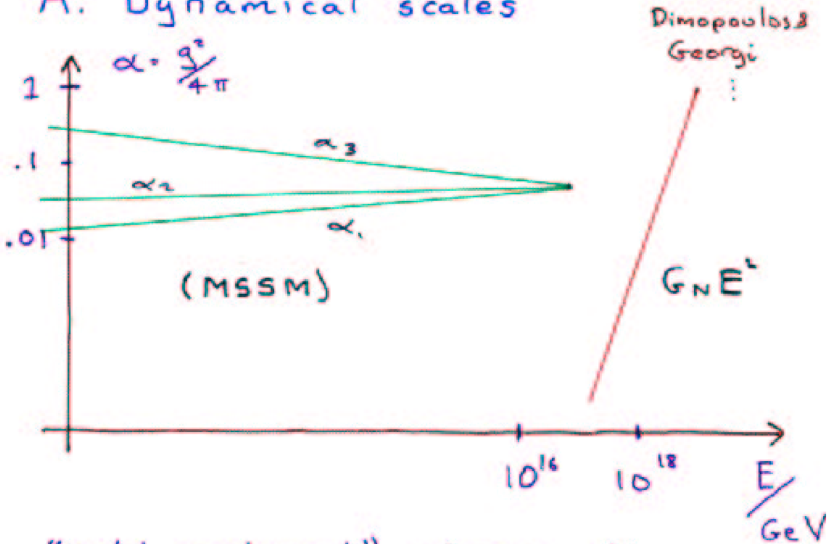
# I. String theory and experiment

## A. Dynamical scales




"old school" string theory

Quantum theory of gravity

$$m_{pl} = (8\pi G_N)^{-1/2} \sim 2.4 \times 10^{18}\ \text{GeV}$$

Unified theory

$$m_{GUT} \sim 2 \times 10^{16}\ \text{GeV}$$

both >> TeV!



Two frameworks:

1) "Large extra dimensions"

fundamental dynamical scale:

$$m_* \sim m_{EW} \sim \text{TeV}$$

Arkani-Hamed, Dimopoulos, Dvali

d-dimensional spacetime:

$$X_d = \mathbb{R}^4 \times \tilde{X}_{d-4}$$

$$S^{(d)}_{grav} = m_{pl,d}^{d-2} \int d^d x \sqrt{g}\, R$$

$$m_{pl,d} \sim m_*$$

$$S^{(4)} = \underbrace{m_{pl,d}^{d-2}\, V_{\tilde{X}}}_{m^2_{pl,4}\ \text{- derived}} \int d^4 x \sqrt{g}\, R$$

$d = 2$: $V_{\tilde{X}} \sim (mm)^2$

gravity at LHC!

2) "Conventional" unified models

a) $d = 10$ string theories

$\vdash \ell_s \dashv$ Tension $\sim 1/\ell_s^2 \equiv m_s^2$

$X_{10} = \mathbb{R}^4 \times \tilde{X}_6$ — "Calabi-Yau" w/ $N=1$ SUSY in $d=4$

dynamical scales:

$$\left.\begin{array}{l} m_{KK} \sim V_{\tilde{X}}^{-1/6} \\ \\ m_s,\ m_{pl,10} \end{array}\right\} \sim m_{GUT}$$

$m_{pl,4}$ still derived

3

b) $d = 11$ M-theory

$X_{11} = \mathbb{R}^4 \times \tilde{X}_7$

$N = 1$ SUSY:

i) $\tilde{X}_7 = X_6^{CY} \times \underset{E_8 \qquad E_8}{\overset{\vdash L \dashv}{\bullet\!\!-\!\!-\!\!-\!\!-\!\!\bullet}}$ Hořava & Witten

ii) $\tilde{X}_7$ "$G_2$ manifold"

gauge dynamics on $d=7$ "defect" $\mathbb{R}^4 \times \Sigma_{d=3}$ Witten Acharya ⋮

dynamical scales:

$m_{pl,11} \gtrsim m_{GUT}$

$m_{KK} \lesssim m_{GUT}$ w/ CY, $G_2$

$L \sim 100/m_{GUT}$

4

# B. Experiments and $M_{GUT}$

1) Indirect tests

a) Extrapolate w/ RG

Assume SUSY at $M_Z \sim 90$ GeV

Assume "desert" $M_{EW} < \Lambda < M_{GUT}$

couplings unify

b) Wait a long time

eg proton decay - via

exchange of particles

w/ mass $M$

$$\tau = \# \frac{M^{2\Delta-8}}{m_p^{2\Delta-7}} \gtrsim 10^{32} \text{ yrs}$$

$\Rightarrow M \sim M_{GUT} \quad (\Delta = 6)$

rules out some GUTs!



2) Direct measurements?

Look for $E \sim M_{GUT}$ processes

in the sky

Inflation:

- Simplest models: $V_{inf} \sim M_{GUT}^4$
- Quantum fluctuations

$$\lambda \sim (10^{14} \text{ GeV})^{-1}$$

$\downarrow$

CMBR anisotropies $3^\circ K + \underline{\underline{\delta T}}$

Large scale structure

New high-precision CMBR measurements:

- MAP satellite (Microwave Anisotropy Probe) taking data now
- Planck Surveyor satellite est. launch 2007
- Polarization measurements

Accuracy in $\delta T / T$ @ <u>fundamental limits</u> (only one universe)

$$\boxed{\text{May be sensitive to dynamics at } E \sim \underset{M_{GUT}}{10^{14}\,\text{GeV}} \;?}$$



# II. Inflation and the CMBR

## A. CMBR and the "horizon problem"

- When universe $\sim 10^5$ yrs old
  Temp $\sim 1$ eV $\sim 10^4$ °K

$$\gamma + e^- + \text{nuclei} \quad \text{- black body}$$
$$\downarrow$$
$$\gamma + \text{(neutral) atoms}$$
"recombination"

- $\gamma$ propagates freely, redshifts as universe expands

2.7° K black body radiation
"<u>C</u>osmic <u>M</u>icrowave <u>B</u>ackground <u>R</u>adiation" COBE etc.

## Horizon problem:

At angles $\delta\theta \gtrsim 0.8^\circ$ on sky:

2 objects at $t_{\text{recombination}}$ are causally disconnected

But $\delta T/T \sim 10^{-4}$ at all $\delta\theta$ on sky



## Structure formation:

Density fluctuations $\delta\rho/\rho$ at $t_{\text{recombination}}$

gravitational collapse

Large scale structure

galaxies, clusters, ...

Temperature fluctuations

$\frac{\delta T}{T}$ in CMBR observed

So we need to generate small $\delta\rho/\rho$

# B. Inflation

- Assume "cosmological constant" when universe $\sim 10^{-38}$ sec. dominates

Guth

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \cancel{8\pi G_N T_{\mu\nu}} + \Lambda g_{\mu\nu}$$

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$H^2 = \frac{\Lambda^2}{3 M_{Pl,4}^2}$$

- $\|\delta x(t)\| = e^{Ht} \|\delta x(0)\|$

$\|\delta x\| > 1/H$ - causally disconnected

"horizon"

Correlated objects rapidly separate



- If universe grows $\sim e^{60}$

"60 e-foldings" $\sim 10^{-35}$ sec

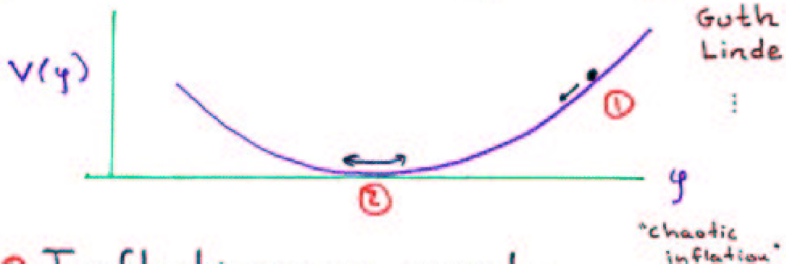
Solves the horizon problem

Leads to flat universe

curvature

Eventually "ordinary" matter / radiation must dominate

$\varphi$ : "inflaton"  $\mathcal{L} \sim (\partial\varphi)^2 - V(\varphi)$




① Inflationary epoch

$\dot{\varphi}^2, \varphi\ddot{\varphi} \ll V; \quad \dot{H} \ll H^2$  "slow roll"

$H^2 = \frac{V}{3m_p^2}$ ; $\dot{\varphi} = -\frac{1}{3H}\partial_\varphi V$

② "Reheating"  $\dot{\varphi}^2, \ddot{\varphi}$ dominate

$1/\omega_{inf} < 1/H$

$\varphi$ decays $\longrightarrow$ "ordinary" particles

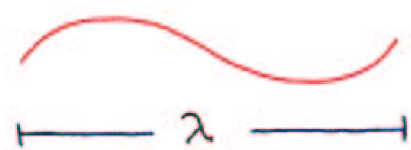


C. Inflation $\rightarrow$ $\delta\rho(x)$, $\delta T(x)$

density  CMBR temp.

- Definitions of wavelength

$$ds^2 = -dt^2 + e^{2Ht}\, d\vec{x}^2$$




$\lambda_c$ measured in coordinates $\delta\vec{x}$

"comoving" wavelength

$\lambda_p$ measured in proper distances

"physical" wavelength grows

Comoving $k_c = \frac{1}{\lambda_c}$ conserved

- Quantum fluctuations of $\varphi$

$\lambda_{phys} \sim \frac{1}{H}$ quantum fluctuations "freeze into" classical perturbations $\delta\varphi$

Hawking radiation

$$\langle \delta\varphi^2 \rangle \Big|_{\lambda_{phys} = 1/H} = \frac{H^2}{(2\pi)^2}$$

- These convert to density perturbations

$$\delta\rho \cdot V'(\varphi)\,\delta\varphi$$

$$\delta\varphi^2 (p_{phys} = H) = \langle \varphi(p)\,\varphi(-p) \rangle$$

15

- Scale of fluctuations <u>now</u>


- $\delta\varphi_{cl}$, $\delta\rho$ generated at $t_i$

$$\lambda^{-1}_{phys}(t_i) = p_{phys} \cdot H(t_i)$$

$$\delta\varphi^2_{cl} \cdot \langle \varphi(p_{ph})\,\varphi(-p) \rangle \Big|_{p_{ph} = H}$$

- Fluctuation stretches

$$\lambda_{end}(t_i) = \frac{1}{H(t_i)} \exp\left\{ \int_{t_i}^{t_e} H(t)\,dt \right\}$$

late $t_i \longrightarrow$ small $\lambda_e$

- Angular scale on sky

$\delta\theta(\lambda_e)$ monotonic, $\sim \lambda_e$ for small $\lambda_e$

$\delta\varphi$ continually produced, stretched

All angular scales

16

• Density inhomogeneities

$$\frac{\delta\rho}{\rho}\Big|_{end}(\lambda_e) = C\,\frac{H}{\dot\varphi}\,\delta\varphi\,(t_i(\lambda_e))$$

$$= \tilde{C}\,\frac{V^{3/2}}{m_p^3\,\partial_\varphi V}\,(\varphi(t_i(\lambda_e)))$$

$$\frac{\delta T}{T_{CMBR}}(\delta\theta) = \underbrace{S(\lambda_e(\delta\theta))}_{\text{computable, depends on known physics}}\,\frac{\delta\rho}{\rho}\Big|_{end}(\lambda_e)$$

↑ measured

CMBFAST

$$\frac{\delta\rho}{\rho} \sim 5\times 10^{-5}$$

COBE
⋮



# D. Primordial gravity waves

$$\delta h_{\mu\nu} = e^1_{\mu\nu}\,\psi^1 + e^2_{\mu\nu}\,\psi^2$$

physical polarizations
(after gauge fixing)

$\psi^i$ - essentially scalar fields

Classical perturbations
generated just as for $\delta\varphi$

$$(\delta\psi^i_{cl})^2 = \langle \psi^i(p_{phys})\,\psi^i(-p)\rangle\Big|_{p_{phys}=H}$$

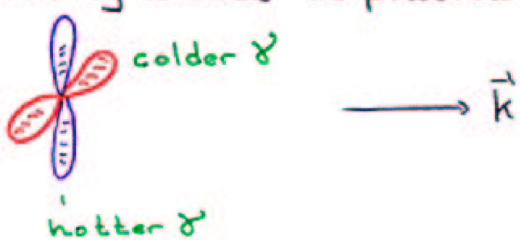
$$= \frac{H^2}{(2\pi\,\underbrace{m_{pl,4}}_{\text{normalization of }\psi})^2}$$

- $\delta h_{\mu\nu}$ has distinct signature

generally, $\gamma_{CMBR}$ polarized by

Thomson scattering
off $e^-$ before
recombination

Gravity waves in plasma:




Spin-2 character of $\delta h$:
unique polarization
signature



Measurable by polarization-
sensitive detectors

$$A_T(\delta\theta(\lambda_c)) = \tilde{D}\,\frac{\sqrt{V}}{M_p^2}\,(\varphi(t(\lambda_c)))$$

Direct measurement
of $V_{inf}$ if we can
measure $A_T$

## E. Scales of inflationary dynamics

Simplest models

$$V(\varphi) = M_1^4 \, f\left(\varphi / M_2\right)$$ Banks et al ⋮

1) Demand "slow roll" for $\gtrsim 60$ efolds

$M_2 \sim$ few $\times$ $M_{pl,4}$

$\langle \varphi \rangle \sim M_2$

2) $\delta\rho/\rho \sim 5 \times 10^{-5}$ from COBE

$M_1 \lesssim M_{GUT}$!

3) Upper bound from ~~polarization~~

$M_1 \lesssim 1.7 \times 10^{16}$ GeV

$H \lesssim 7 \times 10^{13}$ GeV



- Inflaton potential $V(\varphi)$

  "fine-tuned"

Dimensionless coupling

$$\lambda \sim \partial_\varphi^4 V(\varphi) \sim \left(\frac{M_1}{M_2}\right)^4$$

$\ll 10^{-8}$ $(\sim 10^{-12})$

Hard to explain small numbers!

(quantum corrections)

SUSY?

## III. Effects of short-distance physics

$$\left(\frac{\delta\rho}{\rho}\right)^2(\lambda_0) = D^2\,\frac{H^2(t_i(\lambda_0))}{\dot{\varphi}^2}\,\langle\varphi(p_{phys})\,\varphi(-p)\rangle_{p=H}$$

H is relevant dynamical scale

Assume new physics at

$$\Lambda_{UV} \gg H$$

$\Downarrow$

"Integrate out" momenta $p > H$

$\downarrow$

$$S_{eff}^{H} = \int^{H} d^4p\,\{\varphi(p)\,K(p;H,\Lambda_{UV},\ldots)\,\varphi(-p)+\cdots\}$$

use $S_{eff}$ to compute

$$\langle\varphi(p=H)\,\varphi(-p)\rangle$$

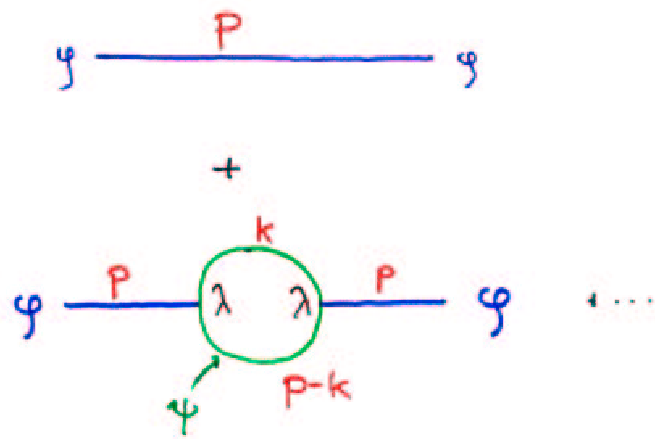
23

## Example:

$$\mathcal{L}_{int}^{\Lambda_{UV}} = \lambda\,\varphi\,\bar{\Psi}\Psi + m\,\bar{\Psi}\Psi + \ldots$$

$m \gg H$

$\langle\varphi(p)\,\varphi(-p)\rangle =$




Compute in de Sitter space

corrections for $k \gg H$ $\sim H^2/k^2$

24

Locality at $p \lesssim H$

$\Downarrow$

$S_{eff}^{(H)}$ analytic in

$p^2$, $R_{\mu\nu\lambda\rho} \sim \partial^2 g \sim H^2$

$\mathcal{L}_{eff}^{(H)}$

$\wr$

$$\varphi(p)\varphi(-p)\left\{p^2 + 2H^2 + c_1 \frac{H^2}{\Lambda_{UV}^2} p^2 + c_2 \frac{1}{\Lambda_{UV}^2} p^4\right\}$$

($\Lambda \sim m_4$ in example?) $+ \cdots$

$$\boxed{\langle \varphi(p=H)\varphi(-p)\rangle = \frac{H^2}{(2\pi)^2}\left(1 + \chi_s \frac{H^2}{\Lambda_{UV}^2}\right)}$$

depends on $c_1, c_2$



Effect on measurable quantities:

$$\frac{\delta\rho}{\rho} \equiv A_s = \tilde{C} \frac{H^2}{2\pi\dot{\varphi}}\left(1 + \frac{1}{2}\chi_s \frac{H^2}{\Lambda_{UV}^2} + \cdots\right)$$

$$A_T = D \frac{H}{m_{pl,4}}\left(1 + \frac{1}{2}\chi_T H^2/\Lambda_{UV}^2 + \cdots\right)$$

Recall: $H^2 = V(\varphi)/3m_{pl,4}^2$

$3H\dot{\varphi} = -\partial_\varphi V$

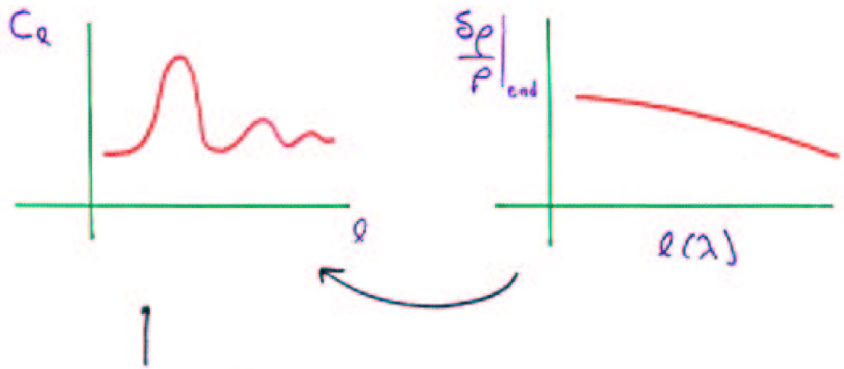
Can we extract $H$-dependence of $A_s$, $A_T$ from measurements?

# IV. Experimental detection

## A. Scale dependence of $\frac{\delta T}{T}$ & $A_T$

$$\frac{\delta T}{T} = \sum_{\ell m} Y_{\ell m}(\theta, \phi)\, C_\ell$$

$$\ell = \ell(\lambda_{end}) \sim 1/\lambda$$




Final (observed) spectrum depends calculably on post-inflationary physics

$\Omega_b$, dark matter, $\Lambda$, ...



"Nearly scale-invariant spectrum"

Recall: $\lambda_e = \lambda_e(\varphi)$ invertible

$$\ell = \ell(\lambda_e) = \ell(\varphi(\lambda_e))$$

Slow roll during inflation:

$$\Downarrow$$

$$\dot H \ll H^2$$

$$\Downarrow$$

$A_{S,T}(V, V')$ change slowly

$$\Downarrow$$

$A_{S,T}$ depends weakly on $\ell$

$$\ln A_S = \alpha_0 + (n_S - 1)\ln \ell + \nu_S (\ln \ell)^2 + \ldots$$

$$\ln A_T = \beta_0 + n_T \ln \ell + \nu_T (\ln \ell)^2 + \ldots$$

$A_S, A_T, n_S, n_T, \nu_S$: "inflationary observables"

• Functional form of $V$, $A_S$, $A_T$

$\ell$-dependence $\Longleftrightarrow$ $\varphi$-dependence

Given:

a) Theoretical input $A_S = A_S(V, \partial_\varphi V)$

$A_T = A_T(V)$

b) Experimental input:

$$A_{S,T} = \sum_n a^{(n)}_{S,T} (\ln \ell)^n$$

$\Downarrow$

• "Reconstruct" $V(\varphi)$

• "Consistency condition"

$$\boxed{n_T = -\kappa \left(\frac{A_T}{A_S}\right)^2 \left(1 + \chi_S \frac{H^2}{\Lambda_{UV}^2} + \dots\right)}$$



# B. Measurability

1) Limits on detectability

a) $A_T$, $n_S$, $n_T$ very small

competes with

• Detector noise

• Astrophysical backgrounds

b) "Cosmic variance"

Only one observable universe!

$$\delta C_\ell \sim \left(\frac{2}{2\ell+1}\right)^{1/2}$$

(sample variance)

2) Polarization measurements

- Post-inflationary physics sharply reduces signal for $\ell < 50$, $\ell > 150$

- Best (optimistic) case
  Cosmic variance-limited measurement of $A_T$ for $50 \leq \ell \leq 150$

Can detect $n_T > 0.01$



$$n_T = -\chi \left(\frac{A_T}{A_s}\right)^2 \left(1 + \chi_s \frac{H^2}{\Lambda^2} + \cdots\right)$$

$$\left(\frac{A_T}{A_s}\right)^2 < 1/15$$

"New physics" observable if $\chi_s \, H^2/\Lambda^2 \gtrsim 0.1 - 1$

# V. Specific models

## A. d=4 field theories (GUTs)

- Renormalizable interactions at $\Lambda_{UV} \sim m_{GUT}$

ex: $\mathcal{L}^{UV}_{int} \sim \lambda \varphi \bar{\Psi} \Psi + m \bar{\Psi} \Psi$

$m \sim m_{GUT}$

now recall: $\varphi \sim$ few $\times\, m_{pl,4}$ during inflation

$$m_\Psi \sim \lambda \varphi + m \sim \lambda m_{pl,4} + m$$

$$\lambda^2 H^2 / m_\Psi^2 \lesssim \frac{H^2}{m_{pl,4}^2} \sim \underline{\underline{10^{-10}}}$$

This is unobservable!

- $\gtrsim m_{GUT}$ effects in 4D models generically unobservable



Notable exception:

$$\lambda \varphi + m \sim \lambda'(\varphi - \varphi_0)$$

$\varphi = \varphi_0$ at some time during in inflationary epoch

Chung et al

Feature in $A_T$, $A_S$ at $\ell(\varphi_0)$

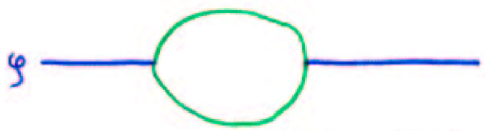
## B. Can we increase effect?

$\chi_s \, H^2/M_{pl,4}^2$ big if $\chi_s \gg 1$

eg: <u>many</u> particles couple to $\varphi$

(not so natural in 4D GUTs)

• Higher-dimensional theories:




loop integral includes sum over Kaluza-Klein momenta

This is highly divergent

Dominated by k ~ cut-off ~ $m_{pl,d}$

$$\boxed{m_{pl,d} \ll m_{pl,4} \qquad \chi \frac{H^2}{M_{pl,4}^2} \sim \frac{H^2}{M_{pl,d}^2}}$$



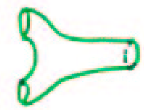
## C. String/M-theory GUTs

1) Weakly coupled string theory

$\Lambda_{UV} \sim m_s \sim M_{GUT}$

$$\chi \, H^2/m_s^2 \sim g_s^2 \, \frac{H^2}{m_s^2} \ll 10^{-6}$$

"string coupling"



$\sim g_s$

2) M-theory models

$X_7 = (CY \times \longmapsto\!\!\!|\ )$ or $G_2$

$$\chi \, H^2/M_{GUT}^2 \sim 10^{-6}$$

Better, but still unobservable

# D. Observable models

Try to lower $m_{pl,d}$

## Constraints

1) Correct $m_{pl,4} = 2\times 10^{18}$ GeV

$$m_{pl,4}^2 = m_{pl,d}^{d-2} V_{d-4}$$

2) $\alpha_{gauge} = g^2/4\pi \sim 1/25$

to get correct gauge couplings at $p \sim$ TeV

3) $m_{KK} > T_{dS} = \frac{H}{2\pi}$

quantum dynamics of $\varphi$ is four-dimensional

4) Energy densities $E_{4D}^4 = E_d^d V_{d-4}$

$$H^2/m_{pl,d}^2 = \frac{1}{3}\left(E_d/M_{pl,d}\right)^d \lesssim \mathcal{O}(1)$$



## Problems

1) Lose precision grand unification

$$m_{fund} \sim m_{pl,11} \sim 0.05\ m_{GUT}$$

2) Proton decay

- dimension 6 operators: $\tau_p \sim \frac{m_{fund}^4}{m_p^5} \sim 10^{-12}$ too small
- dimension $\gtrsim 7$ OK

# VI. Conclusions

## A. Competing effects?

- Multiple scalar fields

$\varphi_{\text{inflaton}}$ , $\sigma_i$

$V = V(\varphi, \sigma_i)$

If $\frac{\partial^2}{\partial \sigma_i^2} V \ll H^2$,

$\langle \delta\sigma_i^2 \rangle$ may contribute to $\frac{\delta T}{T}$ Linde Kofman

$$n_T = -\varkappa \left(\frac{A_T}{A_S}\right)^2 \left(1 + \chi \frac{H^2}{\Lambda^2} + f(\delta\sigma_i^2, \ldots)\right)$$

Langlois
Bartolo, Matterese, Riotto

Observable f requires additional fine tuning of
- V
- initial conditions for $\varphi, \sigma_i$



## B. Need better control of explicit models

M theory on $G_2$ manifolds

Other "brane world" models

(F-theory, D-branes on $X_6^{CY}$)

Compute $\chi_s \frac{H^2}{\Lambda^2}$ explicitly

Effects of other scalar fields

⋮

## C. Other astrophysical probes of new physics?

Example: dark matter

$\Omega_{baryon} \sim 0.015$

$\Omega_{dark\ matter} \sim 0.3$

CMBR
Galactic dynamics
Gravitational lensing data
⋮

Nature of dark matter (cold, hot, ...) effects CMBR, structure formation

Detailed properties (interactions) effect (sub)galactic structure

Spergel & Steinhardt

cf Dimopoulos, Kaloper, Kachru, Lawrence, Silverstein

42

# Short-distance physics and the cosmic microwave background

I. Introduction
II. Inflation and structure formation
III. Impact of new physics
IV. Experimental signatures
V. Observability in 4d GUTs, string/M theory

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hep-th/0201158



"Brane world" scenarios

$$M_d = \mathbb{R}^4 \times M_{d-4}$$

Gauge d.o.f. propagate on codimension k brane/singularity

$$M_{d-k} = \mathbb{R}^4 \times M_{d-k-4}$$

$$\alpha = \frac{g^2}{4\pi} \sim \frac{1}{m_{pl,d}^{d-k-4} V_{d-k-4}} \sim 1/25$$

$$m_{pl,4}^2 \sim m_d^{d-2} V_{d-4}$$

$$V_k \equiv \frac{V_{d-4}}{V_{d-k-4}}$$

$$\widetilde{V}_\ell = m_{pl,d}^{\ell} V_\ell$$

We can rewrite:

$$m_4^2 = m_d^2 \tilde{V}_k / \alpha \qquad (*)$$

Recall:

$$m_{KK} \sim \frac{2\pi}{V_k^{1/k}} \gtrsim T_{ds} = H/2\pi$$

$\tilde{V}_{d-k-4}$ fixed

Places lower limit on $m_d$ via $(*)$

k larger: can push $m_{pl,d}$ down farther



M-theory examples

1) $X_7 = X_6^{CY} \times (\bullet\!\!\longrightarrow\!\!\bullet)$, $\vdash L \dashv$ $\quad d = 11,\ k = 1$

$1/L \gtrsim 10^{12}$ GeV

$m_{pl,11} \gtrsim 6 \times 10^{15}$ GeV

$$\frac{H^2}{m_{pl,11}^2} \lesssim 10^{-4}$$

2) $X_7 = G_2$ manifold $\quad d = 11,\ k = 4$

$m_{11} \sim H \sim 7 \times 10^{13}$ GeV

$m_{KK} \gtrsim 2 \times 10^{12}$ GeV

$$H^2 / m_{pl,11}^2 \sim \mathcal{O}(1)$$