Gravitino Phenomenology with Supernovae

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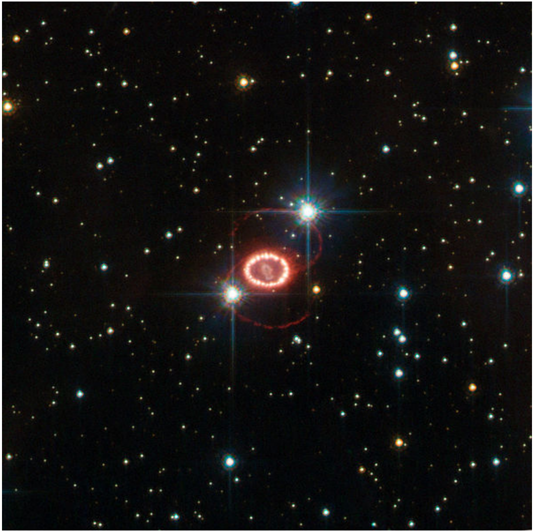

Outline

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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 huge quantum corrections to the Higgs mass 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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Remarks on Supergravity

- The action of the gravity sector is given by

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

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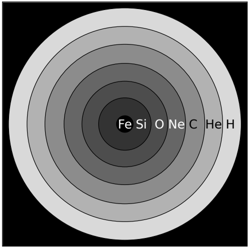
$$\Pi^{(\pm)}_{\mu\nu}(p) = \sum_s \psi^s_\mu(k)\bar{\psi}^s_\nu(k) = -(\not{p} \pm m_{3/2})$$
$$\times \left[\left(g_{\mu\nu} - \frac{p_\mu p_\nu}{m^2_{3/2}} \right) - \frac{1}{3} \left(g_{\mu\sigma} - \frac{p_\mu p_\sigma}{m^2_{3/2}} \right) \left(g_{\nu\lambda} - \frac{p_\lambda p_\nu}{m^2_{3/2}}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

For Completeness: Interactions with matter

$$
\begin{aligned}
e^{-1}\mathcal{L} = & -\frac{1}{2\kappa^2}R - \frac{1}{2}e^{-1}\epsilon^{\kappa\lambda\mu\nu}\overline{\psi}_\kappa\gamma^5\gamma_\lambda D_\mu\psi_\nu + \frac{i}{2}\,m_{3/2}\overline{\psi}_\alpha\sigma^{\alpha\beta}\psi_\beta - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + \frac{i}{2}\overline{\lambda}^{(a)}\left[\gamma^\mu D_\mu - m_{\tilde{\gamma}}\right]\lambda^{(a)} + D_\mu\phi^i D^\mu\phi^{*i} - m_{\phi_i}\phi^{*i}\phi^i \\
& + i\overline{\chi^i}_L\gamma^\mu D_\mu\chi^i_L - \frac{1}{2}m_{\chi_i}\left(\overline{\chi^c_L}^i\chi^i_L + \text{h.c.}\right) \\
& - \frac{i\kappa}{\sqrt{2}}\left(D_\mu\phi^{*i}\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi^i_L - D_\mu\phi^i\overline{\chi}^i_L\gamma^\nu\gamma^\mu\psi_\nu\right) - \frac{\kappa}{4}\overline{\psi}_\mu\sigma^{\rho\sigma}\gamma^\mu\lambda\,F_{\rho\sigma} \\
& - \frac{\kappa^2}{4}\left[ie^{-1}\epsilon^{\kappa\lambda\mu\nu}\overline{\psi}_\kappa\gamma_\lambda\psi_{R\mu} + \overline{\psi}_\mu\gamma^\nu\psi^\mu_R\right]\overline{\chi_L}^i\gamma_\nu{\chi_L}^i \\
& + \frac{1}{2}\left(\partial_\mu S\partial^\mu S - m_S S^2 + \partial_\mu P\partial^\mu P - m_P P^2\right) \\
& + \frac{\kappa}{4}cF_{\mu\nu}F^{\mu\nu}S + i\frac{\kappa}{2}m_{3/2}d\overline{\psi}_\mu\sigma^{\mu\nu}\psi_\nu S \\
& + \frac{\kappa}{8}ce^{-1}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}P + i\frac{\kappa}{4}d\epsilon^{\mu\nu\rho\sigma}\overline{\psi}_\mu\gamma_\nu\psi_\rho\partial_\sigma P + \mathcal{O}(\kappa^2)
\end{aligned}
$$

Supernovae Constraints on superlight Gravitinos

Supernovae



- $M_{\text{core}} > 1.44 M_{\text{Sun}} \longrightarrow$ Core collapse to a sphere of $R \sim 10$ km and nuclear density.
- The mantle and radiation get ejected in a shockwave $\longrightarrow$ a 'Supernova' occurs.

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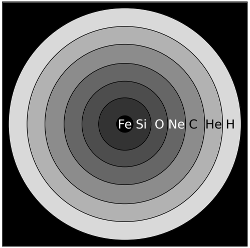

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Energy Loss Argument with Supernovae

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

- During a Supernova, the binding energy of

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

  get released.
- SN neutrinos have been observed in the SN1987A by Kamiokande and IMB. They found $E_\nu \geq 2 \times 10^{53}$erg.
- $\longrightarrow$ Most energy ($> 99\%$) is released in the form of neutrinos.

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

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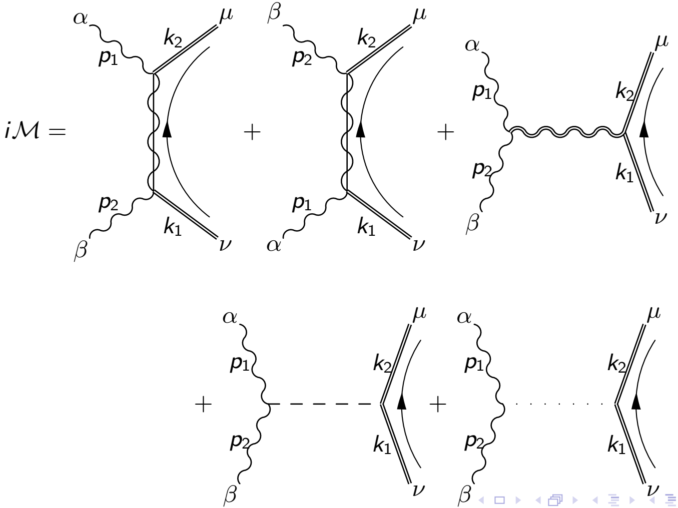
Feynman Diagrams for $\gamma\gamma \longrightarrow \tilde{G}\tilde{G}$



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

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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.

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

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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.

- This result is similar to the ones obtained in J.A. Grifols et al., Phys.Lett. B401, 283 (1997).

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Heavy Sgoldstinos

The result is indirectly based on the assumption of massless sgoldstinos.

This is not necessarily the case and some models inherit very heavy sgoldstinos.

Modified Result for heavy Sgoldstinos

$$\sigma(\gamma\gamma \to \tilde{G}\tilde{G}) \approx \frac{s^3 \kappa^4}{5760\pi m_{3/2}^4},$$

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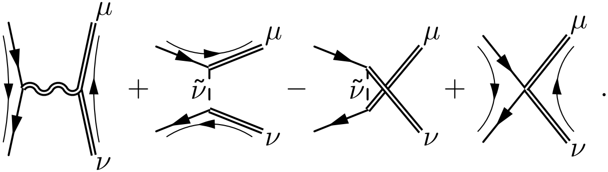
Additional Gravitino Production Channels for heavy Sgoldstinos

Processes like the following become relevant:

$$i\mathcal{M}(\nu\bar{\nu} \longrightarrow \tilde{G}\tilde{G}) =$$



	Light Sgoldstinos:	Heavy Sgoldstinos:
$\frac{L(\nu\bar{\nu}\to\tilde{G}\tilde{G})}{L(\gamma\gamma\to\tilde{G}\tilde{G})}$	$\sim \frac{T_{SN}^2}{m_{\tilde{\gamma}}^2} \sim 10^{-6}$	~ 0.7

The bounds seem to be very model-dependent.

Concluding Remarks

- In SUGRA models the graviton has a superpartner, the gravitino.
- After SUSY breaking the gravitino becomes massive, the mass is depending on the mechanism of symmetry breaking.
- Very light gravitinos would give an additional supernova cooling mechanism, which is constrained by the SN1987A observation.
- This leads to constraints on the mass of superlight gravitinos.
- Unfortunately these are partly depending on the specific SUGRA Model. The independent bounds are rather weak.
- Bilinear R-parity violations lead to the additional production of single gravitinos, but the new contributions turn out to be negligible.

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Thank you for your attention!

R-Parity

- Lepton and baryon number L and B are automatically conserved in the SM.
- This changes with the introduction of SUSY $\longrightarrow$ proton decay becomes possible, but $\tau_P > 2.1 \times 10^{29}$ y.
- To fix this Pierre Fayet introduced a new symmetry called 'R-parity',

$$R_P = (-1)^{3B+L+2s} = \begin{cases} +1 & \text{for particles,} \\ -1 & \text{for sparticles.} \end{cases}$$

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Consequences of conserved R-Parity

- stability of the lightest sparticle
- conserved baryon and lepton number
- sparticles can be produced in pairs only

$$W_{\text{MSSM}} = \mu H_u H_d + \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D^c_j - \lambda^u_{ij} H_u Q_i U^c_j \,,$$

$$W_{\not R} = \mu_i H_u \cdot L_i + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j E^c_k + \lambda'_{ijk} L_i \cdot Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k \,.$$

There is no fundamental reason not to include R-parity violations.

Bilinear R-Parity Violations

- We can add the bilinear term

$$W_{\not{R}_P} = \mu_i H_u \cdot L_i \, ,$$

without threatening the proton stability.

- The baryon number remains conserved.
- A sneutrino obtains a VEV just as the Higgs scalars.
- Neutralinos mix with neutrinos, charginos mix with charged leptons.
- Gravitino obtains new effective couplings to matter.

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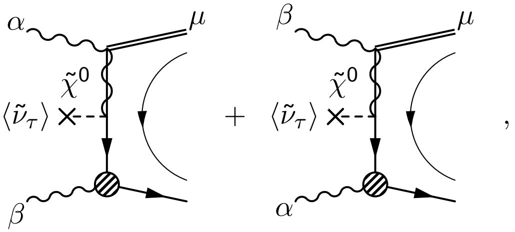
Single Gravitino Production from Photon and Neutrino Collisions

$$i\mathcal{M}(\gamma\gamma \to \tilde{G}\nu) =$$



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