Inflation in the B-L MSSM

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Sep. 8th 2016

based on arXiv:1606.00431 - R.D., Ovrut, Purves

University of Pennsylvania

Motivation

Good inflation model should:

- Solve standard cosmological problems (e.g. flatness, horizon, monopole)
- Solve initial conditions problem
- Satisfy observational constraints ($n_s \sim 0.96$-0.97, $r < 0.1$)
- Have a direct connection to the Standard Model and particle physics

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- Higgs inflation: Bezrukov and Shaposhnikov, arXiv: 0710.3755

- SUSY version:

  - Einhorn and Jones: arXiv:0912.2718

  - Ferrara et al. : arXiv:1004.0712

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Above needs:

- Non-minimal coupling to R
- NMSSM = MSSM + gauge singlet

Content of the B-L MSSM

$$SU(3)_C \times SU(2)_L \times U(1)_{3R} \times U(1)_{B-L}$$

$$\left.\begin{array}{l} Q \sim (\mathbf{3}, \mathbf{2}, 0, 1/3) \quad u^c \sim (\bar{\mathbf{3}}, \mathbf{1}, -1/2, -1/3) \\ \qquad d^c \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/2, -1/3) \\ L \sim (\mathbf{1}, \mathbf{2}, 0, -1) \qquad e^c \sim (\mathbf{1}, \mathbf{1}, 1/2, 1) \\ \qquad \nu^c \sim (\mathbf{1}, \mathbf{1}, -1/2, 1) \end{array}\right\} \times 3$$

$$H_u \sim (\mathbf{1}, \mathbf{2}, 1/2, 0) \qquad H_d \sim (\mathbf{1}, \mathbf{2}, -1/2, 0)$$

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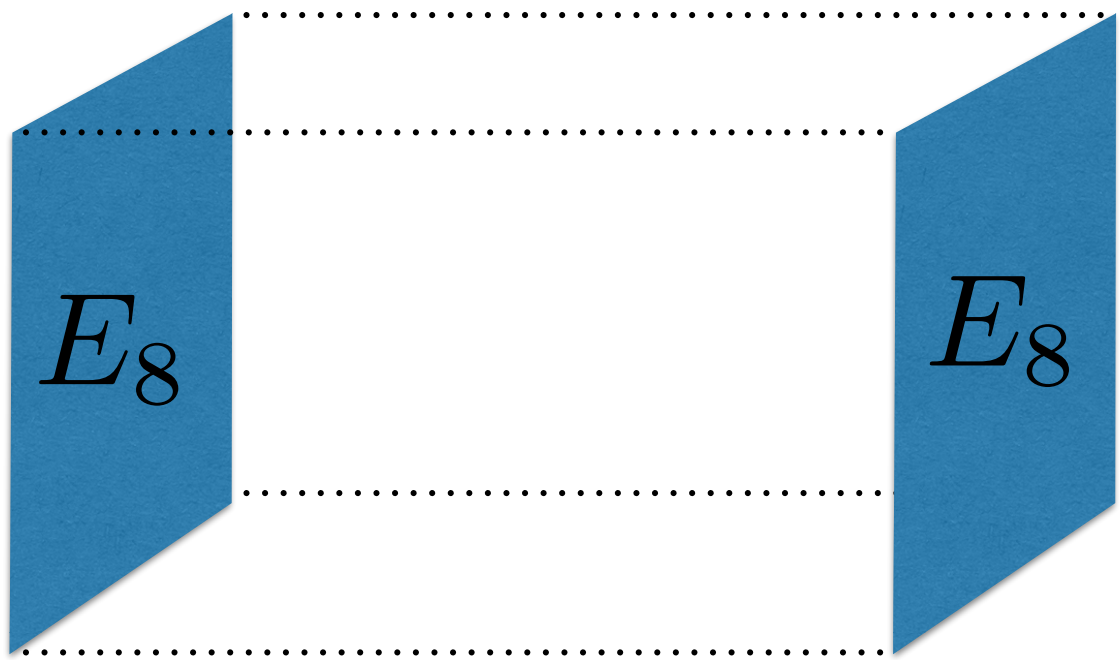
Heterotic M-theory

c.f. Lukas, Ovrut, Waldram arXiv:9710208



Visible sector Hidden sector

R_9

Heterotic M-theory

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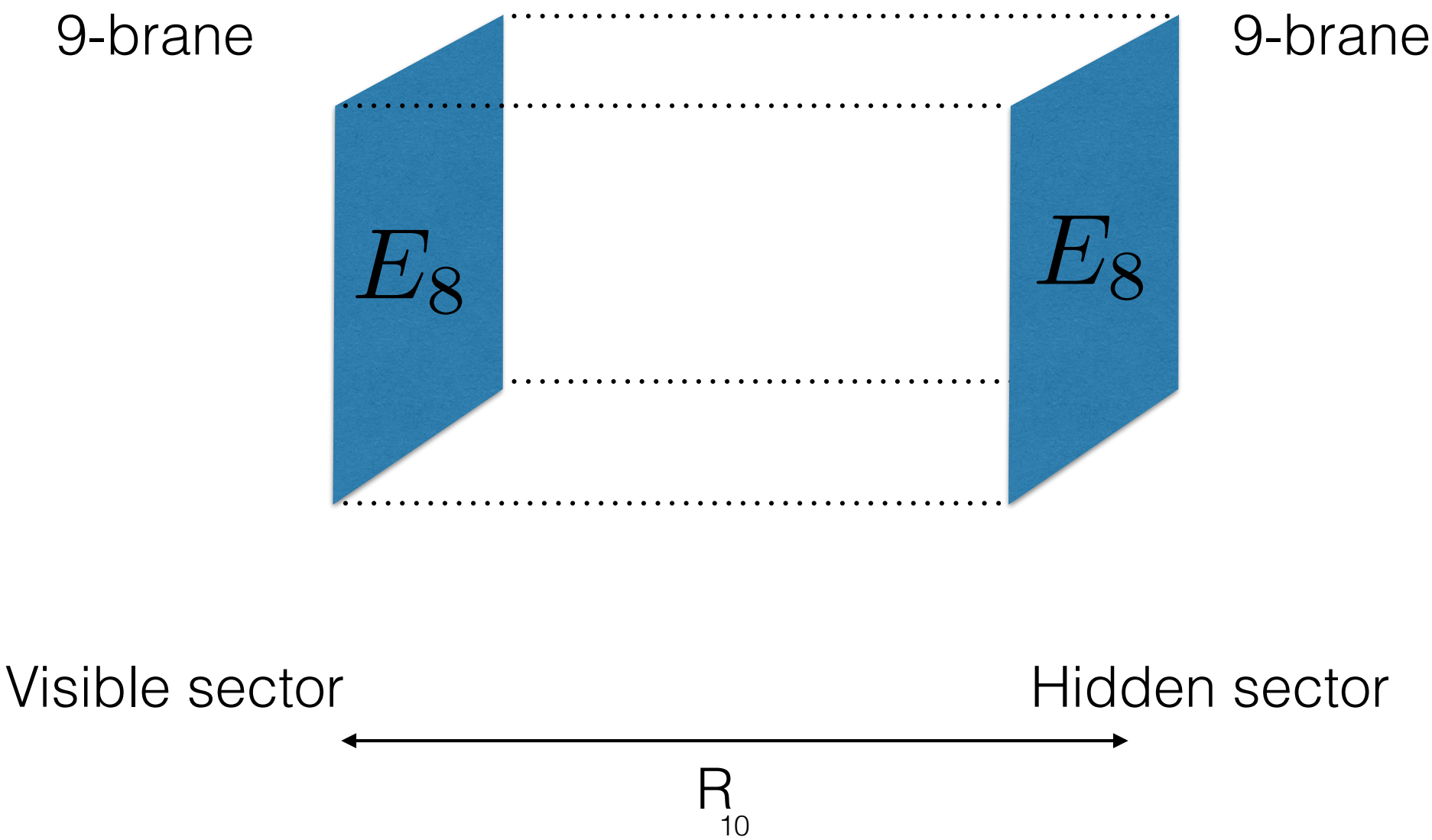

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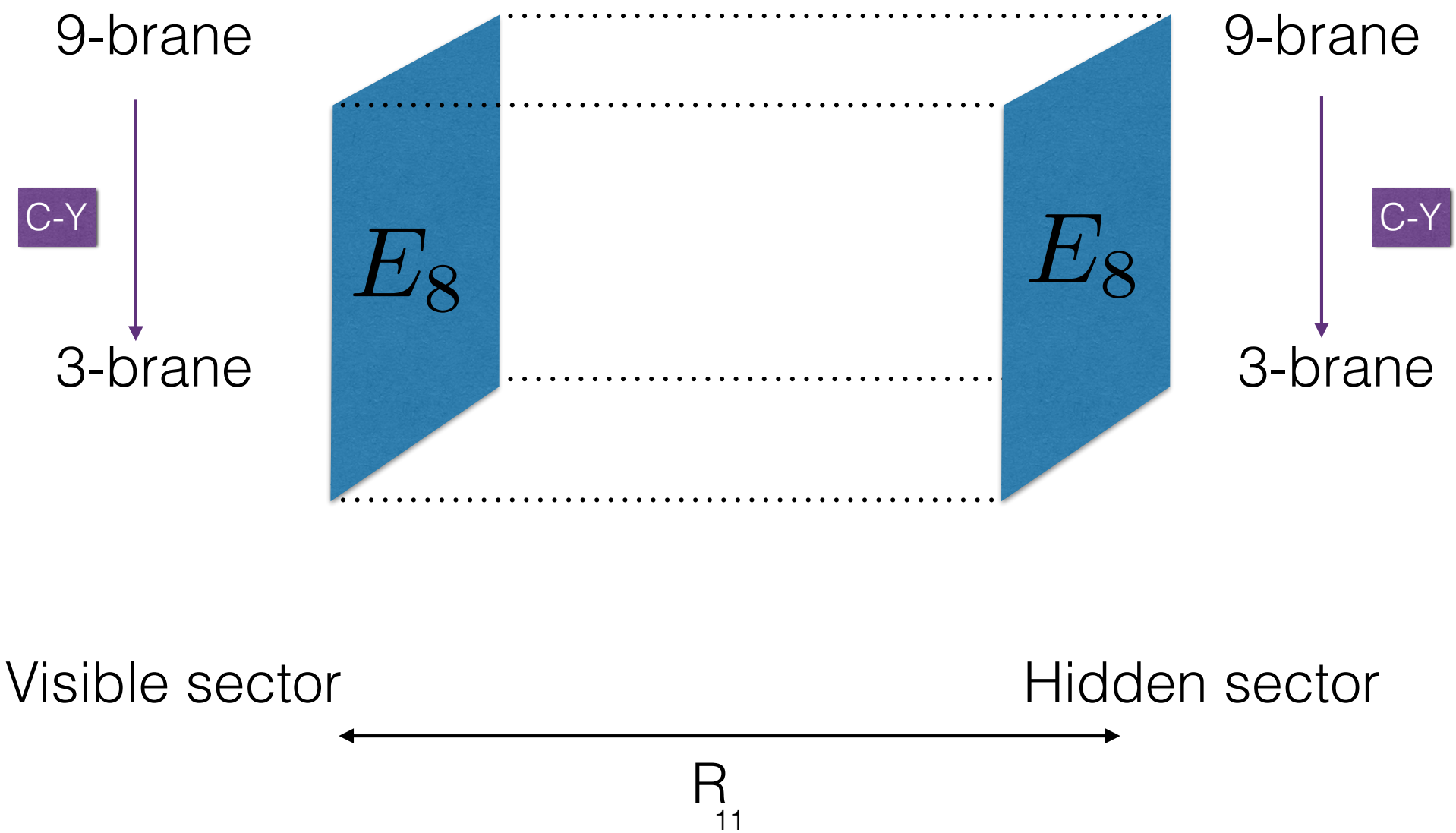

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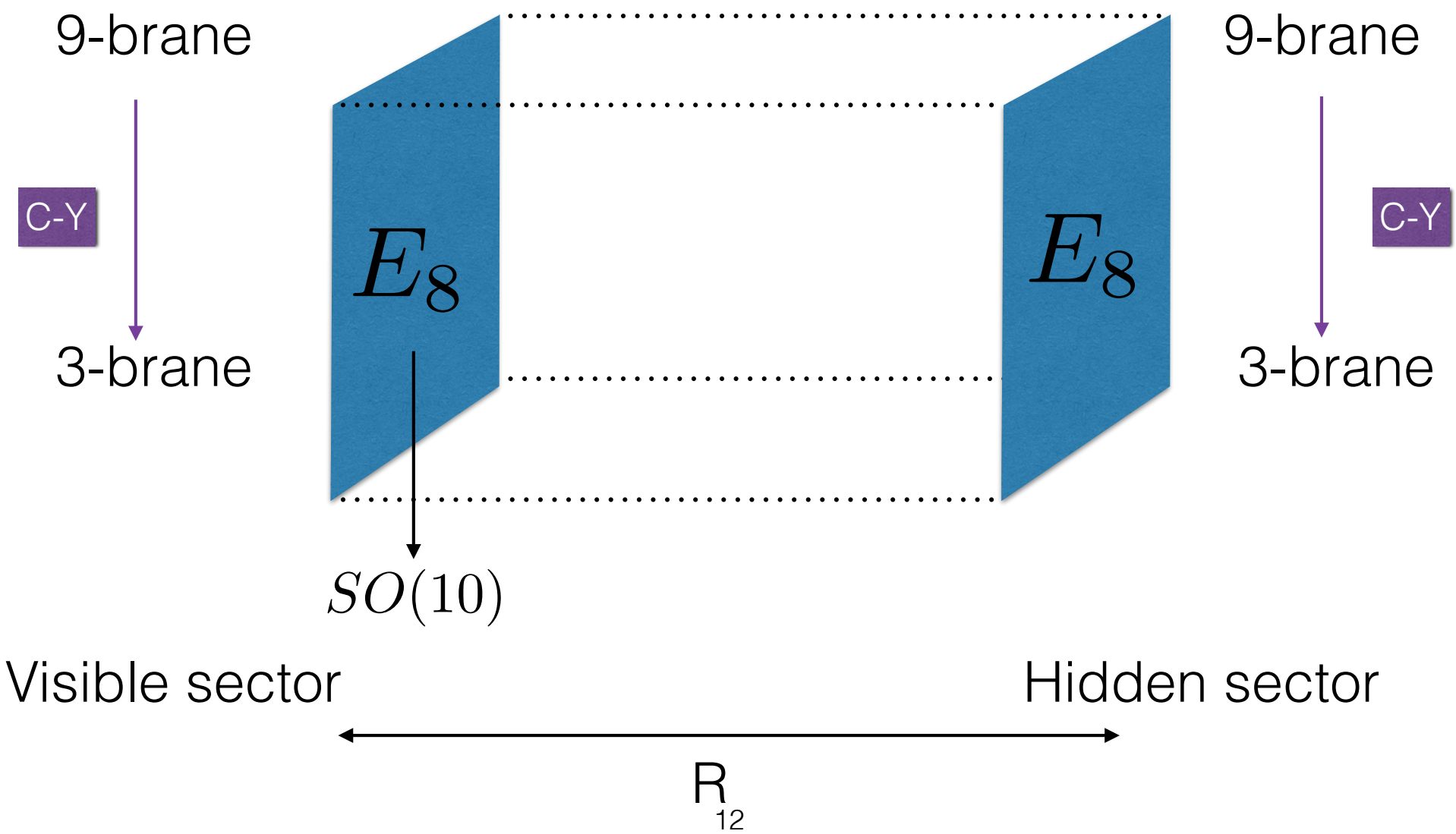

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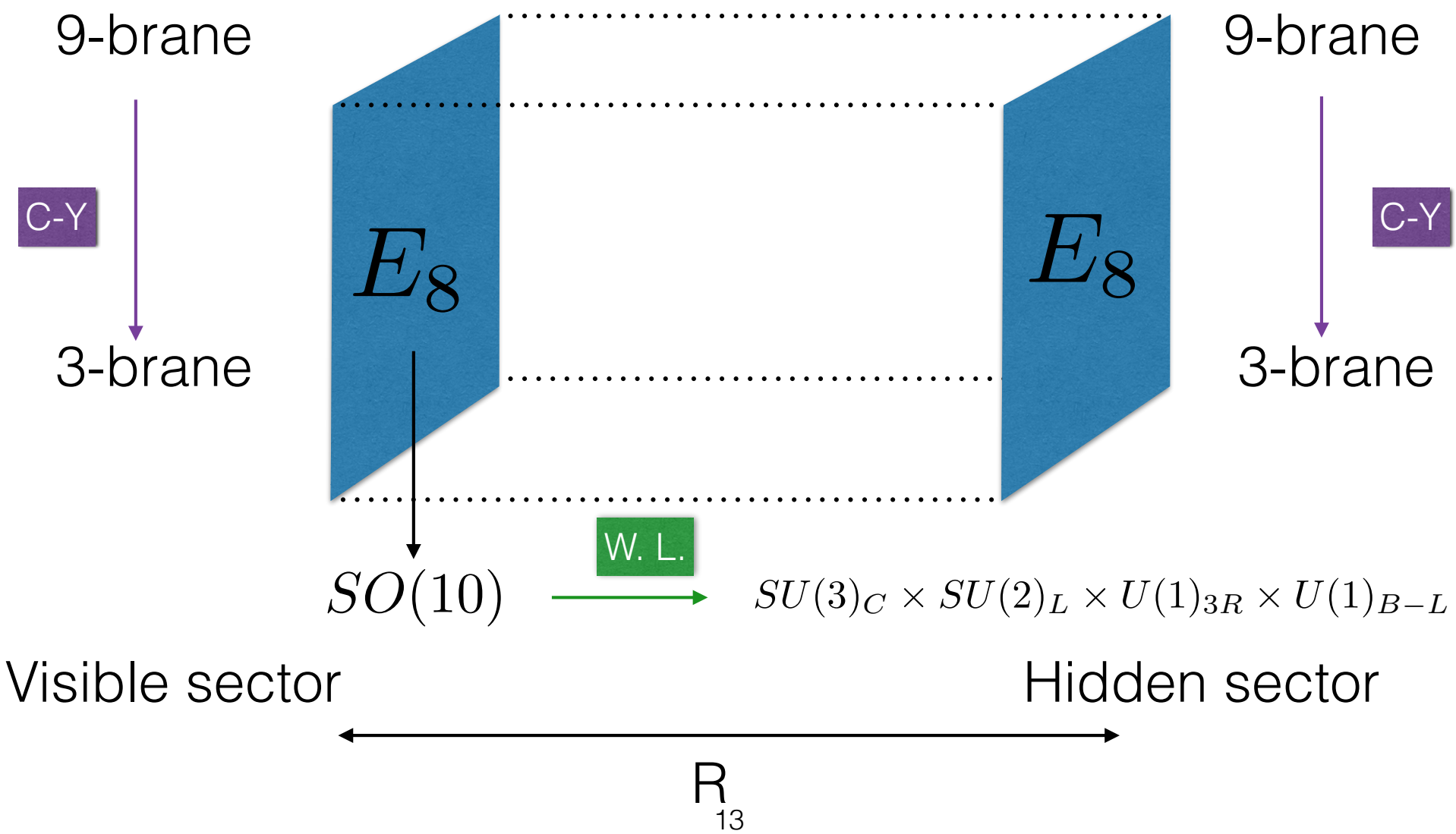

Dimensional reduction

c.f. Lukas, Ovrut, Waldram arXiv:9710208

11 dimensional metric:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + \underbrace{e^{2a(x)}\Omega_{AB}dx^A dx^B}_{\text{C-Y}} + \underbrace{e^{2c(x)}(dx^{11})^2}_{\text{Orbifold}}$$

Four dimensional action:

$$S_{bos} = -\frac{1}{16\pi G_N}\int_{M^4}\sqrt{-g}\left[R + 2K_{i\bar{j}}\partial_\mu Y^i \partial^\mu \bar{Y}^j + V_F + V_D\right]$$
$$-\frac{1}{16\pi\alpha_{GUT}}\int_{M^4}\sqrt{-g}\left[\Re(f(Y^i))\mathrm{tr}F^2 + \Im(f(Y^i))\mathrm{tr}F\tilde{F}\right]$$

Dimensional reduction

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Kähler potential:

$$K = -\ln(S+\bar{S}) - 3\,\ln(T+\bar{T} - \sum_i \frac{|C_i|^2}{M_P^2})$$

No scale supergravity

Dimensional reduction

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Kähler potential:

$$K = -\ln(S+\bar{S}) - 3\,\ln(T+\bar{T} - \sum_i \frac{|C_i|^2}{M_P^2})$$

$$S = e^{6a} + i\sqrt{2}\sigma\ , \quad T = e^{2\hat{c}} + i\sqrt{2}\chi + \frac{1}{2}\sum_i \frac{|C_i|^2}{M_P^2}$$

SUGRA lagrangian

Redefine matter fields + gauge couplings:

$$C_i' = \left(\frac{3}{T+\bar{T}}\right)^{1/2} C_i \ , \qquad g_a' = \left(\frac{2}{S+\bar{S}}\right)^{1/2} g_a \ , \quad \text{for } a = 3, 2, 3R, BL'$$

drop primes:

$$\lim_{M_P \to \infty} K_{i\bar{j}} \partial_\mu C^i \partial^\mu \bar{C}^j = \partial_\mu C^i \partial^\mu \bar{C}^i$$

Work with $M_P = 1$ units from now on

SUGRA lagrangian

scalar kinetic energy: $-K_{i\bar{j}}\partial_\mu C^i \partial^\mu C^{\bar{j}}$

F-term potential: $V_F = e^K \left(K^{i\bar{j}} D_i W \overline{D_{\bar{j}} W} - 3|W|^2 \right)$

$$W = Y_u Q H_u \bar{u} - Y_d Q H_d \bar{d} - Y_d L H_d \bar{d} + Y_u L H_u \bar{\nu} + \mu H_u H_d$$

D-term potential: $V_D = \frac{1}{2} \sum_a D_a^2$

$$D_a^r = -g_a \frac{\partial K}{\partial C_i} [T^r_{(a)}]_i{}^j C_j = \frac{g_a}{\left(1 - \frac{1}{3}\sum_i |C_i|^2\right)} \mathcal{D}^r_{(a)}$$

$$\mathcal{D}^r_{(a)} = -\overline{C}^i [T^r_{(a)}]_i{}^j C_j$$

SUGRA lagrangian

Soft SUSY-breaking terms (from hidden sector):

$$V_{soft} = (m^2_{Q_{\rm f}}|Q_{\rm f}|^2 + m^2_{u_{R,{\rm f}}}|u_{R,{\rm f}}|^2 + m^2_{d_{R,{\rm f}}}|d_{R,{\rm f}}|^2 + m^2_{L_{\rm f}}|L_{\rm f}|^2 + m^2_{\nu_{R,{\rm f}}}|\nu_{R,{\rm f}}|^2 + m^2_{e_{R,{\rm f}}}|e_{R,{\rm f}}|^2) + m^2_{H_u}|H_u|^2 + m^2_{\bar{H}_d}|H_d|^2 + (bH_uH_d + h.c.) + \ldots$$

$$\underbrace{+\ \text{gaugino masses}}_{\text{SUSY fermions}} \qquad \underbrace{+\ \text{tri-linear couplings}}_{\text{small for us - ignore}}$$

SUGRA lagrangian

$$\mathcal{L}_{scalar} = -K_{i\bar{j}}\partial_\mu C^i \partial^\mu \bar{C}^j - V_F - V_D - V_{soft}$$

- Want to inflate
- Simplicity - go for D-flatness

$$V_D = \frac{1}{2}\sum_a D_a^2 \qquad \Rightarrow D_a = \mathcal{D}_a = 0 \forall\ a$$

D-term potential

SU(3): $$-\mathcal{D}^r_{(3)} = (\overline{u}_{R,\mathrm{f}})^m [\Lambda^r]_m{}^n (u_{R,\mathrm{f}})_n + (\overline{d}_{R,\mathrm{f}})^m [\Lambda^r]_m{}^n (d_{R,\mathrm{f}})_n + (\overline{u}_{L,\mathrm{f}})^m [\Lambda^r]_m{}^n (u_{L,\mathrm{f}})_n + (\overline{d}_{L,\mathrm{f}})^m [\Lambda^r]_m{}^n (d_{L,\mathrm{f}})_n$$

SU(2):

$$-\mathcal{D}^r_{(2)} = (\overline{H}_u)^k [\tau^r]_k{}^l (H_u)_l + (\overline{H}_d)^k [\tau^r]_k{}^l (H_d)_l + (\overline{Q}_\mathrm{f})^k [\tau^r]_k{}^l (Q_\mathrm{f})_l + (\overline{L}_\mathrm{f})^k [\tau^r]_k{}^l (L_\mathrm{f})_l$$

U(1)$_{3R}$: $$-\mathcal{D}_{(3R)} = \frac{1}{2}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right) - \frac{1}{2}|\nu_{R,\mathrm{f}}|^2 + \frac{1}{2}|e_{R,\mathrm{f}}|^2 - \frac{1}{2}|u_{R,\mathrm{f}}|^2 + \frac{1}{2}|d_{R,\mathrm{f}}|^2$$

U(1)$_{B\text{-}L}$: $$-\mathcal{D}_{(BL')} = -|\nu_{L,\mathrm{f}}|^2 - |e_{L,\mathrm{f}}|^2 + \frac{1}{3}|u_{L,\mathrm{f}}|^2 + \frac{1}{3}|d_{L,\mathrm{f}}|^2 + |\nu_{R,\mathrm{f}}|^2 + |e_{R,\mathrm{f}}|^2 - \frac{1}{3}|u_{R,\mathrm{f}}|^2 - \frac{1}{3}|d_{R,\mathrm{f}}|^2$$

Construct D-flat direction

- Ignore color-charged fields - set squarks to zero
- Ignore electrically charged fields - charged sleptons and higgs to zero

Construct D-flat direction

- Ignore color-charged fields - set squarks to zero
- Ignore electrically charged fields - charged sleptons and higgs to zero
- Gives us 3 equations we need to solve, from 3R, BL, SU(2) D terms:

$$\left.\begin{aligned} -|H_u^0|^2 + |H_d^0|^2 + |\nu_{L,f}|^2 &= 0 \\ |H_u^0|^2 - |H_d^0|^2 - |\nu_{R,f}|^2 &= 0 \\ |\nu_{R,f}|^2 - |\nu_{L,f}|^2 &= 0 \end{aligned}\right\} \text{ 8 unknowns}$$

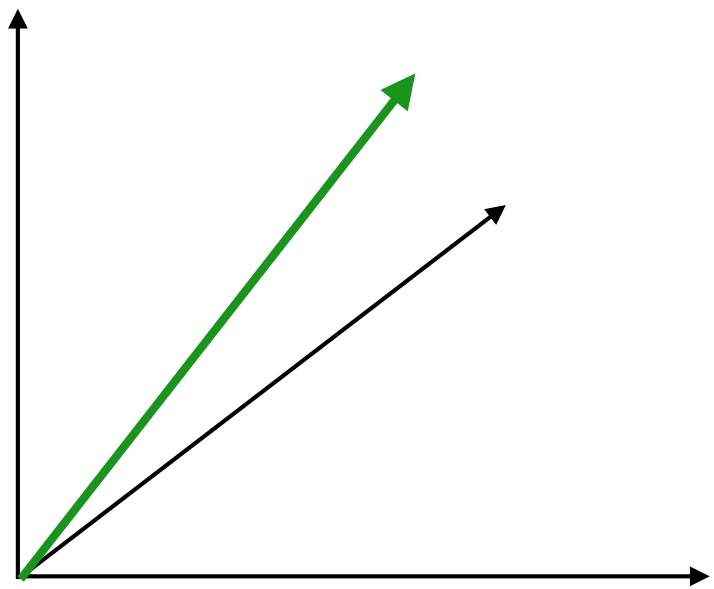
Construct D-flat direction

- Choose 3rd family sneutrinos
- set H_d to zero.
- Ignore phases
- Gives us:

$$\boxed{H_u^0 = \nu_{R,3} = \nu_{L,3}}$$

Construct D-flat direction

- Equation defines a line in 3 dimensional space $\boxed{H_u^0 = \nu_{R,3} = \nu_{L,3}}$
- Rotate to new basis which includes D-flat direction



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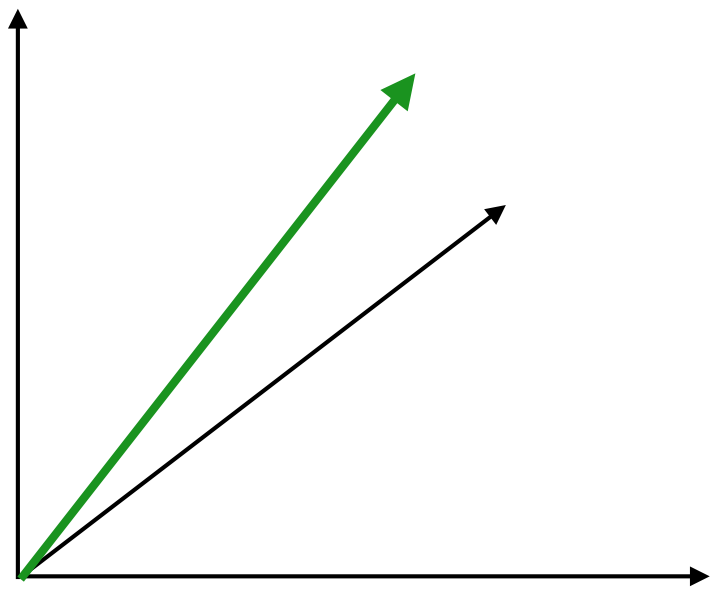

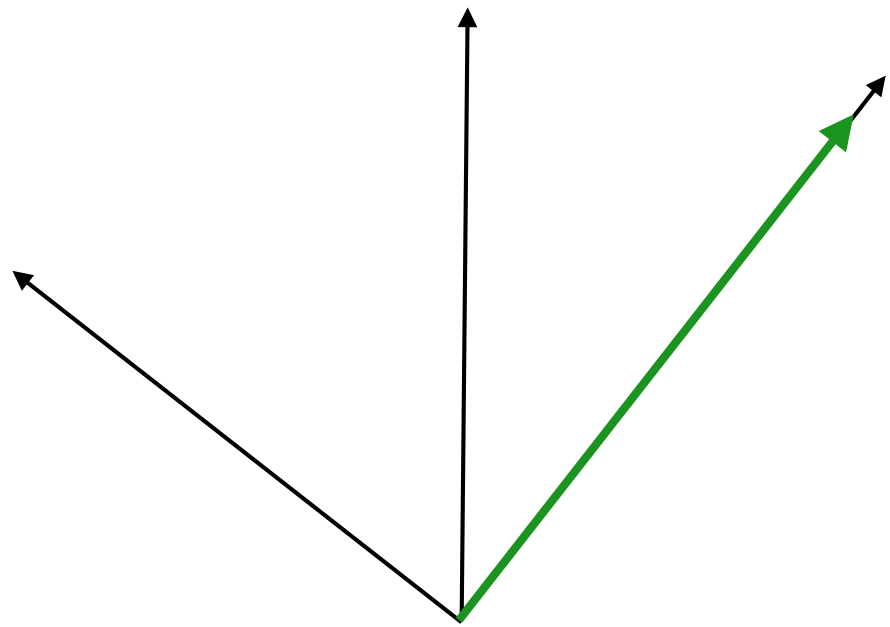

Construct D-flat direction

Redefinition of fields (II):

$$H_u^0 = \frac{1}{\sqrt{3}}\left(\phi_1 - \phi_2 - \phi_3\right)$$

$$\nu_{R,3} = \frac{1}{\sqrt{3}}\phi_1 + \left(\frac{1}{2\sqrt{3}} - \frac{1}{2}\right)\phi_2 + \left(\frac{1}{2} + \frac{1}{2\sqrt{3}}\right)\phi_3$$

$$\nu_{L,3} = \frac{1}{\sqrt{3}}\phi_1 + \left(\frac{1}{2} + \frac{1}{2\sqrt{3}}\right)\phi_2 + \left(\frac{1}{2\sqrt{3}} - \frac{1}{2}\right)\phi_3$$

Construct D-flat direction

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$$\boxed{\phi_2 = \phi_3 = 0} \quad \Rightarrow V_D = 0 \quad \forall\ \phi_1$$

Back to lagrangian

$$\phi_1 = \frac{1}{\sqrt{3}}\left(H_u^0 + \nu_{L,3} + \nu_{R,3}\right)$$

$$V_{soft}(\phi_1) = m^2|\phi_1|^2 \qquad m^2 = \frac{1}{3}(m^2_{H_u^0} + m^2_{\nu_{L,3}} + m^2_{\nu_{R,3}})$$

$$V_F(\phi_1) = \frac{3|\phi_1|^2\left(\mu^2 + Y^2_{\nu 3}|\phi_1|^2\right)}{\left(3 - |\phi_1|^2\right)^2}$$

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- Kinetic energy is non-canonical:

$$-\frac{1}{\left(1 - \frac{1}{3}|\phi_1|^2\right)^2}\partial_\mu\overline{\phi}_1\partial^\mu\phi_1$$

Back to lagrangian

Redefinition of fields (III) - the revenge:

$$\left(\frac{d\psi}{d\phi_1}\right)^2 = \frac{18}{(3-(\phi_1)^2)^2}$$

$$\boxed{\phi_1 = \sqrt{3}\tanh\left(\frac{\psi}{\sqrt{6}}\right)}$$

Inflationary lagrangian

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\psi\partial^\mu\psi - V_F(\psi) - V_{soft}(\psi)$$

$$V_F(\psi) = \frac{\tanh^2\left(\frac{\psi}{\sqrt{6}}\right)\left(\mu^2 + 3Y_{\nu 3}^2\tanh^2\left(\frac{\psi}{\sqrt{6}}\right)\right)}{\left(1-\tanh^2\left(\frac{\psi}{\sqrt{6}}\right)\right)^2}$$

$$V_{soft}(\psi) = 3m^2\tanh^2\left(\frac{\psi}{\sqrt{6}}\right)$$

$$m^2 = \frac{1}{3}(m_{H_u^0}^2 + m_{\nu_{L,3}}^2 + m_{\nu_{R,3}}^2)$$

Inflation

Slow-roll parameters:

$$\eta = \frac{V''}{V} \qquad \epsilon = \tfrac{1}{2}\left(\frac{V'}{V}\right)^2 \qquad \epsilon, \eta \ll 1$$

Physical quantities:

$$n_s \simeq 1 + 2\eta_* - 6\epsilon_* \qquad r \simeq 16\epsilon_*$$

Planck2015 CMB normalization constraint:

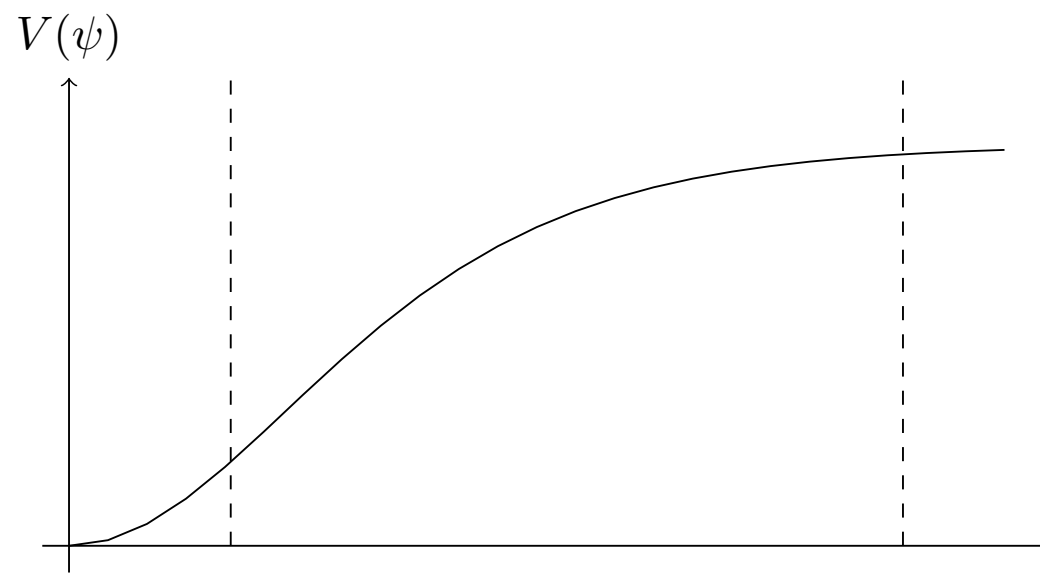
$$V_*^{1/4} = 1.88\left(\frac{r}{0.10}\right)^{1/4} \times 10^{16}\ \mathrm{GeV}$$

Inflation

- Difficult to constrain all parameters at once
- “Turn off” V_F first and concentrate on soft mass.

Pure soft mass inflation

$$V_{soft}(\psi) = 3m^2 \tanh^2\left(\frac{\psi}{\sqrt{6}}\right)$$



epsilon =1, 60 e-folds gives:

$$\psi_{end} = 1.21 \ , \qquad \psi_* = 6.23$$

(physical fields < M_P)

$$n_s \simeq 0.967 \ , \qquad r \simeq 0.00326$$

CMB normalization gives us:

$$V_*^{1/4} = 7.97 \times 10^{15} \text{ GeV}$$

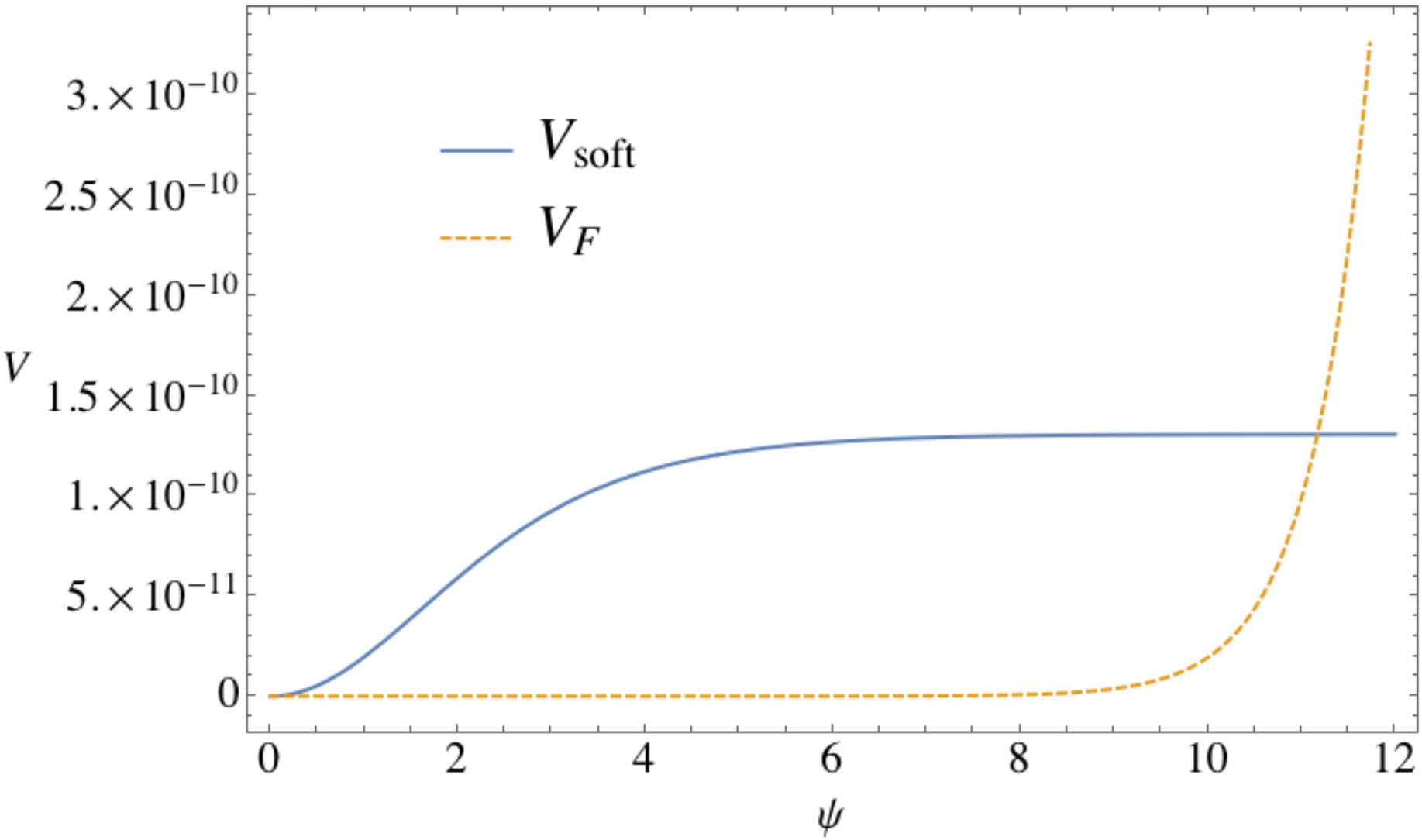
$$m = 1.55 \times 10^{13} \text{ GeV}$$

$V_{soft} + V_F$

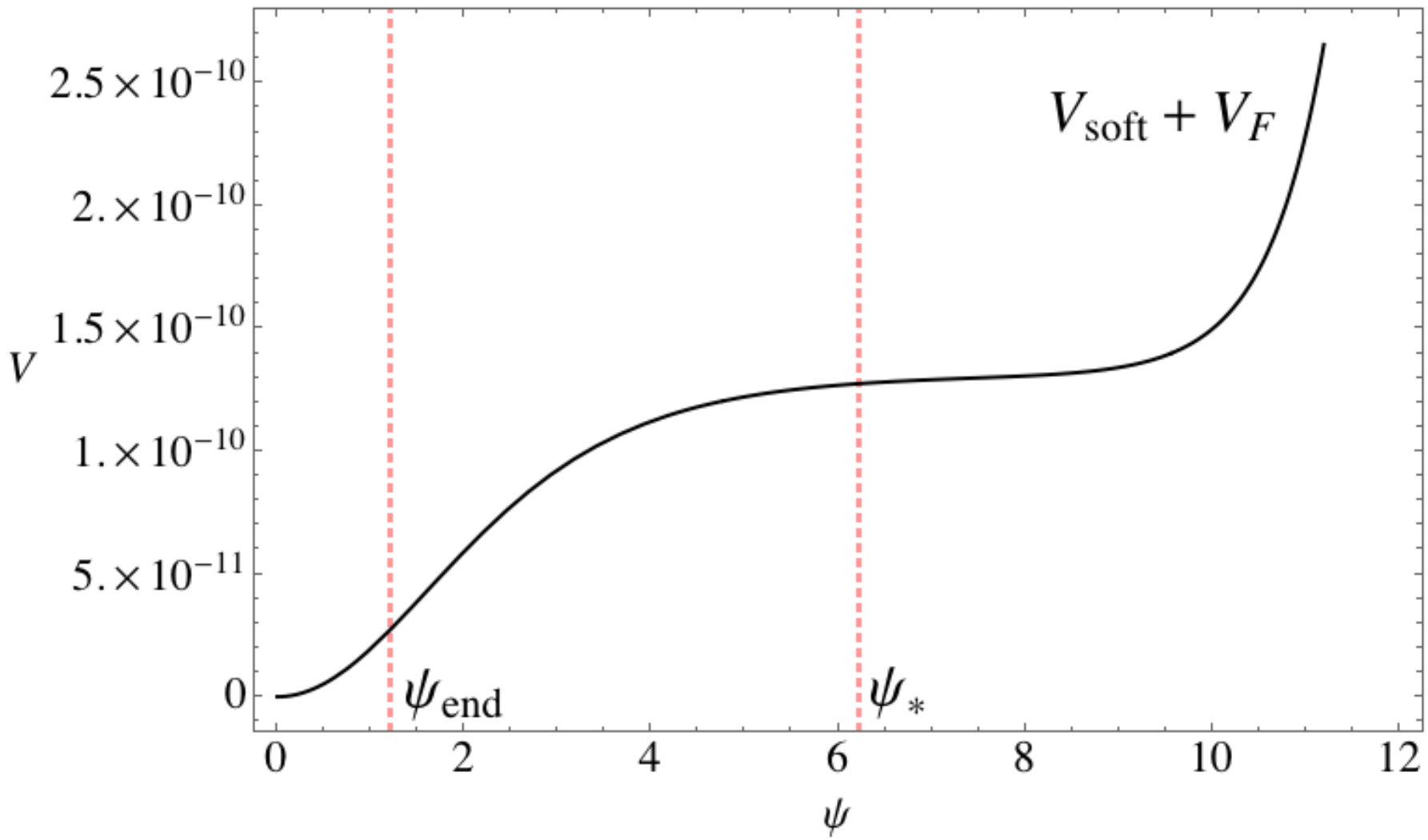
- Turn F-term back eta-problem
- Need to avoid spoiling 60 e-fold constraint
- F-term contribution dominated by μ

$$V_F(\psi) = \frac{\tanh^2\left(\frac{\psi}{\sqrt{6}}\right)\left(\mu^2 + 3Y_{\nu 3}^2 \tanh^2\left(\frac{\psi}{\sqrt{6}}\right)\right)}{\left(1 - \tanh^2\left(\frac{\psi}{\sqrt{6}}\right)\right)^2}$$

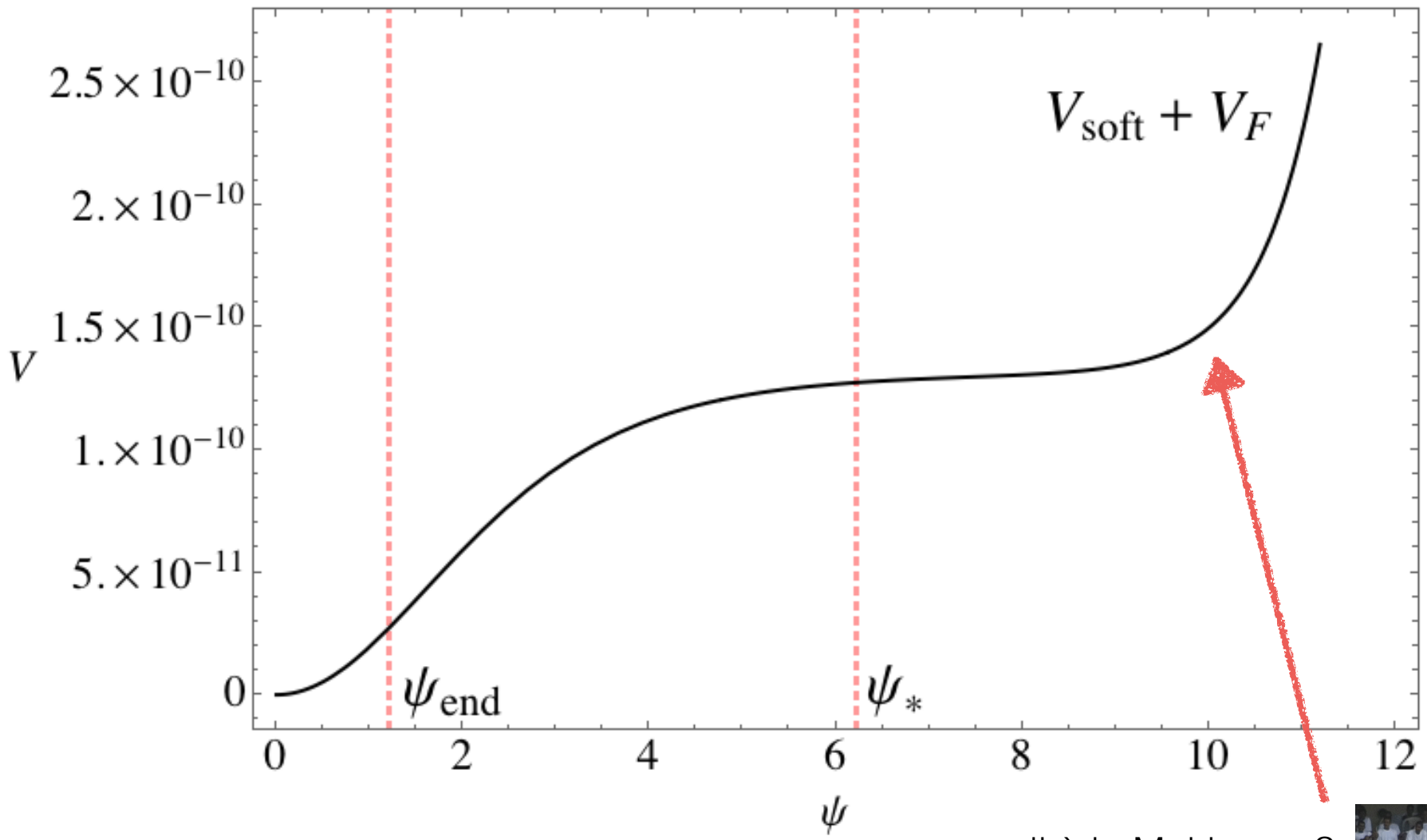
$V_{soft} + V_F$


V_{soft}
V_F
$3.\times10^{-10}$
2.5×10^{-10}
$2.\times10^{-10}$
1.5×10^{-10}
$1.\times10^{-10}$
$5.\times10^{-11}$
0
V
0
2
4
6
8
10
12
ψ

$V_{soft} + V_F$


$V_{\rm soft} + V_F$
$\psi_{\rm end}$
ψ_*
V
ψ
2.5×10^{-10}
$2.\times10^{-10}$
1.5×10^{-10}
$1.\times10^{-10}$
$5.\times10^{-11}$
0
0
2
4
6
8
10
12

$V_{soft} + V_F$



wall à la Mukhanov?
arXiv: 1409.2335

$V_{soft} + V_F$

- Turn F-term back on - eta problem
- Need to avoid spoiling 60 e-fold constraint
- F-term contribution dominated by μ
- Largest value of μ allowed is: $\boxed{\mu = \ 1.20 \times 10^{10} \ \mathrm{GeV}}$

$$\psi_{end} \simeq 1.21 \ , \quad \psi_* \simeq 6.25$$

$$n_s \simeq 0.969 \ , \qquad r \simeq 0.00334$$

$$V_*^{1/4} = 8.07 \times 10^{15} \ \mathrm{GeV} \qquad \boxed{m = 1.58 \times 10^{13} \ \mathrm{GeV}}$$

Planck 2015

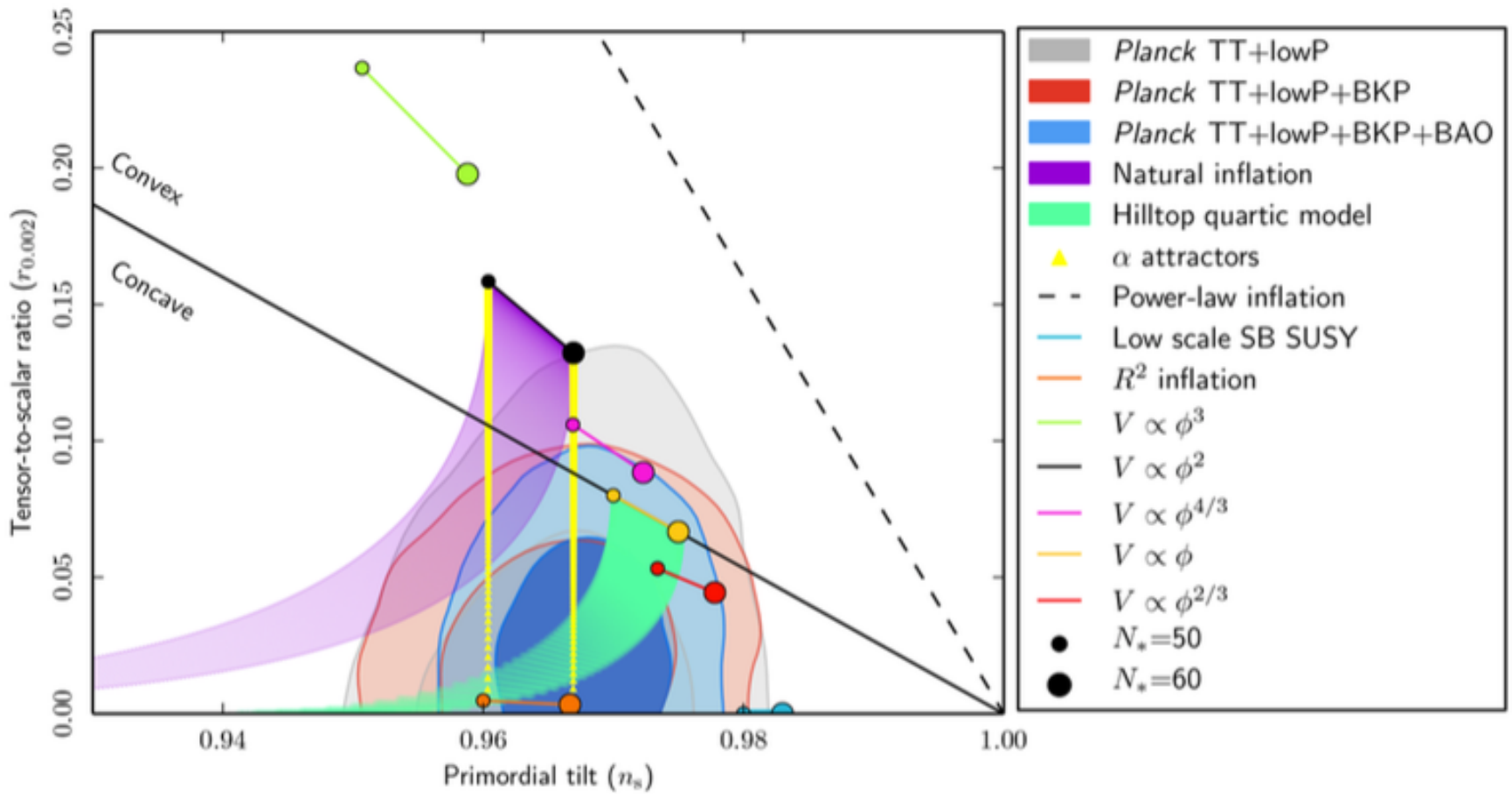
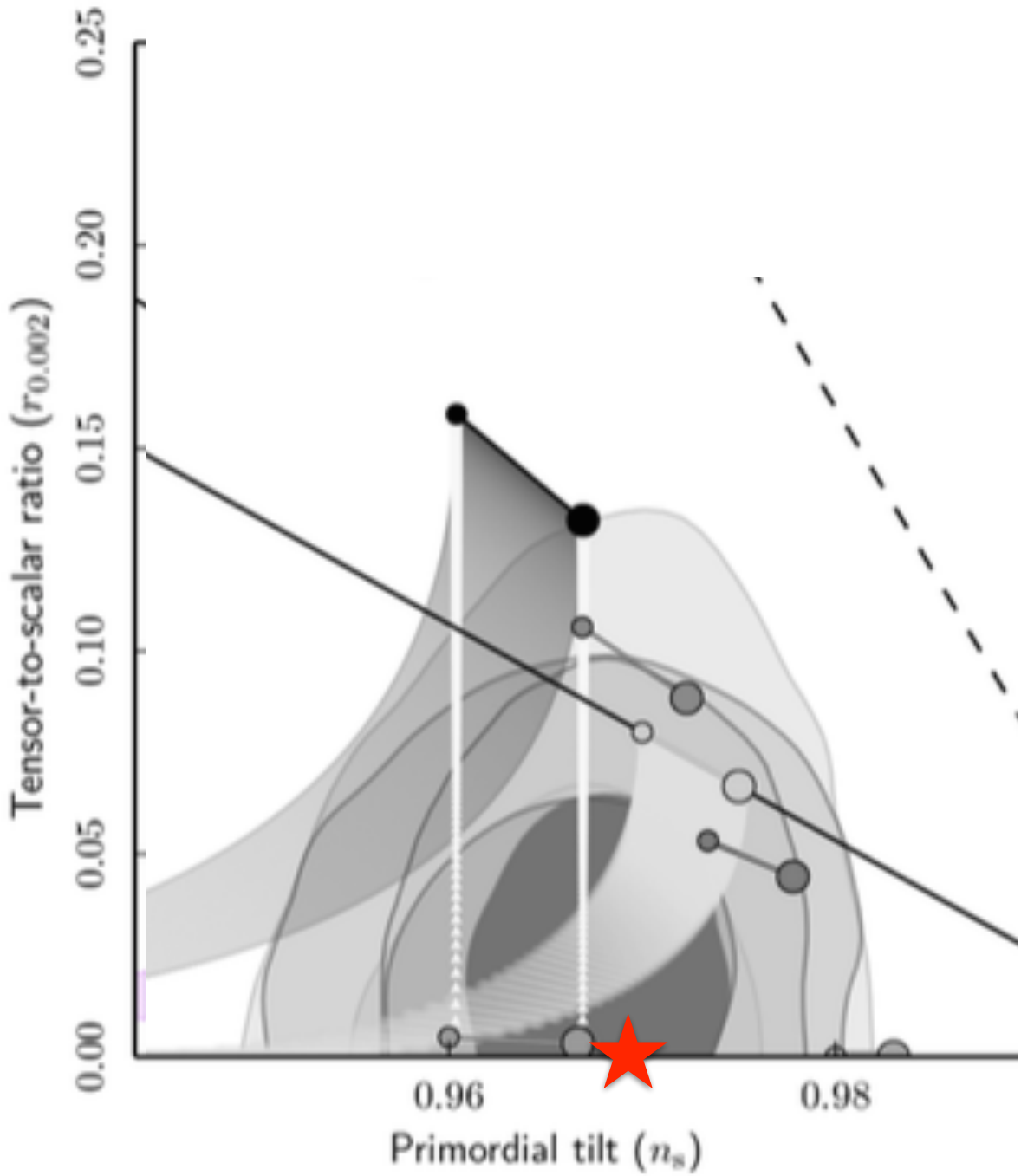


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.


Tensor-to-scalar ratio ($r_{0.002}$)
0.00
0.05
0.10
0.15
0.20
0.25
0.96
0.98
Primordial tilt (n_s)

Stability

- Need to ensure that trajectory is stable during inflation

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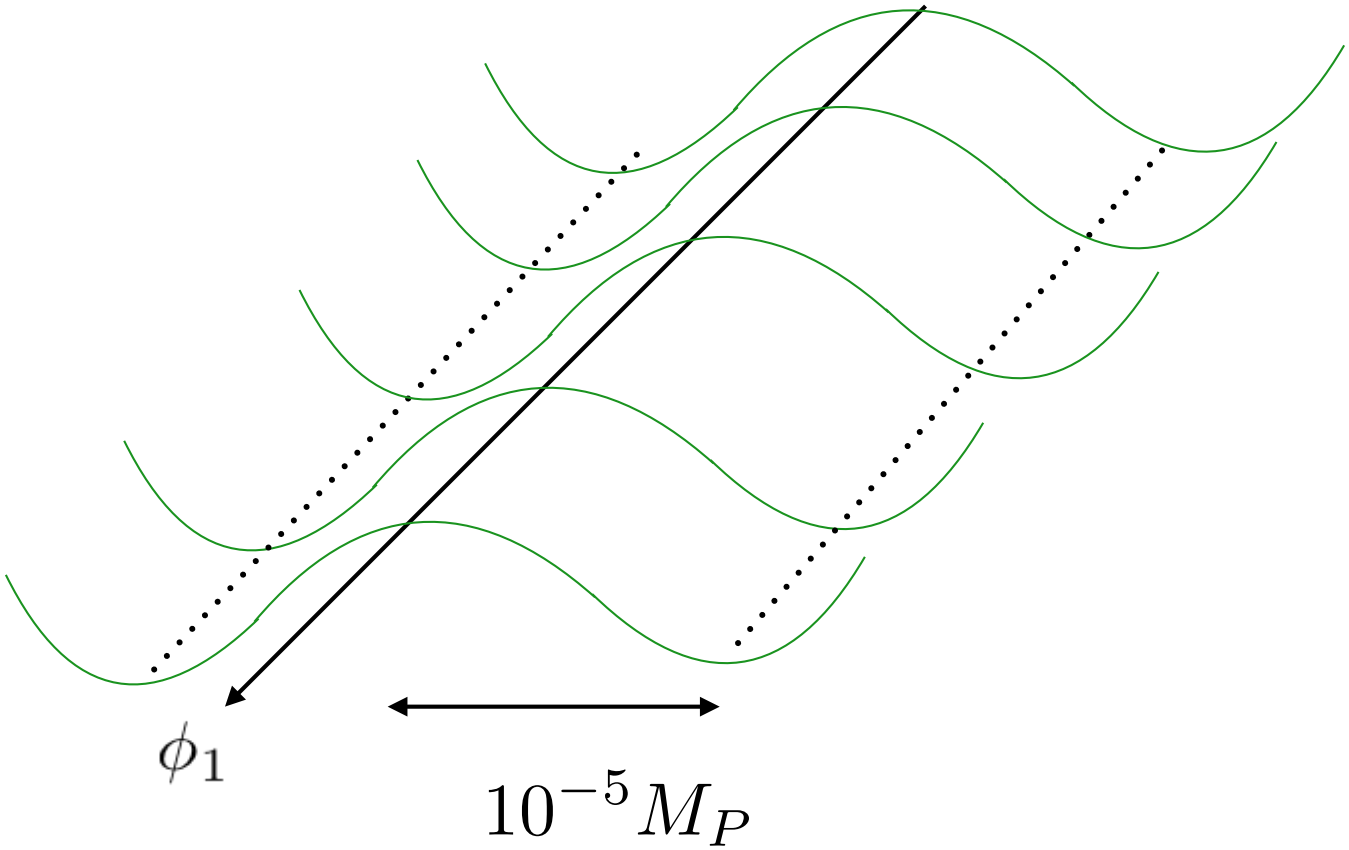
- Soft constraint: any roll-off is $\leq 10^{-5} M_P$

Stability



Stability

- Construct Hessian matrix to check stability:

- Thankfully matrix is block diagonal:

$$
\begin{pmatrix}
\frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{R1}} & \frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{R1}} & 0 & 0 & 0 & 0 & 0 & \cdots \\
\frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{R1}} & \frac{\partial^2 V}{\partial \nu_{R1}\partial \nu_{R1}} & 0 & 0 & 0 & 0 & 0 & \cdots \\
\frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{R1}} & \frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{R1}} & 0 & 0 & 0 & 0 & 0 & \cdots \\
\frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{L1}} & \frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{R1}} & \frac{\partial^2 V}{\partial \nu_{L1}\partial \nu_{R1}} & 0 & 0 & 0 & 0 & 0 & \cdots \\
0 & 0 & 0 & 0 & \frac{\partial^2 V}{\partial e_{R1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{R1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{R1}\partial e_{R1}} & \frac{\partial^2 V}{\partial e_{R1}\partial e_{R1}} & 0 & \cdots \\
0 & 0 & 0 & 0 & \frac{\partial^2 V}{\partial e_{R1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{R1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{R1}\partial e_{R1}} & \frac{\partial^2 V}{\partial e_{R1}\partial e_{R1}} & 0 & \cdots \\
0 & 0 & 0 & 0 & \frac{\partial^2 V}{\partial e_{L1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{L1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{L1}\partial e_{R1}} & \frac{\partial^2 V}{\partial e_{L1}\partial e_{R1}} & 0 & \cdots \\
0 & 0 & 0 & 0 & \frac{\partial^2 V}{\partial e_{L1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{L1}\partial e_{L1}} & \frac{\partial^2 V}{\partial e_{L1}\partial e_{R1}} & \frac{\partial^2 V}{\partial e_{L1}\partial e_{R1}} & 0 & \cdots \\
\vdots & & & & & & & & \ddots &
\end{pmatrix},
$$

Stability

- All blocks are 4 by 4 except for
    - 6 by 6 involving phi2, phi3 phi4
    - 8 by 8 involving e3R e3L Hu+ Hd-

$$
\begin{pmatrix}
\frac{\partial^2 V}{\partial \Re\phi_2 \partial \Re\phi_2} & \frac{\partial^2 V}{\partial \Re\phi_2 \partial \Im\phi_2} & \frac{\partial^2 V}{\partial \Re\phi_2 \partial \Re\phi_3} & \frac{\partial^2 V}{\partial \Re\phi_2 \partial \Im\phi_3} & \frac{\partial^2 V}{\partial \Re\phi_2 \partial \Re H_d^0} & \frac{\partial^2 V}{\partial \Re\phi_2 \partial \Im H_d^0} \\
\frac{\partial^2 V}{\partial \Im\phi_2 \partial \Re\phi_2} & \frac{\partial^2 V}{\partial \Im\phi_2 \partial \Im\phi_2} & \frac{\partial^2 V}{\partial \Im\phi_2 \partial \Re\phi_3} & \frac{\partial^2 V}{\partial \Im\phi_2 \partial \Im\phi_3} & \frac{\partial^2 V}{\partial \Im\phi_2 \partial \Re H_d^0} & \frac{\partial^2 V}{\partial \Im\phi_2 \partial \Im H_d^0} \\
\frac{\partial^2 V}{\partial \Re\phi_3 \partial \Re\phi_2} & \frac{\partial^2 V}{\partial \Re\phi_3 \partial \Im\phi_2} & \frac{\partial^2 V}{\partial \Re\phi_3 \partial \Re\phi_3} & \frac{\partial^2 V}{\partial \Re\phi_3 \partial \Im\phi_3} & \frac{\partial^2 V}{\partial \Re\phi_3 \partial \Re H_d^0} & \frac{\partial^2 V}{\partial \Re\phi_3 \partial \Im H_d^0} \\
\frac{\partial^2 V}{\partial \Im\phi_3 \partial \Re\phi_2} & \frac{\partial^2 V}{\partial \Im\phi_3 \partial \Im\phi_2} & \frac{\partial^2 V}{\partial \Im\phi_3 \partial \Re\phi_3} & \frac{\partial^2 V}{\partial \Im\phi_3 \partial \Im\phi_3} & \frac{\partial^2 V}{\partial \Im\phi_3 \partial \Re H_d^0} & \frac{\partial^2 V}{\partial \Im\phi_3 \partial \Im H_d^0} \\
\frac{\partial^2 V}{\partial \Re H_d^0 \partial \Re\phi_2} & \frac{\partial^2 V}{\partial \Re H_d^0 \partial \Im\phi_2} & \frac{\partial^2 V}{\partial \Re H_d^0 \partial \Re\phi_3} & \frac{\partial^2 V}{\partial \Re H_d^0 \partial \Im\phi_3} & \frac{\partial^2 V}{\partial \Re H_d^0 \partial \Re H_d^0} & \frac{\partial^2 V}{\partial \Re H_d^0 \partial \Im H_d^0} \\
\frac{\partial^2 V}{\partial \Im H_d^0 \partial \Re\phi_2} & \frac{\partial^2 V}{\partial \Im H_d^0 \partial \Im\phi_2} & \frac{\partial^2 V}{\partial \Im H_d^0 \partial \Re\phi_3} & \frac{\partial^2 V}{\partial \Im H_d^0 \partial \Im\phi_3} & \frac{\partial^2 V}{\partial \Im H_d^0 \partial \Re H_d^0} & \frac{\partial^2 V}{\partial \Im H_d^0 \partial \Im H_d^0}
\end{pmatrix}
$$

$$
\begin{pmatrix}
\frac{\partial^2 V}{\partial \Re e_{3R} \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Re e_{3R} \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Im e_{3R} \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Im e_{3R} \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Re e_{3L} \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Re e_{3L} \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Im e_{3L} \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Im e_{3L} \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Re H_u^+ \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Re H_u^+ \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Im H_u^+ \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Im H_u^+ \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Re H_d^- \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Re H_d^- \partial \Im H_d^-} \\
\frac{\partial^2 V}{\partial \Im H_d^- \partial \Re e_{3R}} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Im e_{3R}} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Re e_{3L}} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Im e_{3L}} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Re H_u^+} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Im H_u^+} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Re H_d^-} & \frac{\partial^2 V}{\partial \Im H_d^- \partial \Im H_d^-}
\end{pmatrix}
$$

Stability

- Check eigenvalues - if positive stable

- If negative construct assoc. eigenvectors and look for roll-off

Stability

- Check eigenvalues - if positive stable
- If negative construct assoc. eigenvectors and look for roll-off

- Soft constraint: any roll-off is $\leq 10^{-5} M_P$

Return to particle physics

Return to particle physics

- Can $m_{SUSY} \sim 10^{13}\mathrm{GeV}$, $\mu \lesssim 10^{10}\mathrm{GeV}$ give us reasonable physics?

Redo statistical scan with soft masses thrown about new $\bar{m}$ with $[\bar{m}/f, f\bar{m}]$, $f = 3.3$

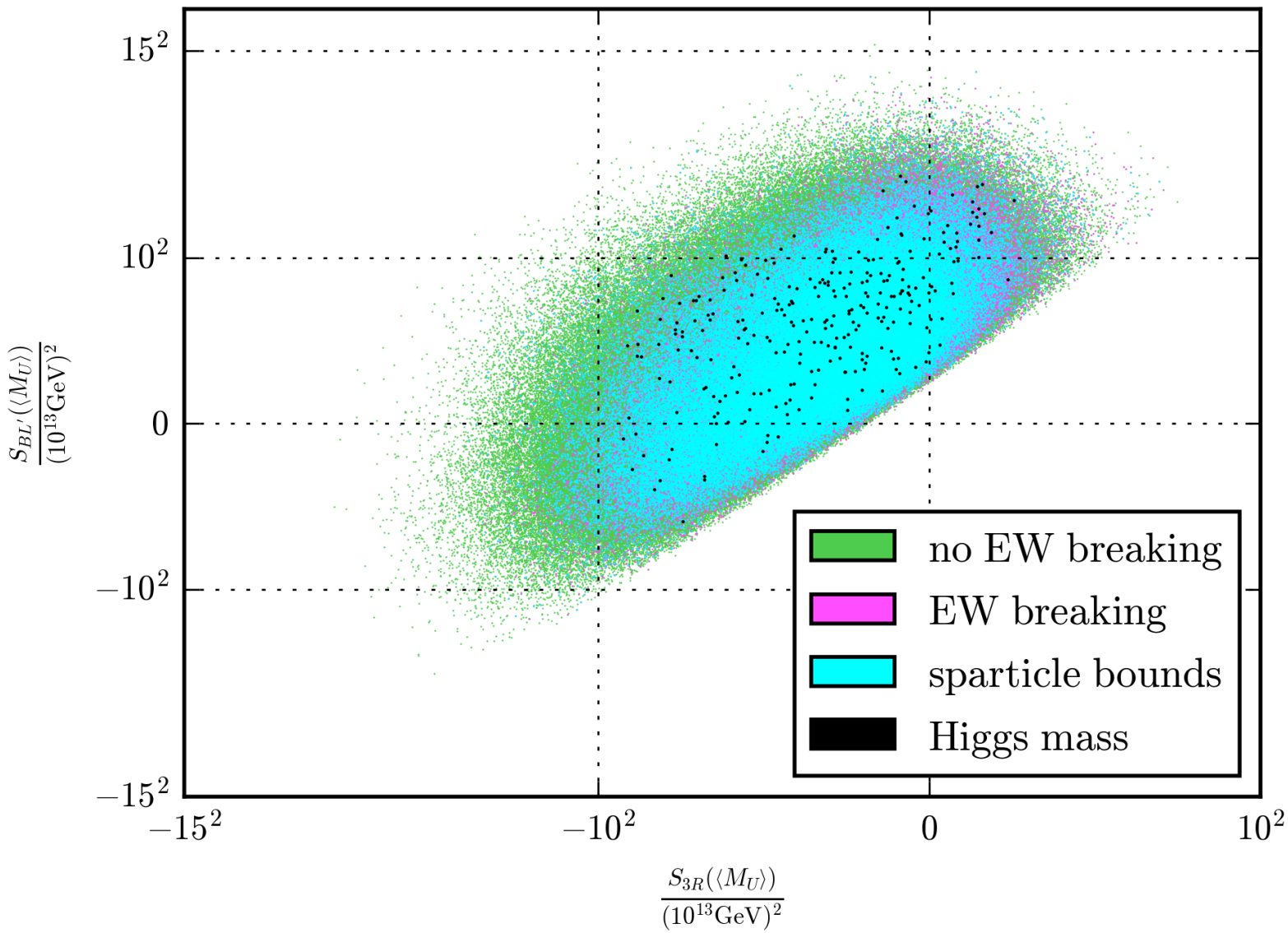
- s.t. average $m^2 = \frac{1}{3}(m^2_{H^0_u} + m^2_{\nu_{L,3}} + m^2_{\nu_{R,3}})$

$$m = 1.58 \times 10^{13}\ \mathrm{GeV}$$

- μ constrained to be < $10^{10}\mathrm{GeV}$

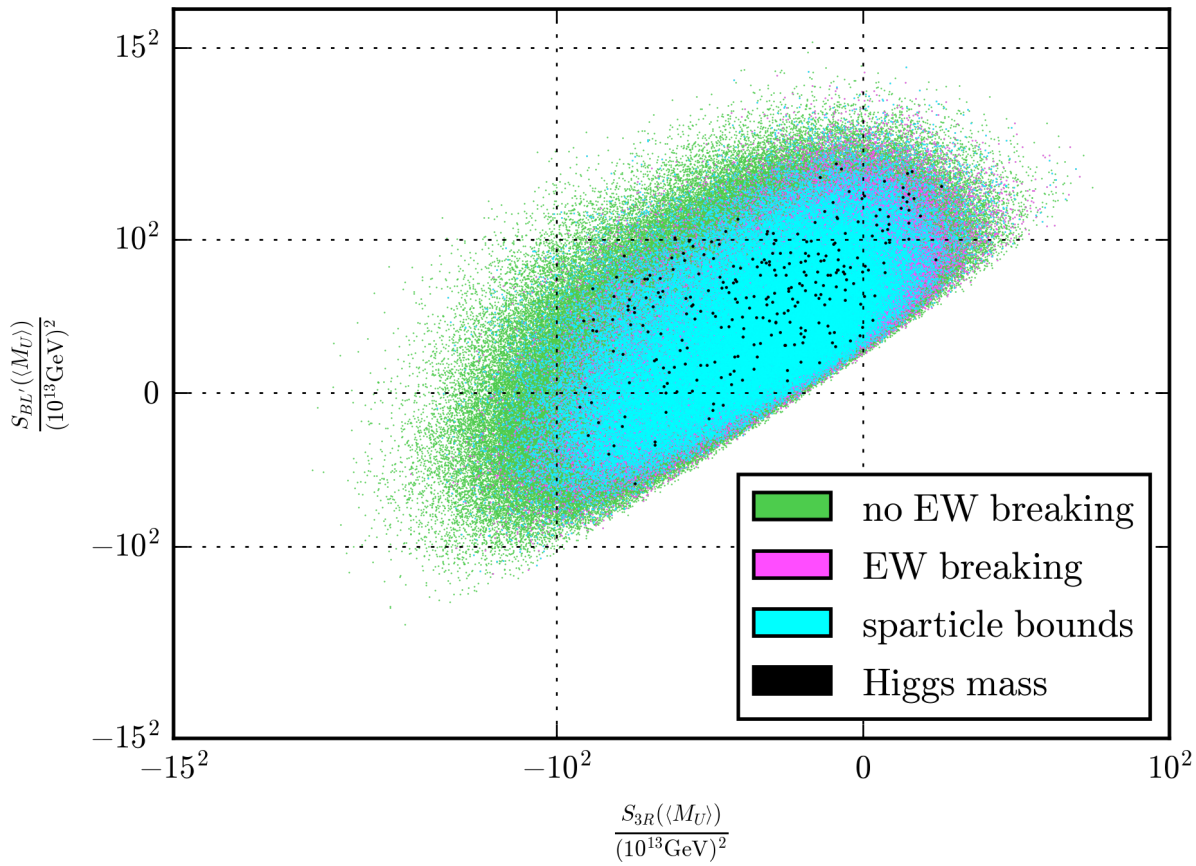
Search for valid low-energy points

Search for valid low-energy points



Search for valid low-energy points

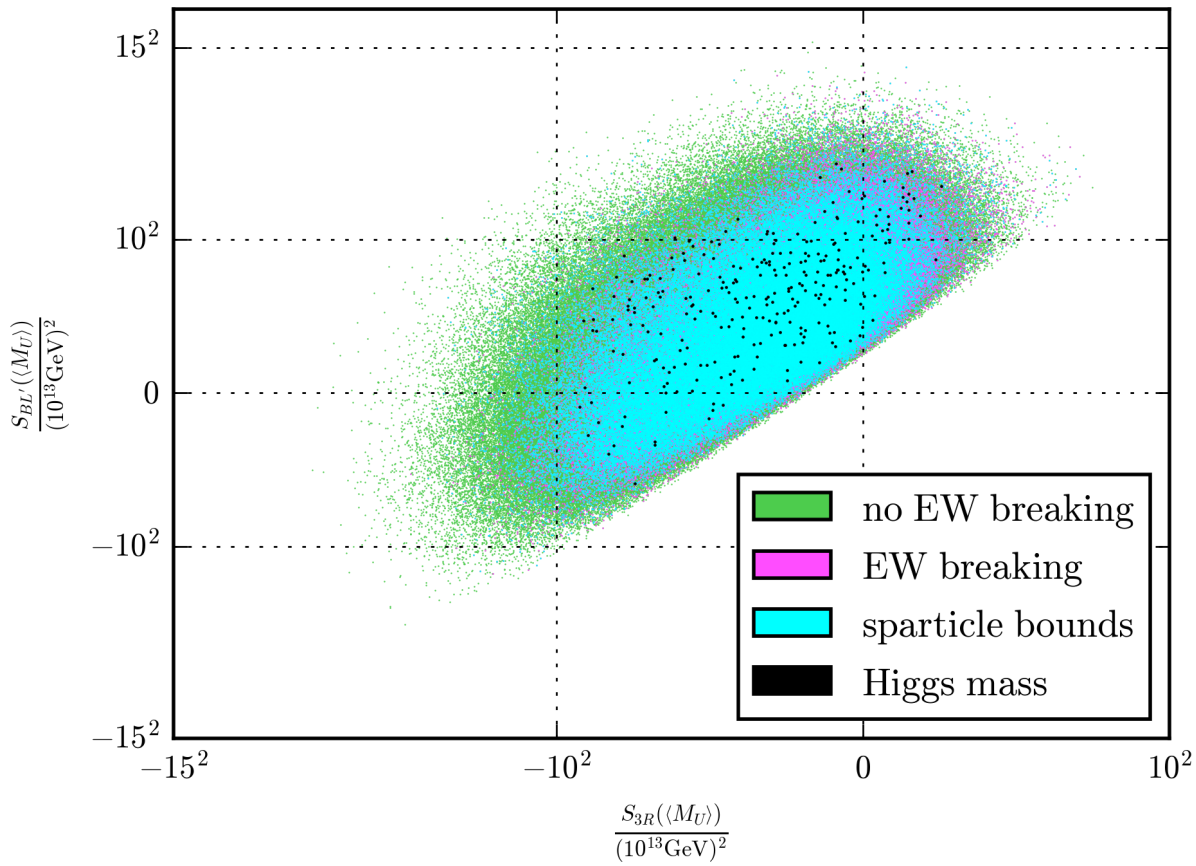
Randomly throw 10-million points:



Search for valid low-energy points

Randomly throw 10-million points:

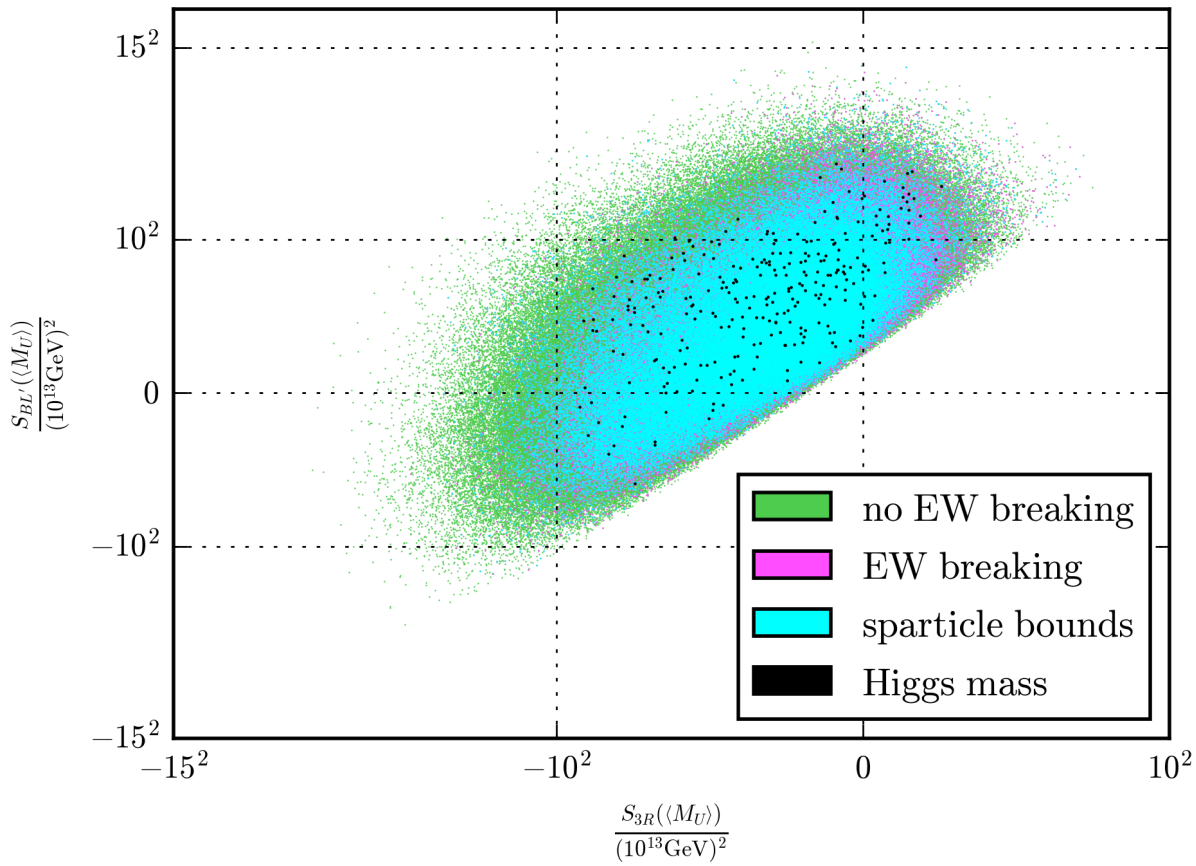
- 841, 952 points that break B-L



Search for valid low-energy points

Randomly throw 10-million points:

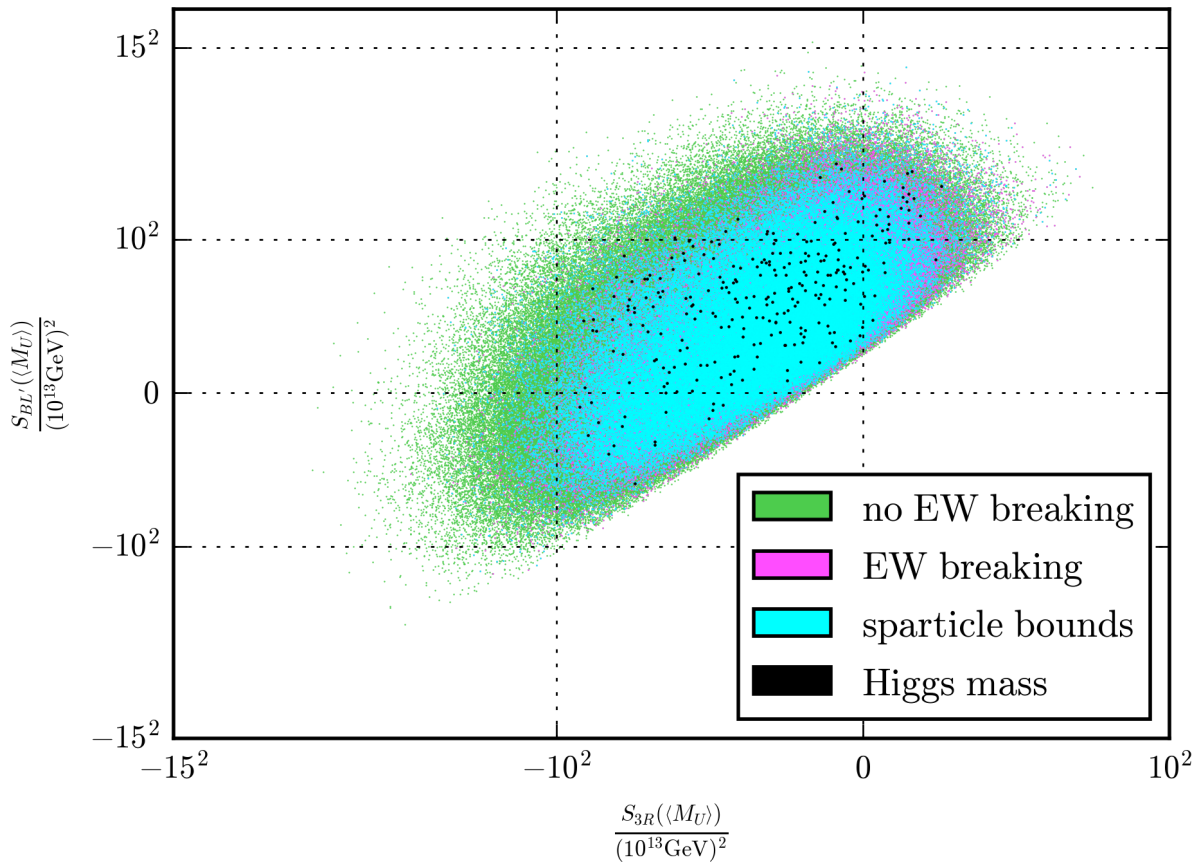
- 841, 952 points that break B-L
- 172, 374 points that break EW



Search for valid low-energy points

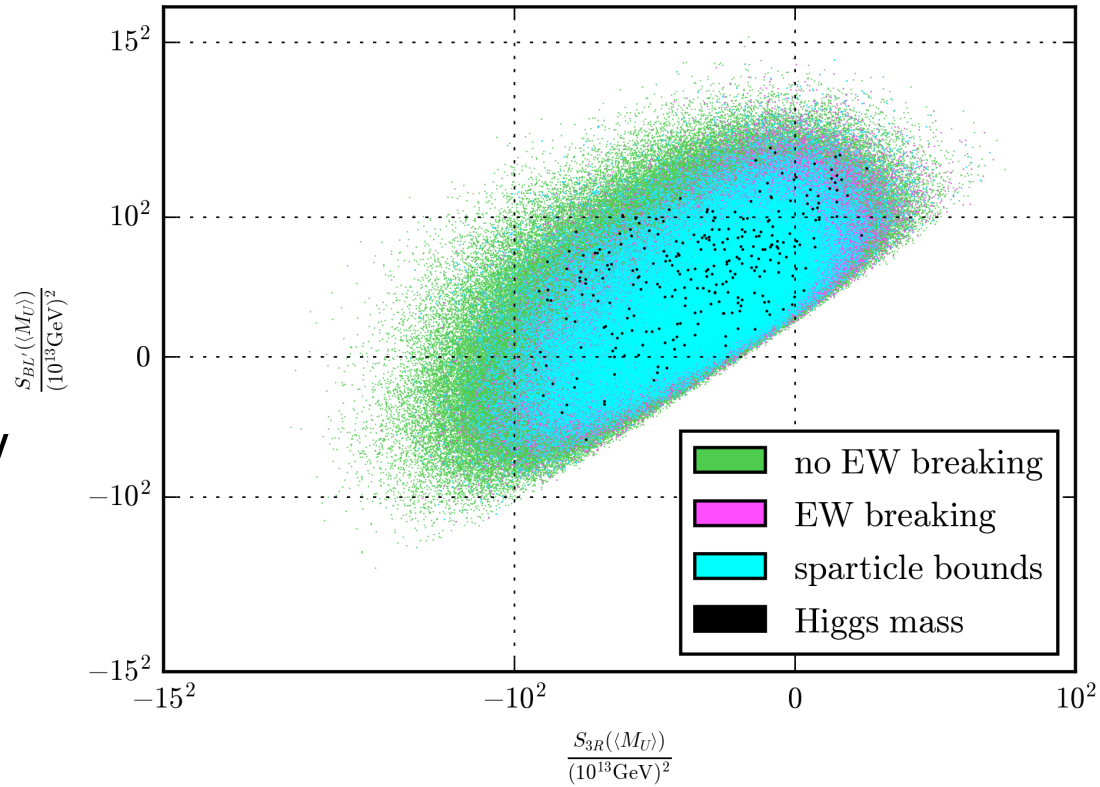
Randomly throw 10-million points:

- 841, 952 points that break B-L
- 172, 374 points that break EW
- 276 points that have m_h^0 = 126 GeV



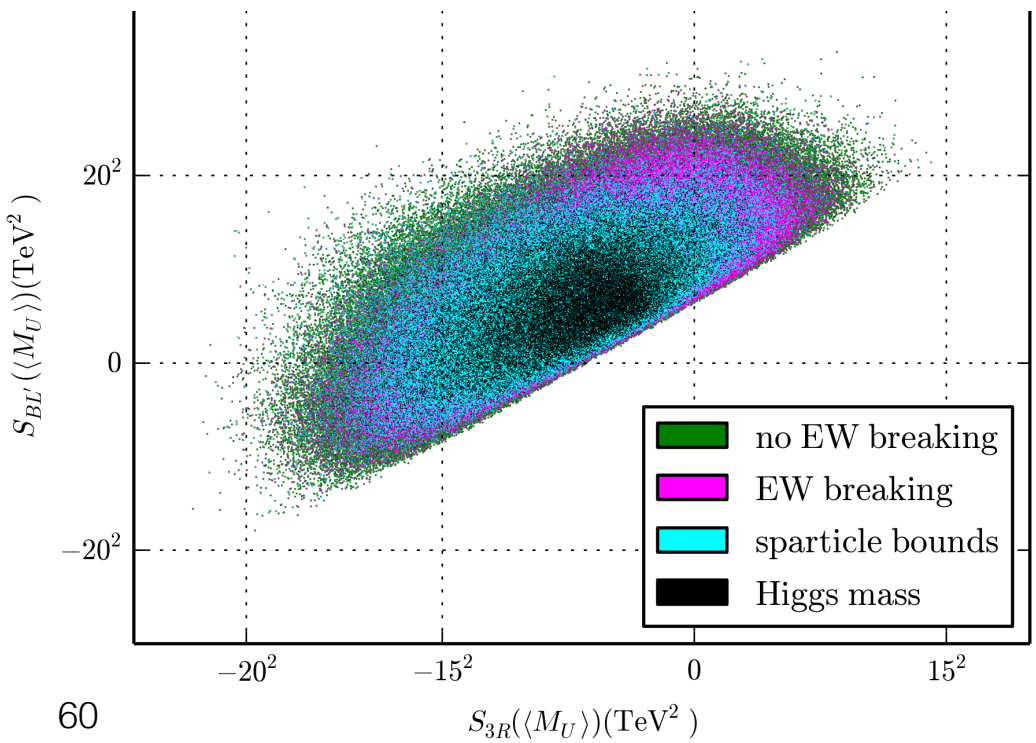
$m_{susy} \sim 10^{13}$ GeV

276 that give $m_h^0 = 126$ GeV



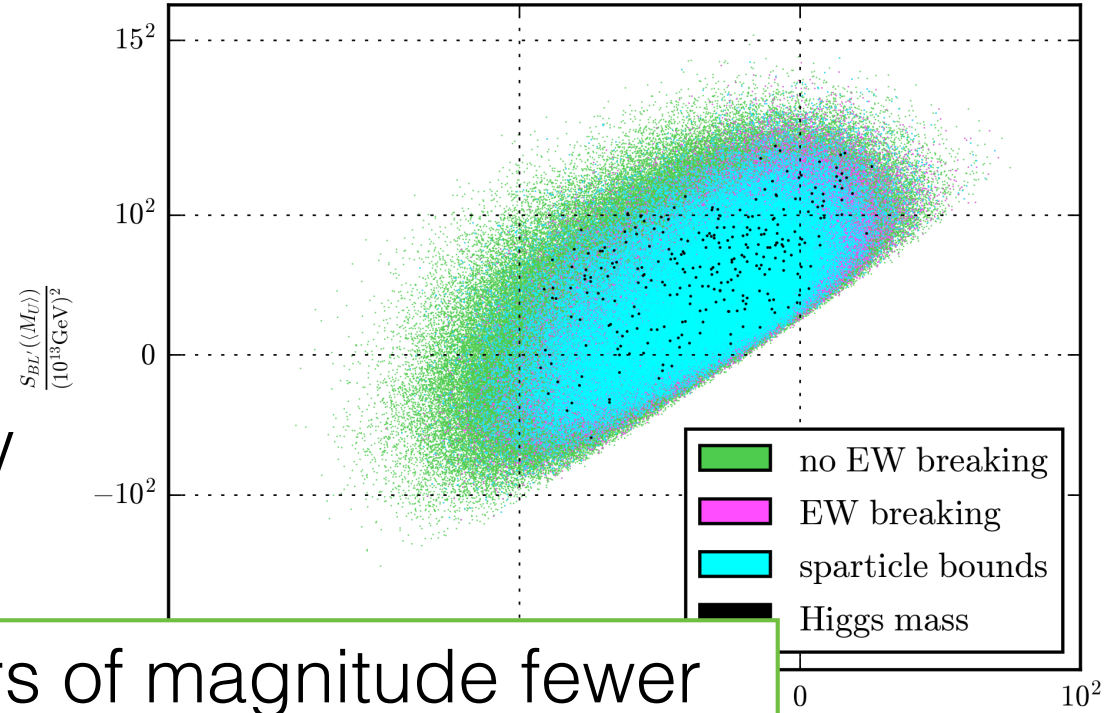
$m_{susy} \sim 10^{3}$ GeV

44,884 that give $m_h^0 =$ 126 GeV



$m_{susy} \sim 10^{13}$ GeV

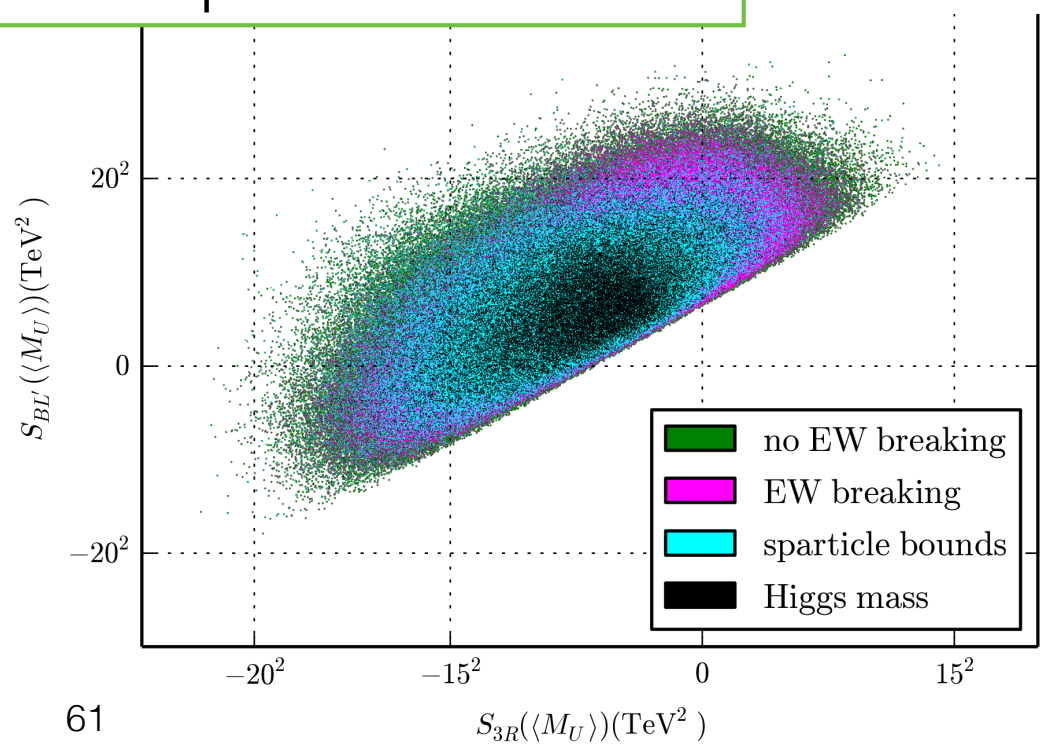
276 that give m_h^0 = 126 GeV



2 orders of magnitude fewer black points

$m_{susy} \sim 10^{3}$ GeV

44,884 that give m_h^0 = 126 GeV



Conclusions

- Can get a reasonable model of inflation from the B-L MSSM using only matter fields, no exotics.
- Cosmological data implies high scale SUSY breaking
- Consistent with SM light higgs and all low energy phenomenology

Ongoing work

- Reheating and dark matter candidates.
- Extending high SUSY breaking scale to bouncing/ ekpyrotic framework.

Thank you!

Work supported by DOE contract No. DE-SC0007901

Backup slide: Construct D-flat direction

- Note: space of D-flat solutions satisfying

$$-|H_u^0|^2 + |H_d^0|^2 + |\nu_{L,f}|^2 = 0$$

$$|H_u^0|^2 - |H_d^0|^2 - |\nu_{R,f}|^2 = 0$$

$$|\nu_{R,f}|^2 - |\nu_{L,f}|^2 = 0$$

is larger than just

$$\boxed{H_u^0 = \nu_{R,3} = \nu_{L,3}}$$

for instance

$$\boxed{H_u^0 = H_d^0}$$

c.f. Ibanez et. al, “Higgsotic inflation” arXiv:1411.5380