Condensate cosmology in O'Raifeartaigh models

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Some observations

Classical flat directions are a generic feature of supersymmetric gauge theories.

- They have been extensively studied in the MSSM[1].

But

- Flat directions also exist in O'Raifeartaigh models[2].

Question

Do flat directions in the SUSY breaking sector have any important cosmological consequences? If so, what are they?

[1] K.Enqvist, A.Mazumdar - hep-ph/0209244

[2] S.Ray - hep-th/0607172; Z.Komargodski, D.Shih - 0902.0030[hep-th]

Some conclusions

SPOILER WARNING

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SPOILER WARNING

Answer

Yes! A condensate can form along the flat direction. This fragments into large, classical objects: **R-balls**.

Gravity mediation:

- R-balls decay to gravitinos, **reheating** the universe.

Gauge mediation:

- R-balls survive to the present day and act as **dark matter**.
- R-balls decay to gravitinos, gauginos or SM gauge bosons **reheating/cooling** the universe.

O'Raifeartaigh models

The scalar component of the Goldstino superfield X is **flat** at tree level in renormalisable O'Raifeartaigh models.

At **one loop** it is lifted by the Coleman-Weinberg potential

$$U_{\text{eff}}(X) \sim \frac{\lambda^2 f^2}{16\pi^2}\left[1 + \ln\left(\frac{|\lambda X|}{M}\right)\right] \quad \text{for } f \ll X^2 \ll M^2$$

It may also be lifted by **non-renormalisable** operators at $X \sim M$.

X is **charged** under an (**approximate**) global U(1) R-symmetry[3] that may be spontaneously broken.

[3] A.E.Nelson, N.Seiberg - hep-ph/9309299

Cosmological evolution

In the early universe **soft terms** from couplings to the **inflaton** dominate the potential[4]

$$V_{\rm eff}(X) \sim -cH^2|X|^2 + \frac{H}{M^{n-3}}\left(\eta X^n + \text{h.c.}\right) + \frac{1}{M^{2n-6}}|\eta|^2|X|^{2n-2}$$

For a **tachyonic** Hubble mass term X is stabilised at

$$X \sim \left(HM^{n-3}\right)^{1/(n-2)}$$

Forms spatially constant **condensate**. Expectation value decreases with H.

[4] M.Dine, L.Randall, S.D.Thomas - hep-ph/9507453

Rotation and fragmentation

At $X \sim \Lambda$, $V_{\text{eff}} \sim U_{\text{eff}}$ and the low energy effective potential takes over.

Λ is **parametrically** between the UV cutoff and the SUSY breaking scales.

Low energy effective potential logarithmic: grows slower than X^2 $\implies$ condensate is spatially unstable and **fragments**[5].

Fragments form **R-balls**: non-topological solitons stabilised by conserved R-charge[6].

[5] A.Kusenko, M.E.Shaposhnikov - hep-ph/9709492;
S.Kasuya, M.Kawasaki - hep-ph/0106119

[6] S.R.Coleman - Nucl.Phys. B262 (1985) 263

R-ball decay

R-balls typically unstable. If R-symmetry is preserved:

- R-balls decay to **light fermions** carrying R-charge.
- Due to a **Fermi pressure** decay only occurs near the surface.

If it is spontaneously broken:

- R-balls also decay to **light bosons**.
- Bosonic decays may occur throughout the interior.

The decay of one X quanta releases fixed energy ΔE so there are **kinematic constraints** on the decay products.

R-ball phenomenology

Two interesting possibilities:

R-ball dark matter

- The lifetime of R-balls is greater than the age of the universe.
- R-balls act as cold dark matter.
- Density must be less than observed CDM density.

R-ball reheating/cooling

- R-balls decay before the present.
- Decay products have temperature ΔE.
- If density large during decay universe reheated/cooled to ΔE.
- Decouples reheating from inflaton dynamics.

Otherwise R-balls may form, but have a small density. Or be **eroded** by scatterings with thermal plasma.

R-ball phenomenology

Calculate the lifetime, dominant decay mode, density and decay product temperature for R-balls.

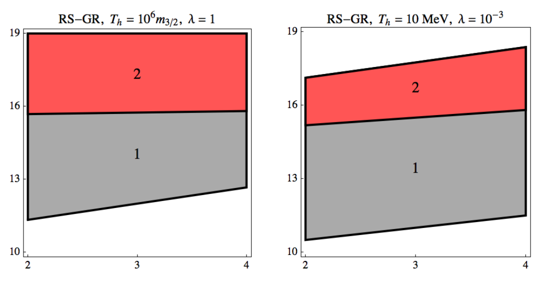
Dissect parameter space into interesting regions and plot as a function of $\log m_{3/2}$ versus $\log \Lambda$.

Also vary superpotential couplings λ and **reheat temperature** T_h.

Assume all fields in the hidden sector other than X are **massive** with $m^2 \sim f$ to minimise model dependence.

R-ball phenomenology

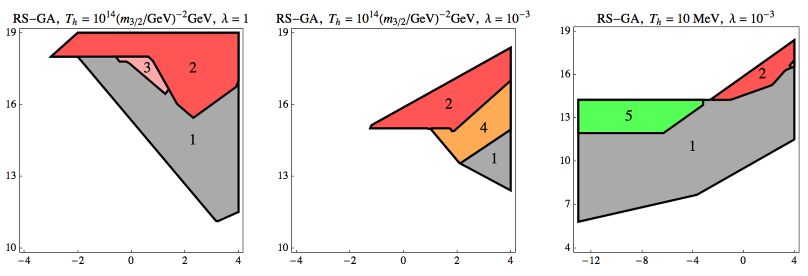
Gravity mediation (R-symmetric)



- Gravitino reheating (2) is only interesting effect.
- Situation similar for R-breaking models.

R-ball phenomenology

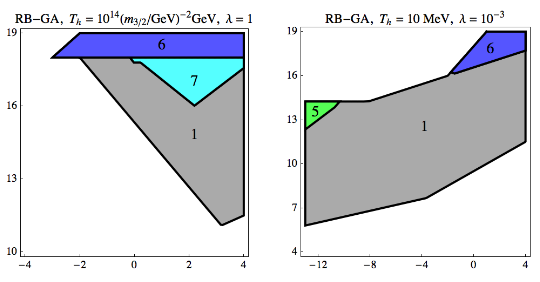
Gauge mediation (R-symmetric)



- Smaller gravitino mass $\implies$ more interest.
- Gravitino reheating (2) or cooling (3).
- Gaugino reheating (4) via **messenger loops**.
- R-ball **dark matter** (5).

R-ball phenomenology

Gauge mediation (R-breaking)



- SM gauge boson reheating (6) or cooling (7) via messenger loop decays.
- R-ball dark matter (5).

Summary

- Flat directions in O'Raifeartaigh models have interesting cosmological history.
- Soft terms driven by inflation lead to the formation of a condensate with large expectation value.
- The condensate is unstable and fragments into R-balls.
- In gravity mediation R-balls decay to gravitinos, reheating the universe.
- For gauge mediation R-balls can provide a good dark matter candidate.
- Alternatively they can decay, either reheating or cooling the universe.
- Conserved R-symmetry permits decay to gravitinos or gauginos, whereas spontaneously broken R-symmetry results in decay to SM gauge bosons.