Gravitational Wave from Metastable SUSY Breaking

Gravitational Wave Probes of Physics Beyond Standard Model,
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Outline

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- Events that occurs at early universe are communicated to present day by particles that have travelled far.
- Clean info can only come by for particles which decoupled from the primordial plasma. Decoupling occurs if process rate is less than expansion rate.

$$\left(\frac{\Gamma}{H}\right)_{\rm neutrino} \sim \left(\frac{T}{\rm 1MeV}\right)^3, \quad \left(\frac{\Gamma}{H}\right)_{\rm graviton} \sim \left(\frac{T}{M_P}\right)^3$$

ν cannot carry info on the state of the Universe at $T \gtrsim 1$ MeV. But gravity can probe T until the Planck scale!

- Gravitational wave provides an unique tool to probe physics occured at the early universe that's hard to access otherwise, e.g. inflation, phase transition, cosmic string, PBH, string theory, quantum gravity ...

- SUSY is beautiful and useful: why light Higgs bosons, hierarchy, predicts dark matter, spacetime SUSY emerges from string theory, ...
- SUSY if exists, must be broken at the low energy since unbroken SUSY predicts lots of new superpartner particles of the standard model.
- Dynamical SUSY breaking provides a natural way to achieve a hierarchy due to tiny non-perturbative gauge dynamics [Witten (82)]

$$M_S = M_P e^{-a/g^2} \ll M_P$$

- However, so far no sign of SUSY has been seen in collider experiment. This has raised discomforts/concerns. e.g. Is SUSY dead? [Scientific American (2012)]
- It is possible that collider may never reach the energy to find particle signature of SUSY. But a new hope is found in GW!

In this talk, I want to talk about:

1. Metastable SUSY breaking is a very interesting sceranio (if not the only) for SUSY breaking
2. Metastable breaking is very naturally achieved if we take into account of the thermal history of the Universe
3. Metastable breaking is detectable via GW produced from an associated FOPT, which is within the sensitivity reach of LISA and DECIGO.

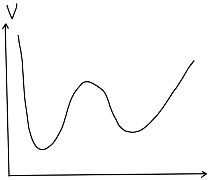
Outline

Spontaneous SUSY breaking

- One way to break SUSY is breaking it spontaneously

$$\mathcal{L} = \mathcal{L}_{SUSY}, \quad Q|0\rangle \neq 0 \ \& \ E_0 \neq 0.$$

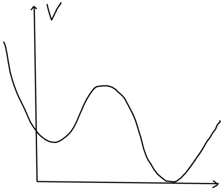
It has been widely thought that the non-SUSY vac is the true vac, i.e. there is no SUSY ground state at all.



- This is hard for model building due to the *Nelson-Seiberg theorem:* Models of spontaneous SUSY breaking requires an R-symmetry in a generic model.
- However, R-symmetry is unwelcome since: it's existence implies that gauginos are massless + it's breaking would lead to light R-axion.

Metastable SUSY breaking

- Another possibility is to break SUSY metastably with the universe living in a susy breaking state, tunnel slowly to a SUSY true ground state somewhere else [Ellis, Llewellyn Smith, Ross (82); Intrigillator, Seiberg, Shih (06)]



- ISS model: SUSY is broken classically. However, SUSY is restored nonperturbatively due to the Affine-Dine-Seiberg (ADS) superpotential.

ISS model

- $\mathcal{N}=1$ susy $SU(N)$ gauge theory with N_f flavors of chiral superfields $\varphi_i, \tilde{\varphi}^i$ and Φ_{ij}, $i,j=1\cdots, N_f$, and the tree level superpotential

$$W_{\rm cl} = h\mathrm{Tr}\varphi\Phi\tilde{\varphi} - h\mu^2\mathrm{Tr}\Phi$$

Classically, there is a R-symm: $\quad Q(\Phi)=2, Q(\varphi)=Q(\tilde{\varphi})=0$ and SUSY is broken due to F-flatness cond.

- The lowest energy state of the theory is

$$\langle\varphi\rangle = \langle\tilde{\varphi}^T\rangle = \mu\begin{pmatrix} \mathbb{1}_N \\ 0_{N_f-N} \end{pmatrix}, \quad \langle\Phi\rangle = 0\,, \qquad V_+ = (N_f-N)|h^2\mu^4|$$

- The Wilsonian coupling is

$$e^{-8\pi^2/g^2(E)} = \left(\frac{E}{\Lambda_m}\right)^{N_f-3N}.$$

Theory is IR free and UV strongly coupled, with a Landau pole at Λ_m. Fortunately, due to Seiberg duality, there is a weakly coupled "electric" dual description, which is UV free and IR strong (will not need this except to know that the complementary descriptions have the theory under control.).

- There is no perturbative corrections. Non-perturbative gauge dynamics give rises to the ADS superpotential. The full superpotential of the theory becomes $W = W_{\rm cl} + W_{\rm ADS}$:

$$W_{\rm ADS} = N \left(h^{N_f} \frac{\det_{N_f} \Phi}{\Lambda_m^{N_f - 3N}} \right)^{\frac{1}{N}} .$$

- The presence of $W_{\rm ADS}$ nontrivially leads to the emergence of a SUSY preserving vacuum at

$$\langle \Phi \rangle = \Phi_0 \delta_{ij} \equiv \frac{\mu}{h \epsilon^{(N_f - 3N)/(N_f - N)}} \delta_{ij}, \quad \langle \varphi \rangle = \langle \tilde{\varphi}^T \rangle = 0,$$

where

$$\epsilon = \mu / \Lambda_m \sim e^{-\# / g^2(\mu)} \ll 1, \quad \text{is indeed nonperturbative.}$$

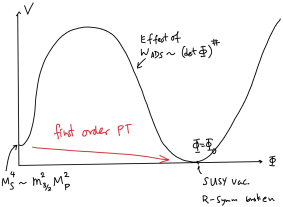
- Note also the SUSY vac is parametrically very far from the metastable vacuum

$$\Phi_0 / \mu = \frac{1}{h \epsilon^{\#}} \gg 1.$$

Metastable vac of ISS

- The potential interpolating the two vacuum is

$$V = V_{\rm meta}\left(\left(\frac{\Phi}{\Phi_0}\right)^{\frac{N_f-N}{N}} - 1\right)^2, \quad V_{\rm meta} := N_f|h^2\mu^4|$$



- The restoration of SUSY is related to the breaking of the R-symmetry is broken nonperturbatively.
- False vacuum decay rate $\Gamma_4/V \sim \exp\left(-\frac{h^2}{\epsilon^{4(N_f-3N)/(N_f-N)}}\right)$ is parametrically small for $\epsilon \ll 1$.
- Small gaugino mass can be achieved [Dine, Mason (06);Kitano, Ooguri, Ookouchi (07); Abel, Durnford, Jaeckel, Khoze (07); Haba, Maru (07)]

Thermal effects on ISS

- Q1. Why is the metastable vacuum chosen in the first place?
  It was found that thermal evolution of univ leads naturally to the metastable vacuum. [Abel, Chu, Jaeckel, Khoze (06); Craig, Fox, Wacker (06); Fischler, Kaplunovsky, Krishnan, Mannelli, Torres (06)]
- Q2. Can we detect this kind of SUSY breaking?
  Exists 1st order phase transition (FOPT) at reheating which could be detected via GW. [Chu, Ito (22)]

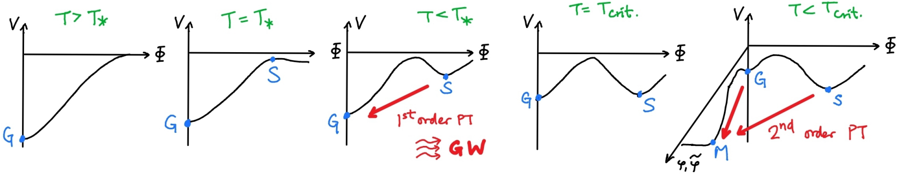
Thermal behaviour of vacuum

- Thermal corrections to the potential is:

$$\Delta V_T(\Phi) = \frac{T^4}{2\pi^2} \sum_i \pm n_i \int_0^\infty dp\, p^2 \ln\left(1 \mp e^{-\sqrt{p^2+m_i^2(\Phi)/T^2}}\right) ,$$

- contributions always < 0; larger contribution for smaller m
- Thermal correction is less than 1% if $T \lesssim 0.3 V_{\rm meta}^{1/4}$

- For MSSM coupled to ISS, we have to sum over the contributions from the ISS sector, MSSM particles and a messenger sector.



- It can be estimated that

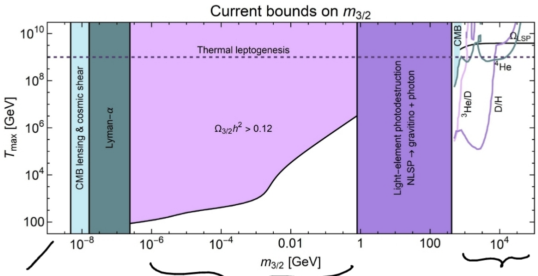
$$T_* \sim h\Phi_0, \quad T_{\rm crit} \sim \frac{\mu}{h^{1/2}}.$$

- At the end of inflation, the universe is reheated to T_R. However, T_R is too small, the thermal corrects maybe too small to explain the naturalness of the metastable SUSY vaccum.
- This confines us to the gravitino mass range

$$m_{3/2} < 4.7eV$$

Constraint on gravitino mass

- Allowed mass regions of $m_{3/2}$ [Hook, McGehee, Murayama (18)]



I: $m_{3/2} < 4.7\text{eV}$

no restriction on T_R

II: $0.4\text{keV} \lesssim m_{3/2} \lesssim 1\text{GeV}$

III: $m_{3/2} \gtrsim 600\text{GeV}$

$T_R \lesssim 0.1\, V_{meta}^{1/4}$

- As the thermal correction is negligible in II & III, it is possible to explain why the universe is naturally in the metastable vac today and to have GW generation only in the the mass region I:

$$m_{3/2} < 4.7eV$$

Outline

Phase transition

- At the end of inflation, the universe is reheated to T_R. To get GW, the interesting case is

$$T_{\rm crit} < T_R < T_*,$$

where GW could be produced from the FOPT.

- Transition rate per unit volume [Linde; Coleman]

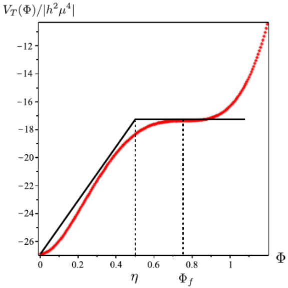
$$\Gamma \simeq e^{-S_3/T}$$

where S_3 is the action for the bounce

$$\Phi''(r) + \frac{2}{r}\Phi'(r) = \frac{1}{N_f}\partial_\Phi V_T(\Phi), \quad \Phi(\infty) = \Phi_f,\ \Phi'(0) = 0.$$

Φ_f denotes the location of the SUSY vacuum.

- Use an piecewise linear approx for the potential, (η = turning point, $N_f K$ = slope),



- The bounce soln can be obtained analytically, with

$$\frac{S_3}{T} = \frac{\sqrt{6}\pi N_f \eta^{5/2}}{5\sqrt{K}T} .$$

Bubble dynamics

Consider $T_R = T_*$, where GW production is expected to be most efficient.

- Dynamics of the bubbles and the production of GW are characterized by two parameters: [Caprini etal. (16)]
  - Vacuum energy released compared to the energy of the radiation bath:
$$\alpha = \frac{V_f - V(\Phi = 0)}{g_* \pi^2 T_*^4/30}.$$
  - Approximate duration of the phase transition:
$$\beta = -H_* T_* \left(\frac{d}{dT} \frac{S_3}{T} \right)_{T=T_*}.$$
- In our case, bubble collisions is the dominant source of GW since the mass of the superpartner particles $M_{\rm SP} \sim TeV \ll T_*$ and so most of the vaccum energy are dumped into the bubbles.

For bubble collisions,

- GW spectrum in terms of energy density:

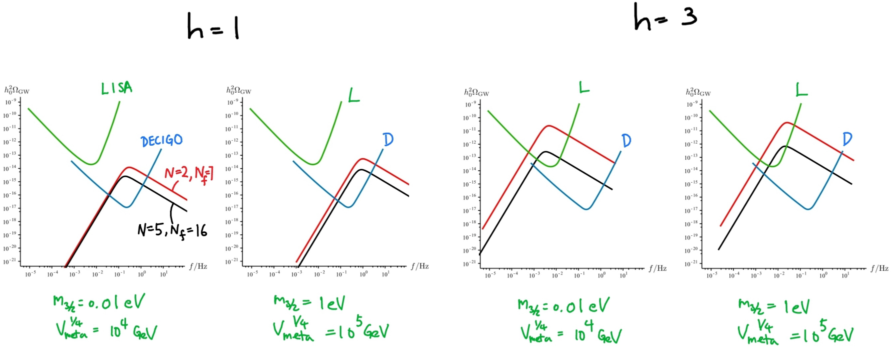
$$h_0^2\Omega_f(f) = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{0.11 v_w^3}{0.42 + v_w^2}\right) \left(\frac{3.8(f/f_p)^{2.8}}{1+2.8(f/f_p)^{3.8}}\right) ,$$

- Peak frequency at present:

$$f_p = 16.5 \times 10^{-6}\,\mathrm{Hz} \left(\frac{0.62}{1.8 - 0.1 v_w + v_w^2}\right) \left(\frac{\beta}{H_*}\right) \left(\frac{T_*}{100\,\mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} .$$

More modern, improved analysis of the bubble dynamics is possible (see e.g. talk of Lewicki), but won't change much of our results

Typical GW spectrum for MSSM with ISS breaking



- bigger h gives larger amplitude and lower f_p
- ligher gravitino mass (lower SUSY breaking scale) gives lower f_p
- spectrum is within reach of the LISA and DECIGO.

What's next?

- Great if we can see sign of metastable SUSY breaking FOPT. It will stimulate further searches in the particle physics channel.
- GW can be used to probe: modification of GR? Hubble constant? inside of black hole? Hawking radiation? other quantum gravity effect?
- New design of GW detector? current detection is based on change of distance, what about change of velocity? Torsion-bar Antenna (TOBA)? ...