Spontaneous Cogenesis from the MSSM Flat Direction as the Origin of Matter and Dark Matter

based on: KK, M. Yamaguchi, arXiv:1201.2636

Kohei Kamada
(DESY theory group)

IPMU, ACP Seminar, 2012/3/21

1. Introduction
2. Spontaneous Cogenesis from the Flat Direction
3. Realization in the MSSM
4. Summary

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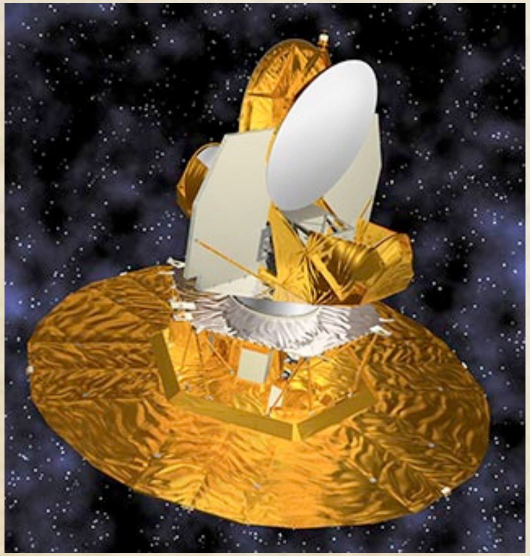
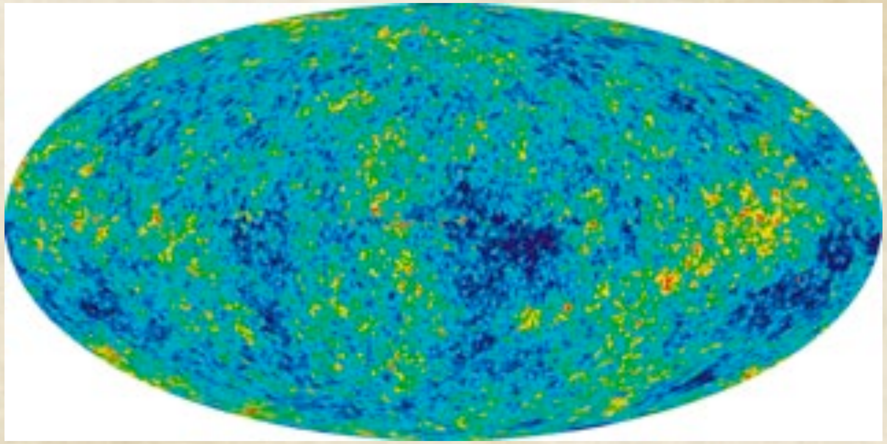
What do we know about the Universe so far?

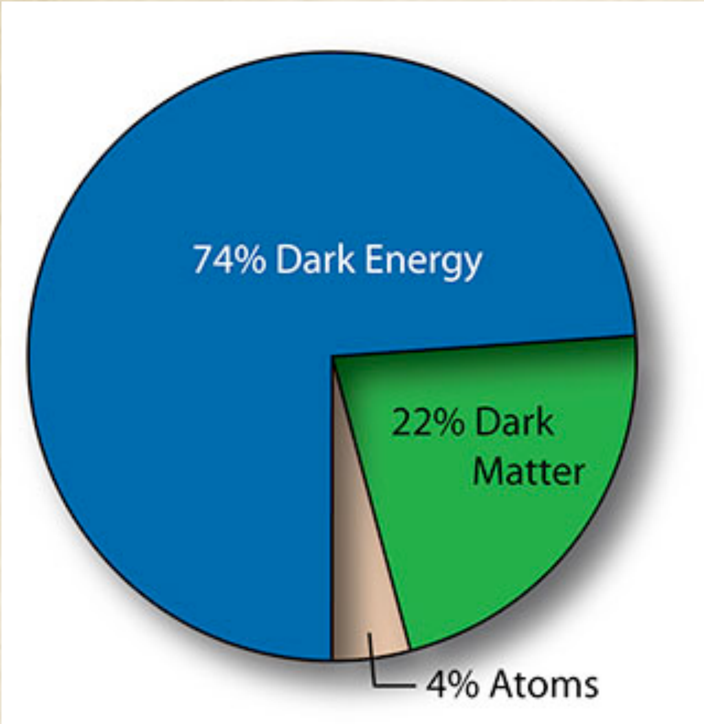
WMAP observation revealed the nature of the Universe.





- Big Bang is now "confirmed".
- Inflation is strongly favored.
- The constraint on the baryon asymmetry becomes than stronger those from BBN.
- … and so on …

Among them, one of the most exciting results of WMAP is...



It reveals the contents of the Universe.

- Dark Energy: 74%
- Dark Matter: 22%
- Matter: 4%

... but we do not what dark energy and dark matter are...

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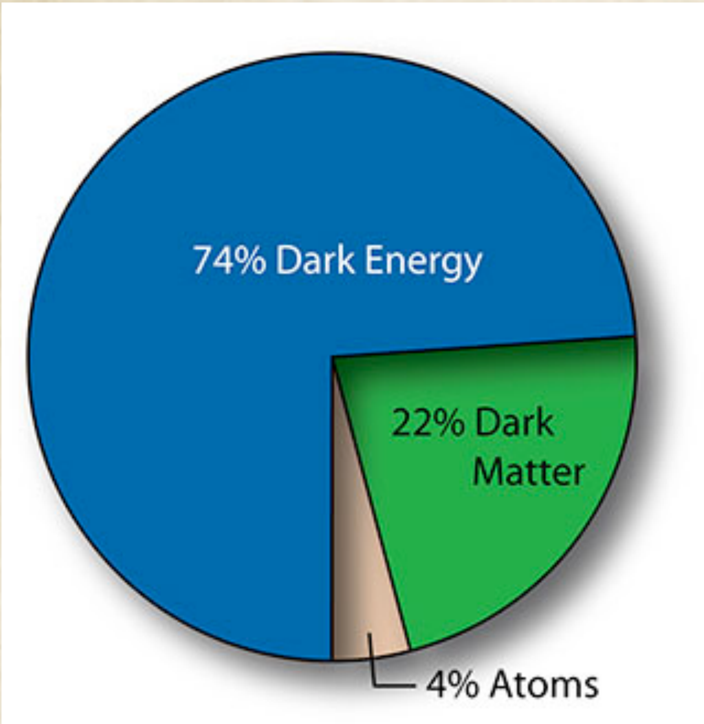

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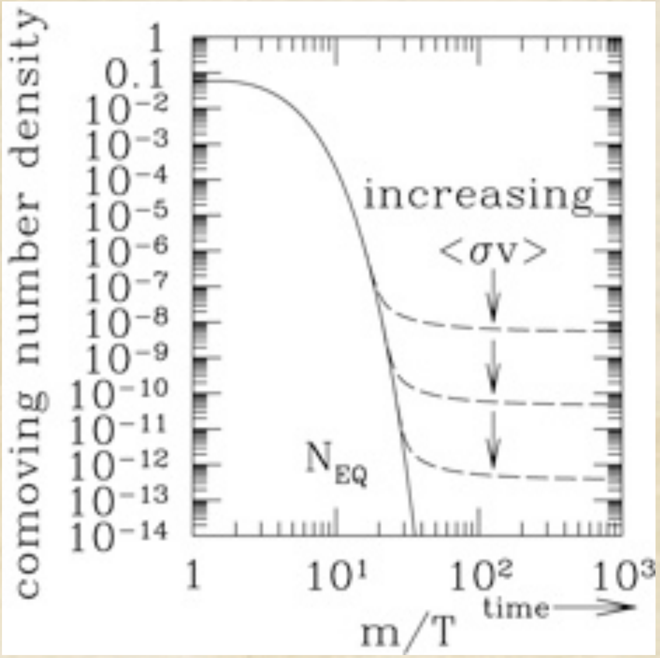
In this talk, I concentrate on Dark Matter.

WIMP miracle

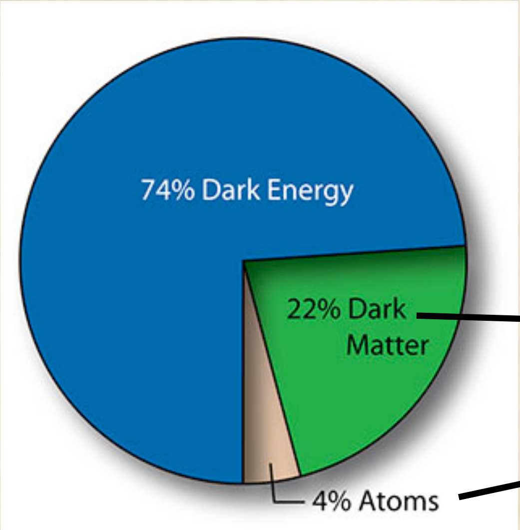
One of the most promising scenario is the thermal freezeout of Weakly Interacting Massive Particles (WIMPs).



Thermal freezeout of TeV scale particles with weak scale cross section predicts that their present abundance is just that of dark matter.

This is great! because we often assume that there is physics beyond the standard model around TeV scale.

Coincidence problem

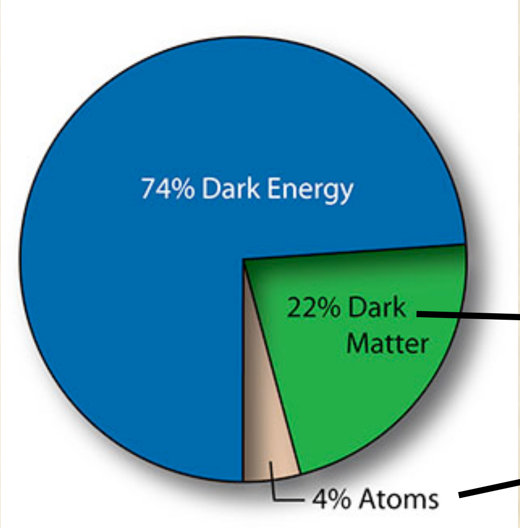


There is a coincidence in the abundance of ordinal matter and dark matter.

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm matter}} \simeq 5$$

Is this just an accidental coincidence or is there a reason to coincide them?

Coincidence problem



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Is this just an accidental coincidence or is there a reason to coincide them?

Thermal WIMP scenario cannot explain this coincidence !!

Present abundance of (ordinary) matter

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otherwise matter and antimatter annihilate away at an early time and matter would not remain.

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Sakharov's condition

Sakharov ('67)

- B(-L) breaking
- C & CP breaking
- Out of thermal equilibrium

It is manifestly different mechanism from thermal WIMP scenario !!

How do we understand this coincidence problem?

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One way is to give up thermal WIMP scenario
and to construct a different scenario !

Asymmetric Dark Matter (ADM)

Kaplan,Luty, Zurek ('09)

- Introduce DM fields and assume that DM has a charge of a hidden symmetry D.
- Produce D asymmetry through a mechanism related to baryogenesis.
- Stability of DM is guaranteed by the D symmetry.

Then, the coincidence problem can be said to be “solved”.

$$M_{\rm DM} = \frac{\Omega_{\rm DM}}{\Omega_B}\frac{n_B/s}{n_{\rm DM}/s}m_{\rm p} = \mathcal{O}(1-10)m_{\rm p},$$

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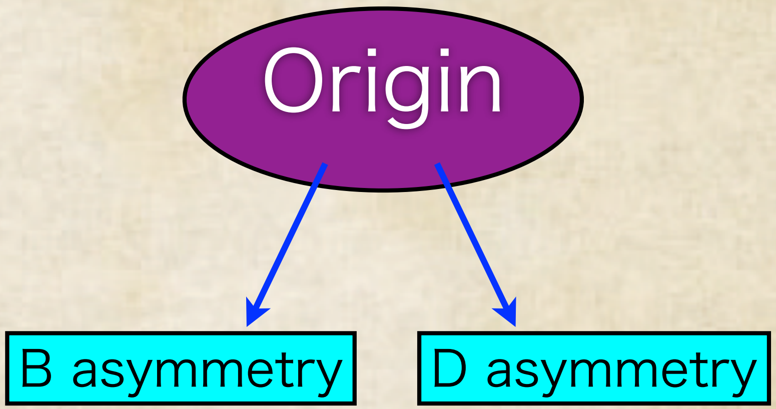

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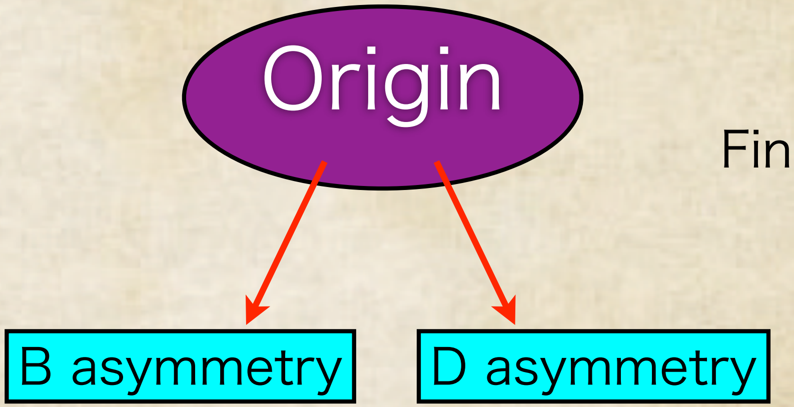

Fine tuning between 2 processes are needed.

→ less attractive

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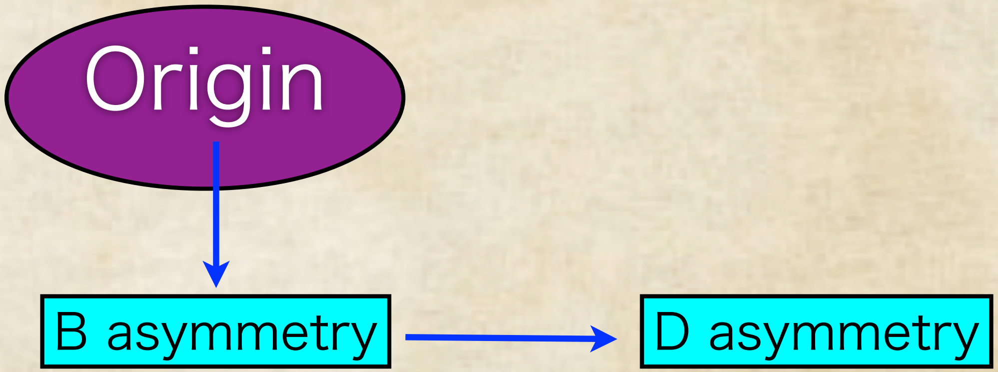
2. B (D) asymmetry is generated first
and B (D) asymmetry is transferred to D (B) asymmetry.



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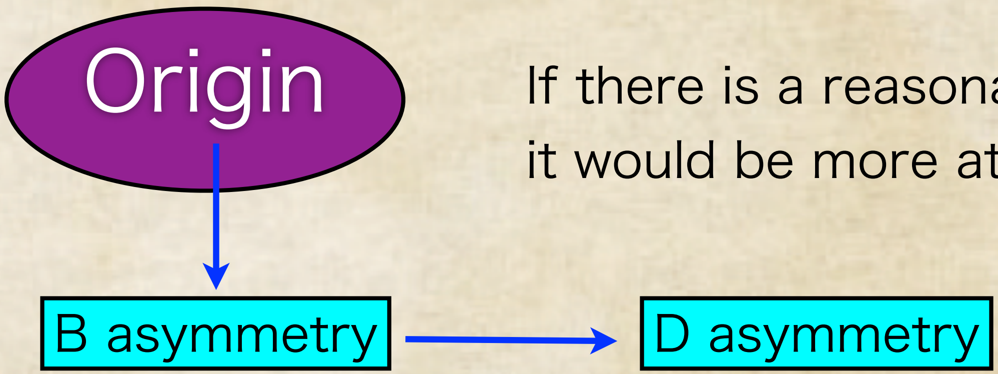

If there is a reasonable mechanism with O(1) transfer, it would be more attractive than the first possibility.

We study
in this direction!

Of course, there are still many proposals...

Nussinov, 1985
Barr, et al, 1990
Kaplan, 1992 Kitano, Low, hep-ph/0411133
Agashe, Servant, hep-ph/0411254
Farrar, G. Zaharijas, hep-ph/0510079
Roszkowsk, O. Seto, hep-ph/0608013
Seto , Yamaguchi, arXiv:0704.0415
Kitano, Murayama, Ratz, arXiv:0807.4313
Kaplan, et al., arXiv:0901.4117
An, et al., arXiv:0911.4463
Frandsen, Sarkar, arXiv:1003.4505
Taoso, et al, arXiv:1005.5711
Cohen, et al, arXiv:1005.1655
Shelton, Zurek, arXiv:1008.1997
Davoudiasl, et al, arXiv:1008.2399
Buckley, Randal, arXiv:1009.0270
Blennow, et al., arXiv:1009.3159
Hall, March-Russel, West, arXiv:1010.0245
Dutta, Kumar, arXiv:1012.1341
Falkowski, Ruderman, Volansky, arXiv:1101.4936
Haba, Matsumoto, Sato, arXiv:1101.5679
Heckman, Rey, arXiv:1102.5346
Graesser, Shoemaker, Vecchi, arXiv:1103.2771, 1107.2666
Frandsen, Sarkar, Schmidt-Hoberg, arXiv:1103.4350
McDermott, Yu, Zurek, arXiv:1103.5472
Buckley, arXiv:1104.1429
Iminniyaz, Drees, Chen, arXiv:1104.5548
Batell, Pradler, Spannowsky, arXiv:1105.1781
Bell, et al., arXiv:1105.3730
Cheung, Zurek, arXiv:1105.4612
Davoudiasl, et al., arXiv:1106.4320
March-Russel, McCullough, arXiv:1106.4319
Cui, Randall, Shuve, arXiv:1106.4834
Arina, Sahu, arXiv:1108.3967
Kane, et. al., arXiv:1108.5178
Buckley, Profumo, arXiv:1109.2164
Barr, arXiv:1109.2562
Ibe, Matsumoto,Yanagida, arXiv:1110.5452
von.Harling, et.al., arXiv:1201.2200

and more...

There are several drawbacks in our scenario...

But our scenario have some interesting features;

- Accommodate TeV scale Dark Matter

- Can be implemented in a simple extension of the MSSM

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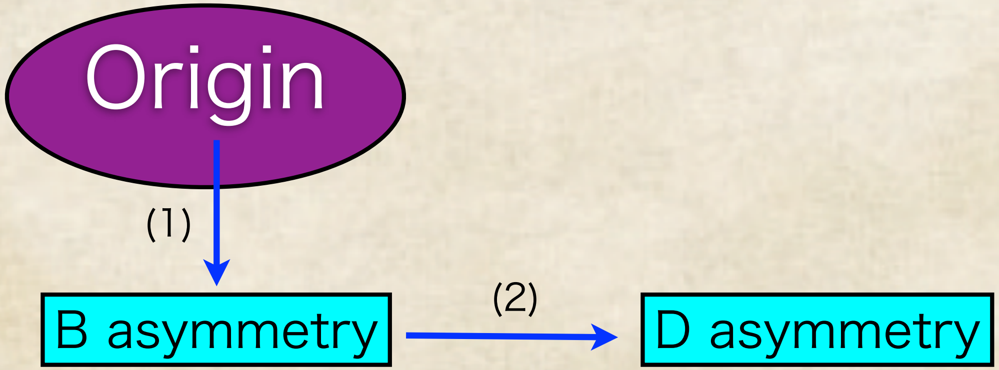
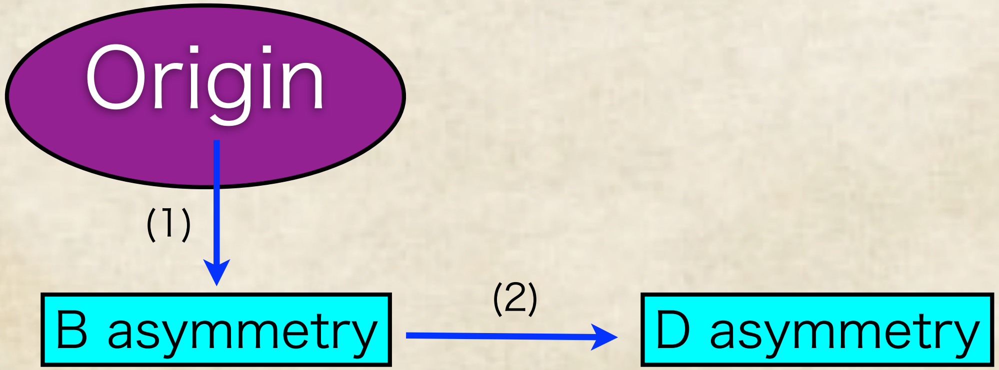
In order to construct a model of ADM, we must specify...



(1)Baryogenesis (DM genesis) mechanism

(2)Transfer mechanism

In order to construct a model of ADM, we must specify...



We choose...

(1)Spontaneous baryogenesis along the MSSM flat direction

(2)Interaction that can be naturally introduced in the context of MSSM

Spontaneous baryogenesis

Cohen, Kaplan ('87)

... one of the most promising mechanism of baryogenesis

it can work even in thermal equilibrium and violate not CP but CPT.

Spontaneous baryogenesis

Cohen, Kaplan ('87)

Assume an effective Lagrangian of the form,

$$\boxed{\mathcal{L}_{\rm eff} = -\frac{\partial_\mu a}{M} J_B^\mu}$$

that represents the coupling between baryon current and the derivative of a scalar field.

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$$\boxed{\mathcal{L}_{\rm eff} = -\frac{\partial_\mu a}{M} J_B^\mu}$$

that represents the coupling between baryon current and the derivative of a scalar field.

Consider a situation where scalar field a acquires non-vanishing velocity,

$$\boxed{\partial_\mu a = (\dot{a}, 0)}$$

Effective Lagrangian reads

$$\boxed{\mathcal{L}_{\rm eff} = -\frac{\dot{a}}{M} n_B}$$

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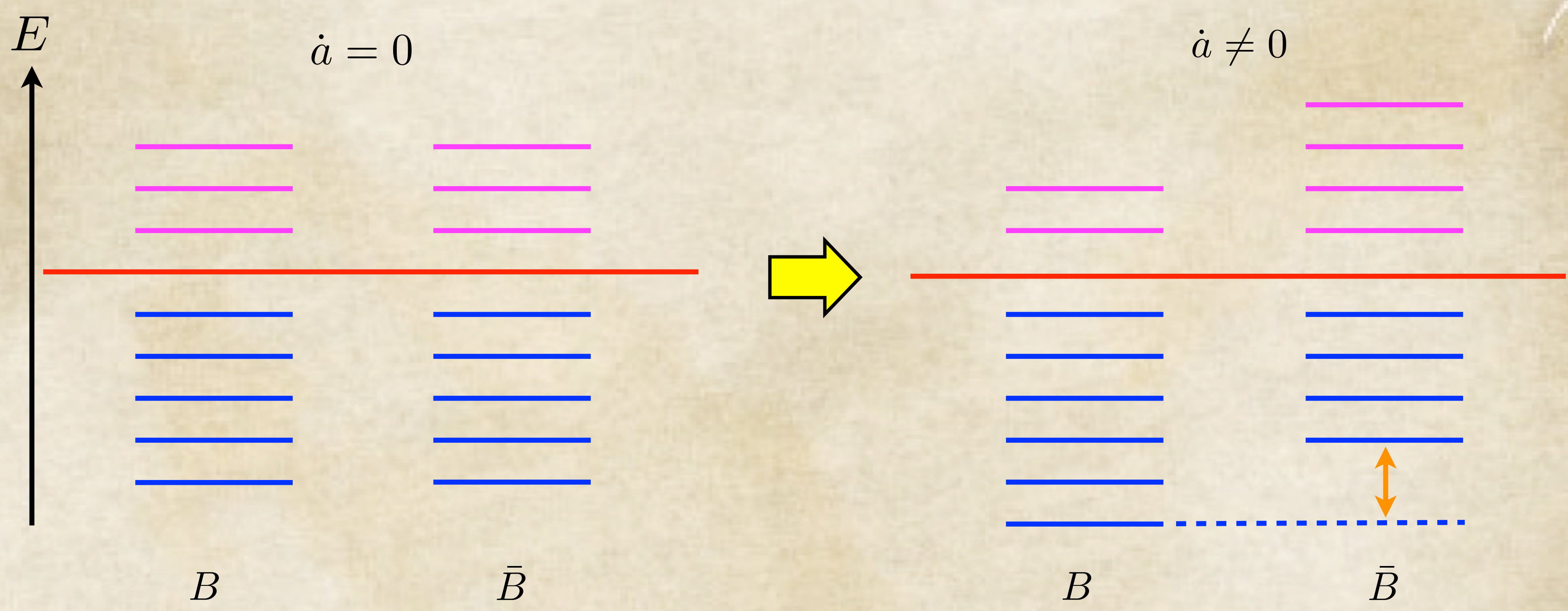
this term represents that

the energy eigenstates of matter and anti-matter differ.



If the system is in thermal equilibrium and symmetry breaking interaction is active, $\mu_m \equiv -B_m \dot{a}/M$ act as chemical potential.

$$n_B \simeq \sum_m B_m \frac{g_m \kappa_m T^2 \mu_m}{6}$$

$$g_m \sim \kappa_m \sim \mathcal{O}(1)$$

The baryon asymmetry is fixed when the symmetry breaking interaction decouples,

$$\frac{n_B}{s} \simeq \begin{cases} \dfrac{15}{4\pi^2 g_{*s}} \sum_m B_m \dfrac{g_m \kappa_m \mu_m}{T_{\rm dec}} & \text{for} \quad T_{\rm dec} < T_R, \\ \dfrac{15}{4\pi^2 g_{*s}} \sum_m B_m \dfrac{g_m \kappa_m \mu_m}{T_{\rm dec}} \left(\dfrac{T_R}{T_{\rm dec}}\right)^5 & \text{for} \quad T_{\rm dec} > T_R, \end{cases}$$

Some questions remain...

What is the scalar field a ?

What is the origin of the derivative coupling?

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What is the origin of the derivative coupling?

One proposal is to

"consider a complex scalar field with baryonic charge."

Chiba, Takahashi, Yamaguchi ('04)

When such a scalar field acquire an expectation value, $U(1)_B$ is broken spontaneously and the NG boson associated with this breaking couples to the baryon current derivatively.

$$\mathcal{L}_{\rm eff} = \sum_m \frac{B_m}{v} (\partial_\mu a) j^\mu_m$$

This is the interaction we want!

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Such scalar fields exist in the supersymmetric theories.

Use the flat direction in the MSSM !
(though the situation becomes a little complicated.)

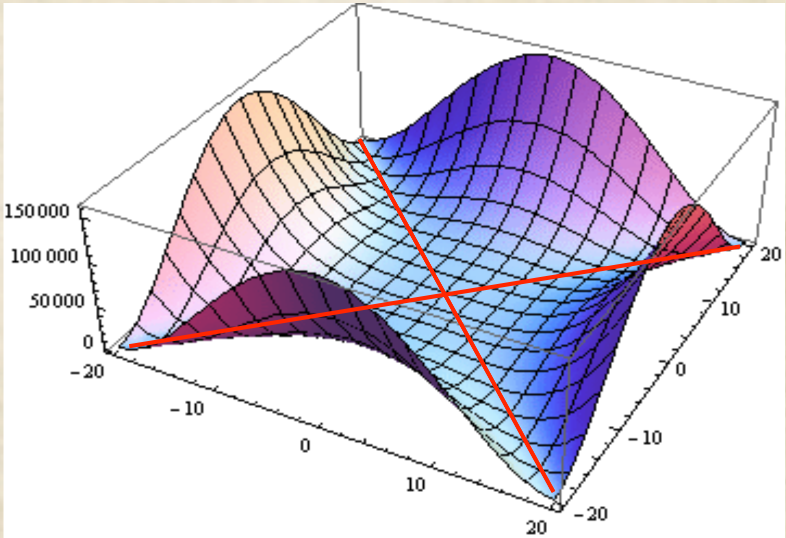
Flat direction in supersymmetric theories

Scalar potential in SUSY

$$V = V_F + V_D = \sum_i |F_i|^2 + \frac{1}{2}\sum_a D^a D^a$$

$$F_i = -\frac{\partial W^*}{\partial \phi_i^*}$$

$$D^a = -g^a(\phi_i^* T^a_{ij} \phi_j)$$



There is non-zero field configuration along which scalar potential vanishes in the global SUSY limit, which we call flat direction.

⇒ can be parameterized in terms of complex scalar field

can carry non-zero baryon/lepton charge

It is known that there are many flat directions in MSSM, which are parameterized by gauge-invariant polynomials.

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which are parame ariant polynomials.

Table 3: The basis B of gauge-invariant monomials

	B−L	Always lifted by $W_{\rm renorm}$?
LH_u	−1	
H_uH_d	0	
udd	−1	
LLe	−1	
QdL	−1	
QuH_u	0	√
QdH_d	0	√
LH_de	0	√
QQQL	0	
QuQd	0	
QuLe	0	
uude	0	
$QQQH_d$	1	√
QuH_de	1	√
dddLL	−3	
uuuee	1	
QuQue	1	
QQQQu	1	
$dddLH_d$	−2	√
$uudQdH_u$	−1	√
$(QQQ)_4LLH_u$	−1	√
$(QQQ)_4LH_uH_d$	0	√
$(QQQ)_4H_uH_dH_d$	1	√
$(QQQ)_4LLLe$	−1	
uudQdQd	−1	
$(QQQ)_4LLH_de$	0	√
$(QQQ)_4LH_dH_de$	1	√
$(QQQ)_4H_dH_dH_de$	2	√

Gherghetta, Kolda, Martin ('96)

It is known that there are many flat directions in MSSM, which are parameterized by gauge-invariant polynomials.

For example...

$$L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix}, H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix}$$

$$\tilde{\bar{u}}_i^{\alpha} = \tilde{\bar{d}}_j^{\beta} = \tilde{\bar{d}}_k^{\gamma} = \frac{1}{\sqrt{3}} \varphi, \quad (j \neq k, \alpha \neq \beta \neq \gamma),$$

What we need for spontaneous genesis is...

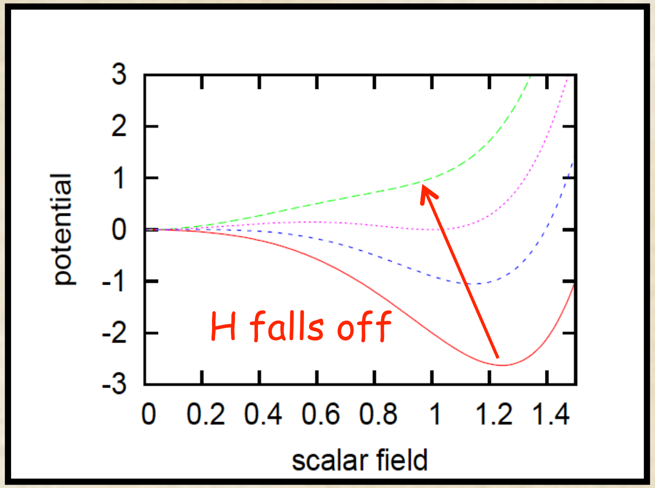
- Large amplitude of scalar fields along flat direction
- Slow-rolling motion of phase of scalar fields (NG boson)
- B-L (&D) breaking interaction

Large amplitude of scalar fields along flat direction

Inflaton-flat direction (Planck suppressed) coupling in Kähler potential generates negative Hubble induced mass during inflation and inflaton oscillation dominated era.

$$\boxed{V_{\rm H} = -c^2 H^2 |\Phi|^2}$$

Dine, Randall, Thomas ('96)



Scalar fields acquire large field values during and after inflation.

Negative thermal log potential is also useful to destabilize the scalar fields.

$$\boxed{V_T = -\alpha^2 T^4 \log(|\phi|^2/T^2)}$$

Anisimov, DIne ('01),
Kasuya, Kawasaki,Takahashi ('03)

Slow-rolling motion of phase of scalar fields (NG boson)

Consider nonrenormalizable B(-L) breaking superpotential of the form,

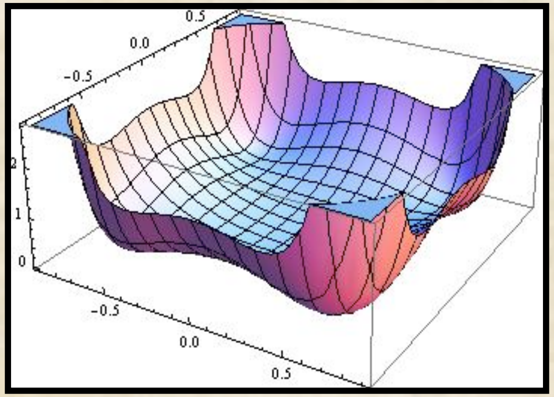
$$\boxed{W_{\rm NR} = \frac{\lambda}{nM^{n-3}}\Phi^n}$$

Flat direction

Cut off scale

Then, B(-L) breaking potential arises from SUSY breaking effect,

$$\boxed{V_{\rm NR} = \left(\frac{a m_{3/2}\lambda}{nM^{n-3}}\Phi^n + {\rm h.c.}\right) + \frac{\lambda^2}{M^{2n-6}}|\Phi|^{2n-2}}$$



A-term:
coupling to SUSY breaking sector

F-term

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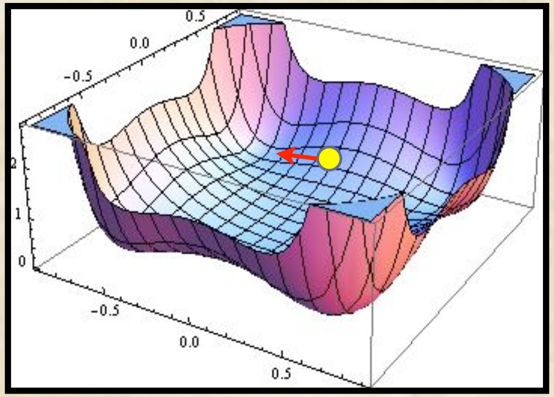

A-term:
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F-term

From this term, phase component of scalar field (NG boson) slow-rolls while its amplitude is very large.

B-L (&D) breaking interaction

Symmetry breaking non-renormalizable superpotential can be introduced as has be done for flat direction, for example,

$$W_{\not{D}} = \frac{\lambda_d}{pM_1^{p-3}} X^{p-2} D^2$$

$$W_{\not{B}} = \frac{\lambda_B}{mM_2^{m-3}} X^m$$

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If there is only one D-B-L mixing interaction,
the resultant baryon, lepton and DM asymmetry have constraints,

$$\frac{n_B}{\Delta_B} = \frac{n_L}{\Delta_L} = \frac{n_D}{\Delta_D}$$

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$$\boxed{\begin{aligned} W_{\not{D}} &= \frac{\lambda_d}{p M_1^{p-3}} X^{p-2} D^2 \\ W_{\not{B}} &= \frac{\lambda_B}{m M_2^{m-3}} X^m \end{aligned}}$$

If there are one D-B-L mixing interaction and B-L violating interaction, the resultant baryon, lepton and DM asymmetry have constraints,

$$\Delta_{L1}\Delta_D n_B - \Delta_{B1}\Delta_D n_L - (\Delta_{B2}\Delta_{L1} - \Delta_{B1}\Delta_{L2}) n_D = 0,$$

As a result, $-B_m\dot{a}/M$ itself does not act as the real chemical potential but its projection to the constraint act as it.

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In the case of only B-L-D mixing interaction, the resultant B-L and DM asymmetry read,

$$\frac{n_{B-L}}{s} \simeq \frac{15}{4\pi^2 g_{*s}} \frac{(\Delta_B - \Delta_L)(\mu_B(T_{\rm dec})\Delta_B + \mu_L(T_{\rm dec})\Delta_L)B^2L^2D^2}{T_{\rm dec}(\Delta_B^2 L^2 D^2 + \Delta_L^2 D^2 B^2 + \Delta_D^2 B^2 L^2)} \times \begin{cases} 1 & \text{for } T_{\rm dec} < T_R, \\ \left(\dfrac{T_R}{T_{\rm dec}}\right)^5 & \text{for } T_{\rm dec} > T_R, \end{cases}$$

$$\frac{n_D}{s} \simeq \frac{15}{4\pi^2 g_{*s}} \frac{\Delta_D(\mu_B(T_{\rm dec})\Delta_B + \mu_L(T_{\rm dec})\Delta_L)B^2L^2D^2}{T_{\rm dec}(\Delta_B^2 L^2 D^2 + \Delta_L^2 D^2 B^2 + \Delta_D^2 B^2 L^2)} \times \begin{cases} 1 & \text{for } T_{\rm dec} < T_R, \\ \left(\dfrac{T_R}{T_{\rm dec}}\right)^5 & \text{for } T_{\rm dec} > T_R. \end{cases}$$

$$\mu_B \equiv -\frac{\dot{a}_+ \cos\xi}{v_a}, \quad \mu_L \equiv -\frac{\dot{a}_+ \sin\xi}{v_a} \qquad \tan\xi \equiv \frac{\text{total lepton charge of flat direction}}{\text{total baryon charge of flat direction}}.$$

$$Y^2 \equiv \sum_m \kappa_m g_m Y_m^2$$ m: light fields

$$\Rightarrow \boxed{\frac{n_D/s}{n_{B-L}/s} = \frac{\Delta_D}{\Delta_B - \Delta_L}}$$

Requirements:

$$\mu_B \Delta_B + \mu_L \Delta_L \neq 0$$

$$\Delta_B - \Delta_L \neq 0, \quad \Delta_D \neq 0$$

Flat direction do not have to have B-L charge !!

In order to explain the present baryon asymmetry,

$$\frac{n_B}{s} = (8.1 - 9.4) \times 10^{-11}$$

(B-L asymmetry is rearranged by the sphaleron process.)

and Dark Matter density,

$$\frac{\rho_{\rm DM}}{s} = \frac{M_\Psi n_D}{s} \simeq 4.1 \times 10^{-10} {\rm GeV}$$

we have the DM mass,

$$M_\Psi \simeq 1.6 {\rm GeV} \times \frac{\Delta_B - \Delta_L}{\Delta_D}$$

In the case of one B-L-D mixing interaction and one B-L violating interaction, situation is a little complicated.

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DM asymmetry is fixed at the decoupling of B-L-D mixing interaction.
B-L asymmetry continued to be rearranged and is fixed at its decoupling.

$$\frac{n_D}{s} \simeq \frac{15}{4\pi^2 g_{*s}} \frac{\Delta_D \left[\mu_B(T_{\rm dec2})\Delta_{L1}B^2 - \mu_L(T_{\rm dec2})\Delta_{B1}L^2\right](\Delta_{B2}\Delta_{L1} - \Delta_{B1}\Delta_{L2})D^2}{\left[\Delta_D^2(\Delta_{L1}^2 B^2 + \Delta_{B1}^2 L^2) + (\Delta_{B2}\Delta_{L1} - \Delta_{B1}\Delta_{L2})^2 D^2\right] T_{\rm dec2}} \times \begin{cases} 1 & \text{for } T_{\rm dec2} < T_R, \\ \left(\dfrac{T_R}{T_{\rm dec2}}\right)^5 & \text{for } T_{\rm dec2} > T_R. \end{cases}$$

$$\frac{n_B}{s} = \frac{30}{23\pi^2 g_{*2}} \frac{(\Delta_{B1} - \Delta_{L1})(\mu_B(T_{\rm dec1})\Delta_{B1} + \mu_L(T_{\rm dec1})\Delta_{L1})B^2 L^2}{(B^2\Delta_{L1}^2 + L^2\Delta_{B1}^2)T_{\rm dec1}} \times \begin{cases} 1 & \text{for } T_{\rm dec1} < T_R, \\ \left(\dfrac{T_R}{T_{\rm dec1}}\right)^5 & \text{for } T_{\rm dec1} > T_R. \end{cases}$$

Requirements:

$$\Delta_D \neq 0, \quad \Delta_{B2}\Delta_{L1} - \Delta_{B1}\Delta_{L2} \neq 0, \quad \mu_B \Delta_{L1} B^2 - \mu_L \Delta_{B1} L^2 \neq 0.$$

In order to have the present baryon and DM abundance,

$$M_\Psi \sim 1\mathrm{GeV} \times \left(\frac{T_{\mathrm{dec2}}}{T_{\mathrm{dec1}}}\right)^6$$

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Only tiny discrepancy two decoupling temperature,

$$T_{\mathrm{dec2}}/T_{\mathrm{dec1}} \sim \mathcal{O}(10^{1/2})$$

this scenario can accommodate dark matter with weak scale mass.

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Let us present a concrete model in the MSSM.

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In order to implement this scenario...

Sphaleron process should not work during spontaneous genesis.
-> Flat direction breaks $SU(2)_L$.

Decoupling temperature must take place earlier than the onset of NG boson oscillation.

Affleck-Dine mechanism should not produce too much baryon asymmetry -> B-L=0 flat direction

An example:

Flat direction with large field values: QQQL flat direction

$$W_{\rm NR} = \frac{QQQL}{4M_*},$$

Symmetry breaking interactions:

$$W_{\rm mix} = \frac{\bar{u}\bar{d}\bar{d}\Psi^2}{\Lambda^2},$$

$$W_{\rm vio} = \frac{\bar{u}^3 L^2}{\Lambda'^2},$$

For the parameters;

$$T_R \simeq T_{\mathrm{dec}1,2} \simeq 10^{12}\ \mathrm{GeV}, \quad m_{3/2} \simeq 10^5\ \mathrm{GeV}, \quad M_* > 5 \times 10^{27}\mathrm{GeV},$$

the present baryon and DM abundance can be explained.

As mentioned before,
TeV scale asymmetric dark matter can be realized.

Comment on the DM annihilation

Symmetric part of dark matter must annihilate sufficiently.

This mechanism can be implemented outside of the cogenesis mechanism itself.

An illustrative example would be

$$\Delta W = \lambda_\Psi S \Psi \bar{\Psi} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3,$$

(NMSSM)

DM can annihilate into phase of singlet S.

#Introducing such a light field is suitable for gravitino problem.

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Summary

- Asymmetric DM is an interesting possibility to explain the coincidence between the present baryon and DM abundance.
- We propose an ADM scenario in the context of spontaneous baryogenesis in the MSSM flat direction.

Interesting point

- Realization of TeV scale ADM
- Simple extension of MSSM

Unsatisfactory point

- High reheating temperature
- How to prove or disprove by experiment?