Dark matter and baryon asymmetry from Q-ball decay in gauge mediation

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Ref.: SK, Kawasaki, PRD84, 123528 (2011)
SK, Kawakami, Kawasaki, to appear on arXiv tomorrow

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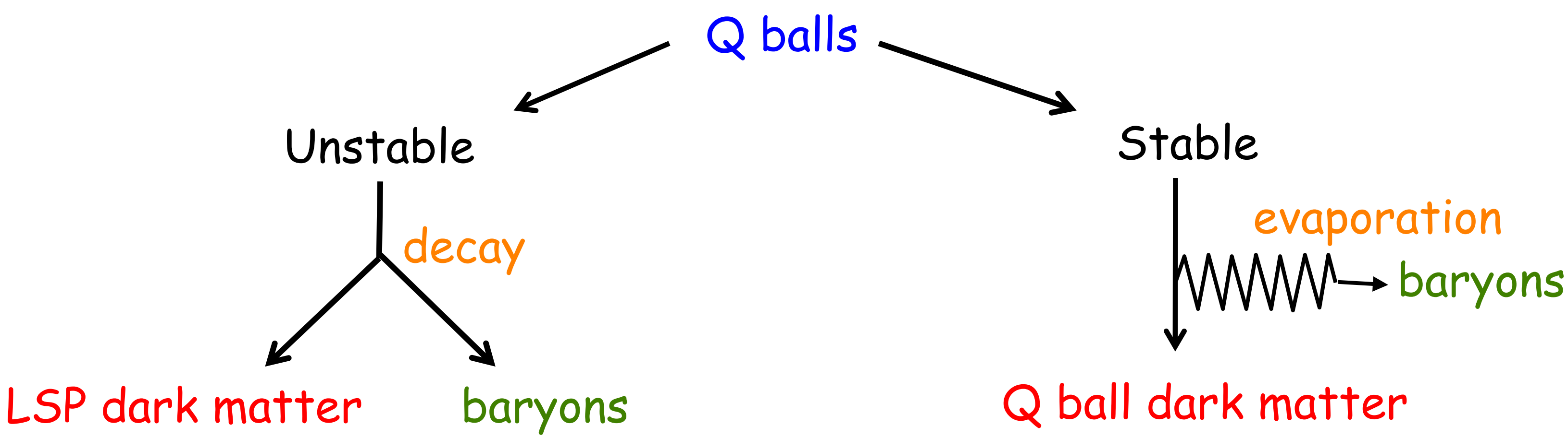
1. Introduction

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.

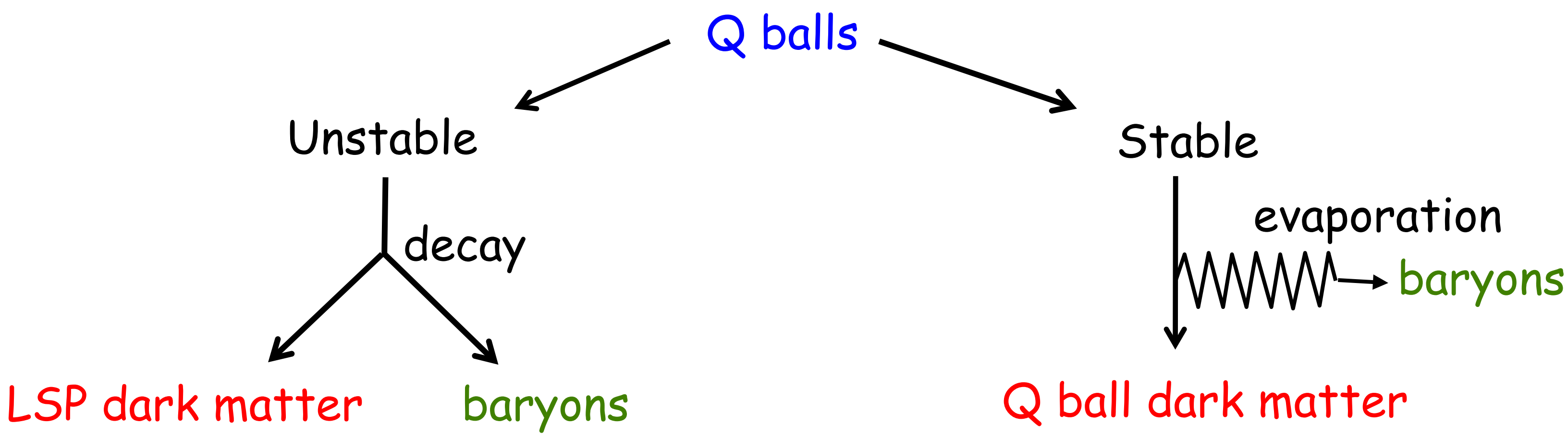


Abundances have a direct relation because of the same origin.

1. Introduction

Affleck-Dine & Q-ball cosmology

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



Gravity mediation

- Neutralino — Enqvist, McDonald (1998)
- Higgsino & Wino — Fujii, Hamaguchi (2002)
- Gravitino — Seto (2006)
- Axino — Roszkowski, Seto (2007)

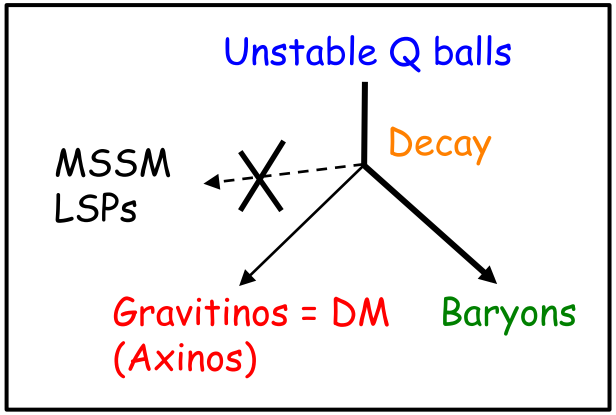
Gauge mediation (small charge)

- Gravitino — Shoemaker, Kusenko (2009) ; Doddato, McDonald (2011); SK, Kawasaki (2011) ←
- Axino — SK, Kawakami, Kawasaki (2012) ←

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

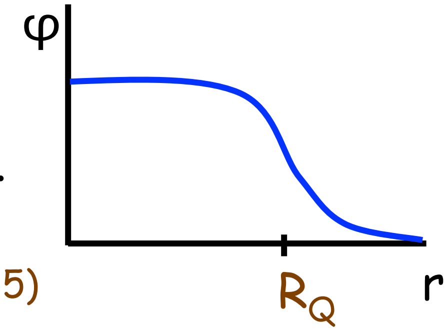
If the Q-ball charge is small enough to decay into nucleons,
but large enough to be kinematically
forbidden to decay into MSSM LSPs,

⇨ Q balls are unstable and decay
mainly into nucleons, ⟶ Baryons
partially into gravitinos (axinos), ⟶ DM
hardly into MSSM LSPs. ⟶ Not spoiling BBN

The rate of the decay into nucleons is saturated,
into gravitinos is not and small
(into axino is generally small, but could be saturated).

With oblate orbit of AD field ⟶ $\Omega_b \sim 0.2\, \Omega_{DM}$

2. Q ball in gauge mediation

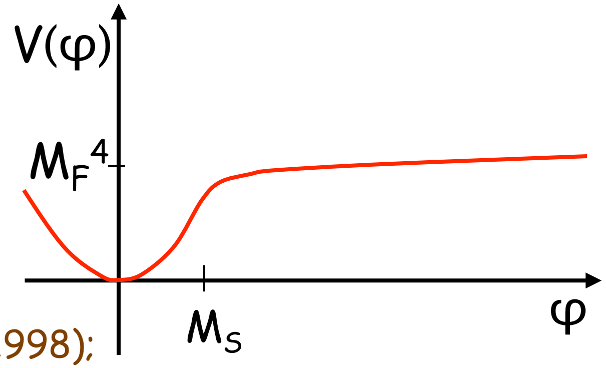


A Q ball is a kind of non-topological soliton, the energy min. configuration of the scalar field with non-zero charge Q.

Coleman (1985)

In MSSM, the AD field consists of some combination of squarks (and sleptons), whose potential in the gauge mediation reads

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

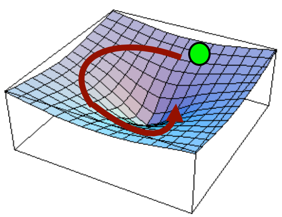


$$m_\phi \sim O(\mathrm{TeV})$$

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

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 #: $B = bQ$

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

3. Q-ball Decay

Kinematics

The Q ball can decay if the mass per charge M_Q/Q is larger than the decay-particle mass m_D.

$$\frac{M_Q}{Q} > m_{\rm D} \quad \Longrightarrow \quad Q < \frac{1024\pi^4}{81}\left(\frac{M_F}{m_{\rm D}}\right)^4$$

Allow

(i) Decay into nucleons ($m_N \approx 1$ GeV)

(ii) Decay into gravitinos/axinos ($m_{3/2}$, $m_{axino} \lesssim$ GeV)

Forbid

(iii) Decay into MSSM LSPs (m_{MLSP}=O(100) GeV)

$$\Longrightarrow \quad Q_{\rm cr} \equiv \frac{1024\pi^4}{81}\left(\frac{M_F}{O(100){\rm GeV}}\right)^4 < Q < \frac{1024\pi^4}{81}\left(\frac{M_F}{\rm GeV}\right)^4$$

Only after the charge becomes smaller than Q_{cr}, MLSPs would be produced.

SK, Takahashi (2007); SK, Kawasaki (2011)

3. Q-ball Decay

Decay rates

The decay process takes place on the surface, and the rate is given by

Cohen, Coleman, Georgi, Manohar (1986)

$$\Gamma_Q \simeq \begin{cases} \Gamma_Q^{(\mathrm{sat})} & (f_{\mathrm{eff}}\phi_Q \gtrsim \omega_Q) \\ 3\pi \frac{f_{\mathrm{eff}}\phi_Q}{\omega_Q}\Gamma_Q^{(\mathrm{sat})} & (f_{\mathrm{eff}}\phi_Q \ll \omega_Q) \end{cases}$$

$$\Gamma_Q^{(\mathrm{sat})} \simeq \frac{1}{Q}\frac{\omega_Q^3}{192\pi^2}4\pi R_Q^2 \simeq \frac{\pi^2}{24\sqrt{2}}M_F Q^{-5/4}$$

$$\mathcal{L}_{\mathrm{int}} = f_{\mathrm{eff}}\phi\psi\bar{\psi}$$

(i) Decay into nucleons **saturated**

$$\Gamma_Q = \Gamma_Q^{(\mathrm{sat})} \Longrightarrow T_{\mathrm{D}} \simeq 2.4\ \mathrm{MeV}\left(\frac{M_F}{10^6\ \mathrm{GeV}}\right)^{\frac{1}{2}}\left(\frac{Q}{10^{23}}\right)^{-\frac{5}{8}}$$

Decay before BBN

(ii-1) Decay into gravitinos **unsaturated**

$$B_{3/2} \equiv \frac{\Gamma_Q^{(3/2)}}{\Gamma_Q^{(\mathrm{sat})}} \simeq \sqrt{3}\pi^2\frac{M_F^2}{m_{3/2}M_{\mathrm{P}}} \lesssim 0.1 g_s \ll 1$$

$$f_{\mathrm{eff}}^{(3/2)} \simeq \frac{1}{\sqrt{6}}\frac{\omega_Q^2}{m_{3/2}M_{\mathrm{P}}}$$

(ii-2) Decay into axinos **saturated/unsaturated**

$$B_{\tilde{a}} \equiv \frac{\Gamma_Q^{(\tilde{a})}}{\Gamma_Q^{(\mathrm{sat})}} \simeq 4.8\times 10^{-4}\left(\frac{f_a}{10^{14}\,\mathrm{GeV}}\right)^{-1}\log\left(\frac{f_a}{10^3\,\mathrm{GeV}}\right)\left(\frac{Q}{10^{21}}\right)^{\frac{1}{2}}$$

Depends on parameters

$$f_{\mathrm{eff}}^{(\tilde{a})} = \frac{\alpha_s^2}{\sqrt{2}\pi^2}\frac{m_{\tilde{g}}}{f_a}\log\left(\frac{f_a}{m_{\tilde{g}}}\right)$$

Covi et al. (2002)

4. Abundances

Since AD field rotates with ellipticity ε, the Q ball decays into nucleons, partially into gravitinos/axinos with branching ratio $B_{3/2}$, $B_{\tilde{a}}$, and into MLSPs only with fraction Q_{cr}/Q, the number densities are related to Φ-numbers as

$$n_b \simeq \varepsilon b n_\phi$$

$$n_{3/2} \simeq B_{3/2} n_\phi$$

$$n_{\tilde{a}} \simeq B_{\tilde{a}} n_\phi$$

$$n_{\rm MLSP} \simeq \frac{Q_{\rm cr}}{Q} n_\phi$$

+

$$Y_b \simeq \frac{3}{4} T_{\rm RH} \left.\frac{n_b}{\rho_{\rm inf}}\right|_{\rm osc}$$

$$\rho_{DM}/\rho_b \simeq 5$$

(DM=3/2 or ã)

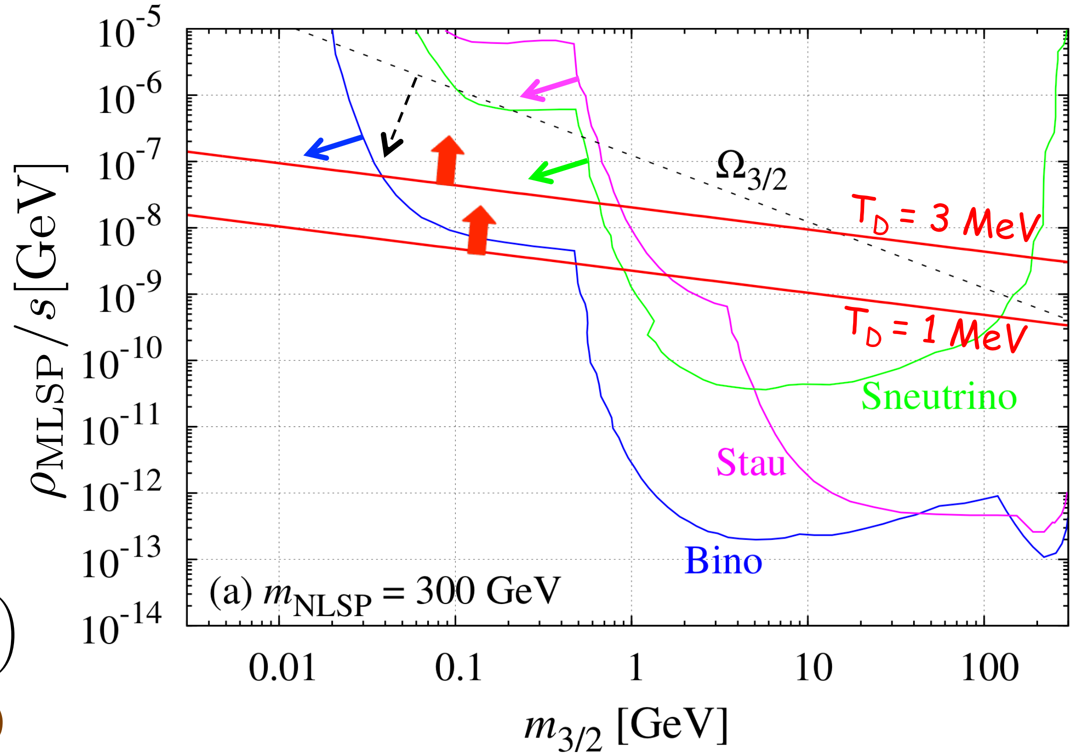
$$\frac{\rho_{\rm MLSP}}{s} \simeq m_N Y_b \frac{\rho_{\rm MLSP}}{\rho_{\rm DM}}$$

Since $B_{3/2}$ << B_a, realizations for the successful scenario appear differently, we consider the gravitino DM and the axino DM separately below.

5. BBN constraints

MLSP abundance has an upper limit in order not to spoil the BBN.

Limits are taken from
Kawasaki, Kohri, Moroi, Yotsuyanagi (2008)



Thermally produced gravitinos do not overclose the universe:

$$T_{\rm RH} \lesssim 3\times 10^7\ {\rm GeV}\left(\frac{m_{\tilde{g}_3}}{500\ {\rm GeV}}\right)^{-2}\left(\frac{m_{3/2}}{\rm GeV}\right)$$

Kawasaki, Takahashi, Yanagida (2006)

Together with that the decay takes place before the BBN: T_D > 1 MeV (or 3 MeV)

$$\Longrightarrow \frac{\rho_{\rm MLSP}}{s} \simeq 7.0\times 10^{-9}\ {\rm GeV}\left(\frac{T_{\rm RH}}{10^6\ {\rm GeV}}\right)^{-1/3}\left(\frac{T_D}{\rm MeV}\right)^2\left(\frac{m_{\rm NLSP}}{300\ {\rm GeV}}\right)^{-3}\left(\frac{Y_b}{10^{-10}}\right)^{4/3}$$

$$\gtrsim 2.3\times 10^{-9}\ {\rm GeV}\left(\frac{m_{3/2}}{\rm GeV}\right)^{-1/3}\left(\frac{T_D}{\rm MeV}\right)^2\left(\frac{m_{\rm NLSP}}{300\ {\rm GeV}}\right)^{-3}$$

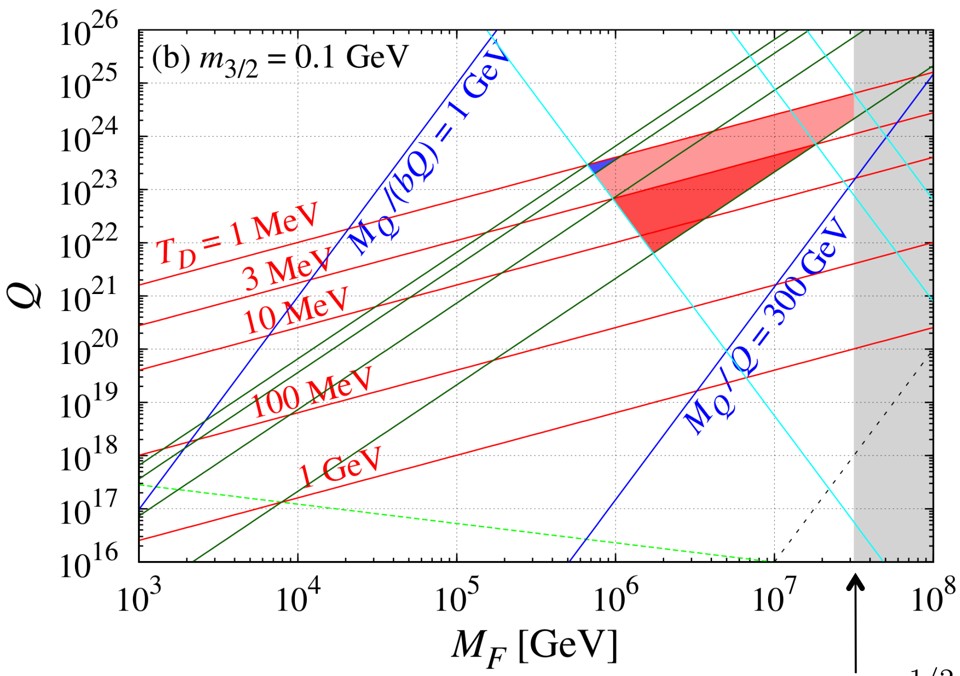
(If the gravitino DM is produced by the MLSP decay only (dotted line):

$$\left.\frac{\rho_{\rm MLSP}}{s}\right|_{\rm max} \simeq 1.5\times 10^{-7}\ {\rm GeV}\left(\frac{m_{\rm NLSP}}{300\ {\rm GeV}}\right)\left(\frac{m_{3/2}}{\rm GeV}\right)^{-1}\left(\frac{Y_b}{10^{-10}}\right)$$

)

$\Longrightarrow$ Typically, $m_{3/2}$ < GeV for m_{MLSP} = 300 GeV.
($m_{3/2}$ < 10^{-2} GeV for m_{MLSP} = 100 GeV)

6. Allowed parameter space



$$M_F \simeq \frac{g^{1/2}}{4\pi}\sqrt{m_{3/2}M_{\rm P}}$$

Reheating temperature

$$Q \simeq 2.4\times 10^{23}\left(\frac{T_{\rm RH}}{10^6\ {\rm GeV}}\right)^{-4/3}\left(\frac{M_F}{10^6\ {\rm GeV}}\right)^{-4}$$

Temperature at the decay

$$Q \simeq 4.0\times 10^{23}\left(\frac{T_{\rm D}}{\rm MeV}\right)^{-8/5}\left(\frac{M_F}{10^6\ {\rm GeV}}\right)^{4/5}$$

MLSP abundance

$$Q \simeq 3.2\times 10^{23}\left(\frac{\rho_{\rm MLSP}/s}{10^{-8}\ {\rm GeV}}\right)^{-1}\times\left(\frac{M_F}{10^6\ {\rm GeV}}\right)^{2}\left(\frac{m_{\rm NLSP}}{300\ {\rm GeV}}\right)^{-3}$$

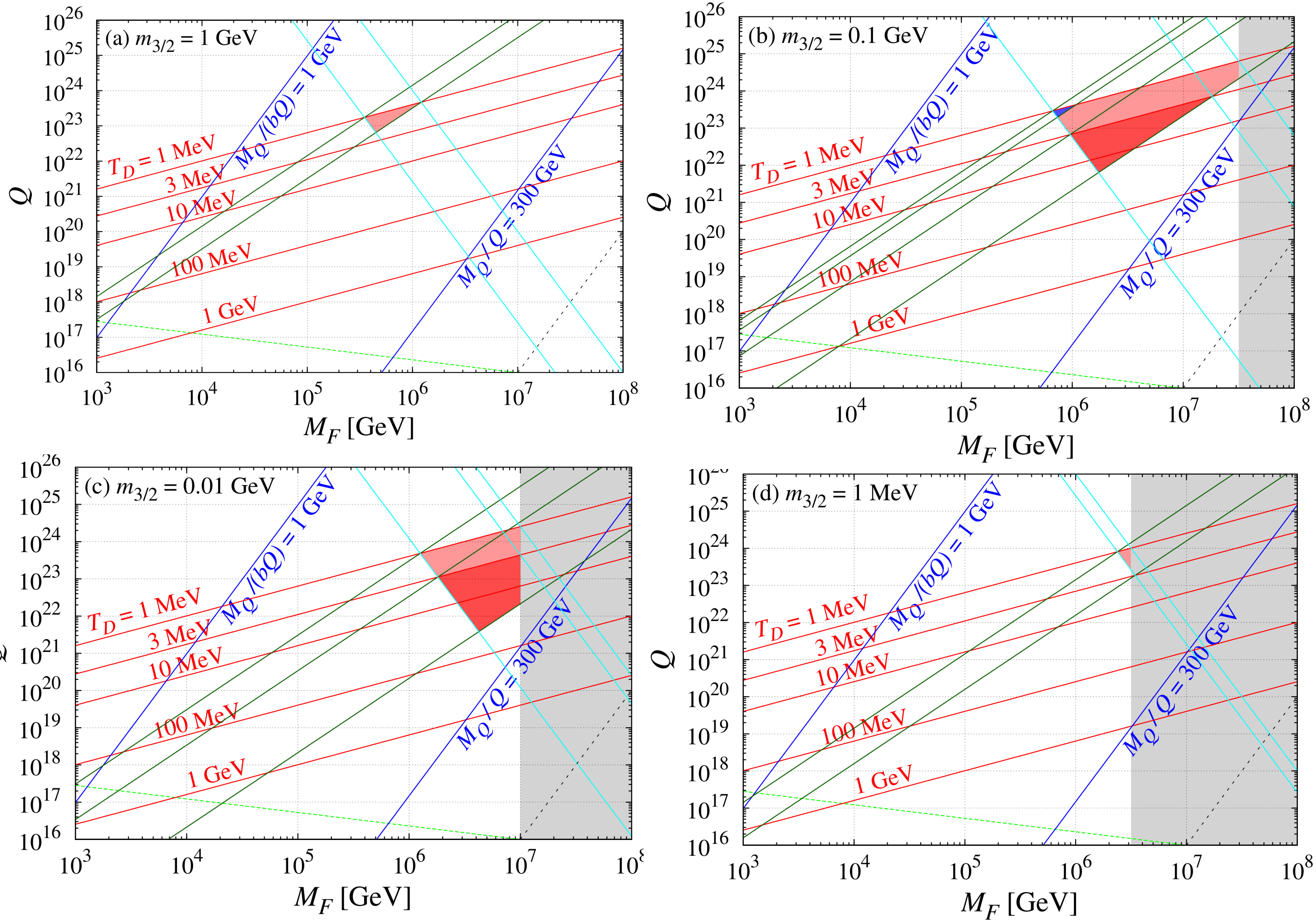
Typically,
$Q \sim 10^{23}$,
$M_F = 10^6$-10^7 GeV.

Charge evaporation (light green)

$$Q_{\rm evap} \simeq 2.3\times 10^{16}\left(\frac{M_F}{10^6\ {\rm GeV}}\right)^{-4/11}\left(\frac{m_\phi}{\rm TeV}\right)^{-8/11}$$

Gauge-med. type (dotted)

$$Q_{\rm gauge} \simeq 10^{12}\left(\frac{M_F}{10^6\ {\rm GeV}}\right)^{4}\left(\frac{m_\phi}{\rm TeV}\right)^{-4}$$



Typically, $m_{3/2} = 10^{-2} - 10^{-1}$ GeV

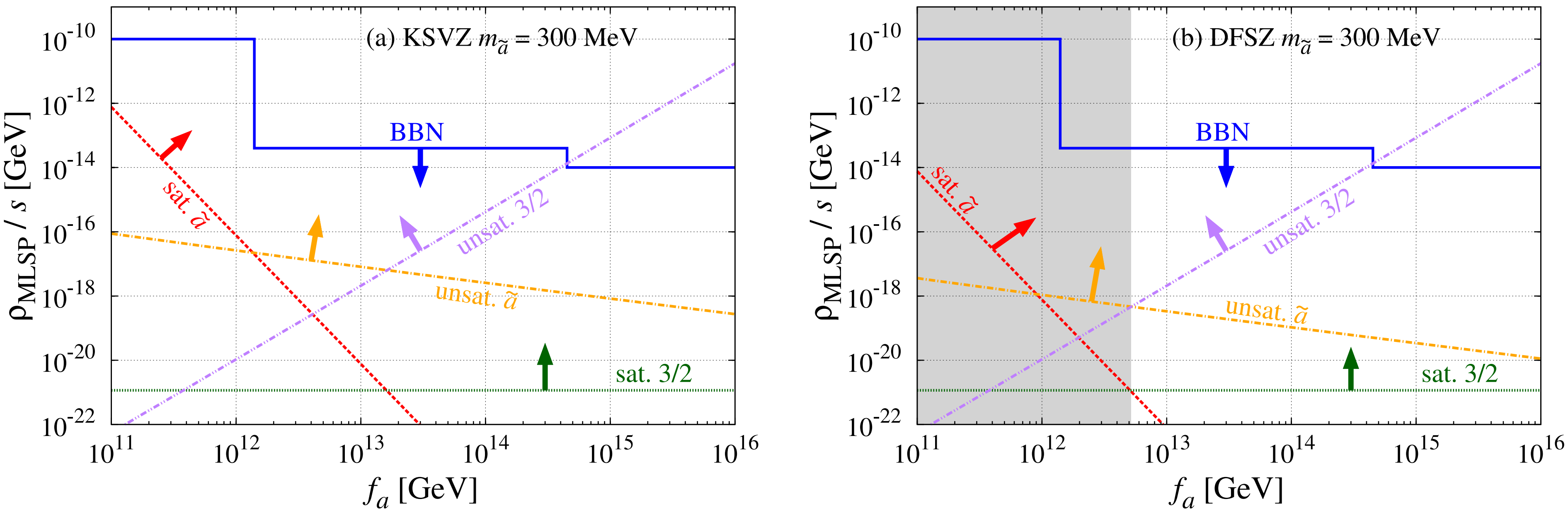
7.1. Axino DM case

Two models: KSVZ & DFSZ.

Two types of decay into axinos: saturated or unsaturated.

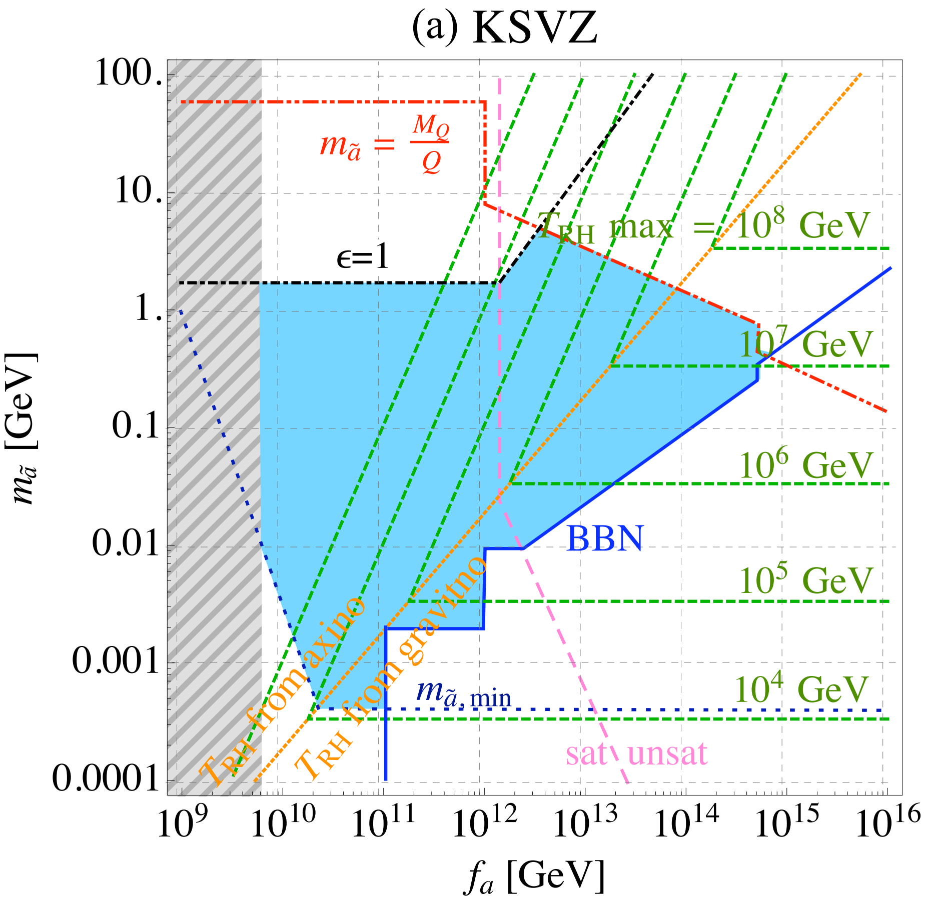
Two components gives the highest possible T_{RH}: gravitinos or axinos.

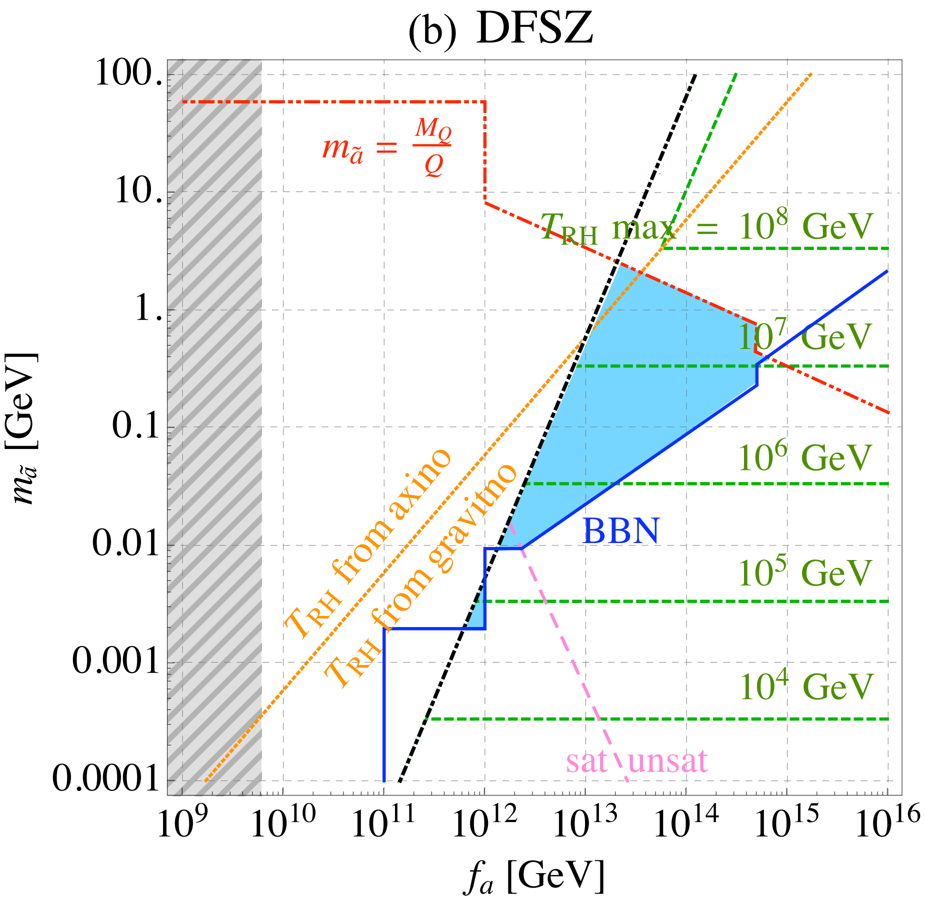
⇨ These complicates the analysis, but the essence is the same.



7.2. Allowed regions

Axino parameter space (f_a, m_a)





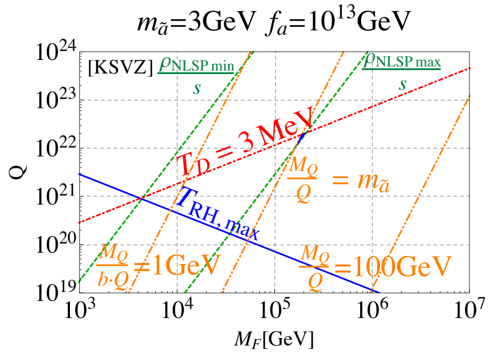
6×10^9 GeV < f_a < 5×10^{14} GeV

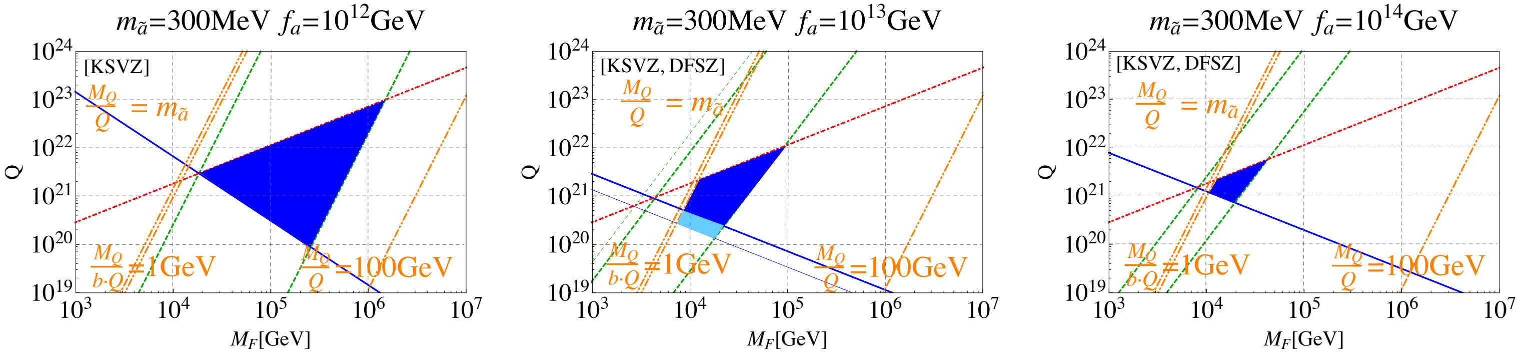
m_a = O(MeV) – O(GeV)

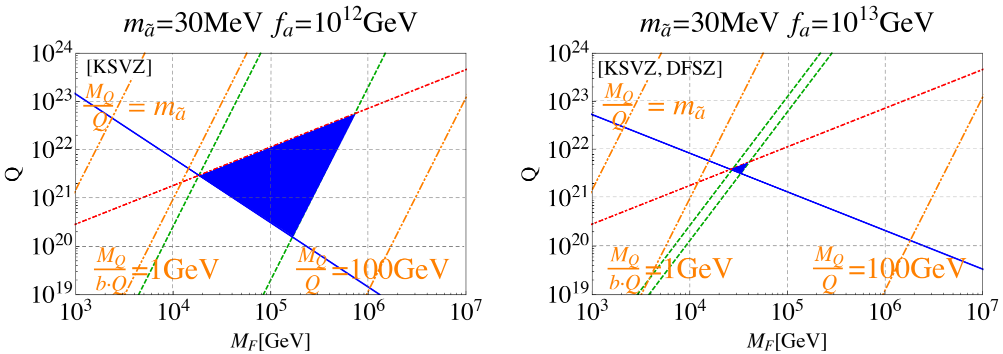
10^{12} GeV < f_a < 5×10^{14} GeV

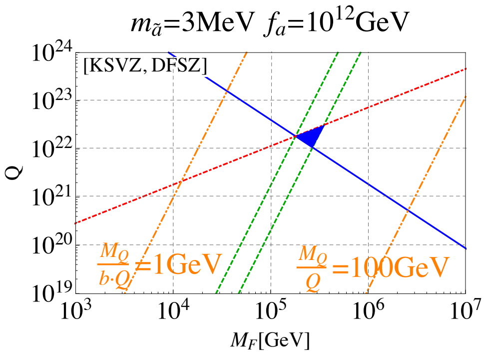
m_a = O(10 MeV) – O(GeV)

Q-ball parameter space
(M_F, Q)







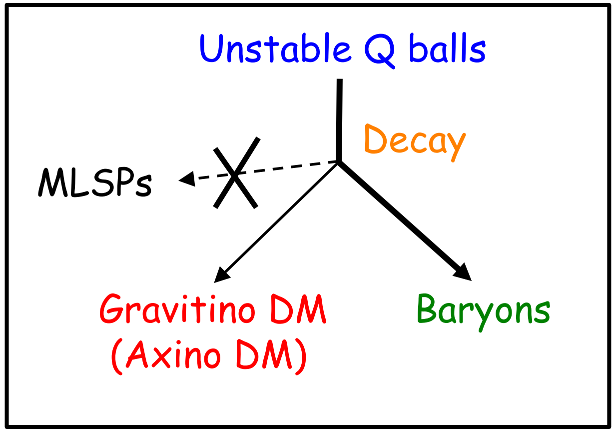


$Q = 10^{20} - 10^{22}$

$M_F = 10^4 - 10^6$ GeV

7. Conclusions

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



Unstable Q balls decay mainly into nucleons, → Baryons
partially into gravitinos/axinos, → DM
hardly into MLSPs. → Not spoiling BBN
(Still, small amount created constrains the model.)

The Q-ball charge is small enough to decay into nucleons,
large enough not to decay into MLSPs.

→ $T_D \sim O(10\ \mathrm{MeV})$

The rate of the decay into nucleons is saturated,
into gravitinos is not and small.
(into axinos is saturated/unsaturated.)

$\Omega_b \sim 0.2\ \Omega_{DM}$ can be explained.