Supersymmetry Breaking, Gauge Mediation and Cosmology

Yutaka Ookouchi (IPMU)

<u>Reference</u>

R. Kitano (Tohoku), H. Ooguri (Caltech), YO :
[hep-ph/0612139], [1001.4535 hep-ph]

K. Hanaki (Michigan), M. Ibe (Tokyo), YO, C-S. Park (USCS) :
to appear

New avenue for model building

- A notional break-through by Intriligator, Seiberg and Shih
- This makes model building simple drastically

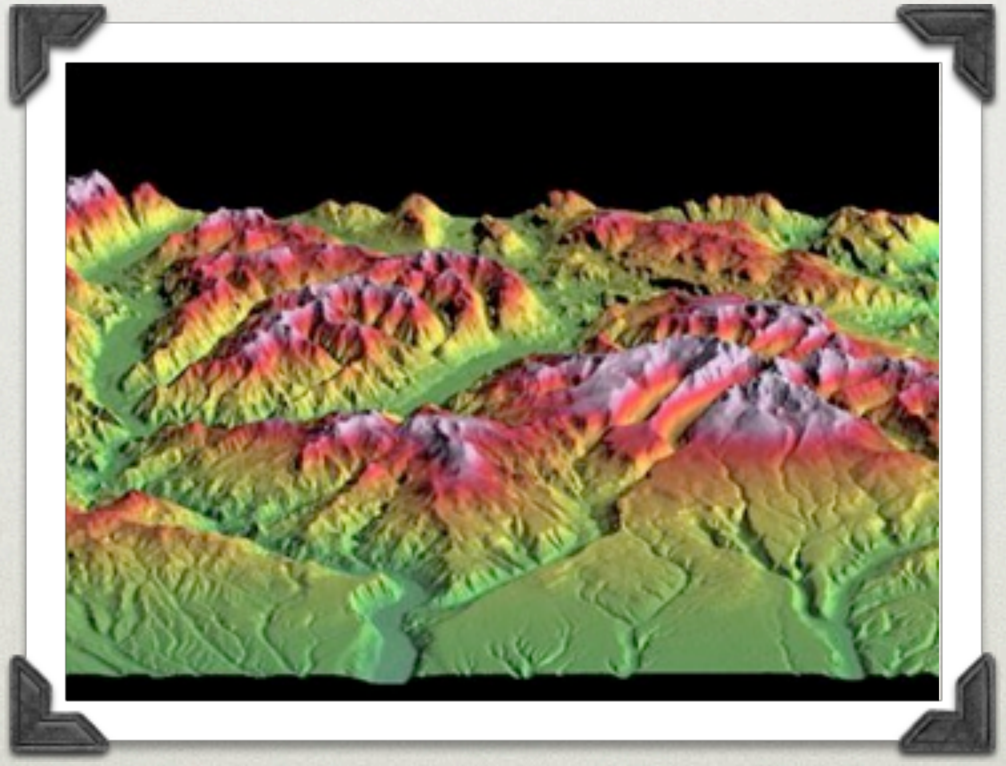
ISS's Message

Accept metastable state within SUSY breaking sector

- In 90s, people had a prejudice to a metastable vacuum
- They tried to construct phenomenological model by using global minimum.

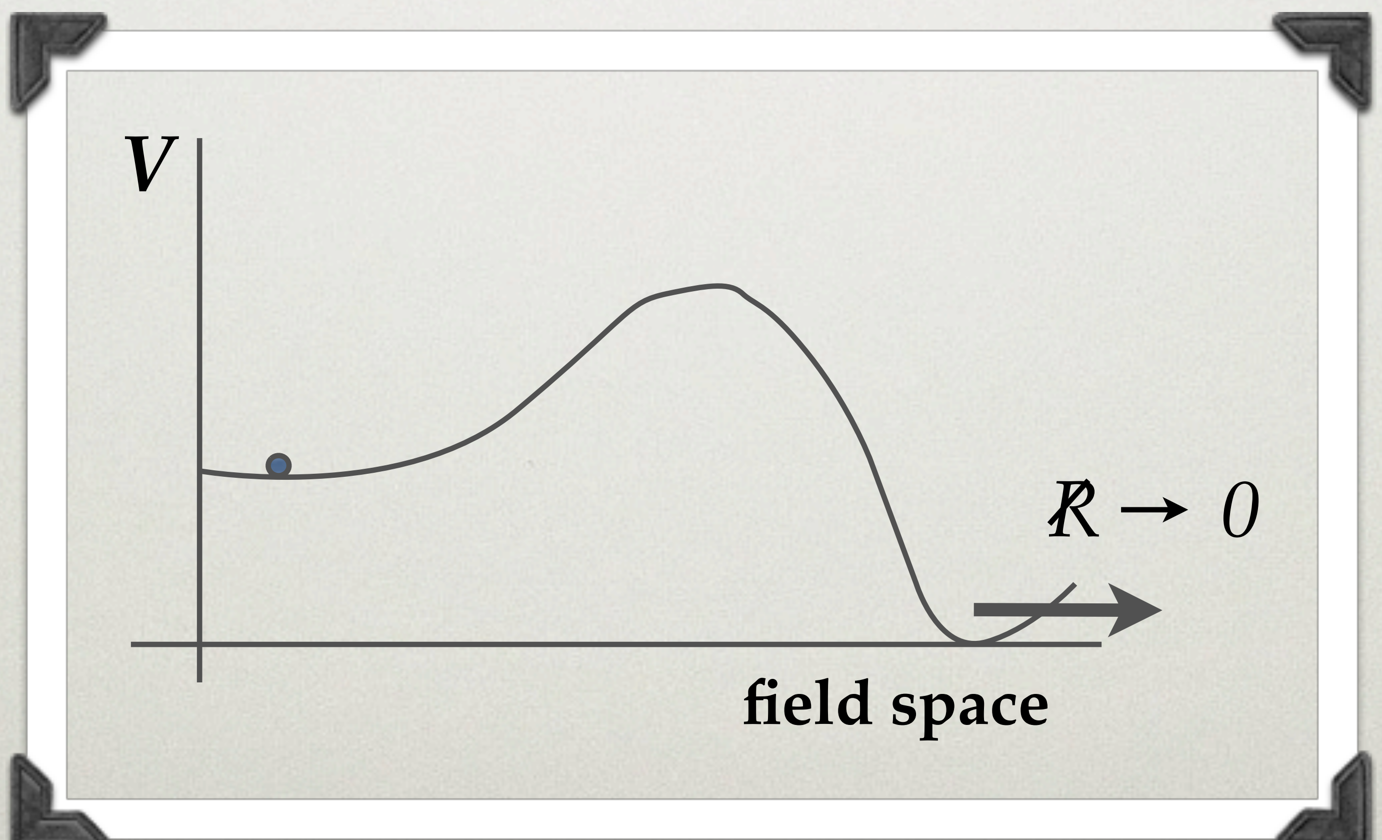
String Landscape

String landscape suggests us rich vacuum structure not only in string theory but also in field theory



R-symmetry and SUSY vacua

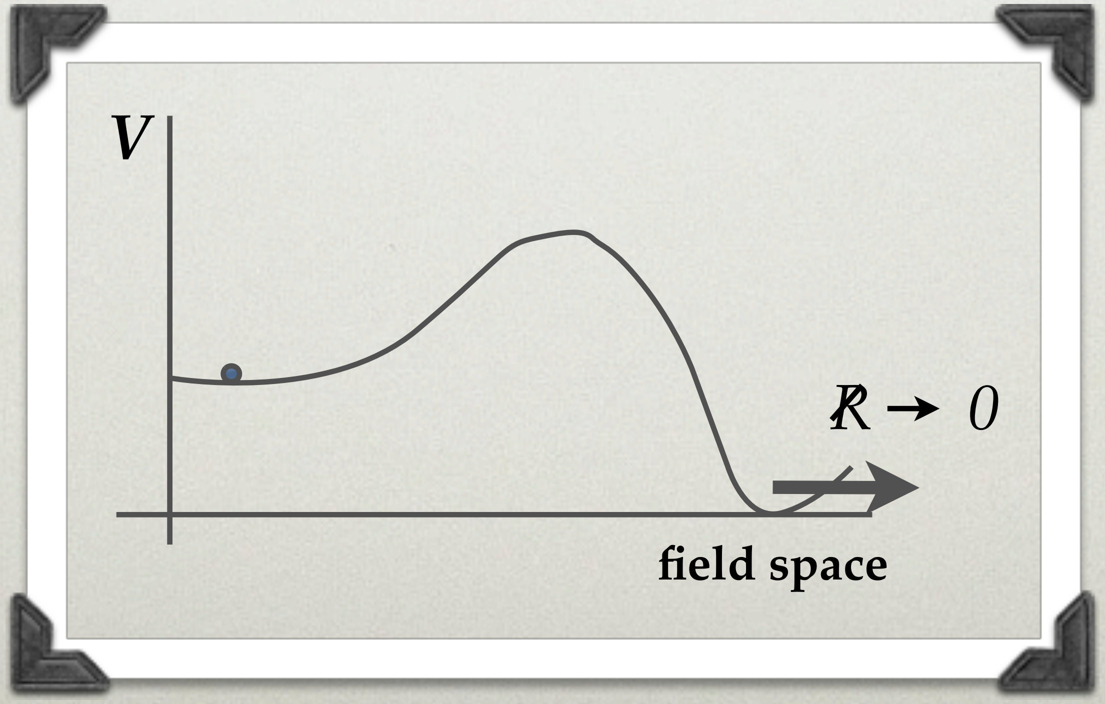
In general situation, existence of *R*-symmetry means there is a supersymmetric vacuum



R-symmetry and gaugino mass

However if vacuum preserve *R*-symmetry gaugino mass prohibited

So approximate *R*-breaking (equivalently metastable SUSY breaking) is inevitable



A Virtue

Vector-like model is available for SUSY breaking!

Vector-like model has nonzero SUSY vacuum

Dynamical SUSY Breaking in Vector-like Model

- The first celebrated discovery of DSB in vector model

  [Izawa-Yanagida, Intriligator-Thomas `96]

- It had taken 10-years to recognize the genericity of DSB in vector-like models

- Accepting metastability within DSB sector gives us flexibility of model building **[Intriligator-Seiberg-Shih `06]**

- Vector-like models are easily embedded into string theory

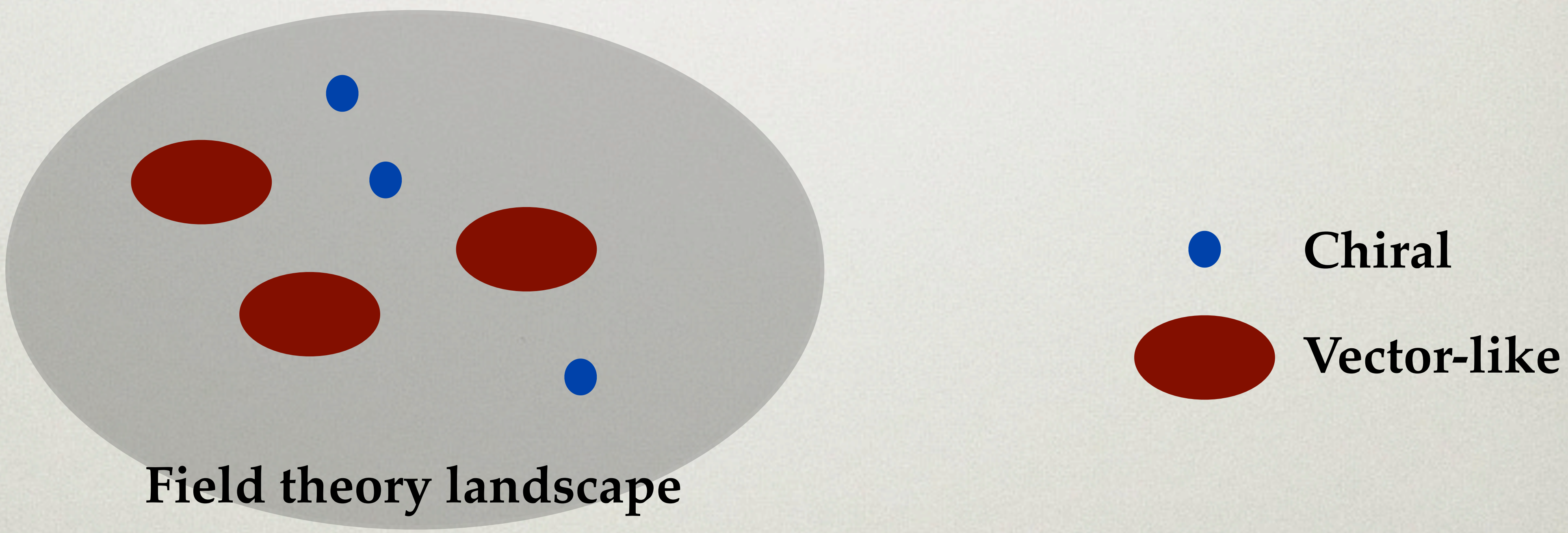
  [de Bore-Hori-Ooguri-Oz `98]

  [Ooguri-YO, Bena-Gorbotov-Hellerman- Seiberg-Shih, ... `06]

Lesson

(Dynamical) SUSY breaking is easy and generic !

Therefore, it is plausible to believe discovery of SUSY in LHC



Main Part:

Cosmological Aspects in Direct Gauge mediation

Is there any new aspect specific to metastable state or vector-like model ? ---- Yes!

What is Direct Gauge Mediation?

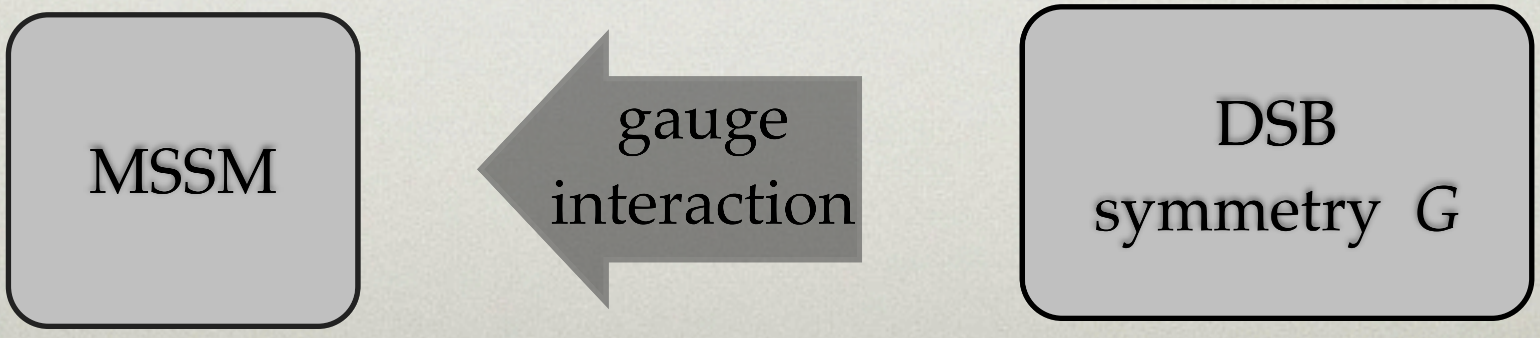
- An economical single package of SUSY breaking and transmitting its effect to SSM
- It was a challenging problem

Direct Gauge Mediation

- Suppose DSB sector preserves unbroken global symmetry G on a SUSY breaking vacuum
- Gauging subgroup and identify with SSM group

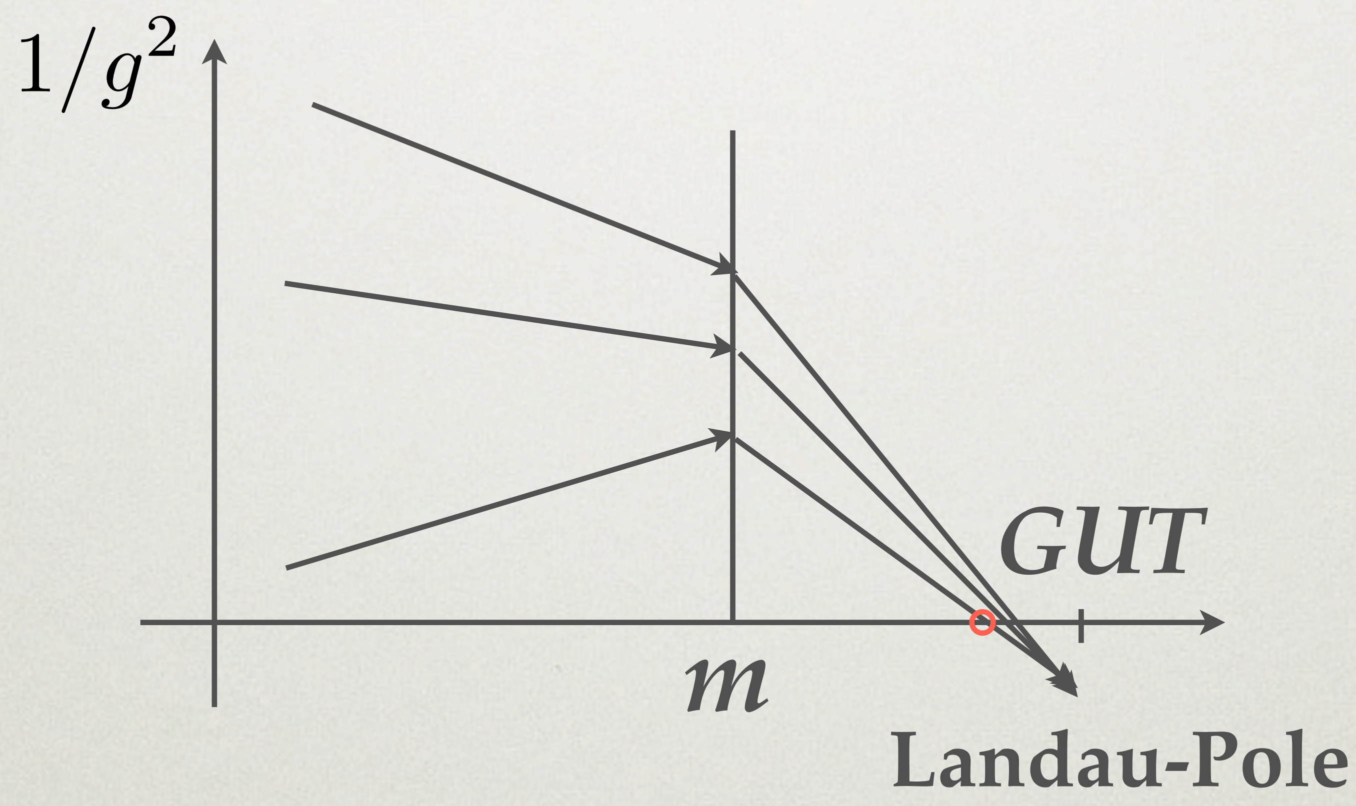
$$G \supset SU(3) \times SU(2) \times U(1)$$

- If a field (messenger) carrying a charge of the group contributes to SUSY breaking, the model is called direct-type



Difficulty I

- Divergence of *SU(3)* coupling below the unification scale (Landau-pole problem)

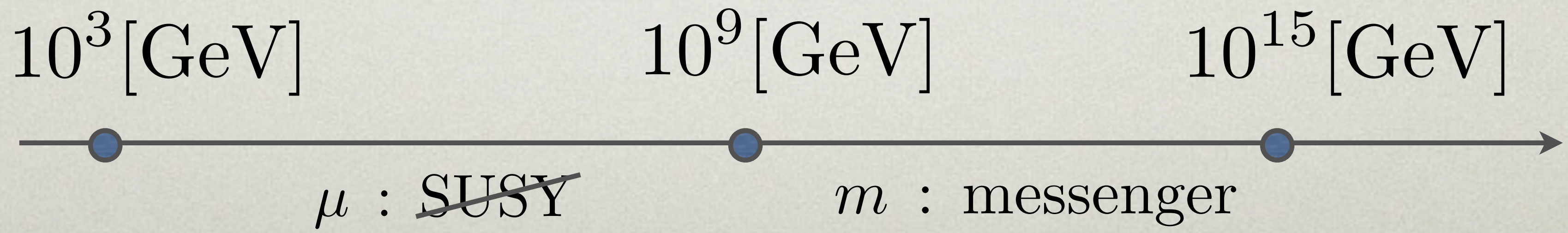


- If no Landau-pole, theory is reliable in a wide range of energy scale

A Typical Feature

- Messenger masses have to be high scale to avoid the Landau-pole problem
- However, the ratio, SUSY breaking and the messenger scale, is fixed by soft SUSY breaking terms

$$\frac{\mu^2}{m} \sim 100[\mathrm{TeV}]$$



Difficulty II

- Since $\mu \ll m$ gaugino mass can be expanded

$$m_\lambda \simeq \frac{g^2}{16\pi^2}\frac{\mu^2}{m}\left(c + \mathcal{O}(\mu/m)\right)$$

- In many direct gauge mediation models, $c = 0$!
  Light gaugino problem [Izawa-Nomura-Tobe-Yanagida `97]

- Severe constraints from experimental data

[Sato-Yonekura `09]

Kitano-Ooguri-YO `06

- To avoid light gaugino, use a higher energy vacuum!! (called uplifted vacuum)

- A metastable state is inevitable for direct gauge mediation (for calculable model) [Komargodski-Shih `09]

  → non-canonical Kahler [Nakai-YO `10]

- The first Landau-pole free model avoiding the light gaugino problem

Kitano-Ooguri-YO `06

- *SU(Nc)* SQCD in free magnetic range
- $SU(N_f-N_c)\times SU(N_c)\times U(1)_B\times U(1)_P$ global sym.

$$W = m_0 Q^I \widetilde{Q}_I + \mu_0 Q^a \widetilde{Q}_a$$

$$I = 1, \cdots N_f - N_c, \quad a = 1, \cdots N_c$$

- *R*-sym. is broken to $\mathbf{Z}_2$

$$W_{\rm def} = -\frac{1}{m_X}(Q^I \widetilde{Q}_a)(Q^a \widetilde{Q}_I)$$

Kitano-Ooguri-YO `06

- Magnetic dual is *SU(Nf-Nc)* SQCD

$$Y_{IJ} = Q^I \widetilde{Q}_J, \quad Z^I{}_a = Q^I \widetilde{Q}_a, \quad \widetilde{Z}^a_I = Q^a \widetilde{Q}_I, \quad \Phi^a{}_b = Q^a \widetilde{Q}_b$$

$$W = \mathrm{Tr}\left[m^2 Y + \mu^2 \Phi - \chi Y \tilde{\chi} - \chi Z \tilde{\rho} - \rho \tilde{Z} \tilde{\chi} - \rho \Phi \tilde{\rho} - m_z Z \tilde{Z}\right]$$

$$m = \sqrt{m_0 \Lambda}, \quad \mu = \sqrt{\mu_0 \Lambda}, \quad m_z = \frac{\Lambda^2}{m_X}$$

$$F_\Phi \neq 0, \quad F_{\text{others}} = 0$$

Kitano-Ooguri-YO `06

- Not only one metastable state

[Hanaki-Ibe-YO-Park: to appear]

$$Y^I{}_J = \frac{\mu^2}{m_z}(\mathbb{I}^n_N)^I_J\,, \qquad \Phi^a{}_b = \frac{m^2}{m_z}\left(\mathbb{I}^n_{N_c}\right)^a{}_b + \gamma_*\left(\mathbb{I}'^{N_c-n}_{N_c}\right)^a{}_b$$

$$\chi^I{}_J = m\delta^I_J\,, \qquad \tilde{\chi}^I{}_J = m\delta^I_J$$

$$\rho^I{}_a = \mu\Gamma^I{}_a\,, \qquad \tilde{\rho}^a{}_I = \mu\Gamma^a{}_I$$

$$Z^I{}_a = -\frac{m\mu}{m_z}\Gamma^I{}_a\,, \qquad \tilde{Z}^a{}_I = -\frac{m\mu}{m_z}\Gamma^a{}_I\,,$$

$$\Gamma^a{}_I = \begin{pmatrix} \mathbb{I}_n & 0_{n\times(\bar{N}-n)} \\ 0_{(N_c-n)\times n} & 0_{(N_c-n)\times(\bar{N}-n)} \end{pmatrix}, \qquad \Gamma^I{}_a = \begin{pmatrix} \mathbb{I}_n & 0_{n\times(N_c-n)} \\ 0_{(\bar{N}-n)\times n} & 0_{(\bar{N}-n)\times(N_c-n)} \end{pmatrix}.$$

$$n = 0, \cdots N_f - N_c$$

Avoiding Light Gaugino

- The fact that metastable state is inevitable for DGM is genuinely new understanding
- Before ISS-paper, nobody accepted a metastable state within SUSY breaking sector

ISS-variants

- A feature shared by many ISS-variants is spontaneous global symmetry breaking, especially breaking of $U(1)_B$ symmetry

- It would be interesting to explore cosmological implications in light of this symmetry breaking

- A model-dependent feature but including various ISS-variants

Our assumption

- String theory does not allow a global symmetry, so it has to be either broken explicitly or gauged

- Laudau-pole free direct mediation model constructed by ISS-like model, non-zero leading order gaugino mass

- Assume an inflation sector, Hubble parameter during the inflation is larger than m

$$H_{inf} \sim 10^{14}\text{GeV} > m > \mu > T_R$$

Cosmological Aspect

- Oscillation of a pseudo-Nambu-Goldston boson
- Solitons: domain wall, magnetic monopole and cosmic string (ex. semi-local vortex in ISS)

  [Eto-Hashimoto-Terashima `06]
- Observation by gravitational wave in future experiment

Symmetry Breaking

$$G = G_{\mathrm{SM}} \times U(1)_B \times G_1 \times G_2 \cdots$$
$$\rightarrow \quad H = G_{\mathrm{SM}} \times H_1 \times H_2 \cdots$$

- Suppose global or local symmetries are broken in a hidden sector

- Embed SM group into unbroken groups

- $U(1)_B$ is always spontaneously broken in ISS-variants

PNGB
(Pseudo-Nambu-Goldstone Boson)

- Nambu-Goldstone boson gets mass by explicit breaking
- PNGB is light when corresponding symmetry is broken by higher dimensional operator
- *U(1)B* is higher dimensional operator

$$W = \frac{1}{M_{\mathrm{pl}}^{N_c-3}} Q^{N_c}$$

Pseudo-Nambu-Goldstone Boson

- From Planck suppressed operators, PNGB mass is given by

$$m^2_{\rm PNGB} = \frac{\Lambda^{2N_c - N_f + 3}}{M_P^{N_c - 2}} m^{N_f - N_c - 3}$$

Sample

$$(N_c, N_f) = (11, 16), \quad \Lambda = 10^{16}[\mathrm{GeV}], \ \mu = 10^9[\mathrm{GeV}],$$

$$m = 10^{13}[\mathrm{GeV}], M_P = \ 10^{19}[\mathrm{GeV}],$$

$$m_{\rm PNGB} \simeq \mathcal{O}(10[\mathrm{MeV}])$$

Overclosing the Universe

- If there is charge conjugation symmetry, two-photon decay is forbidden

- In general, Planck suppressed operators break C-symmetry, which allows us the decay channel

$$\mathcal{L}_{eff} \sim \frac{1}{16\pi^2}\delta C_{break}\frac{\Lambda^{2N_c-N_f}}{M_P^{N_c-3}}m^{N_f-N_c-4}\mathcal{P}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Overclosing the Universe

- Three-photon decay is allowed (highly suppressed by messenger scale)

$$\mathcal{L}_{eff} \sim \frac{e^3}{m^7}(\partial_\rho F_{\alpha\beta})(\partial^\beta F_{\sigma\tau})(\partial^\rho \partial^\alpha F^{\sigma\tau})\mathcal{P}$$

- Both process are highly suppressed, so PNGB is long lived (longer than the age of the universe)

Overclosing the Universe

- When $H \sim m_{PNGB}$, PNGB starts oscillating and dominates the energy density of the universe

- Assume low reheating temperature to avoid gravitino problem

[Moroi-Murayama-Yamaguchi `93]

- Suppose reheating temperature is larger than the one of PNGB oscillation

$$T_{u.b.} > T_R > T_\phi \equiv \sqrt{m_{\rm PNGB} M_P}$$

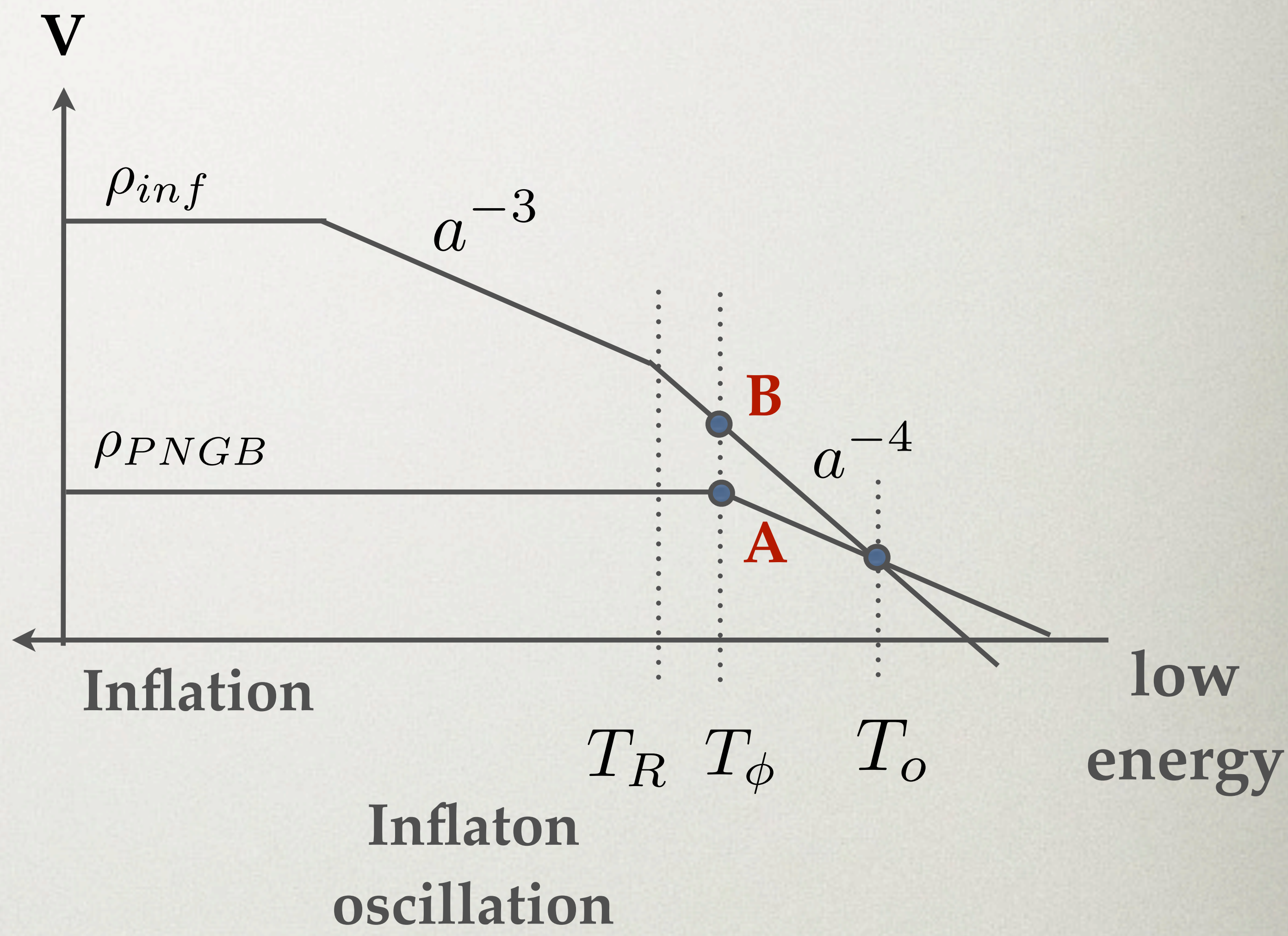
Overclosing the Universe

$$\rho^{(A)}_{PNGB} = m^2_{PNGB} m^2$$

$$\frac{\rho^{(B)}_{inf}}{M_P^2} = H^2 = m^2_{PNGB}$$

$$\rho_{inf}(T) = \rho^{(B)}_{inf} \left(\frac{T}{T_R}\right)^4$$

$$\rho_{PNGB}(T) = \rho^{(A)}_{PNGB} \left(\frac{T}{T_R}\right)^3$$



$$T_o = T_\phi \frac{m^2}{M_P^2}$$

Overclosing the Universe

- *$U(1)_B$* symmetry must be gauged !
- In general, PNGB for other symmetry is not related to a higher dimensional operator, so PNGB can decay fast. No constraint for such symmetry

Solitons

$$G = G_{\mathrm{SM}} \times U(1)_B \times G_1 \times G_2 \cdots$$
$$\rightarrow \quad H = G_{\mathrm{SM}} \times H_1 \times H_2 \cdots$$

- If exist, domain wall give us sever constraint for model model building

$$\pi_0 \left(G/H \right) \neq 0$$

- In ISS-variants, no domain wall in general

Local Monopole

- If π_2 is non-zero, there exists a monopole

$$\pi_2(G/H) \neq 0$$

- Global symmetry related to this monopole should not be gauged

- Standard argument by Kibble mechanism drastically underestimate monopole abundance

[Murayama-Shu `08]

Global Monopole

- If not gauged, monopole is global monopole
- Energy diverges but there is a cut-off (horizon scale)
- monopole and anti-monopole are created in pair interacted by linear potential in distance
- No sever constraint from global monopole

Cosmic String $\pi_1(G/H) \neq 0$

- Both global and local cosmic string is allowed
- Naively energy density scales as a^{-2}

$$\rho_{\rm str} \sim t^{-1} \ \text{(radiation)}, \quad t^{-4/3} \ \text{(matter)}$$

- Cosmic strings reconnect and loose energy by gravitational wave radiation

- Scaling behavior (supported simulations)

$$\rho_{\rm str} \sim t^{-2}$$

$$\frac{\rho_{\rm str}}{\rho_{\rm tot}} \sim G\mu_T \ll 1$$

Cosmic String $\pi_1(G/H) \neq 0$

- DGM model constructed by ISS-variants, $U(1)_B$ breaking scale is related to the messenger scale

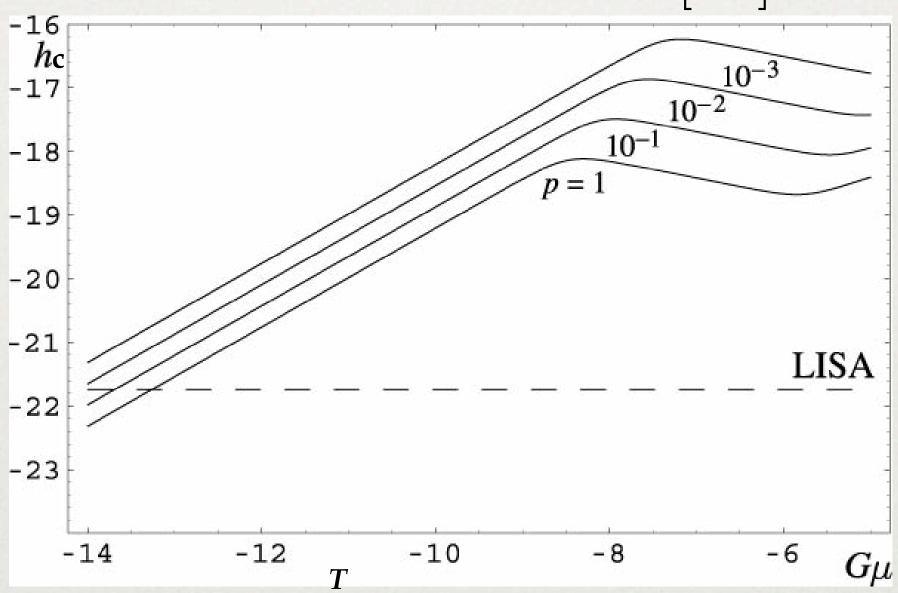
- In KOO model, Abrikosov-Nielsen-Olesen, Semi-local, non-abelian vortices exists

- There is fascinating chance to probe hidden sector by gravitational wave !

Sensitivity of Future Experiment

- Future experiment of gravitational wave detection is strong $\Omega_{gw}(h_c)h^2$

10^{-3}[Hz]



[Damour-Vilenkin `04]

- LISA, BBO can access around $m \sim 10^{12}\,[\mathrm{GeV}], \quad 10^{11}[\mathrm{GeV}]$

$$m_{obs} \leq m \leq H_{inf}$$

Conclusion

- We argued inevitability of metastable state in direct mediation and emphasized that Kitano-Ooguri-YO firstly pointed out this fact
- In ISS-variants, messenger scale has to be high and is related to tension of a cosmic string, which can be probed in future experiments
- PNGB-oscillation and monopole constrain gauging of global symmetries

Komargodski-Shih's Theorem

- Consider generalized O'Raifeartigh model
- Low-energy effective description of DSB model
- There is always a flat direction (pseudomoduli)

[Ray `06]

$$W = fX + \underline{(\lambda_{ab}X + m_{ab})}\phi^a\phi^b + g_{abc}\phi^a\phi^b\phi^c$$

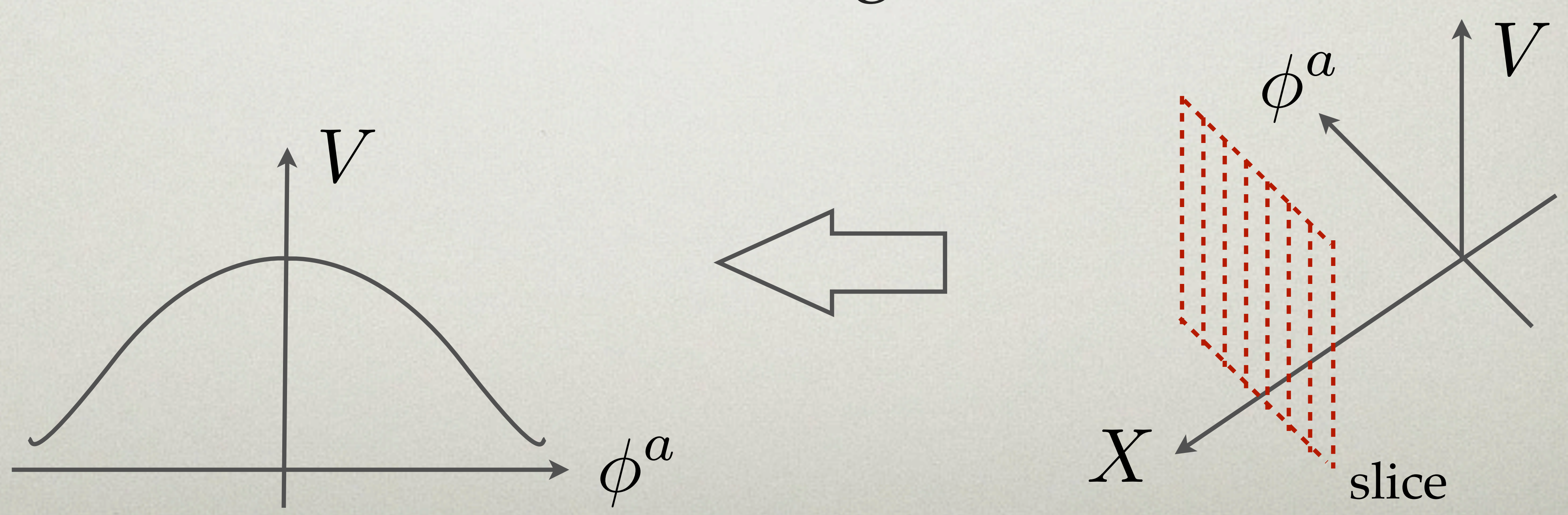
Leading order of gaugino mass

$$\boxed{m_\lambda \sim f\frac{\partial}{\partial X}\log\det(\lambda_{ab}X + m_{ab})}$$

Komargodski-Shih's Theorem

$$W = fX + (\lambda_{ab}X + m_{ab})\phi^a\phi^b + g_{abc}\phi^a\phi^b\phi^c$$

- To generate the leading mass, the determinant of the fermion mass matrix must have zero
- The zero of fermion corresponds to a tachyonic direction of boson in messenger direction



Komargodski-Shih's Theorem

- The gaugino masses can be nonzero at leading order because the pseudomoduli space is not stable everywhere

- It is interesting that gaugino mass is related to the landscape of vacua

Including Gauge Interaction

- How much can we go on this avenue?
- What happen if we allow non-canonical Kahler potential?
- When supertrace of the messenger mass matrix is positive, one can show counter-example of generalization of KS theorem

[Nakai-YO to appear]

$$\mathrm{Str}\mathcal{M}^2_{\mathrm{mess}} > 0$$

Including Gauge Interaction

- Positive supertrace can come from massive gauge boson
- Integrating out chiral superfiled never generate positive sign
- We found a model in which the leading order gaugino mass is nonzero although pseudomoduli space is stable everywhere!

Including Gauge Interaction

- nonzero supertrace implies UV sensitivity

[Trivedi-Poppitz `97]

- Any model with vanishing supertrace, the leading order gaugino mass is nonzero at lowest energy state?

- Answer is Yes! Use *FI*-term

$$\mathcal{M}_B^2 = \begin{pmatrix} (\mathcal{M}_F^* \mathcal{M}_F)_{a\bar{b}} - \xi_{a\bar{b}} & \mathcal{F}_{ab}^* \\ \mathcal{F}_{\bar{a}\bar{b}} & (\mathcal{M}_F \mathcal{M}_F^*)_{\bar{a}b} - \xi_{\bar{a}b} \end{pmatrix},$$

$$\mathrm{Tr}\xi = 0$$

Including Gauge Interaction

- We also found a model in which the leading order gaugino mass is nonzero on the global minimum

  [Nomura-Tobe-Yanagida `97]

- A connection between gaugino mass and vacuum structure was interesting. However, if we allow gauge interaction, the connection does not nessecarily hold