

abundance of χ , normalized by the entropy density, s , is given by [122]

$$\frac{n_\chi}{s} \sim 10^{-5} \left(\frac{228.75}{\mathcal{A}} \right)^{5/4} \sum_{i,j} \left[\int_{T_{\min}}^{T_{\max}} \mathcal{A}_i \mathcal{A}_j \langle v_{\text{rel}} \sigma_{ij \rightarrow \chi} \rangle M_{\text{P}} dT \right], \quad (439)$$

where we have used Eq. (437).

2. Gravitino production

For flat direction(s) $\text{VEV} \geq 10^{12}$ GeV, slow thermalization results in a low reheat temperature, i.e $T_{\text{R}} \leq 10^9$ GeV, which is compatible with the BBN bounds on thermal gravitino production. However gravitinos are also produced during the quasi-thermal phase prior to a complete thermalization of the reheat plasma. Generically gravitinos are produced from the scatterings of gauge, gaugino, fermion and sfermion quanta with a cross-section $\propto 1/M_{\text{P}}^2$.

During the quasi-thermal phase, the gauge and gaugino quanta have large masses $\sim \alpha^{1/2} \varphi_{\text{d}}$ (induced by the flat direction VEV) at a time most relevant for the gravitino production, i.e., when $H \simeq \Gamma_{\text{d}}$, therefore, they decay to lighter fermions and sfermions at a rate $\sim \alpha^{3/2} \varphi_{\text{d}}^2 / m_\phi$, where $\alpha^{3/2} \varphi_{\text{d}}$ is the decay width at the rest frame of gauge/gaugino quanta, and $\varphi_{\text{d}} / m_\phi$ is the time-dilation factor. The decay rate is $\gg \Gamma_{\text{d}}$, thus gauge and gaugino quanta decay almost instantly upon production, and they will not participate in the gravitino production. As a consequence, production of the helicity $\pm 1/2$ states will not be enhanced in a quasi-thermal phase as scatterings with a gauge-gaugino-gravitino vertex will be absent¹⁰².

The following channels contribute to the gravitino production [309]: (a) *fermion + anti-sfermion* \rightarrow *gravitino + gauge field*, (b) *sfermion + anti-fermion* \rightarrow *gravitino + gauge field*, (c) *fermion + anti-fermion* \rightarrow *gravitino + gaugino*, (d) *sfermion + anti-sfermion* \rightarrow *gravitino + gaugino*.

The total cross-section involves cross-sections for multiplets comprising the LH (s)quarks Q , RH up-type (s)quarks u , RH down-type (s)quarks d , LH (s)leptons L , RH (s)leptons e and the two Higgs/Higgsino doublets H_u, H_d . Since particles and anti-particles associated to the bosonic and fermionic components of the multiplets which belong to an irreducible

¹⁰² Otherwise gauge and/or gaugino quanta in the initial state (particularly scattering of two gluons) have the largest production cross-section [309–312].