A Minimal Model of Gravitino Dark Matter

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Outlines

WIMP Dark Matter

- WIMP assumes Dark Matter χ was in full thermal equilibrium with SM particles once upon a time:

$$\textit{Production rate } n_{SM}\langle\sigma(SM \to \chi\chi)v_{SM}\rangle > \textit{Expansion rate } H$$

- The yields keep decreasing and freeze-out at certain temperature. And later they form the relic abundance as we observe today.

  Supersymmetry with R-parity can provide a viable WIMP candidate: neutralino;

- WIMP miracle: Weak scale mass + weak scale cross section leads to the correct relic abundance;

However

The collider searches, dark matter indirect and direct detections keep showing negative results to WIMP scenario...

FIMP Dark Matter

- Feebly interacting massive particles or Freeze-in massive particles never reach thermal equilibrium with SM particles in the whole cosmology history:

$$n_{SM}\langle\sigma(SM \to \chi\chi)v_{SM}\rangle < H \ at \ T_{RH},$$

- The yields of FIMP keep growing and form the relic abundance.

  Two limits:

- IR (m_{DM}) dominated production: renormalizable operator with extremely small coefficient $\sim 10^{-12}$;
- UV (T_{RH}) dominated production: non-renormlizable operator with high dependence on T_{RH}, cofficient $\frac{T^n}{\Lambda^n}$;
- **Gravitino is a natural candidate of UV dominated FIMP.**

SUSY and Dark Matter

SUSY has two natural Dark Matter candidates:

- WIMP: the neutralino $\tilde{\chi}$ (50% of the SUSY DM papers on inspires);
- FIMP: the gravitino, $\tilde{g}$ (45% of the SUSY DM papers on inspires);

Gravitino dark matter

- First candidate to be proposed as a dark matter, before the neutralino, by Fayet in 1981 and Pagels & Primack in 1982;
- Problematic issue of its non-detectability: only R-parity violating decay;
- Once thermalized, the mass is of the order of $\sim 100eV$ which is excluded by Tremaine Gunn/structure formation bounds:

$$\Omega_{3/2} = \frac{n_{3/2} m_{3/2}}{\rho_c^0} \simeq \frac{n_\gamma \times (\frac{2}{g_*^{MSSM}}) m_{3/2}}{10^{-5} h^2 GeV/cm^{-3}} \simeq \frac{0.1}{h^2}(\frac{m_{3/2}}{300eV}).$$

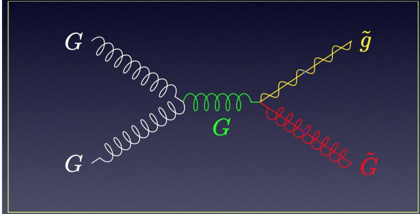
- Considering Freeze-in instead...

T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

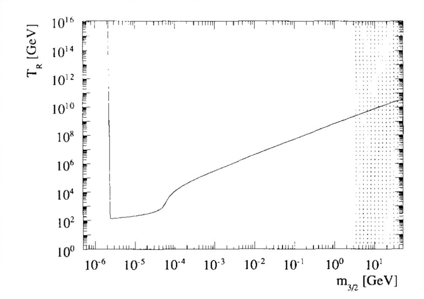
… one can then compute the relic abundance of the gravitino, repopulated by the scattering of SM particles in the thermal bath:

$$\mathcal{L} = \frac{i m_{\tilde{G}}}{8\sqrt{6}\, m_{3/2}\, M_{Pl}} \bar{\psi}\, [\gamma_\mu, \gamma_\nu] \tilde{G}\, G_{\mu\nu}$$

gravitino gluino gluon



$$\Omega_{3/2} h^2 \sim 0.3 \left(\frac{1\ \text{GeV}}{m_{3/2}}\right) \left(\frac{T_{RH}}{10^{10}\ \text{GeV}}\right) \sum \left(\frac{m_{\tilde{G}}}{100\ \text{GeV}}\right)^2$$



The thermal scattering has reopened a cosmologically viable window ($m_{3/2} > 1$ keV) but..

Cosmological Gravitino Problems

- Late decaying superpartners can affect Big Bang Nucleosynthesis (BBN);
- Relic gravitinos produced by scattering and decaying superpartners can overclose the universe;
- Non-discovery of gluino at LHC pushes lower bound on gluino masses, and thus upper bound on T_{RH} of $\sim 10^7$ GeV which can be problematic for some leptogenesis scenario.

Motivation for Weak-scale Supersymmetry

- Hierarchy problem;
- Neutralino as a WIMP candidate;
- Help modify running of the gauge couplings and the unification picture;
- The only graded Lie algebra of symmetries of the S-matrix consistent with relativistic quantum field theory;
- A necessary ingredient for string theory.

Motivation for High-scale Supersymmetry

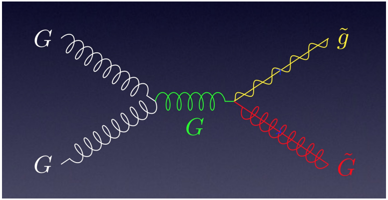
- Hierarchy problem no more;
- Gravitino as a FIMP candidate;
- Help modify running of the gauge couplings and the unification picture probably;
- The only graded Lie algebra of symmetries of the S-matrix consistent with relativistic quantum field theory;
- A necessary ingredient for string theory.

Minimal assumption: Non-Linear SUSY below T_{RH}

- Push the soft mass of the supersymmetric partners to be above T_{RH};
- The low energy spectrum is then only the SM + the gravitino;
- Considering gauge mediation, the gravitino is naturally the LSP;

$$m_{3/2} \ll T_{RH} \lesssim M_{SUSY} \lesssim \sqrt{F} \lesssim \Lambda_{mess} \ll M_{Pl}.$$

- We forbid: – the possibility of thermalization of sparticles – their decays generating sizable amounts of gravitinos after reheating or influencing the BBN.
- Also the previous scattering process is forbidden.



SuperHiggs Mechanism and Equivalence Theorem

- By analogy of Higgs mechanism in electroweak theory, in Supergravity, goldstino ψ is eaten by the gauge field to give mass to the gravitino:

$$\tilde{g}_\mu \sim i\sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu\psi \quad with\ m_{3/2} = \frac{\langle F\rangle}{\sqrt{3}M_{Pl}},$$

- At high energies, the coupling of longitudinal modes is fixed by the supersymmetry breaking scale $\langle F\rangle$, no longer M_{Pl} suppressed;
- Cosmology: For $m_{3/2} \ll T$, the gravitino production is dominated by its helicity $1/2$ component: the goldstino.

Generating the interactions: Low energy theorem

- Put the goldstino in the vierbein:

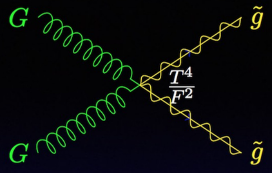
$$e_m^a \ = \ \delta_m^a - \frac{i}{2F^2}\partial_m G\sigma^a \bar{G} + \frac{i}{2F^2} G\sigma^a\partial_m\bar{G};$$

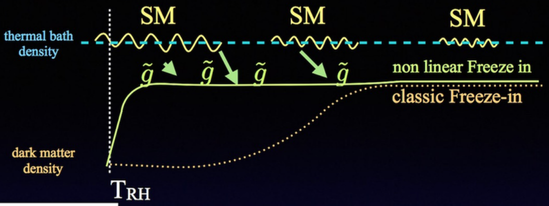
- We can get universal coupling between SM matter and goldstino:

$$L_{2G} = \frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})T_{\mu\nu};$$

- This leads to dimensional-8 operators suppressed by F^2:

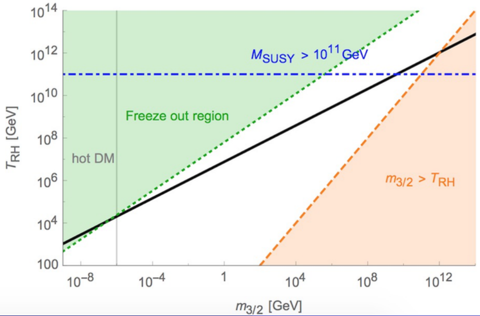
$$\frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\nu H\partial_\mu H^\dagger),$$
$$\frac{1}{8F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}) \times$$
$$(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi + \bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi - \partial_\mu\psi\bar{\sigma}_\nu\psi - \partial_\nu\psi\bar{\sigma}_\mu\psi),$$
$$\sum_a \frac{i}{2F^2}(G\sigma^\xi\partial_\mu\bar{G} - \partial_\mu G\sigma^\xi\bar{G})F^{\mu\nu a}F^a_{\nu\xi},$$





$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\mathrm{RH}}}{5.4\times 10^7\ \mathrm{GeV}}\right)^7$$

Heavy gravitino is compatible with high T_{RH} and no LHC SUSY signals while still giving the right amount of relic abundance.



Non-universal goldstino couplings

- Dimensional-8 operators suppressed by F^2 can also be derived by integrating out the heavy superpartners.
- The difference is just the numerical constant, which is not important.
- R-parity violating operators can have dimension less than 8. Here we assume they are small so that the life time is long enough. Thus the contribution is negligible during the production.
- They can be useful for the indirect detection:

$$e.g. \quad \frac{\mu_i}{F} l_l^i \sigma^\mu \bar{G} D^\mu h^j + h.c,$$

leads to $G \rightarrow \gamma\nu$.

Prospect for Detection

- FIMP from UV dominated production have hardly chance for collider searches and direct detection;
- R-parity violation decay is still allowed;
- Since the energy scale for the decay process is $m_{3/2}$, we can't use goldstino language anymore;
- The coefficients of the R-parity violating operators are not necessarily constrained from preserving baryon asymmetry as in previous studies;
- The different energy distribution profile from the WIMP's may have consequences on the structure formation.

Conclusion

- The high-scale Supersymmetry, although can't solve the hierarchy problem, can still have a natural Dark Matter candidate with the minimal assumption, while keeping the other advantages of supersymmetry.
- The minimal model of Gravitino Dark Matter can automatically avoid the previous two cosmological problems and still gives a high reheating temperature useful for leptogenesis.
- Non-linear Supersymmetry can give the effective couplings between goldstino and SM matters, which are highly dependent on temperature.
- R-parity violation decay and non-trivial energy distribution could be the smoking gun for the gravitino Dark Matter.

Thanks!