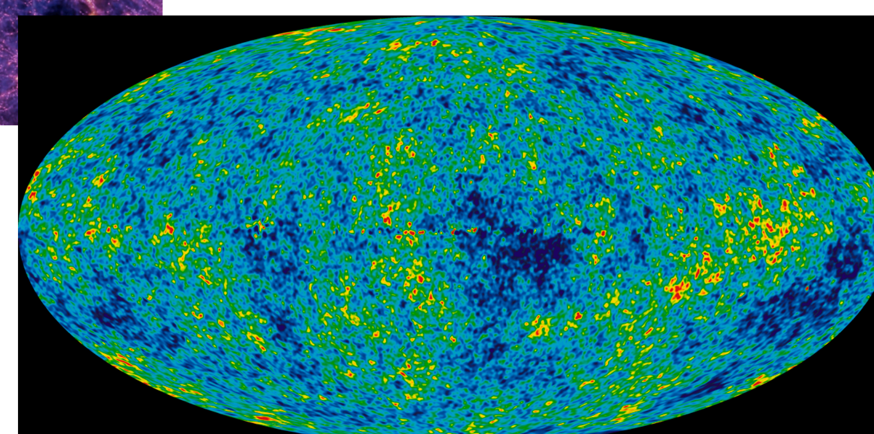
- stable or lifetime well above

  the age of our Universe

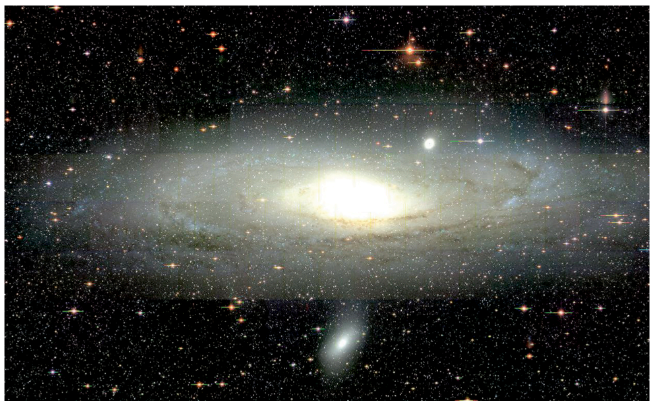
- electrically neutral
- clusters ⟶



- cold / warm
- dissipationless
- color neutral

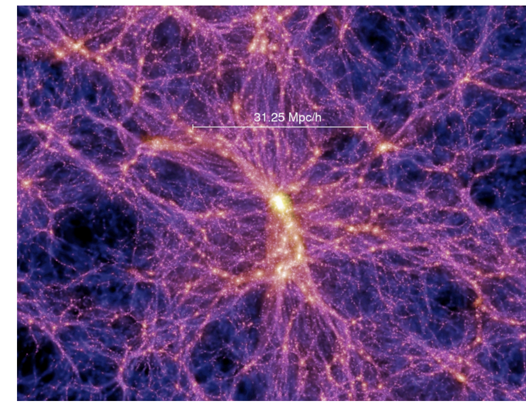


Dark matter



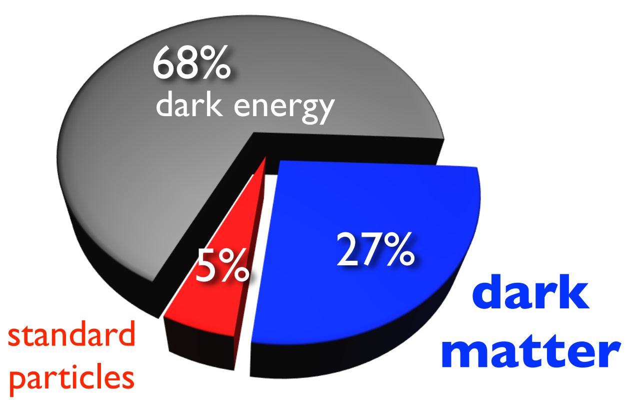
galaxies - rotation velocities

galaxy clusters - gravitational lensing



large scale structure

→ Particle Identity of Dark Matter

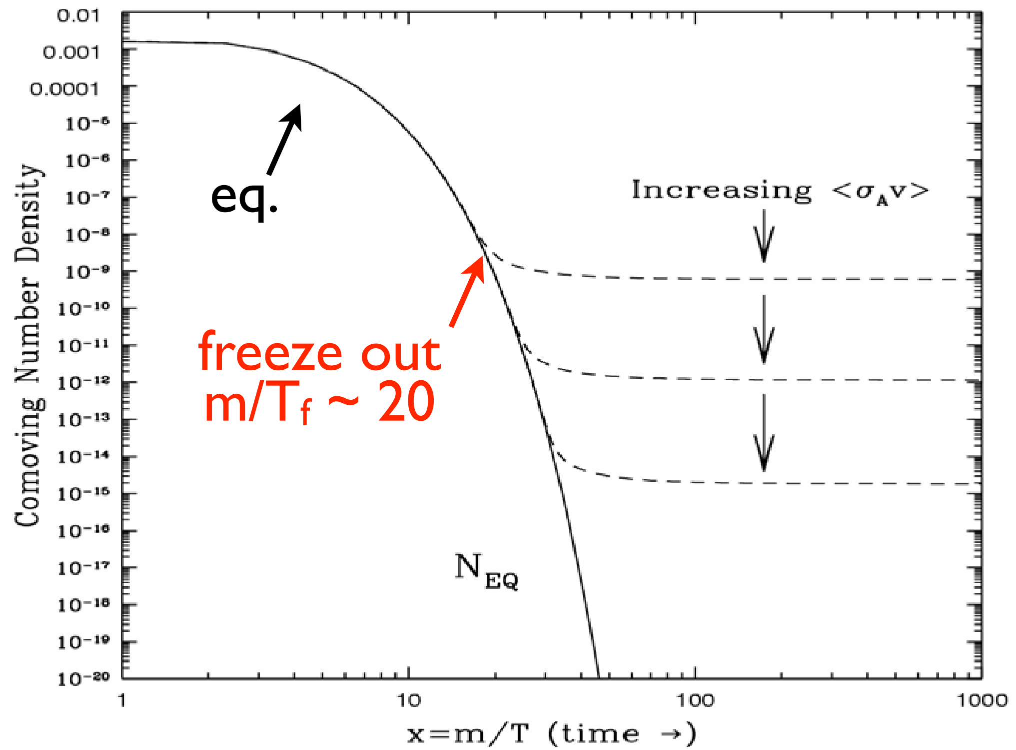


Axions etc.

Steffen

Dark Matter Candidates

WIMP - Weakly Interacting Massive Particle



WIMP miracle

$$\Omega_{DM} \approx \frac{0.2\ \mathrm{pb}}{\sigma_{anni}}$$

$\sigma_{anni} \approx 1$ pb

Fermi-scale annihilation

cross section

EWIP - Extremely Weakly Interacting Particle

thermally produced EWIP DM ← QCD processes in the hot early Universe

axion condensate

Cosmic Relic Abundances

reheating temp. ↓

decoupling temp. of X ↙

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

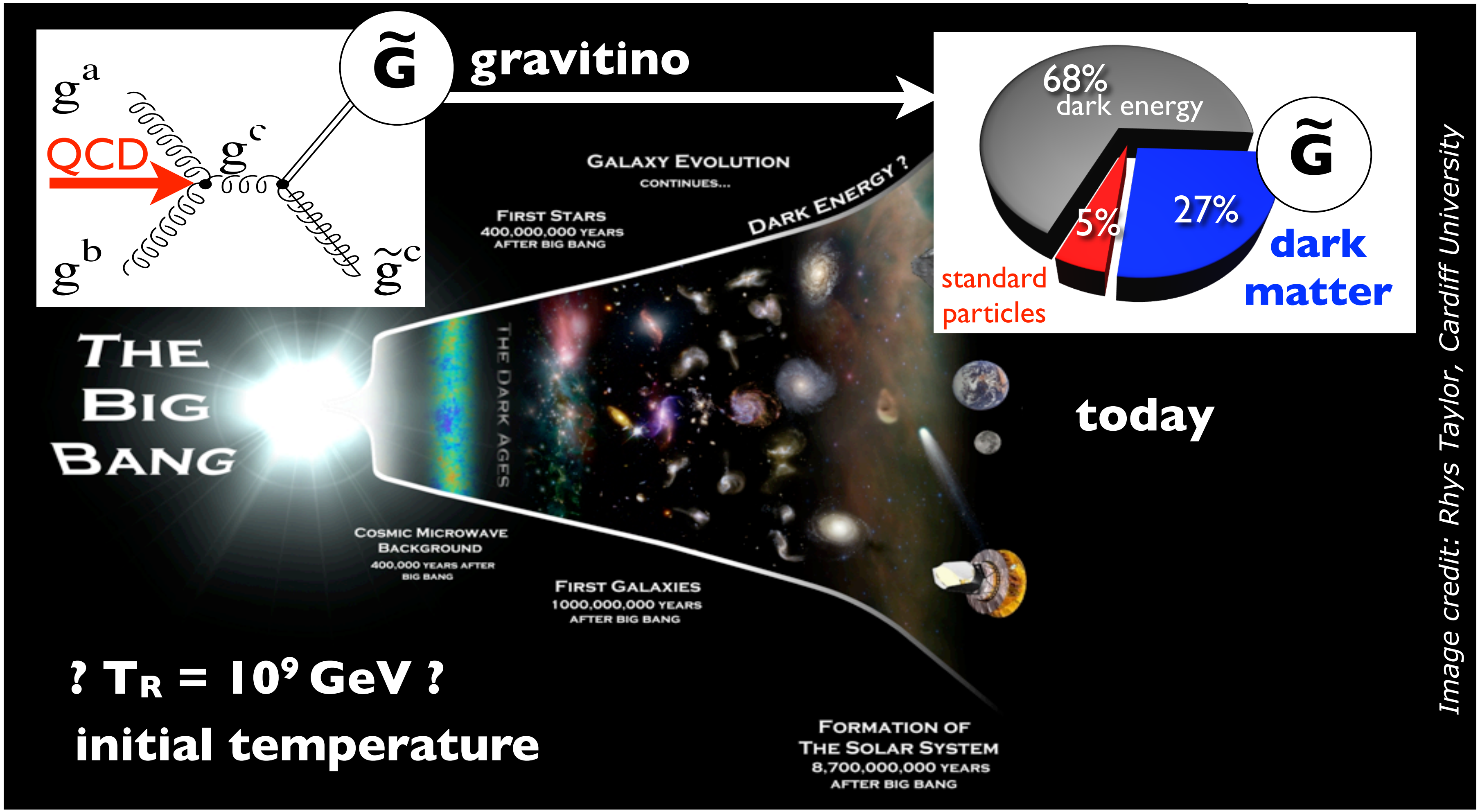
> $T > T_D$: X in thermal eq. with the primordial plasma
>
> $T \sim T_D$: X decouples as a **thermal relic** ($\rightarrow$ B. eq.)

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

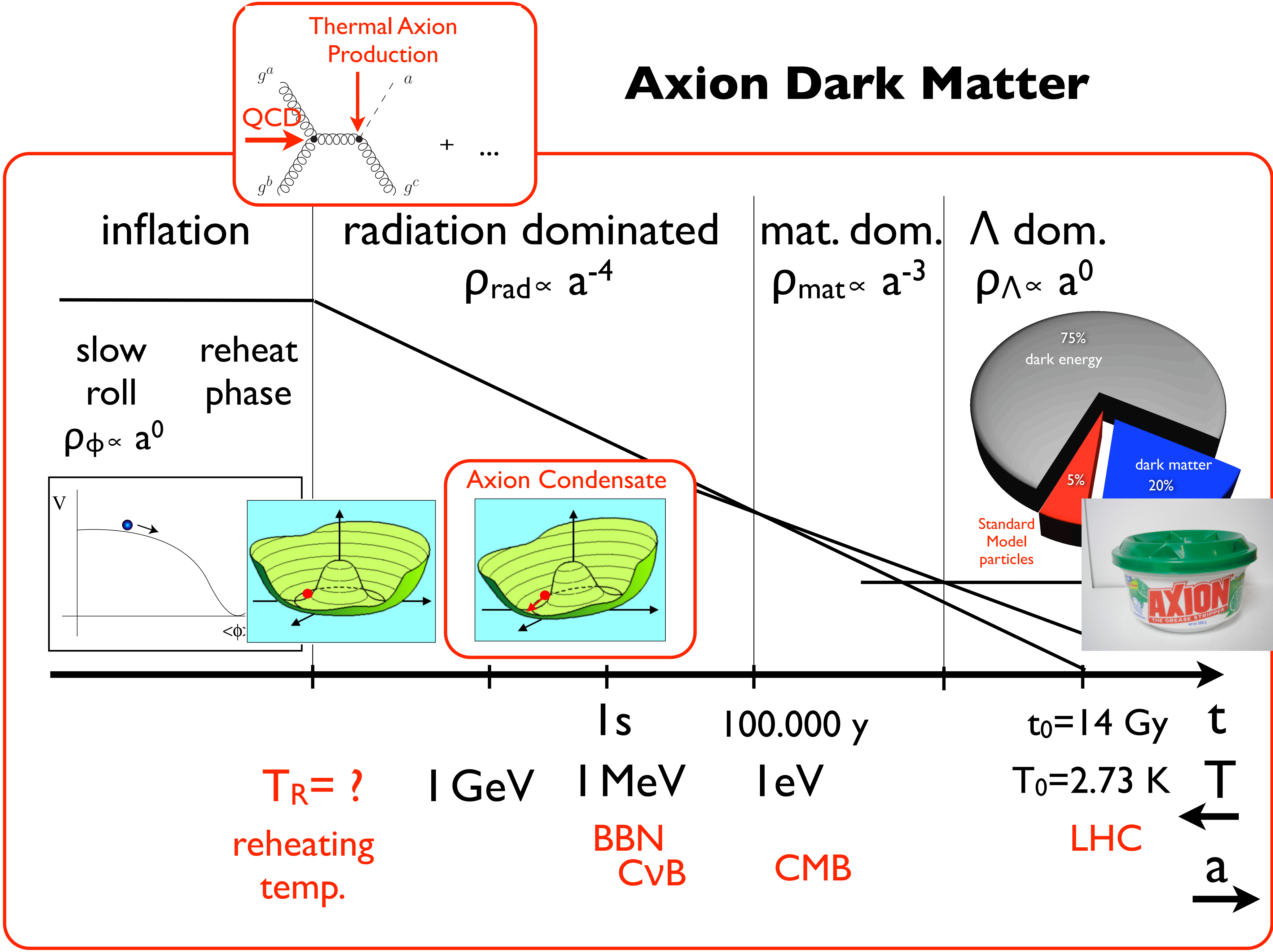
> $T_D >> T$: X is never in th. eq. with the prim. plasma
>
> but **thermally produced** $\longrightarrow$ Boltzmann eq.

↑ **collision term**

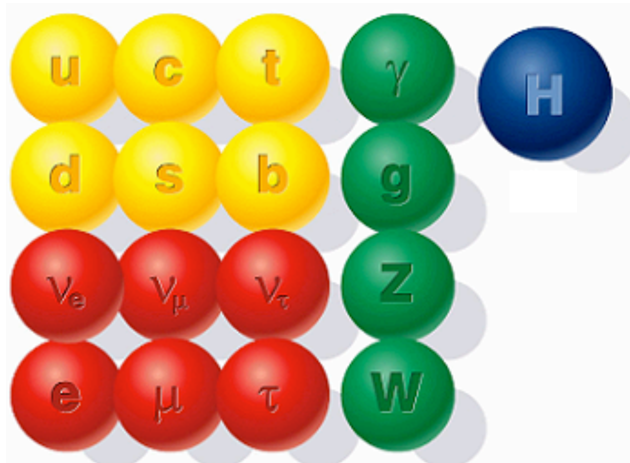
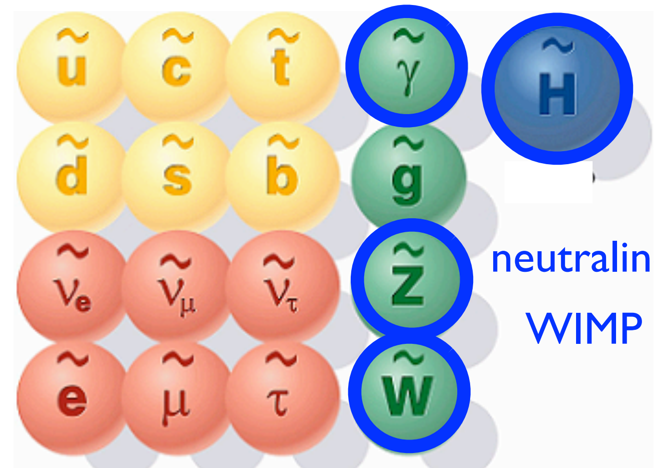
Thermal EWIP DM production in the hot early Universe



Axion Dark Matter

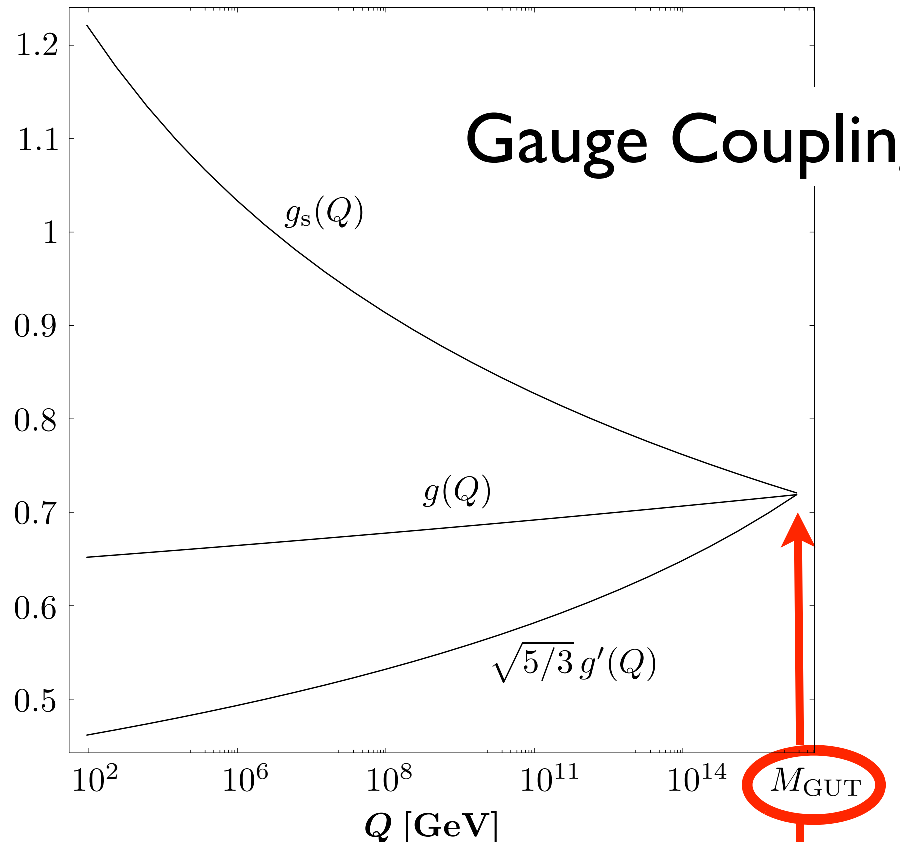


Dark Matter Candidates

interactions	standard particles	superpartners
strong & electroweak	**Standard Model** 	**Supersymmetry**  neutralino WIMP
extremely weak	**Gravity** G graviton	**Supergravity** G̃ gravitino EWIP
	Peccei-Quinn (PQ) Symmetry a axion EWIP	ã axino EWIP

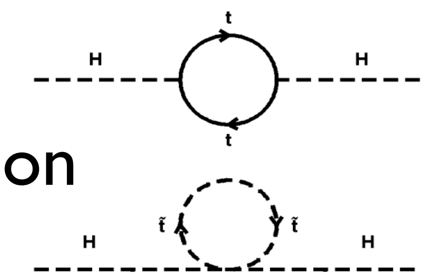
Why Supersymmetry?

Extension of Space-Time Symmetry



Gauge Coupling Unification

Hierarchy Stabilization



(Super-) Gravity

Consistent String Theory

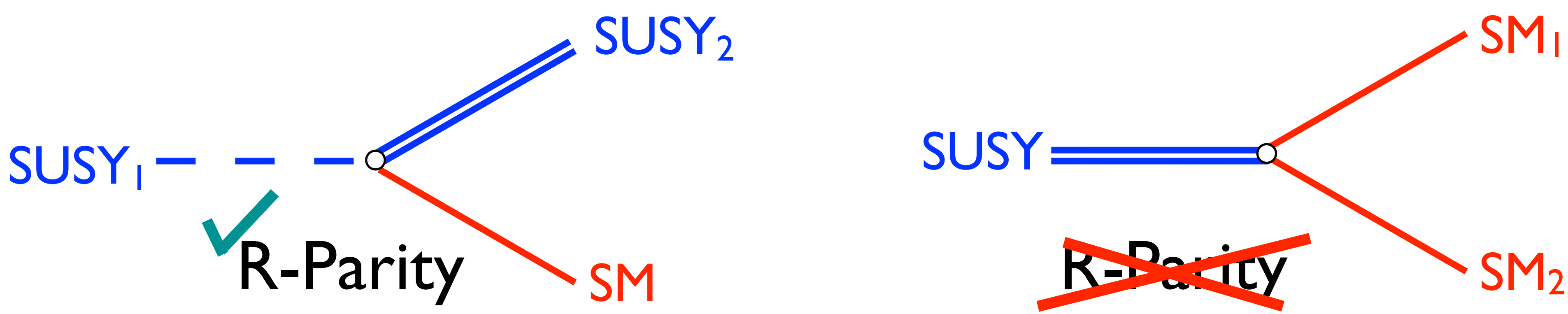
Dark Matter

Gauge Coupling Unification at $M_{GUT} \simeq 2 \times 10^{16}\,\mathrm{GeV}$

R-Parity Conservation

- superpotential: $W_{\mathrm{MSSM}} \leftarrow W_{\Delta L} + W_{\Delta B}$
- non-observation of L & B violating processes (proton stability, ...)
- postulate conservation of R-Parity $\leftarrow$ multiplicative quantum number

$$P_{\mathrm{R}} = (-1)^{3(B-L)+2S} = \begin{cases} +1 & \text{for SM}, H_u, H_d \\ -1 & \text{for } \widetilde{X} \leftarrow \text{superpartners} \end{cases}$$

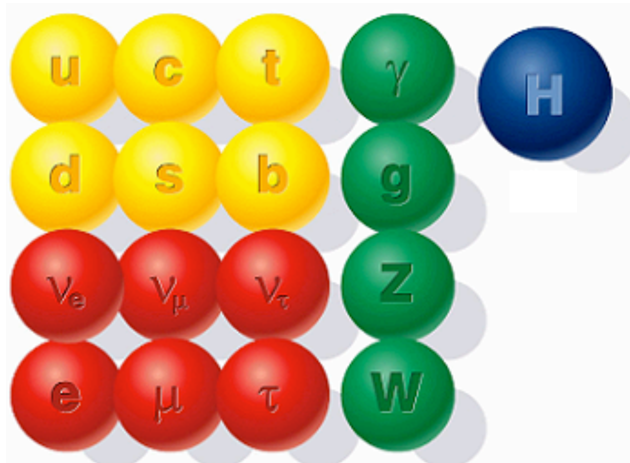


The lightest supersymmetric particle (LSP) is stable!!!

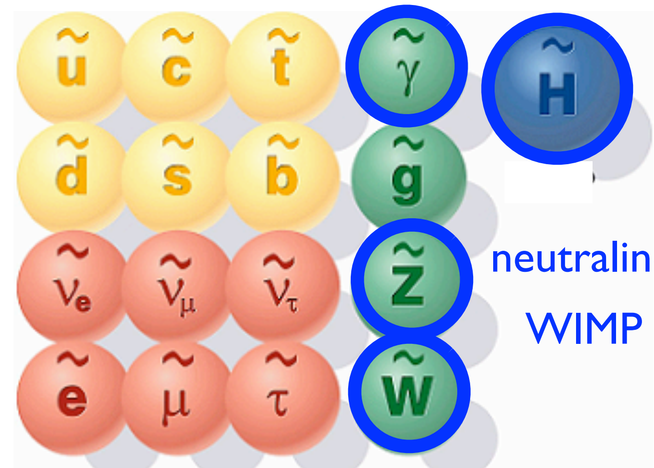
Dark Matter Candidates

interactions	standard particles	superpartners
strong & electroweak	**Standard Model**	**Supersymmetry**

Standard Model



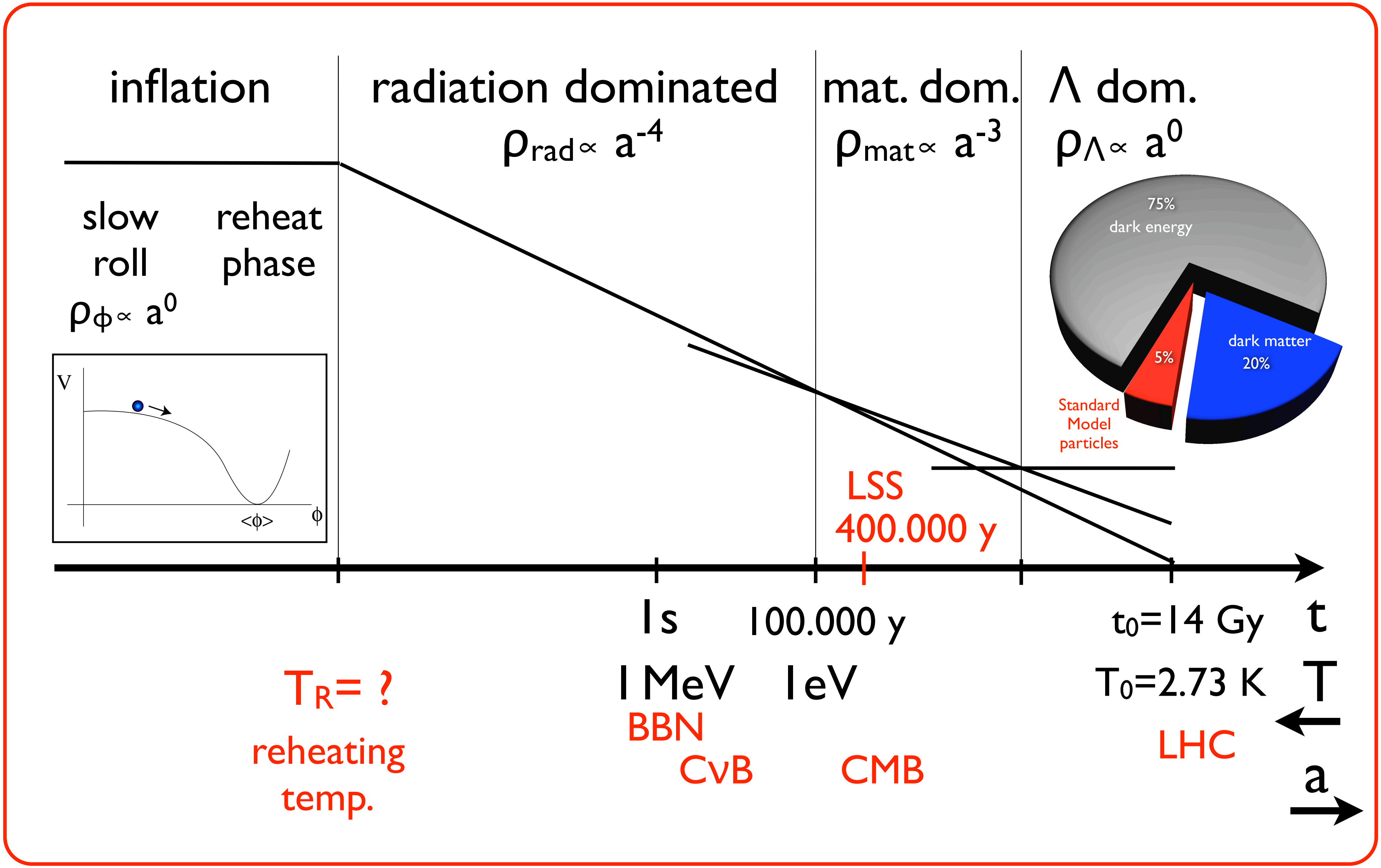
Supersymmetry



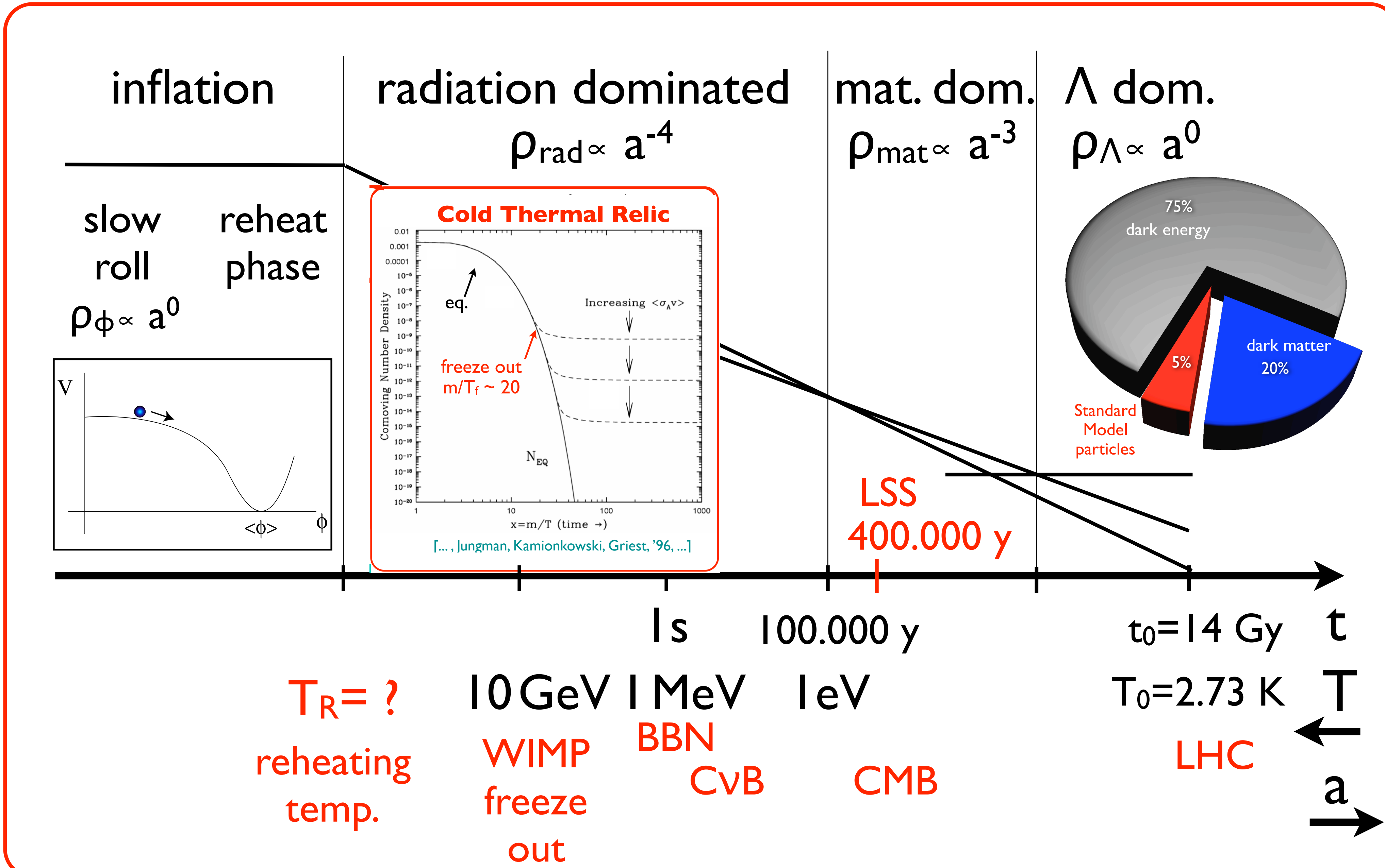
neutralino
WIMP

interactions	standard particles	superpartners
extremely weak	**Gravity** G graviton	**Supergravity** $\tilde{G}$ gravitino EWIP
	Peccei-Quinn (PQ) Symmetry a axion EWIP	$\tilde{a}$ axino EWIP

Standard Thermal History of the Universe

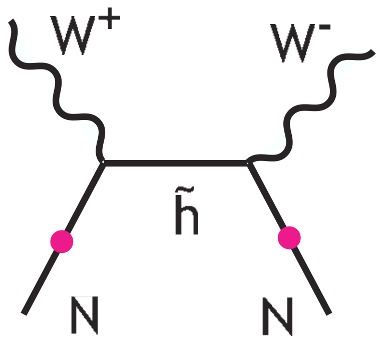


Standard Thermal History of the Universe

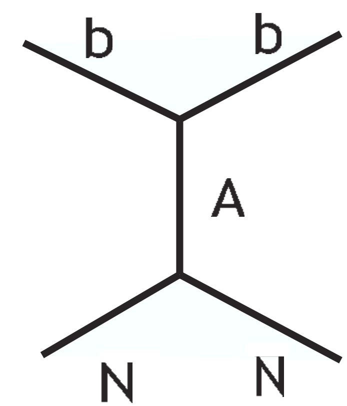


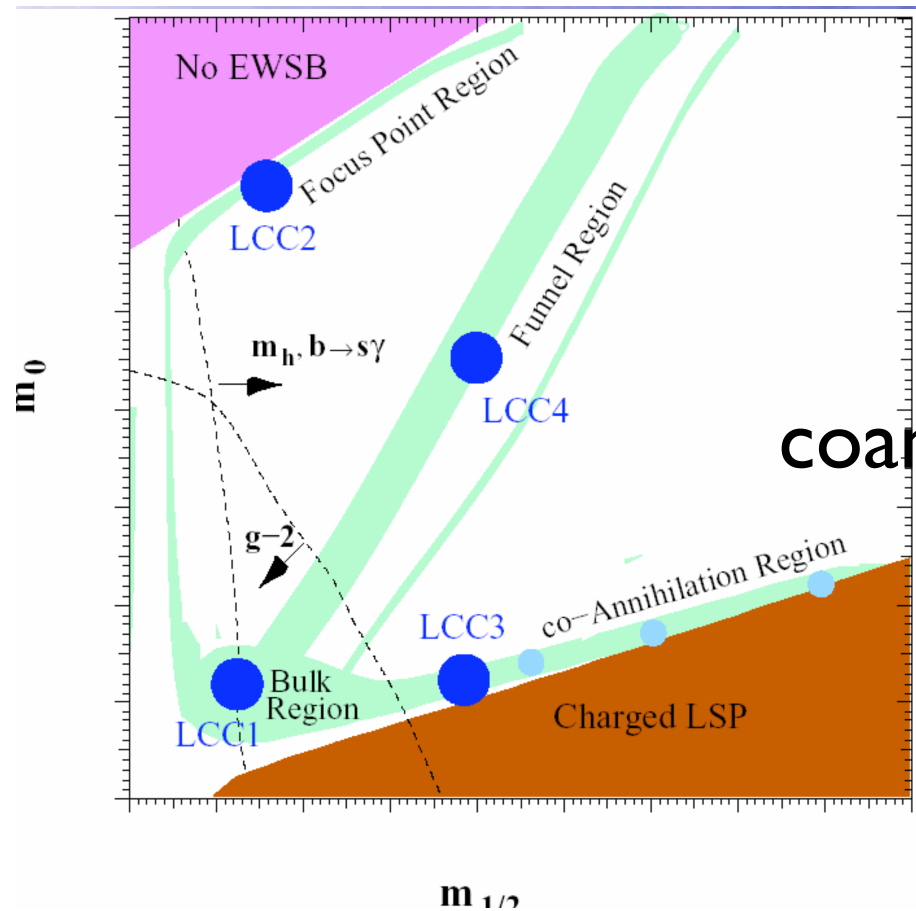
Neutralino LSP Case

focus point region

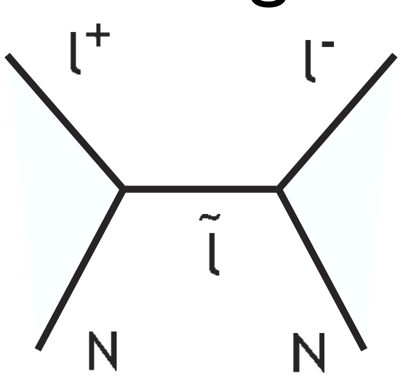


annihilation funnel

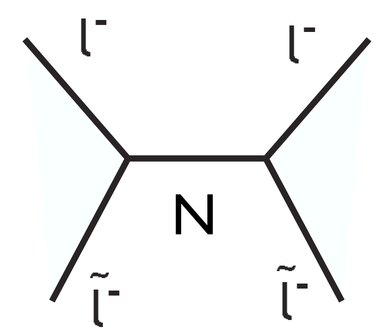




bulk region



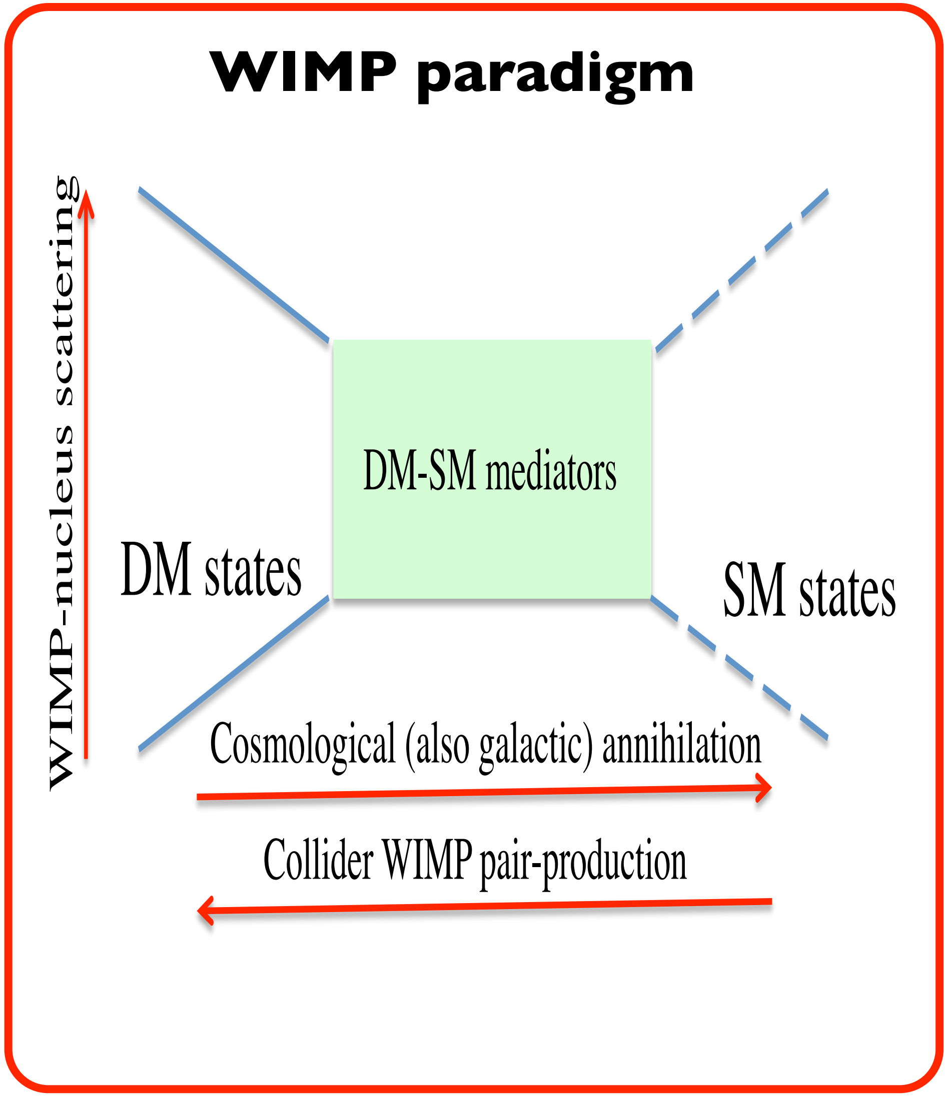
coannihilation region

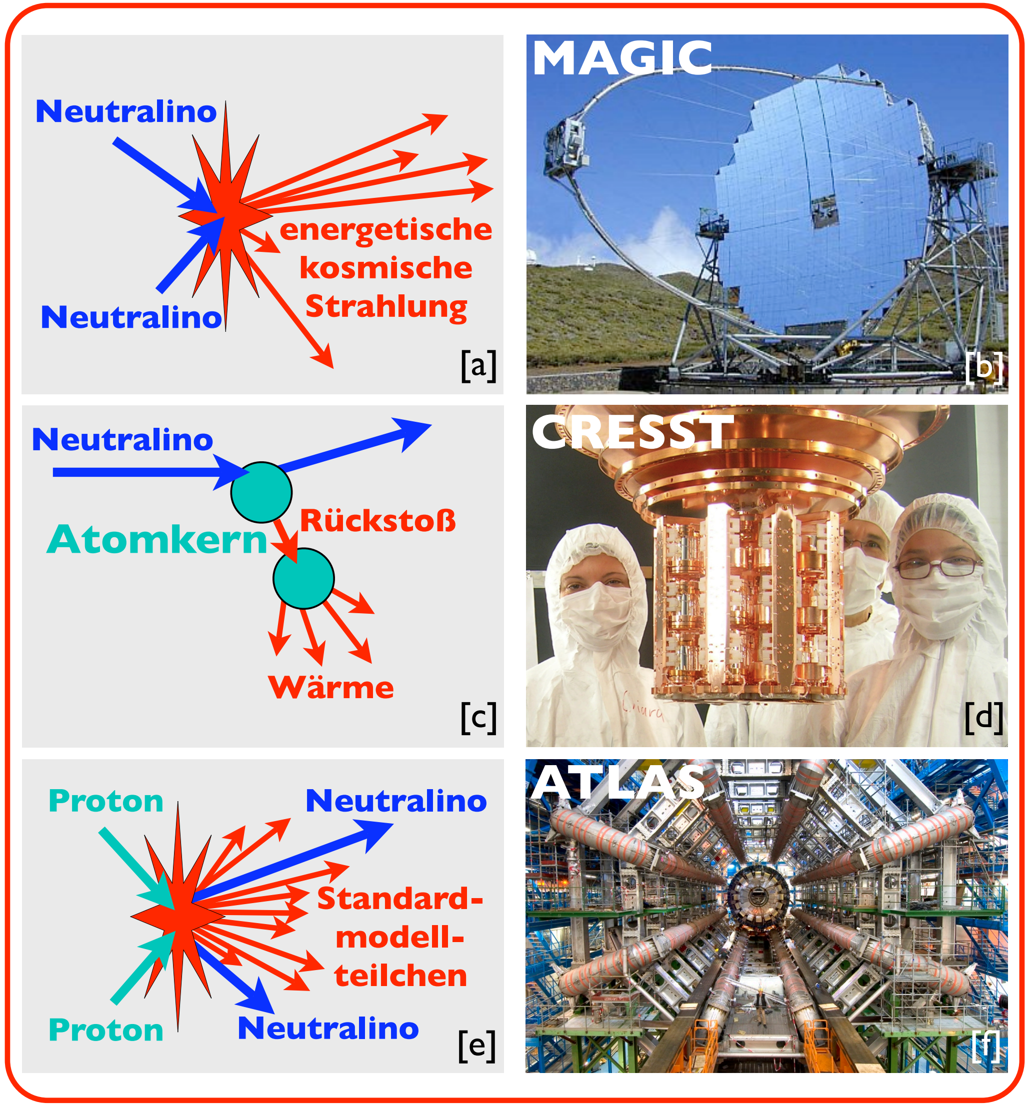


[see Baltz, Battaglia, Peskin, Wizansky, '06]

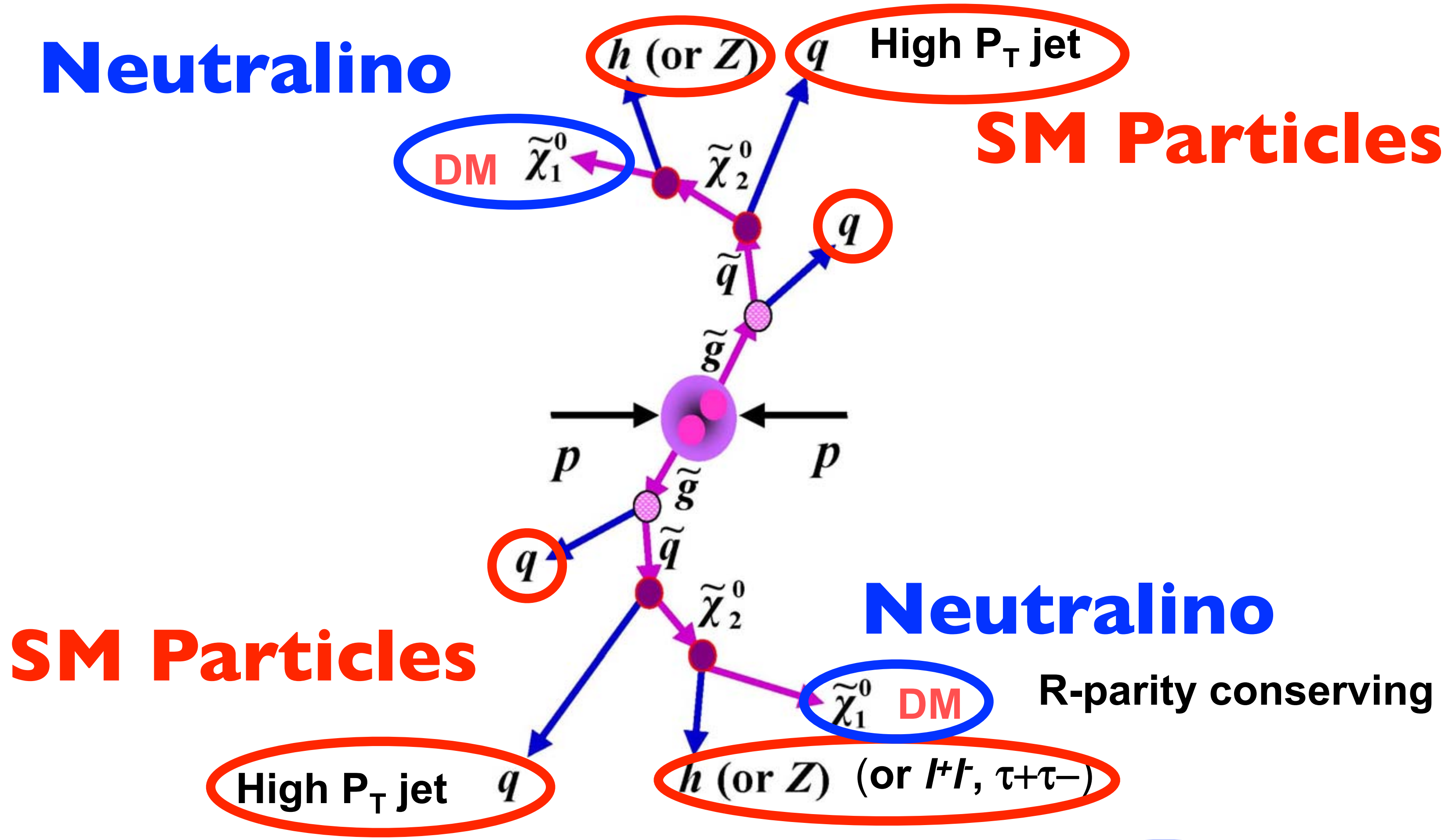
no colored sparticles involved

WIMP paradigm & prospects





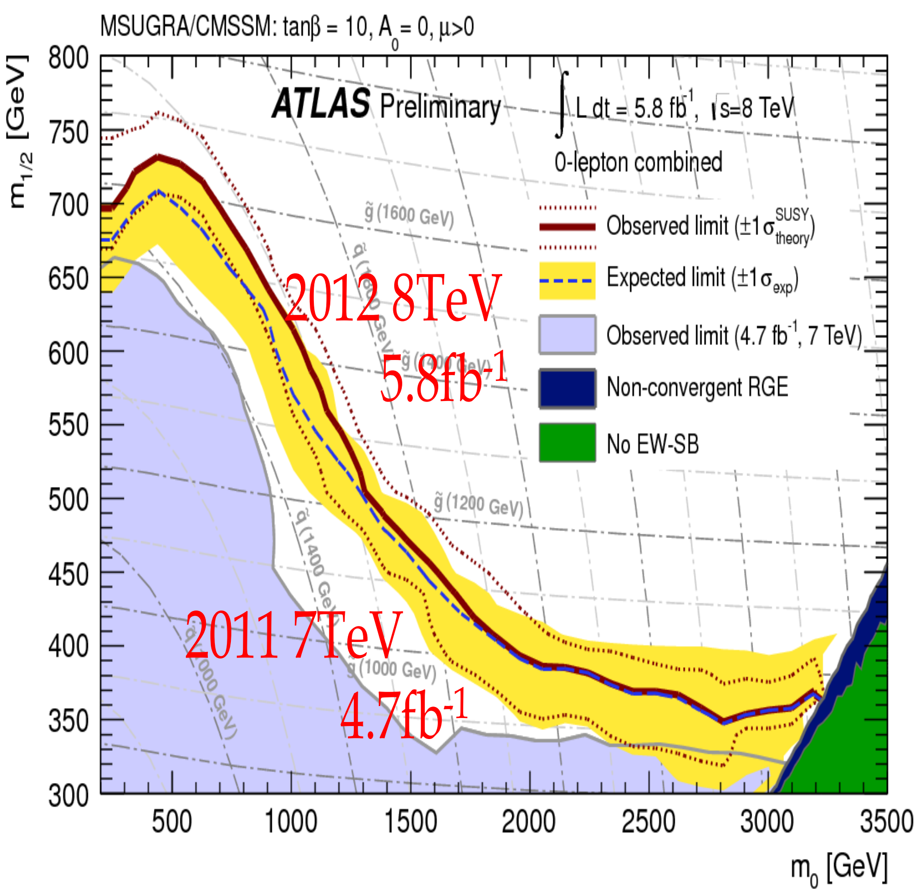
Neutralino DM Production at the LHC

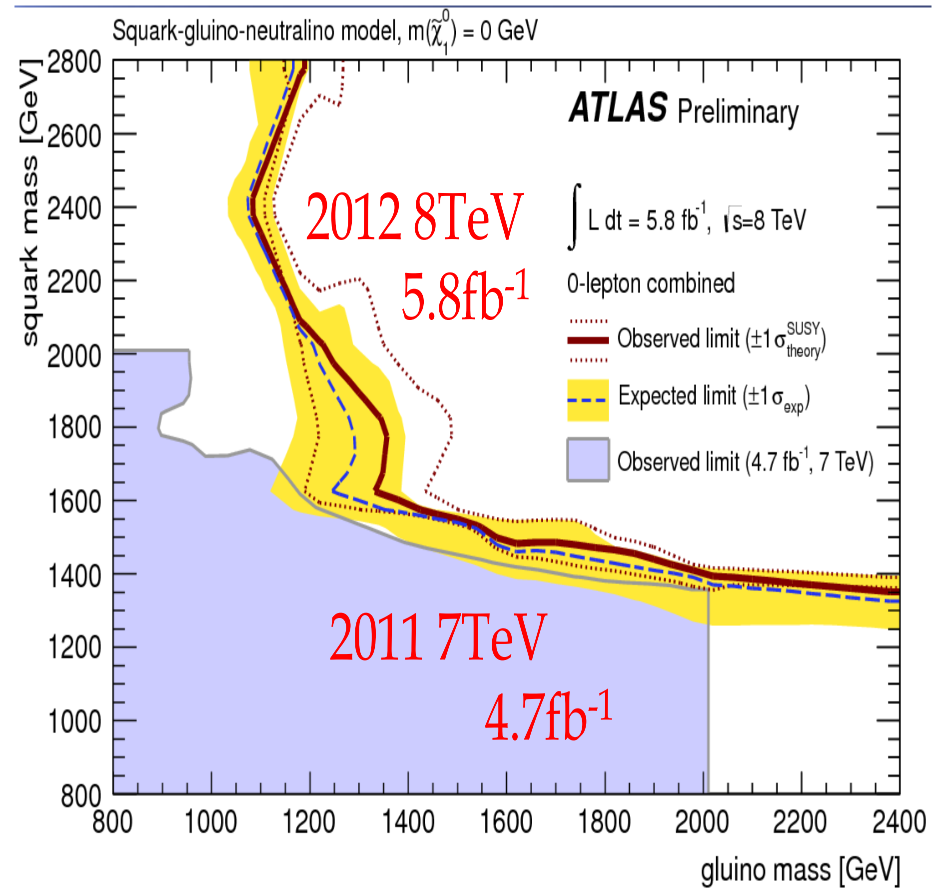


The signal : jets + leptons + missing E_T

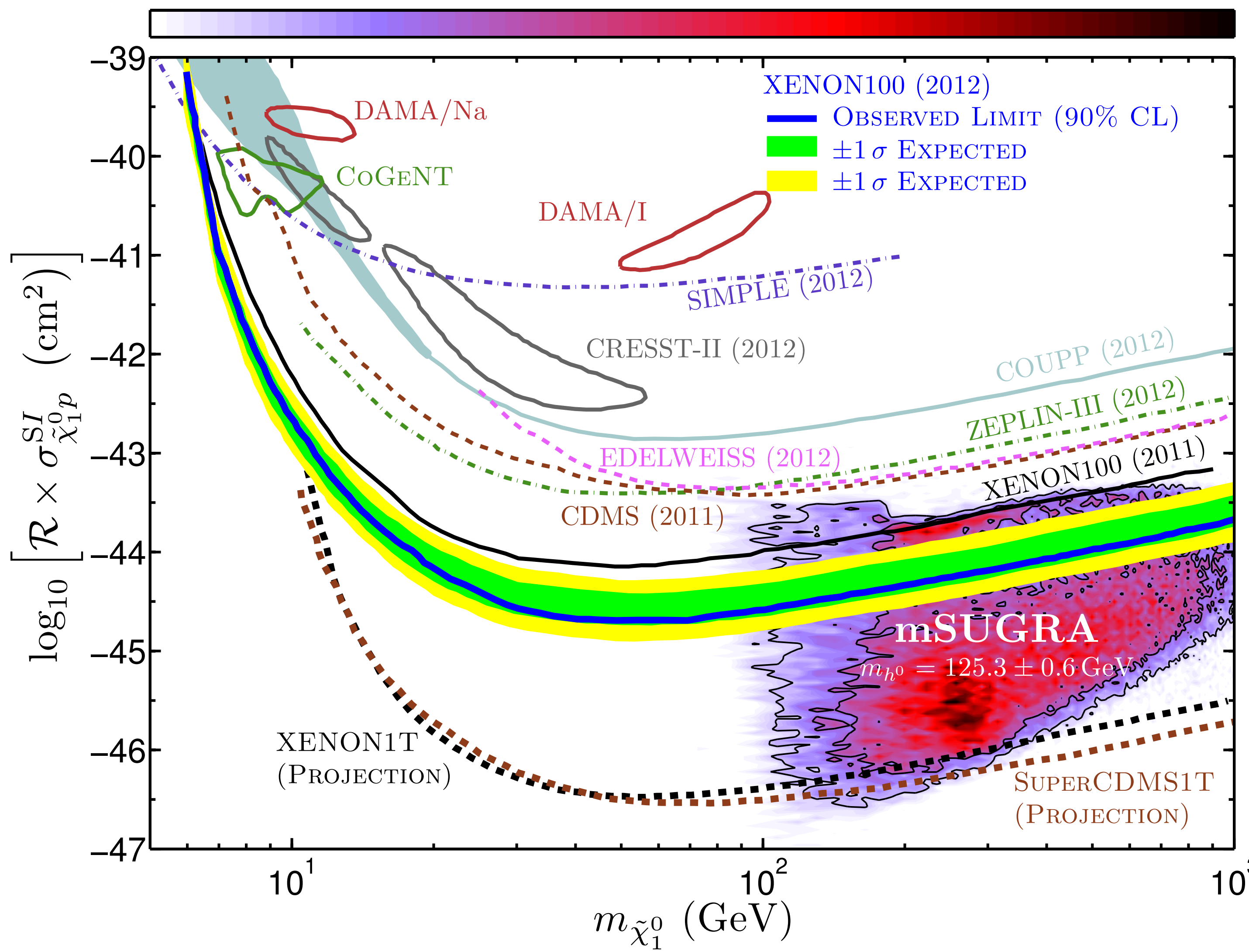
[from B. Dutta's Talk, SUSY 2007]

Collider Dark Matter Searches: Limits Only



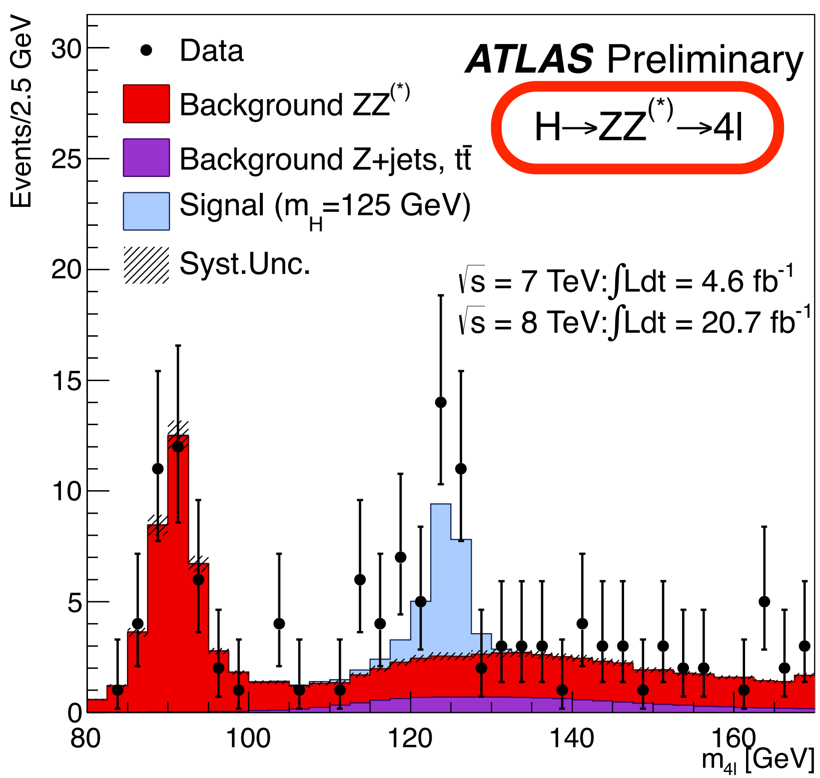


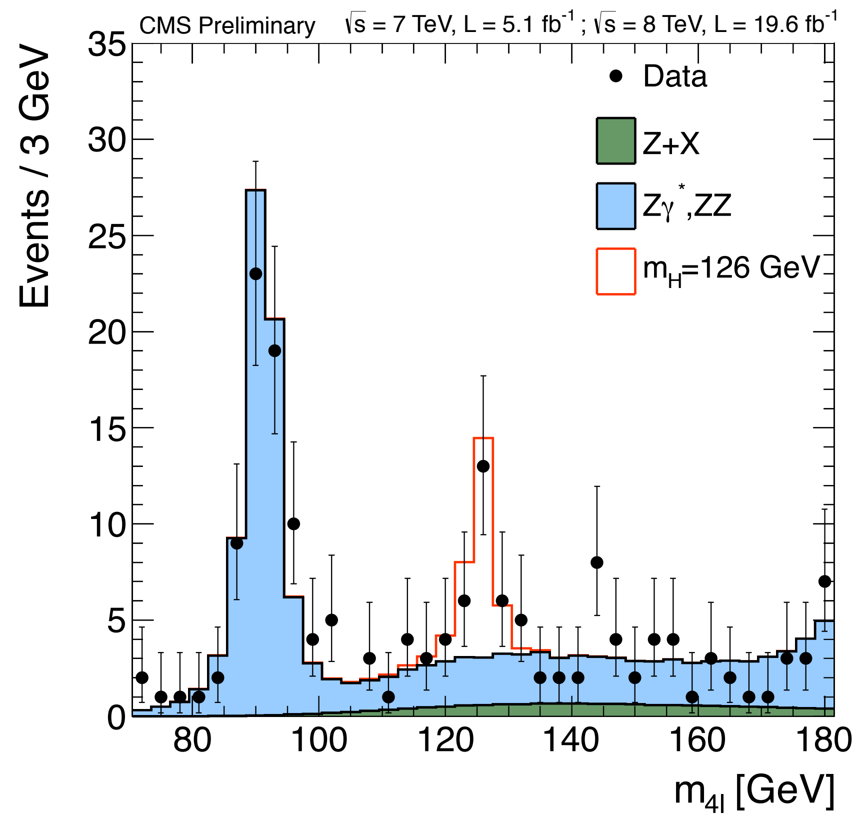
Direct neutralino WIMP dark matter searches



[Akula, Nath, arXiv:1210.0520]

Higgs discovery

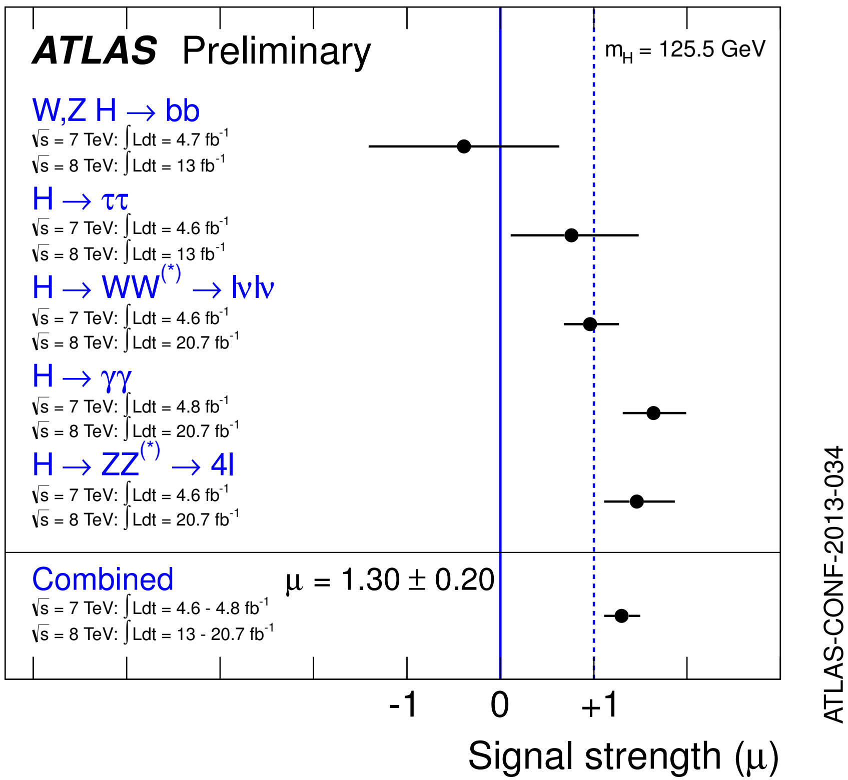




! very impressive !

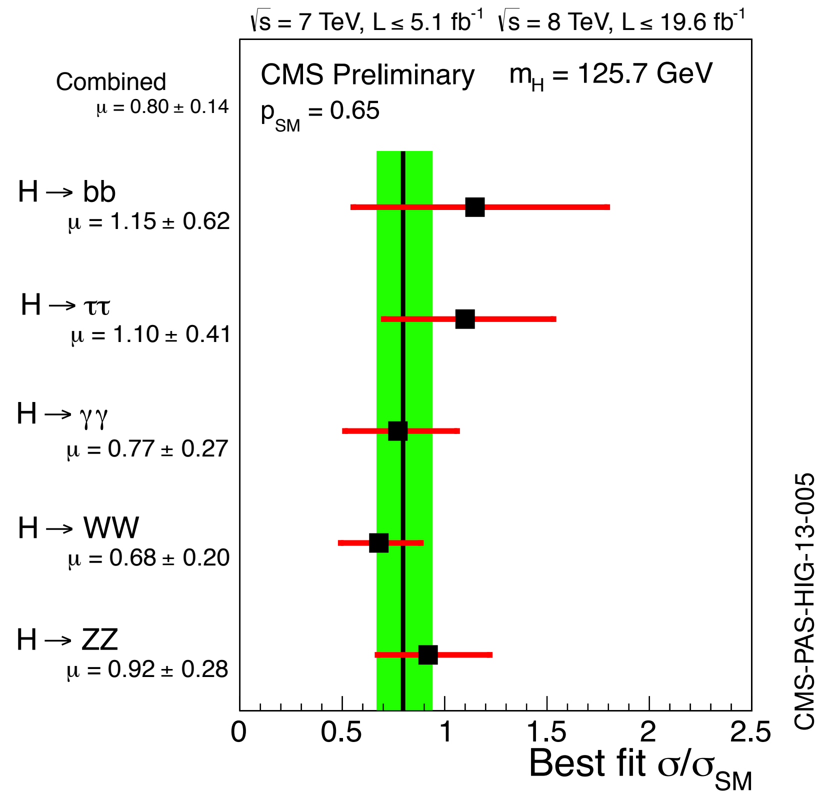
Higgs discovery

ATLAS



note: *bb* and $\tau\tau$ have been updated to full 2012 dataset (recently)

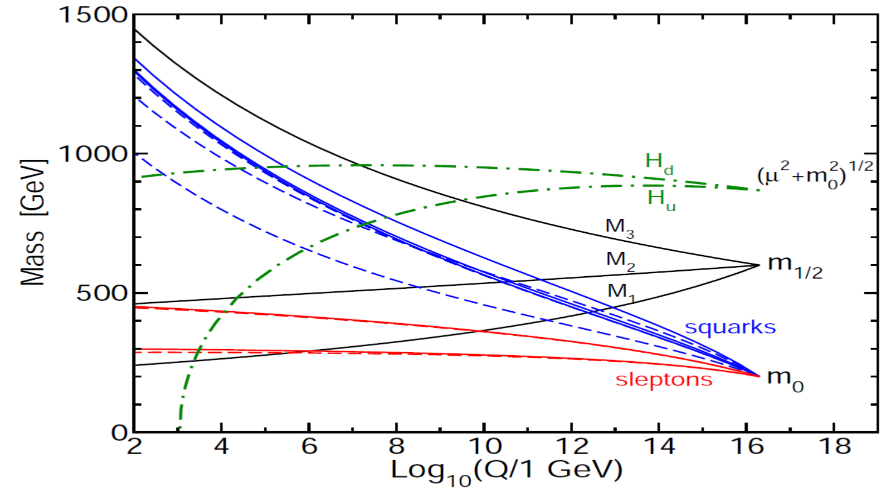
CMS

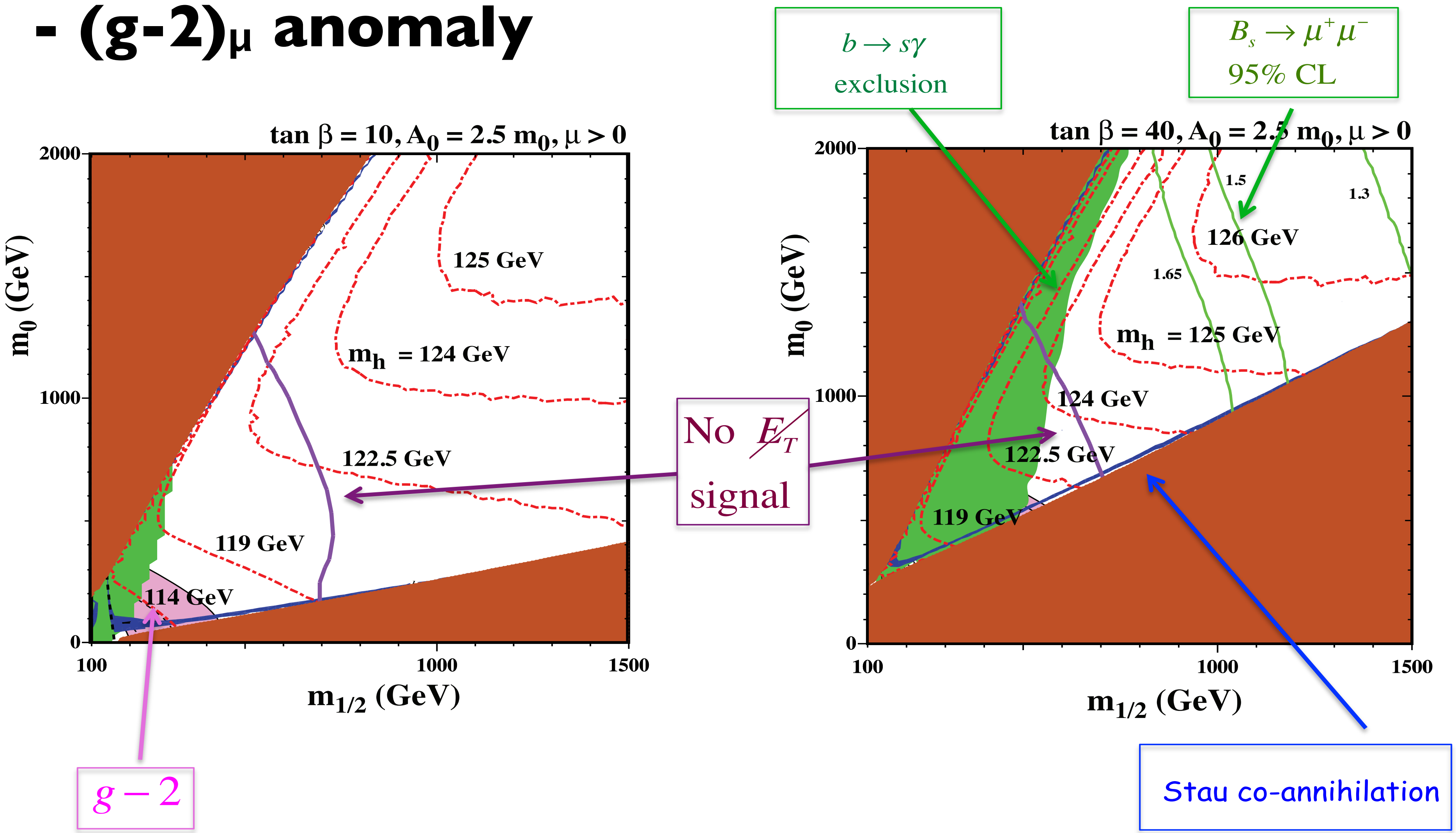


Signal strengths & Standard Model expectations

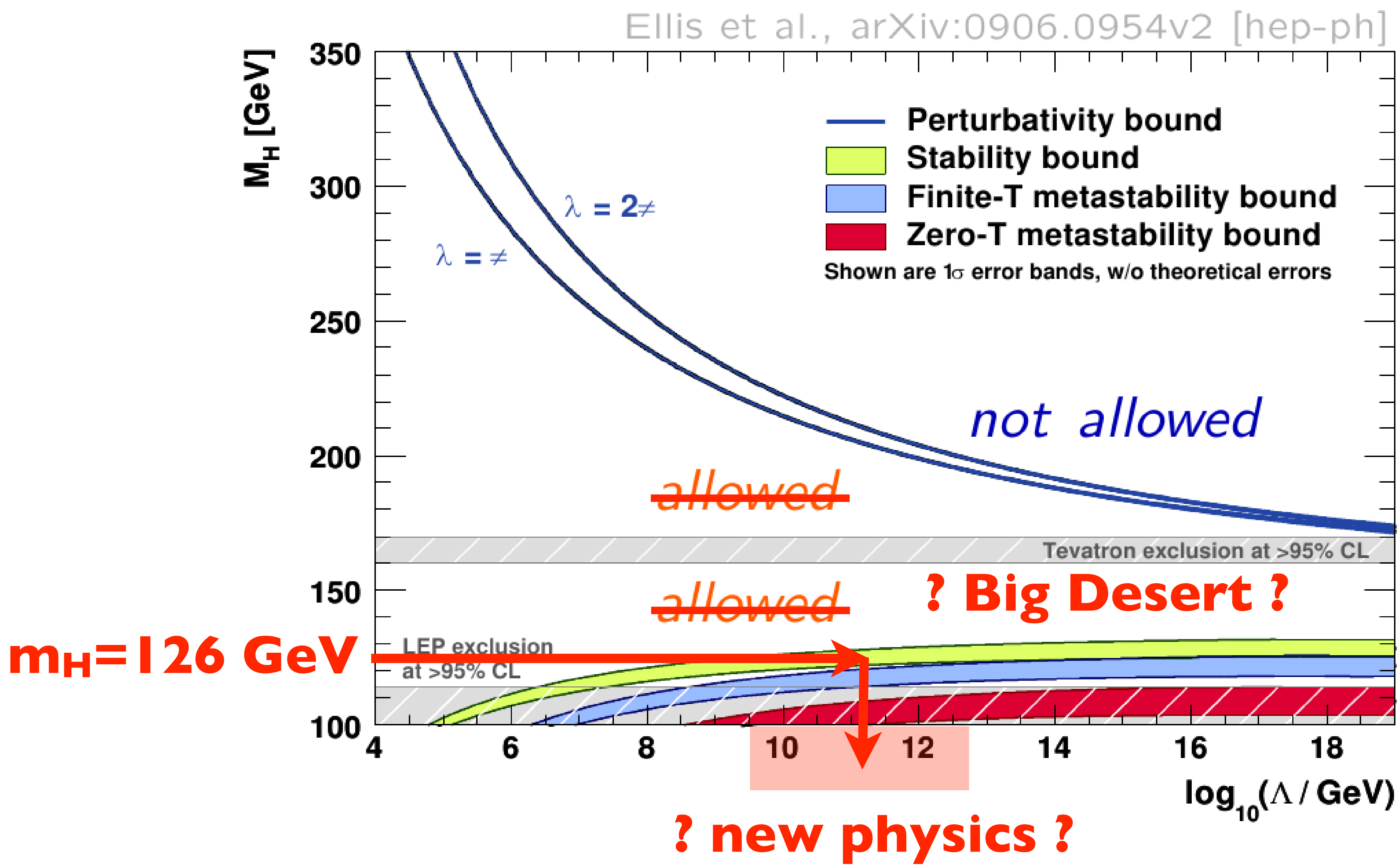
Constrained MSSM

- m_h contours
- sparticle searches
- $(g-2)_\mu$ anomaly

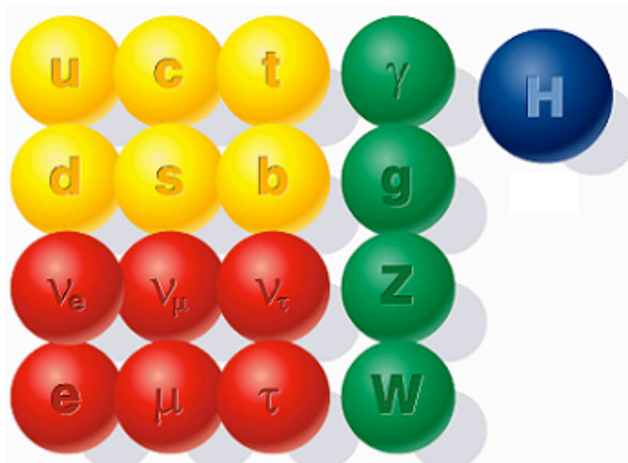
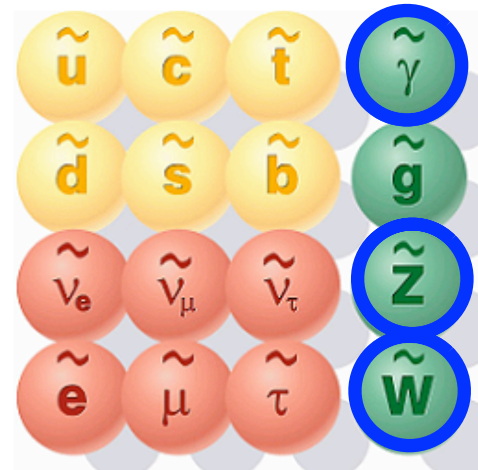




Standard Model after the Higgs discovery



Dark Matter Candidates

interactions	standard particles	superpartners
strong & electroweak $\propto (p/M_W)^n$ $M_W \sim 10^2$ GeV	**Standard Model** 	**Supersymmetry**  neutralino WIMP
extremely weak $\propto (p/M_{Pl})^n$ $M_{Pl} = 2.4 \times 10^{18}$ GeV	**Gravity** G graviton	**Supergravity** $\tilde{G}$ gravitino EWIP
$\propto (p/f_{PQ})^n$ $f_{PQ} > 10^9$ GeV	**Peccei-Quinn (PQ) Symmetry** a axion EWIP	$\tilde{a}$ axino EWIP; σ saxion EWIP

New Class → Extremely Weakly Interacting Particles (EWIPs)

[Cremmer, Ferrara, Girardello, Van Proeyen, '83]

Supergravity (N=1, d=4)

$$
\begin{aligned}
\frac{1}{e}\mathcal{L} \quad = \quad & -\frac{M_{\mathrm{P}}^2}{2}R + g_{ij^*}\mathcal{D}_\mu\phi^i\mathcal{D}^\mu\phi^{*j} - \frac{1}{2}g^2\left[(\mathrm{Re}f)^{-1}\right]^{ab}D_aD_b \\
& + i g_{ij^*}\overline{\chi}^j_L\gamma^\mu\mathcal{D}_\mu\chi^i_L + \varepsilon^{\mu\nu\rho\sigma}\overline{\psi}_{L\mu}\gamma_\nu\mathcal{D}_\rho\psi_{L\sigma} \\
& - \frac{1}{4}\mathrm{Re}f_{ab}F^a_{\mu\nu}F^{b,\mu\nu} + \frac{1}{8}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Im}f_{ab}F^a_{\mu\nu}F^b_{\rho\sigma} \\
& + \frac{i}{2}\mathrm{Re}f_{ab}\overline{\lambda}^a\gamma^\mu\mathcal{D}_\mu\lambda^b - e^{-1}\frac{1}{2}\mathrm{Im}f_{ab}\mathcal{D}_\mu\left[e\overline{\lambda}^a_R\gamma^\mu\lambda^b_R\right] \\
& + \Bigg[-\sqrt{2}g\partial_iD_a\overline{\lambda}^a\chi^i_L + \frac{1}{4}\sqrt{2}g\left[(\mathrm{Re}f)^{-1}\right]^{ab}\partial_if_{bc}D_a\overline{\lambda}^c\chi^i_L \\
& + \frac{i}{16}\sqrt{2}\partial_if_{ab}\overline{\lambda}^a[\gamma^\mu,\gamma^\nu]\chi^i_LF^b_{\mu\nu} - \frac{1}{2M_{\mathrm{P}}}gD_a\overline{\lambda}^a_R\gamma^\mu\psi_\mu \\
& - \frac{i}{2M_{\mathrm{P}}}\sqrt{2}g_{ij^*}\mathcal{D}_\mu\phi^{*j}\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi^i_L + \mathrm{h.c.}\Bigg] \\
& - \frac{i}{8M_{\mathrm{P}}}\mathrm{Re}f_{ab}\overline{\psi}_\mu[\gamma^m,\gamma^n]\gamma^\mu\lambda^aF^a_{mn} \\
& - e^{K/2M_{\mathrm{P}}^2}\Bigg[\frac{1}{4M_{\mathrm{P}}^2}W^*\overline{\psi}_{R\mu}[\gamma^\mu,\gamma^\nu]\psi_{L\nu} + \frac{1}{2M_{\mathrm{P}}}\sqrt{2}D_iW\overline{\psi}_\mu\gamma^\mu\chi^i_L \\
& + \frac{1}{2}\mathcal{D}_iD_jW\overline{\chi^c_L}^i\chi^j_L + \frac{1}{4}g^{ij^*}D_{j^*}W^*\partial_if_{ab}\overline{\lambda}^a_R\lambda^b_L + \mathrm{h.c.}\Bigg] \\
& - e^{K/M_{\mathrm{P}}^2}\left[g^{ij^*}(D_iW)\left(D_{j^*}W^*\right) - 3\frac{|W|^2}{M_{\mathrm{P}}^2}\right] + \mathcal{O}(M_{\mathrm{P}}^{-2})\ .
\end{aligned}
$$

gravitino

gaugino

gauge boson

Planck scale

Supersymmetric Hadronic Axion Model

$$\mathcal{L}_{\mathrm{PQ}}^{\mathrm{int}} = -\frac{\sqrt{2}\alpha_s}{8\pi f_{\mathrm{PQ}}}\int d^2\theta A\, W^b W^b + \mathrm{h.c.}$$

Peccei-Quinn (PQ) scale

saxion axion axino

$$A = (\sigma + ia)/\sqrt{2} + \sqrt{2}\theta\tilde{a} + F_A\theta\theta$$ PQ

gluino gluon

$$W^b = \tilde{g}^b + D^b\theta - \sigma^{\mu\nu}\theta G^b_{\mu\nu} + i\theta\theta\sigma^\mu D_\mu \bar{\tilde{g}}^b$$ field strength

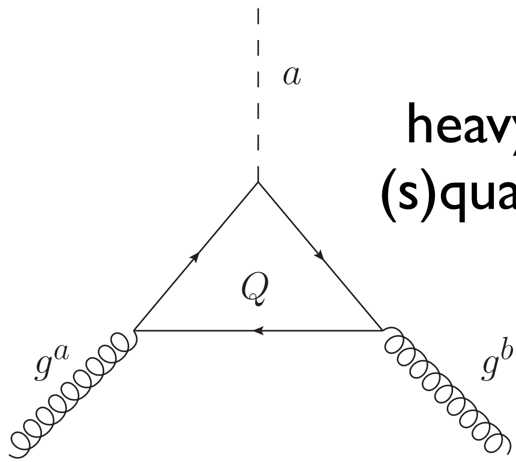
squark

$$D^b = -g_s \sum_{\tilde{q}} \tilde{q}^* t^b \tilde{q} \qquad \alpha_s = g_s^2/4\pi$$

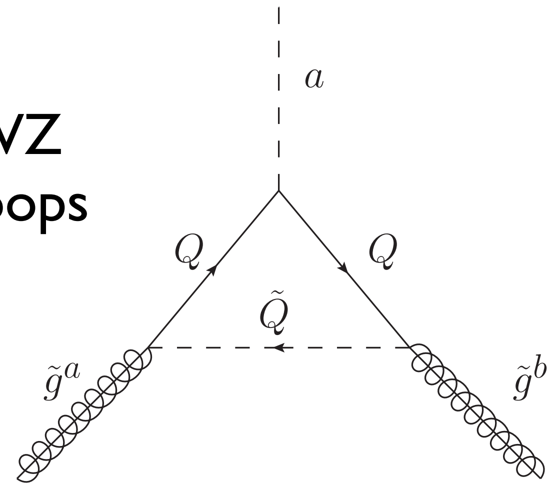
$$\mathcal{L}_{\mathrm{PQ}}^{\mathrm{int}} = \frac{\alpha_s}{8\pi f_{\mathrm{PQ}}}\Big[\sigma\left(G^{b\,\mu\nu}G^b_{\mu\nu} - 2D^bD^b - 2i\bar{\tilde{g}}^b_M\gamma^\mu D_\mu\tilde{g}^b_M\right) + a\left(G^{b\,\mu\nu}\widetilde{G}^b_{\mu\nu} + 2\bar{\tilde{g}}^b_M\gamma^\mu\gamma^5 D_\mu\tilde{g}^b_M\right) - i\bar{\tilde{a}}_M\frac{[\gamma^\mu,\gamma^\nu]}{2}\gamma^5\tilde{g}^b_M G^b_{\mu\nu} + 2\bar{\tilde{a}}_M D^b\tilde{g}^b_M\Big]$$

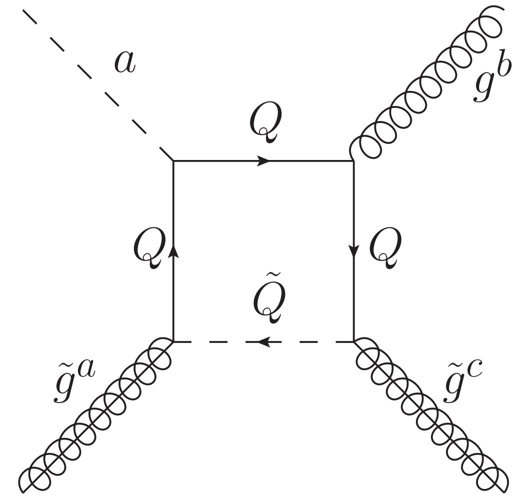
[..., Graf, Steffen, JCAP, 2013]

Supersymmetric Hadronic (KSVZ) Axion Model



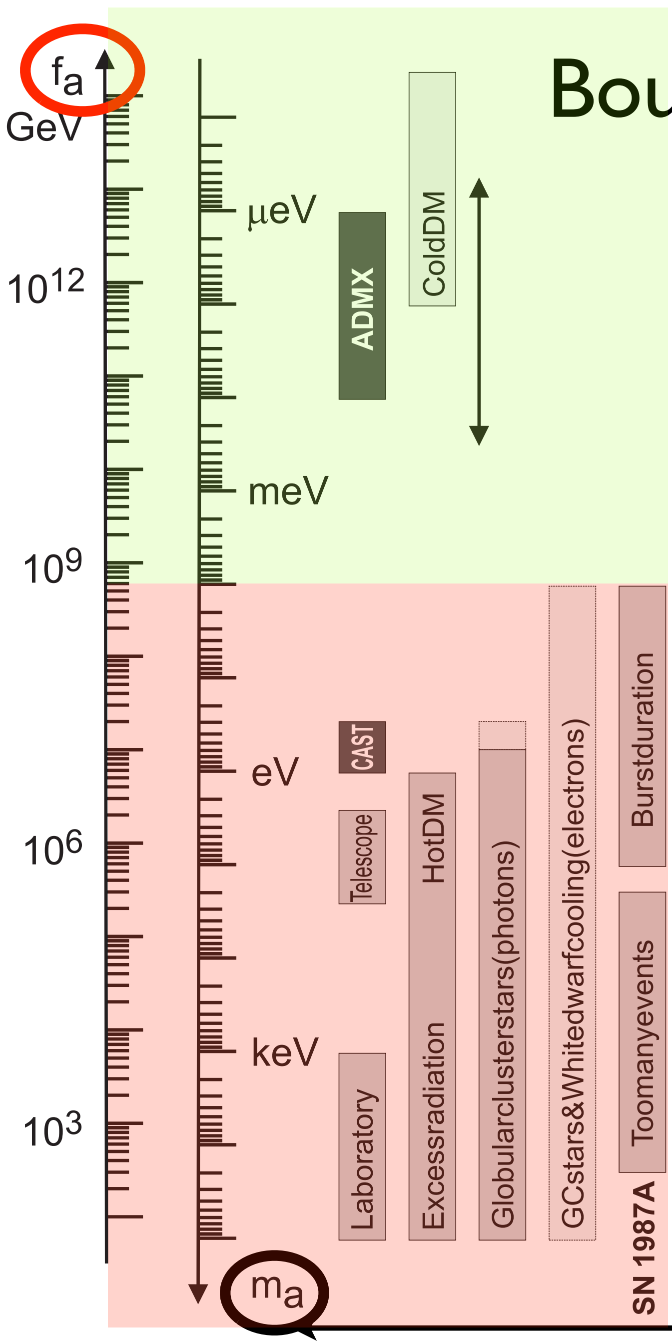
heavy KSVZ
(s)quark loops





KSVZ [Kim ’79; Shifman, Vainshtein, Zakharov ’80]

Constraints on the Peccei-Quinn (PQ) scale f_{PQ}



Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

Peccei-Quinn Scale

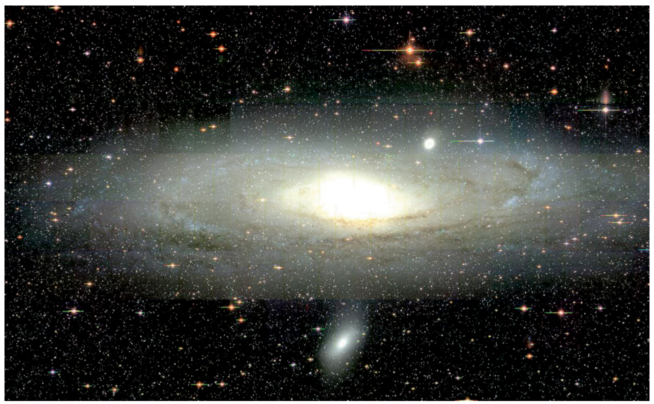
$$f_a \gtrsim 6 \times 10^8\,\mathrm{GeV}$$

Axion Mass

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

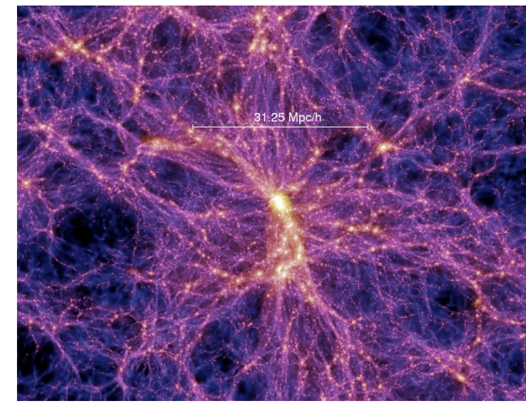
Extremely Weakly Interacting Particles (EWIPs)

well-motivated candidates for **dark matter**

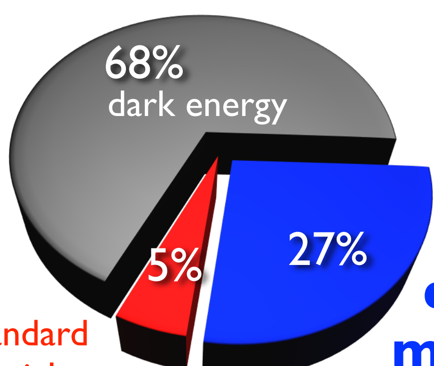


galaxies - rotation velocities

galaxy clusters - gravitational lensing



large scale structure



standard particles

dark matter

Origin

???

←→

EWIPs

$\tilde{G}$ gravitino

a axion

$\tilde{a}$ axino

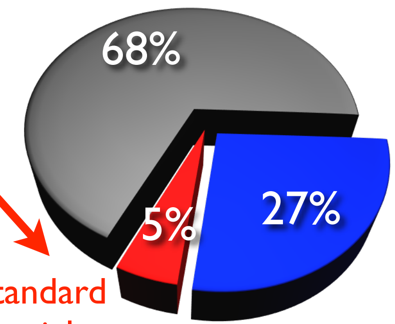
New Physics

High Reheating Temperature Scenarios

Thermal Leptogenesis

requires $\mathbf{T_R > 10^9}$ **GeV**

→ baryon asymmetry



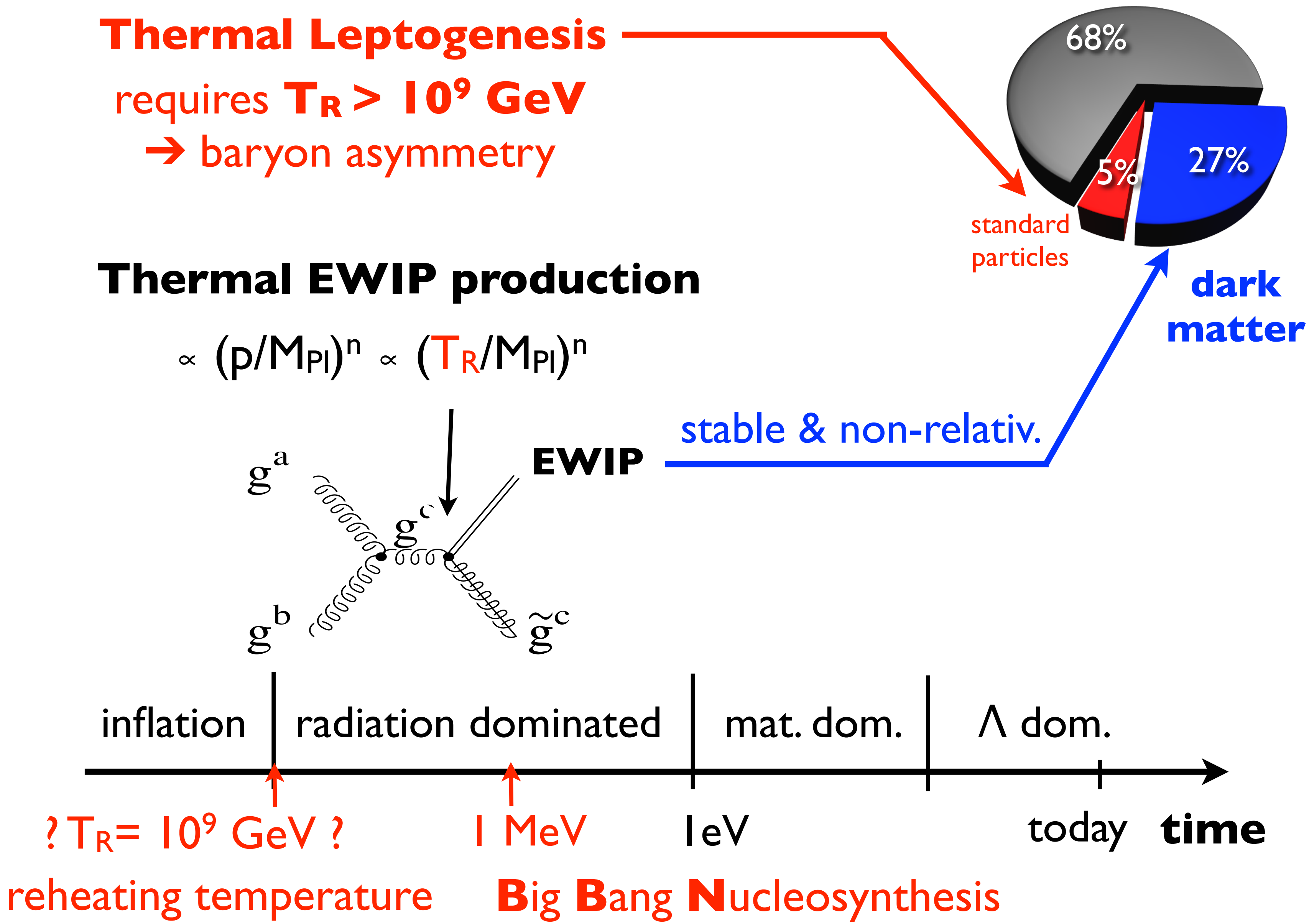
standard particles

inflation | radiation dominated | mat. dom. | Λ dom.

? $T_R = 10^9$ GeV ?   1 MeV   1 eV   today   **time**

reheating temperature   **B**ig **B**ang **N**ucleosynthesis

High Reheating Temperature Scenarios



Cosmic Relic Abundances

reheating temp. ↓   decoupling temp. of X ↙

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

> $T > T_D$: 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.

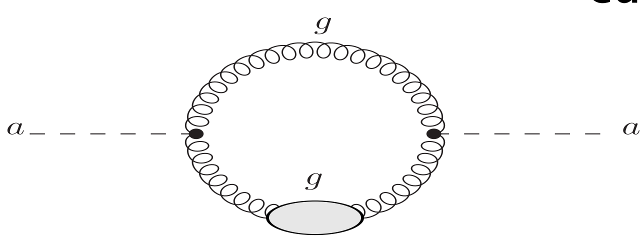
↑ **collision term**

Calculation of the Collsion Term

[cf. Braaten, Yuan, '91]

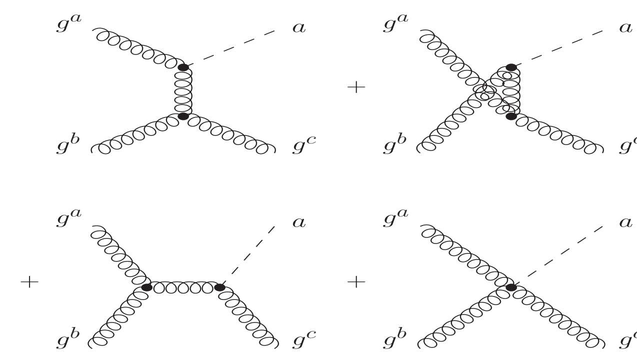
- Thermal Production Rate of X

- Soft Part: k < k_{cut}

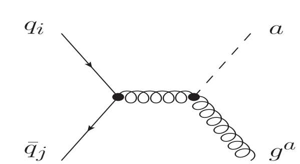


- Hard Part: k > k_{cut}

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



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



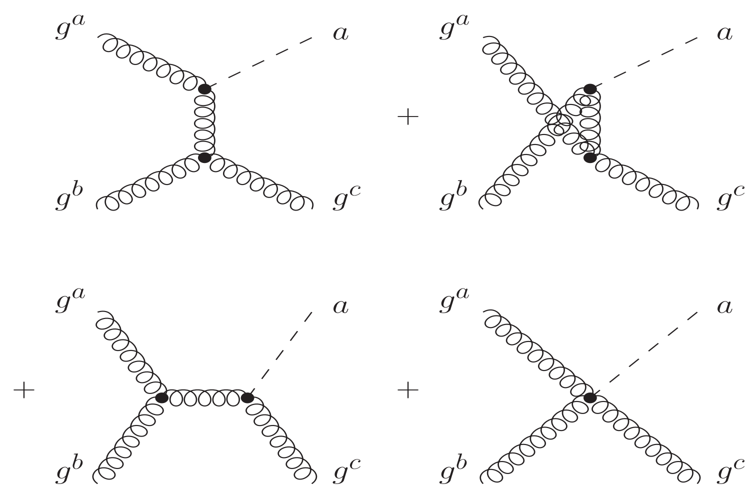
Process C: $q_i + g^a \to q_j + a$ (crossing of B)

- Hard Thermal Loop (HTL) Resummation

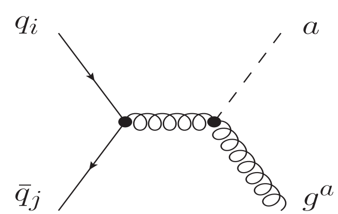
[Graf, FDS, 1008.4528]

Thermal Axion Production in the Hot QGP

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



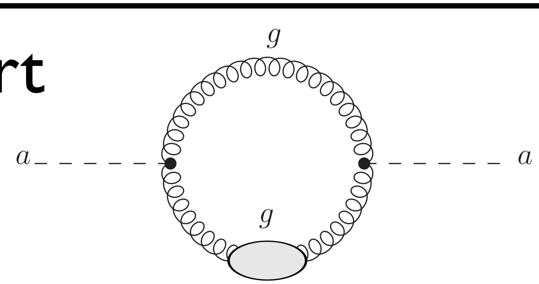
Process B: $q_i + \bar{q}_j \to g^a + a$



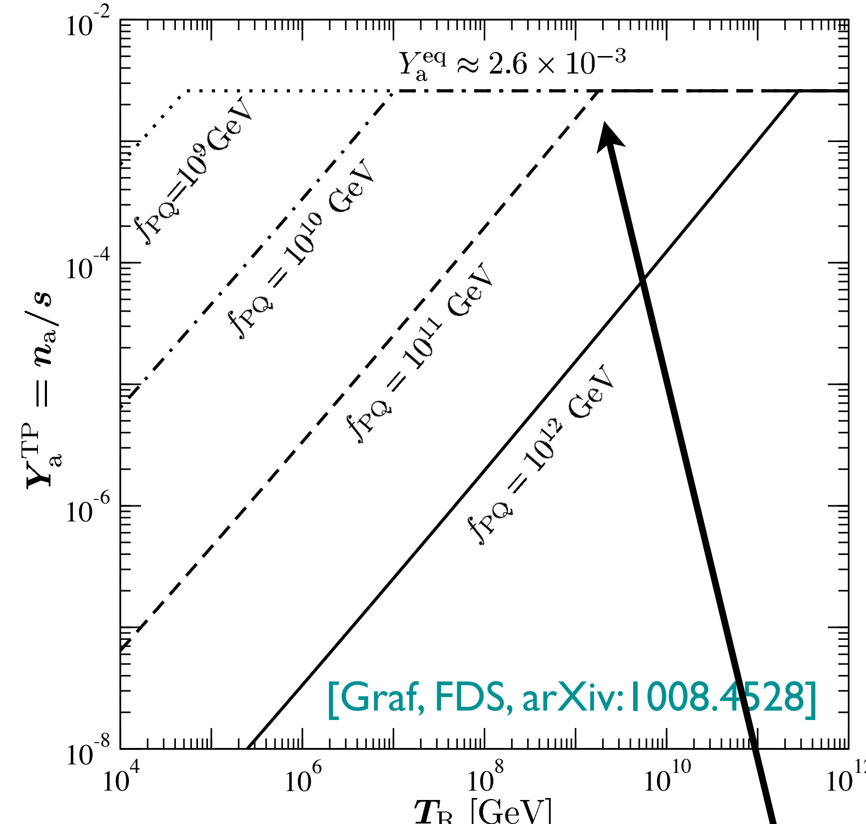
Process C: $q_i + g^a \to q_j + a$ (crossing of B)

Hard Part

Soft Part



Axion Yield

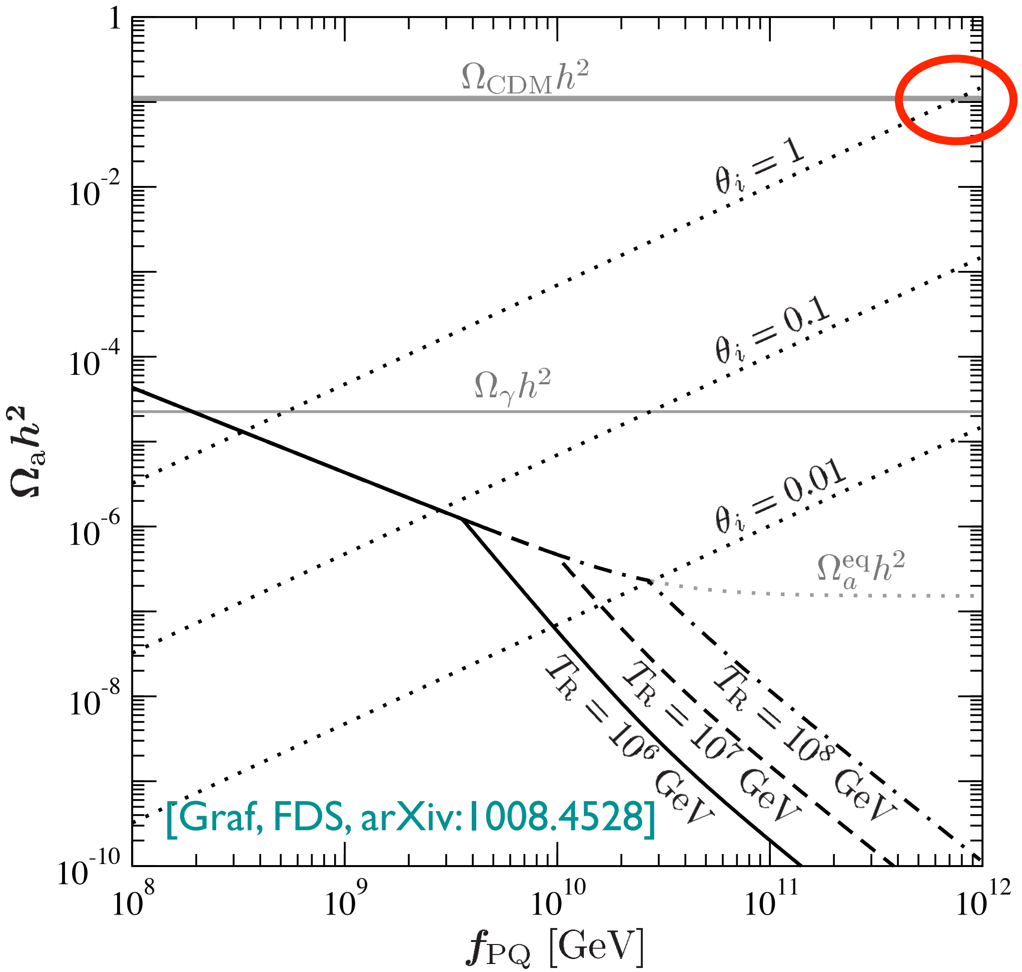


Axion Decoupling Temperature

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

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

Axion Dark Matter



Axion Condensate: CDM

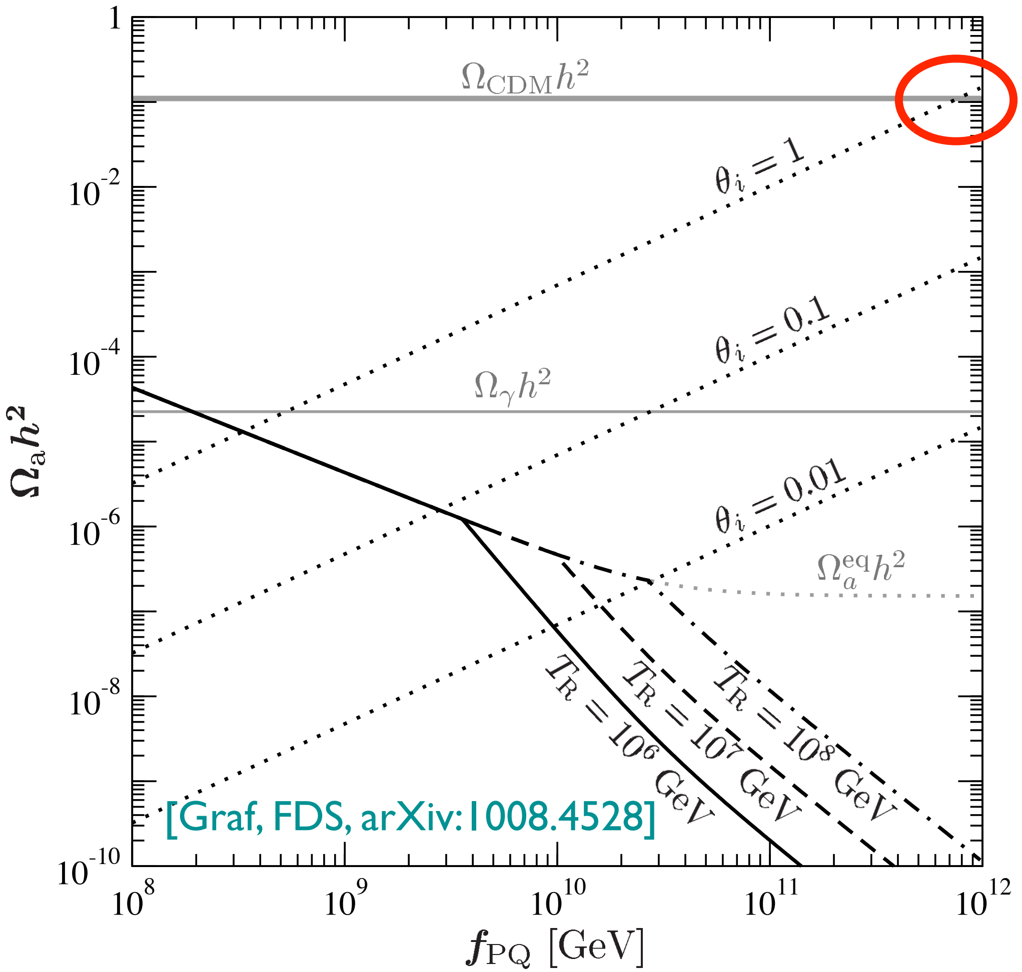
$$\Omega_a^{\rm MIS} h^2 \sim 0.15\, \theta_i^2 (f_{\rm PQ}/10^{12}\,{\rm GeV})^{7/6}$$

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

Axion Mass

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

Axion Dark Matter



Axion Condensate: CDM

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

Thermal Axions: WDM/HDM

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

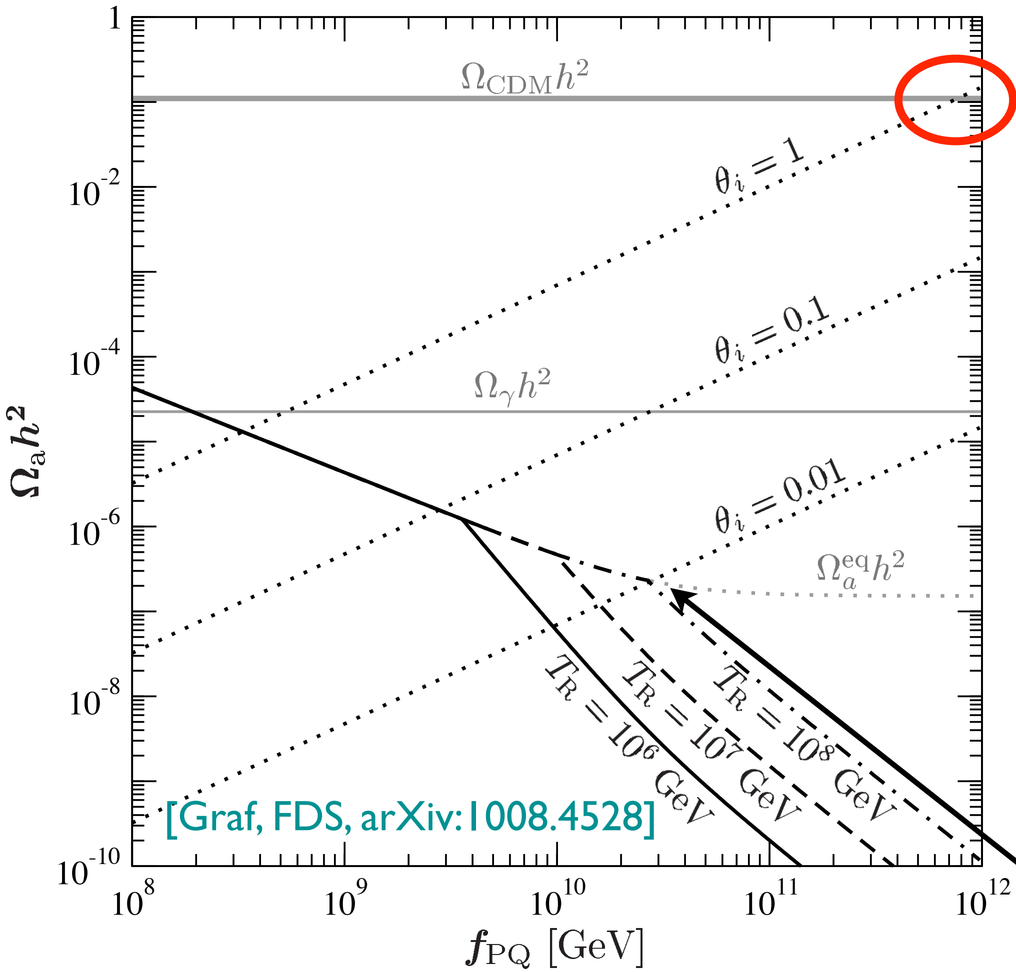
$$18.6 g_s^6 \ln\left(\frac{1.501}{g_s}\right)\left(\frac{10^{10}\,{\rm GeV}}{f_{\rm PQ}}\right)^2\left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right)$$

[Graf, FDS, arXiv:1008.4528]

Axion Mass

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

Axion Dark Matter



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[Graf, FDS, arXiv:1008.4528]

Axion Decoupling Temperature

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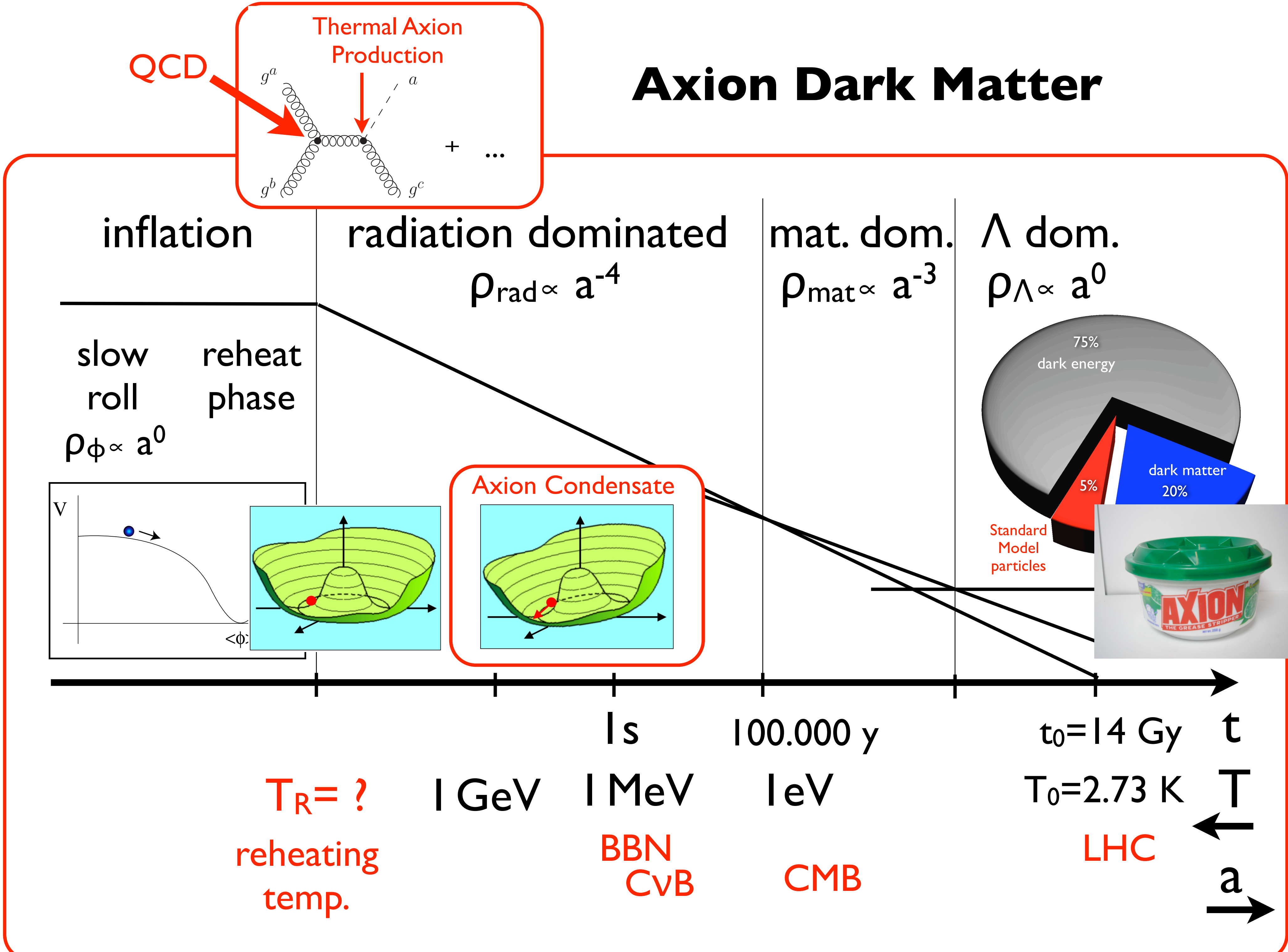
[Masso et al., '02; Sikivie, '08; Graf, FDS, '10]

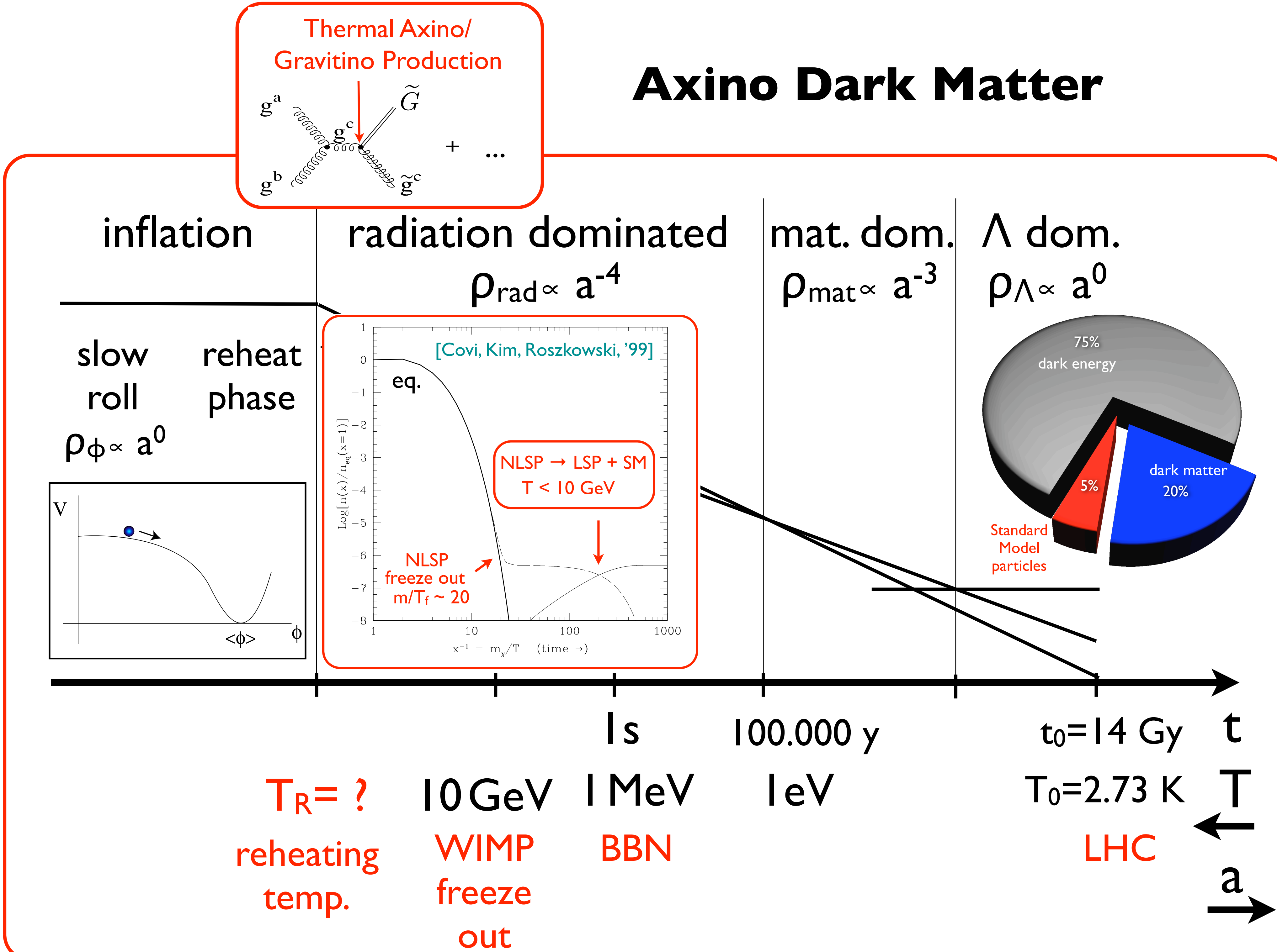
Axion Mass

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

Axion Dark Matter

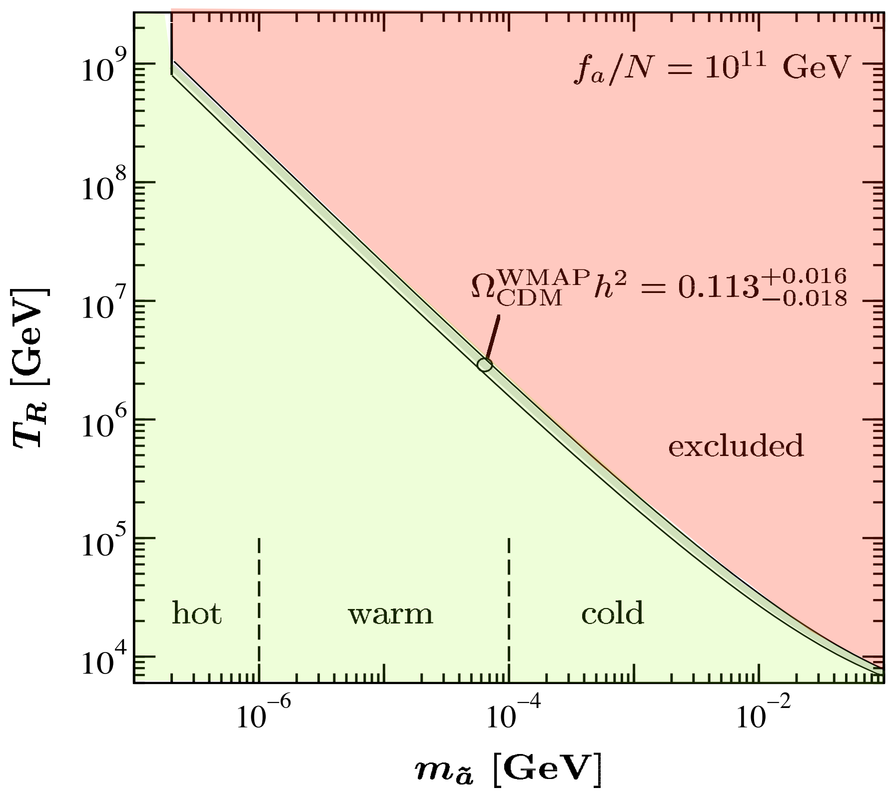


Axino Dark Matter



Axino LSP Case

Thermal $\tilde{a}$ Production



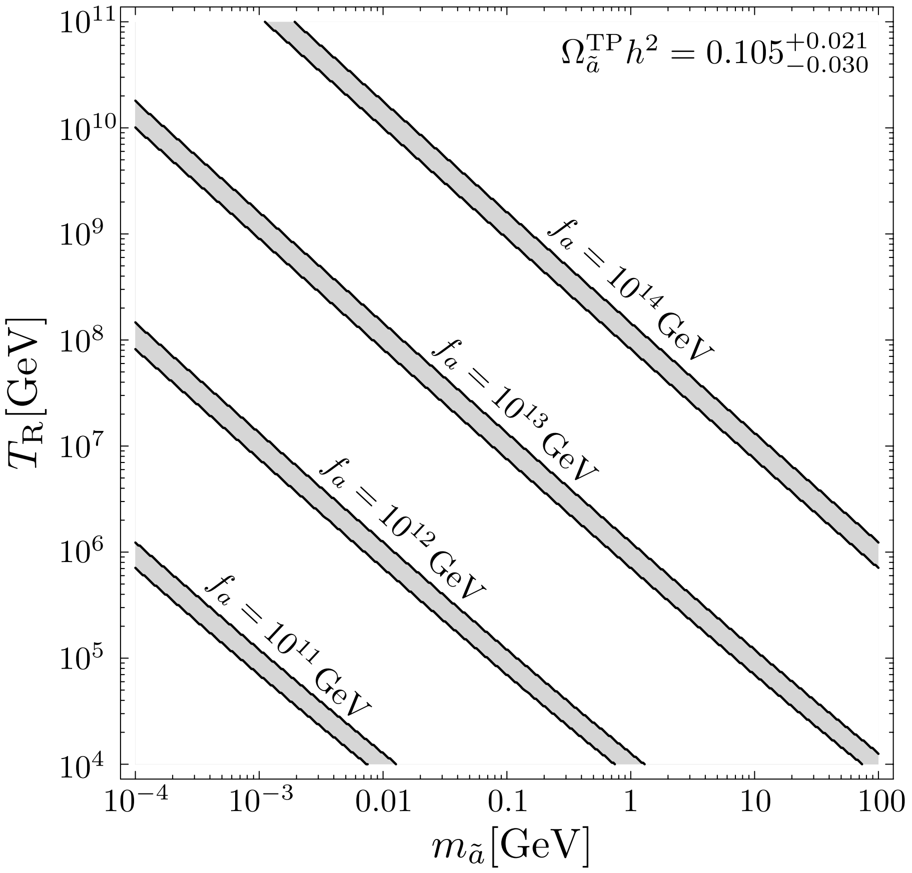
[Brandenburg, FDS, '04]

see also [Covi et al., '01]

and [Strumia, '10]

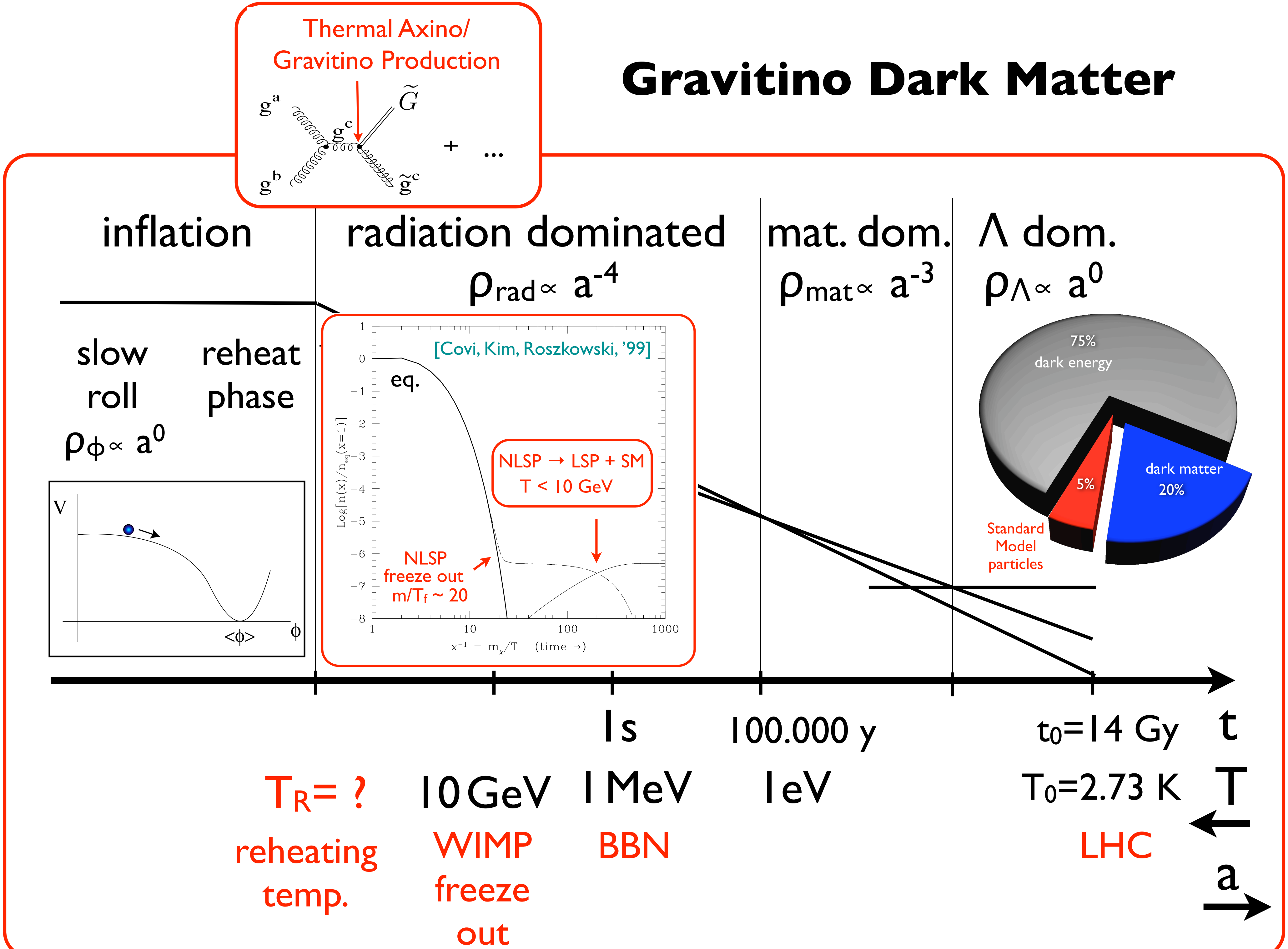
Axino LSP Case

Thermal $\tilde{a}$ Production



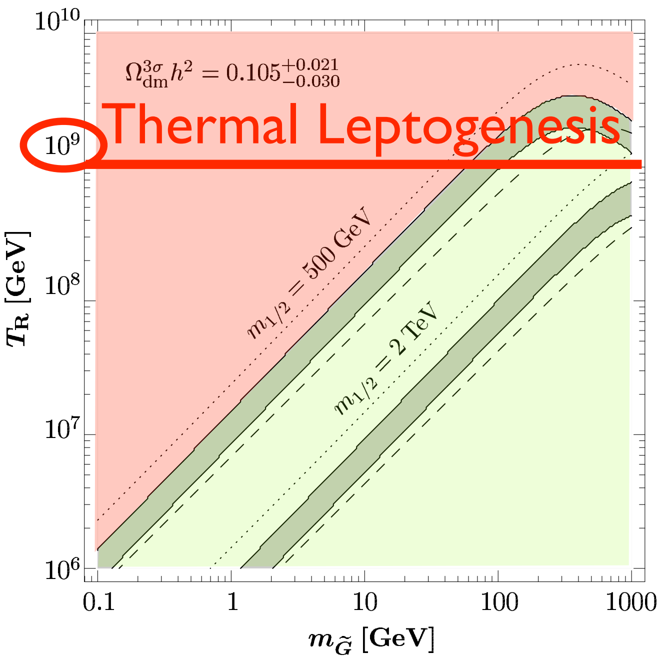
[Freitas, FDS, Tajuddin, Wyler, '09]

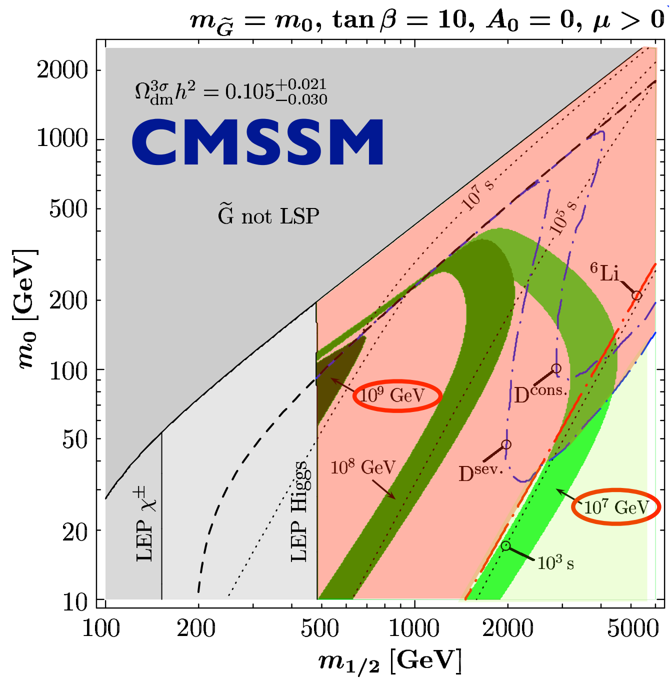
Gravitino Dark Matter



Upper Limits on the Reheating Temperature T_R

Stable Gravitino LSP





Ω_{DM} constraint for gravitino DM

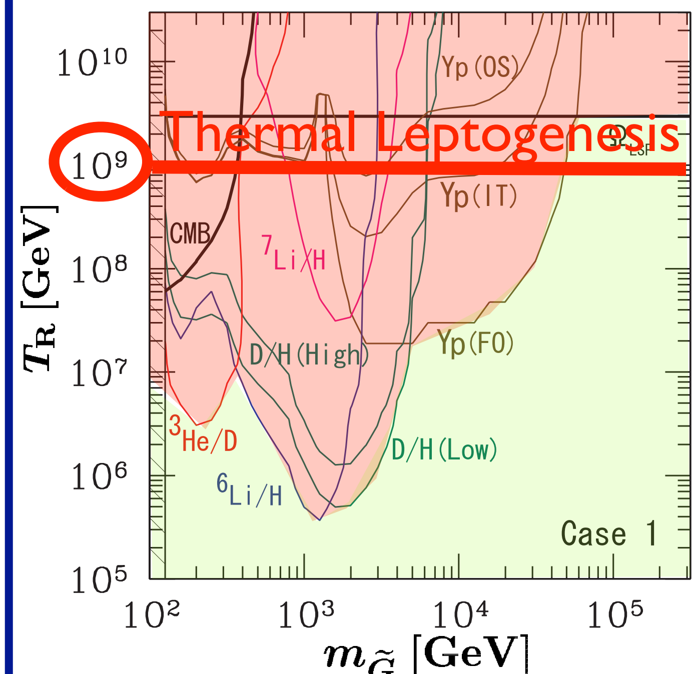
[Pradler, FDS, '07]

+ 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



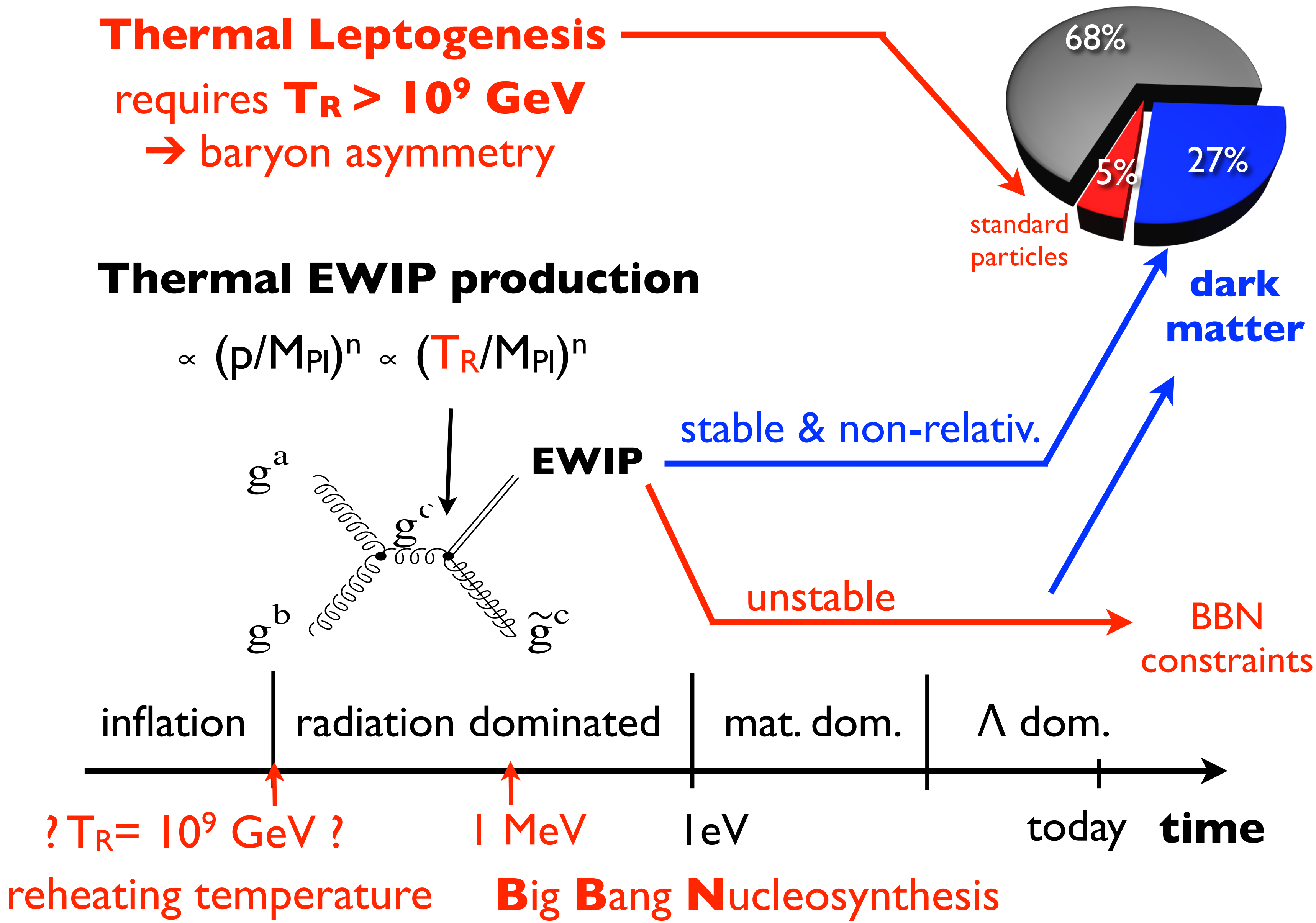
BBN constraints

+ Ω_{DM} constraint for neutralino DM

[Kohri, Moroi, Yotsuyanagi, '05]

Thermal Leptogenesis requires T >10⁹ GeV

High Reheating Temperature Scenarios



Dark Radiation

- Radiation content of the Universe at BBN and later

$$\rho_{\rm rad} = \left[1 + \frac{7}{8} \left(N_\nu + \Delta N_{\rm eff} \right) \left(\frac{T}{T_\nu} \right)^4 \right] \rho_\gamma$$

photon energy density

number of neutrinos

neutrino temperature

Parametrizes contribution of additional relativistic species

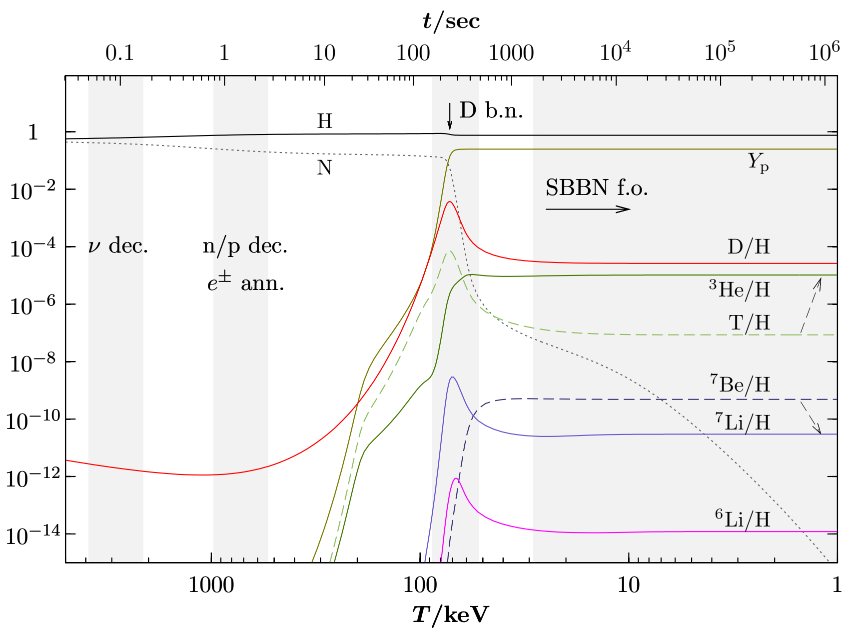
- More radiation → faster expansion → more efficient BBN of ^{4}He
- More radiation → later mat-rad eq → visible in CMB + LSS

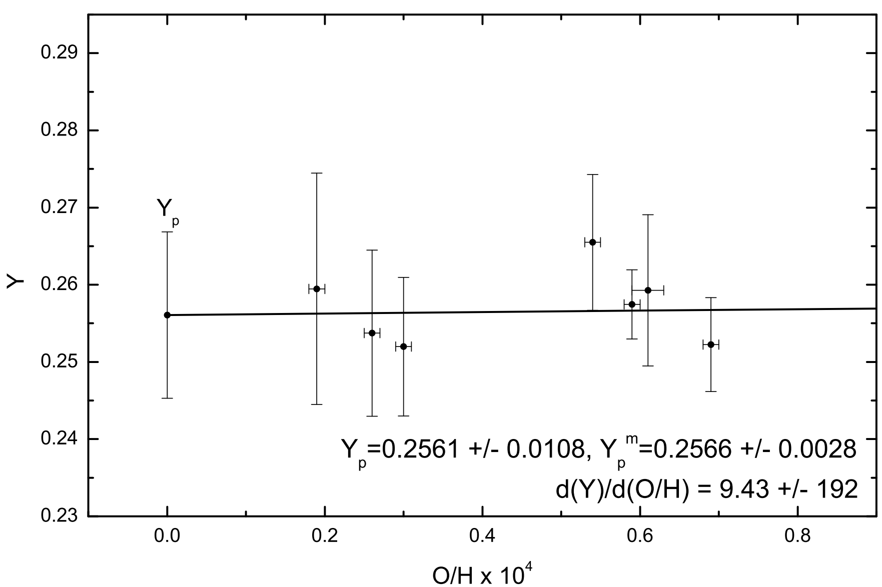
Data	p.m./mean	upper limit
$Y_{\rm p}^{\rm IT}$ [1] + $[{\rm D/H}]_{\rm p}$ [49]	0.76	< 1.97 (3σ)
$Y_{\rm p}^{\rm Av}$ [2] + $[{\rm D/H}]_{\rm p}$ [49]	0.77	< 3.53 (3σ)
CMB + HPS + HST [6]	1.73	< 3.59 (2σ)
Planck+WP+highL+BAO [8]	0.25	< 0.79 (2σ)
Planck+WP+highL+H_0+BAO [8]	0.47	< 0.95 (2σ)

BBN

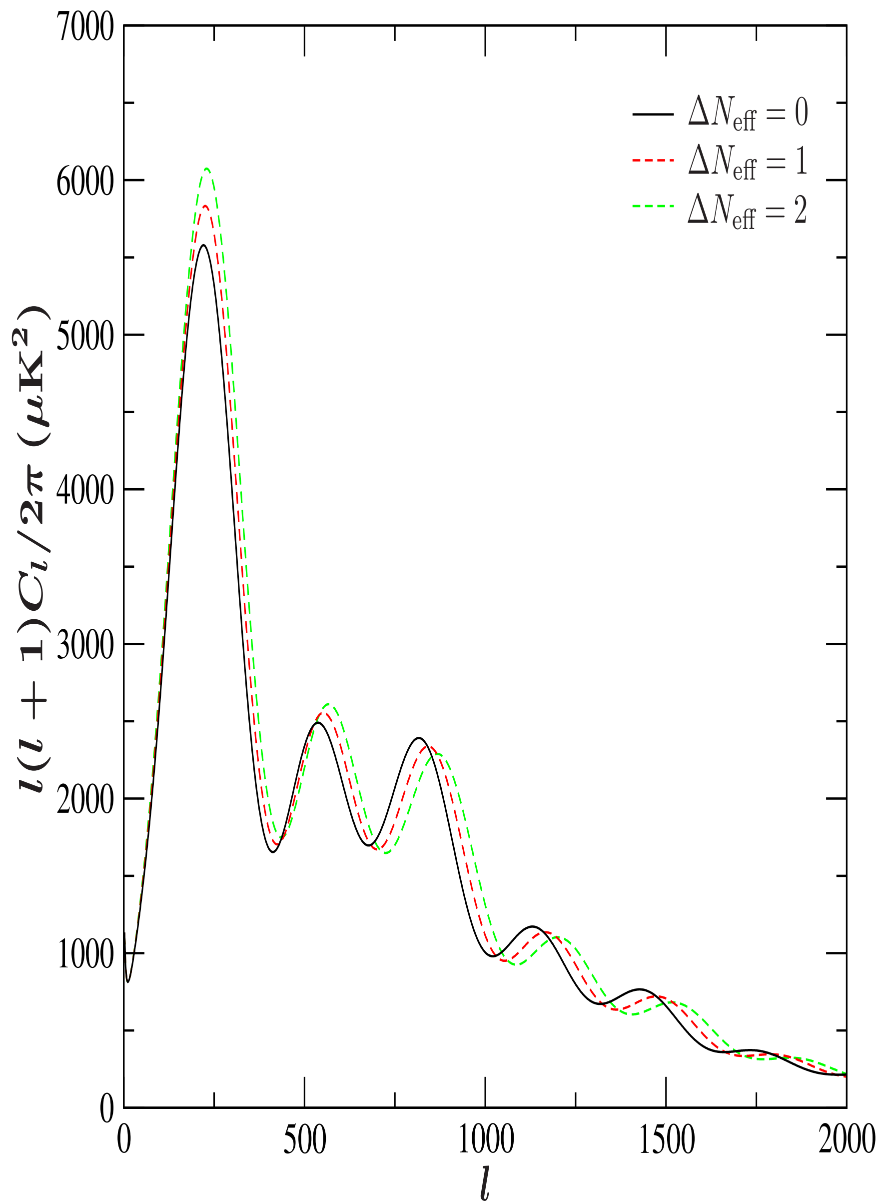
CMB + LSS

BBN


t/sec
0.1
1
10
100
1000
10^4
10^5
10^6
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
H
N
D b.n.
Y_p
SBBN f.o.
ν dec.
n/p dec.
$e^{\pm}$ ann.
D/H
^{3}He/H
T/H
^{7}Be/H
^{7}Li/H
^{6}Li/H
1000
100
10
1
T/keV


0.29
0.28
0.27
0.26
0.25
0.24
0.23
Y
Y_p
Y_p=0.2561 +/- 0.0108, Y_p^m=0.2566 +/- 0.0028
d(Y)/d(O/H) = 9.43 +/- 192
0.0
0.2
0.4
0.6
0.8
O/H x 10^4

CMB + LSS


7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi\ (\mu K^2)$
$\Delta N_{eff} = 0$
$\Delta N_{eff} = 1$
$\Delta N_{eff} = 2$
0
500
1000
1500
2000
l

Planck 2013 results XVI: Cosmological Parameters

Combining *Planck*, *WMAP* polarization and the high-ℓ experiments gives

$$N_{\rm eff} = 3.36^{+0.68}_{-0.64} \quad (95\%; \textit{Planck}+\text{WP}+\text{highL}). \qquad (74)$$

The marginalized posterior distribution is given in Fig. 27 (black curve).

Increasing $N_{\rm eff}$ at fixed θ_* and $z_{\rm eq}$ necessarily raises the expansion rate at low redshifts too. Combining CMB with distance measurements can therefore improve constraints (see Fig. 27) although for the BAO observable $r_{\rm drag}/D_{\rm V}(z)$ the reduction in both $r_{\rm drag}$ and $D_{\rm V}(z)$ with increasing $N_{\rm eff}$ partly cancel. With the BAO data of Sect. 5.2, the $N_{\rm eff}$ constraint is tightened to

$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \quad (95\%; \textit{Planck}+\text{WP}+\text{highL}+\text{BAO}). \qquad (75)$$

Our constraints from CMB alone and CMB+BAO are compatible with the standard value $N_{\rm eff} = 3.046$ at the $1\,\sigma$ level, giving no evidence for extra relativistic degrees of freedom.

Since $N_{\rm eff}$ is positively correlated with H_0, the tension between the *Planck* data and direct measurements of H_0 in the base ΛCDM model (Sect. 5.3) can be reduced at the expense of high $N_{\rm eff}$. The marginalized constraint is

$$N_{\rm eff} = 3.62^{+0.50}_{-0.48} \quad (95\%; \textit{Planck}+\text{WP}+\text{highL}+H_0). \qquad (76)$$

For this data combination, the χ^2 for the best-fitting model allowing $N_{\rm eff}$ to vary is lower by 5.0 than for the base $N_{\rm eff} = 3.046$ model. The H_0 fit is much better, with $\Delta\chi^2 = -4.0$, but there is no strong preference either way from the CMB. The low-ℓ temperature power spectrum does mildly favour the high $N_{\rm eff}$ model ($\Delta\chi^2 = -1.6$) since $N_{\rm eff}$ is positively correlated with $n_{\rm s}$ (see Fig. 24) and increasing $n_{\rm s}$ reduces power on large scales. The rest of the *Planck* power spectrum is agnostic ($\Delta\chi^2 = -0.5$), while the high-ℓ experiments mildly disfavour high $N_{\rm eff}$ in our fits ($\Delta\chi^2 = 1.3$). Further including the BAO data pulls the central value downwards by around $0.5\,\sigma$ (see Fig. 27):

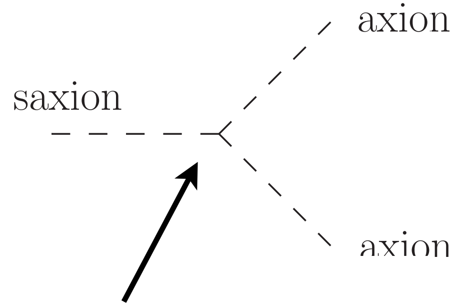
$$N_{\rm eff} = 3.52^{+0.48}_{-0.45} \quad (95\%; \textit{Planck}+\text{WP}+\text{highL}+H_0+\text{BAO}). \qquad (77)$$

The χ^2 at the best-fit for this data combination ($N_{\rm eff} = 3.37$) is lower by 3.6 than the best-fitting $N_{\rm eff} = 3.046$ model. While the high $N_{\rm eff}$ best-fit is preferred by *Planck*+WP ($\Delta\chi^2 = -3.3$) and the H_0 data ($\Delta\chi^2 = -2.8$ giving an acceptable $\chi^2 = 2.4$ for this data point), it is disfavoured by the high-ℓ CMB data ($\Delta\chi^2 = 2.0$) and slightly by BAO ($\Delta\chi^2 = 0.4$). We conclude that the tension between direct H_0 measurements and the CMB and BAO data in the base ΛCDM can be relieved at the cost of additional neutrino-like physics, but there is no strong preference for this extension from the CMB damping tail.

$\Delta N_{\rm eff} = 3.62 + 0.5 - 3.046 = 1.074$ @ 95% CL

Dark Radiation ➜ SUSY + PQ

- Axions from decays of thermal saxions ➞ extra radiation



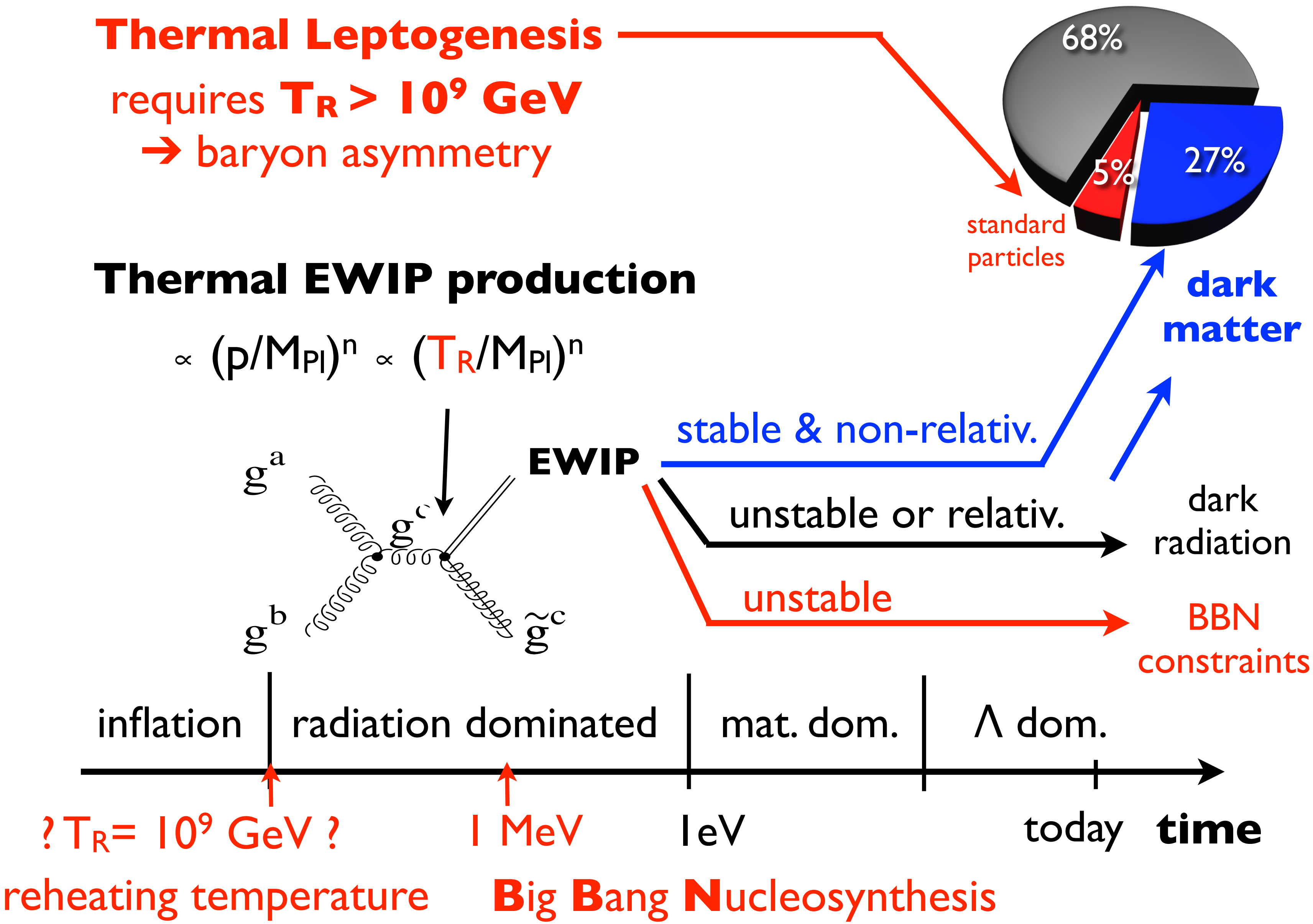
$$\mathcal{L}_{\rm PQ}^{\rm kin} = \left(1 + \frac{\sqrt{2}x}{v_{\rm PQ}}\sigma\right)\left[\frac{1}{2}\partial^\mu a \partial_\mu a + \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma + i\bar{\tilde{a}}\gamma^\mu \partial_\mu \tilde{a}\right] + \ldots$$

$$x = \sum_i \frac{q_i^3 v_i^2}{v_{\rm PQ}^2}. \qquad v_{\rm PQ} = \sqrt{\textstyle\sum_i v_i^2 q_i^2} \qquad f_{\rm PQ} = \sqrt{2} v_{\rm PQ}$$

- $\Delta N_{\rm eff} \propto \left(\frac{100\ {\rm GeV}}{m_\sigma}\right)^{1/2} \left(\frac{f_{\rm PQ}}{10^{11}\ {\rm GeV}}\right) \left(\frac{Y_\sigma^{\rm eq/TP}}{10^{-3}}\right)$

[Graf, FDS, '12]

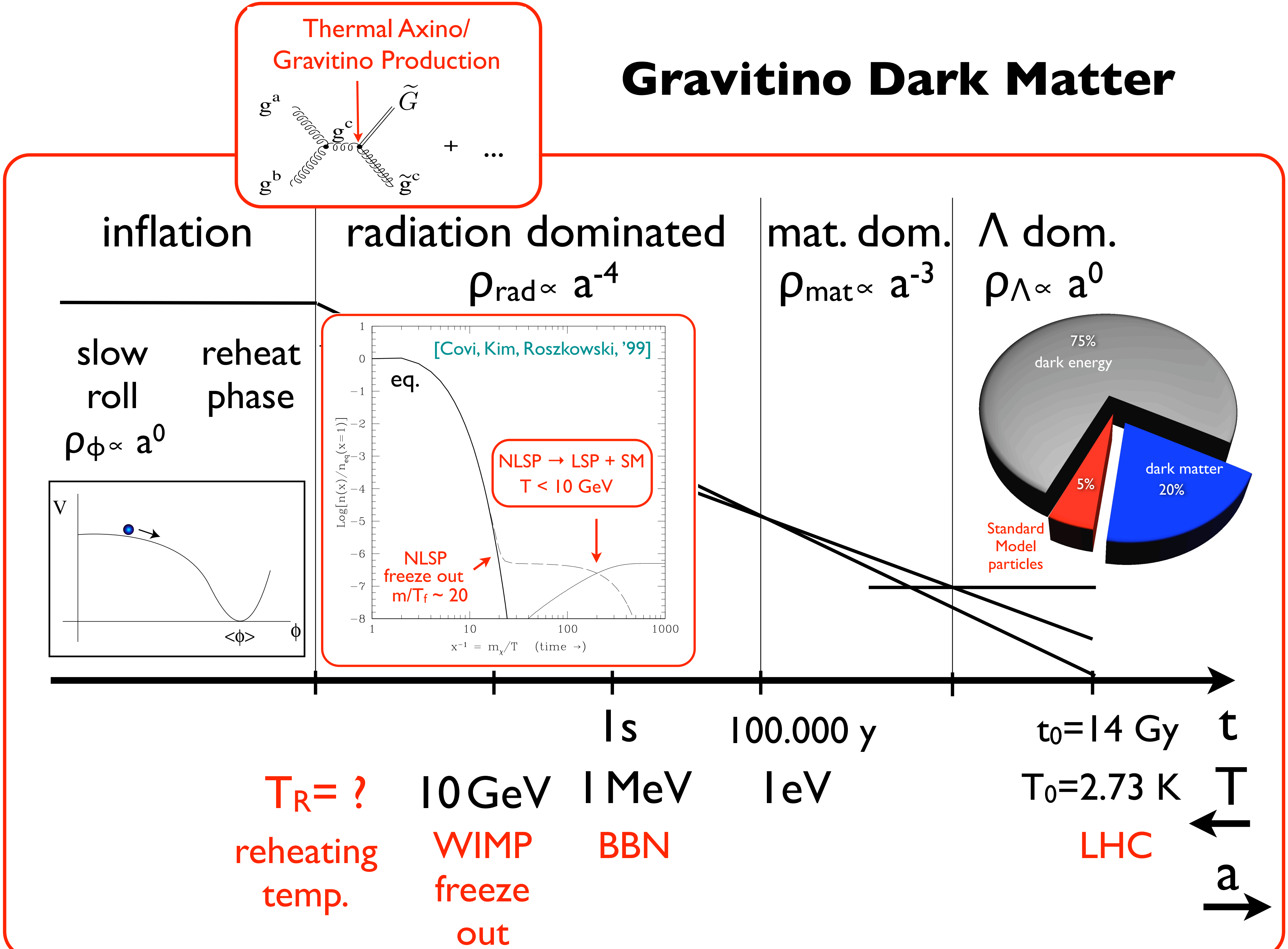
High Reheating Temperature Scenarios



Gravitino Dark Matter Scenario

- **Gravitino is the stable LSP (R-parity conservation is assumed)**
- **Axino is heavy & unstable (decays prior to LOSP decoupling)**
- **Saxion decays into axion dark radiation**
- **Axion contributes to dark radiation and dark matter**
- **Sneutrino NLSP case allows for thermal leptogenesis**

Gravitino Dark Matter



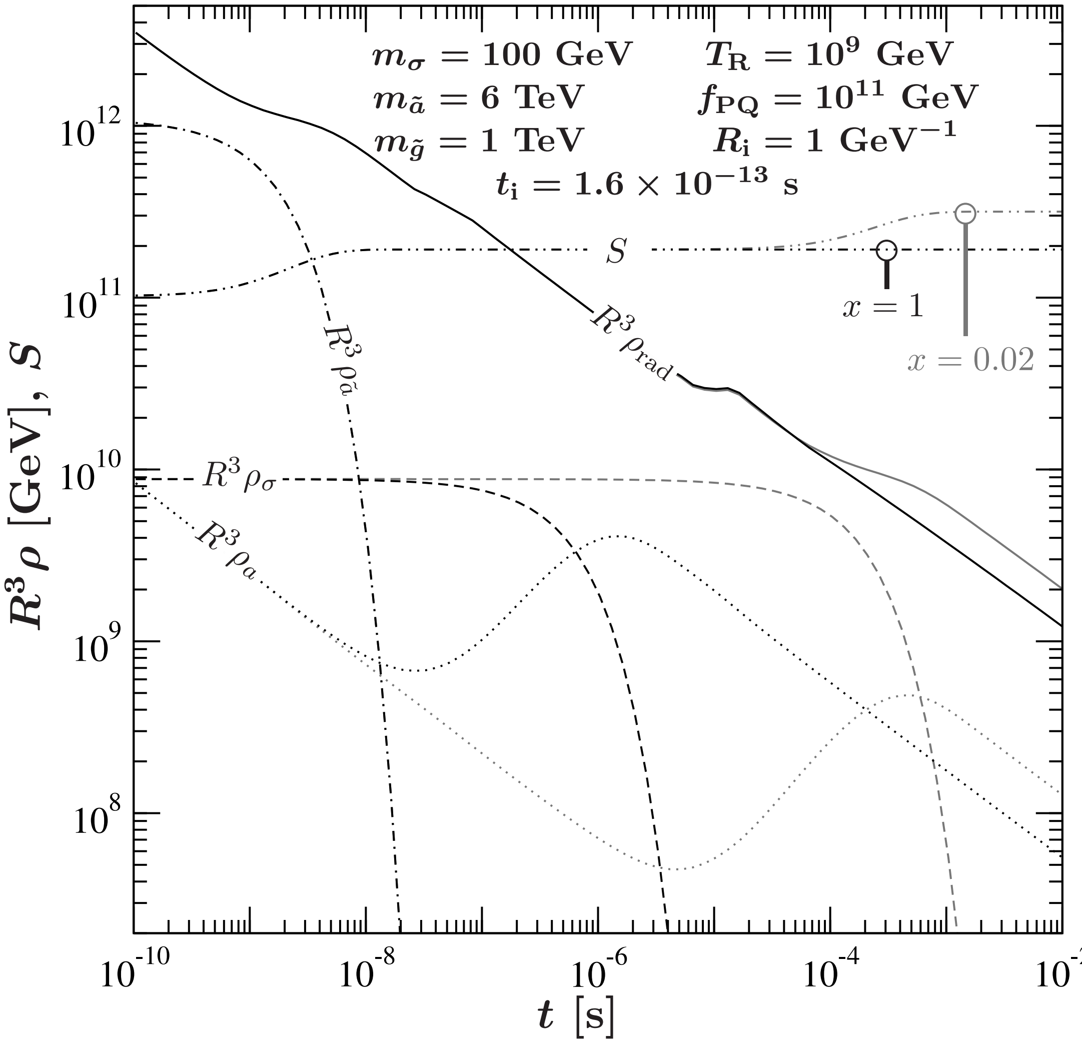
Gravitino Dark Matter Scenario

axino → gluon + gluino

axino → axion + gravitino

saxion → 2 axions

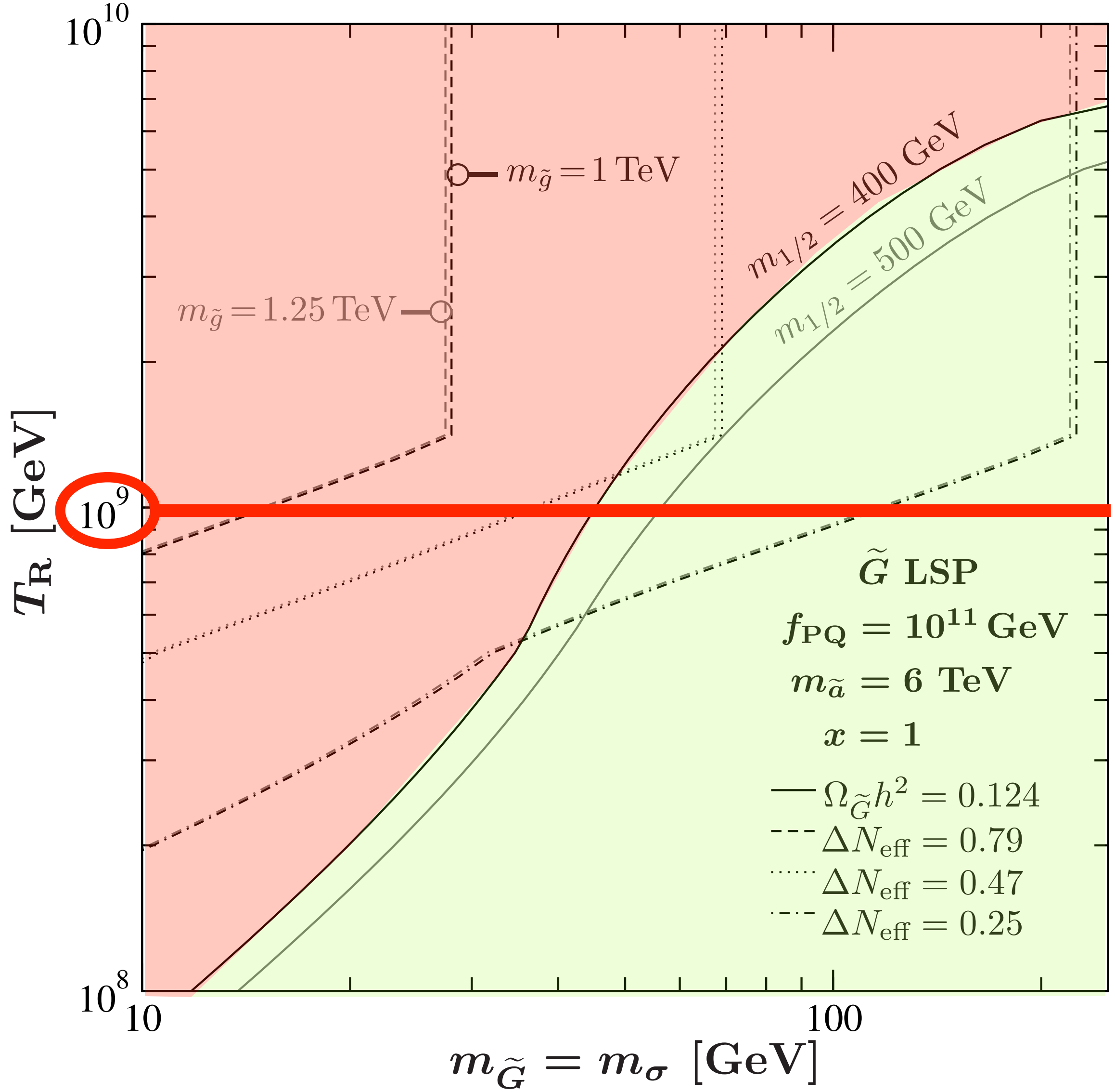
saxion → 2 gluons



$$\mathcal{L}_{\widetilde{G}\tilde{a}a} = \frac{1}{2}\left(\partial_\mu \sigma \overline{\Psi}_{M\nu}\gamma^\mu\gamma^\nu\bar{\tilde{a}}_M + i\partial_\mu a \overline{\Psi}_{M\nu}\gamma^\mu\gamma^\nu\gamma^5\tilde{a}_M\right)$$

[Graf, FDS, 1302.2143]

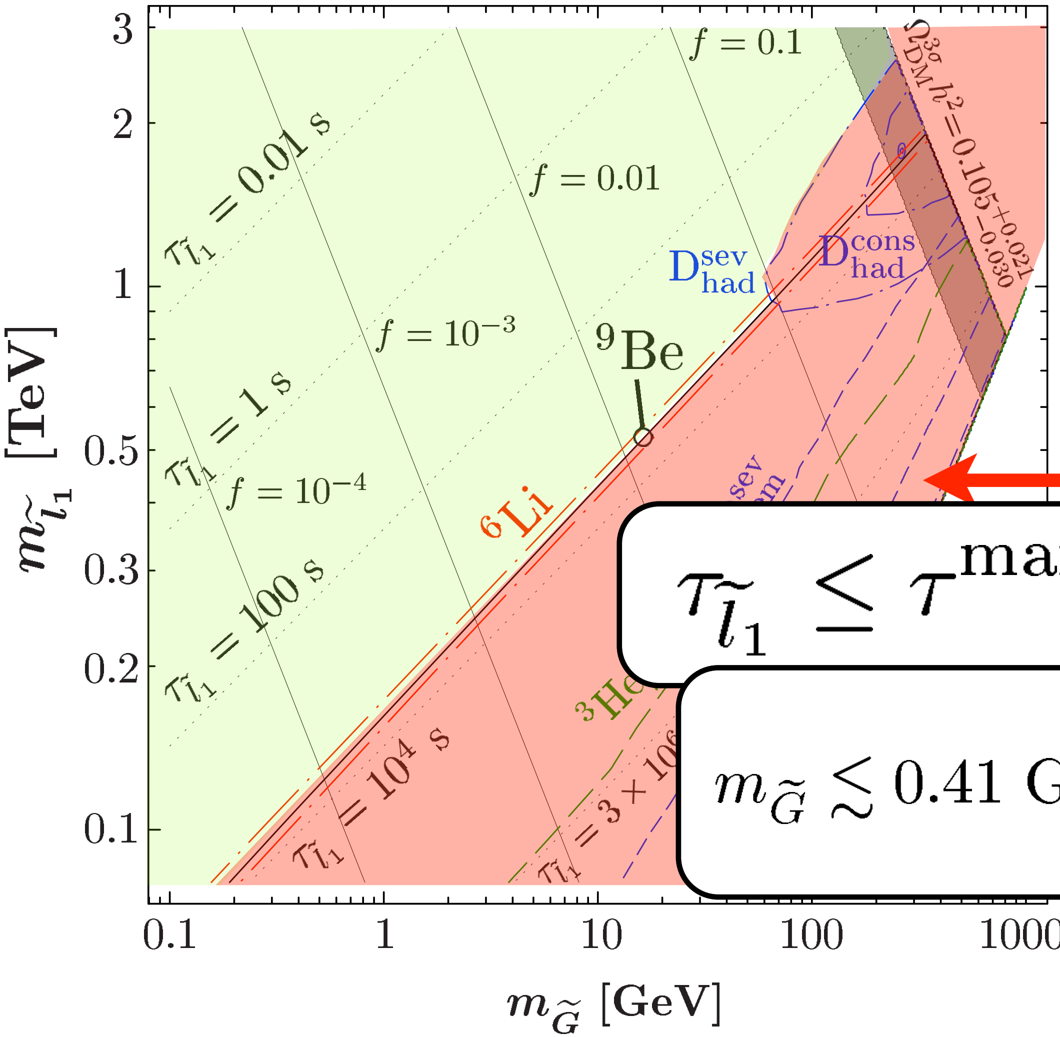
Gravitino Dark Matter Scenario



Gravitino LSP Case with a Charged Slepton NLSP

(C)BBN Constaints

[Pospelov, Pradler, FDS, ’08]



disfavored by cosmological constraints

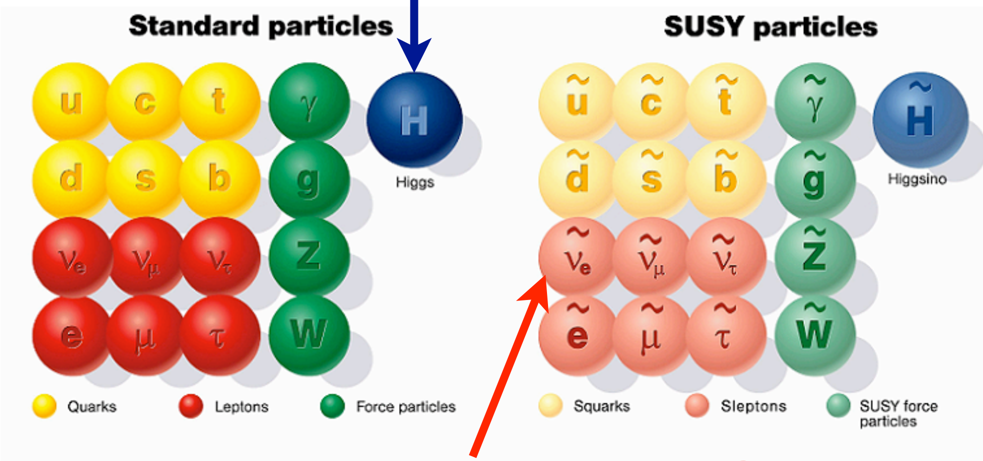
$$\tau_{\widetilde{l}_1} \leq \tau^{\max}$$

$$m_{\widetilde{G}} \lesssim 0.41\ \mathrm{GeV} \left(\frac{\tau_{\widetilde{l}_1}}{10^4\ \mathrm{s}}\right)^{\frac{1}{2}} \left(\frac{m_{\widetilde{l}_1}}{100\ \mathrm{GeV}}\right)^{\frac{5}{2}} \equiv m_{\widetilde{G}}^{\max}$$

Particle Physics

- 2016: Large Hadron Collider (14 TeV) sneutrino discovery at ATLAS & CMS

m_H = 125 GeV



$m_{sneutrino}$ = 415 GeV

- Intrinsic fine tuning problems

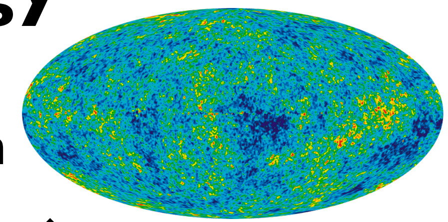
✔ Hierarchy Problem ($m_H << M_{Planck}$)
supersymmetry

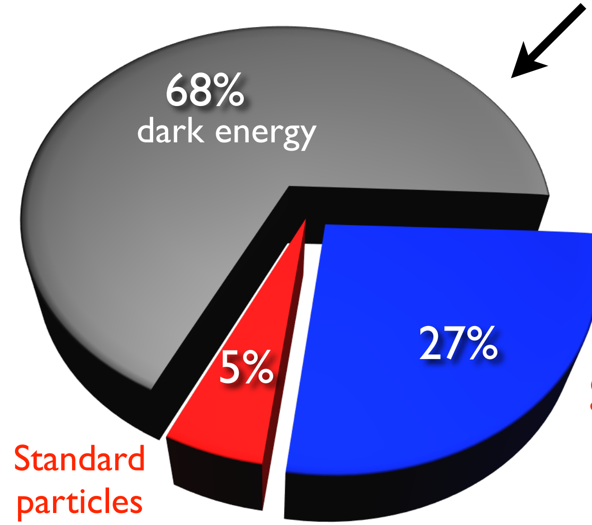
✔ Strong CP Problem ($\Theta_{QCD} << 1$)
Peccei-Quinn symmetry

✔ Small Neutrino Masses ($m_\nu << m_H$)
See-saw mechanism

Cosmology

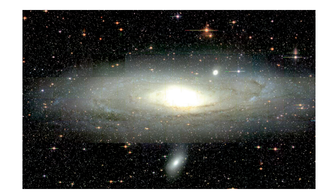
- 2013: Planck sky map of the CMB radiation





ESA

gravitino EWIP dark matter



- Cosmological puzzles

✔ Matter-Antimatter Asymmetry
thermal leptogenesis

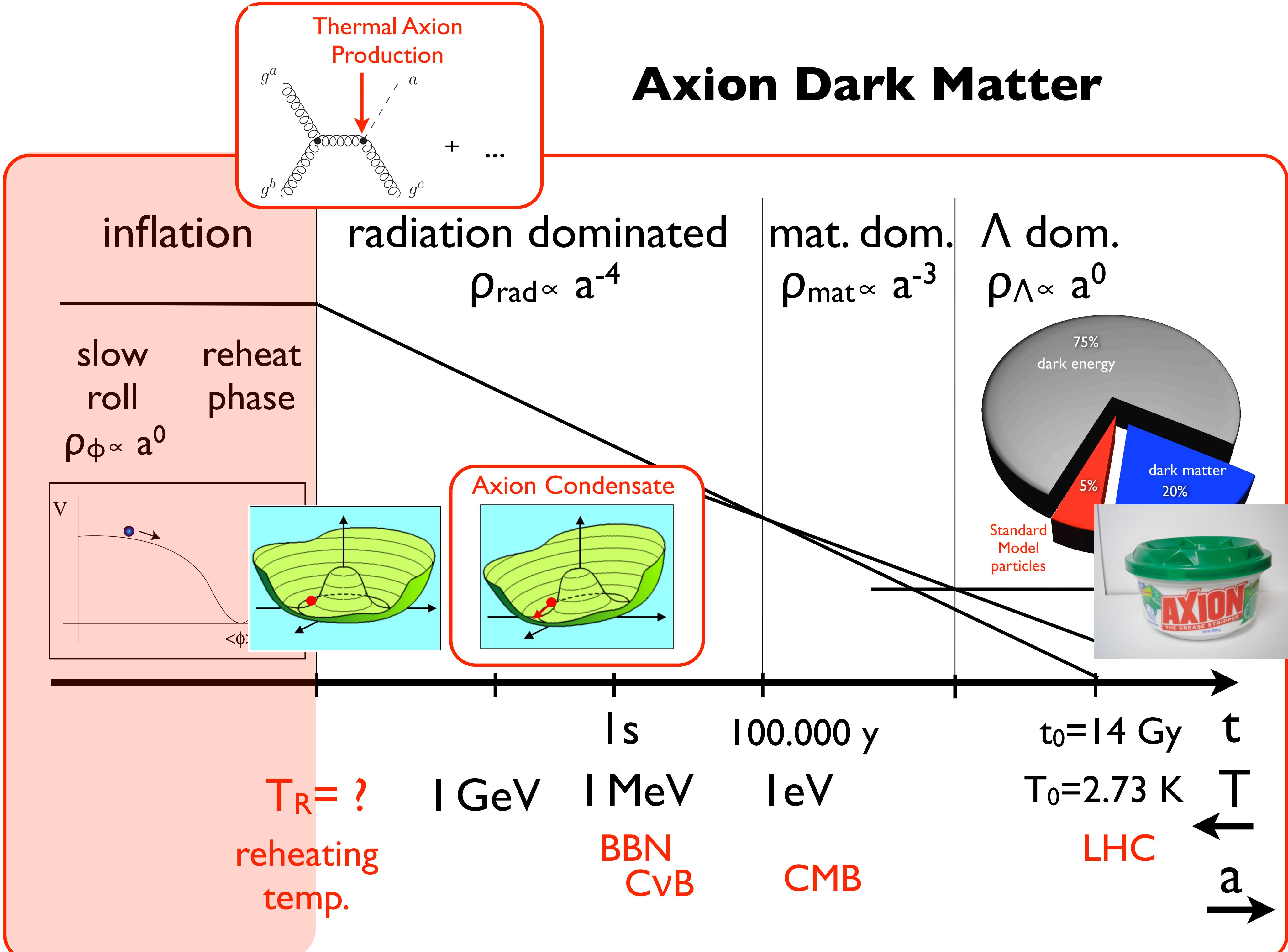
✔ Particle Identity & Origin of Dark Matter
thermally produced gravitinos

? Dark Energy = Cosmological Constant

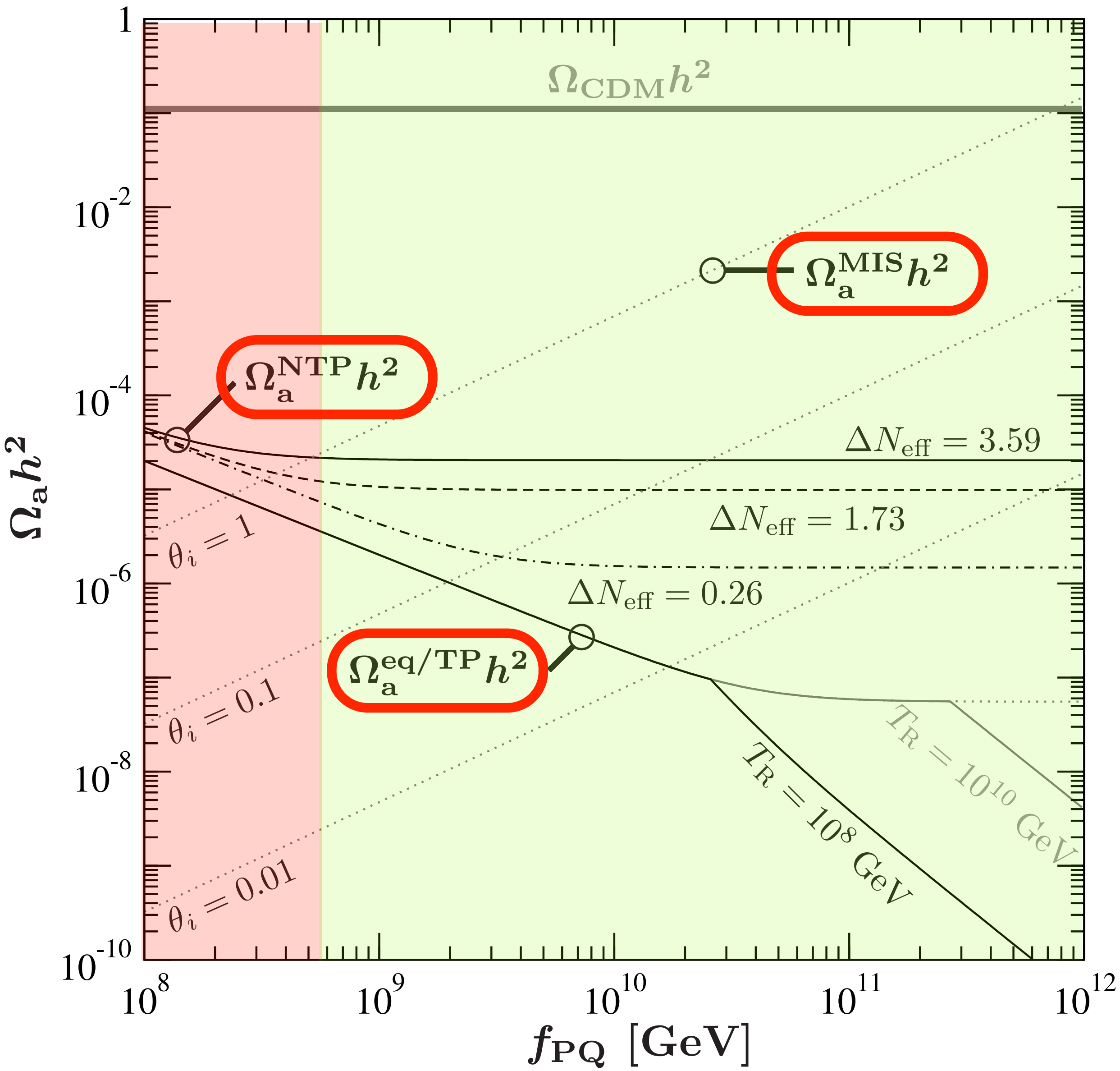
Axion Dark Matter Scenario

- **Axino is a very light stable LSP (R-parity conservation)**
- **Gravitino is the NLSP and decays into axion & axino dark radiation**
- **Saxion decays into axion dark radiation**
- **Axion contributes to dark radiation and dark matter**
- **Stau NLSP case & thermal leptogenesis is possible**

Axion Dark Matter



Lee-Weinberg Curve for Axions



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; ...]

≥ Three Axion Populations

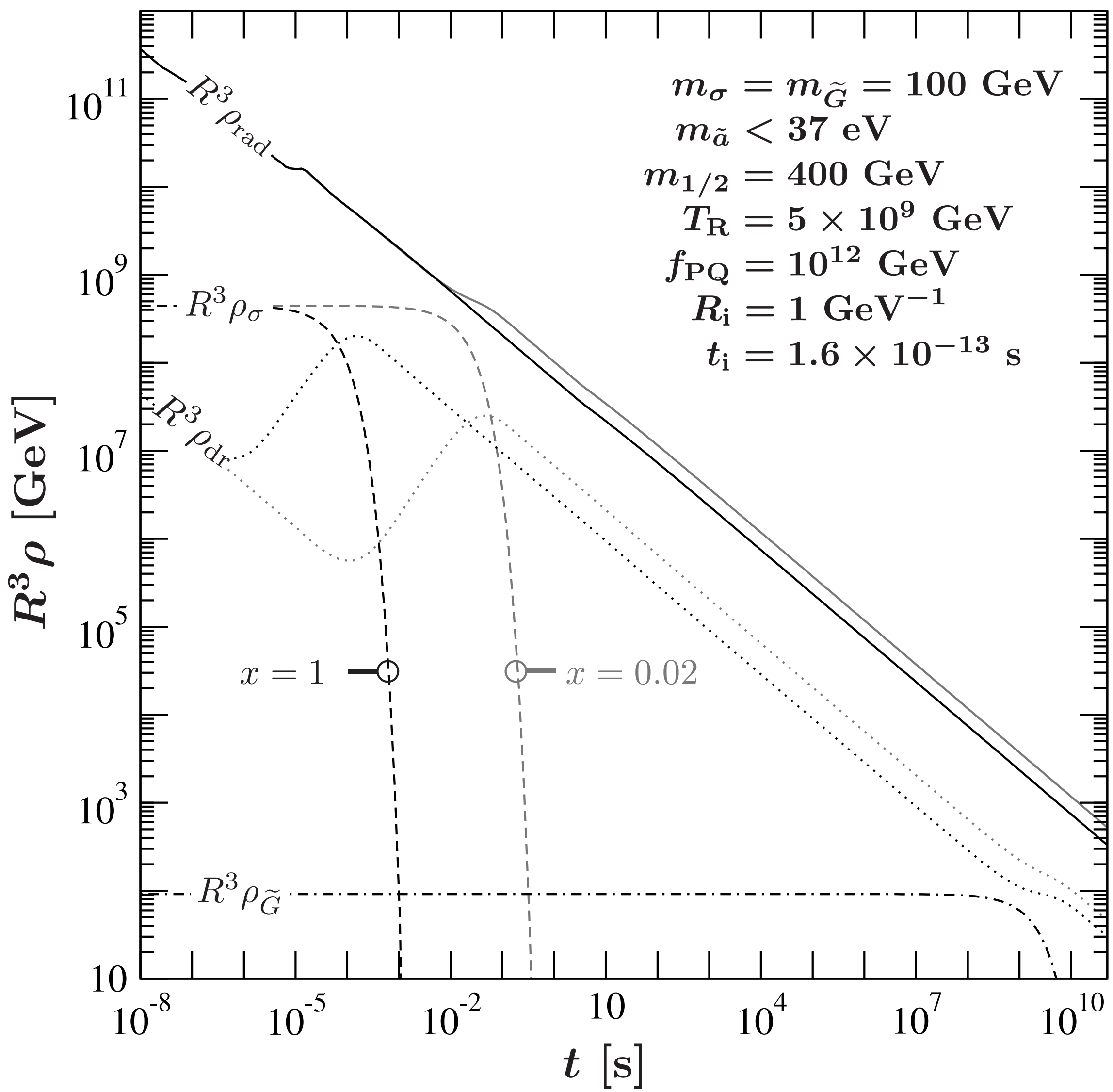
[Graf, Steffen, '12]

Axion Dark Matter Scenario

saxion → 2 gluons

saxion → 2 axions

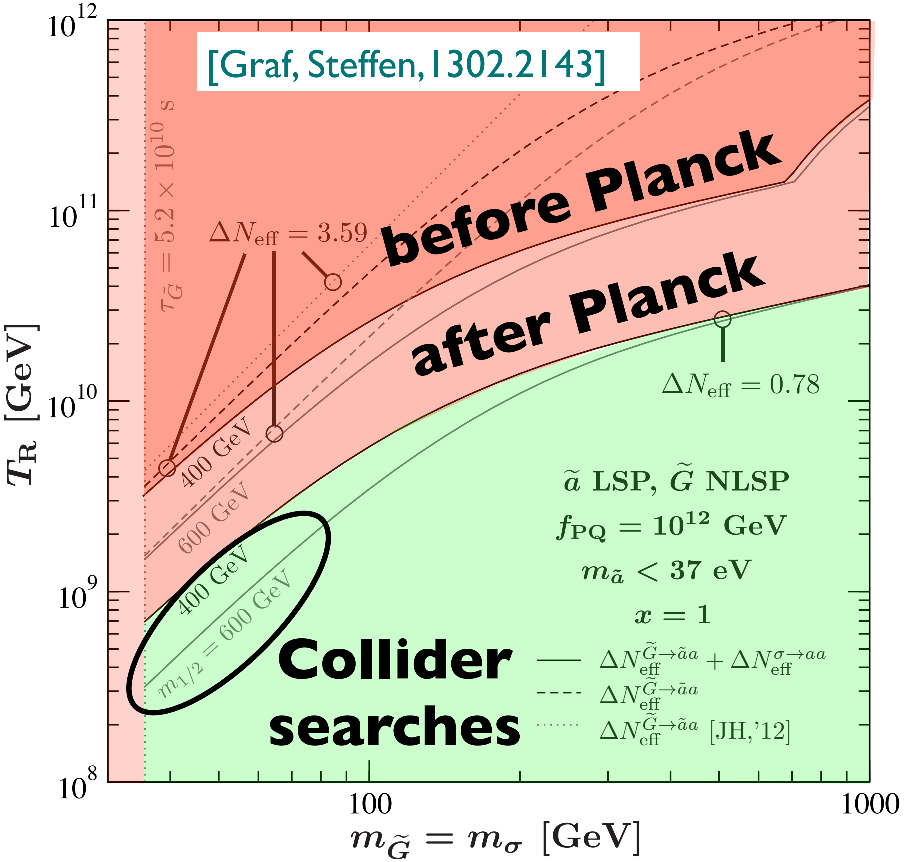
gravitino → axion + axino



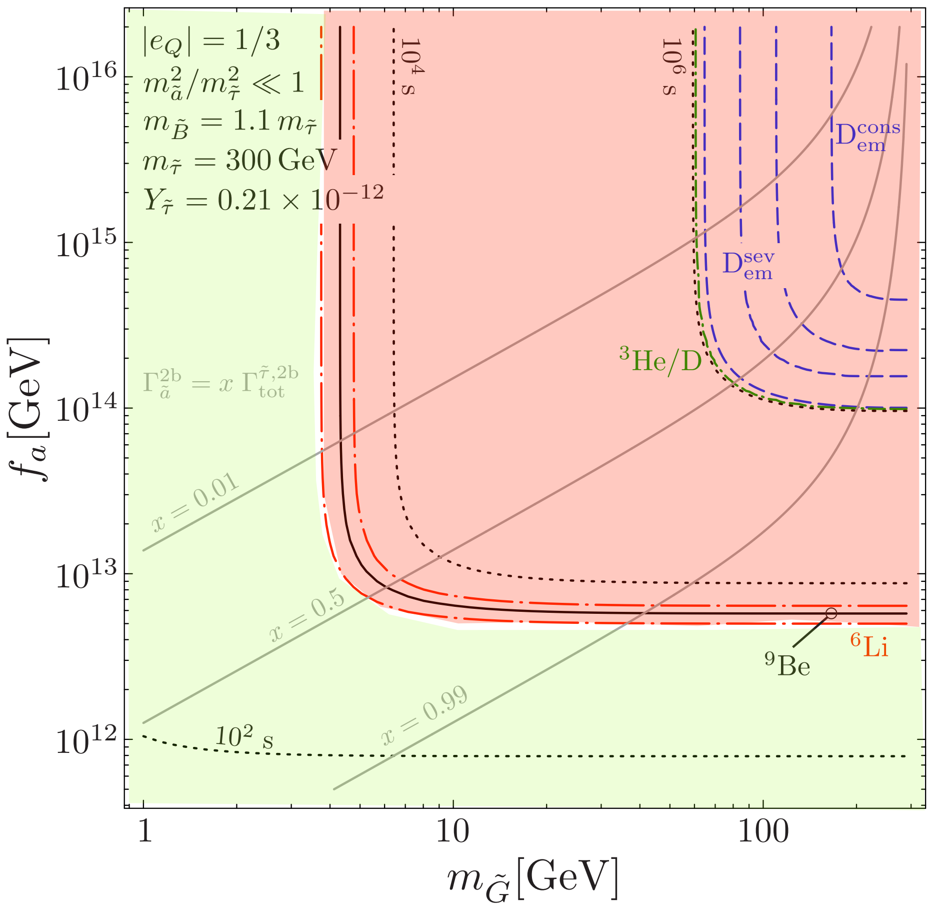
$$\mathcal{L}_{\widetilde{G}\tilde{a}a} = \frac{1}{2}\left(\partial_\mu \sigma \overline{\Psi}_{M\nu}\gamma^\mu\gamma^\nu \bar{\tilde{a}}_M + i\partial_\mu a \overline{\Psi}_{M\nu}\gamma^\mu\gamma^\nu\gamma^5 \tilde{a}_M\right)$$

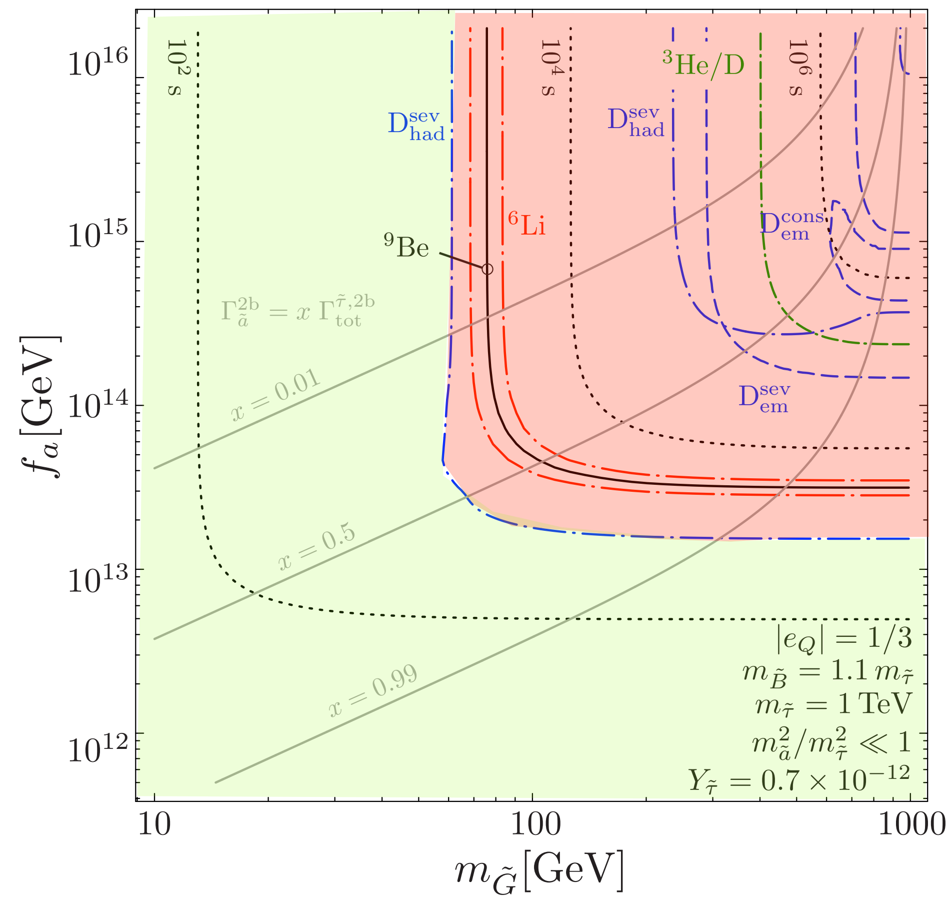
[Graf, FDS, 1302.2143]

Axion Dark Matter Scenario



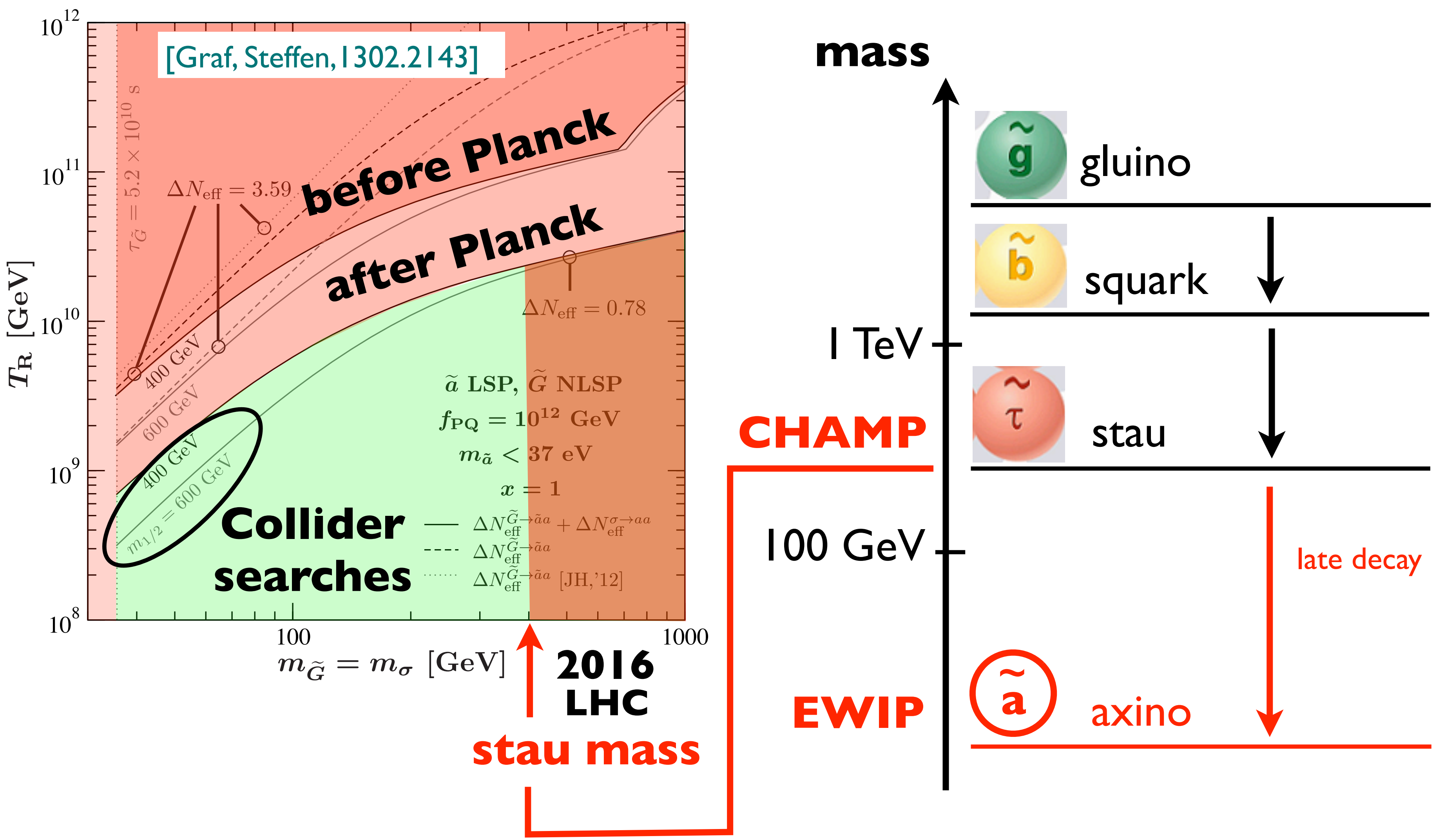
m_{axino}, $m_{gravitino}$ < m_{stau}



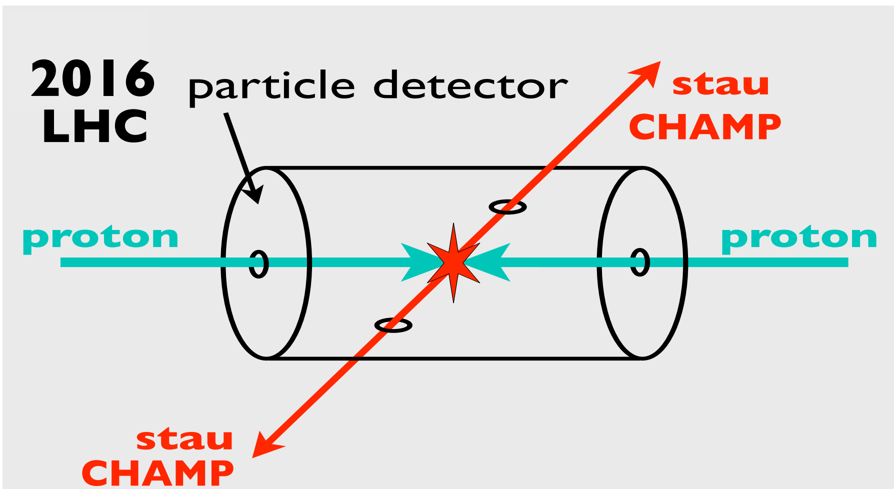


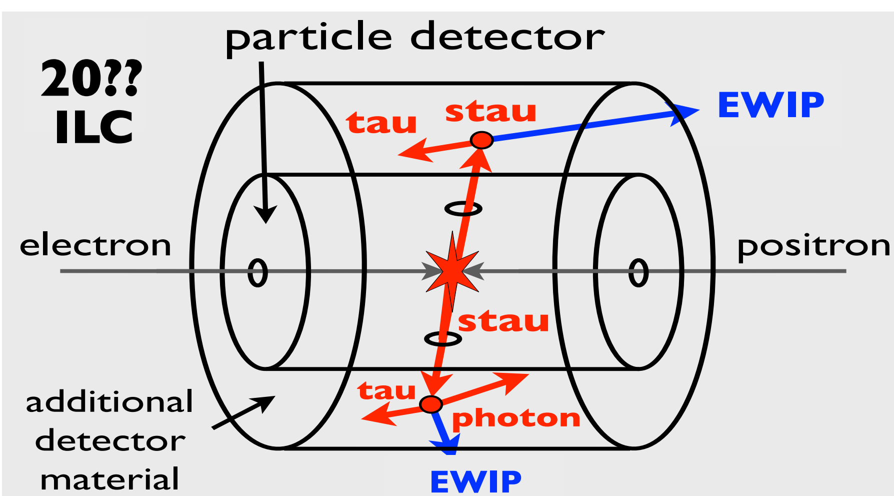
[Freitas, Tajuddin, FDS, Wyler, '09]

Axion Dark Matter Scenario



CHArged Massive Particles (CHAMPs)





Key questions on CHAMP properties

Stable? Lifetime? Decay products?

↓

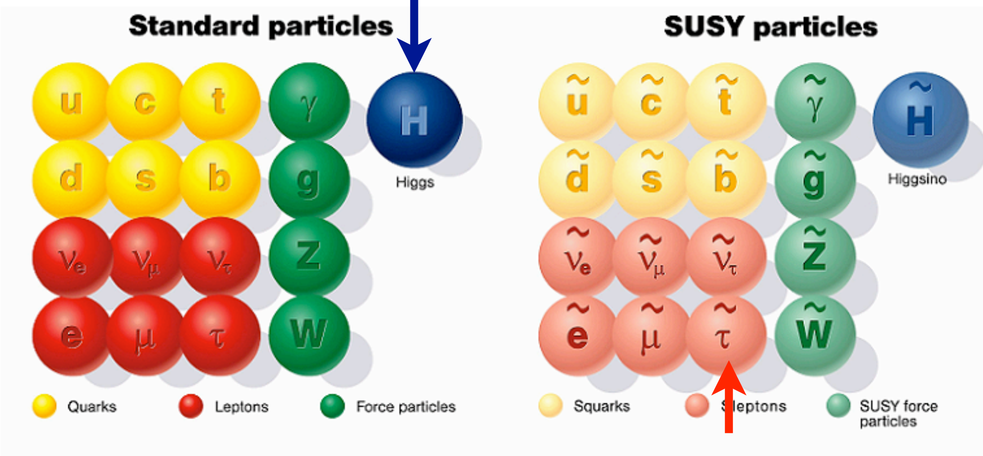
New detector concepts

- **→ stop/collect CHAMPs**
- **→ study CHAMP decays**

Particle Physics

- 2016: Large Hadron Collider (14 TeV)
  stau discovery at ATLAS & CMS

m_H = 125 GeV



m_{stau} = 415 GeV

- Intrinsic fine tuning problems

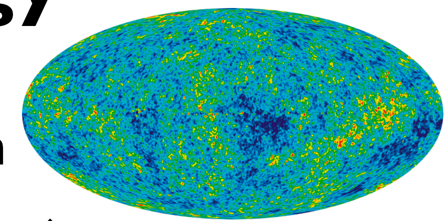
✔ Hierarchy Problem ($m_H << M_{Planck}$)
supersymmetry

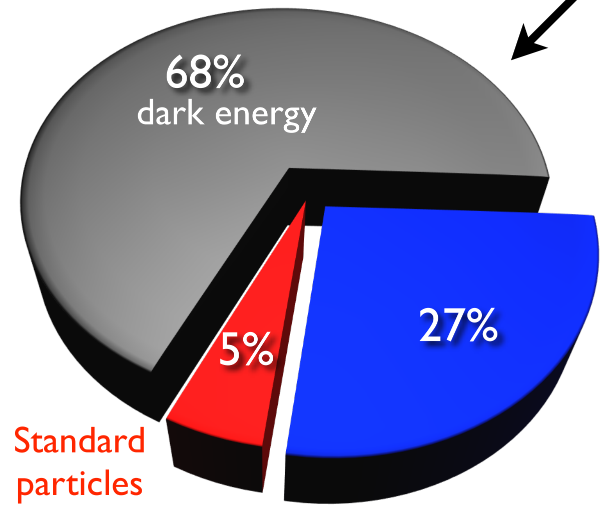
✔ Strong CP Problem ($\Theta_{QCD} << 1$)
Peccei-Quinn symmetry

✔ Small Neutrino Masses ($m_\nu << m_H$)
See-saw mechanism

Cosmology

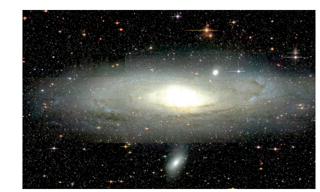
- 2013: Planck sky map
  of the CMB radiation





ESA

axion EWIP
dark matter



- Cosmological puzzles

✔ Matter-Antimatter Asymmetry
thermal leptogenesis

✔ Particle Identity & Origin of Dark Matter
axion condensate

? Dark Energy = Cosmological Constant

Conclusions

- **Cosmological observations still call for new physics**
- **Hierachy problem & strong CP problem → SUSY axion models**
- **EWIPs are a new well-motivated class of particles**
- **EWIP can explain dark matter and dark radiation (?)**
- **High-reheating temperature scenarios → thermal leptogenesis**

  → Gravitino dark matter with sneutino LOSPs

  → Axion dark matter with stau LOSPs
- **Various cosmological aspects & promising collider propects**