Dark matter production and baryogenesis from the Q-ball decay

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Ref.: SK, M. Kawasaki, M. Yamada, PLB 726, 1 (2013)
SK, M. Kawasaki, PRD 84, 123528 (2011)

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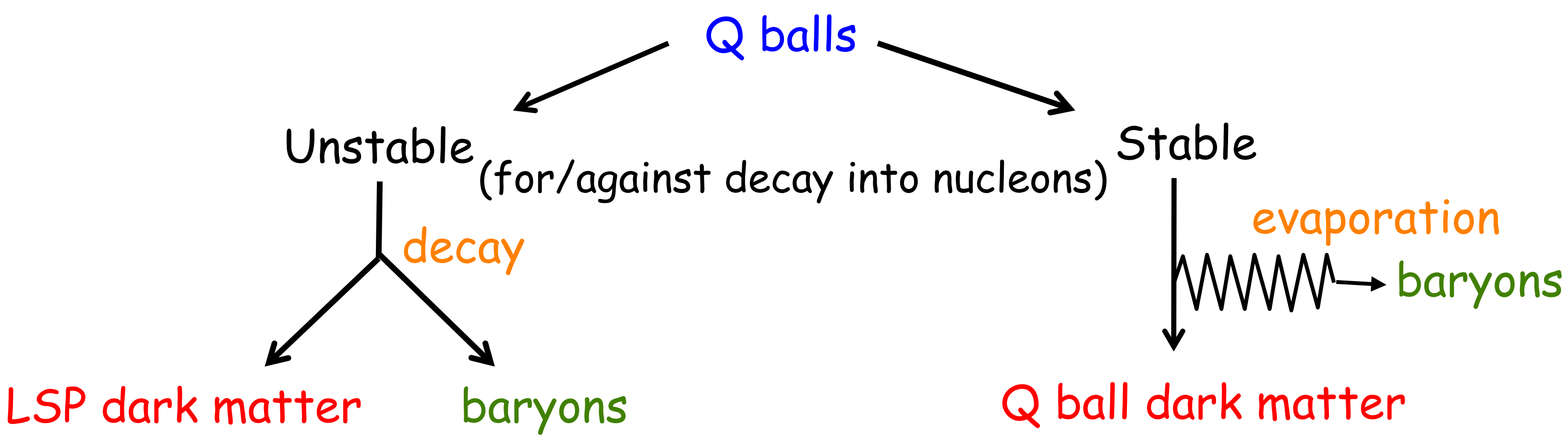
1. Introduction

Affleck-Dine & Q-ball cosmology

Simultaneous explanation for the dark matter & baryon asymmetry in the universe.

- The Affleck-Dine (AD) mechanism is very promising for baryogenesis.
- The AD field consists of some combinations of squarks in MSSM.
- The AD condensate transforms into Q balls.

Q balls will provide both the dark matter and baryon asymmetry.



Abundances have a direct relation because of the same origin.

1. Introduction

Affleck-Dine & Q-ball cosmology

Q balls will provide both the dark matter and baryon asymmetry.

Q balls

Unstable (for/against decay into nucleons) Stable

decay

evaporation → baryons

LSP dark matter baryons

Q ball dark matter

Gravity mediation

Enqvist, McDonald (1998)
Fujii, Hamaguchi (2002)
Seto (2006)
Roszkowski, Seto (2007)

Gauge mediation (small charge)

Shoemaker, Kusenko (2009)
Doddato, McDonald (2011,2013)
SK, Kawasaki (2011)

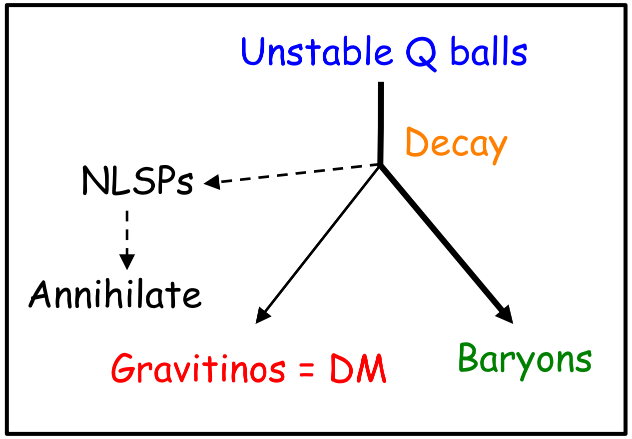
SK, Kawasaki, Yamada (2013) ← This talk

Gauge mediation (large charge)

Kusenko, Shaposhnikov (1998)
SK, Kawasaki (2001)

What to be shown

Very simple scenario to explain
both DM and B in gauge mediation.



Affleck-Dine condensate ⟶ Q balls

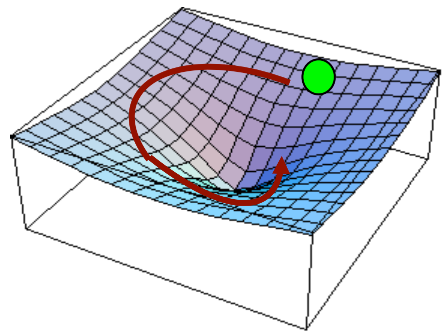
If the charge of the Q ball is small enough,
it can kinematically decay into nucleons.

The decay processes into baryons, gravitinos and NLSPs are studied in detail.

Q balls are unstable and decay
mainly into nucleons, → Baryons
partially into gravitinos, → DM
partially into NLSPs. → Annihilation occurs efficiently. Do not spoil BBN.

⟹ $\Omega_b \sim 0.2\ \Omega_{DM}$ is naturally explained.

2. Affleck-Dine baryogenesis



Affleck-Dine mechanism

Affleck, Dine (1985)

(1) Affleck-Dine (AD) field has large VEV during inflation.

(2) Starts rotation when $H \sim m_{\text{eff}} (= \sqrt{V''})$, after inflation.

⟹ Baryon number production

$$Q = \int d^3x \ \phi^2 \dot{\theta} \quad \left(\Phi = \frac{1}{\sqrt{2}} \phi e^{i\theta} \right)$$

(3) AD field decays into quarks.

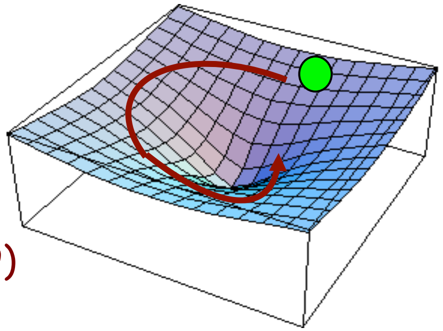
MSSM flat direction works as AD field.

Affleck, Dine (1985), Dine, Randall, Thomas (1996)

The MSSM flat direction is a scalar field consists of squarks, sleptons and maybe higgs whose potential vanishes along that direction.

	B-L		B-L
LH_u	-1	dddLL	-3
udd	-1	uuuee	1
LLe	-1	QuQue	1
QdL	-1		

2. Affleck-Dine Q-ball baryogenesis



Affleck-Dine Q-ball mechanism

Kusenko, Shaposhnikov (1998), Enqvist, McDonald (1998,1999)
SK, Kawasaki (2000,2001)

(1) Affleck-Dine (AD) field has large VEV during inflation.

(2) Starts rotation when $H \sim m_{\rm eff} (= \sqrt{V''})$, after inflation.

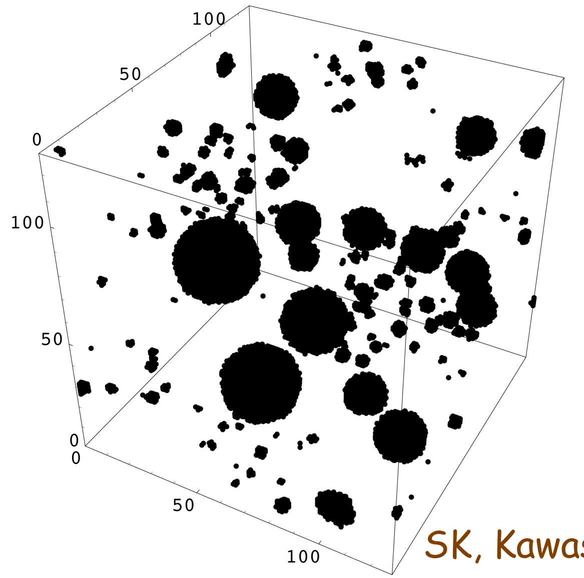
⟹ Baryon number production

$$Q = \int d^3x\ \phi^2 \dot{\theta} \quad \left(\Phi = \frac{1}{\sqrt{2}} \phi e^{i\theta}\right)$$

~~(3) AD field decays into quarks.~~

(3) AD condensate disintegrates into Q balls.

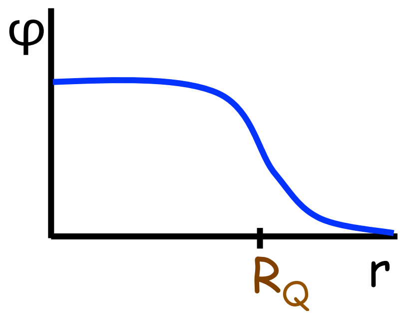
(4) Q balls emits baryons through the decay.



SK, Kawasaki (2001)

[A Q ball is a kind of non-topological soliton, the energy min. configuration of the scalar field with non-zero charge Q.]

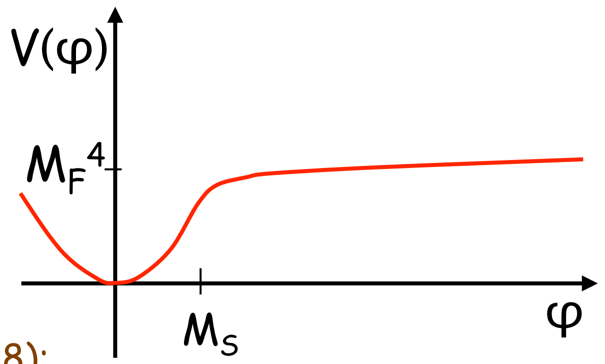
Coleman (1985)



3. Q ball in gauge mediation

The potential of the AD field is lifted by SUSY breaking effects, and in the gauge mediation it reads as

$$V(\Phi) = \begin{cases} m_\phi^2 |\Phi|^2, & (|\Phi| \ll M_S) \\ M_F^4 \left(\log \frac{|\Phi|^2}{M_S^2} \right)^2, & (|\Phi| \gg M_S) \end{cases}$$



$m_\phi \sim O(\mathrm{TeV})$

$$10^3 \ \mathrm{GeV} \lesssim M_F \lesssim \frac{g^{1/2}}{4\pi} \sqrt{m_{3/2} M_{\mathrm{P}}}$$

Kusenko, Shaposhnikov (1998);
de Gouvêa, Moroi, Murayama (1997)

Q balls form during the helical motion of the AD condensate.

$$Q = \beta \left(\frac{\phi_{\mathrm{osc}}}{M_F} \right)^4$$

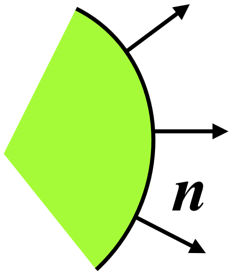
$$\beta = \begin{cases} 6 \times 10^{-4} & (\varepsilon = 1) \\ 6 \times 10^{-5} & (\varepsilon \lesssim 0.1) \end{cases}$$

SK, Kawasaki (2001)

Baryon #: $B = bQ$

$$\begin{cases} M_Q \simeq \frac{4\sqrt{2}\pi}{3} M_F Q^{3/4}, \\ R_Q \simeq \frac{1}{\sqrt{2}} M_F^{-1} Q^{1/4}, \\ \omega_Q \simeq \sqrt{2}\pi M_F Q^{-1/4}, \\ \phi_Q \simeq M_F Q^{1/4}, \end{cases}$$

4. Q-ball Decay



The decay takes place at the surface. Cohen et al. (1986)
Kawasaki, Yamada (2013)

Maximum charge decreasing rate = Maximum out-going flux

$$\mathcal{L}_{\rm int} = f\phi^* q\eta + {\rm h.c.}$$

$$-\frac{d^2Q}{dtd\mathcal{A}} \sim \langle \boldsymbol{n}\cdot\boldsymbol{j}\rangle \sim 2\int \frac{d^3k}{(2\pi)^3}\theta(\omega/2-|\boldsymbol{k}|)\hat{\boldsymbol{k}}\cdot\boldsymbol{n} \sim \frac{\omega_Q^3}{96\pi^2}$$

$$\Longrightarrow \quad \Gamma_Q^{(\rm sat,d)} \simeq \frac{1}{Q}\frac{dQ}{dt} \simeq \frac{1}{Q}\frac{\omega_Q^3}{96\pi^2}4\pi R_Q^2$$

This saturation occurs typically for $f\phi \gtrsim \omega_Q$.

For $f\phi \ll \omega_Q$, $\Gamma_Q \simeq \left(\frac{f\phi_Q}{\omega_Q}\right)^2 \Gamma_Q^{(\rm sat,d)}$ for the gauge-med. type Q ball.

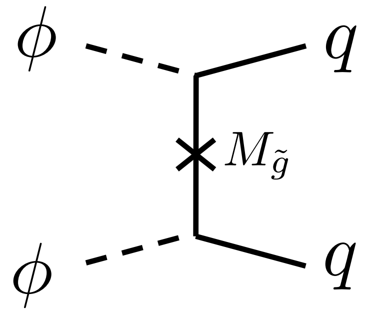
Kawasaki, Yamada (2013)

(the charge decreasing rate is estimated as the product of one-particle decay rate, particle Density and the effective volume.

$$\frac{dQ}{dt} \sim f^2\omega_Q \times \omega_Q\phi_Q^2 \times R_Q^3$$
)

4. Q-ball Decay

■ Main channel: decay into baryons (quarks)



$$\phi \to q + \tilde{g} \longrightarrow \Gamma_Q^{(q)} \simeq N_q \Gamma_Q^{(\mathrm{sat,d})} f_q \simeq g_s$$

$(\omega_Q > M_{\tilde{g}})$

★ $$\phi + \phi \to q + q \longrightarrow \Gamma_Q^{(q)} \simeq 8 N_q \Gamma_Q^{(\mathrm{sat,d})} \quad f_q \simeq M_{\tilde{g}}/\phi_Q$$

$(\omega_Q < M_{\tilde{g}})$

$\omega_Q \to 2\omega_Q$: larger phase space

SK, Kawasaki (2011), SK, Kawasaki, Yamada (2013)

■ Decay into gravitinos

$$\phi \to q + \psi_{3/2} \longrightarrow \Gamma_Q^{(3/2)} \simeq \left(\frac{f\phi_Q}{\omega_Q}\right)^2 \Gamma_Q^{(\mathrm{sat,d})} \quad f_{3/2} \simeq \frac{\omega_Q^2}{\sqrt{3} m_{3/2} M_{\mathrm{P}}}$$

Due to Pauli blocking & $f_{3/2}^2 \ll f_q^2 \longrightarrow B_{3/2} = f_{3/2}^2 / f_q^2$

SK, Kawasaki, Yamada (2013)

■ Decay into NLSPs $(\omega_Q > m_{\mathrm{NLSP}},\ \mathrm{i.e.,}\ Q < Q_{\mathrm{cr}})$

$$\phi \to q + \chi \longrightarrow \Gamma_Q^{(\mathrm{NLSP})} \simeq \Gamma_Q^{(\mathrm{sat,d})} \quad f_{\mathrm{NLSP}} \simeq g$$

Pauli blocking, but $f_{\mathrm{NLSP}} \gg f_q \longrightarrow B_{\mathrm{NLSP}} \simeq \Gamma_Q^{(\mathrm{NLSP})} / \Gamma_Q^{(q)}$

SK, Kawasaki, Yamada (2013)

5. Abundances

Since AD field rotates with ellipticity ε, the Q ball decays into nucleons, partially into gravitinos with branching ratio $B_{3/2}$, and into NLSPs only with fraction Q_{cr}/Q and branching ratio B_{NLSP}, we have

$$\begin{cases} n_b \simeq \varepsilon b n_\phi \\ n_{3/2} \simeq B_{3/2} n_\phi \\ n_{\rm NLSP} \simeq B_{\rm NLSP}(Q/Q_{\rm cr}) n_\phi \end{cases}$$

$$(\omega_Q(Q_{\rm cr}) = m_{\rm NLSP})$$

(i) Bayon number

$$Y_b \equiv \frac{n_b}{s} = \begin{cases} \dfrac{3T_{\rm D}}{4}\dfrac{n_b}{\rho_Q}\Big|_{\rm D} = \dfrac{3T_{\rm D}}{4}\dfrac{n_b}{\rho_Q}\Big|_{\rm osc} \simeq \dfrac{3T_{\rm D}}{4}\dfrac{\varepsilon b n_\phi}{\frac{4}{3}\omega_Q n_\phi} \simeq \dfrac{9T_{\rm D}\varepsilon b}{16\omega_Q}, & ({\rm QD}) \\ \dfrac{3T_{\rm RH}}{4}\dfrac{n_b}{\rho_{\rm rad}}\Big|_{\rm RH} = \dfrac{3T_{\rm RH}}{4}\dfrac{n_b}{\rho_{\rm inf}}\Big|_{\rm osc} \simeq \dfrac{9}{8\sqrt{2}}\varepsilon b \beta^{-3/4}\dfrac{M_F T_{\rm RH}}{M_{\rm P}^2}Q^{3/4}, & ({\rm NQD}) \end{cases}$$

(ii) Dark matter density

$$\frac{\rho_{3/2}}{\rho_b} = \frac{m_{3/2}}{m_N}\frac{n_{3/2}}{n_b} \simeq \frac{m_{3/2}}{m_N}\frac{B_{3/2}}{\varepsilon b} \approx 5$$

Using (i) & (ii), we obtain the region for simultaneously explaining B & DM.

5. Abundances

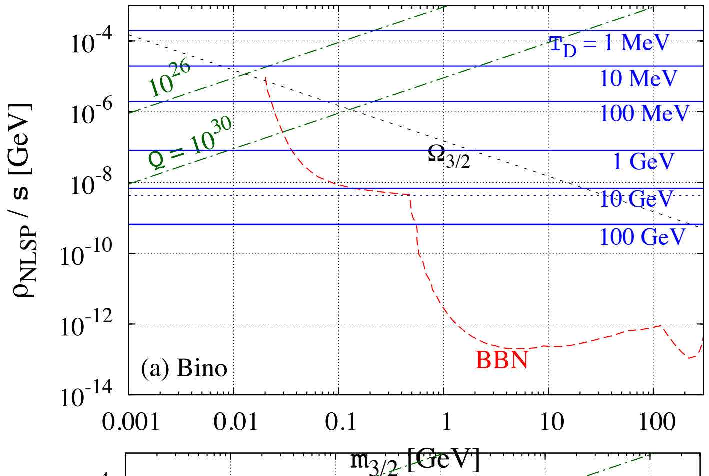
(iii) NLSP density

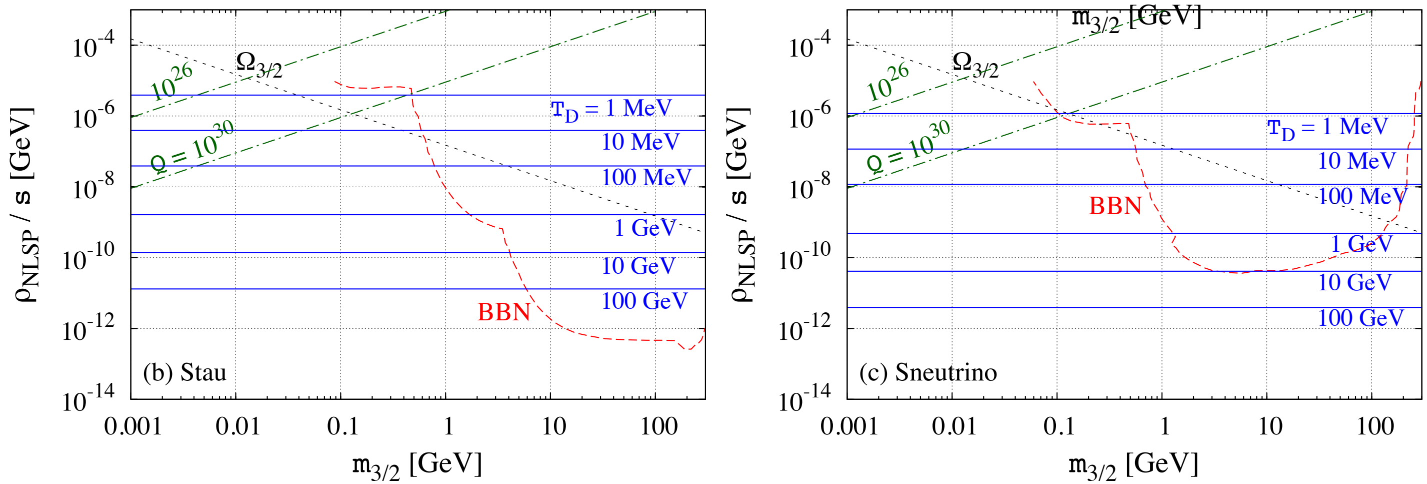
$$\frac{\rho_{\rm NLSP}^{(Q)}}{s} = m_{3/2} Y_{3/2} \frac{\rho_{\rm NLSP}}{\rho_{3/2}} \simeq 5 m_N Y_b \frac{m_{\rm NLSP}}{m_{3/2}} \frac{n_{\rm NLSP}}{n_{3/2}} = 5 m_N Y_b \frac{m_{\rm NLSP}}{m_{3/2}} \frac{B_{\rm NLSP} Q_{\rm cr}}{B_{3/2} Q}$$

However, annihilation takes place afterwards.

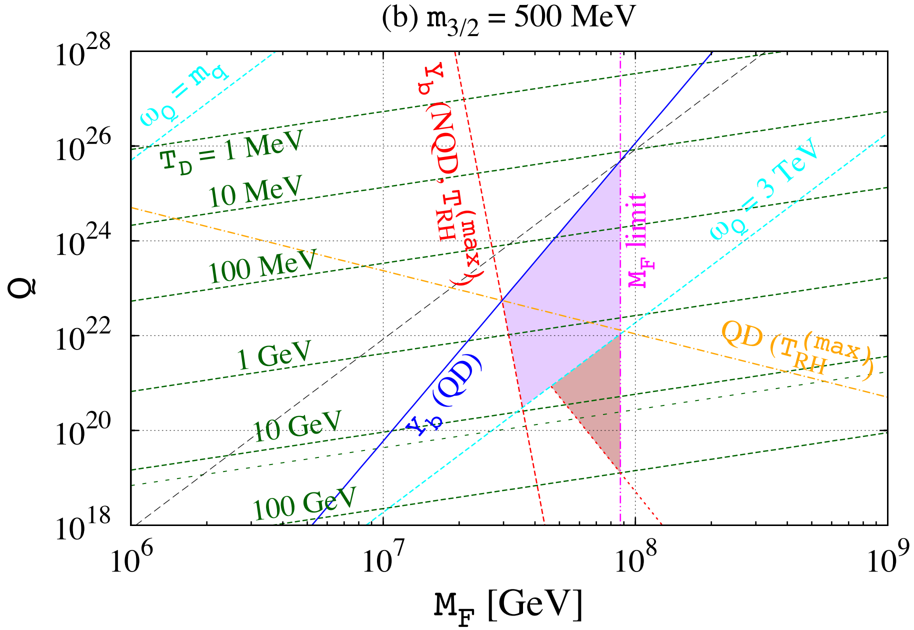
$$\left(n_{\rm NLSP}^{(\rm ann)} \simeq H(T_{\rm D})/\langle \sigma v \rangle \right)$$

No harm for BBN for $m_{3/2}$ < 1 GeV. $(\tilde{\tau}, \tilde{\nu})$
0.1 $(\tilde{B})$





6. Allowed parameter space



(i) B & DM

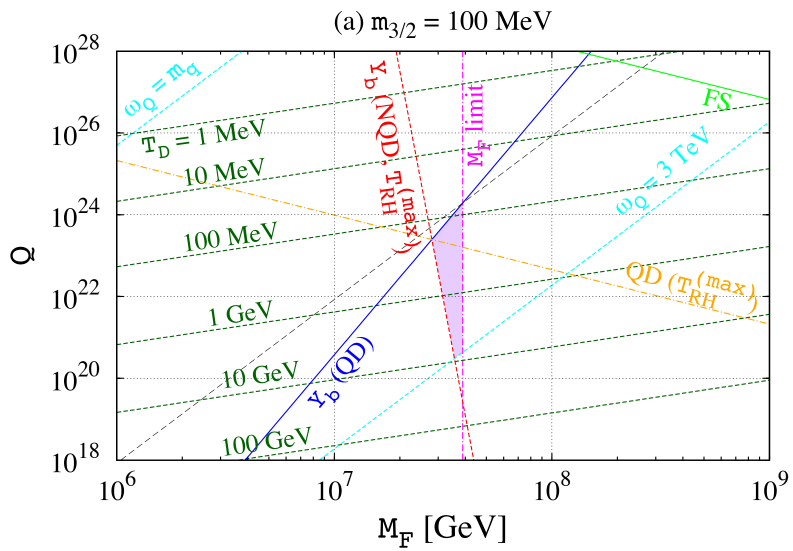
Y_b(QD)

Y_b(NQD) ⟵ T_{RH}-dep.

$$\rho_{3/2}^{(\mathrm{th})} < \rho_{\mathrm{DM}}$$

$$T_{\mathrm{RH}} \lesssim 8.3 \times 10^4 \text{ GeV} \left(\frac{m_{3/2}}{100 \text{ MeV}}\right)\left(\frac{M_{\tilde{g}}}{3 \text{ TeV}}\right)^{-2}$$

(ii) M_F limit $\quad M_F \lesssim \frac{g^{1/2}}{4\pi}\sqrt{m_{3/2}M_{\mathrm{P}}}$



(iii) Decay temperature

$$T_{\mathrm{D}} = \left(\frac{90}{4\pi^2 N_{\mathrm{D}}}\right)^{1/4}\sqrt{\Gamma_Q^{(\mathrm{q})}M_{\mathrm{P}}} \gtrsim O(\mathrm{MeV})$$

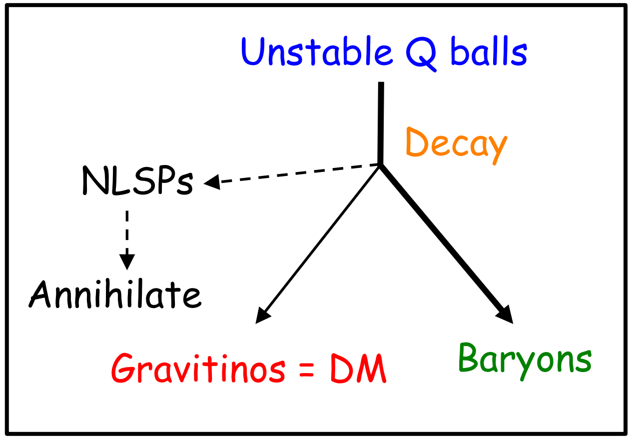
(iv) Kinematics $\quad \omega_Q > m_q$

(v) Free streaming $\quad \ell_{\mathrm{FS}} < \mathrm{Mpc}$

⇨
$$\begin{cases} M_F = 3\times 10^7 - 3\times 10^8 \mathrm{GeV} \\ Q = 10^{19} - 10^{26} \\ m_{3/2} = 50\mathrm{MeV} - 5\mathrm{GeV} \end{cases}$$

7. Conclusions

Very simple scenario to explain
both DM and B in GMSB.



The decay processes into baryons, gravitinos and NLSPs are studied in detail.

Unstable Q balls decay mainly into nucleons, → Baryons
partially into gravitinos, → DM
partially into NLSPs. → Annihilation occurs efficiently. Do not spoil BBN.

$\Omega_b \sim 0.2\ \Omega_{DM}$ is explained typically for

$Q \sim 10^{19} - 10^{26}$, $M_F = 3\times10^{7} - 3\times10^{8}$ GeV, $m_{3/2} \sim 0.05 - 5$ GeV.