Opening the window to the co-genesis with Affleck-Dine mechanism in gravity mediation

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We have proposed a scenario of Baryon and DM co-genesis in gravity or anomaly mediation.
Introduction: SUSY

“SM particles”
- quark
- lepton
- higgs

Gauge boson
- B boson
- W boson
- gluon

Superparticles
- squark
- slepton
- higgsino

Gaugino
- bino
- wino
- gluino

The lightest superparticle (LSP) is a DM candidate
Introduction: SUSY

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- quark
  - B boson
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- gauge boson
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superparticles
- squark
  - B#
- higgsino
- gaugino
  - bino
  - wino
  - gluino

The lightest superparticle (LSP) is a DM candidate

Affleck-Dine mechanism
Introduction: Affleck–Dine baryogenesis

SUSY → many flat directions (denoted by $\phi$)

ex)

\[ \tilde{u}_1^R = \frac{1}{\sqrt{3}} \phi \quad \tilde{d}_1^G = \frac{1}{\sqrt{3}} \phi \quad \tilde{d}_2^B = \frac{1}{\sqrt{3}} \phi \]

squark $\rightarrow$ B#

During inflation

\[ V(\phi) \]

\[ W = \frac{\phi^n}{M_*^{n-3}} \]

\[ -cH^2\phi^2 \]
Introduction: Affleck–Dine baryogenesis

\[ \frac{AH}{M_{*}^{n-3}} + A'm_{3/2} \frac{\phi^n}{M_{*}^{n-3}} \]

\[ W = \frac{\phi^n}{M_{*}^{n-3}} \]

After inflation
Introduction: Affleck–Dine baryogenesis

\[ B = \int dV \text{Im} (\phi \partial_0 \phi^*) \]

\[ V(\phi) = \frac{\phi^n}{M_*^{n-3}} \]

\[ W = \frac{\phi^n}{M_*^{n-3}} \]

\[ A H \frac{\phi^n}{M_*^{n-3}} + A' m_{3/2} \frac{\phi^n}{M_*^{n-3}} \]

After inflation
Introduction: Q-ball

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AD baryogenesis $\rightarrow$ coherent oscillation with B#

spatially unstable

fragment into non-topological solitons

: Q-balls (with B#)

Then, before the BBN,

Q-balls decay into

quarks ($\rightarrow$ baryon)
superparticles ($\rightarrow$ DM)

Baryon and DM have the same origin

naturally explains the observed baryon-to-DM ratio (1/5)
Q–ball decay rates (into binos)

Q–ball decay rates can be roughly estimated from the collection of the elementary processes like

\[ \phi \rightarrow q \times Q \]

B# carried by the Q–ball

Cohen, et. al, 86
Q–ball decay rates (into binos)

Q–ball decay rates can be roughly estimated from the collection of the elementary processes like

\[ \Delta M_Q |_{\Delta Q=1} \]

However, fermion production rates are saturated by the Pauli exclusion principle

\[ \frac{dN_{\tilde{B}}}{dt} \simeq (\text{phase space volume per unit time}) \]

\[ = 4\pi R^2 \times \frac{E^3}{96\pi^2} \times f \left( \frac{m_{\tilde{B}}}{E} \right) \]

\[ \left( E = \Delta M_Q |_{\Delta Q=1} \right) \]
Q-ball decay rates (into quarks)

Q-ball can decay into quarks via gluino exchange

\[ \Delta M_Q \big|_{\Delta Q=2} = 2 \times \Delta M_Q \big|_{\Delta Q=1} \times 2^3 \text{ for quark production rate} \]

- many # of DOFs: color, flavor, left–right handed
  \[ \times n_q \text{ for total quark production rate} \]
  (# of DOFs of quarks interacting with Q-ball)

typically, \[ n_q \approx 15 \]

Therefore, the ratio of the Q-ball decay rates into quarks and binos is given by

\[ \frac{B_q}{B_{\tilde{B}}} = \frac{8 \times n_q}{f \left( \frac{m_{\tilde{B}}}{E} \right)} \]
We assume Q-balls are made up of only right handed squarks.

**mass spectrum**

- heavy
  - gluino, higgsino
  - squark $\sim \Delta M_Q |_{\Delta Q = 1}$
  - bino
  - wino = LSP = DM
    $$m_{\tilde{w}} = O \left( E_{EW} \right)$$

- light
We assume Q–balls are made up of only right handed squarks. Since right handed squarks have no SU(2) charge, these Q-balls do not decay into winos.

Q–balls decay only into quarks and binos.

\[
\frac{B_q}{B_{\tilde{B}}} = \frac{8 \times n_q}{f \left( \frac{m_{\tilde{B}}}{E} \right)}
\]

Then, the binos decay into winos.

If these winos do NOT annihilate,

\[
\frac{\Omega_b}{\Omega_{DM}} = \frac{m_p}{3m_{\tilde{W}}} \frac{B_q}{B_{\tilde{B}}} \sim \frac{1}{5}!
\]
We assume that these winos do NOT annihilate (★★)

Q-balls need to decay after the time of wino freeze-out
We assume that these winos do NOT annihilate (★★)

Q-balls need to decay after the time of wino freeze-out

- Larger Q-balls decay later
  - If a large value of B# is generated
    - by the AD mechanism, large Q-balls are formed

In order to satisfy the condition (★★), a large value of B# is generated

→ B# has to be diluted

thermal inflation
domain wall wall decay
We assume Q-balls are made up of only right handed squarks. Since right handed squarks have no SU(2) charge, these Q-balls do not decay into winos.

Q-balls decay only into quarks and binsos.

branching ratio:

\[
\frac{B_q}{B_{\tilde{B}}} = \frac{8 \times n_q}{f\left(\frac{m_{\tilde{B}}}{E}\right)}
\]

Then, the binsos decay into winos.

If these winos do NOT annihilate,

\[
\frac{\Omega_b}{\Omega_{DM}} = \frac{m_p}{3m_{\tilde{W}}} \frac{B_q}{B_{\tilde{B}}} \sim \frac{1}{5}
\]
Taking bino and wino mass into account, \[ \Delta M_Q|_{\Delta Q=1} \approx m_\phi(\phi_0) \text{ [TeV]} \]

\[ m_{\tilde{B}} = 3m_{\tilde{W}}, \quad n_q = 15 \]

\[ \frac{\Omega_b}{\Omega_{DM}} \gtrsim \frac{1}{5} \]

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Taking bino and wino mass into account, \[ \Delta M_Q\big|_{\Delta Q=1} \approx m_\phi(\phi_0) \ [\text{TeV}] \]

\[ m_{\tilde{B}} = 3m_{\tilde{W}}, \ n_q = 15 \]

\[ m_{\tilde{W}} = \mathcal{O}(100) \ \text{GeV} \]

\[ \frac{\Omega_b}{\Omega_{\text{DM}}} \approx \frac{1}{5} \]

\[ \frac{\Omega_b}{\Omega_{\text{DM}}} \lesssim \frac{1}{5} \]
B# and DM co-genesis: results

\[
\begin{align*}
  m_B &= 3m_{\tilde{W}}, \quad n_q = 15 \\
  \frac{\Omega_b}{\Omega_{DM}} &\approx \frac{1}{5} \\
  m_{\tilde{W}} &= \mathcal{O}(100) \text{ GeV}
\end{align*}
\]

\[
\Delta M_Q|_{\Delta Q=1} \approx m_\phi(\phi_0) \text{ [TeV]}
\]

Already excluded by AMS-02

Will be proved by AMS-02

Ibe, Matsumoto, Yanagida, (2012)
We have proposed a new scenario of B# and DM co-genesis

- Gravity or anomaly mediation with wino LSP is considered
- We assume Q–balls are made up of only right handed squarks

\[
\frac{\Omega_b}{\Omega_{DM}} \approx \frac{1}{5}
\]

O(100) GeV wino DM can explain

This will be proved by AMS–02

- However, some entropy production mechanism is needed

[Diagram: thermal inflation, domain wall decay]
Ordinary scenario of ADBG

Inflaton oscillation dominated era

Radiation dominated era

Energy density of the Universe vs. time

Inflation → Reheating

Q-ball

AD mechanism → Q-ball formation

Q-ball decay

wino freeze out (T ~ O(10) GeV)

BBN (T ~ MeV)

Ordinary scenario:

DM density is determined by the thermal relic density of wino

→ baryon and DM are generated separately
Inflaton oscillation dominated era

Radiation dominated era

Q-ball dominated era

Energy density of the Universe

Inflation

Reheating

Q-ball formation

AD mechanism → Q-ball formation

Q-ball decay

Wino freeze out

BBN (T ~ MeV)

\( \rho_B \rho_{DM} \approx \frac{1}{5} \)

\( \frac{\rho_B}{s} \gg \frac{\rho_B}{s} \bigg|_{\text{obs}} \)

However,
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Inflaton oscillation dominated era

Energy density of the Universe

Inflation

Reheating

Q-ball

AD mechanism → Q-ball formation

Some entropy production → dilute Q-ball (B#)

\[
\frac{\rho_B}{\rho_{DM}} \approx \frac{1}{5}
\]

\[
\frac{\rho_B}{s} \approx \frac{\rho_B}{s}_{\text{obs}}
\]

Q-ball decay

wino freeze out (T ~ O(10) GeV)

BBN (T ~ MeV)

Time
Q-ball decay rate

upper bound of flux (massless):

\[
n \cdot j \lesssim 2 \int \frac{d^3 k}{(2\pi)^3} \theta \left( \frac{\omega_0}{2} - |k| \right) \theta(k \cdot n) \hat{k} \cdot n
\]

\[
= \frac{2}{8\pi^2} \int_0^{\omega_0/2} k^2 dk
\]

bino production rate

\[
\frac{d}{dt} N_{\tilde{B}} \lesssim 4\pi R^2 \times \text{(flux)} = \frac{R^2 \omega_0^3}{24\pi} \quad \ll \ll \Gamma \times Q \sim g^2 \omega_0 \times \phi_0^2/\omega_0^2
\]
\[ \tilde{u}_1^R = \frac{1}{\sqrt{3}} \phi \]
\[ \tilde{d}_1^G = \frac{1}{\sqrt{3}} \phi \]
\[ \tilde{d}_2^B = \frac{1}{\sqrt{3}} \phi \]

**Gluino exchange**

\[ u_1^G, u_1^B \quad u_1^R \]

**Bino exchange**

\[ d_1^R, d_1^B \quad d_2^G \]

**Higgsino exchange**

\[ d_2^G, d_2^R \quad d_2^B \]

Do not change color

(Left handed)

Top, bottom \((Q_3)\)

\[ \rightarrow + 6 \]

\[ n_q = 15 \]

Q

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Q-ball configuration: $\Phi(r) = \Phi_0 \exp(-r^2 / R^2)$

- squarks have large VEV $\rightarrow$ higgs do not have VEV
- $\rightarrow$ bino and wino do not mix with each other
\[ \mathcal{L}_{\text{int}} = g\phi\chi\lambda + M\tilde{g}\lambda\lambda + h.c. \]

we can neglect herisity flip

\( \times 8 \) for \( M > \omega_0 \)
\( \propto M^2 \) for \( M < \omega_0 \)

**FIG. 14:** Diagrams for \( \phi \rightarrow \chi\eta \).
if the gluino mass is sufficiently small, the gluino exchange process can be neglected

\[ L_{\text{int}} = g \phi \chi \lambda + \tilde{M} \tilde{\phi} \lambda \lambda + h.c. \]
\[ \mathcal{L}_{\text{int}} = g \phi \chi \lambda + M \tilde{g} \lambda \lambda + h.c. \]

Loop diagrams can be neglected inside the Q-ball because fields interacting with $\Phi$ gain a large mass of the order of $g\Phi_0 (\gg\gg\gg\gg\omega_0)$.

Loop diagrams can be also neglected outside the Q-ball because the decay rate is determined by the Pauli blocking at the surface of the Q-ball.
\[ \omega_0 = 1 \quad \text{non-zero bino mass} \]

\[
\frac{1}{8\pi^2} \int_0^{1-m} dE \ \text{Min}[E^2, (1 - E) \sqrt{(1 - E)^2 - m^2v}] \quad \text{for} \quad m > 1/2
\]

\[
\frac{1}{8\pi^2} \int_0^{1/2} dE \ \text{Min}[E^2, (1 - E) \sqrt{(1 - E)^2 - m^2v}] + \frac{1}{8\pi^2} \int_{m}^{1/2} dE \ E \sqrt{E^2 - m^2v} \quad \text{for} \quad m < 1/2
\]

\[ v = \frac{p}{E} = \sqrt{E^2 - m^2}/E \]
charge density distribution of Q-balls

Hiramatsu, Kawasaki, Takahashi
1003.1779
constraints from direct detection of wino DM

Moroi, Nakayama
1112.3123