Physics with light Goldstino supermultiplet

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Standard Model: Major Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity
  - …

SUSY can explain all above in green

If SUSY breaking scale is low. . .

- Particles from the hidden sector may be light too
- no SM superpartners at TeV scale. . .
- Then we effectively have SM and Goldstino supermultiplet
- Gravitino is R-odd (and LSP?), search for its pair production (missing energy)
- Sgoldstinos are R-even, search for their single production and decays to SM particles
- Sgoldstinos couple to Higgs. They can

  enrich its collider phenomenology

  and even make EW phase transition of the first order

  (a condition for the EW baryogenesis)
- to be tested with GW interferometers

Outline

1. Supersymmetric models
2. Goldstino supermultiplet
3. Scalar sector and the EW phase transition

Outline

Supersymmetry is a symmetry of bosons and fermions

supercharge $\hat{Q}_{SUSY}$

- SUSY exhanges bosons and fermions:

$$\hat{Q}_{SUSY}\ \text{boson} \longrightarrow \text{fermion}$$
$$\hat{Q}_{SUSY}\ \text{fermion} \longrightarrow \text{boson}$$

  they become superpartners

- In supersymmetric theory

$$\text{bosonic d.o.f.} == \text{fermionic d.o.f.}$$

- $$\left[\hat{Q}_{SUSY}\,,\,\hat{H}\right] == 0$$

  superpartners
  are of the same mass and exhibit the same interactions

How does it work? Supersymmetric QED

- the same number of d.o.f. in bosonic and fermionic sectors

$$\text{Dirac fermion } \Psi : 4\, d.o.f. \longrightarrow \text{complex scalars } \phi_+ , \phi_-$$
$$\text{massless vector } A_\mu : 2\, d.o.f. \longrightarrow \text{Majorana fermion } \lambda$$

- superpartners are of the same masses

$$m\bar{\Psi}\Psi \longrightarrow m^2\phi_+^*\phi_+ + m^2\phi_-^*\phi_- \,, \qquad M_A = M_\lambda = 0\,,$$

- and exhibit the same interactions $\mathscr{L}$ is a scalar !!

$$eA_\mu\bar{\Psi}\gamma^\mu\Psi \longrightarrow ieA^\mu\left(\phi_+\partial_\mu\phi_+^* - \phi_+^*\partial_\mu\phi_+\right) - ieA^\mu\left(\phi_-\partial_\mu\phi_-^* - \phi_-^*\partial_\mu\phi_-\right)$$
$$eA_\mu\bar{\psi}_+\bar{\sigma}^\mu\psi_+ - eA_\mu\bar{\psi}_-\bar{\sigma}^\mu\psi_- \longrightarrow -ie\sqrt{2}\left(\phi_+\bar{\psi}_+\bar{\lambda} - \phi_-\bar{\psi}_-\bar{\lambda}\right) + \text{h.c.}$$
$$\text{total derivative} \longleftarrow e^2A_\mu A^\mu\phi_+^*\phi_+ + e^2A_\mu A^\mu\phi_-^*\phi_-$$
$$\text{total derivative} \longleftarrow -e^2\frac{1}{2}\left(\phi_+^*\phi_+ - \phi_-^*\phi_-\right)^2$$

Most attractive features

- Theory: bosonic loops cancel fermionic ones

  only logarithmic divergences remain:

  stability of the hierarchical structure of energy scales, e.g. $M_W \ll M_{SUSY}$, $M_W \ll M_{GUT}$, $M_W \ll M_{Pl}$ are stable

- Phenomenology: number of particles gets doubled !!

  get new interactions but with the same coupling constants !!

- Cosmology: 1) lightest superpartner is stable !!

  Dark Matter candidate (if neutral: neutralino, gravitino)

  2) scalar potentails typically exhibits typically flat directions !!

  Natural implementation of the Affleck–Dine baryogenesis

SUSY: a couple is more stable and promising state

Supersymmetrizing the Standard Model MSSM

gluons, g	$\longleftrightarrow$	gluino, $\tilde{g}$
photon, γ	$\longleftrightarrow$	photino, $\tilde{\gamma}$
weak gauge bosons, $W^{\pm}, Z$	$\longleftrightarrow$	winos, zino, $\tilde{W}^{\pm}, \tilde{Z}$
quarks, leptons, q, l	$\longleftrightarrow$	squarks, sleptons, $\tilde{q}, \tilde{l}$
	e.g.	
r.h. electron, e_R	$\longleftrightarrow$	r.h. selectron, $\tilde{e}_R$
l.h. top, t_L	$\longleftrightarrow$	l.h. stop, $\tilde{t}_L$
neutrino, ν	$\longleftrightarrow$	sneutrino, $\tilde{\nu}$
SM Higgs boson	$\longleftrightarrow$	higgsino
to avoid the anomaly		due to higgsino set
two Higgs doublets, $h, H, A, H^{\pm}$	$\longleftrightarrow$	neutral $\tilde{h}, \tilde{H}$ and charged $\tilde{H}^{\pm}$ or $\chi^0_{1,2}$ and $\chi^{\pm}$ higgsinos

Problems of a supersymmetric extension

- there are no superpartners of the same mass with the same couplings

$\longrightarrow$ SUSY must be spontaneously broken

- Simple variants are not viable, as

$$\mathrm{STr} \equiv \sum_{\text{bosons}} m^2 - \sum_{\text{fermions}} m^2 = 0$$

breaking must happen in a hidden sector

- superpartners are heavy quarks and squarks are not aligned
  Higgs makes SM particles (and superpartners) massive
  handred new parameters $\Longleftarrow$ mixing and FCNC

Natural conclusion: a big gap is between us

How heavy are superpartners?

- Higgs mass gets corrections of the types

$$\propto \log(m_t^2/m_{\tilde{t}}^2), \quad \text{and} \quad \propto \left(m_{\tilde{t}}^2 - m_t^2\right),$$

the superpartners must be not very far from the TeV-scale

- lightest superpartner is stable (LSP)
  R-parity and still can be thermal DM candidate (WIMPs)
- Absence of rare processes, e.g. $B_s \to \mu^+\mu^-$, would imply $M_{superpartners} \gtrsim 10^2$ TeV, but
- There are several anomalies in particle physics (and closely related) experiments:

$$(g-2),$$
$$\mathrm{Br}(B \to K^*\mu^+\mu^-),$$
$$\Gamma(B \to D^{(*)}\tau\nu)/\Gamma(B \to D^{(*)}l\nu),$$
$$\Gamma(B \to K\mu^+\mu^-)/\Gamma(B \to Ke^+e^-)$$

Outline

Coupling to goldstino

SUSY is spontaneously broken

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons
couple to all massive fields
(Goldberger–Treiman formula like for pion)

$$\mathscr{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

Higgs mechanism:
three modes of H are eaten
giving masses to Z, $W^{\pm}$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino
couples to all fields

$$\mathscr{L}_\psi \sim \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi \to \frac{\partial_\mu J^{\mu}_{SUSY}}{F} \propto \frac{M_{soft}}{F}$$

Super-Higgs mechanism:
goldstino is eaten giving mass to gravitino

ψ — goldstino $\xrightarrow{SUGRA}$ longitudinal gravitino

Coupling to sgoldstinos

Integrating out the hidden sector, except Goldstino multiplet

Physics of Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

$$\cancel{\text{SUSY}} \quad \longleftrightarrow \quad F \equiv \langle F_\varphi \rangle \neq 0 \qquad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta \qquad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$$

$$\mathscr{L}_{S,P} \propto \frac{M_{soft}}{F} \qquad F \sim (\cancel{\text{SUSY}}\ \text{scale})^2 \qquad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$$

If SM superpartners are heavy...

massless at tree level
naturally may be light...

- gravitinos are R-odd, pair production is suppressed

$$A \propto \frac{1}{F} \times \frac{1}{F}$$

- gravitinos are LSP, the only signature is

missing E

- sgoldstinos are R-even

$$A \propto \frac{1}{F}$$

- clear signature:

decay into a pair of SM particles

Coupling to sgoldstinos

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massless at tree level
naturally may be light...
and they are R-even

M_{soft}: MSSM soft terms
superpartner masses and trilinear couplings,

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u \bar{u}_i u_j, \quad \frac{A_{ij}}{F} P h_u \bar{u}_i \gamma_5 u_j$$

Sgoldstino couplings with spurion technique

hep-ph/9703286

$$\Phi = \varphi + \sqrt{2}\psi\theta + F\theta\theta\,, \qquad \Phi_k = \varphi_k + \sqrt{2}\psi_k\theta + F_k\theta\theta\,, \ldots W_\alpha = i\lambda_\alpha + \ldots$$

$$\mathscr{L}_K = \sum_k \left(1 - \frac{m_k^2}{F^2}\Phi^\dagger\Phi\right)\Phi_k^\dagger e^{g_1 V_1 + g_2 V_2 + g_3 V_3}\Phi_k\bigg|_{\theta\theta\,\bar\theta\bar\theta}\,,$$

$$\mathscr{L}_{gauge} = \frac{1}{4}\sum_a \left(1 + \frac{2M_a}{F}\Phi\right)\mathrm{Tr}\, W_\alpha W^\alpha\bigg|_{\theta\theta} + h.c.\,, \quad \to \quad \frac{1}{2}M_a\lambda\lambda + \frac{M_a}{F}\varphi F_{\mu\nu}F^{\mu\nu}$$

$$\mathscr{L}_W = \epsilon_{ij}\Bigg(\left(\mu - \frac{B}{F}\Phi\right)H_D^i H_U^j + \left(Y_{ab}^L + \frac{A_{ab}^L}{F}\Phi\right)L_a^j E_b^c H_D^i + \\ + \left(Y_{ab}^D + \frac{A_{ab}^D}{F}\Phi\right)Q_a^j D_b^c H_D^i + \left(Y_{ab}^U + \frac{A_{ab}^U}{F}\Phi\right)Q_a^i U_b^c H_U^j\Bigg)\bigg|_{\theta\theta} + h.c., \tag{1}$$

Sgoldstino interactions

goldstino — $\mathcal{L}_\psi \propto \frac{1}{F} J^\mu_{SUSY} \partial_\mu \psi$

$$\Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$$

sgoldstino — $\mathcal{L}_{S,P} \propto \frac{M_{soft}}{F}$

Spurion technique…

$$\frac{M_\lambda}{F} \int \Phi W^\alpha W_\alpha d\theta^2 \quad \xrightarrow{SUSY} \quad M_\lambda \lambda\lambda \qquad \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu} \, , \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\frac{A_{ij}}{F} \int \Phi H_u Q_i U_j d\theta^2 \quad \xrightarrow{SUSY} \quad A_{ij} h_u \tilde{q}_i \tilde{u}_j \qquad \frac{A_{ij}}{F} S h_u q_i u_j \, , \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

Flavor blind couplings

$$X = S, P:$$

$\frac{m_f A_0}{F}$: $\quad X l^+ l^-, X q^+ q^-$

$$\frac{\Gamma(X \to f_i^+ f_i^-)}{\Gamma(X \to f_j^+ f_j^-)} \propto \frac{m_{f_i}^2}{m_{f_j}^2}$$

$\frac{M_\lambda}{F}$: $\quad X\gamma\gamma, Xgg, XZZ, XW^+W^-, XZ\gamma$

$$\frac{\Gamma(X \to gg)}{\Gamma(X \to VV)} \propto (N_c^2 - 1)\frac{M_{\lambda_g}^2}{M_{\lambda_V}^2}$$

$$\frac{\Gamma(X \to f^+ f^-)}{\Gamma(X \to VV)} \propto \frac{A_0^2}{M_{\lambda_V}^2}\frac{m_f^2}{m_X^2}$$

$\frac{m_X^2}{F}$: $\quad X\tilde{G}\tilde{G} \qquad \tilde{G}_\mu \propto i\frac{M_{Pl}}{F}\partial_\mu \psi$

$$\frac{\Gamma(X \to f^+ f^-)}{\Gamma(X \to \tilde{G}\tilde{G})} \propto \frac{A_0^2}{m_X^2}\frac{m_f^2}{m_X^2}$$

$$\frac{\Gamma(X \to \tilde{G}\tilde{G})}{\Gamma(X \to VV)} \propto \frac{M_{\lambda_V}^2}{m_X^2}$$

Flavor violating sgoldstino couplings

Parity conservation (left-right models...)

$$[\tilde{m}^{(LR)2}_{D(U,L)}]^\dagger = \tilde{m}^{(LR)2}_{D(U,L)} \qquad h^{(D)}_{ij} = \frac{\tilde{m}^{(LR)2}_{D,ij}}{\sqrt{2}F} \quad h^{(U)}_{ij} = \frac{\tilde{m}^{(LR)2}_{U,ij}}{\sqrt{2}F}$$

$$\mathscr{L}_{P,q} = -P\cdot(h^{(D)}_{ij}\cdot \bar{d}_i\, i\gamma^5 d_j + h^{(U)}_{ij}\cdot \bar{u}_i\, i\gamma^5 u_j)$$

$$\mathscr{L}_{S,q} = -S\cdot(h^{(D)}_{ij}\cdot \bar{d}_i d_j + h^{(U)}_{ij}\cdot \bar{u}_i u_j)$$

Parity violation

$[\tilde{m}^{(LR)2}_{D(U,L)}]^\dagger \neq \tilde{m}^{(LR)2}_{D(U,L)}$ — no difference between S & P

Sgoldstino couplings when superpartners decoupled

$$\Phi = \varphi + \sqrt{2}\psi\theta + F\theta\theta\,, \qquad H_{u,d} = h_{u,d} + \sqrt{2}\chi_{u,d}\theta + F_{u,d}\theta\theta\,, \dots$$

$$\begin{aligned}\mathscr{L}_\Phi = \Bigg(& \Phi^\dagger\Phi - \frac{\widetilde{m}_s{}^2 + \widetilde{m}_p{}^2}{8F^2}(\Phi^\dagger\Phi)^2 - \frac{\widetilde{m}_s{}^2 - \widetilde{m}_p{}^2}{12F^2}(\Phi^\dagger\Phi^3 + \Phi^{\dagger 3}\Phi) \\ & - \frac{\delta_{\lambda_2}}{4F^2} H_u^\dagger H_u (\Phi^\dagger\Phi)^2 - \frac{\delta_{\lambda_3}}{9F^2}(\Phi^\dagger\Phi)^3 - \frac{\delta_{\lambda_4}}{3F^2} H_u^\dagger H_u (\Phi^\dagger\Phi^3 + \Phi^{\dagger 3}\Phi) \\ & - \frac{\delta_{\lambda_5}}{5F^2}(\Phi^\dagger\Phi^5 + \Phi^{\dagger 5}\Phi) - \frac{\delta_{\lambda_6}}{8F^2}(\Phi^{\dagger 2}\Phi^4 + \Phi^{\dagger 4}\Phi^2) - \frac{\delta_{\mu_1}}{2F^2} H_u^\dagger H_u (\Phi^\dagger\Phi^2 + \Phi^{\dagger 2}\Phi) \\ & - \frac{\delta_{\mu_2}}{6F^2}(\Phi^{\dagger 3}\Phi^2 + \Phi^{\dagger 2}\Phi^3) - \frac{\delta_{\mu_3}}{4F^2}(\Phi^{\dagger 4}\Phi + \Phi^\dagger\Phi^4) - \frac{\delta_{C^3}}{2F^2}(\Phi^{\dagger 2}\Phi + \Phi^\dagger\Phi^2)\Bigg)\Bigg|_{\theta\theta\bar\theta\bar\theta} \\ & - \left(F\Phi\Big|_{\theta\theta} + h.c.\right).\end{aligned}$$

and we take the limit where only SM-like Higgs remains

S.Demidov, D.G., E.Kriukova (211x.yyyyy)

Outline

Low energy limit: sgoldstinos and SM Higgs

tree-level potential

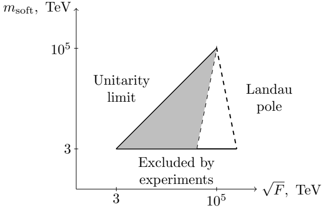
S.Demidov, D.G., E.Kriukova (211x.yyyyy)

$$V_0(h,s,p) = \frac{\lambda_1}{4}h^4 + \frac{\lambda_{hs}}{4}h^2s^2 + \frac{\lambda_{hp}}{4}h^2p^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_p}{4}p^4 + \frac{\lambda_{sp}}{4}s^2p^2 + \\ + \frac{\mu_1}{2}sh^2 + \frac{\mu_s}{6}s^3 + \frac{\mu_{sp}}{2}sp^2 - \frac{M_1^2}{2}h^2 + \frac{M_s^2}{2}s^2 + \frac{M_p^2}{2}p^2 + C^3 s.$$

to fix the minimum of zero-temperature potential $V_0(h,s,p)$ at $\langle h\rangle = v = 246\,\text{GeV}$, $\langle s\rangle = \langle p\rangle = 0$, one sets

$$M_1^2 = \lambda_1 v^2, \qquad C^3 = -\mu_1 v^2/2.$$

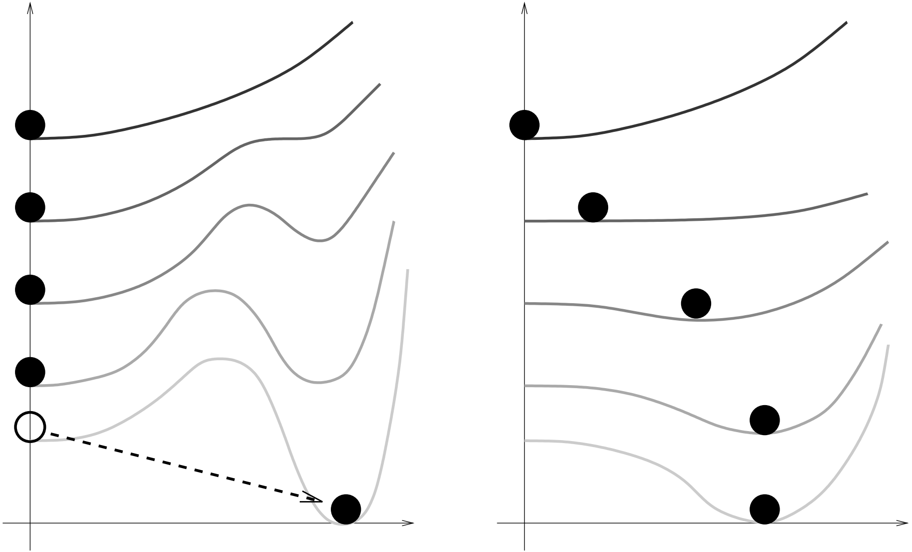
$\lambda \sim 0.3\text{-}0.8\,,\quad m_h/2 < m_s < m_h\,,\quad m_P \sim 400\,\text{GeV}$



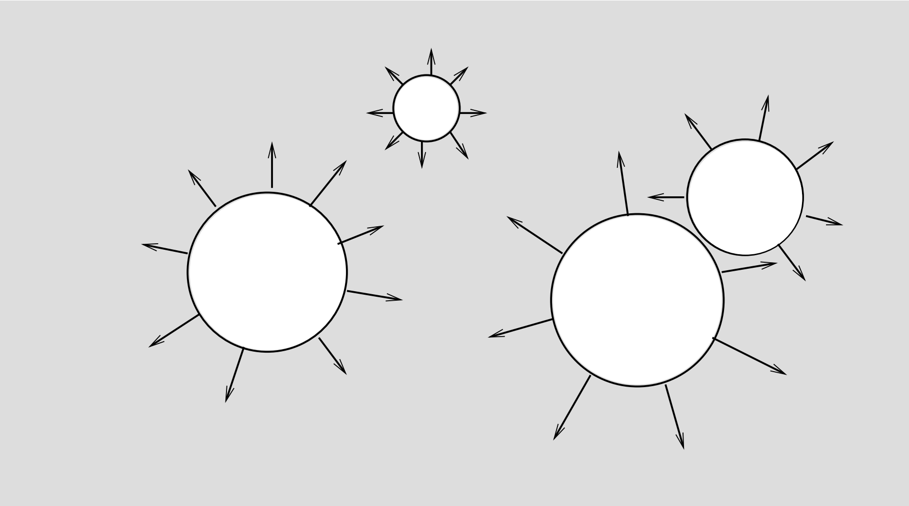
– add Coleman–Weinberg potential (and counterterms)
– add temperature corrections (free energy density of plasma)
– sum daisy diagrams

check for parameters $\mu, m_A \sim$2-10 TeV and $\sqrt{F}$ =10-100 TeV

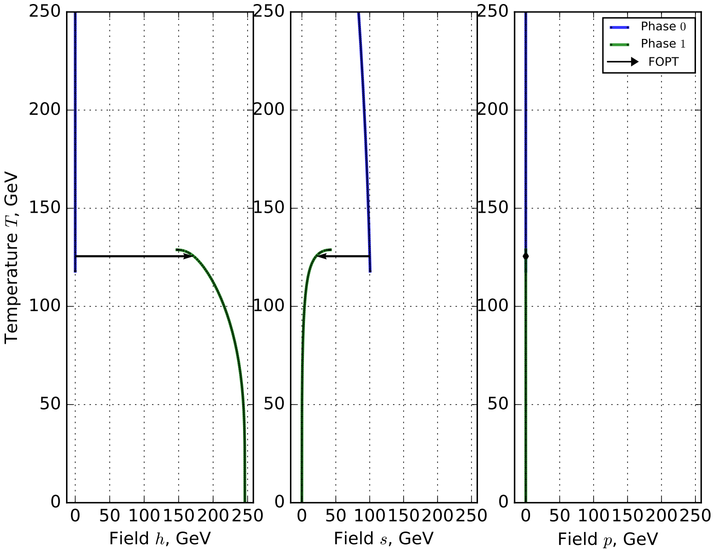
Phase transitions of the I and II orders



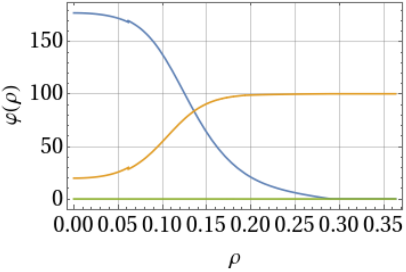
Gravitational waves are produced at the transition

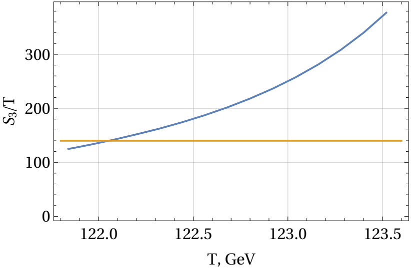


First order EW phase transition (with help of `PhaseTracer`)



The bubbles must nucleate and collide (with help of `FindBounce`)





probability of nucleation

$$P \sim \frac{M_{Pl}^{*4}}{T^4} \exp\left(-\frac{S_3}{T}\right),$$

where S_3 is the Euclidean action calculated on bounce solution,

$$S_3 = \int_0^\infty 4\pi\rho^2 d\rho \left(V_{\rm eff}(T,h,s,p) + \frac{1}{2}\sum_i \left(\frac{d\varphi_i}{d\rho}\right)^2 \right).$$

and we need $S_3/T \sim 140$ G.W. Anderson, L.J. Hall (1992)

GW production: formulas (I)

$$\alpha \equiv \left(\frac{g_* \pi^2 T_{\rm nuc}^4}{30}\right)^{-1} \left(\Delta V_{\rm eff} - \frac{T}{4}\frac{{\rm d}\Delta V_{\rm eff}}{{\rm d}T}\right)\Bigg|_{T_{\rm nuc}},$$

$\Delta V_{\rm eff}$ is the potential value difference between a broken and an unbroken phases.
Parameter β/H_c characterizes the bubble nucleation rate

$$\frac{\beta}{H_c} \equiv T\frac{\rm d}{{\rm d}T}\left(\frac{S_3}{T}\right)\Bigg|_{T_{\rm nuc}}.$$

$$\Omega_{\rm sw}h^2 = 1.23\cdot 10^{-5}\,\frac{v_w H_c}{g_*^{1/3}\beta}\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 S_{\rm sw}(f), \quad \Omega_m h^2 = 1.55\cdot 10^{-3}\,\frac{v_w H_c}{g_*^{1/3}\beta}\left(\frac{\kappa_m\alpha}{1+\alpha}\right)^{3/2} S_m(f),$$

where v_w is the bubble wall velocity (we take 0.55),

$$\kappa_{\rm sw} = \frac{c_s^{11/5}k_a k_b}{\left(c_s^{11/5}-v_w^{11/5}\right)k_b + v_w c_s^{6/5}k_a}, \quad \kappa_m = 0.05\kappa_{\rm sw}, \quad c_s = \frac{1}{\sqrt{3}},$$

$$k_a = \frac{6.9 v_w^{6/5}\alpha}{1.36 - 0.037\sqrt{\alpha}+\alpha}, \quad k_b = \frac{\alpha^{2/5}}{0.017 + (0.9997+\alpha)^{2/5}},$$

GW production: formulas (II)

$S_{\rm sw}(f)$ and $S_m(f)$ are the spectrum shapes,

$$S_{\rm sw}(f) = \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2},$$

$$S_m(f) = \frac{(f/f_m)^3}{(1+f/f_m)^{11/3}\left(1+\frac{8\pi f}{h_*}\right)},$$

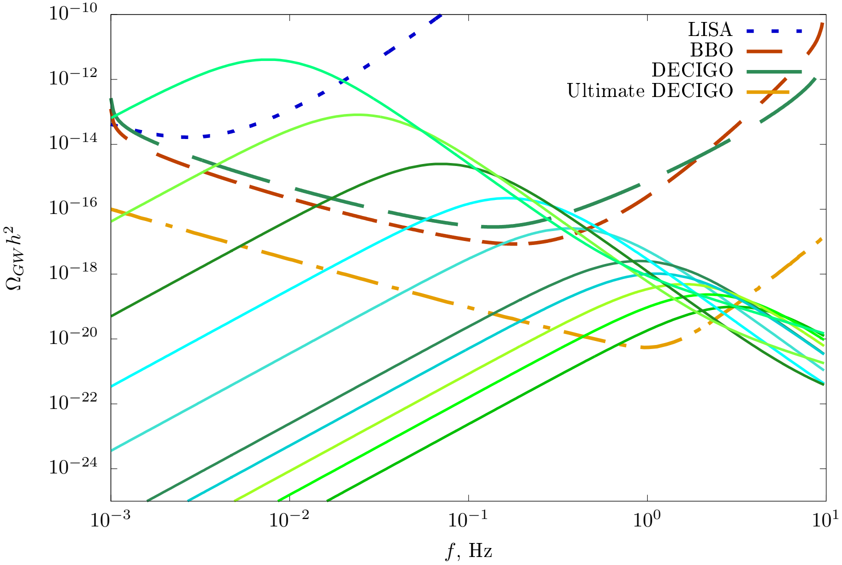
where

$$h_* = 1.65\cdot 10^{-5}\ \text{Hz}\left(\frac{T}{100\ \text{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

and peak frequencies are given by

$$f_{\rm sw} \simeq \frac{1.15\beta h_*}{v_w H_c}, \qquad f_m \simeq \frac{1.65\beta h_*}{v_w H_c}.$$

GW signals for sets of model parameters



Conclusions:

- SUSY is wonderful and we search for it
- Light Sgoldstinos may be the first SUSY particles we will observe
- They can make EW phase transition of the I order (and help to explain BAU?)
- The explanation can be tested
  @ gravitational interferometers
  @ colliders. . . light sgoldstinos