Wyma '05

EXTRA-DIMENSIONAL GRAVITY -

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

$\mu, \nu = 1, \ldots, n$
$(n > 4)$

EXTRA DIMENSIONAL

GRAVITY

INTERESTING (SOLVABLE) POSSIBILITIES WITH EXTRA DIMENSIONAL COSMOLOGY

L Randall

Missing Slide

XTRA D & COSMOLOGY

- EXTRA D should be relevant to Cosmology
- After all, you're changing dimensions of space
- BRANE, XTRA-D COSMOLOGY IN EARLY STAGES
  - DIFFICULT !
    - EE more difficult when $g_{\mu\nu}(t)$
    - SINGULARITIES, HORIZONS still not understood
      - NOT POSSIBLE w/ only QFT
      - need QG, string theory
    - Abundance of Possibilities; where to start?
- Today, I will talk about a few tractable scenarios; well understood

① Late Time Cosmology - Csaki Grojean LR Terning

② SUSY DM Redux (Anomaly-mediated) LR Moroi

③ STATIC BRANES and INFLATION Arkani-Hamed LR Weiner

INTRO

- Extra dimensions not unlikely
  - Consequences for PP?
  - Consequences for cosmology?

best if consistent with 4D but better than 4D

- In Particle Physics, we now are aware of some potential implications

I. Large Extra Dimensions

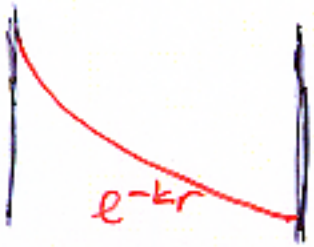
new parameter, volume, to address hierarchy - large ratio of masses

$$M_P^2 = M_{n+4}^{n+2} V_n$$

but large parameter required

II. Warped Extra Dimensions

(NOT LED!)

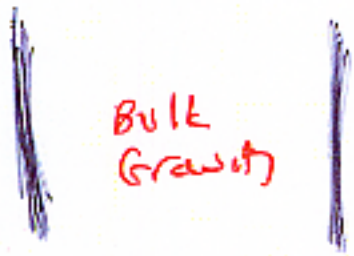


$$\text{TeV} \sim e^{-kr} \underset{\sim M_{pl}}{M}$$

- hierarchy due to exponential → as was good with technicolor
- size not large $\log(10^4) \sim 3.5$
- TeV stable against radiative corrections

III. SEQUESTERING

LR SUNDRUM



- TRUE hidden sector
- no direct coupling SUSY ↔ SM

$\Rightarrow m^2_{ij} S^\dagger S \, \phi_i^\dagger \phi_j$

not flavor conserving

- no flavor changing neutral currents
- SUSY communicated via gravity

Anomaly - Mediated masses

$$M_i = -\frac{b_i g_i^2}{16\pi^2} M_{SUSY}$$

Anomaly-mediated Gaugino Masses

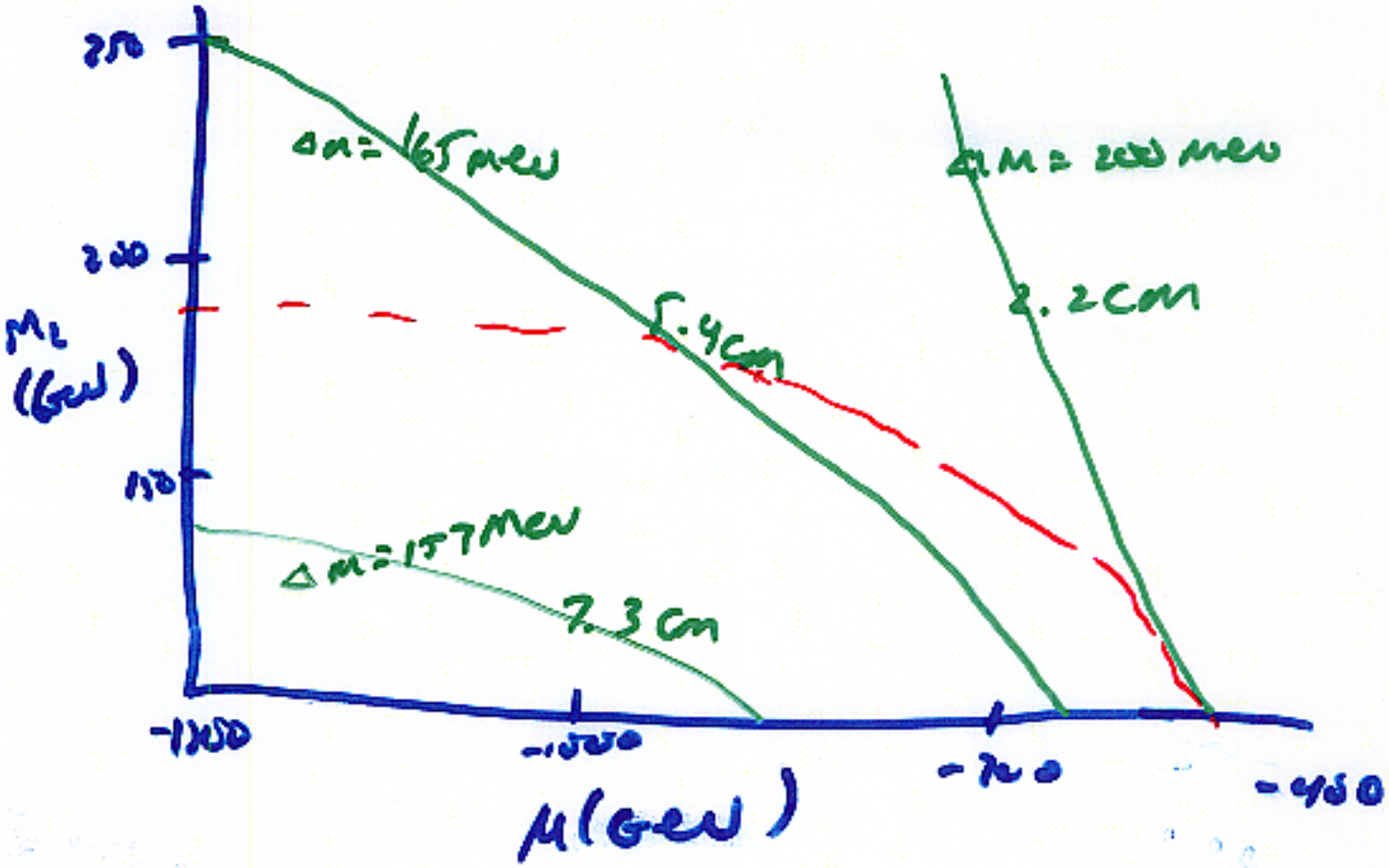
$$M_i = -\frac{b_i g_i^2}{16\pi^2} M_{SUSY}$$

$$M_1 : M_2 : M_3 = 33 : 1 : -6$$

- WINO LSP!
- M_{SUSY} ~10 - 100 TeV
- $M_2 \lesssim$ 200 - 300 GeV
  travels ~3cm
- Fermilab should search for short stopped tracks

$$\tilde{W}^+ \to \tilde{W}^0 + \text{tiny energy in } \pi$$

DISCOVERY POTENTIAL

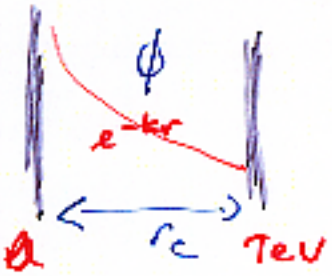


--- DISCOVERY REGION

FENG MOROI LRSTRASSLER SU

COSMOLOGY

A. Standard Big-Bang Cosmology should be standard: LATE TIME COSMOLOGY SHOULD MIMIC 4 DIMENSIONS



Need ϕ to stabilize r_c

Below $m_\phi \sim$ TeV, Standard cosmology

(LED: 10 MeV hard)

Csaki, Graesser, LR, Terning

$$M_p^2 = \frac{M^3}{k}\left(1 - e^{-kr_c}\right)$$

$$H^2 = \frac{1}{3M_p^2}\left(\delta V_{Pl} + \delta V e^{-4kr_c}\right)$$

+ bulk contribution

Dark matter?

Above $m_\phi \sim$ TeV useful to use 4D holographic interpretation

Arkani Hamed, LR, Pratt, Rattazzi

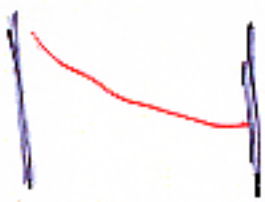
high energy inflation on Planck brane

no problem with high energy

reheat

cool

↓



Inflationary Universe

Cosmology

B) Dark Matter

- other brane, bulk, bent brane

Many possibilities: too unconstrained

Potentially interesting LIGO signature

LIGO but no optical signature

* • SEQUESTERED SUSY, MODULI, DARK MATTER

Anomaly-mediated, sequestered SUSY

- Avoids cosmological moduli problem !
- More dectable SUSY DM !

SUSY MODULI PROBLEM(S)

- $M_{scalar} \sim \frac{M_{SUSY}^2}{M_{pl}} \sim$ TeV
- $\Gamma \sim \frac{M_{scalar}^3}{16\pi^2 M_p^2}$

1) Moduli decay <u>AFTER</u> nucleosynthesis
2) Over production of LSP $\left.\frac{\rho_{LSP}}{s}\right|_{today} \sim 10^{-5}\,\text{GeV}\left(\frac{m_{LSP}}{100\,\text{GeV}}\right)\left(\frac{T_R}{100\,\text{GeV}}\right)\left(\frac{100\,\text{GeV}}{m_\phi}\right)$
   $(n_\phi \sim n_{LSP})$

   $\left.\frac{\rho_{cr}}{s}\right|_{today} \sim 3.6\,h^2\,10^{-9}\,\text{GeV}$

   too much mass density in LSP's

1) Solved if heavy modulus (but why all heavy)

2) Even then, Problem 2

BOTH PROBLEMS SOLVED BY SEQUESTERING

BONUS $\tilde{w}$ Dark Matter Much Easier to Detect!

1) Moduli $\sim 10 - 100$ TeV

2) Decay to LSP a good thing

$\sigma_{\tilde{w}\,\text{annihilation}} > \sigma_{\tilde{\gamma}\,\text{annihilation}}$

$\sim g^2 \qquad \sim e^2$

Big $\sigma \Rightarrow$ too little Dark Matter if standard relic abundance

Moduli decay supplies needed Dark Matter density

more efficiently annihilate

Don't overclose universe

and very massive

MASS DENSITY OF WINO LSP:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \bar{N}_{LSP}\,\Gamma_\phi n_\phi - \langle v_{rel}\,\sigma\rangle n_\chi^2$$

$$\frac{dn_\phi}{dt} + 3Hn_\phi = -\Gamma_\phi n_\phi$$

$$\frac{d\rho_{rad}}{dt} + 4H\rho_{rad} = (m_\phi - \bar{N}_{LSP} m_\chi)\Gamma_\phi n_\phi + 2m_\chi \langle v_{rel}\,\sigma\rangle n_\chi^2$$

$$\langle v_{rel}\,\sigma_{\bar{w}^0\bar{w}^0 \to w^+w^-}\rangle = \frac{g_2^4}{2\pi}\frac{1}{m_\chi^2}\frac{(1-x_w)^{3/2}}{(2-x_w)^2}$$

$$\Gamma_\phi = \frac{1}{2\pi}\frac{m_\phi^3}{\Lambda_{eff}^2}$$

Decay occurs when $\Gamma_\phi \sim H$

$$T_R \sim \left(\frac{\pi^2}{90} g_*\right)^{-1/4}\sqrt{\Gamma_\phi m_*} \sim 7.7\,\text{MeV}\left(\frac{m_\phi}{100\,\text{TeV}}\right)^{3/2}\left(\frac{\Lambda_{eff}}{M^*}\right)^{-1}\left(\frac{g_*}{10^{25}}\right)^{1/4}$$

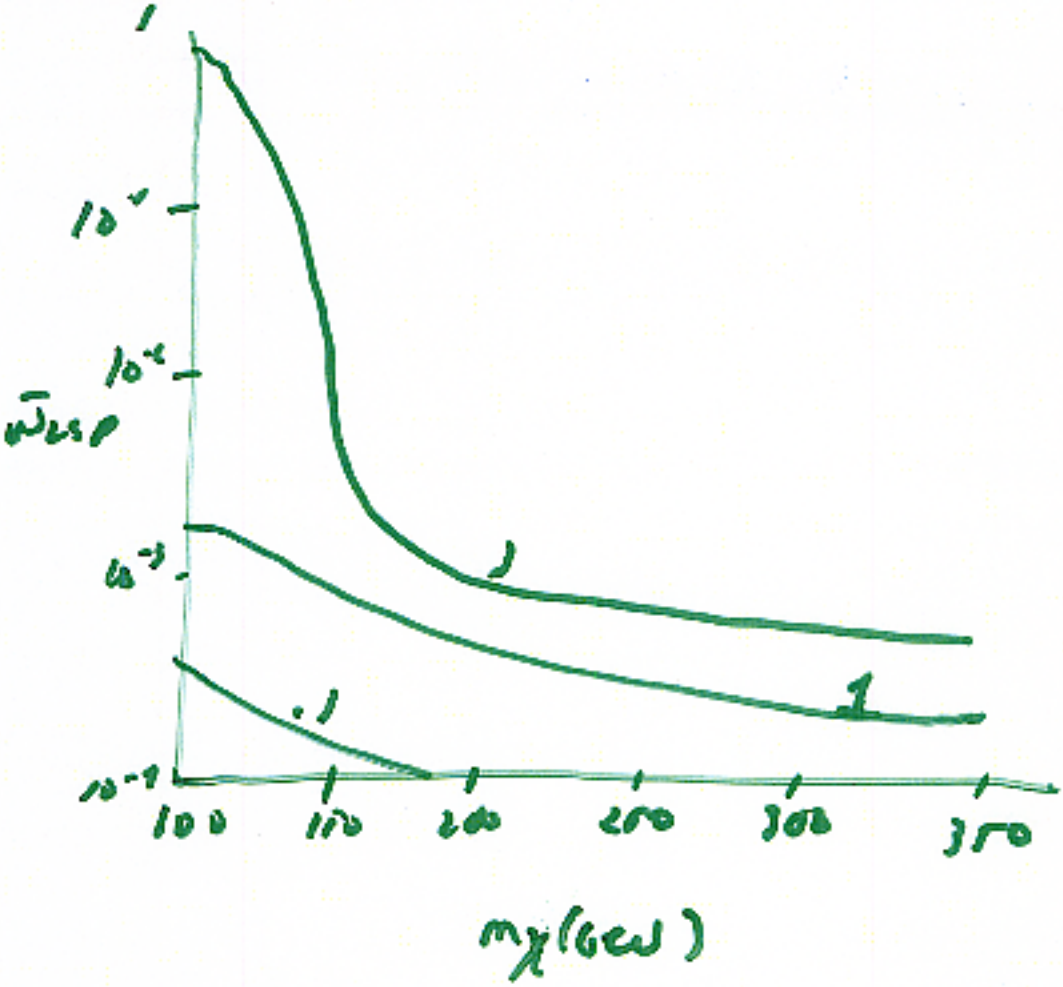
If $T_R > T_{dec}$

$$\Omega_\chi^{(thermal)} h^2 \simeq 5\cdot 10^{-4}\left(\frac{m_\chi}{100\,\text{GeV}}\right)^2$$

MUCH TOO SMALL

BUT $T_{dec} \sim \frac{1}{30} m_\chi \Rightarrow T_R < T_{dec}$

LSP from decay never in chemical eqm: # density ↓ thru annihilation



$\rho \sim \rho_c$ viable possibility

DETECTION

Cake + eat it too!

- Bigger cross-section
  Good for detectability
- Not too few because of moduli decay Probem transformed into boon

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1. Ge detector covers much of parameter space
2. AMS might detect anti-particles
   Annihilation of Dark Matter
   ⇒ Higher flux of anti-particles 20x

WIND CDM much easier to find than $\tilde{\gamma}$ CDM

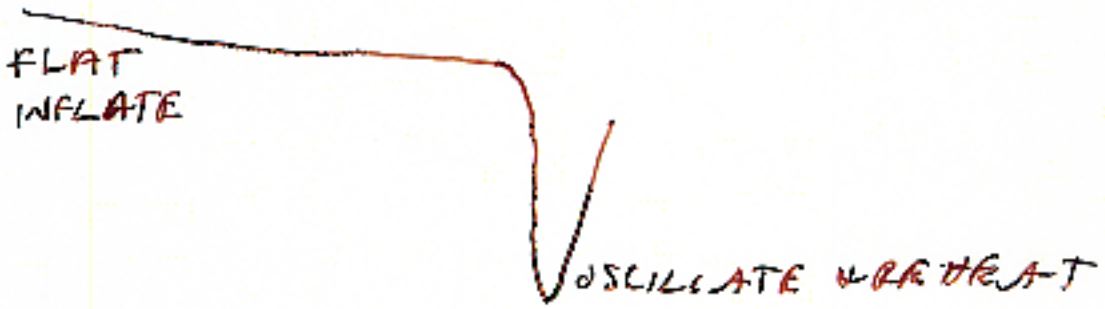
c) SEQUESTERING & INFLATION

Arkani-Hamed
LR
Weiner

- INFLATION CLEARLY REVELS IN ITS SUCCESS TODAY

- DOESN'T ELIMINATE THE GHOST IN THE CLOSET
  - what is the inflationary potential?

- CARTOON



Chaotic: eg $\lambda\phi^4$ $\lambda \sim \beta^{1/2}$
$n \sim \beta^{15}$ GeV

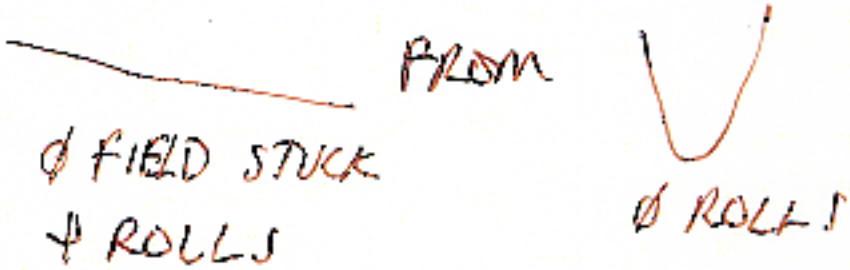
need SUSY to maintain scale origin?

HOW TO MAKE A NATURAL MODEL OF INFLATION?

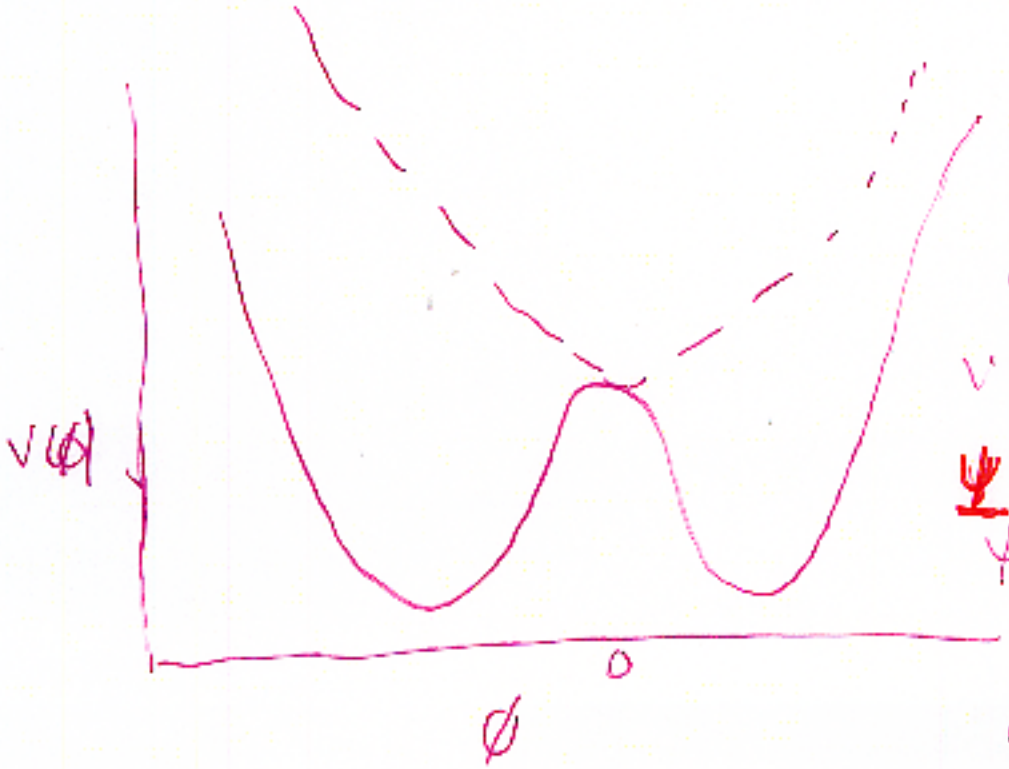
HYBRID (2 FIELD) INFLATION — CNDE

MAKES BIG STEP FORWARD

SEPARATES



eg: $V(\phi,\psi) = \frac{\lambda}{4}(\phi^2 - J)^2 + \frac{1}{2} m_\psi^2 \psi^2 + \frac{1}{2}\lambda' \psi^2 \phi^2$



$\psi > \psi_c$

$\Rightarrow \varphi = 0$

$(\psi_c^2 \sim \lambda/\lambda' J)$

$V(\underset{=0}{\psi}) \sim \frac{1}{4}\lambda m^4 + \frac{1}{2} m^2 \phi^2$

SLOWROLLS!

$\psi < \psi_c$

$\phi \to \sqrt{J}$

INFLATION ENDS

NATURAL?

$m_\phi > m_\psi$

$m_\psi << H$

$\Rightarrow$ supersymmetry to protect mass (maybe WARPING?)

BUT EVEN w/SUSY, Large correction to ψ mass Copeland Liddle Lyth Wands

$$V \supset e^{8\pi \frac{\psi^\dagger \psi}{M_p^2}} \underbrace{(D_i W)(k_{ij})^{-1}(D_j \bar{W})}_{\substack{\text{energy} \sim M^4 \\ \phi \text{ potential energy}}}$$

$$\Rightarrow m_\psi^2 \sim \frac{8\pi M^4}{M_p^2} = 3H^2$$

contribution to ψ mass that manifestly exceeds slow-roll condition

Still need unnatural tuning, even w/SUSY

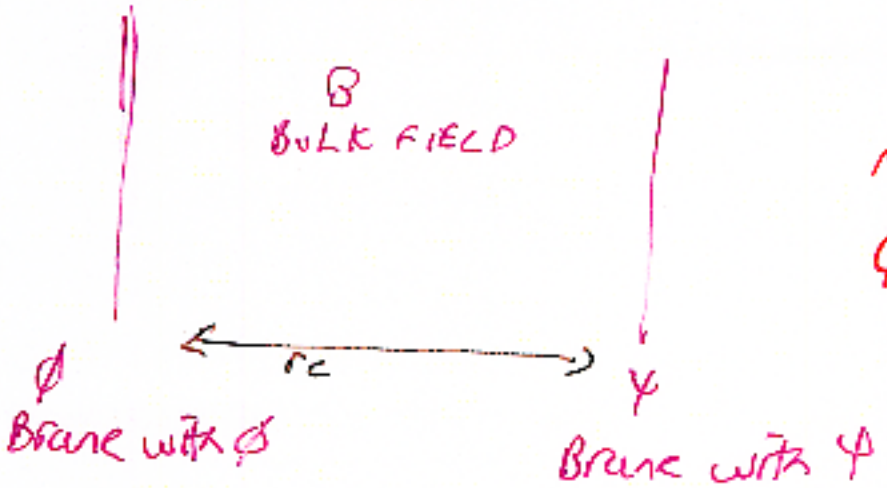
Nothing prevents

$$K \supset \frac{\phi^\dagger \phi \psi^\dagger \psi}{M_p^2} \quad !$$

BRANES & XTRA D TO THE RESCUE

SEQUESTERING

Arkani-Hamed
L.R.
Weiner



NO LOCAL
$\phi^\dagger\phi\ \psi^\dagger\psi$
INTERACTION!

$$W > \frac{1}{\sqrt{M_1}} B\phi^2\delta(0) + \frac{1}{\sqrt{M_2}} \bar{B}\psi^2\delta(0) + m_B B\bar{B} + \delta(0)\, S(\phi^2 - J)^2$$

$$\Rightarrow \underset{\text{w/ B integrated out}}{W} > \frac{\phi^2\psi^2 e^{-m_B r_c}}{\sqrt{M_1 M_2}}$$

absorb scales

$$V > \frac{\phi^2\psi^4}{M^2} + (\phi^2 - J)^2$$

REQUIREMENTS

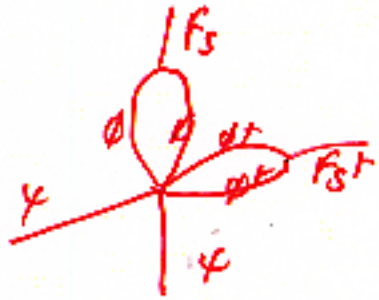
1) $\frac{\psi_i^4}{M_1 M_2} > J$ hybrid INFLATION CONDN

② Density perturbations $\frac{J^3}{m_\psi^2 M_p^3 \psi_{end}} \sim 10^{-5}$

③ sufficient # e-folds

$$N \sim \frac{4\pi J^2}{m_\psi^2 M_p^2} \log\left(\psi_f/\psi_i\right) > 60$$

④ NO LARGE CORRECTION TO ψ MASS



EASY: PROTECTED TO 2 LOOPS

$$\Rightarrow m_\psi^2 \sim \left(\frac{m_\phi}{16\pi^2}\right)^2 \left(\frac{m_\phi}{M_p}\right)^2$$

VERY SMALL

SUCCESS: LARGE VIABLE PARAMETER RANGE

- $m_\phi \sim 10^{-3} M_p$ $\quad m_\psi \sim 10^{-6} m_p$

- $m_\phi \sim 10^{-7} M_p$ $\quad m_\psi \sim 10^{-6} M_p$

  $m_\phi \sim M_I$

  $m_\psi \sim 100\,\mathrm{GeV}$

  $\sim \frac{M_I^2}{M_{pl}}$

  NICE PARAMETERS

  HIERARCHY PROTECTED

- Clearly just one example
- Extra Dim + Branes (even static ones) change complexion of model building
- Even simple straightforward calculable modifications can be relevant

CONCLUSIONS

- EXTRA D COSMOLOGY RICH
- MUCH LEFT TO EXPLORE