# A Minimal Model of Gravitino Dark Matter

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# Outlines

# FIMP Dark Matter

- The collider searches, dark matter indirect and direct detections keep showing negative results to WIMP scenario...
- Alternative: 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 kinetic limits for production:

- IR ($T \sim m_{DM}$) dominated production: renormalizable operator with extremely small coefficient $\sim 10^{-12}$;
- UV ($T \sim T_{RH}$) 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 detectability: only R-parity violating decay;
- Freeze-out: Once thermalized, the mass is of the order of $\sim 100eV$ which is excluded by Tremaine Gunn/structure formation bounds:

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

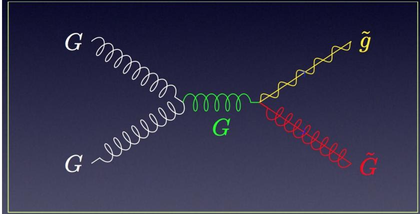
- Considering Freeze-in instead...

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

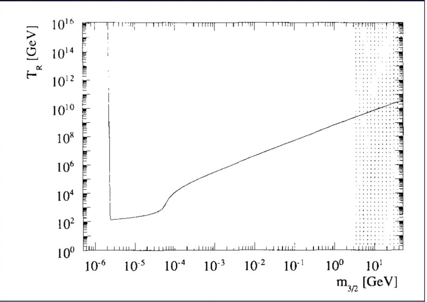
… one can then compute the relic abundance of the gravitino, repopulated by the scattering of SM particles in the thermal bath:

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

gravitino gluino gluon




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




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

# Cosmological Gravitino Problems

For weak-scale SUSY

- 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.

*A Minimal Model of Gravitino Dark Matter*

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

- Considering gauge mediation, the gravitino is naturally the LSP:

$$m_{3/2} = \frac{F}{\sqrt{3}M_{Pl}}, \qquad M_{SUSY} \sim \frac{F}{\Lambda_{mess}},$$

- Push the soft mass of the supersymmetric partners to be above $T_{RH}$;
- The low energy spectrum is then only the SM + the gravitino;

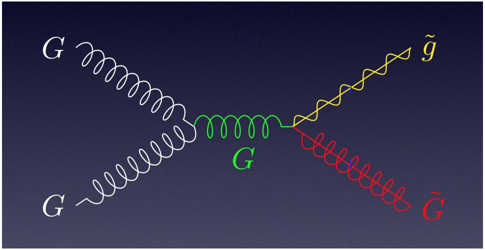
$$m_{3/2} \ll T_{RH} \lesssim M_{SUSY},$$

- The scale hierarchy:

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

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

- 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.




- The gravitino production before $T_{RH}$ is model-dependent.

# SuperHiggs Mechanism and Equivalence Theorem

- By analogy of Higgs mechanism in electroweak theory, in Supergravity, goldstino $\psi$ 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:

$$e^a_m \;=\; \delta^a_m - \frac{i}{2F^2}\partial_m G\sigma^a\bar{G} + \frac{i}{2F^2}G\sigma^a\partial_m\bar{G};$$

- 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 $F^2$:

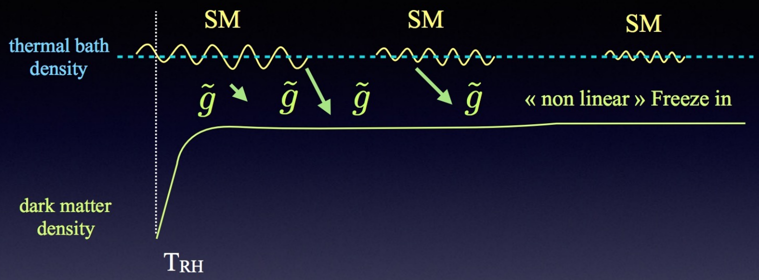
$$\frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\nu H\partial_\mu H^\dagger),$$

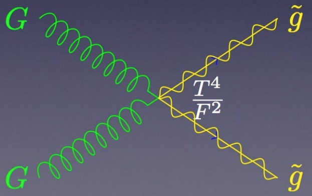
$$\frac{1}{8F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}) \times$$

$$(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi + \bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi - \partial_\mu\psi\bar{\sigma}_\nu\psi - \partial_\nu\psi\bar{\sigma}_\mu\psi),$$

$$\sum_a \frac{i}{2F^2}(G\sigma^\xi\partial_\mu\bar{G} - \partial_\mu G\sigma^\xi\bar{G})F^{\mu\nu a}F^a_{\nu\xi},$$

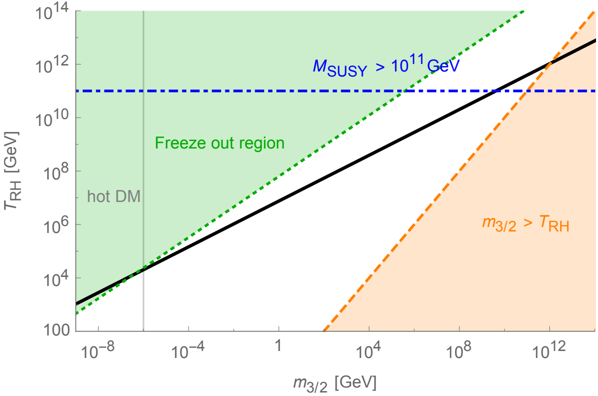
# Minimal Gravitino Dark Matter Model




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

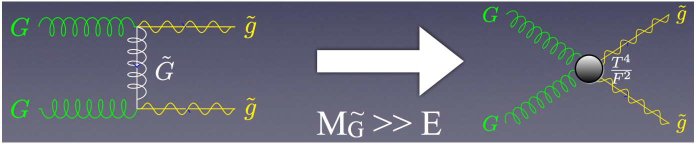
# Minimal Gravitino Dark Matter Model




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.




- Using constrained superfields can lead to the same operators. e.g. $XW^a_\alpha = 0 \to \lambda^a_\alpha = \frac{(\sigma^\mu \bar{\sigma}^\nu)^\beta_\alpha G_\beta F^a_{\mu\nu}}{2\sqrt{2}F_X}$ $\to$kinetic terms of gaugino.
- The difference with the low energy theorem is just the numerical constant, which is not important due to the strong temperature dependence of the yields.

# R-Parity violation operators

- 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:

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

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

# 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 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, leading to the cross sections highly dependent on temperature.
- R-parity violation decay and non-trivial energy distribution could be the smoking gun for the gravitino Dark Matter.

*Thanks!*

# *Backup*

# Freeze-in Production from SM bath

$$R_i = n_{eq}^2 \langle \sigma v \rangle_i = \int f_1 f_2 d\cos\beta \frac{E_1 E_2 dE_1 dE_2}{1024\pi^6} \int |\mathcal{M}|_i^2 d\Omega$$

$$|\bar{\mathcal{M}}|_h^2 = \frac{s^4}{16F^4}(\cos^2\theta - \cos^4\theta)$$
$$|\bar{\mathcal{M}}|_f^2 = \frac{s^4}{256F^4}(1 + cos\theta)^2(1 - 2\cos\theta)^2$$
$$|\bar{\mathcal{M}}|_V^2 = \frac{s^4}{128F^4}(2 - \cos^2\theta - \cos^4\theta)$$

# Freeze-in Production from SM bath

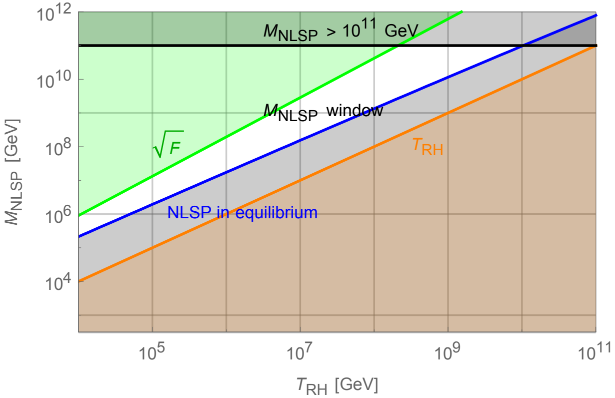
$$R = \sum_i n_{eq}^2 \langle \sigma v \rangle_i = 4 n_{eq}^2 \langle \sigma v \rangle_h + 45 n_{eq}^2 \langle \sigma v \rangle_f + 12 n_{eq}^2 \langle \sigma v \rangle_V$$

$$n_{eq}^2 \langle \sigma v \rangle_h = \frac{48 \zeta(6)^2}{\pi^5 F^4} T^{12} = \frac{48 \pi^7}{(945)^2 F^4} T^{12}$$

$$n_{eq}^2 \langle \sigma v \rangle_f = \frac{72 \zeta(6)^2}{\pi^5 F^4} (\frac{31}{32})^2 T^{12} = \frac{72 \pi^7}{(945)^2 F^4} (\frac{31}{32})^2 T^{12}$$

$$n_{eq}^2 \langle \sigma v \rangle_V = \frac{264 \zeta(6)^2}{\pi^5 F^4} T^{12} = \frac{264 \pi^7}{(945)^2 F^4} T^{12}$$

$$R = \frac{6400.66 \zeta(6)^2}{\pi^5 F^4} T^{12} = \frac{6400.66 \pi^7}{(945)^2 F^4} T^{12} \simeq 21.65 \times \frac{T^{12}}{F^4}$$




$M_{NLSP}$ mass window.