Q-ball dark matter and baryogenesis in high-scale inflation

Shinta Kasuya (Kanagawa University)

With Masahiro Kawasaki (ICRR & IPMU, U Tokyo)

Ref.: SK, Kawasaki, arXiv:14081176.
See also, SK, Kawasaki, PRD89, 103534 (2014).

Particle Cosmology after Planck, Sep. 24, 2014, DESY, Germany

1. Introduction

Affleck-Dine & Q-ball cosmology in gauge mediation

Why interesting?

- Q-ball solution exists in SUSY.

  The potential of the flat direction is flatter than Φ^2.

  The flat direction consists of squarks and sleptons.

- Q balls can form in the early universe.

  They form through the Affleck-Dine baryogenesis.

- Dark matter Q balls can be detected.

  Large Q balls are stable against the decay into nucleons.
  (in gauge-mediated SUSY breaking)

⇨ Q-ball DM & B are explained by AD Q-ball scenario.
(in gauge-mediated SUSY breaking)

1. Introduction

Affleck-Dine & Q-ball cosmology in gauge mediation

Why interesting?

- Q-ball solution exists in SUSY.

    The potential of the flat direction is flatter than Φ^2.

    The flat direction consists of squarks and sleptons.

- Q balls can form in the early universe.

    They form through the Affleck-Dine baryogenesis.

- Dark matter Q balls can be detected. ⇦ **A smoking gun for AD baryogenesis**

    Large Q balls are stable against the decay into nucleons.
    (in gauge-mediated SUSY breaking)

⇨ Q-ball DM & B are explained by AD Q-ball scenario.
(in gauge-mediated SUSY breaking)

2. What to be shown (Conclusion)

A new scenario in Affleck-Dine & Q-ball cosmology

SK, Kawasaki (2014): This talk

Multiple flat directions

⟶ Simple example: Two directions

Direction #1	Direction #2
Gauge-mediation type	**New type**
Unstable Q balls	Stable Q balls
↓ Decay	↓ Survive
Baryons	Q-ball dark matter
	Detectable

Explains the baryon asymmetry & dark matter in the universe w/o too large isocurvature fluctuations in high scale inflation.

2. What to be shown (Conclusion)

How to form?

A new scenario in Affleck-Dine & Q-ball cosmology

SK, Kawasaki (2014): This talk

Multiple flat directions

What are these?

Why multiple?

→ Simple example: Two directions

Direction #1	Direction #2
Gauge-mediation type	**New type**
Unstable Q balls	Stable Q balls
↓ Decay	↓ Survive
Baryons	Q-ball dark matter
	Detectable

What are these?

Explains the baryon asymmetry & dark matter in the universe w/o too large isocurvature fluctuations in high scale inflation.

How to suppress?

3. MSSM flat directions

Dine, Randall, Thomas (1996)
Gherghetta, Kolda, Martin (1996)

The flat direction Φ is a (complex) scalar field whose potential vanishes along that direction in SUSY limit.

D-flat & F-flat (at renorm. level)

Φ is made of squarks (and sleptons).

The potential is lifted by ~~SUSY~~ and non-renormalizable superpotential.

$$W_{\rm NR} = \frac{\lambda \Phi^n}{n M_{\rm P}^{n-3}}$$

(Ex.)

Directions with L & e: LLe (3)

Directions with L, u & e: LLe, uuuee (4)

(Gauge-inv. Monomials)

LLe directions

$$L = \frac{1}{\sqrt{3}} \begin{pmatrix} \Phi \\ 0 \end{pmatrix}, \quad L = \frac{1}{\sqrt{3}} \begin{pmatrix} 0 \\ \Phi \end{pmatrix}, \quad e = \frac{1}{\sqrt{3}} \Phi$$

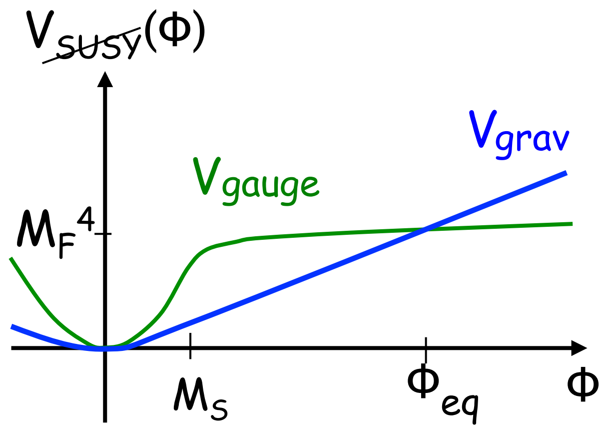
Table 5
Complex dimensionalities of moduli subspaces in the MSSM

Flat directions	D-flat	Superpotential Terms n=3	n=4	n=5	n=6	n=7	n=8	n=9
L,d	3	3	3	1	1	√		
L,e	5	3	3	1	√			
u,d	9	9	6	6	√			
u,e	3	3	√					
Q,L	12	12	√					
Q,u	15	13	√					
Q,u,e	18	16	1	1	1	1	1	√
L,u,d	12	12	9	5	√			
L,d,e	6	4	4	√				
L,u,e	6	4	√					
u,d,e	12	12	√					
Q,L,e	15	13	√					
Q,L,d	21	19	√					
Q,L,u	21	19	√					
Q,u,d	24	20	√					
L,u,d,e	15	13	√					
Q,L,d,e	24	22	√					
Q,L,u,e	24	20	√					
Q,u,d,e	27	23	√					
Q,L,u,d	30	26	√					
Q,L,u,d,e	33	29	√					

Gherghetta, Kolda, Martin (1996)

4. Scalar potential in the gauge mediation

$$V(\Phi) = V_{\not{\mathrm{SUSY}}} + V_A + V_{\mathrm{NR}} + V_H$$



$$V_{\not{\mathrm{SUSY}}} = V_{\mathrm{gauge}} + V_{\mathrm{grav}}$$

$$V_{\mathrm{gauge}} = \begin{cases} m_\phi^2 |\Phi|^2 & (|\Phi| \ll M_m) \\ M_F^4 \left(\log \frac{|\Phi|^2}{M_m^2}\right)^2 & (|\Phi| \gg M_m) \end{cases}$$

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

$10^3\ \mathrm{GeV} \lesssim M_F \lesssim \frac{g^{1/2}}{4\pi}\sqrt{m_{3/2} M_{\mathrm{P}}}$ Kusenko, Shaposhnikov (1998) de Gouvêa, Moroi, Murayama (1997)

$$V_{\mathrm{grav}} = m_{3/2}^2 |\Phi|^2 \left(1 + K \log \frac{|\Phi|^2}{M_*^2}\right)$$

$K < 0, \quad |K| = 0.01 - 0.05$ Enqvist, McDonald (1998)

$$V_A = a m_{3/2} \frac{\lambda \Phi^n}{M_P^{n-3}} + \mathrm{h.c.}, \quad V_{\mathrm{NR}} = \frac{\lambda^2 |\Phi|^{2(n-1)}}{M_{\mathrm{P}}^{2(n-3)}}, \quad V_H = -cH^2|\Phi|^2,$$

5. Affleck-Dine mechanism

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

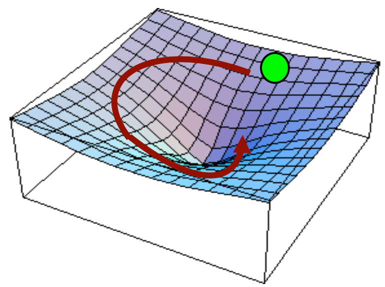
$$V(\Phi) = V_{\text{SUSY}} + V_A + V_{\text{NR}} + V_H$$

$$V_A = a m_{3/2} \frac{\lambda \Phi^n}{M_P^{n-3}} + \text{h.c.}, \quad V_{\text{NR}} = \frac{\lambda^2 |\Phi|^{2(n-1)}}{M_{\text{P}}^{2(n-3)}}, \quad V_H = -cH^2|\Phi|^2,$$

Field dynamics

(i) During and after inflation, Φ stays at the min. by V_{NR} & V_H.

$$\phi_{\text{min}} = \sqrt{2}\left(\frac{c^{1/2} H M_{\text{P}}^{n-3}}{\lambda}\right)^{1/(n-2)}$$



(ii) When H~V'', Φ starts oscillation.

(iii) At the same time, Φ starts rotation due to V_A.

Baryon number production

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

6. Q-ball formation

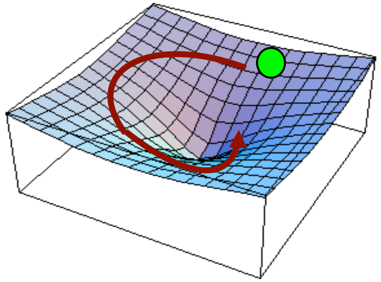
Same as the previous slide.

Field dynamics

(i) During and after inflation, Φ stays at the min. by V_{NR} & V_H.

(ii) When H~V'', Φ starts oscillation.

(iii) At the same time, Φ starts rotation due to V_A.



Baryon number production

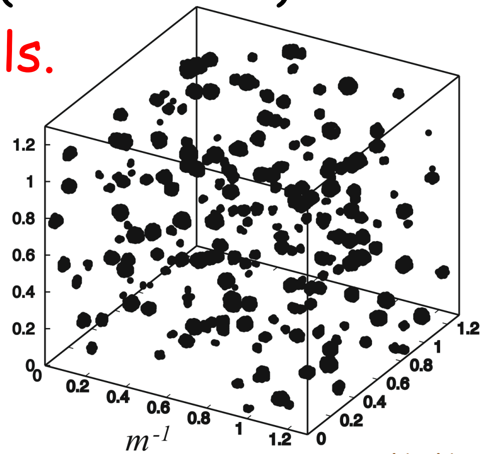
$$Q = \int d^3x \ \phi^2 \dot{\theta} \quad \left(\Phi = \frac{1}{\sqrt{2}} \phi e^{i\theta} \right)$$

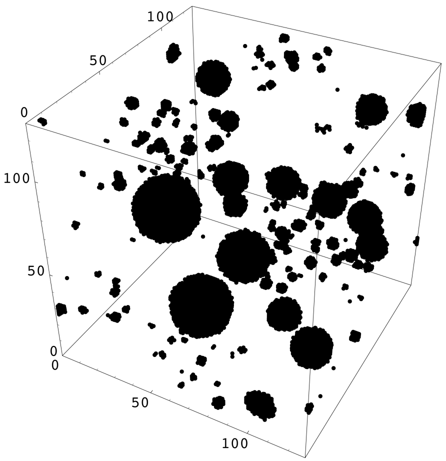
(iv) Φ feels spatial instabilities (sub-H scale).

Instabilities grow into Q balls.

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

V is shallower than ϕ^2.

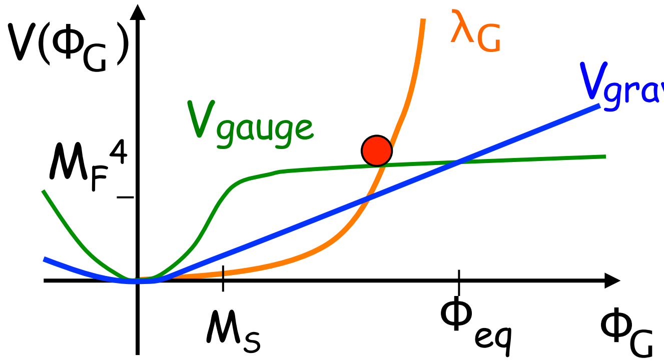


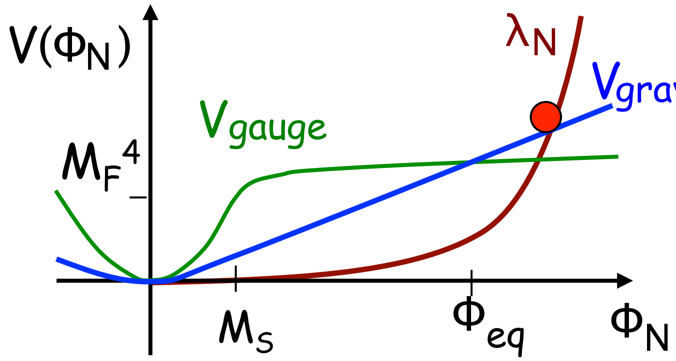


SK, Kawasaki (2001)

7. Q balls in the gauge mediation

$\lambda_G > \lambda_N$





Gauge-mediation type

$$Q_{\rm G} = \beta_{\rm G}\left(\frac{\phi_{\rm rot}}{M_F}\right)^4$$ SK, Kawasaki (2001)

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

$$\begin{cases} M_Q \simeq \dfrac{4\sqrt{2}\pi}{3}\zeta M_F Q_{\rm G}^{3/4} \\ R_Q \simeq \dfrac{1}{\sqrt{2}}\zeta^{-1} M_F^{-1} Q_{\rm G}^{1/4} \\ \omega_Q \simeq \sqrt{2}\pi\zeta M_F Q_{\rm G}^{-1/4} \end{cases}$$

$\omega_Q > b m_N$ (for small enough Q)

Kinematically, it decays.

New type

$$Q_{\rm N} = \beta_{\rm N}\left(\frac{\phi_{\rm rot}}{m_{3/2}}\right)^2$$ SK, Kawasaki (2000)

$\beta_{\rm G} = 0.02$ Hiramatsu et al. (2010)

$$\begin{cases} M_Q \simeq m_{3/2} Q_{\rm N} \\ R_Q \simeq |K|^{-1/2} m_{3/2}^{-1} \\ \omega_Q \simeq m_{3/2} \end{cases}$$

$\omega_Q \simeq m_{3/2} < b m_N$ Stable Q balls

(Baryon number: B=bQ)

8. Isocurvature fluctuations

$$H_{\rm inf} \simeq 10^{14}\,{\rm GeV}\left(\frac{r}{0.16}\right)^{\frac{1}{2}}$$ BICEP2 (2014)

⇩

Isocurvature fluctuations are typically too large in high-scale inflation.

The amplitude of baryonic isocurvature fluctuations (super-H scale):

$$S_b = \frac{\delta\rho_b}{\rho_b} \simeq \frac{\delta n_b}{n_b} \simeq \frac{\delta n_\phi}{n_\phi} \simeq \delta\theta \simeq \frac{H_{\rm inf}}{2\pi\phi_{\rm inf}}$$

Observational constraint Planck Collaboration (2013)

$$S_b^{\rm (obs)} \simeq \frac{\Omega_{\rm CDM}}{\Omega_b}(\beta_{\rm iso}A_s)^{1/2} = 5.0\times 10^{-5}$$

S_b to be small enough:

$$S_b < S_b^{\rm (obs)} \longrightarrow \phi_{\rm inf} > \frac{H_{\rm inf}}{2\pi S_b^{\rm (obs)}} = 3.5\times 10^{17}\,{\rm GeV}\left(\frac{H_{\rm inf}}{10^{14}\,{\rm GeV}}\right)\left(\frac{S_b^{\rm (obs)}}{5.0\times 10^{-5}}\right)^{-1}$$

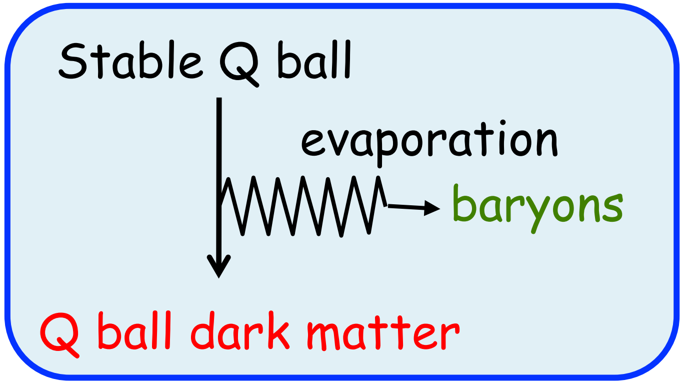
The field amplitude during inflation should be as large as M_P.

$$\Rightarrow \lambda \lesssim 2^{\frac{n}{2}-1}c^{\frac{1}{2}}\frac{H_{\rm inf}}{M_{\rm P}} \simeq 10^{-4}c^{\frac{1}{2}}\left(\frac{H_{\rm inf}}{10^{14}\ {\rm GeV}}\right)$$

Harigaya et al. (2014)

We adopt $\lambda \lesssim 10^{-4}$, and see if the scenario works.

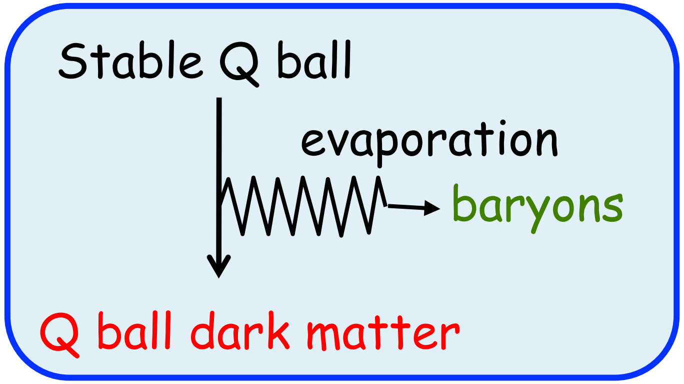
9. Single flat direction case



Gauge mediation (large charge)

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

9. Single flat direction case



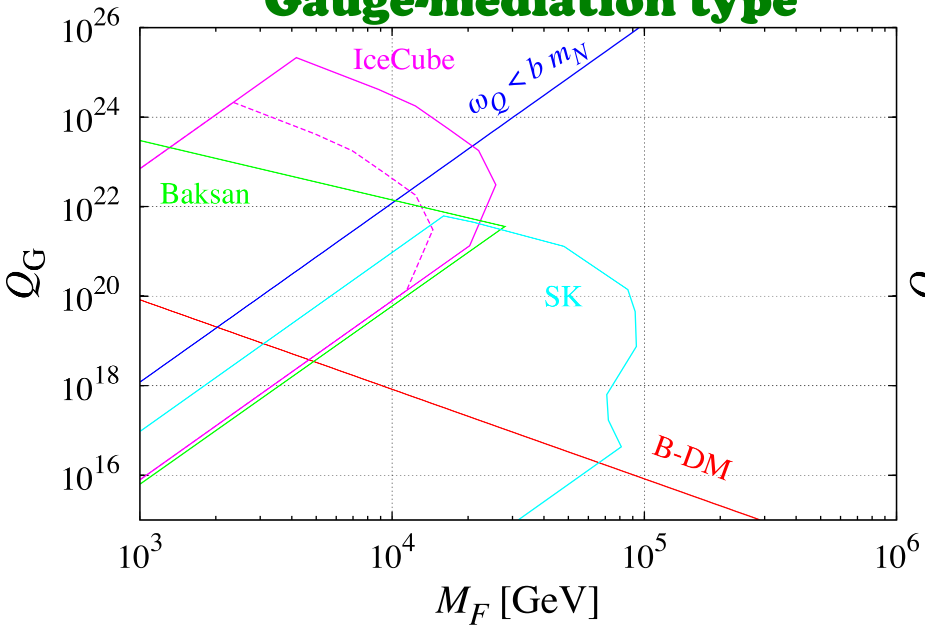
We re-analyzed this scenario, and
it is now excluded by (old) observation.

SK, Kawasaki (2014)

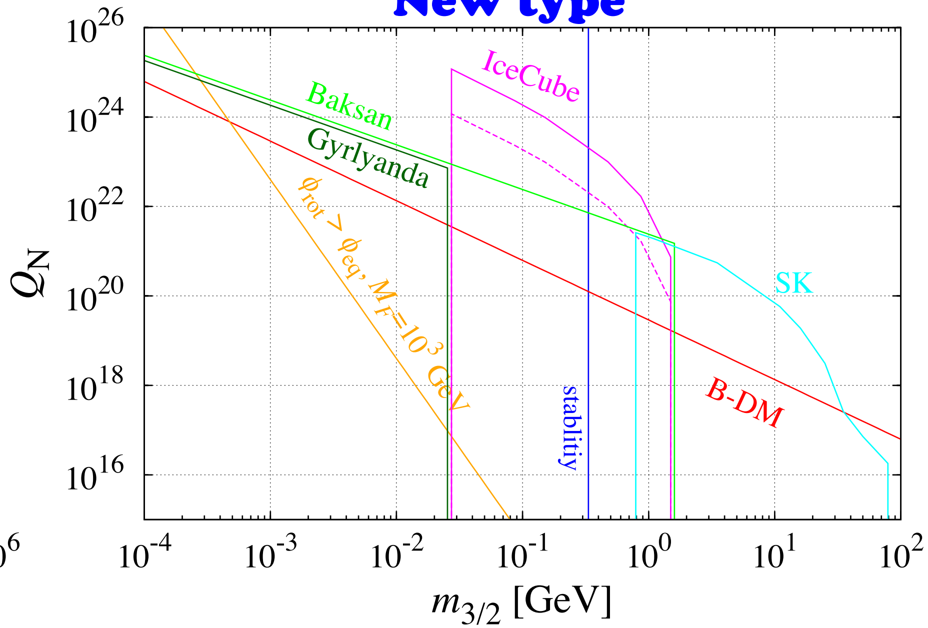
Gauge mediation (large charge)

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

Gauge-mediation type



New type



10. Multiple flat directions: Two fields case

n=4 λ_G ($\lesssim 10^{-4}$) form the unstable Q ball to create baryon asymmetry.

$$Q_G = \frac{4\beta_G}{\lambda_G^{\frac{4}{n-1}}}\left(\frac{M_P}{M_F}\right)^{\frac{4(n-3)}{n-1}} \underset{(n=4)}{=} \frac{4\beta_G}{\lambda_G^{\frac{4}{3}}}\left(\frac{M_P}{M_F}\right)^{\frac{4}{3}} \quad \text{(Gauge-med. type)}$$

$$Y_b = \frac{9}{4} b \lambda_G^{-\frac{3}{n-1}} T_{RH} M_F^{-\frac{2(n-4)}{n-1}} M_P^{\frac{n-7}{n-1}} \underset{(n=4)}{=} \frac{9}{4} b \lambda_G^{-1} T_{RH} M_P^{-1}$$

$$\longrightarrow \quad T_{RH} = 3.2 \times 10^4 \text{ GeV} \left(\frac{b}{1/3}\right)^{-1} \left(\frac{\lambda_G}{10^{-4}}\right) \left(\frac{Y_b}{10^{-10}}\right)$$

n=4 λ_N ($< \lambda_G$) form the stable Q ball to be the dark matter.

$$Q_N = \frac{2\beta_N}{\lambda_N^{\frac{2}{n-2}}}\left(\frac{M_P}{m_{3/2}}\right)^{\frac{2(n-3)}{n-2}} \underset{(n=4)}{=} \frac{2\beta_N}{\lambda_N}\left(\frac{M_P}{m_{3/2}}\right) \quad \text{(New type)}$$

$$\frac{\rho_Q}{s} = \frac{9}{4} \lambda_N^{-\frac{2}{n-2}} T_{RH} \left(\frac{m_{3/2}}{M_P}\right)^{\frac{2}{n-2}} \underset{(n=4)}{=} \frac{9}{4} \lambda_N^{-1} T_{RH} \left(\frac{m_{3/2}}{M_P}\right)$$

$$\longrightarrow \quad m_{3/2} = 1.8 \text{ MeV} \left(\frac{b}{1/3}\right) \left(\frac{\lambda_N}{10^{-7}}\right) \left(\frac{\lambda_G}{10^{-4}}\right)^{-1} \quad \text{(B-DM relation)}$$

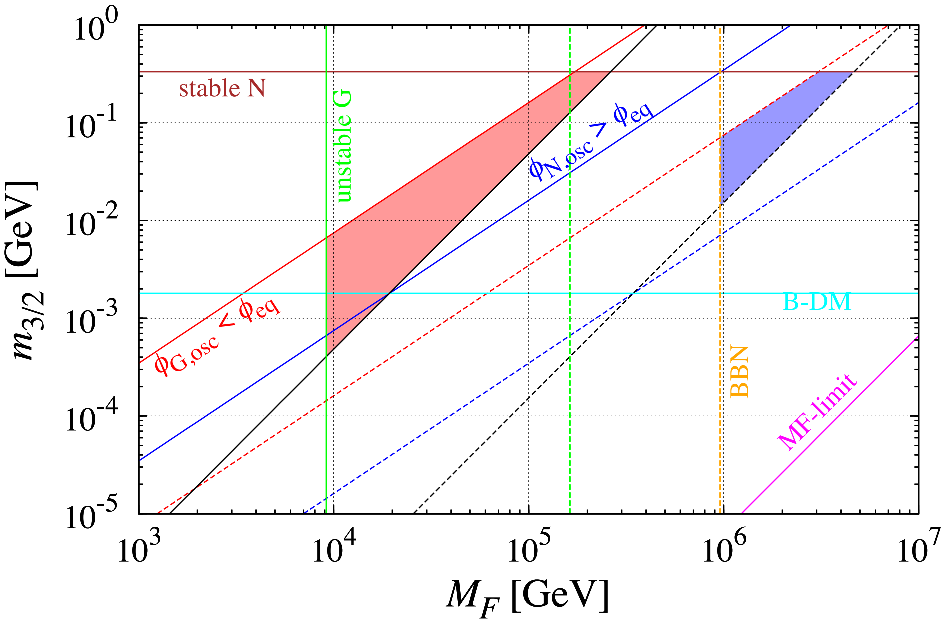
Conditions

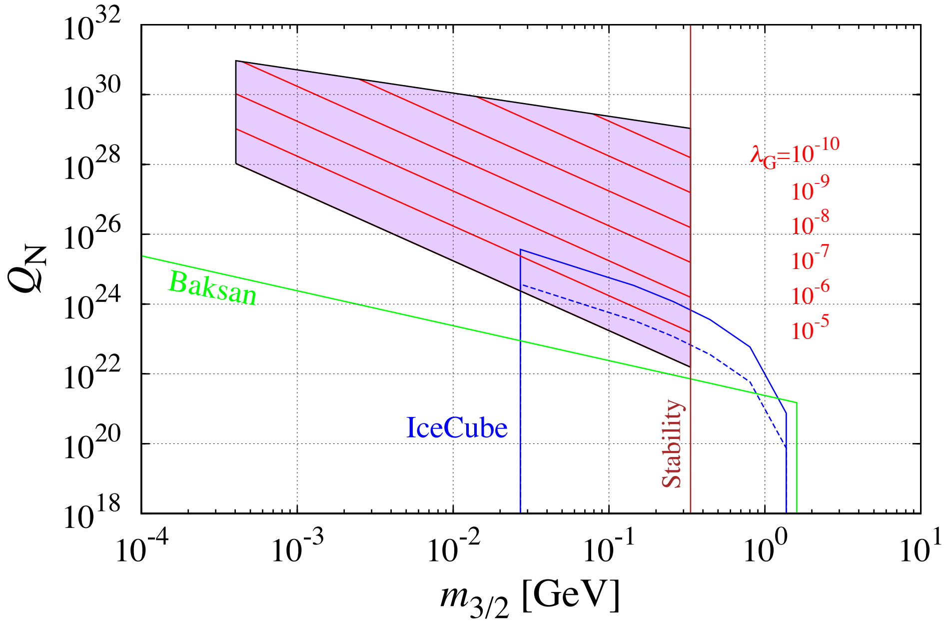
(a) The direction with λ_G forms the gauge-med. type, which is (b) unstable, and (c) decays before BBN.
(d) The direction with λ_N forms the new type, which is (e) stable.

10. Multiple flat directions: Two fields case

n=4 λ_G ($\lesssim 10^{-4}$) form the unstable Q ball to create baryon asymmetry.

n=4 λ_N ($< \lambda_G$) form the stable Q ball to be the dark matter.





10^4 GeV $\lesssim M_F \lesssim 10^7$ GeV

MeV $\lesssim m_{3/2} \lesssim$ GeV

$10^{24} \lesssim Q_N \lesssim 10^{31}$

IceCube-like experiment can detect Q-ball dark matter.

11. Conclusion

A new scenario in Affleck-Dine & Q-ball cosmology

Multiple flat directions ⟶ Simple example: Two directions

Direction #1

Gauge-mediation type

Unstable Q balls

↓ Decay

Baryons

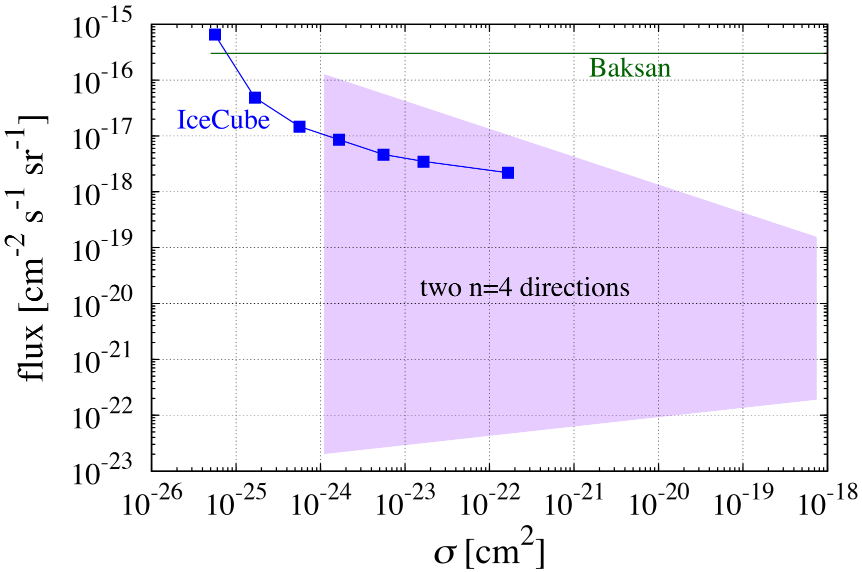
Direction #2

New type

Stable Q balls

↓ Survive

Q-ball dark matter **Detectable**



Explains the baryon asymmetry and dark matter in the universe while evading too large isocurvature fluctuations in high-scale inflation.

Q-ball detection will be a smoking gun for the Affleck-Dine baryogenesis.