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

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Ref.: SK, Kawakami, Kawasaki, arXiv:1202.4067

2012.5.30, Planck 2012, Warsaw, Poland

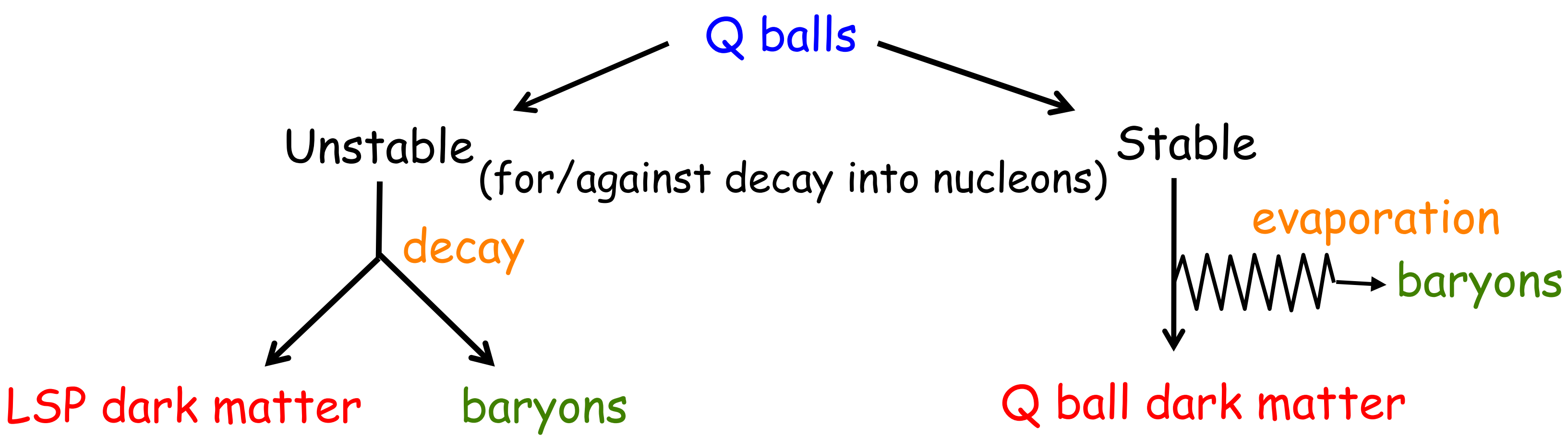
1. Introduction

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.

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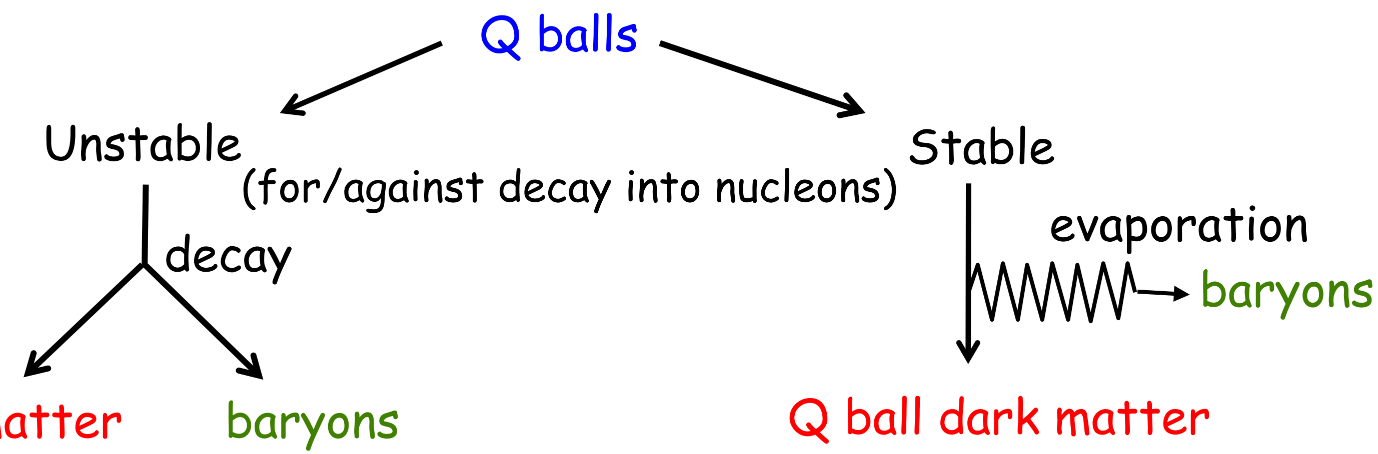


Gravity mediation

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

Gauge mediation

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

(Axino is a fermionic superpartner of axion, which is introduced to solve the strong CP problem in QCD.)

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)
  - decay → LSP dark matter, baryons
- Stable
  - evaporation → baryons
  - → Q ball dark matter

LSP dark matter

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) ←

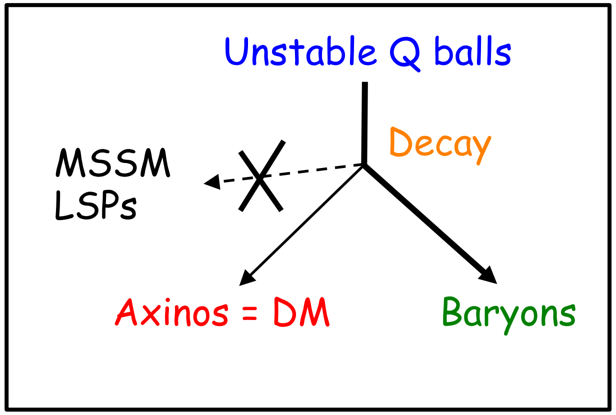
Q ball dark matter

Gauge mediation (large charge)

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

(Axino is a fermionic superpartner of axion, which is introduced to solve the strong CP problem in QCD.)

What to be shown



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

Affleck-Dine condensate ⟶ Q balls

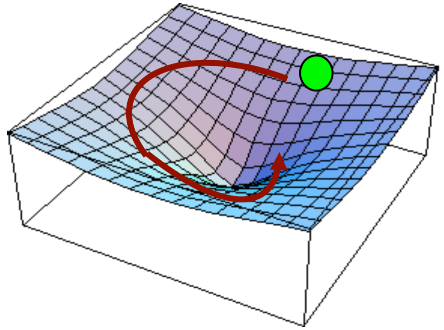
If the Q-ball charge is small enough to decay into nucleons,
but large enough to be kinematically
forbidden to decay into MSSM LSPs,

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

The rate of the decay into nucleons is saturated,
into axino is generally small, but could be saturated.

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

2. Affleck-Dine baryogenesis



Affleck-Dine mechanism

Affleck, Dine (1985)

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

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

MSSM flat direction works as AD field.

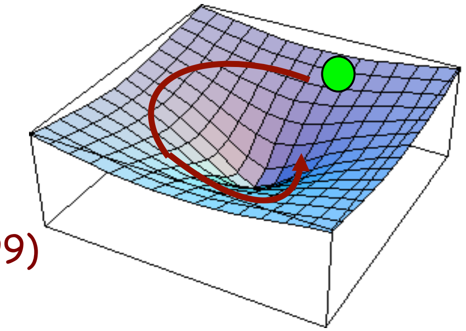
Affleck, Dine (1985), Dine, Randall, Thomas (1996)

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

Some examples:

LH_u	dddLL
udd	uuuee
LLe	QuQue
QdL	

2a. Affleck-Dine Q-ball baryogenesis



Affleck-Dine Q-ball mechanism

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

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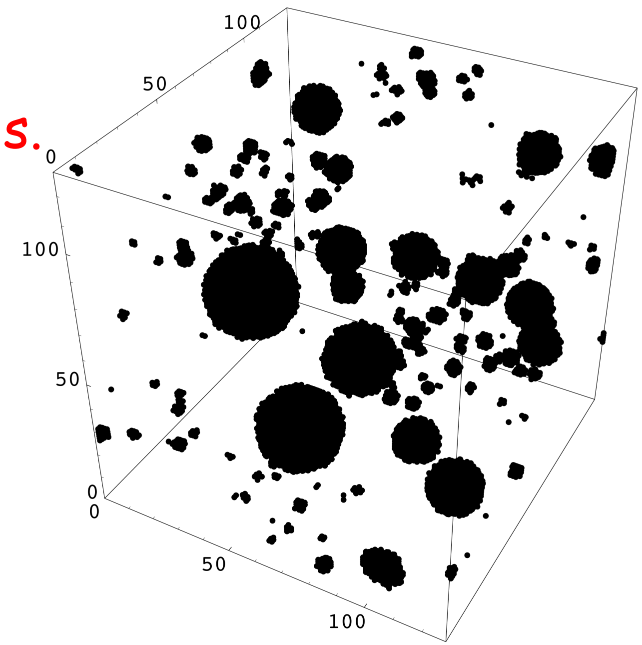
~~(3) AD field decays into quarks.~~

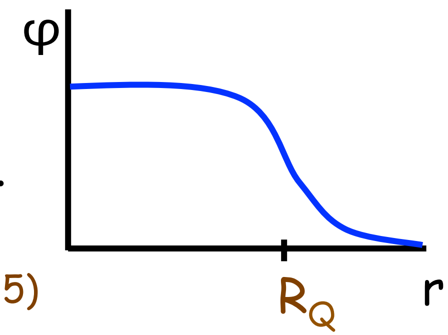
(3) AD condensate disintegrates into Q balls.

(4) Q balls emits baryons.
(through the decay or
the evaporation in thermal bath)



SK, Kawasaki (2001)

3. Q ball in gauge mediation

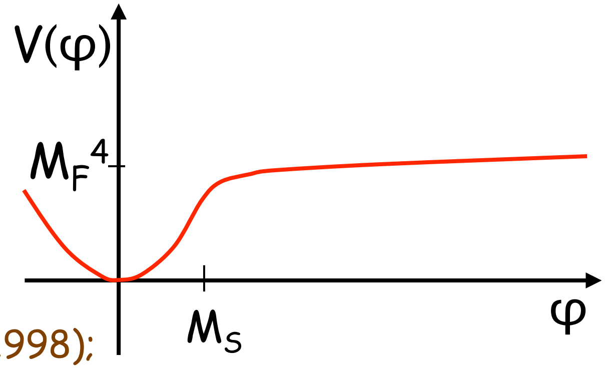


A Q ball is a kind of non-topological soliton, the energy min. configuration of the scalar field with non-zero charge Q.

Coleman (1985)

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 #: $B = bQ$

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

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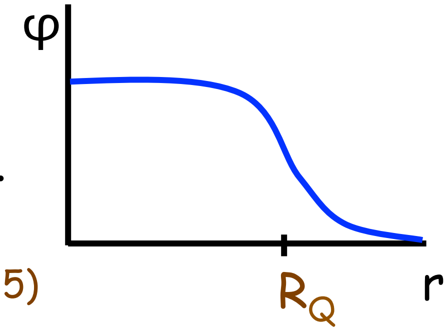

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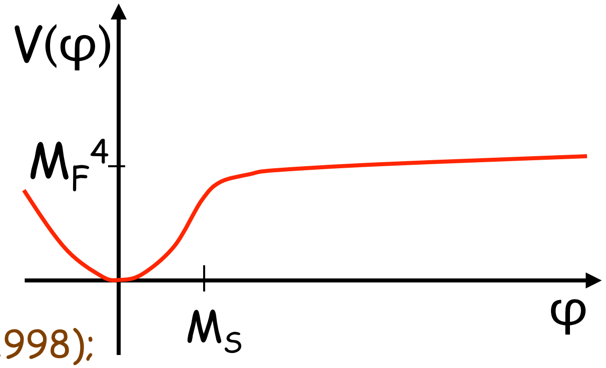

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4. Q-ball Decay

Kinematics

The Q ball can decay if the mass per charge M_Q/Q ($\sim Q^{-1/4}$) is larger than the decay-particle mass m_D.

$$m_{\rm D} < \frac{M_Q}{Q} \left(\propto Q^{-1/4}\right) \Longrightarrow Q < \frac{1024\pi^4}{81}\left(\frac{M_F}{m_{\rm D}}\right)^4$$

Allowed

(i) Decay into nucleons ($m_N \approx 1$ GeV, i.e., $m_D \approx 0.3$ GeV for b=1/3)

(ii) Decay into axinos ($m_{\tilde{a}} <$ GeV) ($m_{\tilde{a}} = m_{3/2}$ is assumed)

Forbidden

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

$$\Longrightarrow Q_{\rm cr} \equiv 10^{11}\left(\frac{M_{\rm D}}{100\,{\rm GeV}}\right)^{-4} < Q < 10^{21}\left(\frac{M_{\rm D}/b}{\rm GeV}\right)^{-4} \quad \text{(for } M_F=10^4\text{GeV)}$$

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

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

4. Q-ball Decay

Decay rates

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

Cohen, Coleman, Georgi, Manohar (1986)

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

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

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

(i) Decay into nucleons **saturated**

$$\Gamma_Q = \Gamma_Q^{(\mathrm{sat})} \Longrightarrow T_{\mathrm{D}} \simeq 4.3\,\mathrm{MeV}\left(\frac{M_F}{10^4\,\mathrm{GeV}}\right)^{1/2}\left(\frac{Q}{10^{21}}\right)^{-5/8}$$

Decay before BBN

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

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

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

Covi et al. (2002)

For saturated case, $B_{\tilde{a}} = 1$.

(iii) Decay into gravitinos **unsaturated**

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

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

Gravitino production is negligible.

5. Abundances

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

$$n_b \simeq \varepsilon b n_\phi$$
$$n_{\tilde{a}} \simeq B_{\tilde{a}} n_\phi$$
$$n_{\rm MLSP} \simeq \frac{Q_{\rm cr}}{Q} n_\phi$$

+

$$Y_b \simeq \frac{3}{4} T_{\rm RH} \left. \frac{n_b}{\rho_{\rm inf}} \right|_{\rm osc}$$
$$\rho_{\tilde{a}}/\rho_b \simeq 5$$
$$\frac{\rho_{\rm MLSP}}{s} \simeq 5 m_N Y_b \frac{\rho_{\rm MLSP}}{\rho_{\tilde{a}}}$$

⟹

$$\left. \frac{Y_b}{10^{-10}} \right|_{\rm sat} \simeq 2.3\times 10^2 \left(\frac{m_{\tilde{a}}}{\rm GeV}\right) \left(\frac{\beta}{6\times 10^{-5}}\right)^{-3/4} \left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right) \left(\frac{M_F}{10^4\,{\rm GeV}}\right) \left(\frac{Q}{10^{21}}\right)^{3/4}$$

$$\left. \frac{Y_b}{10^{-10}} \right|_{\rm unsat} \simeq 0.11 \left(\frac{m_{\tilde{a}}}{\rm GeV}\right) \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^{-1} \log\left(\frac{f_a}{10^3\,{\rm GeV}}\right) \left(\frac{\beta}{6\times 10^{-5}}\right)^{-3/4} \left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right) \left(\frac{M_F}{10^4\,{\rm GeV}}\right) \left(\frac{Q}{10^{21}}\right)$$

$$\left. \frac{\rho_{\rm MLSP}}{s} \right|_{\rm sat} \simeq 6.2\times 10^{-18}\,{\rm GeV} \left(\frac{Y_b}{10^{-10}}\right) \left(\frac{m_{\tilde{a}}}{\rm GeV}\right)^{-1} \left(\frac{m_{\rm MLSP}}{100\,{\rm GeV}}\right)^{-3} \left(\frac{M_F}{10^4\,{\rm GeV}}\right)^4 \left(\frac{Q}{10^{21}}\right)^{-1},$$

$$\left. \frac{\rho_{\rm MLSP}}{s} \right|_{\rm unsat} \simeq 1.3\times 10^{-14}\,{\rm GeV} \left(\frac{Y_b}{10^{-10}}\right) \left(\frac{m_{\tilde{a}}}{\rm GeV}\right)^{-1} \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right) \left(\log \frac{f_a}{10^3\,{\rm GeV}}\right)^{-1} \left(\frac{m_{\rm MLSP}}{100\,{\rm GeV}}\right)^{-3} \left(\frac{M_F}{10^4\,{\rm GeV}}\right)^4 \left(\frac{Q}{10^{21}}\right)^{-3/2}$$

6. Constraints on abundances

Q-ball decay at $T=T_D$

- baryons $n_b^{(Q)}/s$
- axinos $\rho_{\tilde{a}}^{(Q)}$
- MSSM LSPs $\rho_{\rm MLSP}^{(Q)}$

6. Constraints on abundances

Q-ball decay at $T=T_D$ (> 3MeV)

baryons $n_b^{(Q)}/s \ (\approx 10^{-10})$

axinos $\rho_{\tilde{a}}^{(Q)} \ (= \rho_{\rm DM})$

MSSM LSPs $\rho_{\rm MLSP}^{(Q)}$

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

$$\rho_{\rm MLSP}^{(Q)} < \rho_{\rm MLSP}^{(\rm BBN)}$$

Thermally produced gravitinos/axinos do not contribute to DM density.

$$\rho_{3/2}^{(\rm TH)}, \ \rho_{\tilde{a}}^{(\rm TH)} < \rho_{\tilde{a}}^{(Q)}$$

⇒ Highest possible T_{RH}

gravitino $T_{\rm RH,max}^{(3/2)} = 3 \times 10^7 \ {\rm GeV} \left(\frac{m_{3/2}}{\rm GeV}\right)$

Moroi, Murayama, Yamaguchi (1993)
Kawasaki, Takahashi, Yanagida (2006)

axino $\Omega_{\rm KSVZ\,\tilde{a}}^{\rm TH} h^2 \simeq 10^{-2} \left(\frac{m_{\tilde{a}}}{\rm GeV}\right) \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^{-2} \left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right)$ → $T_{\rm RH,max}^{(\rm KSVZ\ \tilde{a})} = 10^8 \ {\rm GeV} \left(\frac{m_{\tilde{a}}}{\rm GeV}\right)^{-1} \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^2$

$$\Omega_{\rm DFSZ\,\tilde{a}}^{\rm TH} h^2 \simeq \begin{cases} 10^{-3} \left(\frac{m_{\tilde{a}}}{\rm GeV}\right) \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^{-2} \left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right) & (T_{\rm RH} \gtrsim 2 \times 10^7\,{\rm GeV}) \\ 2 \times 10^{-3} \left(\frac{m_{\tilde{a}}}{\rm GeV}\right) \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^{-2} & (T_{\rm RH} \lesssim 2 \times 10^7\,{\rm GeV}) \end{cases}$$

→ $T_{\rm RH,max}^{(\rm DFSZ\ \tilde{a})} = 10^9 \ {\rm GeV} \left(\frac{m_{\tilde{a}}}{\rm GeV}\right)^{-1} \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^2$

→ $\left(\frac{m_{\tilde{a}}}{\rm GeV}\right) \left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^{-2} \lesssim 55$

$T_{\rm RH,max}^{(3/2)}$ is imposed.

Covi et al. (2001), Brandenburg, Steffen (2004), Strumia (2010),
Chun (2011), Choi et al. (2012), SK, Kawakami, Kawasaki (2012)

6. Constraints on abundances

Q-ball decay at $T=T_D$ (> 3MeV)

- baryons $n_b^{(Q)}/s$ $(\approx 10^{-10})$
- axinos $\rho_{\tilde{a}}^{(Q)}$ $(= \rho_{\rm DM})$
- MSSM LSPs $\rho_{\rm MLSP}^{(Q)}$

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

$$\rho_{\rm MLSP}^{(Q)} < \rho_{\rm MLSP}^{(\rm BBN)}$$

Thermally produced gravitinos/axinos do not contribute to DM density.

$$\rho_{3/2}^{(\rm TH)},\ \rho_{\tilde{a}}^{(\rm TH)} < \rho_{\tilde{a}}^{(Q)}$$

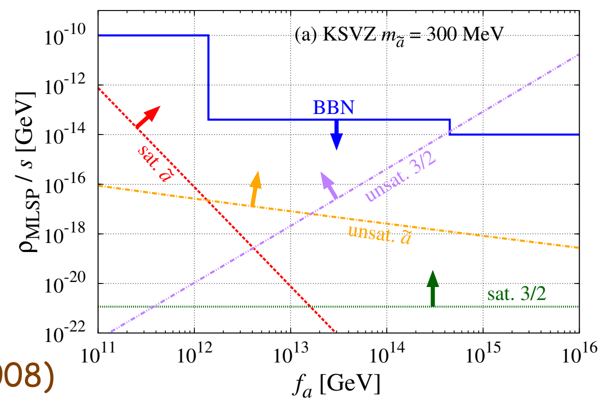
⇒ Highest possible T_{RH}

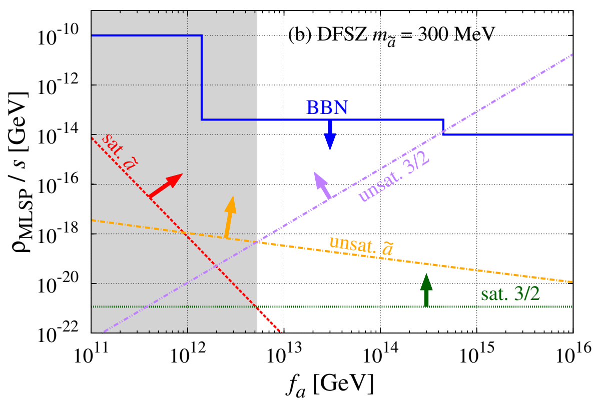
⇒ Lowest possible MLSP abundance $\rho_{\rm MLSP,min}^{(Q)}$

⇓

$$\rho_{\rm MLSP,min}^{(Q)} < \rho_{\rm MLSP}^{(\rm BBN)}$$

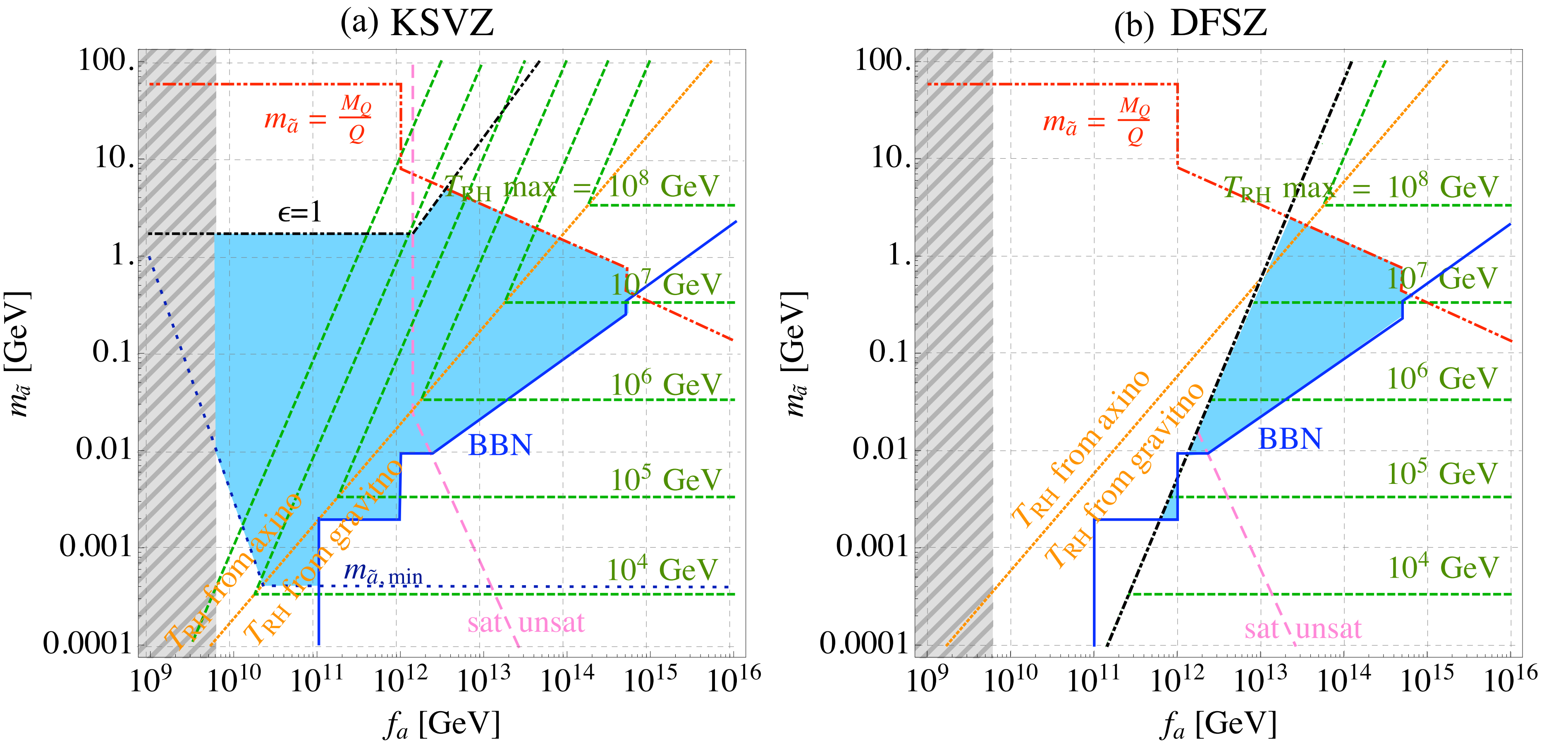
BBN constraints from
Kawasaki, Kohri, Moroi (2005)
Kohri, Moroi, Yotsuyanagi (2006)
Kawasaki, Kohri, Moroi, Yotsuyanagi (2008)





7. Allowed regions

Axino parameter space (f_a, $m_{\tilde{a}}$)



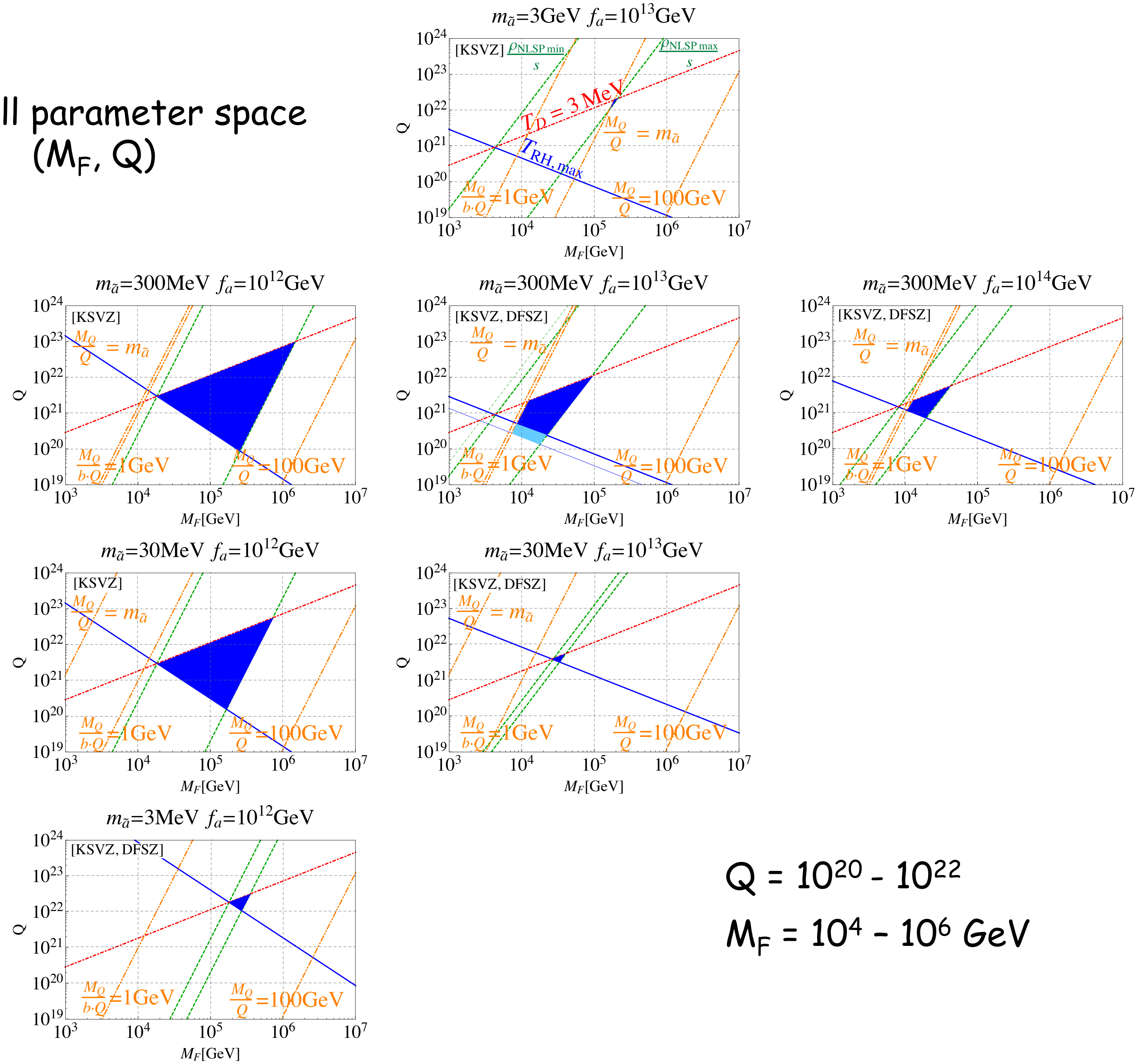
6×10^9 GeV < f_a < 5×10^{14} GeV

$m_{\tilde{a}}$ = O(MeV) – O(GeV)

10^{12} GeV < f_a < 5×10^{14} GeV

$m_{\tilde{a}}$ = O(10 MeV) – O(GeV)

Q-ball parameter space (M_F, Q)

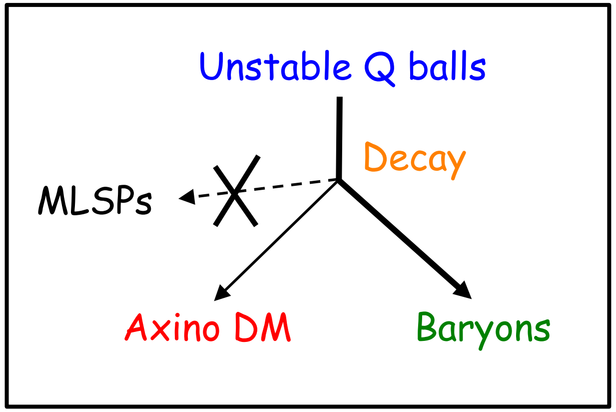


$Q = 10^{20} - 10^{22}$

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

8. Conclusions

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



Unstable Q balls decay mainly into nucleons, → Baryons
partially into axinos, → DM
hardly into MSSM LSPs. → 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 MSSM LSPs.

→ $T_D \sim O(10\ \mathrm{MeV})$

The rate of the decay into nucleons is saturated,
into axinos is not saturated
(saturated in some cases).

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