Naturalizing Supersymmetry

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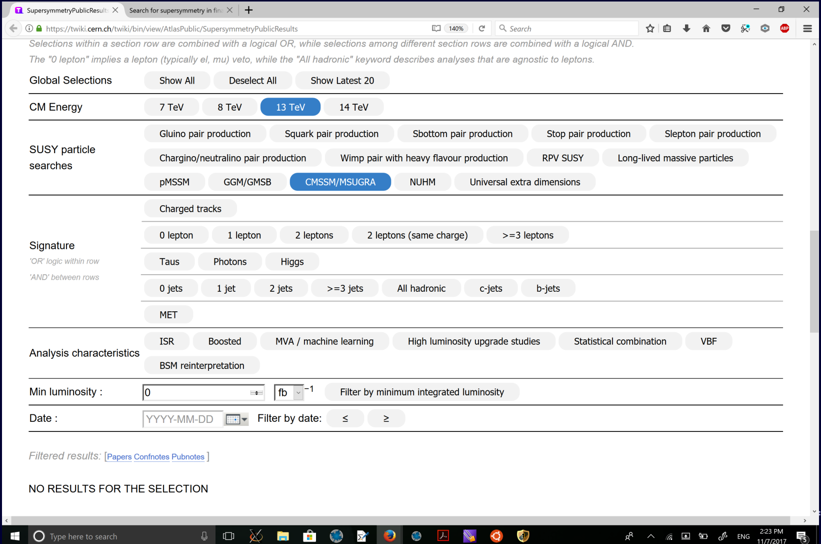
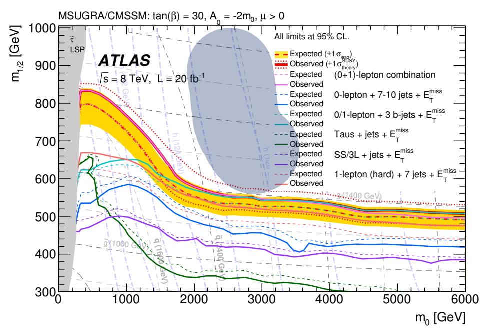
Outline

Goodbye to Generic Supersymmetry



Status of Generic SUSY

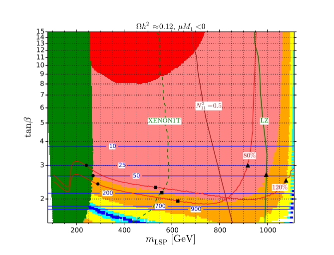
- Fine tunning of CMSSM
  - Best case scenario, generic SUSY has heavy masses
  - $\Delta_{BG} \sim M_{SUSY}^2 / m_Z^2$

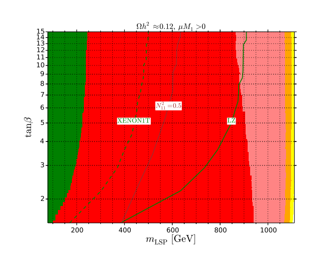


Status of Generic SUSY

- Fine tunning of CMSSM
- Dark Matter of generic SUSY
  - Simple thermal relics strained but not gone

    Red: LUX(SI), Green: LUX(SD), Orange: (XENON1T), Yellow: (LZ)





Badziak, Olechowski, Szczerbiak

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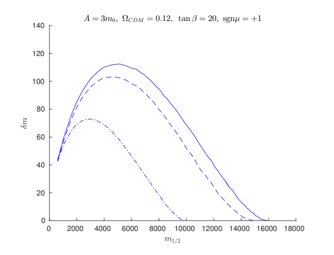
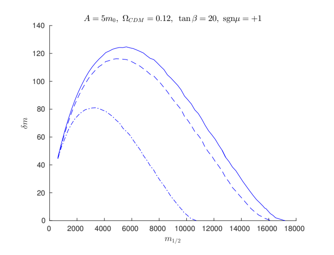
  - Stop coannihilation $\to$ dark matter but heavy





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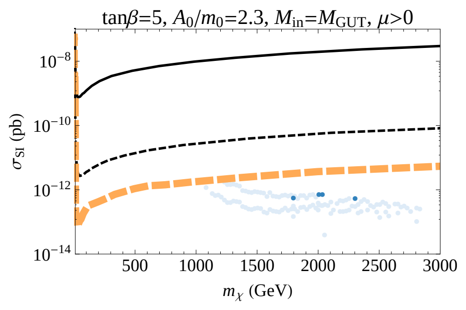
  - Stop coannihilation $\rightarrow$ dark matter but heavy
    Very difficult to detect



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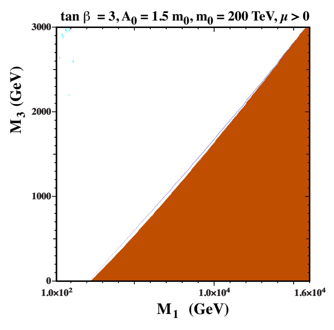

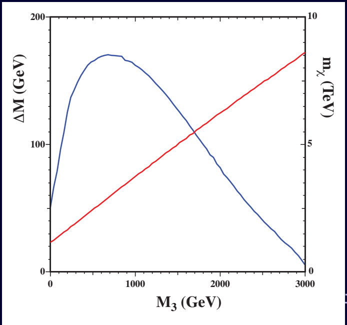

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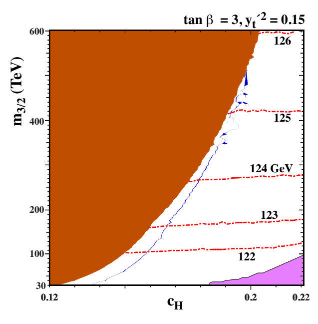

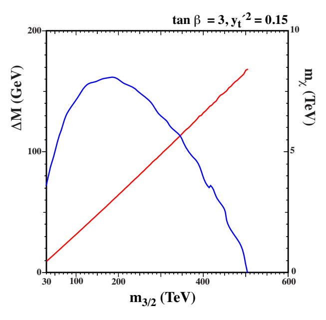

Status of Generic SUSY

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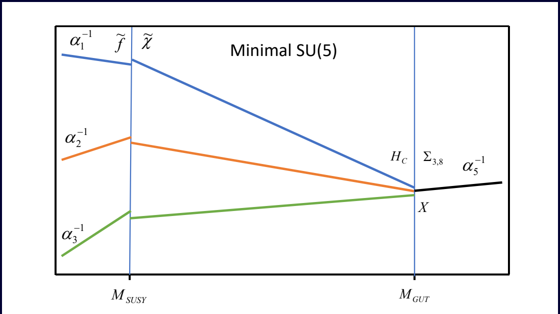
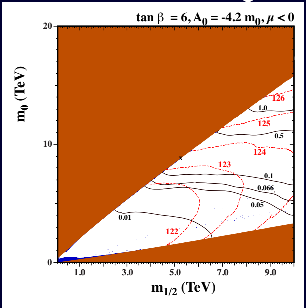
- Gauge coupling unification of generic SUSY
  - As long as $\mu \lesssim 10^6$ GeV couplings unify



Status of Generic SUSY

- Fine tunning of CMSSM
- Dark Matter of generic SUSY
- Gauge coupling unification of generic SUSY
  - As long as $\mu \lesssim 10^6$ GeV couplings unify
  - Complete models with low tuning are complicated



Dynamical Relaxation

$$-\mathcal{L} \supset \boxed{\left(-M^2 + m_R\phi\right)|H|^2} + \boxed{\tfrac{1}{2}(m_R\phi)^2} + \boxed{V_{stop}}$$

- Two distinct contributions to Higgs mass
  - M^2: All radiative corrections plus tree-level piece
  - $m_R\phi$: symmetry breaking field dependent Higgs mass
- $m\phi = M^2$ special dynamically
  - $m_R\phi > M^2 \rightarrow \langle H\rangle = 0$
  - $m_R\phi < M^2 \rightarrow \langle H\rangle \neq 0$
- Shift symmetry breaking $\rightarrow$ slowly relax back to minimum
  - Rolling ϕ scans Higgs mass
- Higgs dependent potential to stop relaxion
  - $\langle H\rangle = 0 \rightarrow \frac{\partial V_{stop}}{\partial\phi} = 0$ $\quad\quad$ $\langle H\rangle \neq 0 \rightarrow \frac{\partial V_{stop}}{\partial\phi} < 0$

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Simple Dynamical Relaxation Model

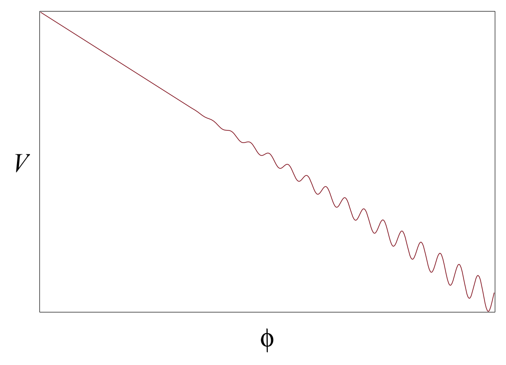
$$\mathcal{L} \supset \left(-M^2 + m_R\phi\right)|H|^2 + \frac{1}{2}(m_R\phi)^2 + \Lambda_{QCD}^4 \cos\left(\frac{\phi}{f}\right)$$

- Low scale theory: SM + axion Graham, Kaplan, Rajendran
- Axion Nambu-Goldston boson of $\mathrm{U}(1)_{PQ}$
  - m_R small breaking of axion shift symmetry
  - All breaking proportional to m_R so technically natural
- Quark condensate further break $U(1)_{PQ}$

$$-\mathcal{L} \supset y\langle H\rangle e^{i\frac{\phi}{f}}\langle\bar{q}_L q_R\rangle + y^\dagger\langle H^\dagger\rangle e^{-i\frac{\phi}{f}}\langle\bar{q}_R q_L\rangle = 2y\langle H\rangle\langle\bar{q}_L q_R\rangle\cos\left(\frac{\phi}{f}\right)$$

Insensitivity to Initial Conditions

- $\langle H \rangle$ sensitive to ϕ's approach to $m_H^2 = 0$
  - ϕ must stop with $(-M^2 + g_R \phi)/M^2 \ll 1$
  - $\Lambda^4(H) = f_\pi^2 m_\pi^2 \rightarrow$ relaxion must be moving slowly



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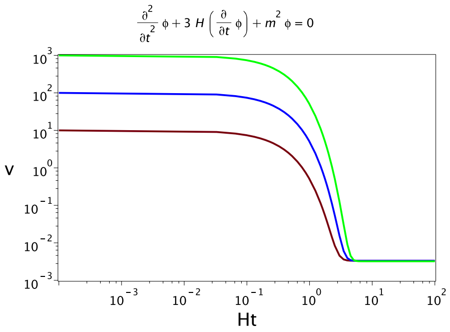
  - $\Lambda^4(H) = f_\pi^2 m_\pi^2 \to$ relaxion must be moving slowly
- Hubble friction makes approach to $m_H^2 = 0$ similar
  - $\dot{\phi} \simeq v_{term}$ (Independent of IC)
  - Slow $v_{term} \to (-M^2 + g_R\phi)/M^2 \ll 1 \qquad (\phi \sim M^2/g_R)$



Strong CP Problem

- Instanton potential stops relaxion

$$\frac{\partial V}{\partial \phi} = g^2\phi + \frac{m_\pi^2(\langle H\rangle)f_\pi^2}{f}\sin\left(\frac{\phi}{f}\right) + .. \sim 0$$

- Relaxion stopping point

$$\sin\left(\frac{\phi}{f}\right) \sim 1 \qquad \rightarrow \qquad \theta_{QCD} = \frac{\phi}{f} \sim 1$$

- Neutron EDM constraints

$$\theta_{QCD} \lesssim 10^{-11}$$

Relaxion Constraints

- Inflation dominates vacuum energy
  - Inflation unaffected by relaxion

$$V_{inf} > V_{rel} \quad \rightarrow \quad H_I > \frac{M^2}{M_P}$$

- Relaxion classical rolls ($\dot{\phi}\Delta t > H$)

$$\boxed{H_I < (gM^2)^{1/3} \simeq \left(\frac{m_\pi^2 f_\pi^2}{f}\right)^{1/3} = 6 \times 10^{-5} \left(\frac{10^9\ \mathrm{GeV}}{f}\right)^{1/3}}$$

- Upper bound on allowed radiative corrections to $m_H^2 \ll M_P^2$
  - $\theta_{QCD} \sim 1$

$$M < \left(\frac{m_\pi^2 f_\pi^2 M_P^3}{f}\right)^{1/6} \sim 10^7 \mathrm{GeV} \left(\frac{10^9\ \mathrm{GeV}}{f}\right)^{1/6}$$

The Numbers

- Shift symmetry breaking parameter

$$g \sim \frac{m_\pi^2 f_\pi^2}{M^2 f} = 10^{-27}\ \mathrm{GeV} \left(\frac{10^7\ \mathrm{GeV}}{M}\right)^2 \left(\frac{10^9\ \mathrm{GeV}}{f}\right)$$

- Super-Planckian relaxion excursion

$$\phi \sim \frac{M^2}{g} = \frac{M^4 f}{m_\pi^2 f_\pi^2} \sim 10^{41}\ \mathrm{GeV} \left(\frac{M}{10^7\ \mathrm{GeV}}\right)^4 \left(\frac{f}{10^9\ \mathrm{GeV}}\right)$$

- Many e-folds of inflation

$$N \gtrsim \frac{H^2}{g^2} \gtrsim \frac{M^4}{g^2 M_P^2} = \frac{M^8 f^2}{m_\pi^4 f_\pi^4 M_P^2} \sim 10^{44} \left(\frac{M}{10^7\ \mathrm{GeV}}\right)^8 \left(\frac{f}{10^9\ \mathrm{GeV}}\right)^2$$

Non-QCD Axion Model

- $\theta \sim 1$ non problem for other $SU(N)_R$

	$SU(N)_R$	$SU(2)_W$	$U(1)_Y$
N	N	1	1
N^c	$\bar{N}$	1	1
L	N	2	1
L^c	$\bar{N}$	2	-1

- Couple additional fields to Higgs

$$\mathcal{L} \supset m_L L L^c + m_N N N^c + y h L N^c + \tilde{y} h^\dagger L^c N + \frac{\phi}{32\pi^2 f} \tilde{G}'^{\mu\nu} G'_{\mu\nu}$$

- Relaxion effective theory

$$V_{stop} = \left(m_N + \frac{\tilde{y} y}{m_L} |h|^2 \right) \langle N N^c \rangle \cos\left(\frac{\phi}{f}\right)$$

- Higgs vev must be able to stop relaxion
  - Coincidence of scales

$$f_{\pi'} < \langle h \rangle \qquad f_{\pi'} \gtrsim \frac{y \tilde{y}}{16\pi^2} \langle h \rangle$$

Two-Field Relaxion Mechanism

- Add additional shift symmetric particle

$$\phi \to \phi + \alpha f_\phi \qquad \sigma \to \sigma + \beta f_\sigma$$

- Shift symmetry broken by mass and couplings
  - $m_{\phi,\sigma}$ lead to field evolution
  - $g_{\phi,\sigma}$ cancels radiative corrections

$$V = \frac{1}{2}|m_\phi|^2\phi^2 + \frac{1}{2}|m_\sigma|^2\sigma^2 + \left(m_N - g_\phi\phi - g_\sigma\sigma + \frac{\lambda|H|^2}{M_L}\right)\langle NN^c\rangle \cos\left(\frac{\phi}{f_\phi}\right)$$

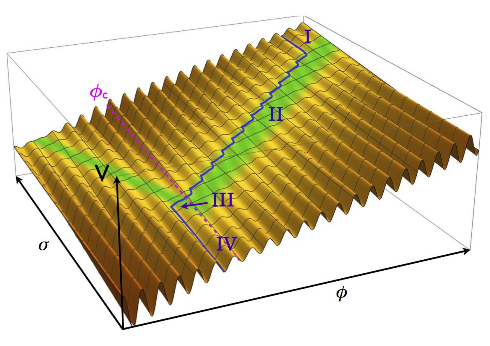
- Correction to stopping potential canceled by amplitudon
  - Cancellation allows ϕ to roll until EWSB
  - Cancellation realized dynamically

$$g_\sigma\sigma \sim m_N - g_\phi\phi$$

Phase I: σ Rolls

- I. σ rolls ϕ is stuck

$$V = \frac{1}{2}|m_\phi|^2\phi^2 + \frac{1}{2}|m_\sigma|^2\sigma^2 + \boxed{\left(m_N - g_\phi\phi - g_\sigma\sigma + \frac{\lambda}{M_L}|H|^2\right)} \langle NN^c\rangle \cos\left(\frac{\phi}{f_\phi}\right)$$



- ϕ trapped

$$|m_S|^2\phi \ll \frac{\Lambda_N^3}{f_\phi}\boxed{|\mathcal{A}(\phi,\sigma,0)|}$$

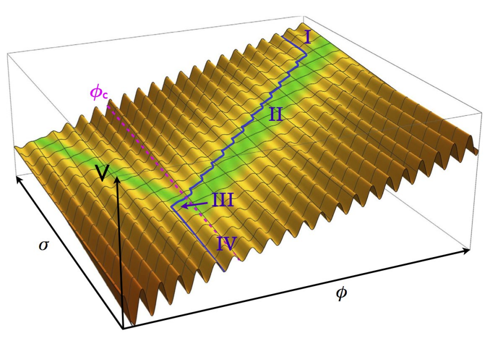
- σ slow rolls

$$\frac{\partial V_{\phi,\sigma}}{\partial\sigma} \simeq |m_\sigma|^2\sigma$$

Phases II: ϕ and σ Track Each Other

- $\boxed{\text{II. } \phi \text{ tracks } \sigma \ (\mathcal{A} \simeq 0)}$

$$V = \frac{1}{2}|m_\phi|^2\phi^2 + \frac{1}{2}|m_\sigma|^2\sigma^2 + \boxed{\left(m_N - g_\phi\phi - g_\sigma\sigma + \frac{\lambda}{M_L}|H|^2\right)} \langle NN^c \rangle \cos\left(\frac{\phi}{f_\phi}\right)$$



- ϕ rolls

$$|m_\phi|^2\phi \gtrsim \frac{\Lambda_N^3}{f_\phi} \boxed{|\mathcal{A}(\phi, \sigma, 0)|}$$

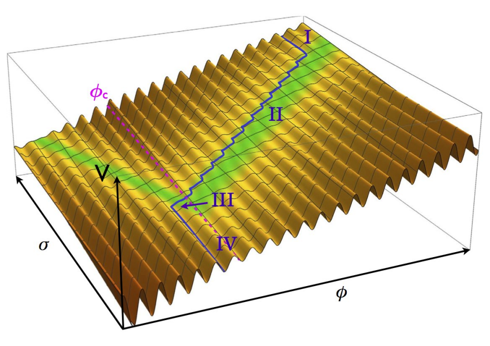
- ϕ tracks σ

$$\frac{g_S}{\sqrt{2}}\frac{d\phi}{dt} < -\frac{g_T}{\sqrt{2}}\frac{d\sigma}{dt}$$

Phases III, IV: EWSB $\to \phi$ Trapped

- III. Higgs mass becomes negative
- IV. ϕ is trapped

$$V = \frac{1}{2}|m_\phi|^2\phi^2 + \frac{1}{2}|m_\sigma|^2\sigma^2 + \underbrace{\left(m_N - g_\phi\phi - g_\sigma\sigma + \frac{\lambda}{M_L}|H|^2\right)}_{A}\langle NN^c\rangle \cos\left(\frac{\phi}{f_\phi}\right)$$



- A grows with v

$$\frac{\partial A}{\partial t} \simeq \frac{\partial A}{\partial v}\frac{\partial v}{\partial t} > 0$$

- ϕ trapped again

$$|m_\phi|^2\phi \ll \frac{\Lambda_N^3}{f_\phi}|\mathcal{A}(\phi, \sigma, v)|$$

Supersymmetric Two-Field Relaxation

- Shift symmetric Kähler potential
  - $\mathrm{Im}(S, T)$ have shift symmetry

$$K \supset (S + S^\dagger)^2 + (T + T^\dagger)^2 \ldots$$

- Rolling/stopping from shift symmetry breaking in superpotential

$$W = \boxed{\frac{m_S}{2} S^2 + \frac{m_T}{2} T^2} + \boxed{\left(m_N + i g_S S + i g_T T + \frac{\lambda}{M_L} H_u H_d \right)} N\overline{N}$$

- SUSY breaking generates relaxion dependent Higgs soft masses

$$F_S = i m_S \phi \qquad \rightarrow \qquad \int d^4\theta \frac{(S + S^\dagger)^2}{M^{*2}} |H_{u,d}|^2 = \frac{m^2 \phi^2}{M^{*2}} |H_{u,d}|^2$$

- Instanton potential from gauge kinetic function (Axion)

$$\frac{\phi}{32\pi f_\phi} G^{a\mu\nu} G^a_{\mu\nu} \qquad \rightarrow \qquad \int d\theta^2 c_a \frac{S}{16\pi^2 f_\phi} \mathrm{Tr}(\mathcal{W}_a \mathcal{W}_a) + \mathrm{h.c.}$$

Higgs Mass of SUSY Relaxion

- Generic Kähler generates relaxion dependent Higgs mass matrix

$$K \supset Z\left(S + S^\dagger\right)\left[|H_u|^2 + |H_d|^2\right] + C(S + S^\dagger)H_u H_d + h.c.$$

- Relaxion dependent Higgs sector parameters

$$m^2_{H_{u,d}} = c_{u,d}\frac{m^2\phi^2}{f^2} \qquad \mu = \mu_0 - c_\mu \frac{m\phi}{f} \qquad B_\mu = c_0\mu\frac{m\phi}{f} + c_B\frac{m^2\phi^2}{f^2}$$

- $\mathrm{Det}(M_H^2) < 0$ signifies EWSB

$$\mathrm{Det}(M_H^2) = \left(m^2_{H_u} + |\mu|^2\right)\left(m^2_{H_d} + |\mu|^2\right) - |B_\mu|^2$$

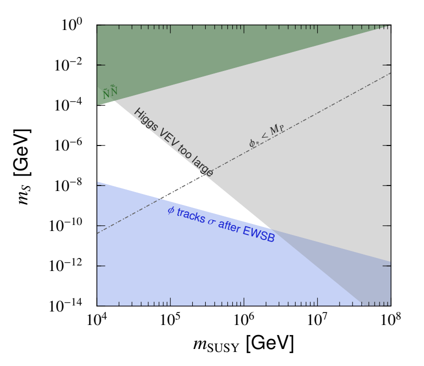
- $m\phi/f \gg \mu_0 \rightarrow \mathrm{Det}(M_H^2) > 0$

$$\left(c_u + |c_\mu|^2\right)\left(c_d + |c_\mu|^2\right) - |c_B|^2 > 0$$

- $\mathrm{Det}(M_H^2) < 0$ EWSB occurs
  - for $\mu \simeq 0$ and $c_u c_d < c_B^2$

Constraint Summary

- $\zeta = 10^{-8} \quad r_{TS} = 0.1 \quad r_\Lambda = 1 \quad r_{\mathrm{SUSY}} = 1.$



- Parameters

$$g_S = \zeta \frac{m_S}{f_\phi} \quad g_T = \zeta \frac{m_T}{f_\sigma}$$

$$f \equiv f_\phi = f_\sigma \quad r_{TS} \equiv \frac{m_T}{m_S}$$

$$r_\Lambda \equiv \frac{\Lambda_N}{f} \quad r_{\mathrm{SUSY}} \equiv \frac{m_{\mathrm{SUSY}}}{f}$$

$$M_L = m_{\mathrm{SUSY}} \ ,$$

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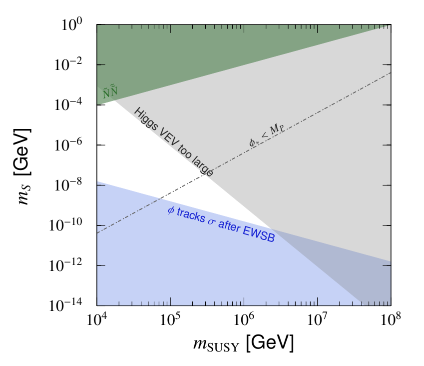


- Barrier too small to stop ϕ

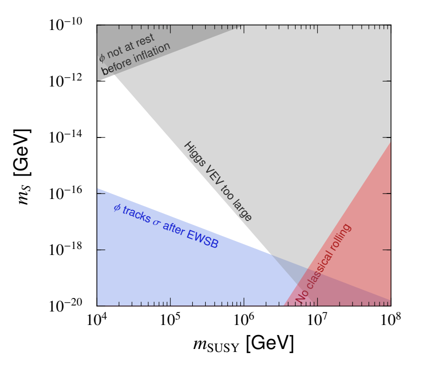
$$V' = \frac{m^2}{2}\phi + \frac{\lambda v^2 \sin(2\beta)}{4M_L}\frac{\Lambda_N^3}{f} \neq 0$$

- $\mathcal{A}$ changes too slowly with v

$$\frac{\partial \mathcal{A}}{\partial t} \simeq \frac{\partial \mathcal{A}}{\partial v}\frac{\partial v}{\partial t}$$

Constraint Summary

- $\zeta = 10^{-8} \quad r_{TS} = 0.1 \quad r_\Lambda = 10^{-4} \quad r_{\text{SUSY}} = 10^{-4}.$



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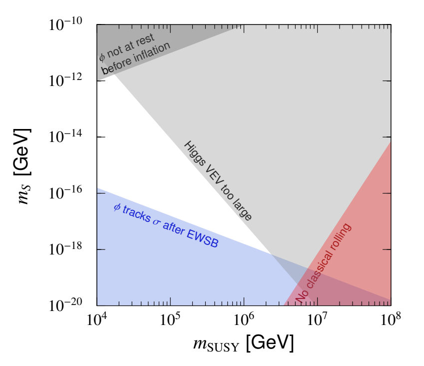

- Quantum spread of σ

$$\frac{\dot{\sigma}}{H_I} > H_I$$

Constraint Summary

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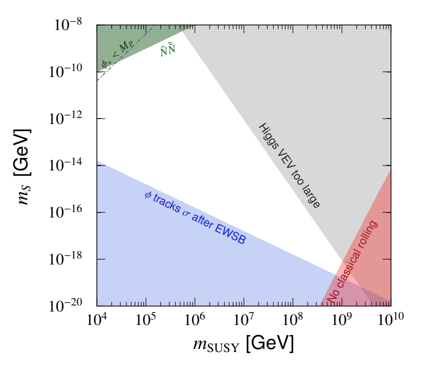

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$$f \equiv f_\phi = f_\sigma \quad r_{TS} \equiv \frac{m_T}{m_S}$$

$$r_\Lambda \equiv \frac{\Lambda_N}{f} \quad r_{\mathrm{SUSY}} \equiv \frac{m_{\mathrm{SUSY}}}{f}$$

$$M_L = m_{\mathrm{SUSY}} \ ,$$

The Numbers

- Shift symmetry breaking parameter

$$m \simeq \frac{v^4}{f^2 m_{SUSY}} \sim 3 \times 10^{-6}\ \mathrm{GeV} \left(\frac{10^5\ \mathrm{GeV}}{m_{SUSY}}\right)^2 \left(\frac{10^5\ \mathrm{GeV}}{f}\right)$$

- Sub-Planckian relaxion excursion

$$\Delta\phi > \phi_* \sim 10^{17}\ \mathrm{GeV} \times \left(\frac{m_{\mathrm{SUSY}}}{10^5\ \mathrm{GeV}}\right) \left(\frac{f_\phi}{10^5\ \mathrm{GeV}}\right) \left(\frac{10^{-5}\ \mathrm{GeV}}{m_S}\right)$$

- Many e-folds of inflation

$$N_e \simeq \frac{H_I \Delta\phi}{\left|\frac{d\phi}{dt}\right|} \gtrsim \frac{H_I^2}{|m_S|^2} = 10^{12} \times \left(\frac{H_I}{100\ \mathrm{GeV}}\right)^2 \left(\frac{10^{-4}\ \mathrm{GeV}}{|m_S|}\right)^2$$

- Inflation scale still very low

$$\boxed{H_I < (m m_{SUSY} f_\phi)^{1/3} \simeq v \left(\frac{v}{f_\phi}\right)^{1/3} = 33\ \mathrm{GeV} \left(\frac{10^9\ \mathrm{GeV}}{f}\right)^{1/3}}$$

Low-Scale Inflation

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V_\phi}{V}\right)^2 \qquad \eta = M_P^2 \frac{V_{\phi\phi}}{V}.$$

- Difficulties of low scale inflation

$$\epsilon = 8.6 \times 10^{-31}\left(\frac{H}{1\ \mathrm{GeV}}\right)^2$$

- For low-scale inflation we know η

$$n_s - 1 = 2\eta - 6\epsilon \simeq 2\eta \simeq -0.03 \qquad \eta \simeq -1.5 \times 10^{-2}$$

- D-term inflation can realize these unusual parameters
  - Small ϵ realized through small gauge coupling
  - $g \ll 1$ is technically natural

Slow-Roll Parameters and Low-Scale Inflation

- Power Spectrum Determines first derivative of potential

$$A_{\mathcal{R}} = \frac{1}{8\pi^2}\frac{H^2}{M_P^2\epsilon} \quad \rightarrow \quad \left.\frac{dV(\tau)}{d\tau}\right|_{CMB} = \frac{3}{2\pi}\frac{1}{A_{\mathcal{R}}^{1/2}}H^3$$

- Spectral index determines second derivative of potential

$$n_s - 1 \simeq 2\eta \quad \rightarrow \quad \left.\frac{d^2V(\tau)}{d\tau^2}\right|_{CMB} = -\frac{3}{2}(1-n_s)H^2$$

- Number of e-folds determines field value

$$N_{CMB} \simeq \int \frac{d\tau}{M_P\sqrt{2\epsilon}} \quad \rightarrow \quad \Delta\tau = \frac{N_{CMB}}{A_{\mathcal{R}}^{1/2}}H$$

- $\eta = 1$ end inflation gives second derivative

$$\left.\frac{d^2V(\tau)}{d\tau^2}\right|_0 = 3H^2$$

Generalities of Low-Scale Inflation

- Energy of Low scale inflation much larger than slopes

$$V^{1/4} \sim H^{1/2} M_P^{1/2} \qquad \left(-\frac{d^2 V(\tau)}{d\tau^2}\right)^{1/2} \sim \left(\frac{dV(\tau)}{d\tau}\right)^{1/3} = H$$

- Potential derivatives give estimate of field movement
  - Some possible exceptions (See Ryuji Daido Poster)

$$\left.\frac{d^2 V(\tau)}{d\tau^2}\right|_0 (\Delta\tau)^2 = 3H^2 M_P^2 \qquad \rightarrow \qquad \Delta\tau = M_P$$

- Inflaton mass not expected change Hugely
  - Model below get a factor of 100 larger

$$m_\tau \sim H$$

- Mass of “inflaton" much smaller than vev

Reheating After Inflation

- Generic couplings to τ must be small (kinematically forbidden)

$$-\mathcal{L} \supset |\lambda|^2 |\tau|^2 |\varphi|^2 + \lambda \tau \bar{\psi} \psi \qquad \rightarrow \qquad \lambda \ll 1$$

- Generic reheat temperature quite small

$$\Gamma \sim \frac{|\lambda|^2}{8\pi} m_\tau \qquad \rightarrow \qquad T_r \sim 0.4 \text{ MeV} \left(\frac{H_I}{1 \text{ GeV}} \right)^{3/2} \left(\frac{\lambda}{10^{-13}} \right)$$

- Inflaton needs to be neutral to keep potential flat
  - Must couple to gauge singlet

$$\mathcal{L} \supset \frac{\tau}{M_P} H \bar{Q} u \quad \rightarrow \quad \Gamma \sim \frac{m_\tau^3}{M_P^2} \quad \rightarrow \quad T_r \sim m_\tau \left(\frac{m_\tau}{M_P} \right)^{1/2}$$

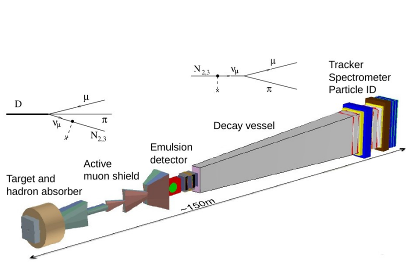
- Higgs portal offers renormalizable operators

$$\mathcal{L} \supset \lambda \left(|\tau|^2 - \tau_0^2 \right) |H|^2$$

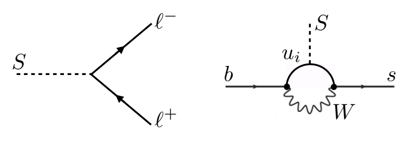
Detection: Ship Experiment

- SHiP is a beam Dump experiment
  - 400 GeV/c proton beam incident on target
  - Center of mass energy of 27 GeV
- Detector displaced from collisions
  - Only long-lived particles decay in detector
- Meson production: B,K
  - More kaons but screened so less important

$$N_K = 8 \times 10^{17} \qquad N_B = 7 \times 10^{13}$$



Higgs Portal Detection at SHiP



- Couple “inflaton”, $\tau = S$, to SM gauge singlet operator

$$V \supset \lambda\left(|\tau|^2 - \tau_0^2\right)|H|^2 \quad \rightarrow \quad \tan(2\theta) = \frac{\lambda \tau_0 v}{|m_h^2 - m_\phi^2|}$$

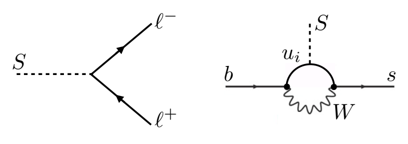
- “Inflaton” low-energy couplings proportional to Higgs couplings

$$V \supset g_\star \frac{m_f}{v}\tau \bar{f} f \qquad\qquad g_\star = \sin\theta$$

- “Inflaton” produced from B meson decays

$$L \supset \boxed{\frac{3\sqrt{2}G_F m_t^2 V_{ts}^* V_{tb}}{16\pi^2}\frac{m_b}{v} g_\star}\,\tau \bar{s}_L b_R + \text{h.c.} \quad \rightarrow \quad \Gamma(B \rightarrow X_s + \tau) = \frac{1}{8\pi}\frac{(m_b^2 - m_\tau^2)^2}{m_b^3}\left|\boxed{h_{\tau b}}\right|^2$$

Higgs Portal Detection at SHiP



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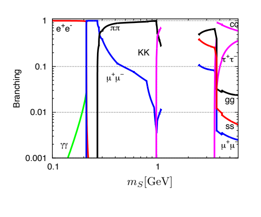
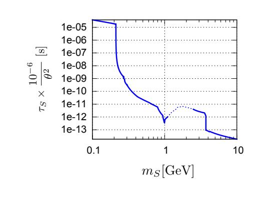
Decays of Inflaton

- Inflaton decay width proportional to Higgs

$$\Gamma_\tau(m_\tau) = g_\star^2 \Gamma_h(m_\tau)$$





SHiP Collaboration

Decays of Inflaton

- Inflaton decay modes proportional to Higgs

$$\Gamma_\tau(m_\tau) = g_\star^2 \Gamma_h(m_\tau)$$

- Inflaton lifetime can be quite long

$$\Gamma(\tau \to \ell\bar{\ell}) = \frac{g_\star^2\, m_\ell^2 m_\tau}{8\pi v^2}\left(1 - \frac{4m_\ell^2}{m_\tau^2}\right)^{3/2} \qquad c\tau_\tau \simeq 50\,\mathrm{m}\times \begin{cases} \left(\frac{0.02}{g_\star}\right)^2 \left(\frac{50\,\mathrm{MeV}}{m_\tau}\right) \\ \left(\frac{5\times 10^{-5}}{g_\star}\right)^2 \left(\frac{250\,\mathrm{MeV}}{m_\tau}\right) \end{cases}$$

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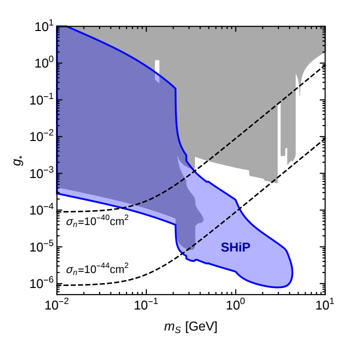
- Number of decays in detector from lifetime

$$N_{\mathrm{det}} \sim BR(B \to X_s + \tau) N_B \left[\exp\left(-\frac{l}{\gamma\,\beta\,c\,\tau_\tau}\right) - \exp\left(-\frac{l+\Delta l}{\gamma\,\beta\,c\,\tau_\tau}\right)\right]$$

Constraints on Higgs Portal

- SHiP can detect light inflaton with small mixing



SHiP Collaboration

D-term Inflation

- D-term with FI term

$$V_D = \frac{g^2}{2}\left[|\phi_+| - |\phi_-| - \xi\right]^2$$

- Inflaton couples directly to $U(1)$ charged particles

$$W = \kappa T \phi_+ \phi_-$$

- $\langle \phi_\pm \rangle = 0$ during inflation

$$|\kappa T| > \sqrt{g^2 \xi}$$

- Potential perfectly flat at tree level

$$V_D = \frac{g^2}{2}\xi^2$$

Coleman-Weinberg Potential

- During inflation $\phi_\pm$ massive
  - integrating $\phi_\pm$ generates potential for T
- Potential to one-loop for $|\kappa T| > \sqrt{g^2 \xi}$

$$V = \frac{g^2 \xi^2}{2} \left(1 + \frac{g^2}{8\pi^2} \ln \left[\frac{|\kappa T|^2}{Q^2} \right] \right)$$

- Slow roll parameters

$$\boxed{\epsilon = \frac{g^2}{16\pi^2} \frac{1}{N_{CMB}}} \qquad \eta = -\frac{1}{2N_{CMB}}$$

- Number of e-folds possible for $\sigma_0 = M_P$

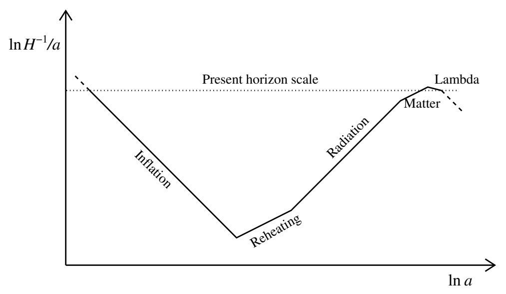
$$N_{max} = \frac{2\pi}{g^2} = 3.8 \times 10^{27} \left(\frac{1 \text{ GeV}}{H_I} \right)^2$$

- For small g, ϵ small enough

$$A_{\mathcal{R}}^{1/2} = 5 \times 10^{-5} \left(\frac{N_{CMB}}{40} \right) \left(\frac{H_I}{10^7 \text{ GeV}} \right) \boxed{\left(\frac{7.3 \times 10^{-7}}{g} \right)}$$

N_{CMB} and the History of the Universe

- N_{CMB} depends on expansion of universe after inflation
  - Lower $\rho_{reh} \rightarrow$ decrease radiation domination
  - Slower expansion during RD less e-folds needed



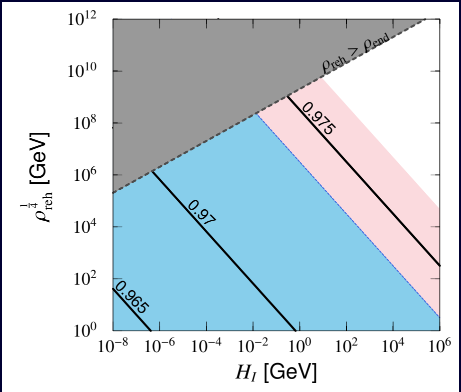
Liddle, Leach

- Instantaneous reheat/low-scale inflation

$$N_{CMB} = 35 + \frac{1}{3}\ln\left(\frac{H_I}{1\ \mathrm{GeV}}\right) + \frac{1}{3}\ln\left(\frac{\rho_{reh}^{1/4}}{100\ \mathrm{GeV}}\right)$$

The Spectral Tilt

- Reduced N_{CMB} puts n_s in $1-\sigma$ lines



- Spectral tilt

$$n_s - 1 = 2\eta = -0.026\left(\frac{39}{N_{CMB}}\right)$$

- Number of e-folds

$$N_{CMB} = 35 + \frac{1}{3}\ln\left(\frac{H_I}{1\ \mathrm{GeV}}\right) + \frac{1}{3}\ln\left(\frac{\rho_{reh}^{1/4}}{100\ \mathrm{GeV}}\right)$$

Reheating After Inflation

- Couple ϕ_+ through dynamical sector to flat direction

$$\Delta W = \kappa_1 R M_- \phi_+ + \kappa_2 R H_u H_d + m_R R \bar{R}$$

- $V \supset |F_R|$, gives trilinear couplings for inflaton
  - $\bar{R}$ will cancel any vev of ϕ_+ keeping everything light

$$\Delta V \supset |\kappa_1 M_- \phi_+ + \kappa_2 H_u H_d + m_R \bar{R}|^2$$

- Reheat temperature can be large
  - If reheat temperature low, Higgs portal relevant

$$T_R = 153 \text{ GeV} \times \left(\frac{106.75}{g_\rho}\right)^{1/4} \left(\frac{\langle M_- \rangle}{10^{16} \text{ GeV}}\right) \left(\frac{10^3 \text{ GeV}}{m_{\phi_+}}\right)^{1/2} \left(\frac{\kappa_1}{10^{-13}}\right) \left(\frac{\kappa_2}{10^{-7}}\right)$$

Conclusions

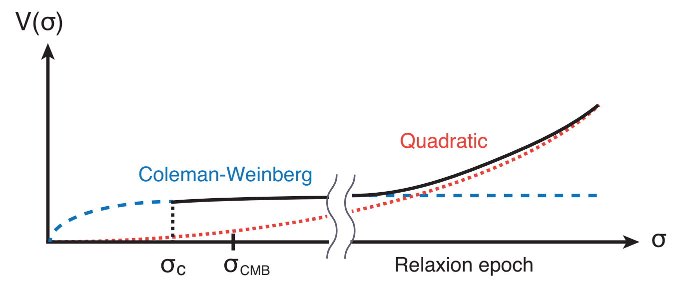
- Many of the nice features of SUSY are now complicated
  - Fine tuning is reemerging
  - Well-tempered neutralinos are all but gone
- Gauge coupling unification is till alive and kicking
  - Need pertubative/sequestered solution to naturalness
- Cosmological relaxation $\rightarrow$ natural supersymmetry
  - Does not necessarily affect unification
- Natural relaxation needs natural low-scale inflation
- Slow-roll parameters give generic features of inflaton
  - Inflaton of low-scale inflation is light
  - Some field will have large vev
- Low-scale inflation can be seen in low energy experiments
  - D-term inflation gives a viable low-scale model

Inflaton as the Second Field

- The inflaton can play the roll of the amplitudon ($T = \tau + i\sigma$)

$$W_{S,T} = \frac{m_S}{2} S^2 + \frac{m_T}{2} \boxed{T}^2 \qquad W_{inf} = \kappa \boxed{T} \phi_+ \phi_-$$

- D-term and relaxion have very different energies

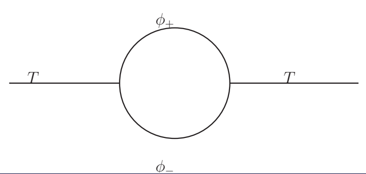


Shift Symmetry Breaking of Inflaton Sector

- Inflaton has relatively large shift symmetry breaking

$$W = \kappa T \phi_+ \phi_- \qquad \kappa \gtrsim 10^{-2}$$

- Loop correction transmit shift symmetry breaking to Kähler



$$K \supset \frac{|\kappa|^2}{16\pi^2}|T|^2$$

- SUGRA corrections to scalar potential generate mass for T

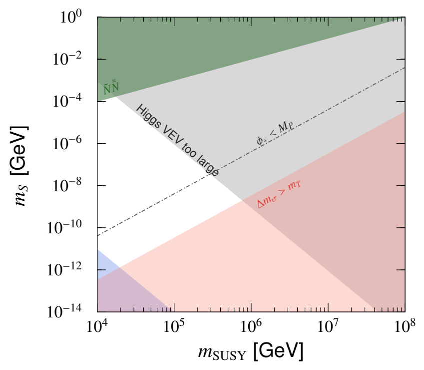
$$V \supset e^{\frac{K}{M_P}}|F_S|^2 + \ldots \qquad \rightarrow \qquad V \supset \frac{|\kappa|^2}{16\pi^2}\frac{|F_S|^2}{M_P^2}|T|^2$$

- Kähler corrections give lower bound on m_T

$$m_T \gtrsim \frac{\kappa}{4\pi}\frac{|F_S|}{M_P} = \frac{\kappa}{4\pi}\frac{m_{SUSY} f}{M_P}$$

Constraint Summary

- $\zeta = 10^{-8} \quad r_{TS} = 0.1 \quad r_\Lambda = 1 \quad r_{\mathrm{SUSY}} = 1.$



- Parameters

$$g_S = \zeta \frac{m_S}{f_\phi} \quad g_T = \zeta \frac{m_T}{f_\sigma}$$

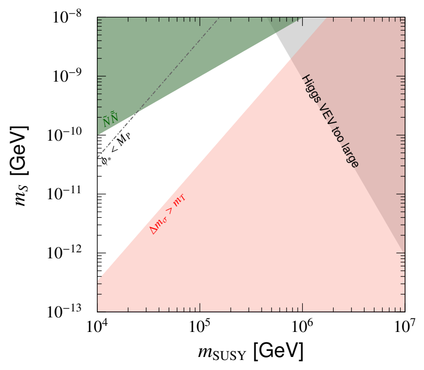
$$f \equiv f_\phi = f_\sigma \quad r_{TS} \equiv \frac{m_T}{m_S}$$

$$r_\Lambda \equiv \frac{\Lambda_N}{f} \quad r_{\mathrm{SUSY}} \equiv \frac{m_{\mathrm{SUSY}}}{f}$$

$$M_L = m_{\mathrm{SUSY}} \ ,$$

Constraint Summary

- $\zeta = 10^{-14} \quad r_{TS} = 0.1 \quad r_\Lambda = 1 \quad r_{\rm SUSY} = 1.$



- Parameters

$$g_S = \zeta \frac{m_S}{f_\phi} \qquad g_T = \zeta \frac{m_T}{f_\sigma}$$

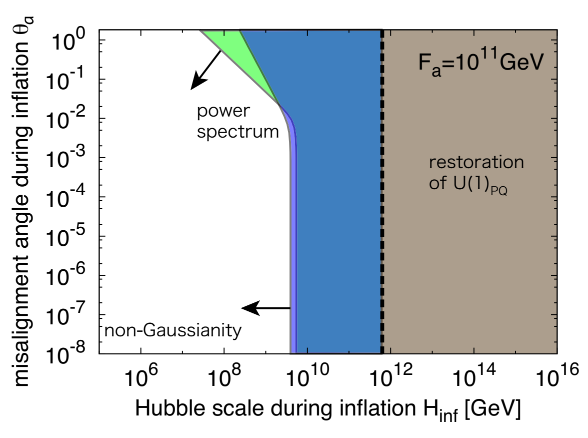
$$f \equiv f_\phi = f_\sigma \qquad r_{TS} \equiv \frac{m_T}{m_S}$$

$$r_\Lambda \equiv \frac{\Lambda_N}{f} \qquad r_{\rm SUSY} \equiv \frac{m_{\rm SUSY}}{f}$$

$$M_L = m_{\rm SUSY} \, ,$$

Axion Parameter Space

- PQ breaking before inflation with $F_a = 10^{11}$ GeV



String Formation: Two Sectors of U(1) Breaking

- Hidden sector breaking of U(1)

$$V = \frac{g^2}{2}\left(|\phi_+|^2 - \xi\right)^2 + |\lambda T|^2|\phi_+|^2 + C\phi_+ + C^\dagger\phi_+^\dagger \quad \supset \quad |C|v_+\cos(\theta + \theta_c)$$

- Superpotential connects phase of two sectors

$$V_F \supset |\lambda T\phi_+ + \lambda_- TM_-|^2 \quad \supset \quad \lambda\lambda_+|T|^2 M_- v_+ \cos(\theta)$$

- Quantum fluctuations could still form strings ($\phi_+ = v_r e^{i\alpha}$)

$$\langle\alpha^2\rangle = \frac{H^3}{12\pi^2 m v_r^2} < 1$$

- Quantum fluctuation at end of inflation

$$H_I < 1 \times 10^9\ \mathrm{TeV} \times \left(\frac{|\kappa_+|}{10^{-12}}\right)\left(\frac{|M_+|}{10^{16}\ \mathrm{GeV}}\right)\left(\frac{\kappa}{10^{-2}}\right)^{-\frac{1}{2}}\left(\frac{A_s}{2.1\times 10^{-9}}\right)^{-\frac{1}{4}}\left(\frac{1-n_s}{0.03}\right)^{-\frac{1}{2}}.$$

Why Dynamical D-Terms

- Field independent FI terms hard to realize in SUGRA
- Field dependent gravity generated FI tend to be large

$$\sqrt{\xi} \sim \langle \phi_\xi \rangle \sim M_P$$

- Dynamically generated FI terms
  - Dynamical scale can be arbitrary

$$\sqrt{\xi} \sim \langle \phi_\xi \rangle \sim \Lambda$$

- Dynamical D-terms provide U(1) breaking during inflation