Predictive Theories of Inflation + Dark Energy

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Precision Cosmology

- Inflation

  CMB - n_s, $dn_s/d\ln k$, T/S, ...

  Probes High Energies

- Dark Energy

  $q = q(z)$ $\quad w = w(z)$

  Probes nature of our Vacuum

Inflation:

- Acceleration $V(\phi)$ Very Flat, Low Curvature
  Small Self Coupling

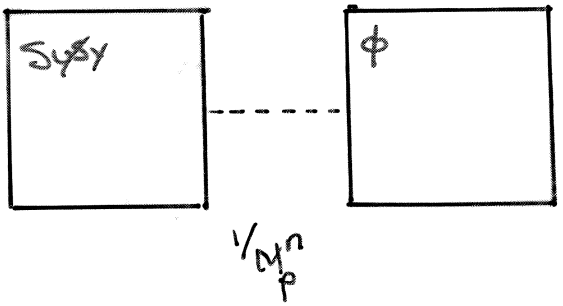
$$\frac{d^n V}{d\phi^n} \lesssim H^2 M_p^{2-n} \qquad \frac{H^2}{M_p^2} \lesssim 10^{-10}$$

↳ tuning

- SUSY

Moduli - Natural Directions $V(\phi) = 0$ SUSY

~~SUSY~~ $V(\phi) = m^2 M_p^2 f(\phi/M_p)$



↳ Hubble Scale mass

Inequalities Saturated $m^2 \sim H^2$

Typically Need Additional factor 10^{-3}

$n_s \simeq 1$

- String Landscape Huge -
  Might be Regions Flat Enough Predict $N \sim N_{min}$

- Mechanism further Flatten $V(\phi)$

  Requirements

  - Ingredients Generic Not too Clever, Intricate

  - Calculable in Low Energy Theory

    - Small Field Inflation $\Delta\phi \ll M_p$
      Renormalizable Terms Only

    - Large Field Inflations $\Delta\phi \geq M_p$
      Possible?
      All Non-Renormalizable Terms ---

* - Predictive

  Can Draw $V(\phi)$ ----

  Quantum Theory

  - Q-Stable technically Natural
  - Finit # of Parameters
    & Predictions (Very Insensitive)

- Kinetic Seizing

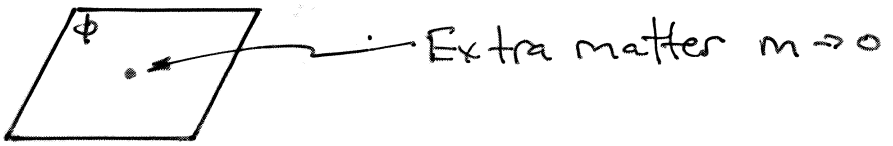
$Z(\phi)\,\partial\phi\,\partial\phi + V(\phi)$ $\qquad g_{ij} = \partial_i \partial_j Z$

↳ Large Kinetic Inertia
Slows Down inflaton Motion

Canonical Field - Suppresses Self Caplings
↳ Flattens Potential

Large Z Can Arise from IR Dynamics , γ

- Enhanced Symmetry Points on Moduli Space

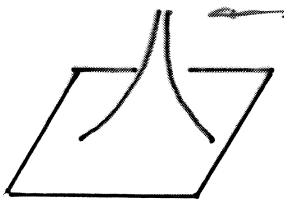


Origin of Coulomb, Higgs Branches $m_\gamma \to 0$

Extra Matter - SCFT - Gauge Dynamics ← (large Fraction)

$\partial\phi$ —( )— $\partial\phi$ $\qquad Z(\phi) \sim \left(\frac{M}{|\phi|}\right)^{\gamma}$

↳ Power Law Large !



Long Throat -
Stretches
Potential.

- Moduli + $V_{soft}(\phi)$

$$Z(\phi)\,\partial\phi\,\partial\phi + V(\phi)$$

Wavefunction + Vertex Q-Corrections

Exact Results - RG Evol. SUSY

V_{soft}

Holomorphic	$f(\phi)$	Closely Related SUSY
Non-holomorphic	$f(\phi^*,\phi)$	Not Related SUSY

But $m^2\phi^\dagger\phi$ Special

$$K \supset Z\phi^\dagger\phi \qquad Z = 1 + z\theta^2\bar\theta^2 m^2 \qquad \gamma = \frac{\partial \ln Z}{\partial \ln \mu}$$

Super Space β-fcns

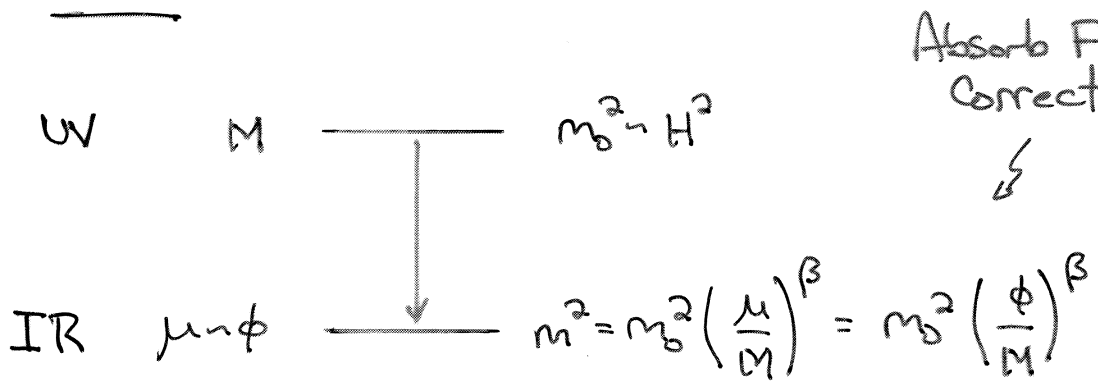
$$\beta_H = \Gamma(\tilde H) = \gamma(H) + \frac{\partial \Gamma}{\partial H}(H)\,\tilde H$$

SCFT — Known Exactly — Unknown — But $g\gamma' \sim \gamma$

- Super Conformal Points on Moduli Space

$$V = V_0 + m^2 \phi^\dagger \phi + \cdots$$

RG effect on m^2



Super Conformal Attractive Fixed Point $\gamma' > 0$, $m^2 \downarrow$

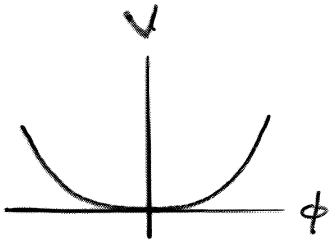
Not a miracle

$$V = V_0 + m^2 \frac{|\phi|^{2+\beta}}{M^\beta} + \cdots$$

$D(m^2) > 2$

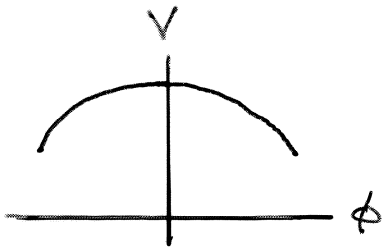
↳ Flattening

Two Possibilities:



$m_0^2 > 0$

$\Delta\phi \gg M_p$



$m_s^2 < 0$

Tachyonic
ϕ Rolls Away
from Super Conformal Point

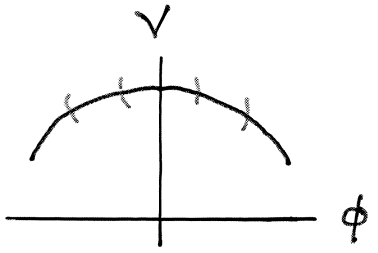
*

- Example SQCD $\frac{3}{2} N_c < N_f < 3N_c$

$M = Q\bar{Q}$
$B = Q \cdots Q$
$\bar{B} = \bar{Q} \cdots \bar{Q}$

Include Holomorphic Susy + m_λ ...

Inflation on



Regions

i) $\phi < H$ CFT Matter Relevant

ii) Eternally inflating Region - Initial Conditions

$$\dot{\phi}_{ce} \simeq -\frac{V'}{3H}$$

$$\phi < \left(\frac{H^2}{M_0^2}\left(\frac{M}{H}\right)^{\beta}\right)^{1/(1+\beta)} H$$

$$\langle \dot{\phi}^2 \rangle \sim H^4$$

iii) $\partial\phi\,\partial\phi\,\frac{(\partial\phi\,\partial\phi)^n}{\phi^{4n}}$ $\frac{\dot{\phi}^2}{\phi^4}$ Same as i)

iv) $\frac{\delta\rho}{\rho+p} \sim \frac{H^2}{2\pi\dot{\phi}} \sim \frac{3}{(1+\beta/2)}\,\frac{H^2}{2\pi M_0^2}\,\frac{H M^{\beta}}{\phi^{1+\beta}}$

$$H < \phi\Big|_{\substack{\text{Horizon}\\ \text{Crossing}}} < M$$

v) e-foldings ϕ increases

$$N \sim \frac{3H^2}{(1+\beta/2)m_\phi^2}\left(\frac{M}{\phi}\right)^\beta$$

Doesn't Depend on Details of How inflation Ends

vi) H.O.T. $V(\phi)$

$$\frac{m_\phi^2}{M_p^2}\phi^4 \lesssim m^2\phi^2$$

$$\phi < \left(\frac{m_\phi}{\tilde{m}_0}\frac{M_p}{M^\beta}\right)^{1/(1-\beta)}$$

Outside CFT Region

vii) End SUSY / Reheating $\frac{\delta\rho}{\rho} \sim 10^{-5}$, $N \sim 60$

H	β_{m^2}	T_R
10^8 GeV	0.66	10^3 GeV
10^4 GeV	0.26	Direct Coupling MSSM

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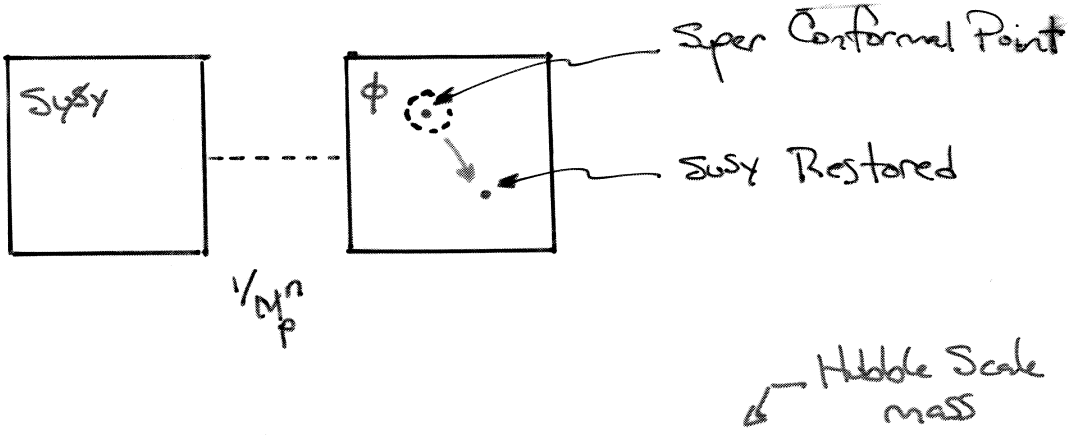

Inequalities Saturated $m^2 \sim H^2$

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Predictions

Inflation took Place on Calculable Part of $V(\phi)$

H^2, m_0^2, β

1. $\frac{\delta\rho}{\rho+p} \sim \frac{H^2}{2\pi\dot{\phi}}$

   ↳ small, H small

   $r = T/S$ Unobservably Small

2. Spectral Index

   $n_S \simeq 1 - \frac{2(1+\beta_{m^2})}{N} \simeq 0.95 - 0.98$

   Red Spectrum

3. Slope of Spectral Index

   $\frac{dn_S}{d\ln k}$ Unobservably Small

Inflation Conclusions

- Generic Mechanism --
  flatten SUSY Potential Moduli

- Ingredients Generic
  String Landscape --- Eternally inflating
  Vacuum Selection

- Predictive --

Extremely Light Scalars $m_\phi \ll m_{3/2}$

- Dark Energy Modulus $V(\phi)$

  Kinetic Seizing $Z \sim \left(\frac{H_0}{M_P}\right)^{\beta = 1/2} \sim 10^{30}$

  $m_\phi^2 \sim m m^{-1} \rightarrow m^2 \sim H_0^2$!!!

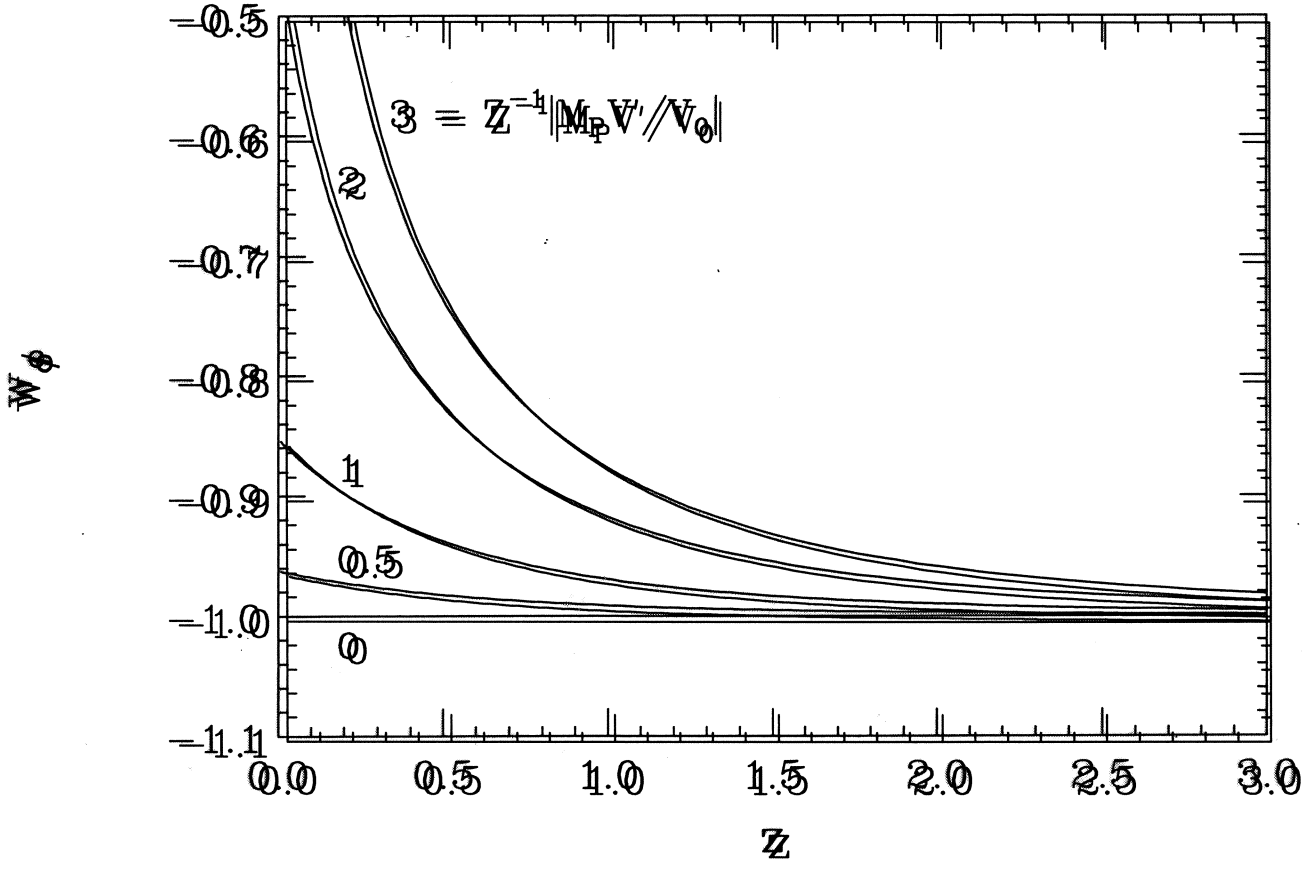
  few-Parameter family of Predictions $w = w(z)$ Plots ...

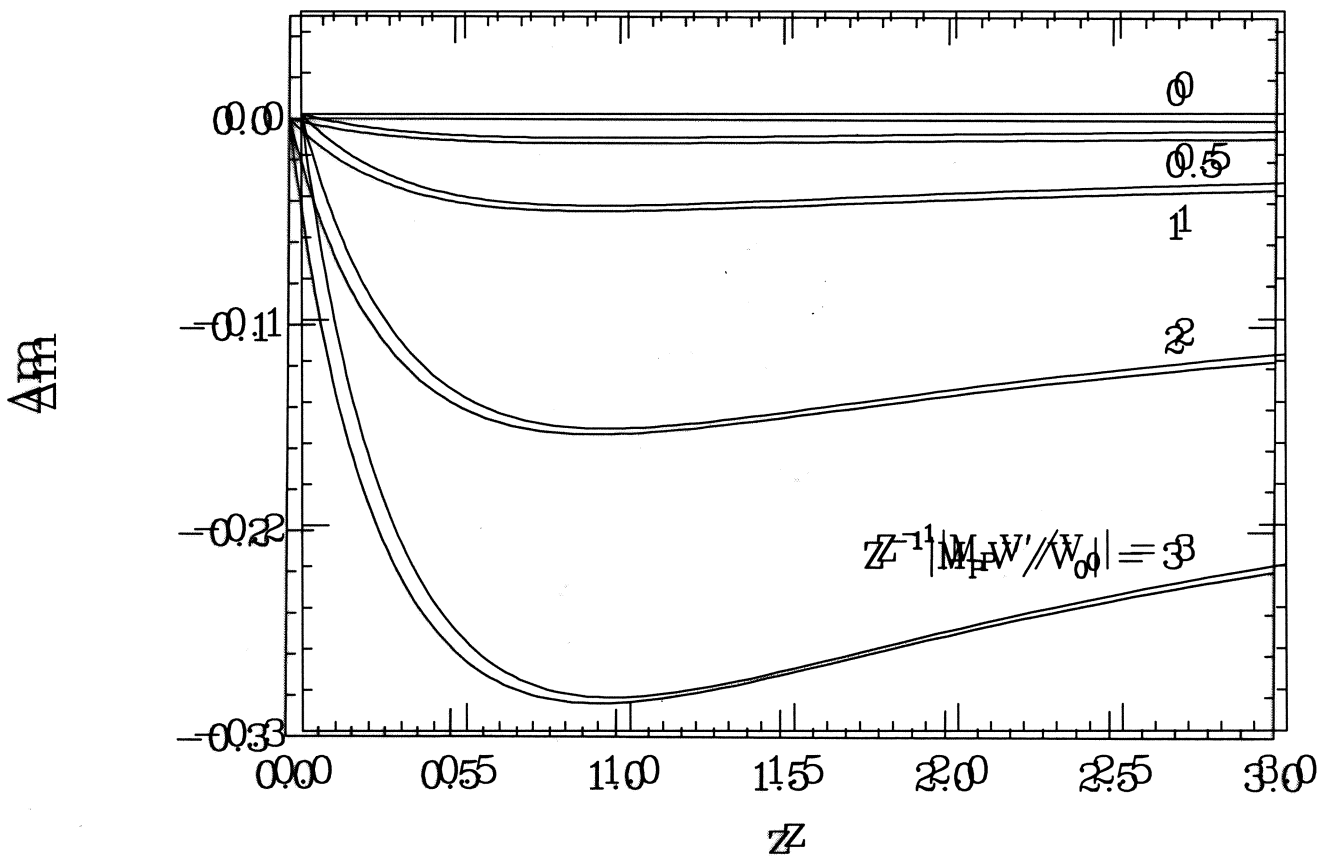
  CC Problem c.f. Quintessence

- Very Long Range Sub-gravitational Forces

  VEP 10^{-15} -- $V \sim \frac{1}{r^{1+\beta}}$

- EWSB


−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
−1.1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3 = Z^{-1}|M_P V'/V_0|
2
1
0.5
0
w_φ
z


0.0
−0.11
−0.22
−0.33
0.000
0.550
1.100
1.650
2.200
2.750
3.300
0
0.5
1
2
3