Late time stau dilution by Q balls

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Ref. SK & F.Takahashi, arXiv:0708nnnn

Aug. 22, 2007, at COSMO-07, Sussex, UK

§1. Introduction

Gauge-med. ~~SUSY~~ ⟹ No FCNC & ~~CP~~ problems.

↳ $m_{3/2} \ll M_W$ ⟹ Gravitino LSP = good DM

If stau is NLSP ⟹ Long lifetime

⟹ M_P could be measurable for $m_{3/2}$~O(10) GeV.

Buchmüller et al. (04)

Collider experiments (LHC, ILC,…)

⟹ Affects BBN

- Energetic decay destroys light elements.
- Bound state (^{4}He-stau$^-$) catalyze nucl. react.

Pospelov (07)
Kohri,Takayama (07)
Kaplinghat,Rajaraman (06)
and others…

^{6}Li is over-produced very much.

Cosmological disaster

⟹ $\tau_{stau} < 10^3$ sec or $\Delta \sim 10^3$

Hamaguchi et al. (07)

§1. Introduction (cont'd)

Late-time dilution is not so easy.

$$T_D \gtrsim \text{a few MeV}$$ Kawasaki et al.(99,00), Hannestad (04), Ichikawa et al. (05)

$$T_D < T_{fo} \sim 10\,\mathrm{GeV}\left(\frac{m_{\tilde{\tau}}}{200\,\mathrm{GeV}}\right)$$

$$T_D < T_{eq}$$

Example

X : even R-parity

$$m_X < m_{\tilde{\tau}} < m_{\tilde{X}}$$

X should couple to SM more strongly than stau.

$\Longrightarrow$ Very difficult, if not impossible.

Large Q ball

Long lifetime

$$m_{eff} \sim \omega_Q < m_{\tilde{\tau}}$$

Decay products are SM particles.

§2. Q balls in GMSB

A Q ball is a kind of non-topological soliton, the energy min. configuration of the scalar field with non-zero charge Q. Coleman (85)

Φ : MSSM flat directions (e.g., LH_u, udd, LLe,…) Dine et al. (96) Gherghetta et al. (96)

$$V(\Phi) \simeq M_F^4 \left(\log \frac{|\Phi|^2}{M_S^2}\right)^2 + c_g m_{3/2}^2 \left[1 + K \log \frac{|\Phi|^2}{M^2}\right] |\Phi|^2 + \frac{\lambda^2 |\Phi|^{2(n-1)}}{M_P^{2(n-3)}} - c_H H^2 |\Phi|^2$$

Gauge-med. Gravity-med. NR op. H-induced

Q-ball formation

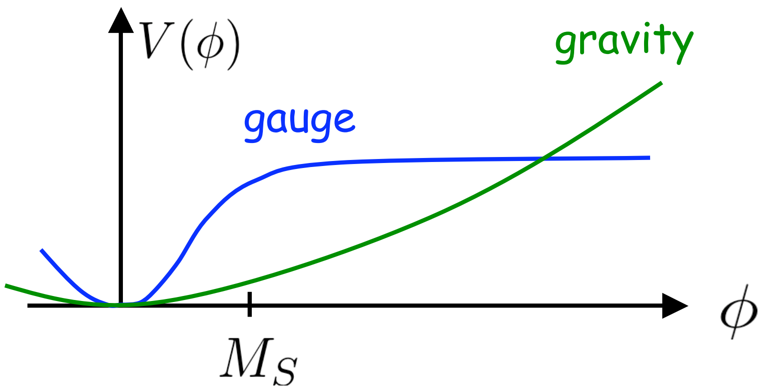
Kusenko,Shaposhnikov (98)
Enqvist,McDonald (98,99)
SK,Kawasaki (00,01)

(1) Large VEV during inflation, trapped by H-ind. & NR op.

(2) Φ starts rotation when H ~ $m_{\phi,\mathrm{eff}}$.

(3) Φ feels spatial instabilities.

(4) Instabilities go non-linear, and Φ deforms into Q balls.



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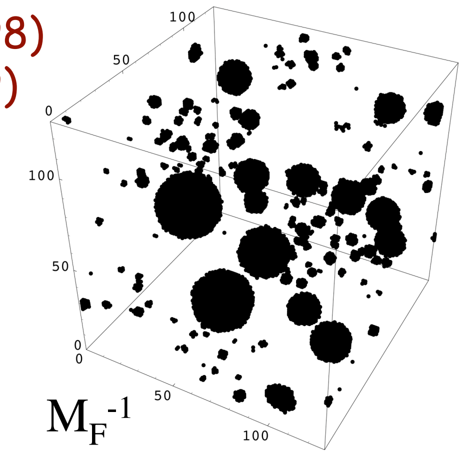
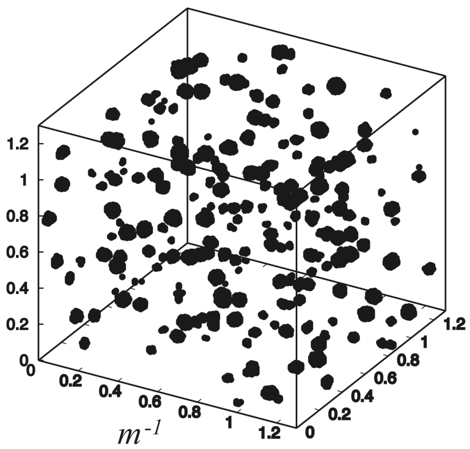




	Gauge-med. type	Gravity-med. (or New) type
Charge	$Q = \beta \left(\frac{\phi_{osc}}{M_F}\right)^4$	$Q = \beta' \left(\frac{\phi_{osc}}{m_{3/2}}\right)^2$
Size	$R_Q \sim M$ …	… $\vert K\vert^{-\frac{1}{2}} m_{3/2}^{-1}$
Mass	$M_Q \sim M$ …	… $\sim m_{3/2} Q$
Mass/Charge	$\omega_Q \sim M_F Q^{-1/4}$	$\omega_Q \sim m_{3/2}$
Decay rate	$\Gamma_Q \sim \frac{M_F}{48\pi} Q^{-5/4}$	$\Gamma_Q \sim \frac{m_{3/2}}{48\pi \vert K\vert} Q^{-1}$

Cohen et al. (86)

ω_Q < m_{stau} for large Q

($m_{3/2}$~10 GeV)

Long lifetime for large Q

§3. Dilution factor

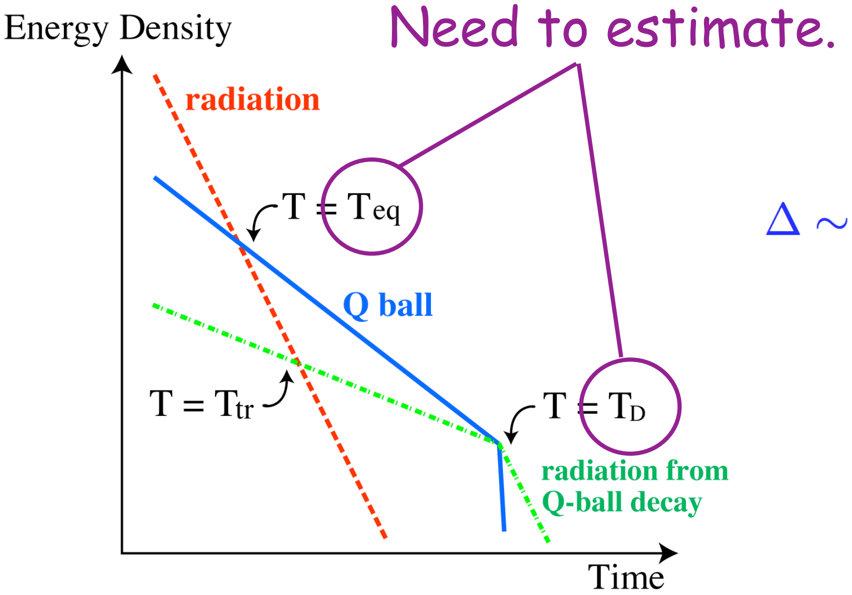
$$\frac{n_{\tilde{\tau}}}{s} = \frac{1}{\Delta}\left(\frac{n_{\tilde{\tau}}}{s}\right)_{\rm thermal}$$

Q-domi. starts after stau freeze-out: Case A $\quad H \sim \frac{T^2}{M_P}$

Q-domi. starts before stau freeze-out.

Radiation dominated by relic one: Case B $\quad H \sim \frac{(T^3 T_{eq})^{\frac{1}{2}}}{M_P}$

Radiation dominated by new one: Case C $\quad H \sim \frac{T^4}{T_D^2 M_P}$



$$\Delta \sim \begin{cases} \frac{T_{eq}}{T_D} & (\text{Case A}: T_{eq} < T_{fo}) \\ \frac{(T_{fo}T_{eq})^{\frac{1}{2}}}{T_D} & (\text{Case B}: T_{tr} < T_{fo} < T_{eq}) \\ \left(\frac{T_{fo}}{T_D}\right)^3 & (\text{Case C}: T_D < T_{fo} < T_{tr}) \end{cases} .$$

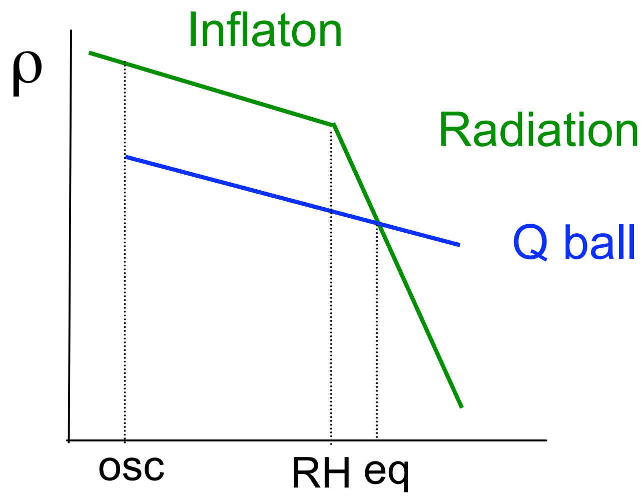
$$T_{fo} \sim \frac{m_{\tilde{\tau}}}{20} \sim 10\,\text{GeV}\left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)$$

$$T_{tr} \sim (T_{eq}T_D^4)^{\frac{1}{5}}$$

§4. Entropy production by the Q ball decay

Large Q, i.e., large ϕ $\Longrightarrow$ Gravity (New) type Q ball

Φ starts oscillation when H ~ $m_{3/2}$.



At T=T_{RH}, $\left.\frac{\rho_Q}{\rho_{inf}}\right|_{RH} \sim \frac{m_{3/2}^2\phi_{osc}^2}{m_{3/2}^2 M_P^2} \sim \left(\frac{\phi_{osc}}{M_P}\right)^2$

$$\Longrightarrow \quad T_{eq} \sim T_{RH}\left(\frac{\phi_{osc}}{M_P}\right)^2$$

$$T_D \sim (\Gamma_Q M_P)^{\frac{1}{2}} \sim \left(\frac{m_{3/2}M_P}{48\pi|K|}\right)^{\frac{1}{2}} \beta^{-\frac{1}{2}}\frac{m_{3/2}}{\phi_{osc}}$$

$$\Longrightarrow \quad \Delta \sim \frac{T_{eq}}{T_D} \sim 10^3 \left(\frac{T_{RH}}{8\times 10^7 \mathrm{GeV}}\right)\left(\frac{\phi_{osc}}{5\times 10^{14}\mathrm{GeV}}\right)^3$$

$Q \sim 10^{24}$

$T_{eq} \sim 4$ GeV

$T_D \sim 4$ MeV

Dynamically,

$$\phi_{osc} \sim \left(\frac{H_{osc}}{\lambda M_P}\right)^{\frac{1}{n-2}} M_P$$

n=7 dddLL, λ~10

n=6 LLe or udd, λ~0.002

§5. Summary

Cosmic abundance of a long-lived charged particle such as a stau
is tightly constrained by the catalyzed big bang nucleosynthesis.

One of the solutions is to dilute them by a huge entropy production.

We evaluate the dilution factor in the case when the freeze-out
temperature is relatively low as in the stau NLSP scenario.

Q balls are the most promising source for this purpose.

Such Q balls are naturally produced in the gauge-med. SUSY scenario.