Gravitino Phenomenology with Supernovae

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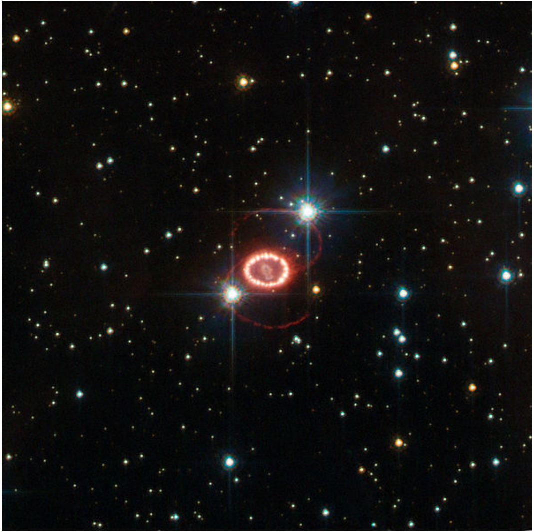

Outline

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1. Supersymmetry and Supergravity
2. Gravitino Phenomenology
3. Supernovae Constraints on superlight Gravitinos
4. Concluding Remarks

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Supersymmetry and Supergravity

Supersymmetry

- Supersymmetry is an hypothetical extension of the spacetime symmetries.
- Its generators satisfy the super algebra

$$\left\{Q_\alpha, \overline{Q}_{\dot\beta}\right\} = 2\sigma^{\mu}_{\alpha\dot\beta}P_\mu$$

- These generators relate bosonic states with fermionic ones and vice versa,

$$Q|\text{boson}\rangle \sim |\text{fermion}\rangle\,, \quad Q|\text{fermion}\rangle \sim |\text{boson}\rangle$$

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Supersymmetry - Motivations

Gauge Coupling Unification

- In the MSSM the gauge couplings unify at high energies.

Hierarchy Problem

- The quantum corrections to the Higgs mass of bosons and fermions can cancel in a supersymmetric theory.

Dark Matter

- SUSY leads to the introduction of new particles which could act as DM.

Theoretical Appeal

- The SUSY algebra is the most general Lie algebra of a symmetry of the S-matrix (Haag-Łopuszański-Sohnius-Theorem).

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SUSY Breaking

In a supersymmetric theory the particles form **supermultiplets** (ϕ, χ, F), whose bosonic and fermionic fields should be degenerate in mass. If this would be the case in nature, where is the selectron?

- If SUSY is a symmetry of nature, it must be a broken one.
- This can be achieved if one of the fields acquire a vacuum expectation value (VEV) $\langle F \rangle$.
- After SUSY breaking a massless Goldstone fermion, the goldstino, appears in the spectrum. It has scalar superpartners, the sgoldstinos.

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Local SUSY

Up until now we considered **global** Supersymmetry. What happens if we promote SUSY to a local symmetry?

The SUSY generators are connected to the generators of the Poincaré group:

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Remarks on Supergravity

- The action of the gravity sector is given by

$$S = \int d^4xe \left[-\frac{1}{2\kappa^2} R - \frac{1}{2} \epsilon^{\kappa\lambda\mu\nu} \overline{\psi}_\kappa \gamma^5 \gamma_\lambda \partial_\mu \psi_\nu \right]$$

- Renormalizability?
- The spectrum consists of a massless spin-2 graviton and its spin-$\frac{3}{2}$ superpartner, the **gravitino**.
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Local SUSY breaking and Gravitino Mass

A non-zero gravitino mass is a clear indicator of SUSY breaking. The mass $m_{3/2}$ is connected to the SUSY breaking scale Λ_{SUSY},

$$m_{3/2} \sim \kappa \Lambda_{\mathrm{SUSY}}^2 \,, \quad \text{where } \kappa = \sqrt{8\pi G_N} \,.$$

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Super-Higgs Mechanism

Gravitino Phenomenology

More about free Gravitinos

- As a spin $\frac{3}{2}$ field its dynamics are governed by the Rarita-Schwinger equation,

$$\epsilon^{\mu\nu\kappa\lambda}\gamma^5\gamma_\nu\partial_\kappa\psi_\lambda + \frac{1}{2}m_{3/2}\left[\gamma^\mu, \gamma^\nu\right]\psi_\nu = 0\,.$$

- Its solution can be written as

$$\psi_\mu \sim e^{-ipx}\tilde{\psi}_\mu$$

$$\tilde{\psi}_\mu(\vec{p}, \lambda) = \sum_{s,m}\left\langle\left(\frac{1}{2}, s\right)(1, m)\,\middle|\,\left(\frac{3}{2}, \lambda\right)\right\rangle u(\vec{p}, s)\epsilon_\mu(\vec{p}, m)\,.$$

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We will also need the spin polarization tensor,

$$\Pi^{(\pm)}_{\mu\nu}(p) = \sum_s \psi^s_\mu(k)\bar{\psi}^s_\nu(k) = -(\not{p} \pm m_{3/2})$$
$$\times \left[\left(g_{\mu\nu} - \frac{p_\mu p_\nu}{m^2_{3/2}} \right) - \frac{1}{3} \left(g_{\mu\sigma} - \frac{p_\mu p_\sigma}{m^2_{3/2}} \right) \left(g_{\nu\lambda} - \frac{p_\lambda p_\nu}{m^2_{3/2}} \right) \gamma^\sigma \gamma^\lambda \right]$$
$$= \frac{2}{3}\frac{k_\mu k_\nu}{m^2_{3/2}} \not{k} \pm \frac{1}{3}\frac{4k_\mu k_\nu - k_\mu \not{k} \gamma_\nu - k_\nu \gamma_\mu \not{k}}{m_{3/2}} + \mathcal{O}(m^0_{3/2}) \,.$$

Superlight gravitinos

In 1977 the French physicist Pierre Fayet came to the conclusion

"[...]that the super-Higgs mechanism gives to the gravitino, and to gravitation effects in particle physics, their chance to be detected, since weak interactions can be generated from gravitational ones."

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Equivalence Theorem

- If $m_{3/2}$ is very small, its couplings to matter will be enhanced.
- The interactions will be dominated by its $\frac{1}{2}$ helicity states.
- It behaves like the goldstino and we can write

$$\psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu \chi \,.$$

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For Completeness: Interactions with matter

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{2\kappa^2} R - \frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}\overline{\psi}_\kappa \gamma^5 \gamma_\lambda \partial_\mu \psi_\nu - \frac{1}{4}\, m_{3/2}\overline{\psi}_\alpha \left[\gamma^\alpha, \gamma^\beta\right] \psi_\beta - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + \frac{1}{2}\overline{\lambda}^{(a)} \left[\gamma^\mu \partial_\mu - m_\gamma\right] \lambda^{(a)} - \frac{i}{8}\kappa \left[\overline{\psi}_\mu \left[\gamma^\alpha, \gamma^\beta\right] \gamma^\mu \lambda_{(a)}\right] F^{(a)}_{\alpha\beta} \\
& - \frac{\kappa}{2} h_{\mu\nu} \left[\frac{1}{2}\eta^{\mu\nu}\left(\eta_{\alpha\beta}\partial_\lambda A^\alpha \partial^\lambda A^\beta - \partial_\beta A^\alpha \partial_\alpha A^\beta\right) + \eta_{\alpha\beta}\partial^\nu A^\alpha \partial^\mu A^\beta \right. \\
& \qquad \left. + \delta^\nu_\alpha \delta^\mu_\beta \partial_\lambda A^\alpha \partial^\lambda A^\beta - \delta^\nu_\alpha \partial_\beta A^\alpha \partial^\mu A^\beta - \delta^\mu_\beta \partial^\nu A^\alpha \partial_\alpha A^\beta \right] \\
& - \frac{\kappa}{4} m_{3/2} h_{\alpha\beta}\left(\eta^{\alpha\mu}\eta^{\beta\nu} + \eta^{\alpha\nu}\eta^{\beta\mu} - \eta^{\mu\nu}\eta^{\alpha\beta}\right)\overline{\psi}_\mu \psi_\nu \\
& - i\frac{\kappa}{4}\partial_\lambda h_{\alpha\beta}\epsilon\overline{\psi}_\mu \gamma_5 \left\{\gamma_\sigma, \sigma^{\rho)\lambda}\right\}\psi_\nu \\
& + \frac{\kappa}{4}\left(\epsilon^{\mu\sigma\nu(\lambda}\overline{\psi}_\mu \gamma_5 \gamma^{\rho)}\partial_\sigma \psi_\nu h_{\lambda\rho} - \epsilon^{\mu\sigma\nu(\lambda}\partial_\sigma \overline{\psi}_\mu \gamma_5 \gamma^{\rho)}\psi_\nu h_{\lambda\rho}\right) \\
& + \frac{\kappa}{4} c F_{\mu\nu} F^{\mu\nu} S + i\frac{\kappa}{2} m_{3/2} d \overline{\psi}_\mu \sigma^{\mu\nu}\psi_\nu S \\
& + \frac{\kappa}{8} c\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} P + i\frac{\kappa}{4} d\epsilon^{\mu\nu\rho\sigma}\overline{\psi}_\mu \gamma_\nu \psi_\rho \partial_\sigma P\,.
\end{aligned}
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Supernovae Constraints on superlight Gravitinos

Energy Loss Argument with Supernovae

Low mass WIMPs are able to contribute to the energy loss of stars and supernovae.

- During a Supernova, the binding energy of

$$E \sim \frac{G_N M^2}{R} \sim 3 \times 10^{53} \text{erg}$$

  get released.
- Most of this energy ($> 99\%$) is released in the form of neutrinos.
- These neutrinos have been observed in the SN1987A by Kamiokande and IMB.

→ They found $E_\nu \geq 2 \times 10^{53}$erg.

Every anomalous energy loss mechanism is bounded by $L_X < 10^{52} \frac{\text{erg}}{\text{s}}$.

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Constraints on $m_{3/2}$ from Supernovae - Our Approach

1. Find the dominating channels of gravitino production in a supernova.
2. Calculate the cross-section.
3. Use known properties of supernovae to calculate the luminosity of the gravitinos produced in a supernova.
4. The luminosity is bounded by $L < 10^{52} \frac{\text{erg}}{\text{s}}$. This constraint comes from
   - Stellar Models,
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5. This can be translated into constraints on $m_{3/2}$.

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Dominant Channels of Gravitino Production

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1. photon-photon collision $\gamma\gamma \longrightarrow \tilde{G}\tilde{G}$,
2. nucleon-nucleon Bremsstrahlung $NN \longrightarrow NN\tilde{G}\tilde{G}$,
3. electron-electron Bremsstrahlung $e^-e^- \longrightarrow e^-e^-\tilde{G}\tilde{G}$,
4. and electron-positron annihilation $e^-e^+ \longrightarrow \tilde{G}\tilde{G}$.

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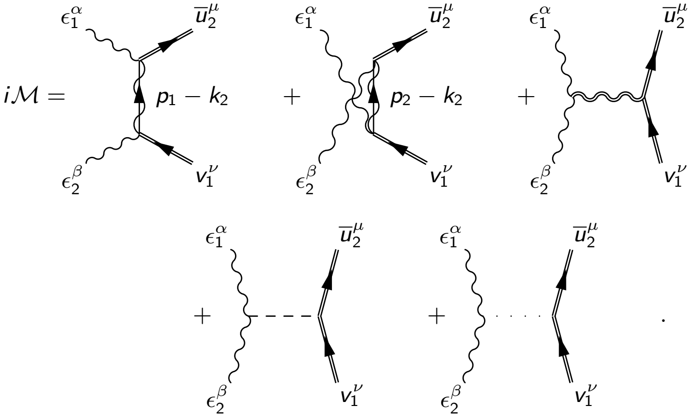
Feynman Diagrams for $\gamma\gamma \longrightarrow \tilde{G}\tilde{G}$



Amplitude

$$i\mathcal{M} = i\mathcal{M}_{\text{Photino}} + i\mathcal{M}_{\text{Graviton}} + i\mathcal{M}_{\text{Scalar}} + i\mathcal{M}_{\text{Pseudoscalar}} \, ,$$

where

$$\begin{aligned}
i\mathcal{M}_{\text{Photino}} &= \frac{i\kappa^2}{4}\ \epsilon_1^\alpha \epsilon_2^\beta\ p_1^\kappa p_2^\lambda \quad \overline{u}_2^\mu \sigma_{\alpha\kappa}\gamma_\mu \frac{\not{q}_1 - m_\gamma}{q_1^2 - m_\gamma^2}\gamma_\nu \sigma_{\beta\lambda} v_1^\nu \\
&+ \frac{i\kappa^2}{4}\ \epsilon_2^\alpha \epsilon_1^\beta\ p_2^\kappa p_1^\lambda \quad \overline{u}_2^\mu \sigma_{\alpha\kappa}\gamma_\mu \frac{\not{q}_2 - m_\gamma}{q_2^2 - m_\gamma^2}\gamma_\nu \sigma_{\beta\lambda} v_1^\nu \, , \\
i\mathcal{M}_{\text{Graviton}} &= \frac{\kappa^2}{2(p_1+p_2)^2}\Big((\epsilon_1\cdot\epsilon_2)p_1^\lambda p_2^\rho + \frac{1}{2}\left((p_1\cdot\epsilon_2)(p_2\cdot\epsilon_1) - (p_1\cdot p_2)(\epsilon_1\cdot\epsilon_2)\right)\eta^{\lambda\rho} \\
&+ (p_1\cdot p_2)\epsilon_1^\lambda\epsilon_2^\rho - (p_2\cdot\epsilon_1)\epsilon_2^\rho p_1^\lambda - (p_1\cdot\epsilon_2)p_2^\lambda\epsilon_1^\rho + (\rho\leftrightarrow\lambda)\Big) \\
&\overline{u}_2^\mu\Big[\epsilon_{\mu\sigma\nu(\lambda}\gamma^5\gamma_{\rho)}(k_2-k_1)^\sigma + \frac{i}{2}\epsilon_{\mu\sigma\nu(\lambda}\gamma^5\left\{\gamma^\sigma, \sigma_{\rho)\tau}\right\} \\
&- 2im_{3/2}(2\eta_{\mu(\lambda}\eta_{\rho)\nu} - \eta_{\mu\nu}\eta_{\lambda\rho})\Big] v_1^\nu \, , \\
i\mathcal{M}_{\text{Scalar}} &= \frac{i\kappa^2 m_\gamma}{(p_1+p_2)^2}\ \epsilon_1^\alpha\epsilon_2^\beta\ \left((p_1\cdot p_2)\eta_{\alpha\beta} - p_1^\beta p_2^\alpha\right)\eta_{\mu\nu}\ \overline{u}_2^\mu v_1^\nu \, , \\
i\mathcal{M}_{\text{PseudoScalar}} &= -\frac{i\kappa^2 m_\gamma}{2m_{3/2}}\frac{1}{(p_1+p_2)^2}\ \epsilon_1^\alpha\epsilon_2^\beta\ p_1^\kappa p_2^\lambda\ \epsilon_{\kappa\lambda\alpha\beta}\ (p_1+p_2)^\zeta\ \epsilon_{\mu\delta\nu\zeta}\ \overline{u}_2^\mu\gamma^\delta v_1^\nu \, .
\end{aligned}$$

Power-Counting of $m_{3/2}$

After squaring the amplitude we obtain terms like

$$\overline{|\mathcal{M}_{\text{PseudoScalar}}|^2} = \frac{1}{m_{3/2}^2}\text{Tr}\left[\Pi^{\nu\nu'}(k_1)\Theta_{\text{PS},\mu'\nu'}\Pi^{\mu'\mu}(k_2)\Theta_{\text{PS},\mu\nu}\right] ,$$

$$\overline{\left|\mathcal{M}_i^\dagger \mathcal{M}_{\text{PseudoScalar}}\right|} = \frac{1}{m_{3/2}}\text{Tr}\left[\Pi^{\nu\nu'}(k_1)\Theta_{i,\mu'\nu'}\Pi^{\text{PS},\mu'\mu}(k_2)\Theta_{2,\mu\nu}^{(m_1,\dots,m_M)}\right] .$$

Cross-Section

The result for the cross-section is given by

$$\sigma(\gamma\gamma \to \tilde{G}\tilde{G}) = \frac{\kappa^4 m_{\tilde{\gamma}}^4 s}{1728\pi m_{3/2}^4} \left[\frac{1}{1+x}\left(x+7-\frac{12}{x}-\frac{24}{x^2}\right)+\frac{1}{x+2}\left(\frac{48}{x^3}+\frac{24}{x^2}-\frac{6}{x}\right)\log(1+x)\right],$$

where $x \equiv \frac{s}{m_{\tilde{\gamma}}^2}$. For this calculation we used the Mathematica package **FeynCalc**.

In the limit $m_{\tilde{\gamma}} \gg \sqrt{s}$ this yields

$$\sigma(\gamma\gamma \to \tilde{G}\tilde{G}) = \frac{\kappa^4 s^2 m_{\tilde{\gamma}}^2}{576\pi m_{3/2}^4} + \mathcal{O}(x^0).$$

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Luminosity

The gravitino luminosity is given by

$$L = V \int \frac{d^3 p_1}{(2\pi)^3\, 2p_1^0}\, 2n_\gamma(p_1^0) \int \frac{d^3 p_2}{(2\pi)^3\, 2p_2^0}\, 2n_\gamma(p_2^0) \int \frac{d^3 k_1}{(2\pi)^3\, 2k_1^0} \int \frac{d^3 k_2}{(2\pi)^3\, 2k_2^0}$$
$$(2\pi)^4 \delta^{(4)}(p_1 + p_2 - k_1 - k_2)(k_1^0 + k_2^0) \overline{\left| \mathcal{M}(\gamma\gamma \to \tilde{\mathcal{G}}\tilde{\mathcal{G}}) \right|^2},$$

leading to

$$L > \frac{8V}{(2\pi)^6} \int d^3 p_1 d^3 p_2 e^{-(p_1^0 + p_2^0)/T} (p_1^0 + p_2^0)\,(1 - \cos\alpha)\,\sigma(\gamma\gamma \longrightarrow \tilde{G}\,\tilde{G})$$
$$= \frac{160}{\pi^5} \left(\frac{\kappa}{m_{3/2}} \right)^4 m_{\tilde{\gamma}}^2 V T_{SN}^{11}.$$

Lower Bound on $m_{3/2}$

Now we are able to translate this relation into a constraint on $m_{3/2}$ using the observational bound from SN1987A.

$$m_{3/2} > 1.8 \times 10^{-5}\text{eV}\,.$$

But this bound is valid only as long as the gravitinos are not trapped inside the SN core like the neutrinos.

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Trapped Gravitinos

The mean-free-path of a gravitino in the SN core is given by

$$\lambda_{\mathrm{MFP}} \sim \left(n_\gamma(T_{SN}) \sigma(\gamma \tilde{G} \longrightarrow \gamma \tilde{G}) \right)^{-1} = \frac{8\pi^3}{9\zeta(3)} m_{3/2}^4 \kappa^{-4} m_{\tilde{\gamma}}^{-2}\, T^{-7}\,.$$

The bound is only valid if $\lambda_{\mathrm{MFP}} > R_{SN}$.
We obtain

$$\lambda_{\mathrm{MFP}} \sim 2.1 \times 10^6 \left(\frac{m_{3/2}}{1.8 \times 10^{-5}\mathrm{eV}} \right)^4 \mathrm{km} \gg 10 \left(\frac{R_{SN}}{10\mathrm{km}} \right) \mathrm{km}\,.$$

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The whole argument breaks down, if the gravitino is so light such that $\lambda_{\mathrm{MFP}} \ll R_{\mathrm{SN}}$. This gives us an upper bound on the gravitino mass.

Main Result

We can exclude the range

$$6.2 \times 10^{-8}\mathrm{eV} < m_{3/2} < 1.8 \times 10^{-5}\mathrm{eV}$$

for the gravitino mass based on the observation of SN1987A.

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Outlook

- This result was verified during the first months of my Master's thesis.
- This is work in progress. Right now we are working on including bilinear R parity violations.
- In scenarios with bilinear RPV, we typically obtain a non-vanishing sneutrino VEV and neutralino-neutrino mixing.
- This gives rise to an effective gravitino-photon-neutrino vertex.
- Therefore single gravitino production becomes possible and we are looking for the dominating channels.

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Concluding Remarks

- Supersymmetry and its local version, Supergravity are very appealing extensions of the SM.
- In some Supergravity models there are superlight gravitinos.
- A significant and observable amount of these could be produced in Supernovae. This would extend the known energy loss mechanisms of SN.
- The observation of SN1987A allows us to exclude the mass range $6.2 \times 10^{-8}\text{eV} < m_{3/2} < 1.8 \times 10^{-5}\text{eV}$.
- In the future we hope to find new results for models with R parity violations.

Thank you for your attention!