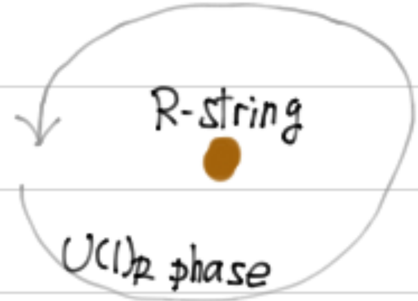
Cosmic R-string in thermal history

日露共同研究ミニワークショップ

Keisuke Ohashi @ Osaka City University

based on a work with
Minoru Eto, Yuta Hamada, Kohei Kamada
Tatsuo Kobayashi and Yutaka Ookouchi

arXiv:1211.7237 & arXiv:1303.2704



§1 Introduction

- R-string : global string (vortex) winding $U(1)_R$ phase

  topologically stable soliton

  $\Leftarrow$ its vacuum is stable.

  Spontaneously $\cancel{U(1)_R}$

- $U(1)_R$ symmetry (global sym)

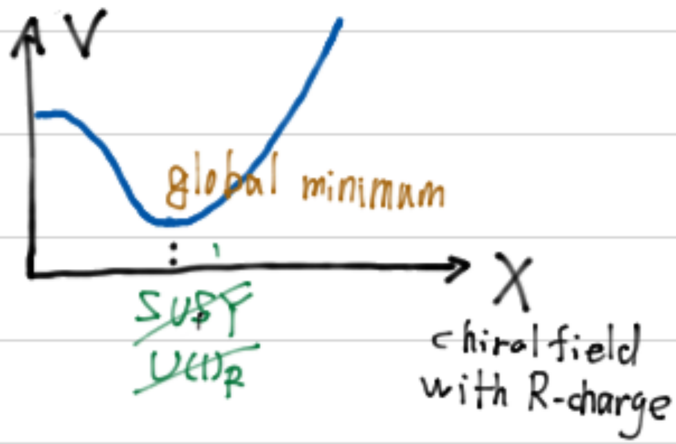
  chiral field

$$W(\Phi_i) \longrightarrow W'(\Phi_i) = W(\lambda^{q_i}\Phi_i) = \lambda^2 W(\Phi_i)$$

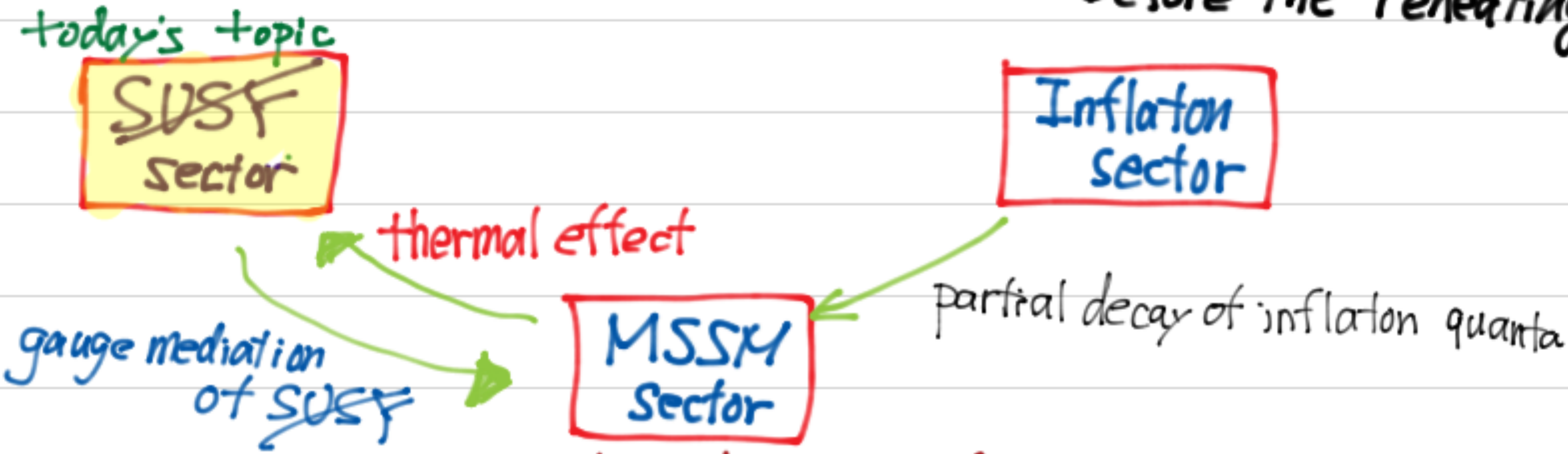
superpotential

- spontaneous $\cancel{U(1)_R}$ $\Rightarrow$ $\cancel{SUSY}$
- Coupling to supergravity

  breaks $U(1)_R$ explicitly.



- We consider the inflation oscillation dominated era.
  before the reheating



thermal plasma of SM particles.
with $T > T_R$
reheating temperature.

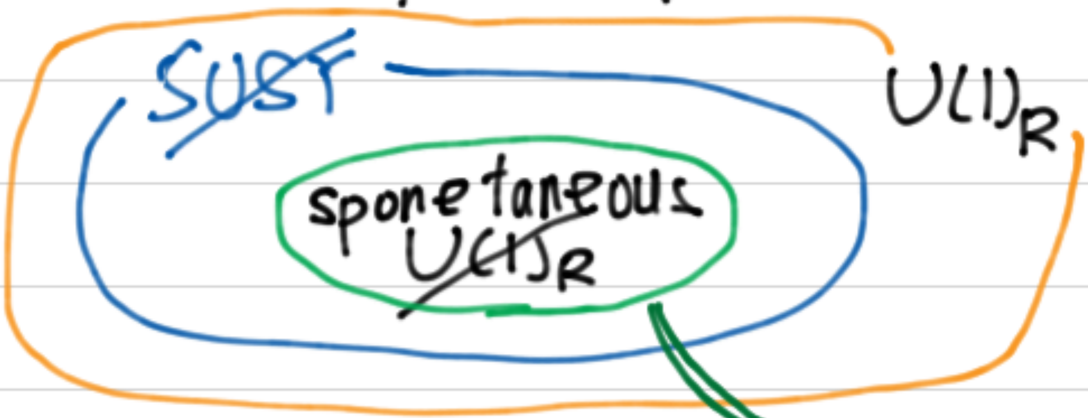
- a relation between T and H in this era.
  Hubble parameter

$$T = \left(\frac{72}{5\pi^2 g_*}\right)^{1/8} \left(T_R^2 M_{pl} H\right)^{1/4}$$

$g_* \sim 220$ $\quad$ M_{pl}: the reduced planck mass

Let's consider the ~~SUSY~~ sector.

- $U(1)_R$ sym plays important role in ~~SUSY~~.



Nelson -Seiberg theorem

gaugino masses

- Through the cosmological phase transition, solitonic objects may appear.
  domain wall. cosmic string. monopole.....
  by Kibble-Zurek mechanism

● R-String cannot be obserbed at the present era

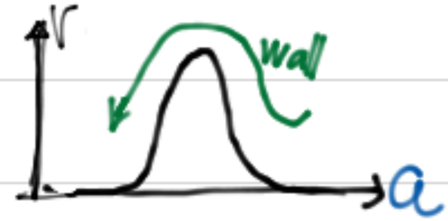
R-string + Supergravity

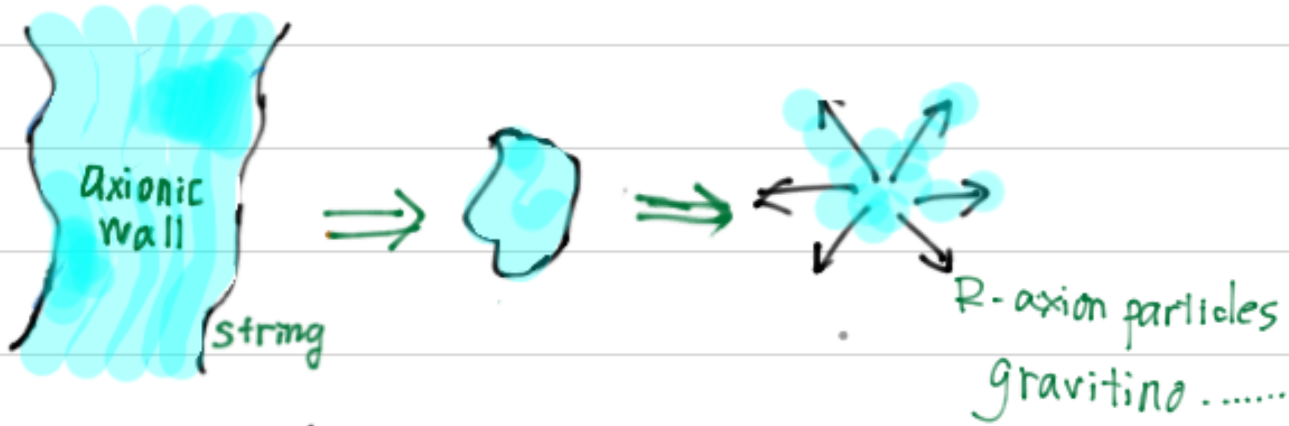
→ explicit ~~$U(1)_R$~~ → potential for R-axion ($U(1)_R$-phase a)

$H \sim m_a$

↑

R-axion mass

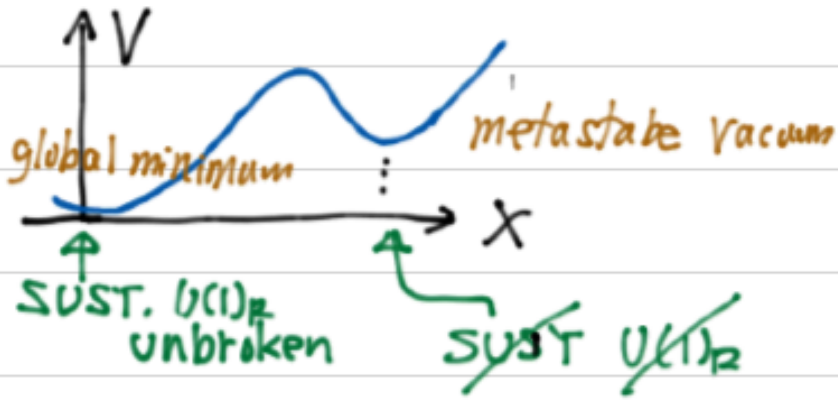




collapse with life time $\sim \frac{1}{H} \sim \frac{1}{m_a}$

T. Hiramatsu, M. Kawasaki, K. Saikawa, T. Sekiguchi
arXiv: 1202.5851

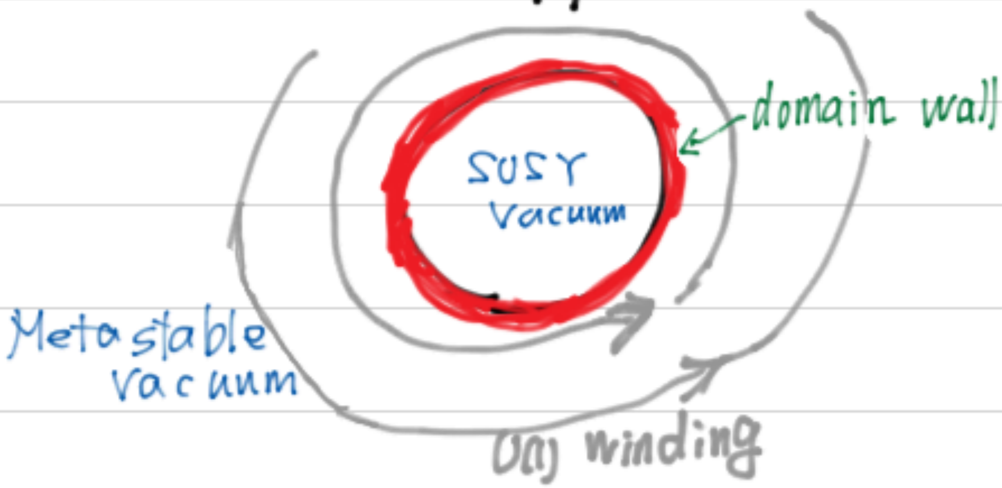
- the string landscape suggests **the complicated vacuum structure**



In a meta stable vacuum,

R-string can transform to **R-tube.**

R-tube appears



Is R-tube stable?

roll-over ⇒

The SUSY vacuum expands in the Universe?

⇓

It decays by forming axion-wall?

Existence of R-tube may causes dengerous roll-over process without any tunneling effect.

⇒ new strong condition for the realistic models of the SUSY sector.

§2. Model for the SUSY sector

without thermal effect.

We consider a model with

- chiral superfields
  (scalar components also…)

	X	Φ (messenger)	$\tilde{\Phi}$ (messenger)
R-charge	2	0	0
U(1)	0	1	−1
$SU(3)\times SU(2)\times U(1) \supset$		$\mathbb{R}$	$\bar{\mathbb{R}}$

super potential $W = X(\kappa\, \phi\tilde{\phi} - \mu^2)$

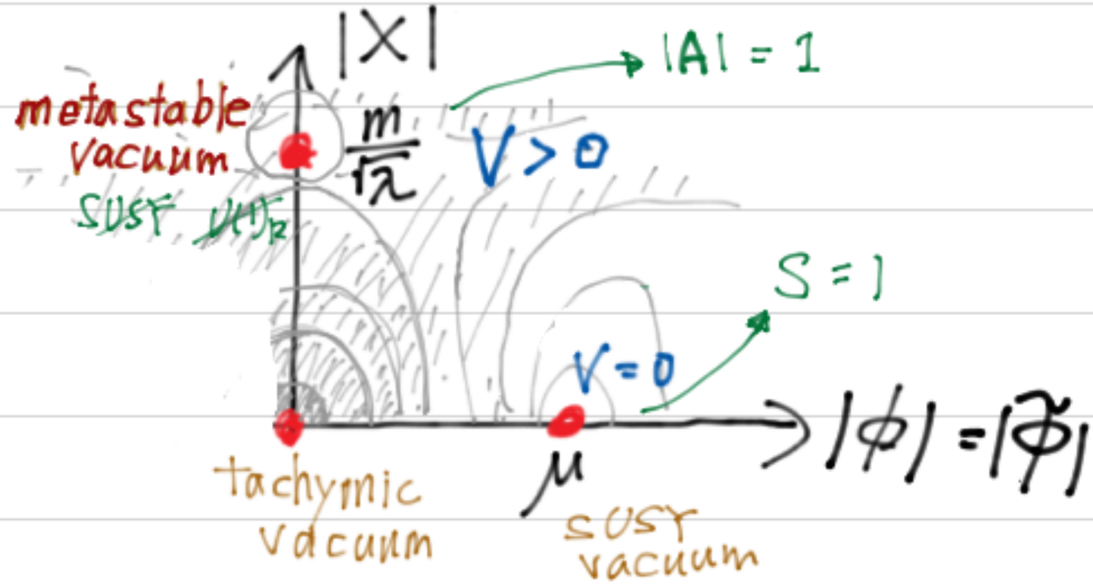
$\kappa = 1$ for simplicity

- Kähler metric to allow a metastable vacuum.

$$(g_{X\bar{X}})^{-1} = 1 - \frac{1}{2m^2}|X|^2 + \frac{\lambda}{4m^4}|X|^4 , \qquad g_{\phi\bar{\phi}} = 1$$

off.diagonal parts = 0

- vacua



- Lagrangian

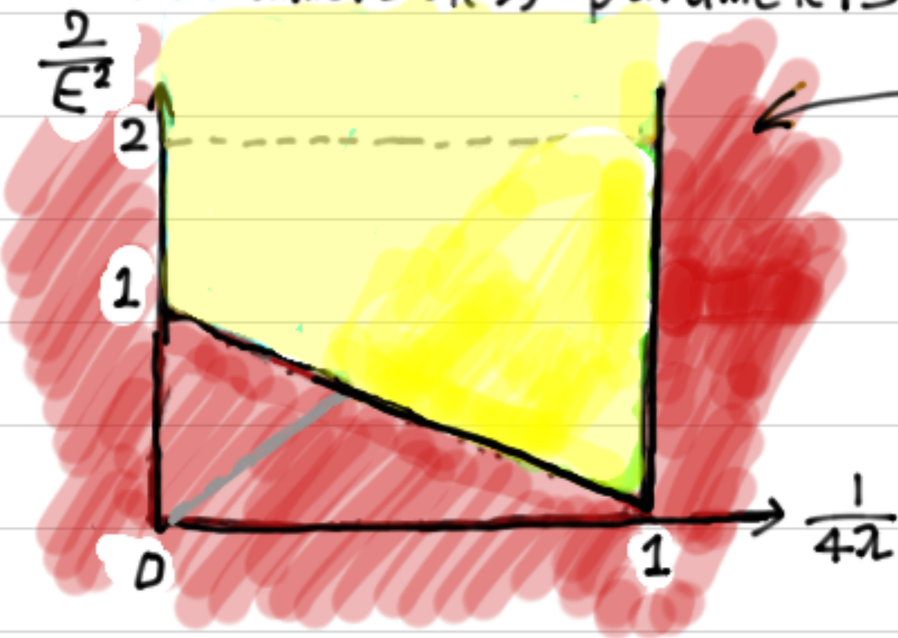
$$\mu^{-4}\mathcal{L} = \frac{1}{\nu(A)}|\hat{\partial}_\mu A|^2 + \epsilon^2|\hat{\partial}_\mu S|^2 - \left(\nu(A)|S^2-1|^2 + \frac{4}{\epsilon^2}|AS|^2\right)$$

$$\nu(A) = 1 - \frac{1}{2\lambda}|A|^2 + \frac{1}{4\lambda}|A|^4$$

with introducing dimensionless variables

$$X = \frac{m}{\sqrt{\lambda}}A, \quad \phi = \tilde{\phi}^\dagger = \mu S, \quad x_\mu = \frac{m}{\sqrt{\lambda}\mu^2}\tilde{x}_\mu, \quad \epsilon \equiv \frac{\sqrt{\lambda}\mu}{m}$$

- Two dimensioless parameters $\{\lambda, \epsilon\}$



prohibited region for existence of the metastable vacuum

- masses of modes at the metastable vacuum

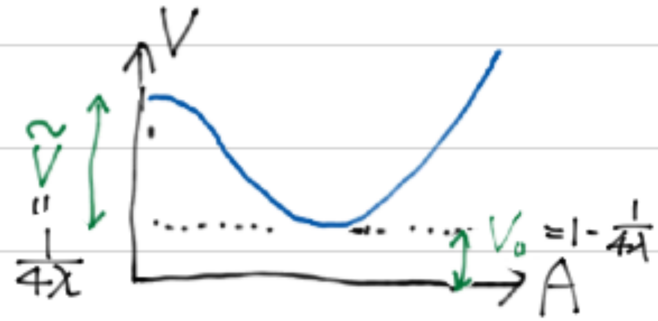
$$m_A^2 = \frac{1}{\lambda}\left(1-\frac{1}{4\lambda}\right) > 0 , \quad m_S^2 = \frac{2}{\epsilon^2}\left(\frac{2}{\epsilon^2}+\frac{1}{4\lambda}-1\right) > 0$$

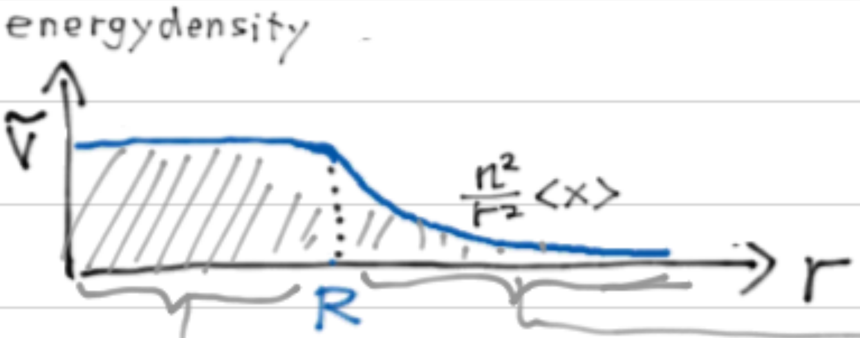
• R-string configulation

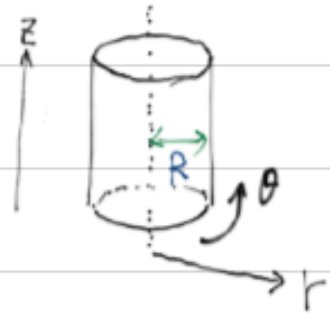
ansatz

$$A = f(r)\, e^{in\theta}, \qquad \text{winding number } n \in \mathbb{Z}$$

with $S = 0$







tension, IR cutoff

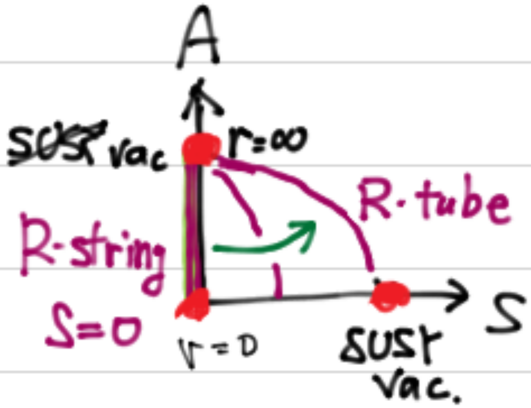
$$\frac{T}{2\pi} \approx \text{const.} + \frac{n^2}{\nu(1)} \operatorname{Log} \frac{\Lambda}{R} + \frac{1}{2} \tilde{V} R^2$$

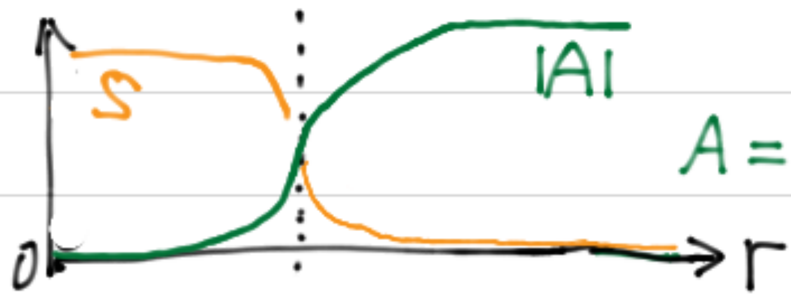
which is minimized at

$$R \approx \frac{n}{\sqrt{\nu(1)\,\tilde{V}}} = \frac{n}{m_A}$$

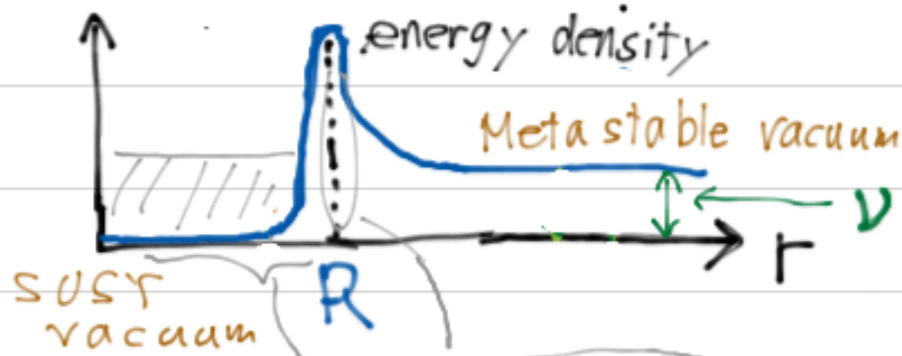
← mass of A

• R-tube configulation.





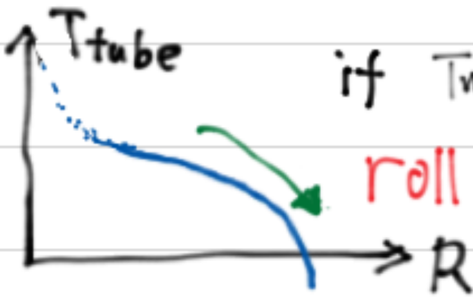
$$A = |A| e^{in\theta}$$



$$V(1) = 1 - \frac{1}{4\lambda}$$

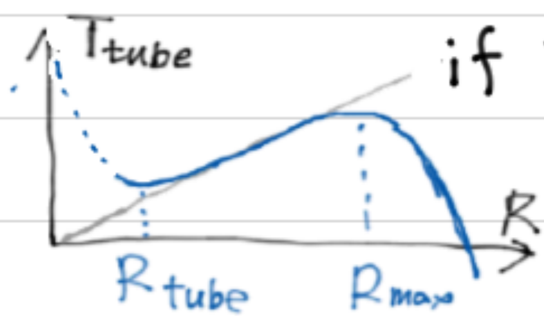
Rough sketch of (dimensionless) Tension of R-tube

$$\frac{T_{tube}}{2\pi} \approx \frac{n^2}{V(1)} \log \frac{\Lambda}{R} + T_{wall} R - \frac{1}{2} V(1) R^2$$



if $T_{wall} < 2n$

roll over!!



if $T_{wall} > 2n$

Let us check effective potential for R by using numelical calculation (the relaxation method)

- The Relaxation method $(\phi^\alpha = A, s)$

Introducing a 'relaxation time' τ as $\phi^\alpha(\tau, x^i)$

τ-dependence of the fields ϕ^α is determined by

$$\partial_i\left(\frac{\delta \mathcal{L}}{\delta \partial_i \phi^\alpha}\right) - \frac{\delta \mathcal{L}}{\delta \phi^\alpha} = -\underbrace{g_{\alpha\beta}}_{\text{metric}} \underbrace{\frac{\partial \phi^\alpha}{\partial \tau}}_{\text{friction term}}$$

Then, energy behaves as

$$\frac{dE}{d\tau} = -\int d^d x \; g_{\alpha\beta} \frac{\partial \phi^\alpha}{\partial \tau} \frac{\partial \phi^\beta}{\partial \tau} < 0$$

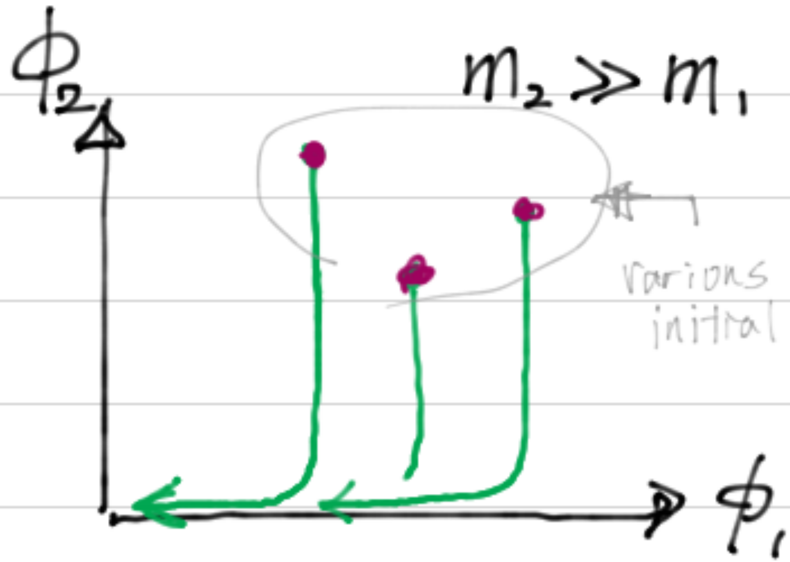
In a limit of $\tau \to \infty$

convergence of the energy $\Longleftrightarrow$ $\boxed{\text{a solution of e.o.m. } \phi^\alpha = \phi^a_{\text{sol}}(x^i)}$

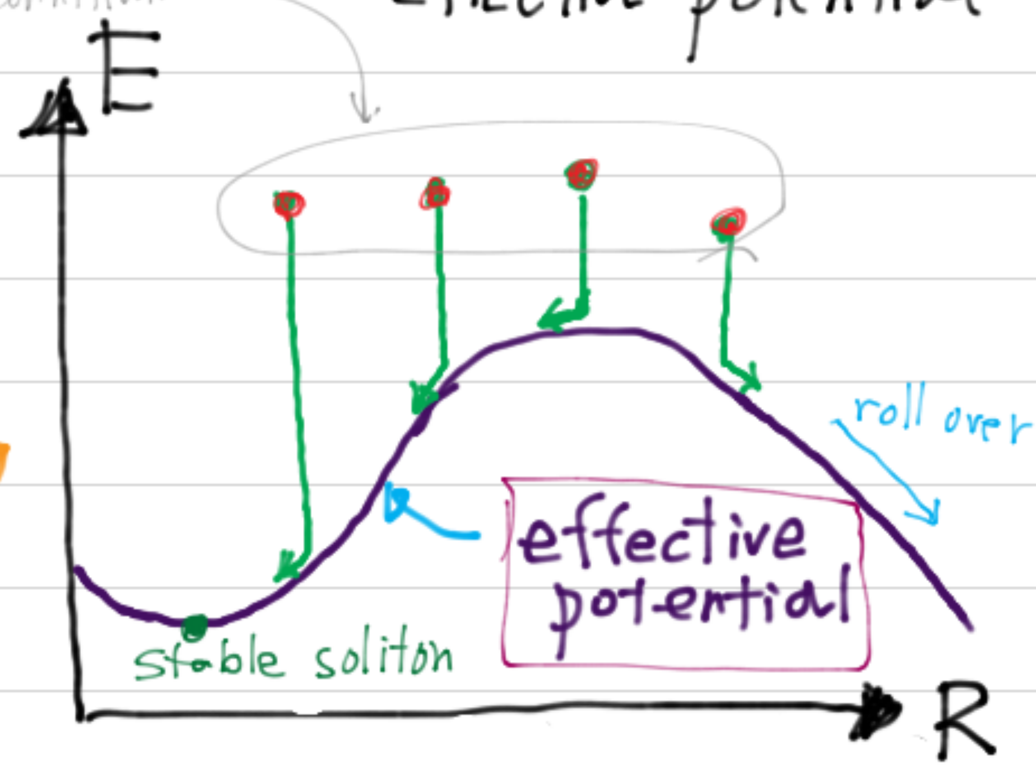
features of the relaxation method

massive mode $\phi_n(\tau) - \phi_n(\infty) \propto e^{-m_n^2 \tau}$ ← mass of massive mode

energy of state $E(\tau) - E(\infty) \propto e^{-2 m_1^2 \tau}$ ← mass of the lightest mode



defiinition of
effective potential

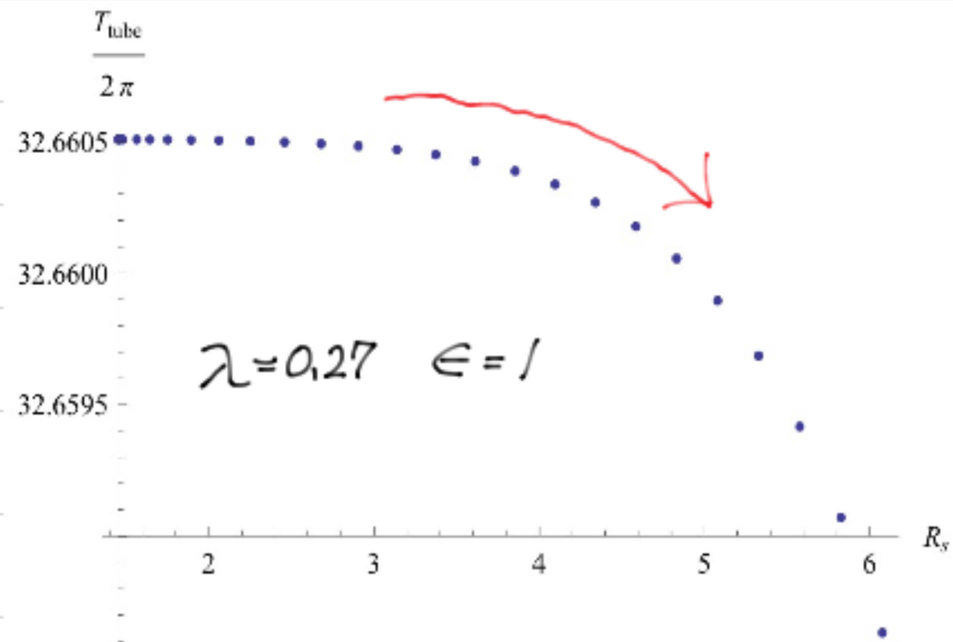


radius R
sometimes behaves
as a very light mode

with finite relaxation time $\tau \simeq 50$ and various initial conditions, Effective potentials for R are obtained..

$$R \equiv \int dr\, r^2 |A'|^2 \Big/ \int dr\, r\, |A'|^2$$

- Unfortunately, we find a rolling-over potential always. (monotonically decreasing)



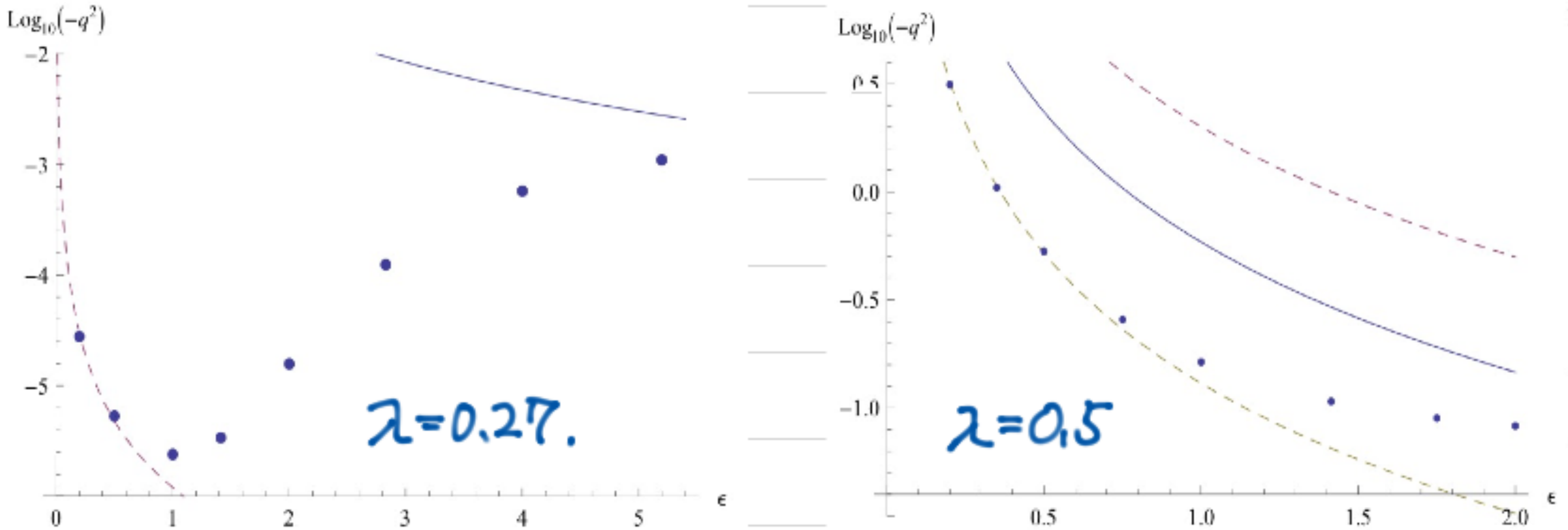
← the most subtle potential with a large plateau.

$\Updownarrow$

tiny tachyonic mass of a mode around R-string

R-strings are always unstable through a classical process!!

tackyonic masses for flactuations
along the messenger direction
around a R-string solution ($S=0$).



$\epsilon=1$ tiny tachyonic mass$^2 \sim 10^{-5.6} \times |m_\phi|^2$

tachyonic mass
at the origin
for $\phi, \tilde{\phi}$.

§3. Thermal Effect from SM particle plasma.

Metastable vac.
$\langle|\phi^2|\rangle = 0$

condensation of messengers

pressure from gauge boson plasma

a mass term

$$\underbrace{\boxed{\frac{g^2}{2}\left(|\phi|^2+|\tilde{\phi}|^2\right)}}_{m_B^2} A_\mu A^\mu$$

Actually we get a thermal potential

$$V_{th} = 3\,\frac{T^4}{2\pi^2} J_B\left(\frac{m_B^2}{T^2}\right) = -\frac{\pi^2}{30}T^4 + \underbrace{\frac{1}{8}m_B^2 T^2}_{} + \cdots$$

review
M. Quiros hep-ph/9901312

thermal mass for $\phi, \tilde{\phi}$,

Thermal mass makes R-tube (string) stable?

We find that.

Sufficiently high temparature makes
R-string stable.

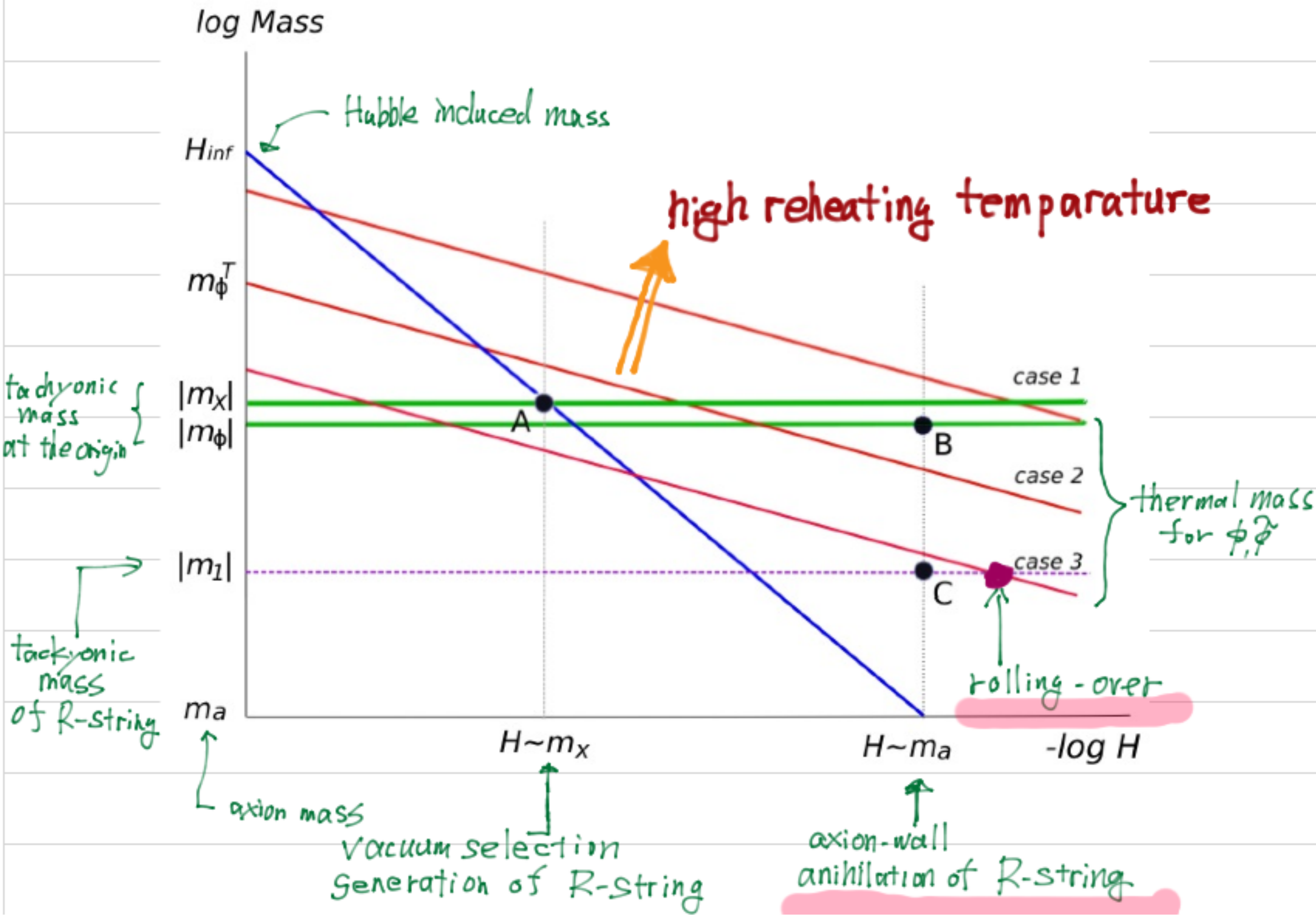
so that

$$m_\phi^T \equiv \underbrace{\frac{g}{4}}_{\text{gauge coupling}} T > \underbrace{m_1}_{\text{tachyonic mass around R-string}} \equiv \left|\frac{\epsilon}{\sqrt{2}} g\right| \mu$$

Note that Large $T = T(T_R, \overset{\text{Hubble parameter.}}{H})$

$\Longleftrightarrow$ Large T_R (reheating temparature)

Large T_R gives a large thermal mass, $m_\phi^T = \frac{g}{4} T$, which avoid the rolling-over process



- But, high reheating temp. T_R causes cosmological problems.

For instance, to avoid the gravitino problem, we need

$$T_R < T_R^{gr} \equiv 6.4\times 10^8\, m_{3/2} \left(\frac{m_\lambda}{100\,\mathrm{GeV}}\right)^{-2}$$

gravitino mass

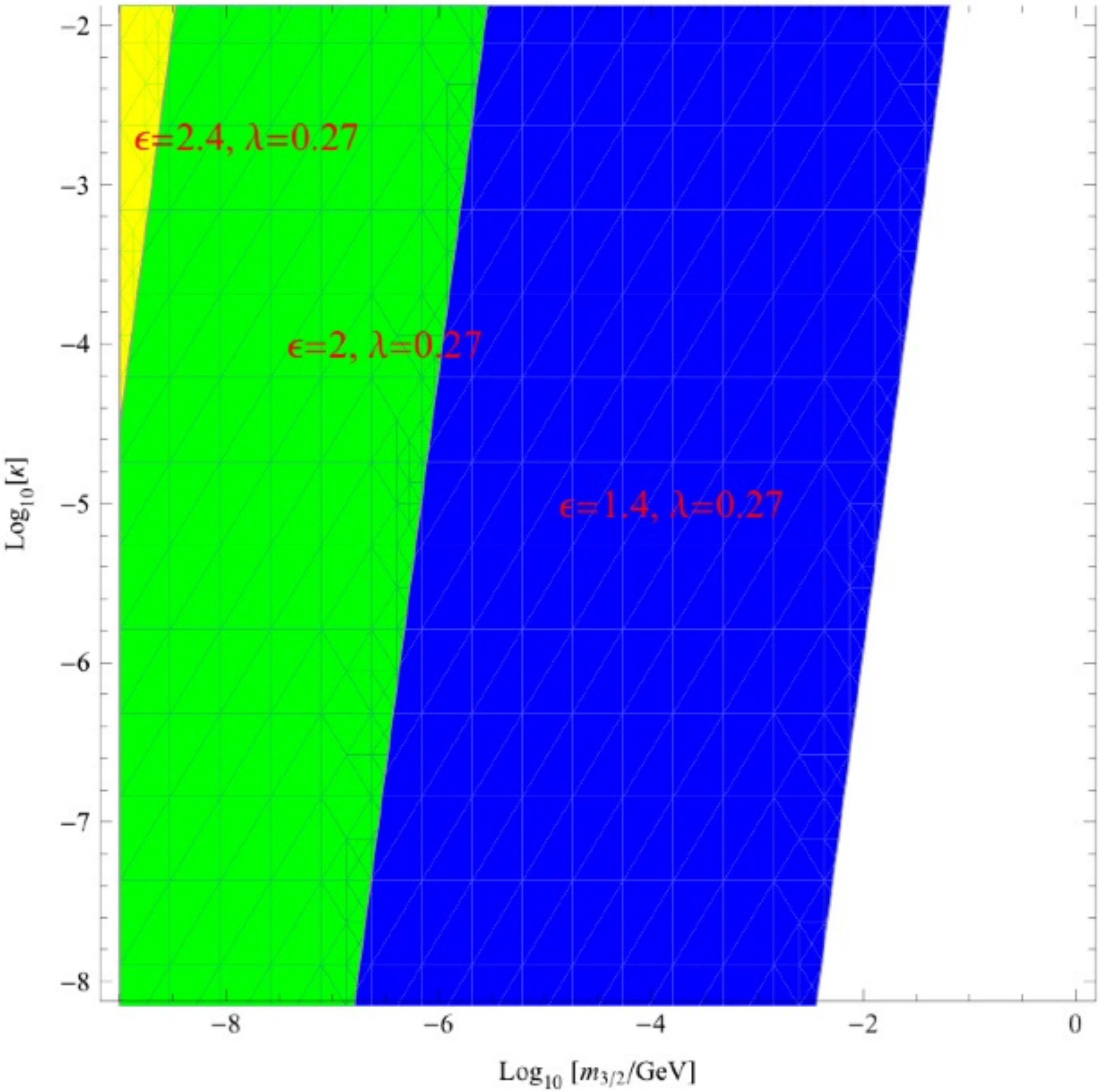
Kawasaki-Kohri-Moroi astro-ph/0402490, 0408426

gaugino mass

$$m_\lambda = \mathcal{O}(0.1)\times\frac{1}{16\pi^2}\,\frac{\left(1-\frac{1}{4\lambda}\right)\sqrt{\lambda}\,\mu^2}{\kappa\, m}$$

We have to check if there exists an allowed reagion for T_R avoiding these problems with a given parameter set $\{\lambda, \epsilon, \kappa, m_{3/2}\}$

Allowed reagion for κ, $m_{3/2}$ with some sets of $\{\lambda, \epsilon\}$.



§4. Conclusion

- Existence of R-tube causes dengerous
  the rolling-over problem

- Thermal effect may avoid this problem.

- Due to existence of (unstable) R-tube,
  the metastable vacuum requires
  a strong new condition on a model
  for the SUSY sector.