Nonthermal Dark Matter & Baryogenesis from Moduli Decay

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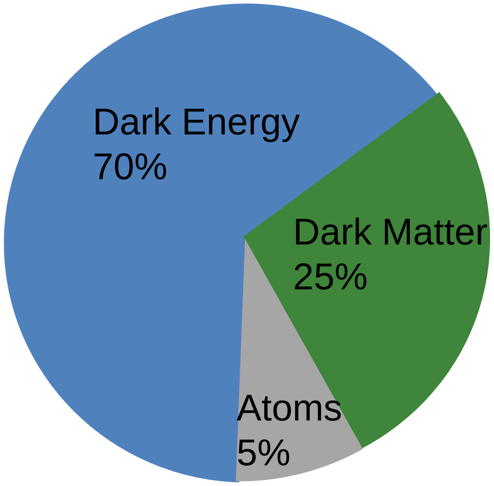
Outline:

- Introduction
- Nonthermal DM from moduli decay
- An explicit model
- Baryogenesis (Post-sphaleron, Affleck-Dine)
- Summary and outlook

Based on recent work:

PRD 82, 035004 (2010) PRD 83, 083502 (2011) PRD 86, 095016 (2012)
PRD 88, 023525 (2013) PRD 88, 095015 (2013) JCAP 1410, 002 (2014)
JHEP 1606, 153 (2016) in preparation

Introduction:



Big problems to address:

1) Dark Matter (DM)

$$\left(\frac{n_{DM}}{s}\right)_{obs} \sim 5\times10^{-10}\left(\frac{1\ GeV}{m_{DM}}\right)$$

What is the nature of DM? How was it produced?

2) Baryon Asymmetry of Universe (BAU)

$$\left(\frac{n_b}{s}\right)_{obs} \sim 10^{-10}$$

Why is it nonzero? How was it generated?

A possible coincidence puzzle?

Why DM and baryons have comparable energy densities?

Thermal DM:

Starting in thermal equilibrium at $T >> m_\chi$:

1) $T >> m_\chi : \quad \chi\chi \leftrightarrow f\bar{f}, \ldots \quad \Rightarrow \quad n_\chi \propto T^3 \;,\; n_\chi / s = const$

2) $T < m_\chi : \quad \chi\chi \rightarrow f\bar{f}, \ldots \quad \Rightarrow \quad n_\chi \propto \exp(-m_\chi / T)$

3) $T \approx T_f : \quad freeze-out \quad \Rightarrow \quad n_\chi / s = const$

$$\Omega_\chi h^2 \approx 10^{-1} \Rightarrow \boxed{< \sigma_{ann} v >_f = 3 \times 10^{-26}\ cm^3 s^{-1}}$$

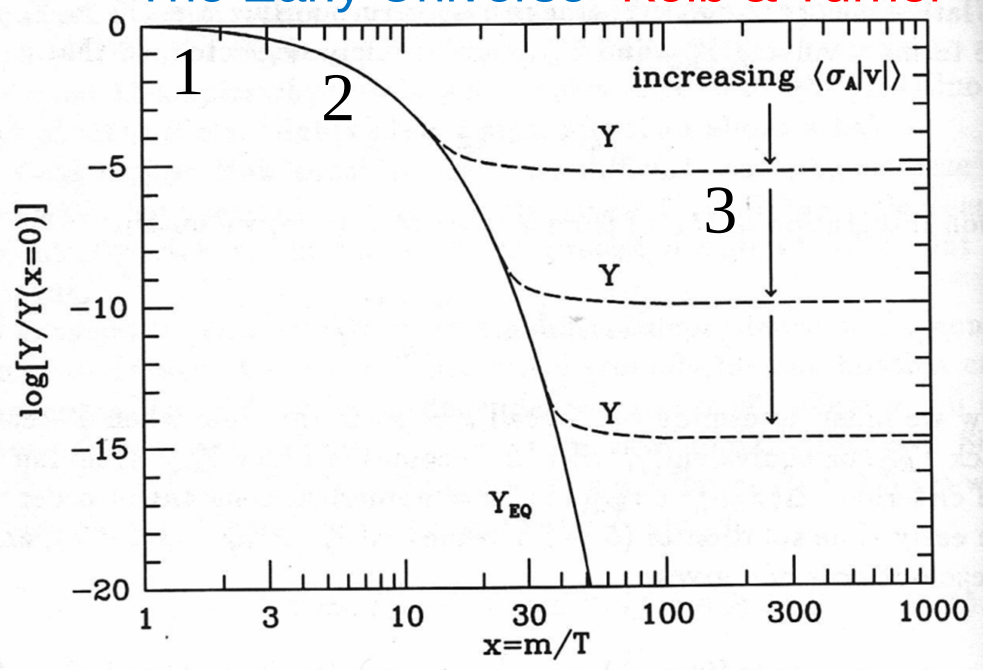
WIMP miracle:

$$< \sigma_{ann} v >_f = \frac{\alpha_\chi^2}{m_\chi^2}$$

$$\alpha_\chi \sim O(10^{-2}),\ m_\chi \sim 10 - 10^3\ GeV$$

$$\Omega_\chi h^2 \sim 10^{-3} - 1$$

“The Early Universe” Kolb & Turner



Moduli, denoted by ϕ, commonly arise in SUSY and string models.
They are massive and long lived:

$$\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2} \qquad \text{(typically: } c \sim 0.1-1 \text{)}$$

Moduli dynamics in the early universe: $(m_\phi << H_{\inf})$

1) Displaced during inflation $\phi_0 \sim M_P$

2) Start oscillating and quickly dominate $H_0 \sim m_\phi$

3) Decay and reheat the universe $T_R \sim \left(\frac{m_\phi}{50\ TeV}\right)^{3/2} \times 3\ MeV$

BBN requires that:

$$T_R > 3\ MeV \Rightarrow \boxed{m_\phi > 50\ TeV}$$

String compatifications with TeV scale SUSY in the visible sector and much heavier volume modulus constructed in recent years.

1) KKLT with mixed anomaly-modulus mediated SUSY breaking

K. Choi, A. Falkowski, H. P. Nilles, M. Olechowski NPB 718, 113 (2005)

$$m_{\phi} : m_{3/2} : m_{soft} \sim 4\pi^2$$

2) LVS with gravity-mediated SUSY breaking

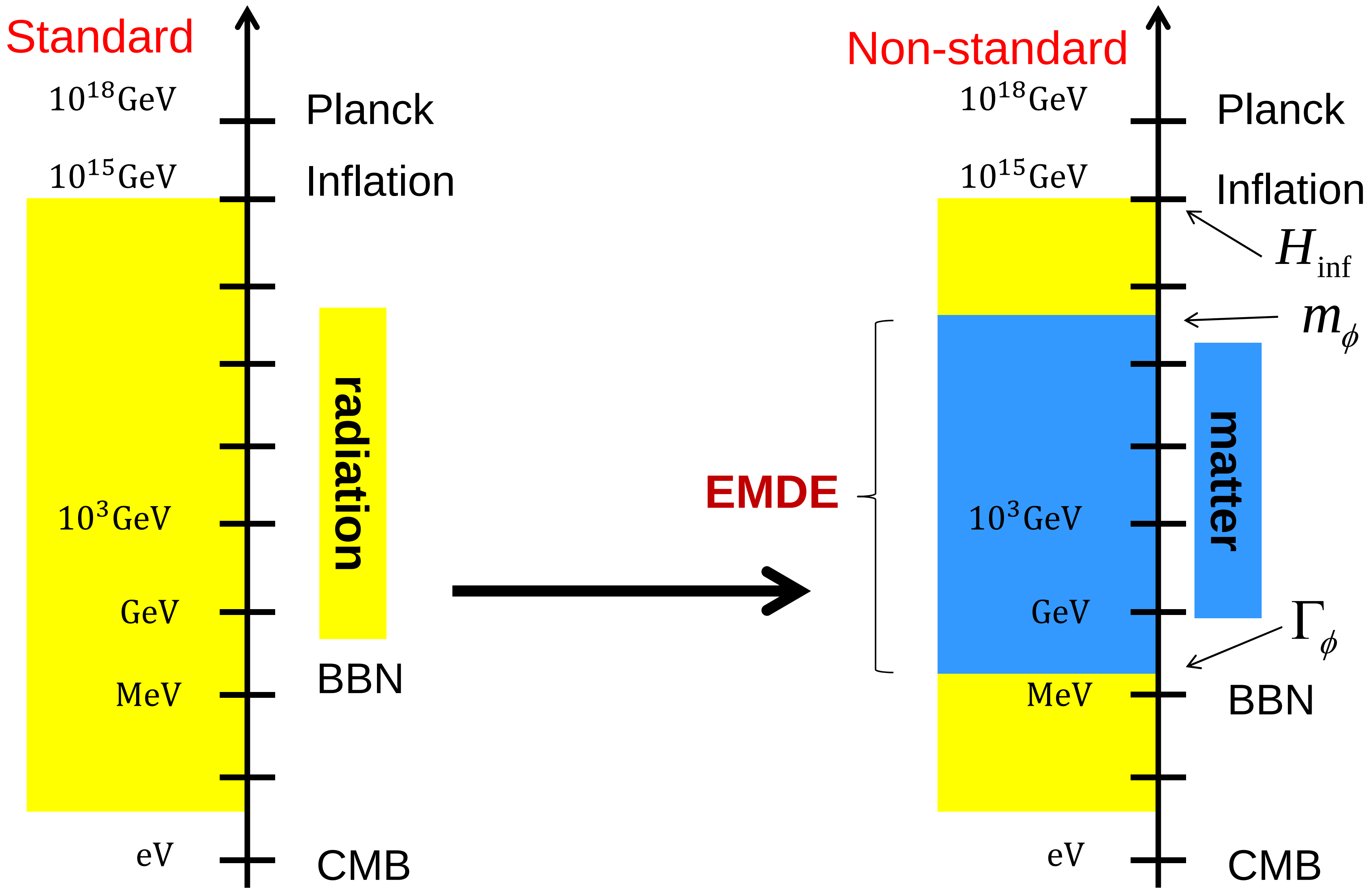
Cicoli, Conlon, Quevedo JHEP 0801, 052 (2008)

$$m_{soft} << m_{\phi} << m_{3/2} \quad (m_{soft} m_{3/2} \sim m_{\phi}^2)$$

In both setups, one can obtain:

$$m_{\phi} \sim (1 - few) \times 1000 \ TeV \Rightarrow T_R \sim O(GeV)$$

Moduli change thermal history of the universe:



G. Kane, K. Sinha, S. Watson IJMPD 8, 1530022 (2015)

Moduli decay reheats the universe and releases huge entropy:

$$\frac{s_{after}}{s_{before}} = \left(\frac{s_R}{s_0} \frac{a_R^3}{a_0^3} \right) = \left(\frac{\rho_R}{\rho_0} \frac{a_R^4}{a_0^4} \right)^{3/4}$$

$$\Gamma_\phi < H < m_\phi : \ \ a \propto t^{2/3}$$

$$\frac{s_{after}}{s_{before}} \sim \left(\frac{\rho_R}{\rho_0} \left(\frac{m_\phi}{\Gamma_\phi} \right)^{8/3} \right)^{3/4} \sim \frac{M_P}{m_\phi} \ \ (>> 10^{10})$$

Late reheating washes out any pre-existing DM and baryon relic abundance generated prior to EMDE.

Moduli decay is not instant. It is a gradual process that creates a subdominant but continuously growing thermal bath.

$$\Gamma_\phi << H << m_\phi :$$

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi \qquad \dot{\rho}_r + 4H\rho_r = +\Gamma_\phi \rho_\phi$$

$$\rho_r = \frac{\pi^2}{30} g_*(T)\ T^4 \Rightarrow H \approx 0.33 \times \frac{5}{2} \times \frac{g_*(T)}{g_*^{1/2}(T_R)} \ \frac{T^4}{T_R^2 M_P}$$

Thermal processes (freeze-out, freeze-in) can produce DM.

D. Chung, E. Kolb, A. Riotto PRD 60, 063504 (1999)
G. Giudice, E. Kolb, A. Riotto PRD 64, 043512 (2001)
A. Erickcek PRD 92, 103505 (2015)

They may also generate baryon asymmetry.

S. Davidson, M. Losada, A. Riotto PRL 84, 4284 (2000)

Final value of relic density related to that at the time of formation:

$$\frac{n}{s} = \frac{n_R}{s_R} = \frac{n_f}{s_f}\left(\frac{a_R^3}{a_f^3}\right)\left(\frac{T_f^3}{T_R^3}\right)$$

$$\Gamma_\phi < H < m_\phi : \ \ a \propto t^{2/3}, H \propto T^4 :$$

$$\frac{n}{s} = \frac{n_f}{s_f}\left(\frac{T_R}{T_f}\right)^5$$

$$T_f > 100 T_R \Rightarrow \frac{n}{s} < 10^{-10}$$

Production during EMDE is negligible if $T_f > 100 \ \ GeV$.

Non-thermal DM from Moduli Decay:

As long as moduli decay is the only source of entropy generation, production before/during EMDE typically negligible.

DM particles can be directly produced from moduli decay.

$$\left(\frac{n_\chi}{s}\right)_{dec} = Y_\phi \, Br_\chi$$

$$Y_\phi \equiv \frac{n_\phi}{s} = \frac{3T_R}{4m_\phi}$$

Br_χ : Branching ratio for decay to DM particles

This can account for the entire DM relic abundance if:

$$\left(\frac{n_\chi}{s}\right)_{dec} \geq \left(\frac{n_\chi}{s}\right)_{obs} \approx 5\times 10^{-10}\left(\frac{1\ GeV}{m_\chi}\right)$$

Two different scenarios are possible.

Annihilation Scenario:

$$\left(\frac{n_\chi}{s}\right)_{dec} > \left(\frac{n_\chi}{s}\right)_{obs} \quad , \; < \sigma_{ann} v >_f \; = 3\times 10^{-26}\ cm^3 s^{-1} \left(\frac{T_f}{T_R}\right)$$

Residual annihilation is efficient, and can lower the abundance to the correct value.

M. Kawasaki, T. Moroi, T. Yanagida PLB 370, 52 (1996)
T. Moroi, L. Randall NPB 570, 455 (2000)
...

This scenario only works for large annihilation cross sections (thermal underproduction):

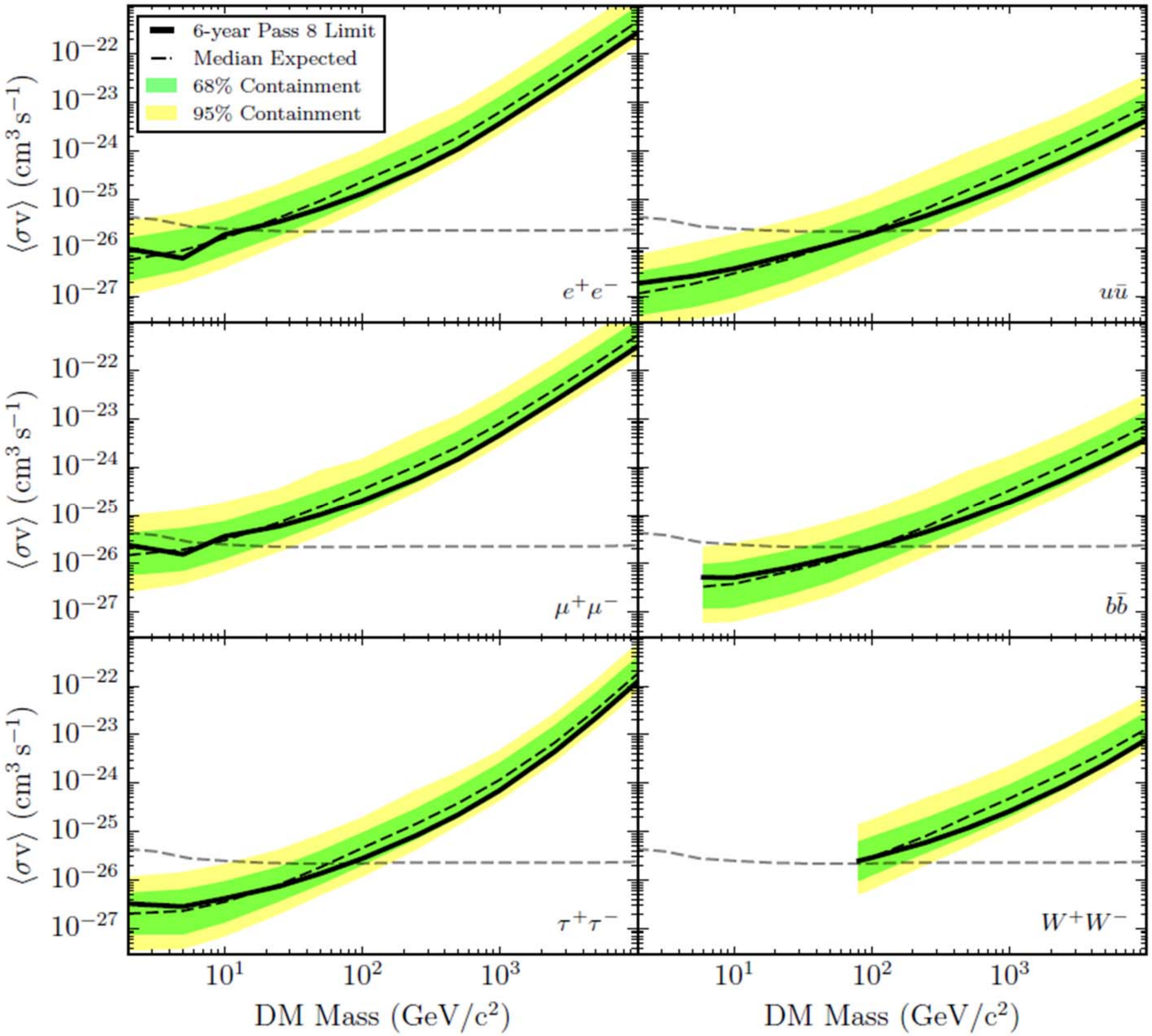
$$T_R = T_f \left(\frac{3\times 10^{-26}\ cm^3 s^{-1}}{< \sigma_{ann} v >_f}\right)$$

Experiments set increasingly tighter constraints on $< \sigma_{ann} v >_f$.

Indirect Detection Experiments:

Stringent bounds from non-detection of gamma-rays from dSphs.

Fermi Collaboration PRL 115, 231301 (2015)



Branching Scenario:

Annihilation is inefficient in this case, moduli decay directly sets the right DM abundance.

G. Gelmini, P. Gondolo PRD 74, 023510 (2006)
R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)

$$\left(\frac{n_\chi}{s}\right)_{dec} = \left(\frac{n_\chi}{s}\right)_{obs}$$

$$Br_\chi \, Y_\phi \approx (5 \times 10^{-10}) \left(\frac{1 \; GeV}{m_\chi}\right)$$

This scenario can work for both small and large annihilation cross sections (thermal over/under production).

DM abundance is completely decoupled from $< \sigma_{ann} v >_f$.

May be promising to address the DM-baryon coincidence problem.

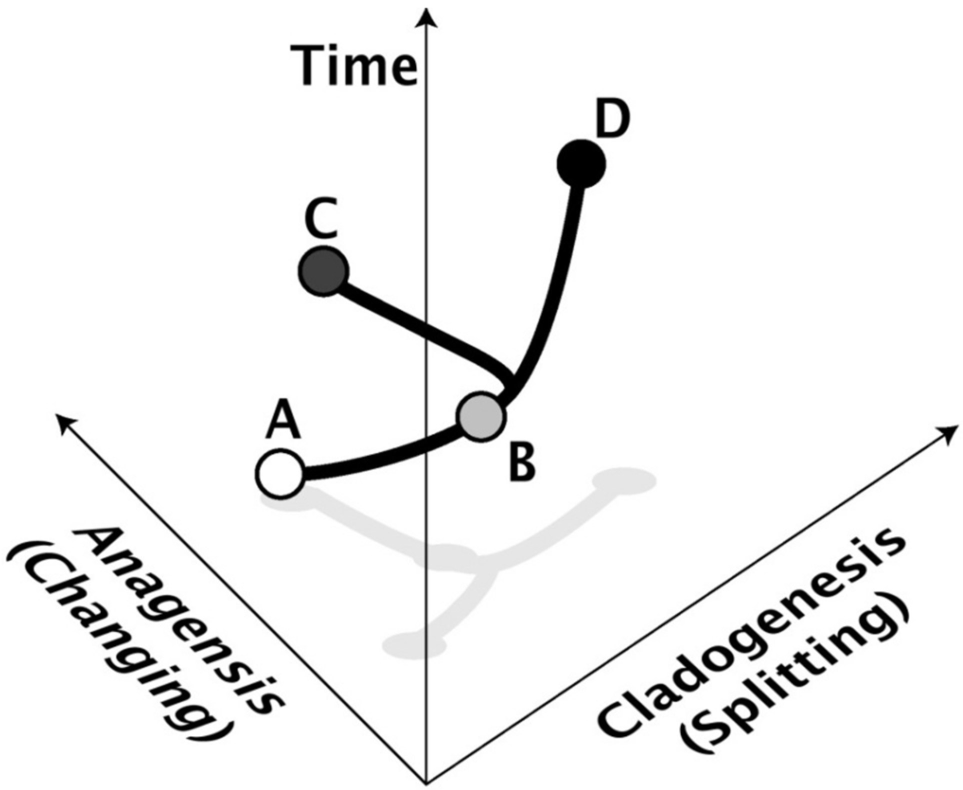
Moduli decay the common source of DM and baryon asymmetry.

Relic densities controlled by respective couplings to the modulus.

Cladogenesis:

"An evolutionary splitting event in a species in which each branch and its smaller branches forms a clade"

R. A., B. Dutta, K. Sinha PRD 83, 083502 (2011)



D: Modulus

A: Dark Matter

C: Ordinary Matter

Constraints and Challenges:

1) Suppressing gravitino production.

$\phi \to \tilde{G}\tilde{G}$ is the main source of gravitino production.

M. Endo, K. Hamaguchi, F. Takahashi PRL 96, 211301 (2006)

Helicity-1/2 gravitinos pose the main threat.

M. Dine, R. Kitano, A. Morisse, Y. Shirman PRD 73, 123518 (2006)

$$\frac{n_{3/2}}{s} = Y_\phi \, Br_{3/2} < \left(\frac{n_\chi}{s}\right)_{obs} \approx 5\times 10^{-10} \left(\frac{1 \ GeV}{m_\chi}\right)$$

$$Y_\phi \sim 7\times 10^{-8} c^{1/2} \left(\frac{m_\phi}{50 \ TeV}\right)^{1/2} \geq 7\times 10^{-8} \ c^{1/2}$$

$m_\chi \geq 10 \ GeV:$ $\boxed{Br_{3/2} < 7\times 10^{-4}}$ or $\boxed{c << 1}$

2) Obtaining the right DM relic density.

$$\frac{n_\chi}{s} = Y_\phi \; Br_\chi \approx 5\times 10^{-10} \left(\frac{1 \; GeV}{m_\chi} \right)$$

$Br_\chi < 7\times 10^{-4}$ and/or $c << 1$

Typically, the main decay mode is to gauge/Higgs bosons.

2-body decays to gauginos and Higgsinos may be suppressed.

T. Moroi, L. Randall NPB 570, 455 (2000)

M. Cicoli, C. Burgess, F. Quevedo JHEP 1110, 119 (2011)

M. Cicoli, A. Mazumdar JCAP 1009, 025 (2010)

However, 3-body decays produce gauginos: $Br_\chi \sim 3\times 10^{-3}$.

R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)

Decay to gauge non-singlets must be suppressed

3) Generating the correct baryon asymmetry of the universe.

Recall the dilution factor from modulus decay:

$$\left(\frac{s_{after}}{s_{before}}\right) \sim \frac{M_P}{m_\phi} \quad (>> 10^{10})$$

How to generate the desired baryon asymmetry?

Non-thermal post-sphaleron baryogenesis

R.A., B. Dutta, K. Sinha PRD 81, 053538 (2010) & PRD 83, 083502 (2011)

Or, from a process that itself releases entropy.

Affleck-Dine baryogenesis

G. Kane, J. Shao, S. Watson, H-B Yu JCAP 1111, 012 (2011)
R.A., M. Cicoli, F. Muia JHEP 1606, 153 (2016)

An Explicit Model:

As an explicit example, let us consider the volume modulus in the LARGE Volume Scenarios (LVS).

V. Balasubramanian, P. Berglund, J. Conlon, F. Quevedo
JHEP 0503, 007 (2005)

$$K \supset -3\ln(\tau_b + \bar{\tau}_b) \quad , \quad W \supset W_{flux} + Ae^{-a\tau_s}$$

Large volume can be obtained after stabilization of τ_b.

M. Cicoli, J. Conlon, F. Quevedo JHEP 0801, 052 (2008)

For large volume, one can have a sequestered scenario such that:

$$m_{soft} << m_{\tau_b} << m_{3/2} \qquad (m_{soft} m_{3/2} \sim m_{\tau_b}^2)$$

For example, TeV scale SUSY can be obtained for:

$$m_{3/2} \sim 10^{10}\ GeV \quad , \quad m_{\tau_b} \sim 5 \times 10^6\ GeV \quad , \quad m_{soft} \sim 1\ TeV$$

Hierarchy of Scales:

$$M_P$$

$$M_S \sim \frac{M_P}{\mathcal{V}^{1/2}}$$

$$m_{3/2} \sim m_{\tau_s} \sim \frac{W_0 M_P}{\mathcal{V}}$$

$$m_{\tau_b} \sim \frac{W_0 M_P}{\mathcal{V}^{3/2}}$$

$$m_0, m_{1/2} \sim \frac{M_P}{\mathcal{V}^2}$$

MSSM

$$M_P$$

$$M_S \sim \frac{M_P}{\mathcal{V}^{1/2}}$$

$$m_{3/2} \sim m_{\tau_s} \sim \frac{W_0 M_P}{\mathcal{V}}$$

$$m_{\tau_b} \sim m_0 \sim \frac{W_0 M_P}{\mathcal{V}^{3/2}}$$

Split SUSY

$$m_{1/2} \sim \frac{M_P}{\mathcal{V}^2}$$

$$m_{\tau_b} < m_{3/2} \Rightarrow \boxed{Br_{3/2} = 0}$$

Decay to gauge bosons arises at one-loop level:

$$\Gamma_{\phi \to gg} \sim \left(\frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2} \qquad \phi = \sqrt{\frac{3}{2} \ln}\ (\tau_b + \bar{\tau}_b)$$

Giudice-Masiero term: $\Gamma_{\phi \to H_u H_d} = \frac{Z^2}{24\pi} \frac{m_\phi^3}{M_P^2}$

$\boxed{c << 1}$ possible

Decay to gauginos (and Higgsinos) mass suppressed:

$$\Gamma_{\phi \to \tilde{g}\tilde{g}} \propto \frac{m_\phi m_{soft}^2}{M_P^2} \Rightarrow \boxed{Br_\chi << 1}$$

LVS can accommodate both branching & annihilation scenarios.

R.A., M. Cicoli, B. Dutta, K. Sinha PRD 88, 095015 (2013)

R.A., M. Cicoli, B. Dutta, K. Sinha JCAP 1410, 002 (2014)

Post-sphaleron Baryogenesis:

B and *L* are accidental symmetries of SM at the perturbative level.

We adopt a bottom-up approach and consider a minimal extension of the SM with renormalizable $\not{B}$ interactions:

R.A., B. Dutta PRD 88, 023525 (2013)

R.A., B. Dutta, K. Sinha PRD 82, 035004 (2010)

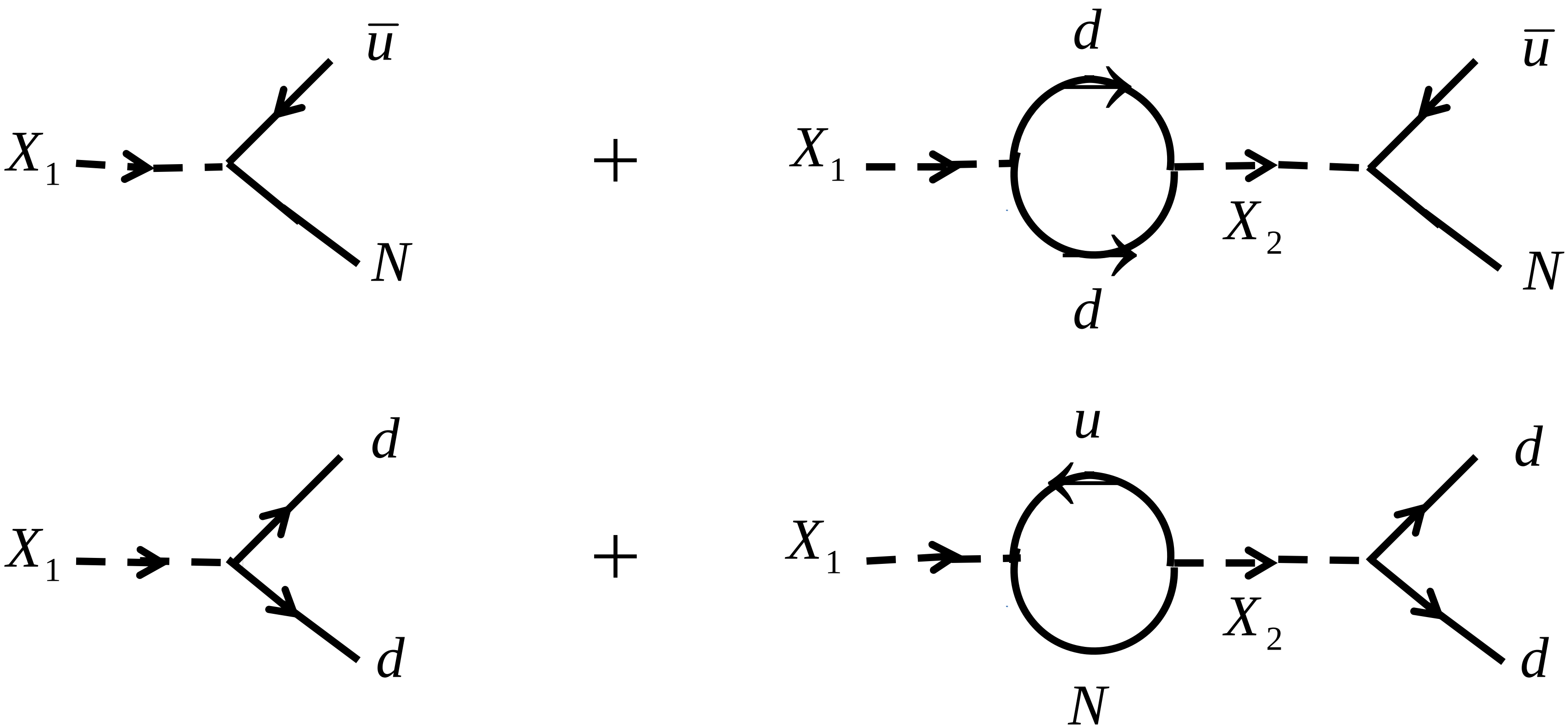
$$L_{new} = \lambda'_{\alpha ij} X_\alpha d_i^c d_j^c + \lambda_{\alpha i} N X_\alpha^* u_i^c + m_\alpha^2 |X_\alpha|^2 + \frac{m_N}{2} NN$$
$$+ h.c. + kinetic\ terms$$

$X_{1,2}$: **Iso-singlet** color-triplet scalars *Y* =+4/3

N : Singlet fermion

This is the minimum field content that is required to generate a nonzero baryon asymmetry via out-of-equilibrium decay of *X*.

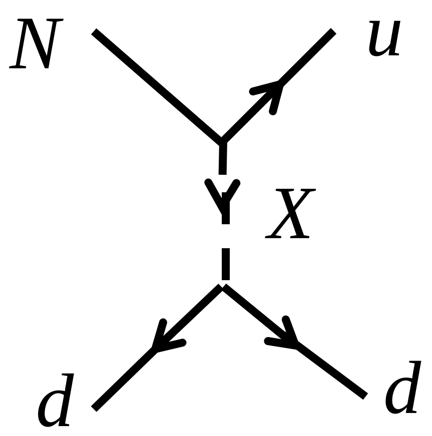
E. Kolb, S. Wolfram NPB 172, 224 (1980); Erratum-ibid 195, 542 (1982)



$$\varepsilon_1 = \frac{1}{8\pi} \frac{\sum_{i,j,k} \mathrm{Im}(\lambda_{1k}^{*}\lambda_{2k}\lambda'_{1ij}\lambda'_{2ij})}{\sum_{i,j} |\lambda'_{1ij}|^2 + \sum_{k} |\lambda_{1k}|^2} \frac{m_1^2}{m_1^2 - m_2^2}$$

$$\varepsilon_2 = \varepsilon_1(1 \leftrightarrow 2)$$

X mediates a 4-fermion interaction:



$$\frac{\lambda\lambda'}{m_X^2} N u_i^c d_j^c d_k^c$$

This operator results in the following decays:

$$m_N > m_p + m_e: \quad N \to p + e^- + \bar{\nu}_e \ , \ \ \bar{p} + e^+ + \nu_e$$

$$m_N < m_p - m_e: \quad p \to N + e^+ + \nu_e \ , \ \ N + e^- + \bar{\nu}_e$$

N is stable and becomes a viable DM candidate if:

$$m_p - m_e \leq m_N \leq m_p + m_e$$

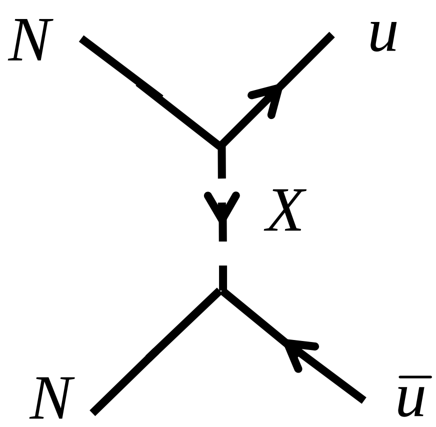
The condition is stable against radiative corrections for:

$$\lambda < O(10^{-1})$$

Stability of DM candidate is tied to the stability of proton.

No additional symmetry, like *R*-parity, is invoked.

$$< \sigma_{ann} v >_f \sim |\lambda|^4 \frac{|\vec{p}|^2}{m_X^4}$$



$$m_X \sim O(TeV):$$

$$< \sigma_{ann} v >_f \ll 10^{-31} cm^3 / s$$

Thermal freeze-out results in overproduction of DM.

Nonthermal mechanism needed to obtain the DM relic abundance.

DM and BAU both produced via **Branching scenario**.

This may in addition address the DM-baryon coincidence.

$$\frac{n_N}{s} = Y_\phi \; Br_N$$

$$\frac{n_b}{s} = Y_\phi \; Br_X \varepsilon$$

$$Br_N \geq Br_X \;\; Br_{X \to N}$$

$$\frac{\Omega_{DM}}{\Omega_b} (\approx 5) = \frac{n_N}{n_b} \; \frac{m_N}{m_b} \sim \frac{Br_{X \to N}}{\varepsilon}$$

Comparable energy densities may be obtained rather naturally.

R.A., B. Dutta, B. Dev arXiv:17??.???? (in preparation)

Affleck-Dine Baryogensis:

The MSSM contains many flat directions φ :

$$D^a = \phi^+ T^a \varphi = 0 \qquad F_\varphi = \frac{\partial W_{MSSM}}{\partial \varphi} = 0$$

Example:

$$L_1 = \begin{bmatrix} \varphi \\ 0 \end{bmatrix} \qquad L_2 = \begin{bmatrix} 0 \\ \varphi \end{bmatrix} \qquad e_3 = \varphi$$

Flat directions are characterized by gauge-invariant monomials.

T. Gherghetta, C. Kolda, S. Martin NPB 468, 37 (1996)

Many flat directions carry baryon and/or lepton number.

Directions with $B - L \neq 0$, the so-called Affleck-Dine (AD) field can be utilized for baryogenesis.

I. Affleck, M. Dine NPB 249, 361 (1985)

The AD field is lifted by SUSY breaking and non-renormalizable superpotential terms:

M. Dine, L. Randall, S. Thomas NPB 458, 291 (1996)

$$W \supset \lambda_n \frac{\varphi^n}{n M_P^{n-3}}$$

$$V(\varphi) = (m_\varphi^2 + c_H H^2)|\varphi|^2 + \lambda_n^2 \frac{|\varphi|^{2(n-1)}}{M_P^{2(n-3)}} + \left[(A + a_H H) \frac{\lambda_n \varphi^n}{n M_P^{n-3}} + h.c. \right]$$

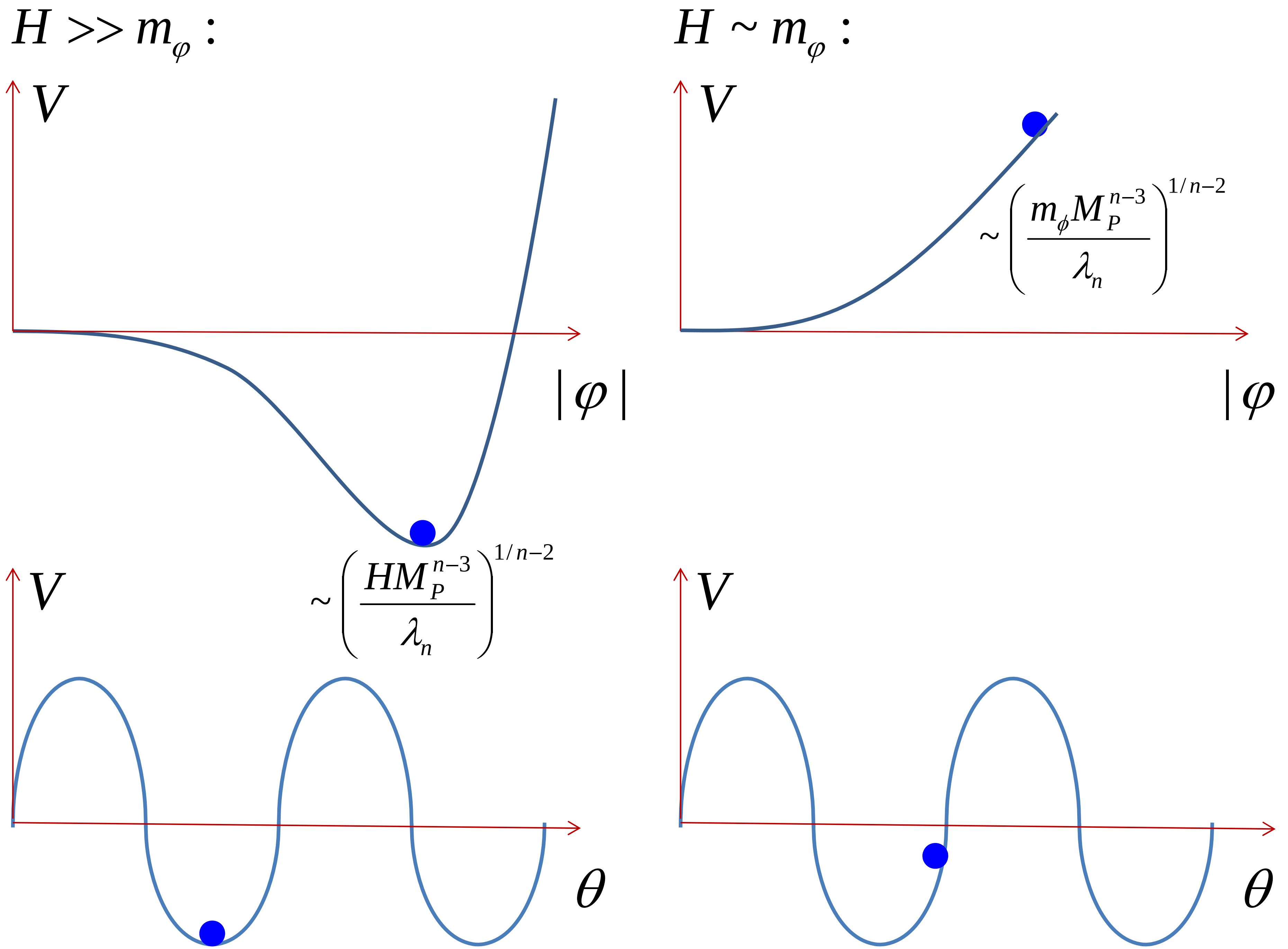
The AD field can acquire a large VEV during inflation if:

$$c_H < 0 \ , \ m_\phi << H_{\inf}$$

It starts oscillating in the radial direction when $H \sim m_\varphi$.

At the same time, it undergoes motion in the angular direction.

This gives rise to a baryon number stored in the condensate.

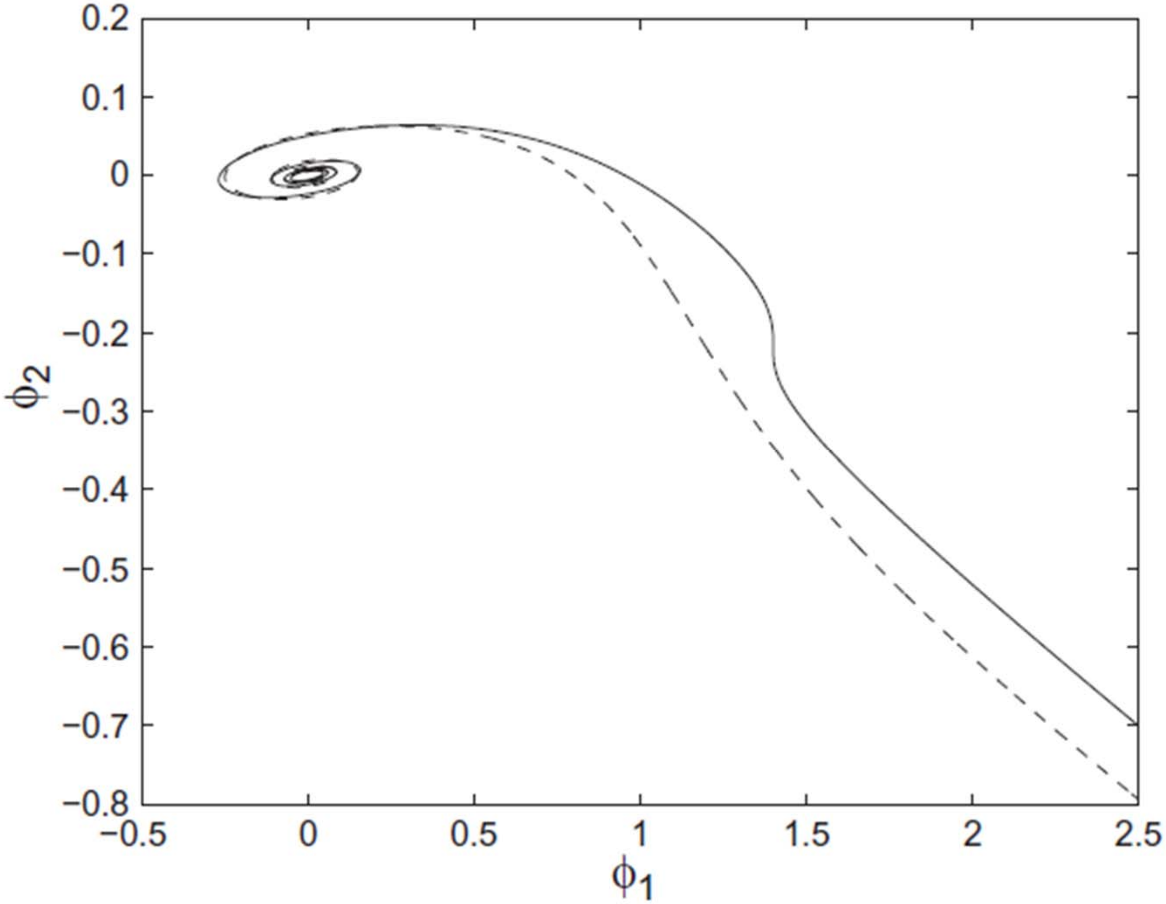


$H >> m_\varphi$:
$H \sim m_\varphi$:
V
$|\varphi|$
$\sim \left(\frac{HM_P^{n-3}}{\lambda_n}\right)^{1/n-2}$
$\sim \left(\frac{m_\phi M_P^{n-3}}{\lambda_n}\right)^{1/n-2}$
θ

$$n_B = \beta i(\dot{\varphi}^+\varphi - \dot{\varphi}\varphi^+)$$

β : Baryon number of the AD field

$$\dot{n}_B + 3Hn_B = 2\beta \ \mathrm{Im}(\frac{\partial V(\varphi)}{\partial \varphi}\varphi)$$



$$\frac{n_B}{n_\varphi} \sim \beta \ \frac{|A|}{m_\varphi}$$

Question:

Can one obtain $c_H < 0$ in explicit models of inflation that are embedded in supergravity?

Very difficult to realize both inflation and AD baryogenesis, if:

(1) c_H is determined by the *F*-term of the inflaton only.

(2) $m_{3/2} \leq H_{\rm inf}$.

(3) Contribution of the inflaton *F*-term negligible after inflation.

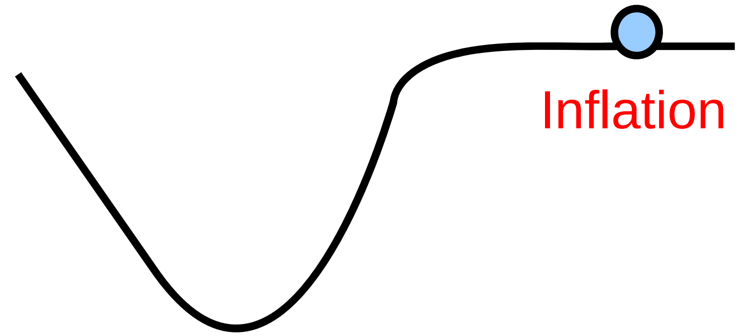
B. Dutta, K. Sinha PRD 86, 103517 (2012)
B. Dutta, K. Sinha PRD 82, 095003 (2010)
D. Marsh JHEP 1205, 041 (2012)

To relax one or more of these conditions in explicit models.

R.A., M. Cicoli, F. Muia JHEP 1606, 153 (2016)

“Kahler moduli inflation”

J. Conlon, F. Quevedo JHEP 0601, 146 (2006)



$$V = V_0 - C\tau_{\rm inf}\frac{e^{-a_{\rm inf}\tau_{\rm inf}}}{\nu^2}$$

$$m_\phi^2 = m_{3/2}^2 + V_0 - F^i F^j \partial_i \partial_j \ln K$$

We modify the Kahler potential as follows:

$$K = \frac{1}{\nu^{3/2}}\left(1 - c_{\rm inf}\frac{\tau_{\rm inf}^{3/2}}{\nu}\right) + \varphi\overline{\varphi} + \ldots$$

In the LVS minimum, we must have:

$$m_\varphi^2 > 0$$

Making the AD field can become tachyonic during inflation.

For MSSM-like spectrum, we find that $m_\varphi^2 > 0$ during inflation.

On the other hand, for the split-SUSY spectrum, we find:

$$m_\varphi^2 \propto -H_{\rm inf}^2 \quad (c_H < -1)$$ (during inflation)

$$m_\varphi^2 \propto (c_{\rm inf} - \frac{1}{3})H_{\rm inf}^2$$ (after inflation)

This leads to a viable AD baryogenesis, provided that:

$$c_{\rm inf} > \frac{1}{3} \Rightarrow m_\varphi^2 > 0$$

Gaugino masses and *A*-terms are similar (and much smaller than scalar masses) during and after inflation.

Sequence of events:

(1) Inflation takes place. ϕ and φ acquire large displacements.

(2) First stage of reheating from inflaton decay. ϕ and φ start oscillating about their corresponding minima.

(3) Motion of φ results in generation of baryon asymmetry. ϕ oscillations dominate the universe.

(4) Baryon asymmetry is transferred to quarks upon φ decay. Decay of ϕ leads to a final stage of reheating.

The BAU is given by:

$$\frac{n_B}{s} \sim \frac{|A| \ T_{rh}}{m_{\tau_b}^2} \left(\frac{\varphi_0}{M_P} \right)^2$$

Success of the model requires:

(1) Enough inflation that creates density perturbations of the correct size.

(2) Generation of the observed value of baryon asymmetry via the AD mechanism.

	M [GeV]	m_0 [GeV]	$T_{\rm rh}$ [GeV]	ϕ_0/M_p
(A)	5.4×10^5	3×10^{10}	6.7×10^3	0.03
(B)	5.2×10^4	9.2×10^9	1.1×10^3	0.08
(C)	5×10^3	2.8×10^9	195	0.19

The constraints on gaugino masses and the reheat temperature are mainly set by inflation.

Summary and Outlook:

- Important questions: origin of DM relic abundance and BAU
  Strong observational probes of the early universe

- Moduli typically alter thermal history giving rise to EMDE
  Entropy release will dilute any pre-existing relic density

- Non-thermal DM from EMDE a viable and attractive scenario
  Can yield the correct density for large & small annihilation rate
  Explicit realization non-trivial but possible

- Non-thermal baryogenesis needed in this scenario
  Post-sphaleron baryogenesis & DM-baryon coincidence
  Successful implementation of AD baryogenesis non-trivial

- Novel observational signatures can help us test the scenario
  DM substructure, DM-DR correlation, PBHs, …