Goldstino Production with Low Reheating Temperatures

Angelo Monteux
based on arXiv:1505.03149, in collaboration with Chang Sub Shin

New High Energy Theory Center
Rutgers University

SUSY 2015, August 27th 2015

Introduction

- review: thermal history of the universe
- dynamics of reheating; what is T_R?
- processes during matter-domination
- freeze-in vs. freeze-out
- (lack of) kinetic equilibrium
- consequences for Dark Matter, BBN and LHC
- conclusions

Thermal history of the universe

The highest temperature that we have direct observational evidence of is $T \approx 5$ MeV (BBN, CMB).

Still, we can explain features of the present universe by assuming particular dynamics of the earlier universe:

- dark matter abundance from WIMP freeze-out, assuming that at some point $T > M_{WIMP}$.
- baryogenesis at the weak scale or above, leptogenesis at RH neutrino scale.
- flatness / horizon problem $\longrightarrow$ inflation at some unknown high scale.

In particular, inflation sets an upper energy scale given by the *reheating temperature*

$$T_R \sim \sqrt{\Gamma_I M_P}$$

Thermal history of the universe

The highest temperature that we have direct observational evidence of is $T \approx 5$ MeV (BBN, CMB).

Still, we can explain features of the present universe by assuming particular dynamics of the earlier universe:

- dark matter abundance from WIMP freeze-out, assuming that at some point $T > M_{WIMP}$.
- baryogenesis at the weak scale or above, leptogenesis at RH neutrino scale.
- flatness / horizon problem $\longrightarrow$ inflation at some unknown high scale.

In particular, inflation sets an upper energy scale given by the *reheating temperature*

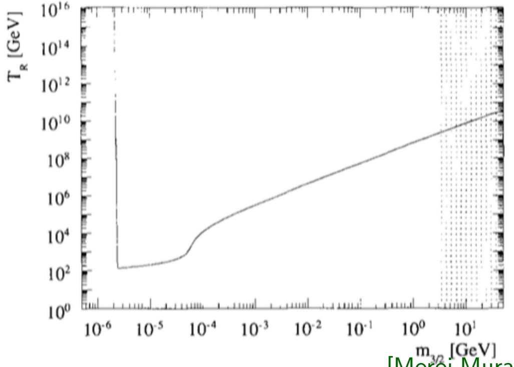
$$T_R \sim \sqrt{\Gamma_I M_P}$$

Reheating and Super-Weakly interacting particles

As example, goldstino production dominated by highest temperatures

$$\mathcal{L} \supset \frac{\tilde{m}^2}{F^2}\zeta\psi\phi - i\frac{m_\lambda}{\sqrt{2}F}\zeta\sigma^{\mu\nu}\lambda^a F^a_{\mu\nu}$$

For high $T_R \gg$TeV, goldstino production through $gg \to \lambda\zeta$, $\lambda\lambda \to \zeta\lambda \ldots$



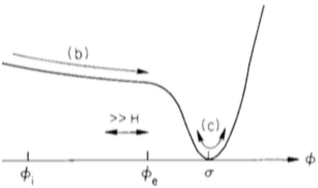
$$\Omega_{3/2} \sim 0.2 \left(\frac{T_R}{10^{10}\ \text{GeV}}\right) \times \times \left(\frac{100\ \text{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\ \text{TeV}}\right)^2$$

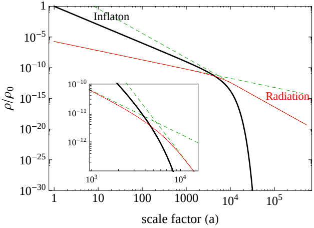
(cutoff at T_R)

[Moroi,Murayama,Yamaguchi, Phys.Lett.1993]

[Bolz,Brandenburg,Buchmuller, Nucl.Phys.2001]

More on Reheating





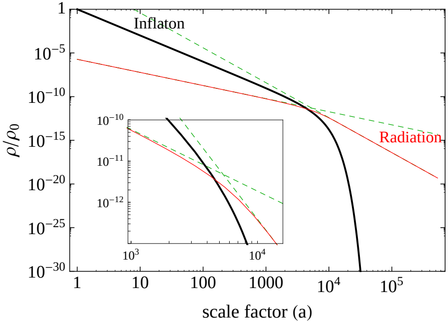
After (slow-roll) inflation, the inflaton field Φ coeherently oscillates around the minimum of its potential, damped by decays into SM particles. Universe is *matter-dominated* until the inflaton has decayed away.

The reheating temperature is the maximum temperature of the plasma in (our) radiation-dominated era.

Low scale of inflation typically gives low T_R:

$$\text{e.g. if } \Gamma_I = \frac{m_\Phi^3}{M_P^2} \qquad \rightarrow \qquad T_R \sim 1 \text{ GeV} \left(\frac{m_\Phi}{10^6 \text{ GeV}} \right)^{3/2}$$

(** similar if other source of matter-domination, e.g. unstable moduli **)



$$\begin{cases} \rho_{MD} \propto a^{-3} \\ \rho_{MD}^{rad} \propto a^{-3/2} \\ T_{MD} \propto a^{-3/8} \end{cases}$$

$$\begin{cases} \rho_{RD} \sim a^{-4} \\ T_{RD} \propto a^{-1} \end{cases}$$

.

The radiation bath reaches a higher temperature during matter-domination: in particular, the highest temperature ever reached is

$$T_{MAX} \sim \left(\frac{V_I^{1/4}}{T_R} \right)^{\frac{1}{2}} T_R \gg T_R$$

Between T_{MAX} and T_R, entropy injection by inflaton decay $\Longrightarrow$ Early processes diluted away and remnants are dominated by the lowest temperature at which the processes are still relevant (e.g. WIMP production with low T_R).

[Giudice,Kolb,Riotto, PRD 64 023508]

Super-Weakly interacting particles & matter domination

[AM,C.S.Shin, 1505.03149, PRD]

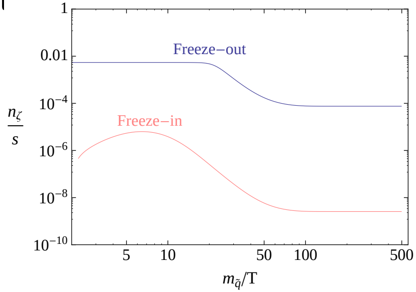
As example, goldstino in MSSM (also multiple goldstini)

$$\mathcal{L} \supset \frac{\tilde{m}^2}{F^2}\zeta\psi\phi - i\frac{m_\lambda}{\sqrt{2}F}\zeta\sigma^{\mu\nu}\lambda^a F^a_{\mu\nu}$$

For $T_R \ll T < m_{\tilde{q}}$, consider decay of squarks or gauginos into goldstinos:

$$\tilde{q} \leftrightarrow \zeta q, \qquad \lambda^a \leftrightarrow \zeta A_\mu.$$

SUSY breaking F-term determines interaction strength: either freeze-in or freeze-out



$\leftarrow F = (100\ \text{TeV})^2$

$\leftarrow F = (5000\ \text{TeV})^2$

Chemical freeze-out and kinetic equilibrium

If ζ in kinetic equilibrium ($f_\zeta \propto \exp(-p/T)$), the Boltzmann equation is

$$\dot{n}_\zeta + 3Hn_\zeta = \left(\langle\Gamma\rangle_{\tilde{q}} n_{\tilde{q}}^{eq} - \underline{\langle\sigma v\rangle_{\zeta q} n_\zeta n_q^{eq}}\right) = \langle\Gamma\rangle_T n_{\tilde{q}}^{eq}(1 - \underline{n_\zeta/n_\zeta^{eq}})$$

where the second term represent inverse decays (relevant when $n_\zeta \simeq n_\zeta^{eq}$). e.g. for WIMPs, $\chi + SM \to \chi + SM$ stays in equilibrium long after $\chi + \chi \to SM + SM$ freezes out.

Different for superWIMPS:
$\mathcal{M}(\zeta + \psi \to \zeta + \psi) \propto 1/F^4, \quad \mathcal{M}(\tilde{q} \to q\zeta) \propto 1/F^2 \implies f_\zeta(p) \neq f_\zeta^{eq}(p)$.

The Boltzmann equation for the distribution function is

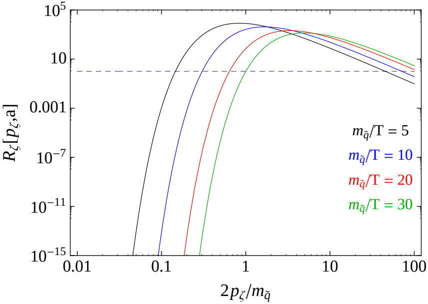
$$\frac{df_\zeta}{dt} = \frac{\partial f_\zeta}{\partial t} - Hp\frac{\partial f_\zeta}{\partial p} = C[f_\zeta],$$

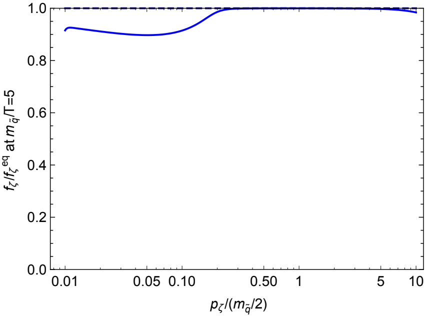
$$\frac{\partial f_\zeta}{\partial \ln a} - \frac{\partial f_\zeta}{\partial \ln p} = \left(1 - \frac{f_\zeta}{e^{-p/T}}\right)\left(\frac{\Gamma_{\phi\to\zeta\psi}\tilde{m}_\phi T}{Hp^2}\right)\exp\left\{-\frac{p}{T}\left(1 + \frac{\tilde{m}_\phi^2}{4p^2}\right)\right\}$$

Momentum-dependent freeze-out

Goldstinos are in chemical (thus, kinetic) equilibrium if they can inverse-decay back into the heavy squarks. Momentum-dependent statement.

$$R_\zeta(p,a) = \frac{\text{production rate}}{\text{expansion rate}}(p,T) \qquad f_\zeta(p,T)/f_\zeta^{eq}(p,T)$$





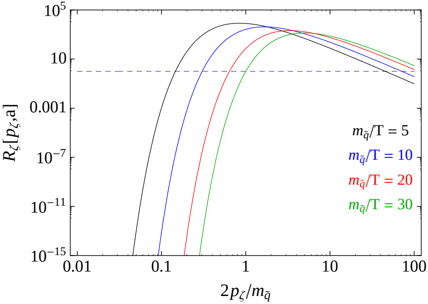
Analytically, given $T_\zeta(a) = \left(\frac{T_R}{0.13 m_{\tilde q}}\right)^{5/3}\left(\frac{a_R T_R}{a}\right)$,

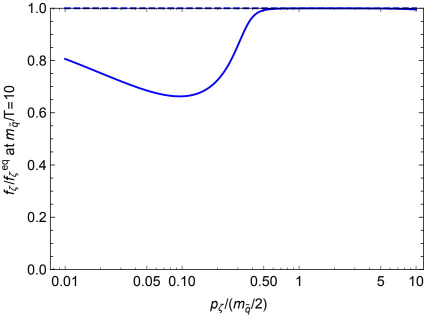
$$f_\zeta(p,a) = \begin{cases} \exp\left[-\left(p/T_\zeta(a)\right)^{6/11}\right], & p < p_{f.o.}(a) \\ \exp[-p/T(a)], & p > p_{f.o.}(a) \end{cases}$$

Momentum-dependent freeze-out

Goldstinos are in chemical (thus, kinetic) equilibrium if they can inverse-decay back into the heavy squarks. Momentum-dependent statement.

$$R_\zeta(p, a) = \frac{\text{production rate}}{\text{expansion rate}}(p, T) \qquad f_\zeta(p, T)/f_\zeta^{eq}(p, T)$$





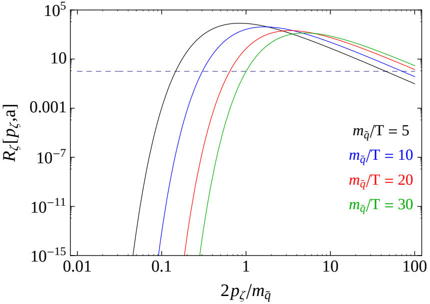
Analytically, given $T_\zeta(a) = \left(\frac{T_R}{0.13 m_{\tilde q}}\right)^{5/3} \left(\frac{a_R T_R}{a}\right)$,

$$f_\zeta(p, a) = \begin{cases} \exp\left[-\left(p/T_\zeta(a)\right)^{6/11}\right], & p < p_{f.o.}(a) \\ \exp[-p/T(a)], & p > p_{f.o.}(a) \end{cases}$$

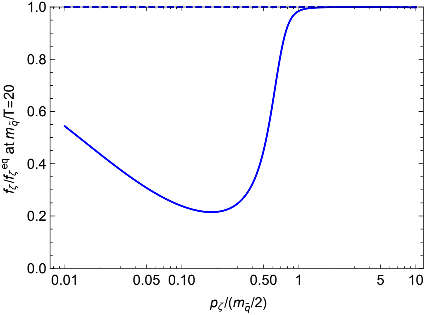
Momentum-dependent freeze-out

Goldstinos are in chemical (thus, kinetic) equilibrium if they can inverse-decay back into the heavy squarks. Momentum-dependent statement.

$$R_\zeta(p,a) = \frac{\text{production rate}}{\text{expansion rate}}(p,T)$$



$$f_\zeta(p,T)/f_\zeta^{eq}(p,T)$$



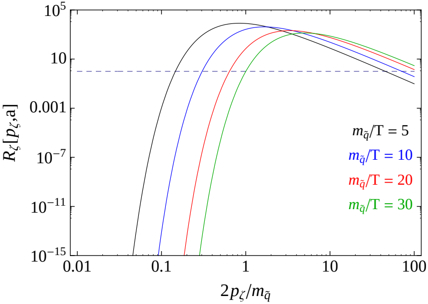
Analytically, given $T_\zeta(a) = \left(\frac{T_R}{0.13 m_{\tilde{q}}}\right)^{5/3}\left(\frac{a_R T_R}{a}\right)$,

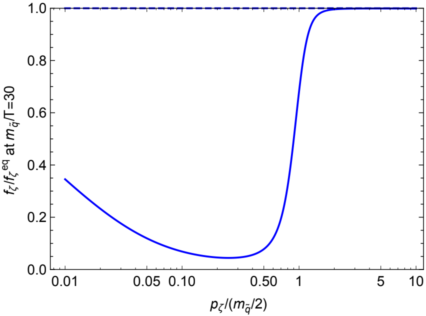
$$f_\zeta(p,a) = \begin{cases} \exp\left[-\left(p/T_\zeta(a)\right)^{6/11}\right], & p < p_{f.o.}(a) \\ \exp[-p/T(a)], & p > p_{f.o.}(a) \end{cases}$$

Momentum-dependent freeze-out

Goldstinos are in chemical (thus, kinetic) equilibrium if they can inverse-decay back into the heavy squarks. Momentum-dependent statement.

$$R_\zeta(p,a) = \frac{\text{production rate}}{\text{expansion rate}}(p,T) \qquad f_\zeta(p,T)/f_\zeta^{eq}(p,T)$$





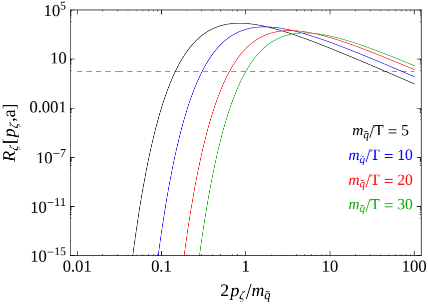
Analytically, given $T_\zeta(a) = \left(\frac{T_R}{0.13 m_{\tilde q}}\right)^{5/3}\left(\frac{a_R T_R}{a}\right)$,

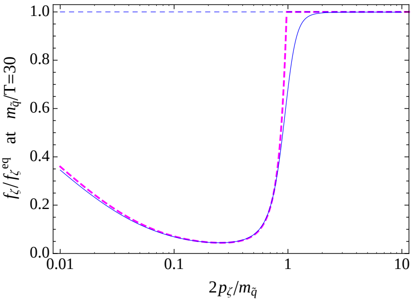
$$f_\zeta(p,a) = \begin{cases} \exp\left[-\left(p/T_\zeta(a)\right)^{6/11}\right], & p < p_{f.o.}(a) \\ \exp[-p/T(a)], & p > p_{f.o.}(a) \end{cases}$$

Momentum-dependent freeze-out

Goldstinos are in chemical (thus, kinetic) equilibrium if they can inverse-decay back into the heavy squarks. Momentum-dependent statement.

$$R_\zeta(p,a) = \frac{\text{production rate}}{\text{expansion rate}}(p,T) \qquad f_\zeta(p,T)/f_\zeta^{eq}(p,T)$$

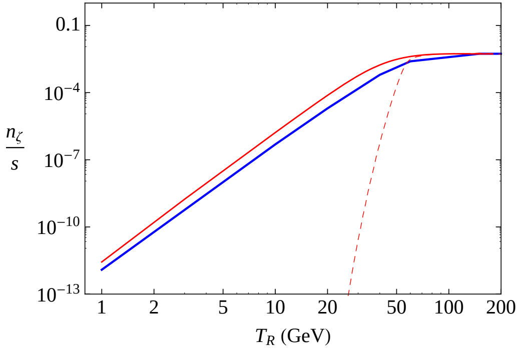




Analytically, given $T_\zeta(a) = \left(\frac{T_R}{0.13 m_{\tilde{q}}}\right)^{5/3}\left(\frac{a_R T_R}{a}\right)$,

$$f_\zeta(p,a) = \begin{cases} \exp\left[-\left(p/T_\zeta(a)\right)^{6/11}\right], & p < p_{f.o.}(a) \\ \exp[-p/T(a)], & p > p_{f.o.}(a) \end{cases}$$

For example, for $m_{\tilde{q}} = 1$ TeV, $F = (100\text{ TeV})^2$, the resulting yield is:



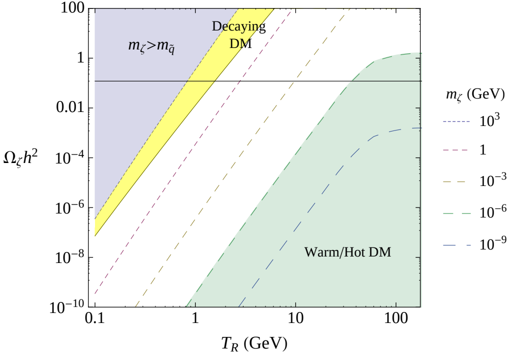
blue: our results.
red: assuming kinetic equilibrium (overestimates by a factor of ~ 4).
dashed red: neglecting matter-dominated era before T_R.

Late-Time Implications: Dark Matter

$$(\Omega_\zeta h^2)_{FO} \simeq 0.19 \left(\frac{m_\zeta}{1\,\mathrm{MeV}}\right)\left(\frac{T_\mathrm{R}}{10\,\mathrm{GeV}}\right)^5\left(\frac{1\,\mathrm{TeV}}{m_{\tilde{q}}}\right)^5$$

$$(\Omega_\zeta h^2)_{FI} \simeq 0.11 \left(\frac{m_\zeta}{2\,\mathrm{MeV}}\right)\left(\frac{T_\mathrm{R}}{10\,\mathrm{GeV}}\right)^7\left(\frac{(500\,\mathrm{TeV})^2}{F_\zeta}\right)^2\left(\frac{1\,\mathrm{TeV}}{m_{\tilde{q}}}\right)^4$$

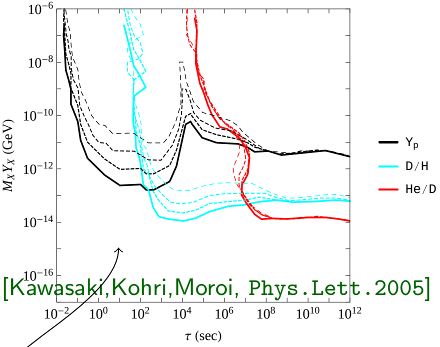
For example, for $F = (100\ \mathrm{TeV})^2$ (corresponding to freeze-out), we have



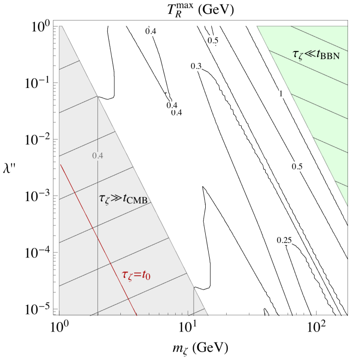
Late-Time Implications: RPV

With baryonic RPV, $W_{BRPV} = \frac{\lambda''_{ijk}}{2} u_i^c d_j^c d_k^c + h.c.$
Proton decay $p \to \zeta K$ forces $m_\zeta > m_p$.
Goldstino Decay $\zeta \to u_i d_j d_k$ disintegrates light elements:

$$\tau_\zeta = 1.57 \times 10^3\,\text{sec} \left(\frac{1}{\lambda''_{ijk}}\right)^2 \left(\frac{10\,\text{GeV}}{m_\zeta}\right)^9 \left(\frac{m_{\tilde{q}}}{1\text{TeV}}\right)^4 \left(\frac{F_\zeta}{(100\,\text{TeV})^2}\right)^2$$



[Kawasaki,Kohri,Moroi, Phys.Lett.2005]



$X \to udd$, with $M_X = 10, 10^2, 10^3, 10^4$ GeV.

Very-Late-Time Implications: LHC

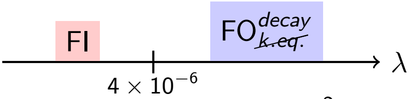
More generally, freeze-in during matter-dominated era (almost always) predicts displaced vertices at the LHC in most of the parameter space (in our case, long lifetime of the squark decaying to goldstino).

[Co,D'Eramo,Hall,Pappadopulo, 1506.07532]

If $B \to X + SM$ with $\Gamma_B = \lambda^2 \frac{m_B}{8\pi}$, fitting the observed DM abundance gives, for $m_X = 100$ GeV and $m_B = 300$ GeV:

$$\lambda = 2 \times 10^{-8} \quad \text{if} \quad T_R = 4.6 \text{ GeV}$$
$$= 2 \times 10^{-7} \quad \text{if} \quad T_R = 2.4 \text{ GeV}$$

Demarcation between FI and FO:



Lifetime at the LHC: $$c\tau_B \simeq 10^{-5} m \left(\frac{10^{-6}}{\lambda}\right)^2 \left(\frac{300 \text{ GeV}}{m_B}\right)$$
$$\simeq 10 m \left(\frac{T_R}{10 \text{ GeV}}\right)^7 \left(\frac{300 \text{ GeV}}{m_B}\right)^9 \left(\frac{m_X}{100 \text{ GeV}}\right)$$

Conclusions

I have discussed the possibility of super-weakly interacting particles thermally produced during an early matter-dominated era. If the Universe never reheated at high energies, this was the only chance!

The correct dark matter density can be reproduced for reheating temperatures as low as 1 GeV (even for much heavier, TeV-scale, squarks)

If the interaction strength is not too small, *thermal equilibrium* of the goldstinos can be mantained by chemical interactions only, and this is *momentum-dependent*. Kinetic interactions are frozen out at low momentum and the distribution function acquires a non-standard form.

Thank you!

…questions?

Extra slides

Example: WIMP freeze-out in matter-domination

Decoupling during RD era, for $T_R \gg T_{FO}$:

$$(\Omega_X h^2)_0 \sim 0.1 \left(\frac{M_X / T_{FO}}{10} \right) \frac{10^{-8}\ \text{GeV}^{-2}}{\langle \sigma v \rangle}$$

For example, implies unitarity bound $M_X \lesssim 300$ TeV.

Decoupling during MD era, for $T_R \ll T_{FO}$:

[Giudice,Kolb,Riotto, PRD 64 023508]

$$T_{FO} \gg T_{MAX}: \qquad \Omega_X h^2 \sim 10^2 \left(\frac{10^3 T_R}{M_X} \right)^7 \left(\frac{\alpha}{0.01} \right)$$

$$T_{FO} \ll T_{MAX}: \qquad \Omega_X h^2 \sim (\Omega_X h^2)_0 \left(\frac{T_R}{T_{FO}} \right)^3$$

Removes unitarity bound. Lower cross section, higher mass range allowed (e.g. WIMPzillas).

Examples: WIMP freeze-out in matter-domination

WIMP decoupling during MD era, for $T_R \ll T_{FO}$:

[Giudice,Kolb,Riotto, PRD 64 023508]