Gravitino / Axino dark matter

and

Affleck-Dine baryogenesis

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L. Roszkowski and O. Seto
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§ Dark matter

- Zwicky (1933)

  Coma cluster

  $$\langle v^2 \rangle_{obs} \gg \langle v^2 \rangle \simeq G \frac{\langle M \rangle}{\langle r \rangle}$$

- Rotation curves of galaxies (late 1970)

  ⋮

- WMAP (2003)

  $\Omega_b \simeq 0.04$

  $\Omega_m \simeq 0.23$

  $\Omega_\Lambda \simeq 0.73$

WIMP candidate

- Neutralino

  $\chi \sim (\tilde{B}, \tilde{W}, \tilde{H}_1, \tilde{H}_2)$

- Gravitino

  $m_{3/2} \simeq 10^2$ GeV in Gravity med. SUSY.

  $\Omega_{3/2} \sim 0.1 \Leftrightarrow T_R \sim 10^{10}$ GeV

  Thermal leptogenesis....?!

  $T_R > M_{N_1} \gtrsim 10^9$ GeV

- Axion
- Axino
- ...

§ Baryogenesis

Several mechanisms

- Baryogenesis via leptogenesis

- "$\cancel{B+L}$" and "$\cancel{B-L}$ by $\cancel{L}$"

  ↑ N_R in Seesaw

- Out of eq decay

  cf GUT baryogenesis

- Affleck - Dine

$$\langle \tilde{q} \rangle \text{ or } \langle \tilde{\ell} \rangle \neq 0$$

- Electroweak baryogenesis

- "$\cancel{B+L}$"
- First order phase trasition

Affleck-Dine baryogenesis

baryon asymmetry from

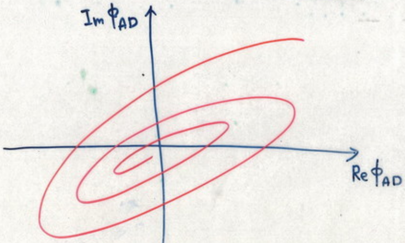
scalar condensate with baryonic charge.

↑

"Affleck-Dine field"

candidate : flat direction
consist of squarks.

$$\boxed{n_b = i\, q\, (\dot{\phi}^*_{AD}\, \phi_{AD} - \phi^*_{AD}\, \dot{\phi}_{AD})}$$



§§ Evolution of Affleck-Dine field

Superpotential

$$W = \frac{\lambda}{n M^{n-3}} \phi_{AD}^{n}$$

$n=4$: $LH_u, \cdots$
$n=6$: $udd, \cdots$

Potential in inflaton dominated stage

$$V(\phi) = -c_1 H^2 |\phi|^2 + \left(c_2 \frac{\lambda H}{n M^{n-3}} \phi^n + h.c. \right)$$

$$+ |\lambda|^2 \frac{|\phi|^{2n-2}}{M^{2n-6}}$$

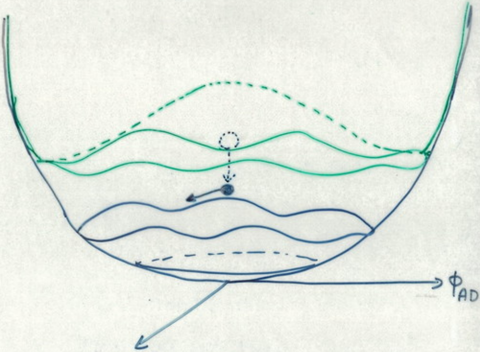
minimum : $|\phi| \simeq \left(\frac{H M^{n-3}}{\lambda} \right)^{\frac{1}{n-2}}$

Potential at $H \lesssim m_{3/2}$

$$V(\phi) = m_{AD}^2 |\phi|^2 + \left(A \frac{m_{3/2}}{n M^{n-3}} \phi^n + h.c \right)$$

$$+ |\lambda|^2 \frac{|\phi|^{2n-2}}{M^{2n-6}}$$

Potential of Affleck-Dine field



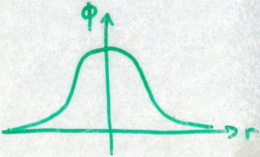
Q-ball

Non-topological soliton of scalar field with conserved global U(1) charge

Coleman 1984

In supersymmetric models,

- the scalar field ⟺ Affleck-Dine field (Squark, Slepton, Higgs)
- the U(1) charge ⟺ B (B-L) charge



Q-ball solution

Lagrangian

$$\mathcal{L} = -|\partial\Phi|^2 - V(|\Phi|)$$

Charge

$$Q = iq\int d^3x\,(\Phi\dot{\Phi}^* - \Phi^*\dot{\Phi})$$

Minimize

$$E + \omega\left[Q - iq\int d^3x\,(\Phi\dot{\Phi}^* - \Phi^*\dot{\Phi})\right]$$

$$\Phi = \frac{1}{\sqrt{2}}e^{i\omega q t}\phi_{(r)}$$

EOM for $\phi_{(r)}$

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} + \left(\omega^2 q^2\phi - \frac{dV}{d\phi}\right) = 0$$

Condition for Q-ball solution

$$\omega_0^2 < \omega^2 < m_\phi^2$$

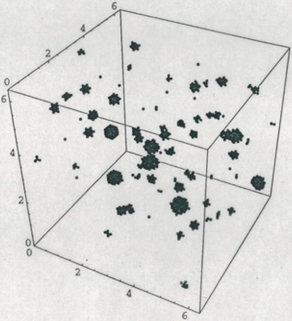
$$\omega_0^2 \equiv \min\left[\frac{2V(\phi)}{\phi^2}\right]$$

$V(\phi)$ is flatter than ϕ^2

Q-ball formation

Instability

condition $\frac{k^2}{a^2} + V'' - \dot{\theta}^2 < 0$



[Kasuya & Kawasaki]

Q-ball in SUSY models

Potential

$$V = m_\phi^2 \left(1 + K \ln\frac{|\phi|^2}{\Lambda^2}\right)|\phi|^2 + \dots$$

$$K = -(0.01 \sim 0.1)$$

flatter than ϕ^2 ⇔ Q-ball cond.

Enqvist and McDonald

Properties of Q-ball

- $\omega \simeq m_\phi$
- $R \simeq \sqrt{\frac{2}{|K| m_\phi^2}}$
- $E \simeq Q m_\phi$

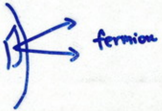
⇒ unstable

- $Q \simeq 6 \times 10^{-3} \left(\frac{|\phi_{os}|}{m_\phi}\right)^2 \epsilon \,, \quad \epsilon \equiv \frac{n_b}{n_\phi}$

Decay

Q-ball decay from surface

∵ Pauli exclusion principle



$$\langle n \cdot j \rangle \le \int \frac{d^3k}{(2\pi)^3}\, \theta\!\left(\frac{\omega_0}{2} - |\vec{k}|\right) \theta(\vec{k}\cdot\vec{n})\, \frac{\vec{k}}{|\vec{k}|}\cdot\vec{n}$$

$$= \frac{\omega_0^{\,3}}{192\pi^2}$$

$$\frac{dQ}{dA\,dt} \le \frac{\omega_0^{\,3}}{192\pi^2}$$

Cohen et al (1986)

Decay temperature

$$T_d \sim 1\,\mathrm{GeV} \left(\frac{0.01}{|K|}\right)^{1/2} \left(\frac{m_\phi}{1\,\mathrm{TeV}}\right)^{1/2} \left(\frac{10^{20}}{Q}\right)^{1/2}$$

LSP overproduction

WIMP (neutralino) freeze out

$$T_f \simeq \frac{m_\chi}{25} \sim O(1)\ \mathrm{GeV}$$

If $T_f > T_d$

At least 3 particles with $R=-1$ per one baryon number.

$$n_{LSP} = 3\left(\frac{N}{3}\right)\left(\frac{f_B}{1}\right) n_b + n_{LSP}^{(thermal)}$$

$$\Big\downarrow \quad \frac{n_b}{s} \sim 10^{-10} \qquad f_B \equiv \frac{n_b(Q\text{-ball})}{n_b(Total)}$$

$$\frac{\rho_\chi}{s} = \frac{n_\chi}{s} m_\chi = 4\times10^{-10}\underline{\underline{\left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)}}\ \mathrm{GeV}$$

Enqvist and McDonald
(1999)

If annihilation occurs,

$$\frac{n_\chi}{s} \simeq \left[\sqrt{\frac{8\pi^2 g_*}{45}} \langle \sigma v \rangle M_P T_d \right]^{-1}$$

$$\simeq 3 \times 10^{-12} \left(\frac{3 \times 10^{-8}\,\mathrm{GeV}^2}{\langle \sigma v \rangle} \right) \left(\frac{1\,\mathrm{GeV}}{T_d} \right)$$

Then

$$\chi_1^0 \simeq \tilde{H} - \tilde{W}$$

Fujii & Hamaguchi (2002)

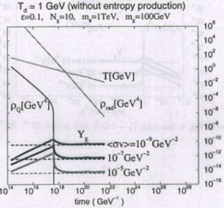


FIG. 2. The same as Fig. 1, but with $T_d = 1$ GeV and $\langle \sigma v \rangle = 10^{-9}$, 10^{-7}, and 10^{-5} GeV^{-2}.

FIGURES

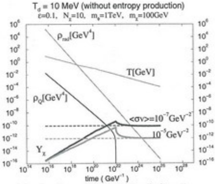


FIG. 1. The evolution of the abundance of the neutralino dark matter generated from the Q-ball decay for $T_d = 10$ MeV with $\langle \sigma v \rangle = 10^{-7}$ GeV^{-2} and 10^{-5} GeV^{-2}, which are represented by thick solid lines. The abundances estimated by the analytic formula in Eq. (68) are shown in dashed lines. In this figure, we have assumed that the energy density of the Q-ball is small enough with respect to that of the radiation. The parameters are taken to be $m_\phi = 1$ TeV, $m_\chi = 100$ GeV, $\epsilon = 0.1$ and $N_\chi = 10$.

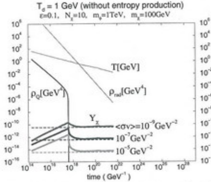


FIG. 2. The same as Fig. 1, but with $T_d = 1$ GeV and $\langle \sigma v \rangle = 10^{-9}$, 10^{-7}, and 10^{-5} GeV^{-2}.

§ Gravitino dark matter

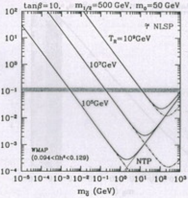
Gravitino dark matter

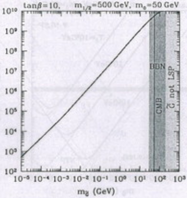
$\Omega_{3/2} h^2$ can be 0.1.

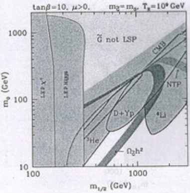
However, potentially

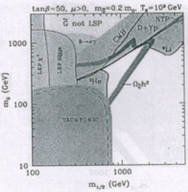
Next-to-lightest SUSY particle (NSP) problem

Cerdeno et al









§§ $m = 4$

$\phi \sim LH_u$

Baryon asymmetry is successfully generated

Fujii, Hamaguchi, Yanagida

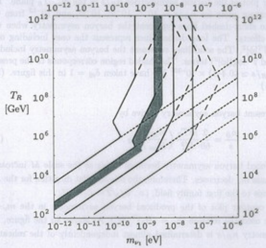
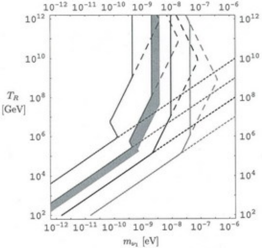


Figure 2: The contour plot of the baryon asymmetries n_B/s in the m_{ν_1}–T_R plane. The lines represent the contour plots for $n_B/s = 10^{-9}$, 10^{-10}, 10^{-11}, and 10^{-12} from the left to the right. The short-dashed lines represent the baryon asymmetry when one neglects the thermal effects. The long-dashed lines represent the ones including only the thermal mass $\propto T^2|\phi|^2$. The solid lines represent the baryon asymmetry including both thermal mass and $T^4 \log(|\phi|^2)$ terms. The shaded region corresponds to the present baryon asymmetry, $n_B/s \simeq (0.4\text{–}1) \times 10^{-10}$. We have taken $\delta_{\rm eff} = 1$ in this figure. (See discussion in the text.)



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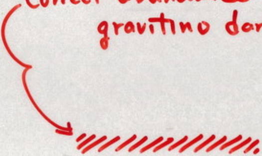
Thus, after all, the present baryon asymmetry is give by

$$\frac{n_B}{s} = \frac{2}{69}\frac{MT_R}{M_*^2}\left(\frac{m_{3/2}}{H_{\rm osc}}\right)\delta_{\rm eff}\,. \tag{25}$$

We see that the produced baryon asymmetry becomes larger as the scale M increases, i.e., as the neutrino mass m_ν decreases. Therefore, the relevant flat direction for the AD leptogenesis corresponds to the first family field, i.e., $\phi/\sqrt{2} = L_1 = H_u$.

Fig. 8 shows the contour plot of the produced baryon asymmetry in the m_ν–T_R plane. (Here we have used the relation $m_\nu = \langle H_u\rangle^2/M$.) As shown in the figure, the present baryon asymmetry n_B/s is determined almost independently of the reheating

Correct abundance of gravitino dark matter



§§ $n = 6$

$$\phi \sim \bar{u}\bar{d}\bar{d}, \ldots$$

$$\frac{n_b}{s} \simeq \begin{cases} 10^{-10} \left(\frac{T_R}{100\,\mathrm{GeV}}\right)\left(\frac{M}{M_p}\right)^{3/2} \\ \text{m_ϕ driven oscillation} \\ 10^{-10} \left(\frac{10^{-9/2}}{h}\right)^2 \left(\frac{M}{10^{-3} M_p}\right)^{3/2} \quad \text{for } \underline{T_R \sim 10^{10}\,\mathrm{GeV}} \\ \text{thermal mass driven oscillation} \\ 10^{-11} \underline{\left(\frac{10^{10}\,\mathrm{GeV}}{T_R}\right)} \left(\frac{M}{10^{-3} M_p}\right)^3 \left(\frac{10^{-2}}{\alpha}\right) \\ \text{two loop effect driven oscillation} \end{cases}$$

Remember

$$\Omega_{3/2} \sim 0.1 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)$$

Thermal effect oscillation

⇒ AD fields decay before Q-ball formation

Too few gravitinos for m_ϕ driven oscillation...

Gravitinos from Q-ball

$$\text{Q-ball} \xrightarrow[\text{decay}]{} \text{NSP} \xrightarrow[\text{decay}]{} \text{LSP gravitino}$$

$$\text{NSP would be} \left\{ \begin{array}{l} \text{lightest } \chi^0 \\ \text{or} \\ \text{stau. } \tilde{\tau} \end{array} \right.$$

Since $n_{NSP} = n_{3/2}$,

if no annihilation of NSP

$m_{3/2} \simeq 1\ \text{GeV} \ll 10^{2-3}\ \text{GeV}$ is required!

unlikely

with annihilation

$$Y_N \simeq 10^{-12} \left(\frac{10^{-8}\ \text{GeV}^2}{\langle \sigma v \rangle} \right) \left(\frac{1\ \text{GeV}}{T_d} \right)$$

$$\sim 10^{-12} \left(\frac{100\ \text{GeV}}{m_{DM}} \right)$$ correct abundance

$\langle \sigma v \rangle \simeq 10^{-8} - 10^{-7}\ \text{GeV}^2$ is possible

for $\chi_1^0 \sim \tilde{H}$, or $\tilde{\tau}$ NSP.

§ Axino dark matter

Abundance

$$Y_{\tilde a} \equiv \frac{n_{\tilde a}}{s} = Y_{\tilde a}^{TP} + Y_{\tilde a}^{NTP}$$

i) Thermal

- scattering

$i + j \rightarrow \tilde a + \ldots$

- decay

$i \rightarrow \tilde a + \ldots$

L.Covi et al (2001)

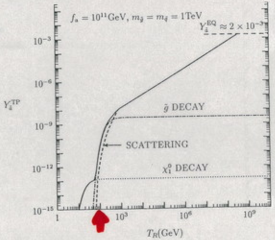


Figure 2: $Y_{\tilde a}^{TP}$ as a function of T_R for representative values of $f_a = 10^{11}$GeV and $m_{\tilde q}$
$m_{\tilde g} = 1$TeV.

ii) Non-thermal

- freeze out NSP $\rightarrow \tilde a + \ldots$

$Y_{NSP}^{TP} \sim 10^{-11}$

- Q-ball $\longrightarrow$ NSP $\longrightarrow \tilde a + \ldots$

$$Y \sim 10^{-10} N \left(\frac{f_B}{1}\right)\left(\frac{n_b/s}{10^{-10}}\right)$$

Ω_{DM}

$$\Omega_{\tilde a} h^2 \simeq 0.11 \left(\frac{m_{\tilde a} f_B N}{4.6\ \mathrm{GeV}}\right)\left(\frac{\Omega_b h^2}{0.02}\right)$$

$$\Omega_{DM} \sim \Omega_b$$

Big Bang Nucleosynthesis Constraint

Late decaying particle may be dangerous.

e.g. "Gravitino problem"

"NSP problem in gravitino LSP"

NSP → $\psi_{3/2}$ via $\frac{1}{M_P}$

NSP → $\tilde a$ via $\frac{1}{f}$

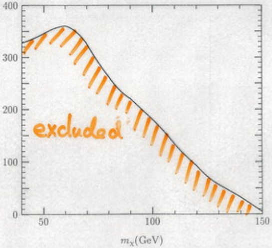


Figure 4: Lower bound on the axino mass from considering hadronic showers according to the condition (5.29), for $C_{aYY} Z_{11} = 1$ and $f_a/N = 10^{11}$ GeV. The bound disappears for $m_\chi = 150$ GeV when the lifetime drops below 0.1 sec.

L.Covi et al (2001)

§ Summary

Gravitino dark matter

No gravitino problem

but, NSP problem ...

⇒ High T_R is available and favored

⇒ $\Omega_{3/2} \sim 0.1$

$\frac{n_b}{s} \sim 10^{-10}$ by Affleck-Dine

c.f. Thermal leptogenesis

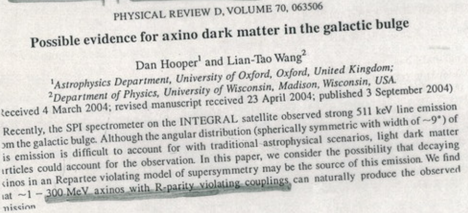
No Q-ball influence

Axino dark matter

Axinos from Q-balls in
Affleck-Dine baryogenesis

$\Omega_b \sim \Omega_{DM}$ is the consequence of
(sub-) GeV axino mass.

An application



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Possible evidence for axino dark matter in the galactic bulge

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Recently, the SPI spectrometer on the INTEGRAL satellite observed strong 511 keV line emission
om the galactic bulge. Although the angular distribution (spherically symmetric with width of ~9°) of
is emission is difficult to account for with traditional astrophysical scenarios, light dark matter
rticles could account for the observation. In this paper, we consider the possibility that decaying
inos in an Repartee violating model of supersymmetry may be the source of this emission. We find
at ~1 − 300 MeV axinos with R-parity violating couplings can naturally produce the observed
nission