Cosmological Aspects of the Landscape

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Outline

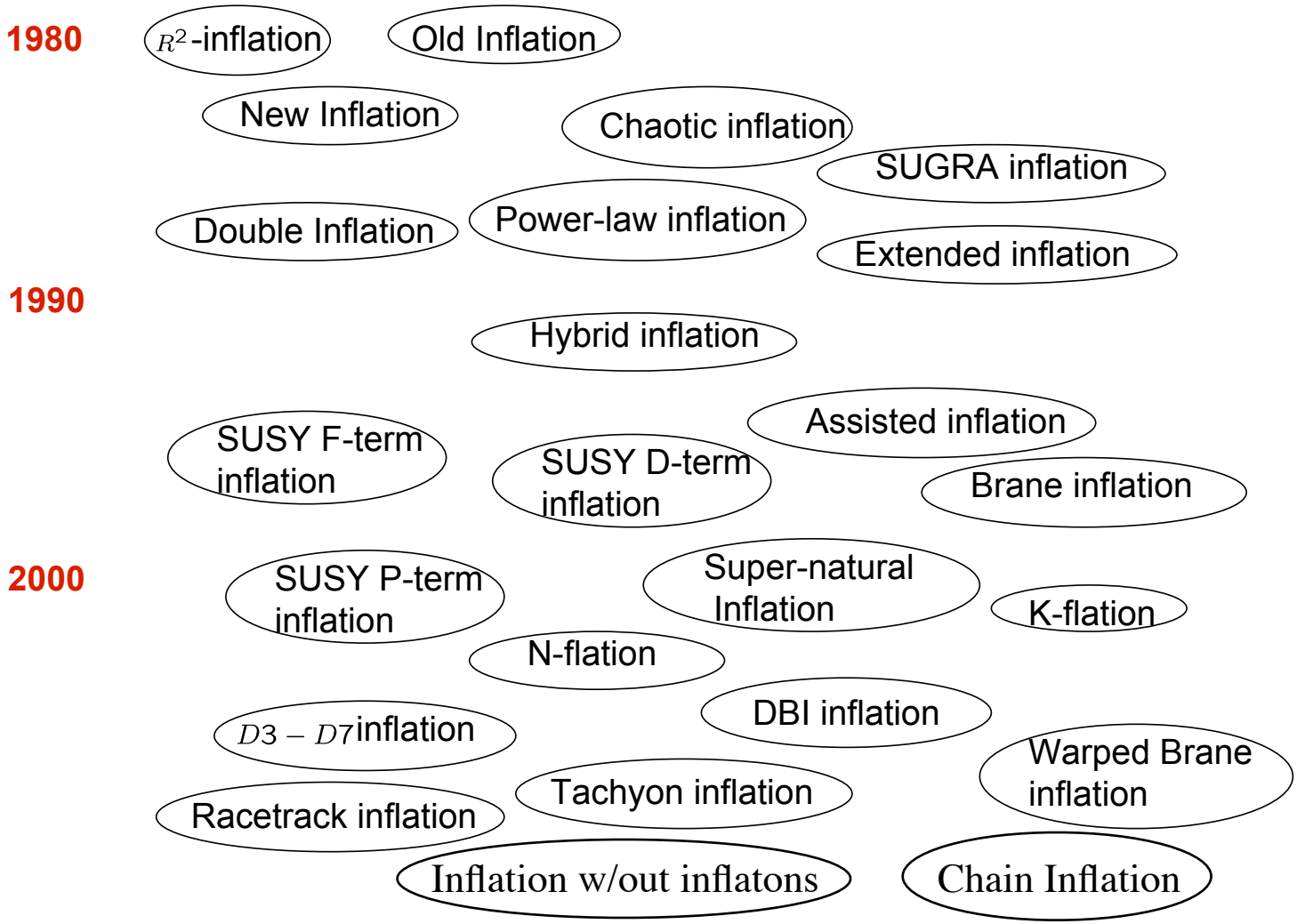
- Motivation
  - Inflation from String theory and moduli stabilization
- Dynamical moduli stabilization & enhanced symmetry
- Special case study: The dilaton
- Fluctuations of light scalars
  - Density fluctuations w/out inflatons
- Conclusions ...

Light Scalars

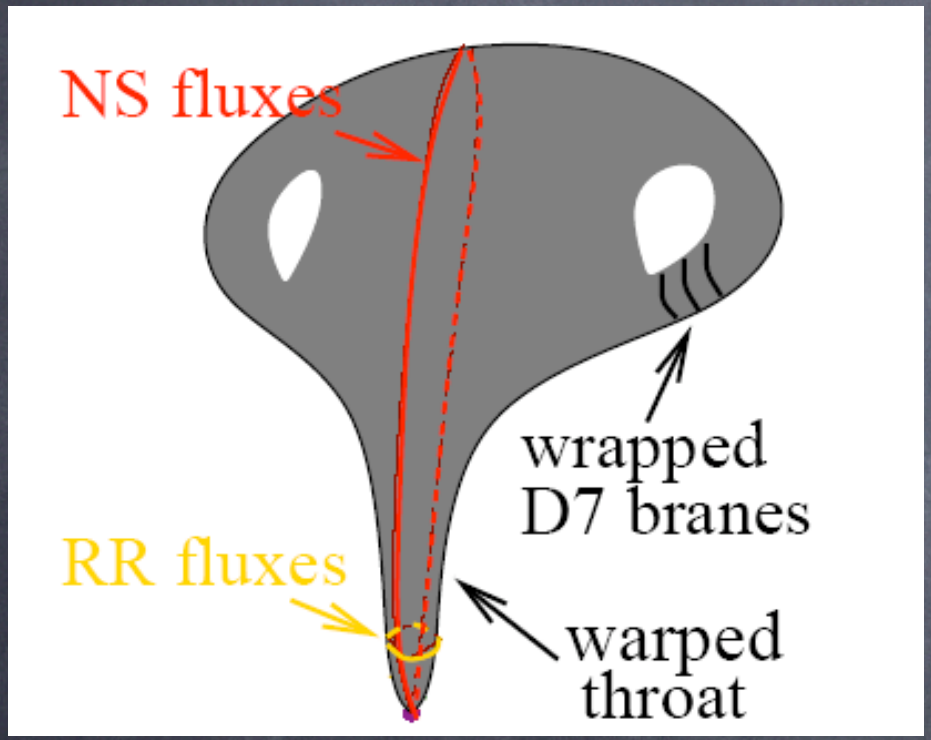
- Theories w/ extra symmetries, extra dimensions, branes, etc.. --> lots of light scalars
- Stabilizing moduli important for realistic cosmology building in string theory
- Some light scalars can be useful:
  Inflaton? Dark Energy? Dark Matter?

Inflation w/ UV completion?

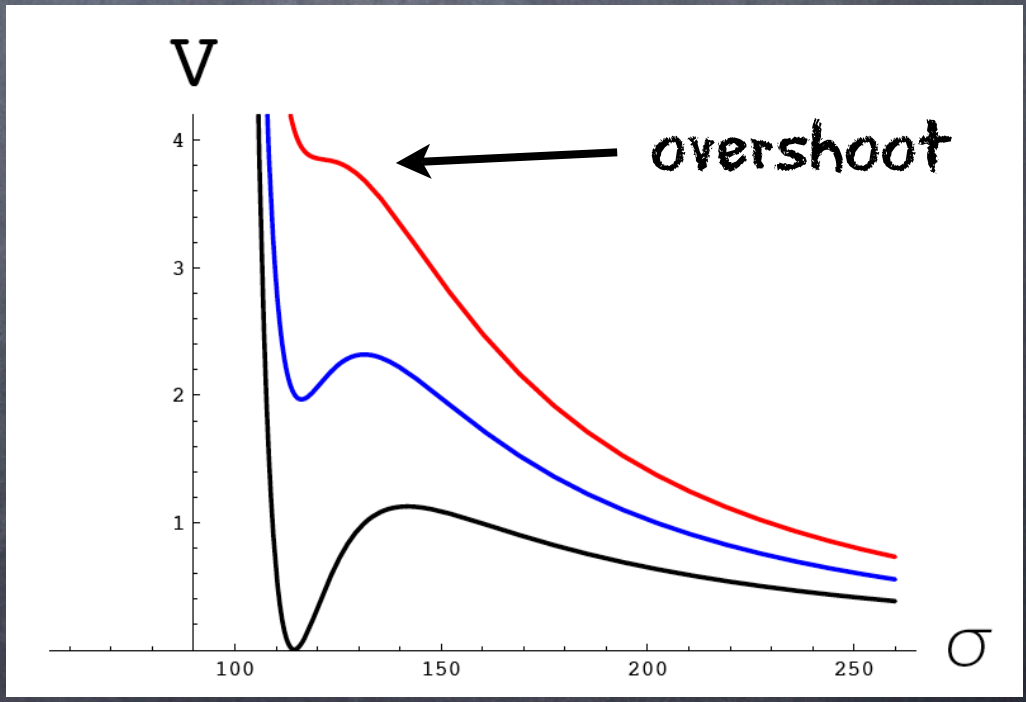
Inflation in the context of ever changing fundamental theory



Towards inflation in string theory (e.g., KKLT, KKMMMLT, BBCEGKLQ, etc..)

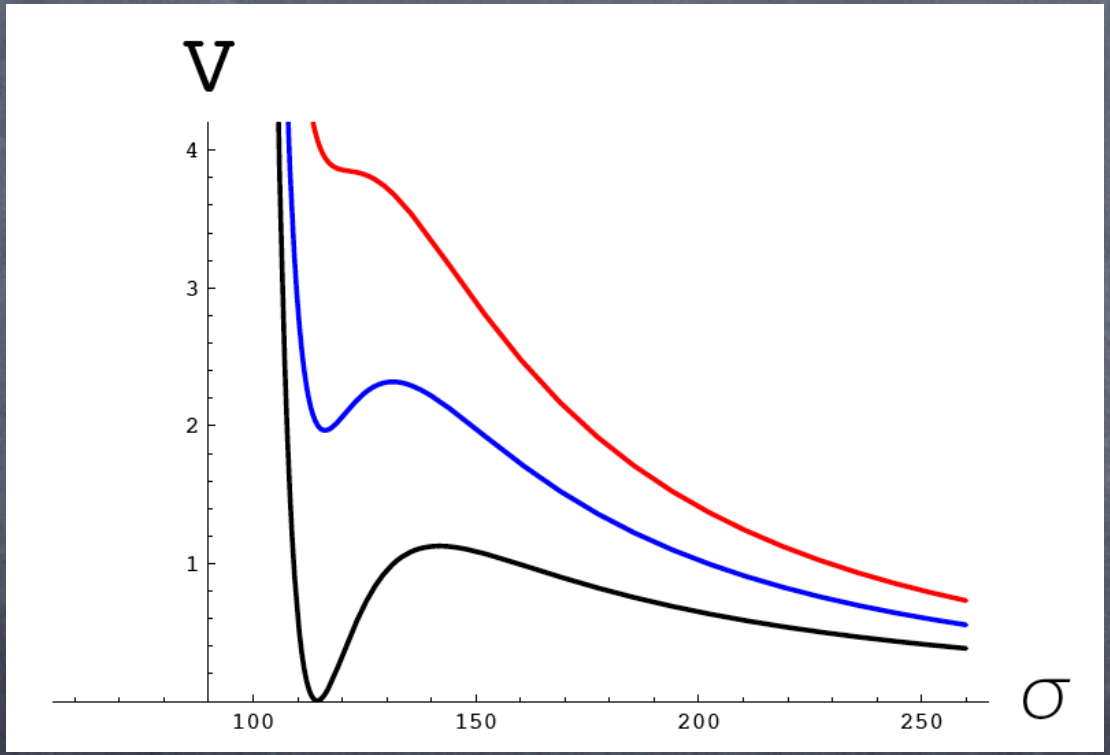


Universe is hot
--> Finite Temp.



Many moduli - flat directions to stabilize

Why do we expect to find moduli in the minimum?



Postulate a symmetry...

Review of Strings on S^1

SUGRA Massless modes:

$$R \equiv \sqrt{G_{55}} \to \phi \qquad A_\mu^{R/L} = G_{\mu 5} \pm B_{\mu 5} \qquad U(1)$$

Higgsed scalar w/ winding charge (w/ knowledge of string theory)

$$m_w^2 = m_s^2(\omega^2 R^2 - 4) \qquad w = \pm 2$$

Time dependent effective mass

$$m_w^2 = g^2 \phi^2(t)$$

Enhanced gauge symmetry - ESP @ self-dual radius

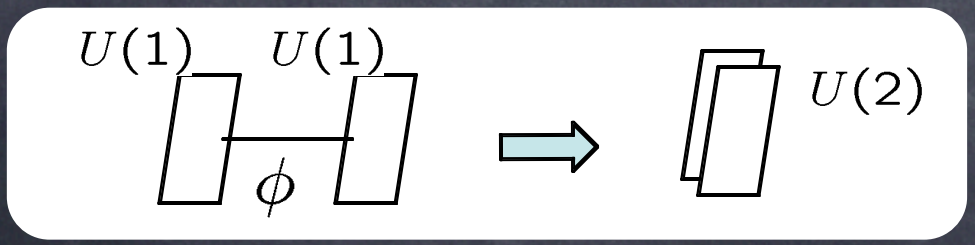
$$R \to l_s \qquad m_w \to 0 \qquad U(1) \to SU(2)$$

8 new scalars
4 new vectors

Enhanced Symmetry

Many examples of ESPs in string theory

- Heterotic strings on T^6 - Enhanced gauge symmetry
- Type II on K3 - ESPs at singularities
- Wrapped branes and strings on collapsing cycles (e.g. conifolds and flops)
- Coincident branes (open strings become light)



Moduli Trapping

- Kofman, Linde, Liu, Maloney, McAllister, Silverstein hep-th/0403001
- S.W. hep-th/0404177
- Cremonini & S.W. hep-th/0601082
- Greene, Judes, Levin, Weltman, & S.W. - to appear soon

$$\ddot{\phi} + 3H\dot{\phi} + g^2\langle\chi^2\rangle\phi = 0$$

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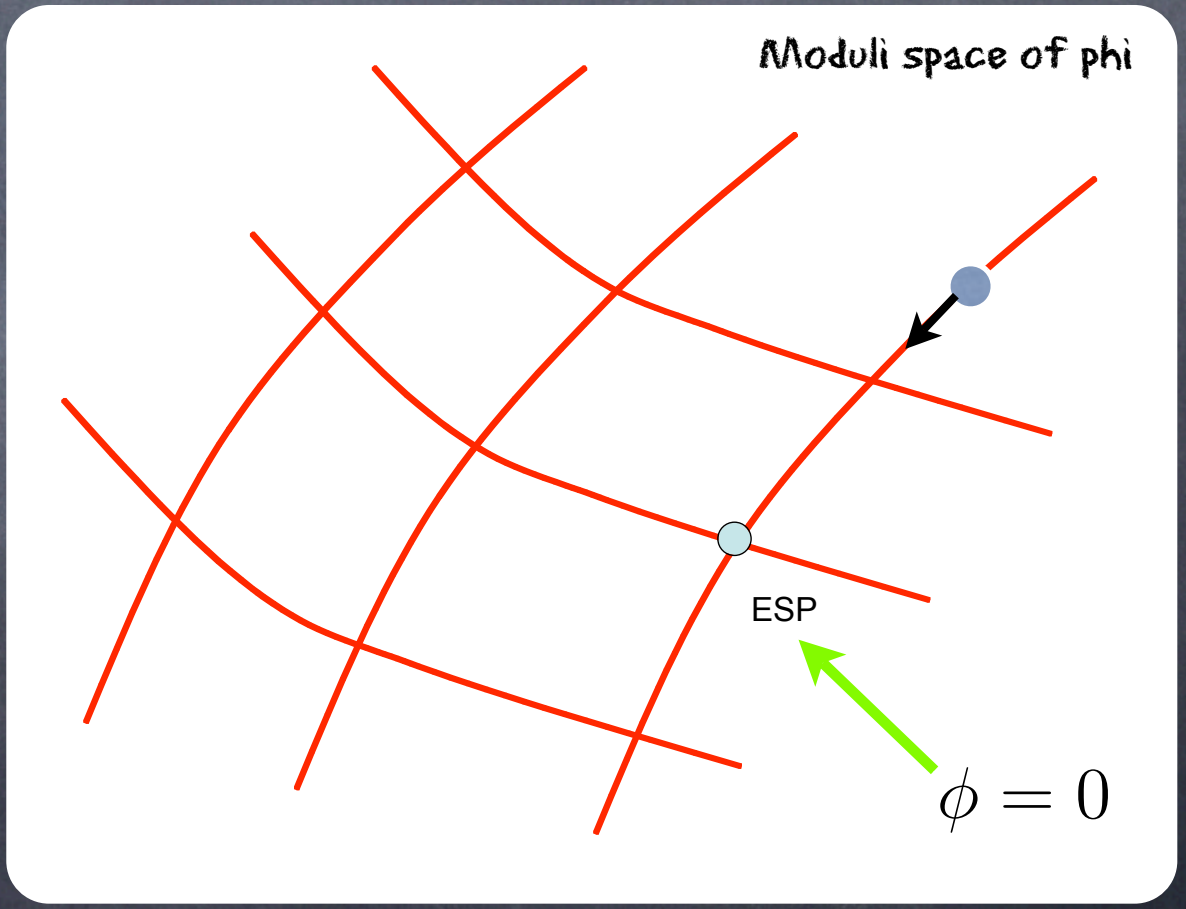
Initially: $\langle\chi^2\rangle = 0$

Adiabaticity parameter

$$\frac{\dot{\omega}}{\omega^2} \approx \frac{\dot{m}}{m^2} \sim 1$$

Near ESP modes become excited

-Particle production-



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Initially: $\langle\chi^2\rangle = 0$

Adiabaticity parameter

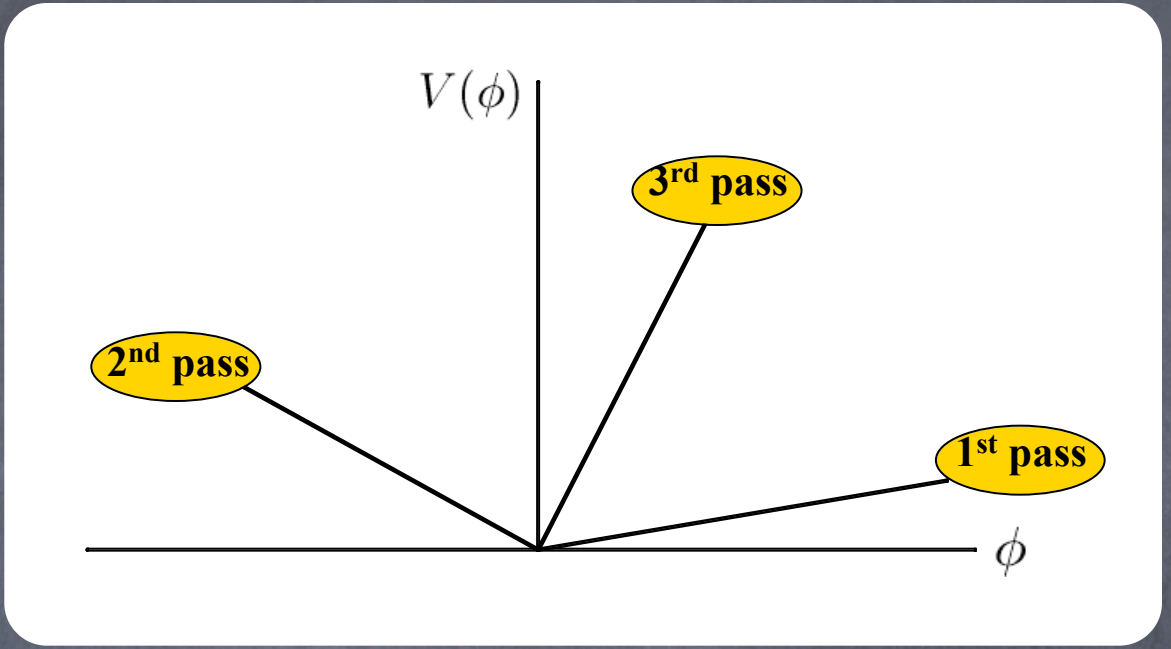
$$\frac{\dot{\omega}}{\omega^2} \approx \frac{\dot{m}}{m^2} \sim 1$$

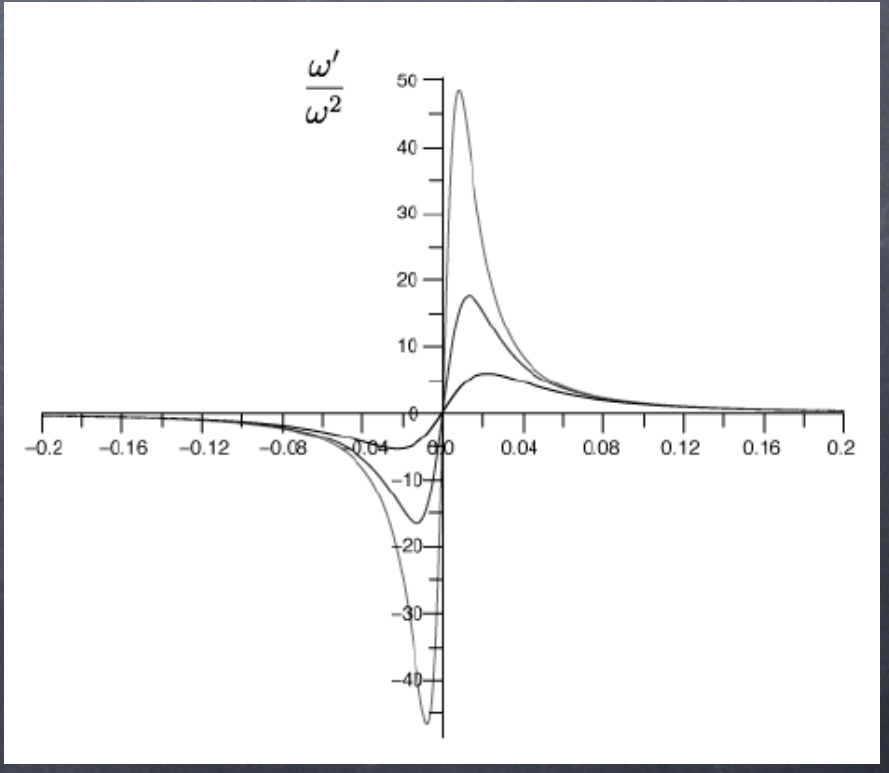
Near ESP modes become excited

-Particle production-

$$n_k \approx e^{-\frac{\pi k^2}{g v_0}}$$

$$\ddot{\phi} + 3H\dot{\phi} = -g n_\chi \frac{\phi}{|\phi|}$$





Observations

- Moduli dynamics require careful study of moduli space - new light d.o.f. (c.f. Vafa - Swampland)
- Points of enhanced symmetry seem to be dynamical attractors - some pts. in landscape preferred dynamically
- ESPs are fixed pts. of effective actions... even after phase transition (protected by symmetry - c. f. Dine)
- Fixed points of dualities natural places to find moduli
- Can moduli dynamics + gravity generate hierarchies?
- The dilaton - S-duality?

Dilaton Trapping

- Cremonini & S.W. hep-th/0601082

Heterotic String on 6-torus:

$$m^2 = m_s^2 \left(\frac{n}{R_i} - \omega R_i \right)^2$$

Trapping drives moduli to self-dual point: $R_i = 1$

Assume 11-D Poincare invariance good symmetry in M-theory

$$m^2 = m_p^2 \left(\frac{n}{R_{11}} - \omega R_{11} \right)^2 \quad ?$$

Plan of attack:

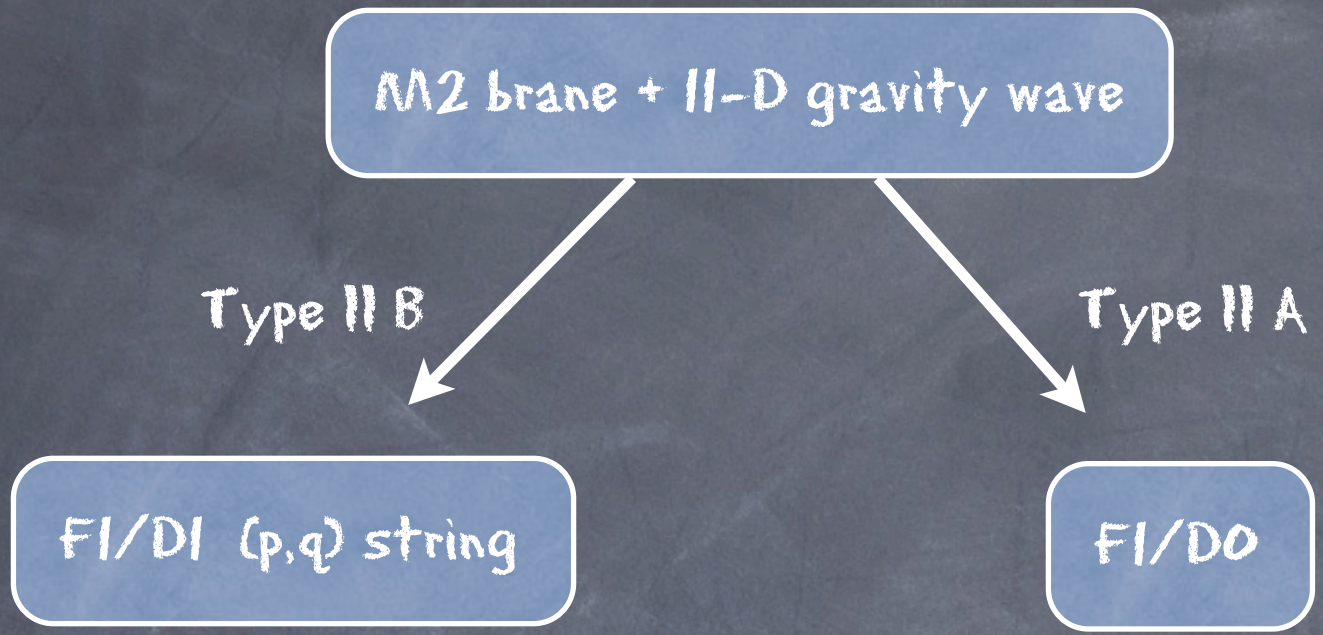
- Given Knowledge of 11 - D SUGRA Massless modes, find critical points where additional massless states appear
- In string theory case this is done by mass spectrum of string
- In M-theory --> mass spectrum of super-membrane

Supermembrane Theory:

- Quantization difficult (non-linearities)
- Not all states known to correspond to string states upon reduction
- T-duality in M-theory remains to be understood (S-duality in 10-D ?)

Possible Resolution: (Tseytlin-Russo)

- Supermembrane can be quantized in special limits (e.g. Large cycles)
- Focus on BPS spectrum --> States remain uncorrected for all values of R
- Match states to 10-D string spectrum



Mass of M2/GW state

$$M^2 = M_{11}^2 \left(\frac{n}{R_{11}} + \omega R_{11} \right)^2$$

Non-threshold - BPS

Wrapped M2 (winding mode)

Gravity Wave (KK-mode)

M2 tension & remaining cycle set scale

Membrane Production

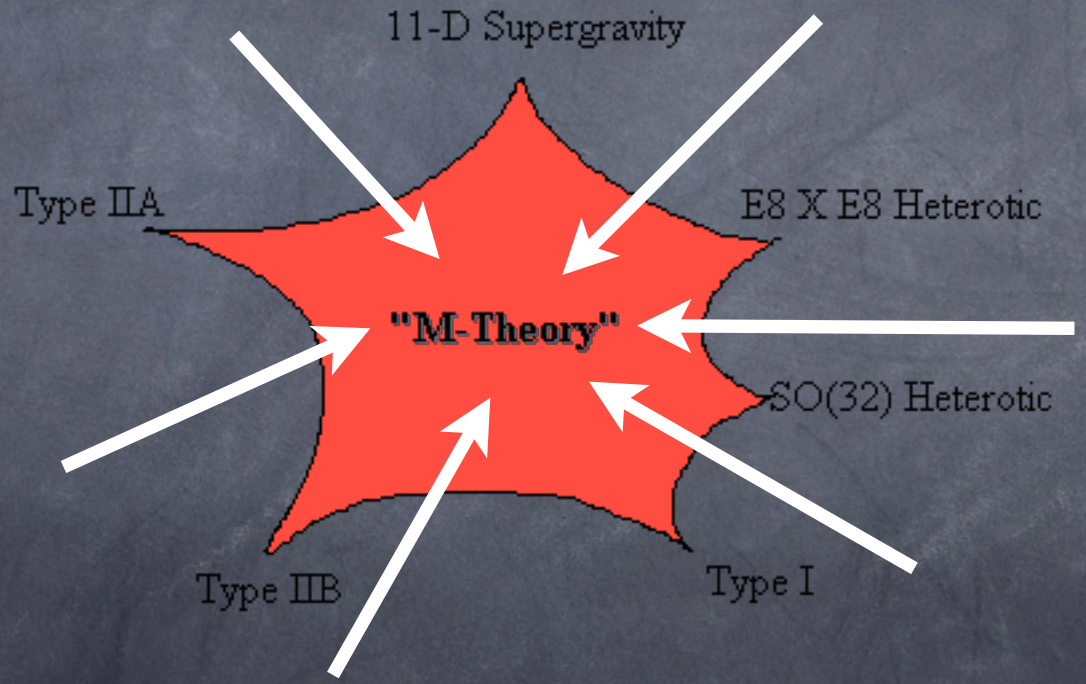
$$n_k = \left(\frac{\pi}{3}\right)^2 e^{-\frac{(n+\omega)m_p}{h}} e^{-\frac{k_3^2+h^2}{m_p h}}$$

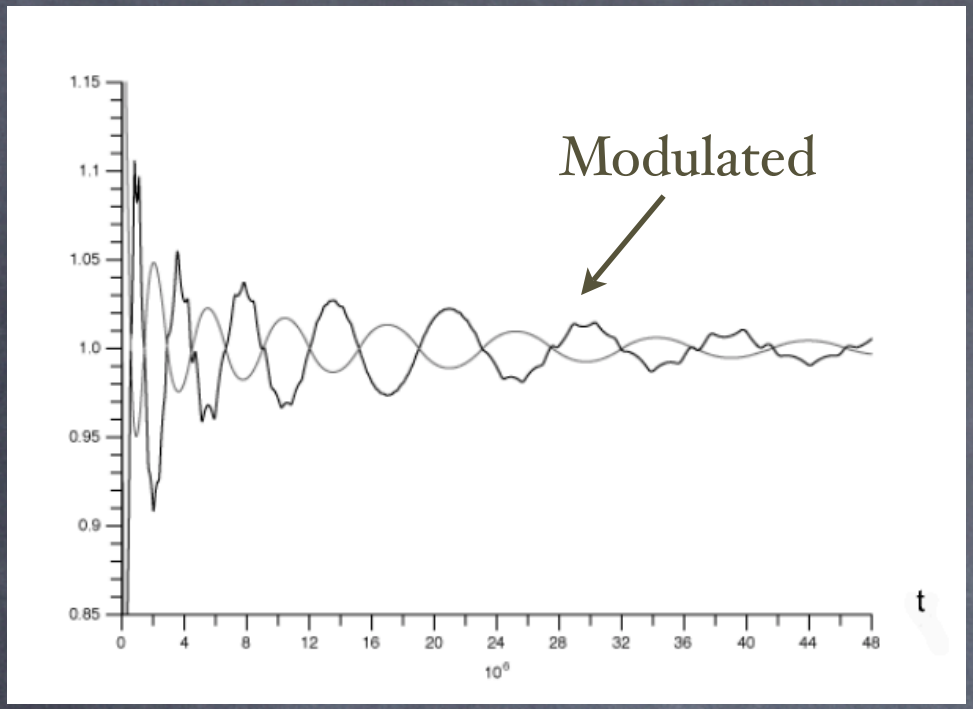
- ESP states require n,w have different signs
- This was possible in HE String because of Tachyon charge
- N=2 theory --> No tachyon charge
- Need state below SUGRA BPS bound (c.f. Vafa)
- Try compactification w/ singularities? (lesson from K3)
- Heterotic M-theory?

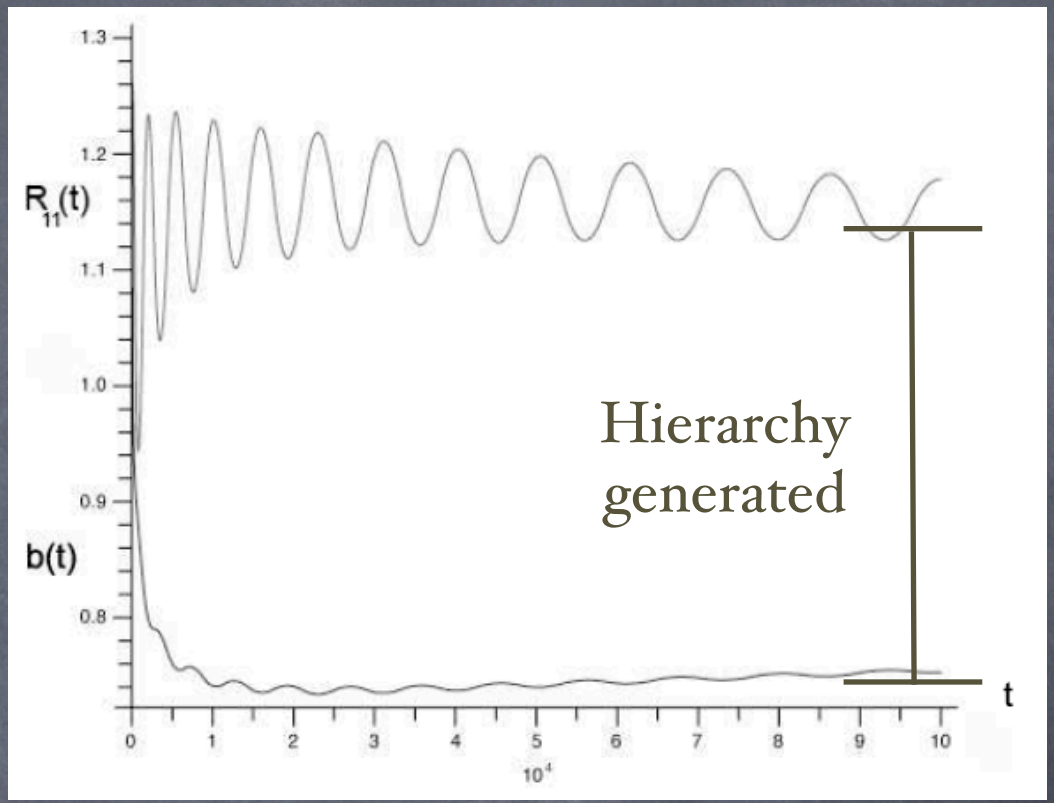
??????

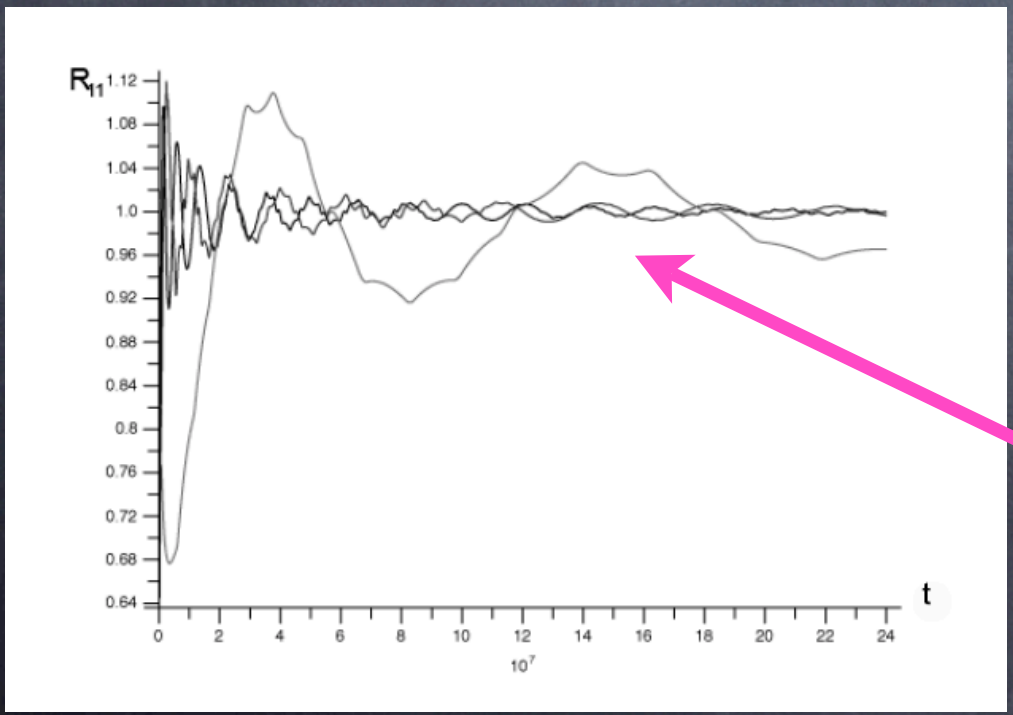
Lesson Learned

- If states are found and accounted for on landscape, seems we are attracted to fixed pts. of dualities and therefore regions of strong coupling where theory breaks down.









Gravity affects behavior

Upshot

- Dynamics, gravity, and hidden states (ESPs) make landscape a very complicated place
- Better understanding of string solutions including dynamics / time dependent backgrounds needed
- May be early to speak of anthropics on the landscape

Modulated Perturbations

- Dvali Gruzinov, Zaldarriaga astro-ph/0303591 & astro-ph/0305548
- Kofman astro-ph/0303614 & astro-ph/0403315
- Kofman & S.W. - in progress

Light scalars during inflation

$$m_\chi < H \qquad \delta\chi \sim \frac{H}{2\pi}$$

Couplings controlled by moduli will fluctuate

$$V(\phi) = \frac{1}{2}m^2(\chi)\phi^2 + \lambda^4(\chi)\phi^4$$

$$\frac{\delta\chi}{\chi} \rightarrow \left(\frac{\delta m}{m} \text{ or } \frac{\delta\lambda}{\lambda}\right) \rightarrow \frac{\delta\rho}{\rho} \rightarrow \frac{\delta T}{T}$$

- New way to generate density and temperature fluctuations
- Causal and nearly Gaussian since fluctuations generated during inflation
- Perturbations could be generated in processes following inflation
  (e.g. preheating, reheating, baryogenesis?)

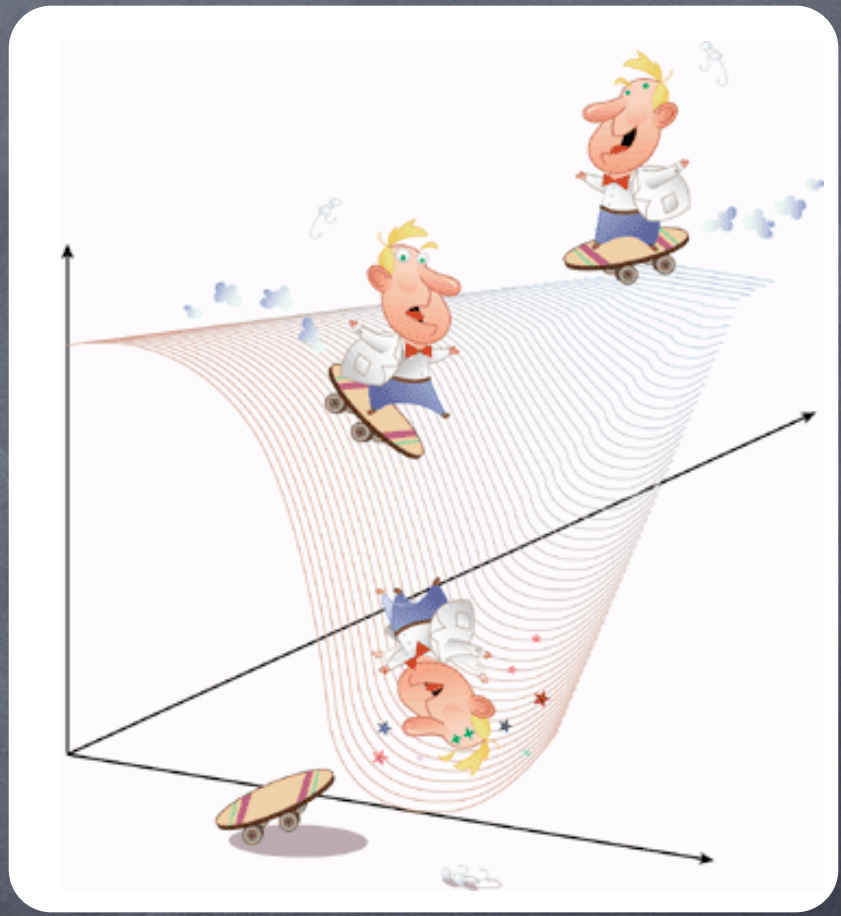
Hybrid Inflation & Tachyonic Preheating

$$V = \frac{\lambda}{4}\left(\sigma^2 - v^2\right)^2 + \frac{1}{2}g^2\phi^2\sigma^2 + V(\phi)$$

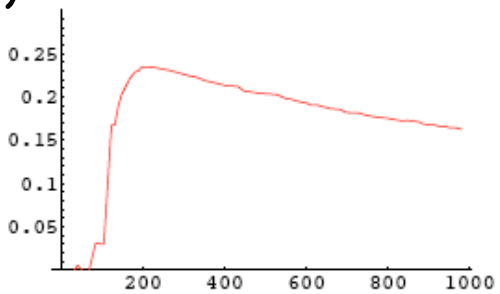
Tachyonic preheating sets in at bifurcation point:

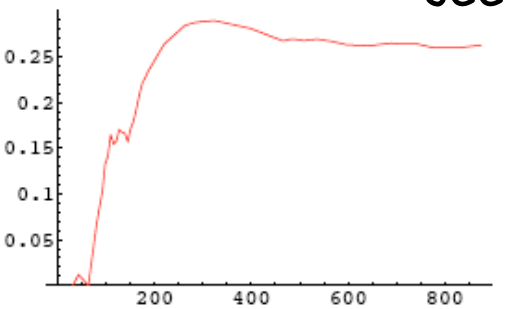
$$\phi_c = \frac{\sqrt{\lambda}v}{g}$$

Transition from inflation to radiation very rapid --> "instantaneous"

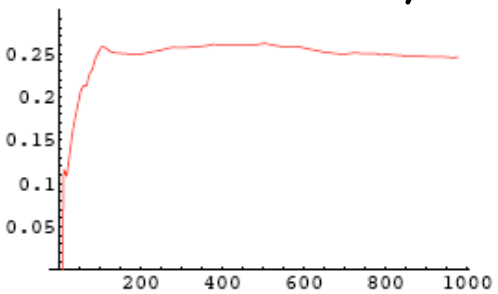


w(t)





see work of Kofman, et. al.



$$V = \frac{\lambda}{4}\left(\sigma^2 - v^2\right)^2 + \frac{1}{2}g(\chi)^2\phi^2\sigma^2 + V(\phi)$$

e.g. D-term inflation w/ non-trivial gauge kinetic function

Tachyonic preheating sets in at bifurcation point:

$$\phi_c = \frac{\sqrt{\lambda}v}{g} \longleftarrow \frac{\delta g}{g} \to \frac{\delta\phi_c}{\phi_c}$$

End point of inflation and particle creation will be inhomogeous

--> Density fluctuations!

Junction Conditions

Match perturbed metric and extrinsic curvature across surface

$$ds^2 = -\left(1+2\Phi\right) + a^2\left(1-2\Phi+h_{ij}^{\pm}\right)d\vec{x}^2$$

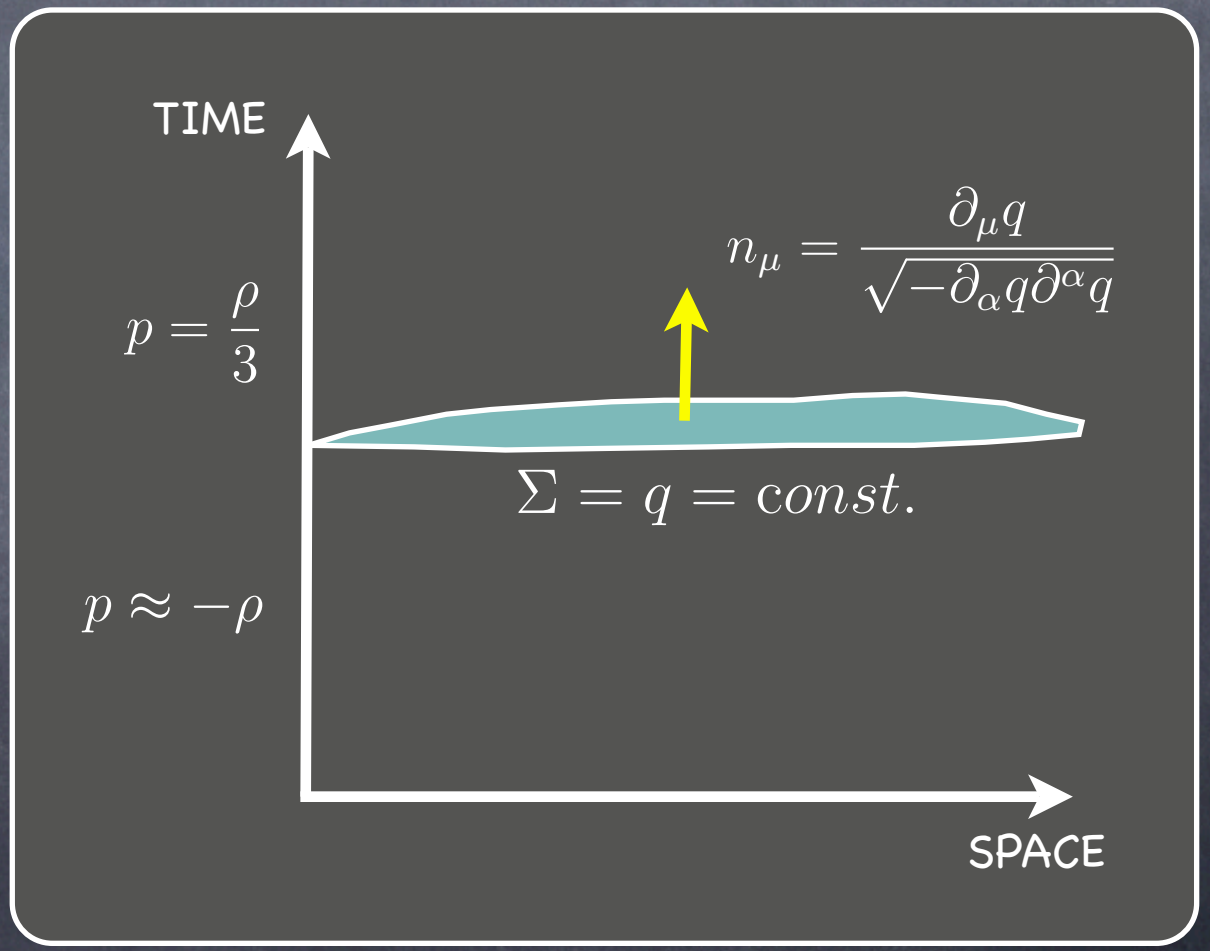
Background

$$[a]_{\pm} = 0, [H]_{\pm} = 0$$

Perturbations

$$[\Phi]_{\pm} = 0, \left[\dot{\Phi} + \dot{H}\frac{\delta q}{\dot{q}}\right]_{\pm}$$

$$[h_{ij}]_{\pm} = 0, \left[\dot{h}_{ij}\right]_{\pm} = 0,$$

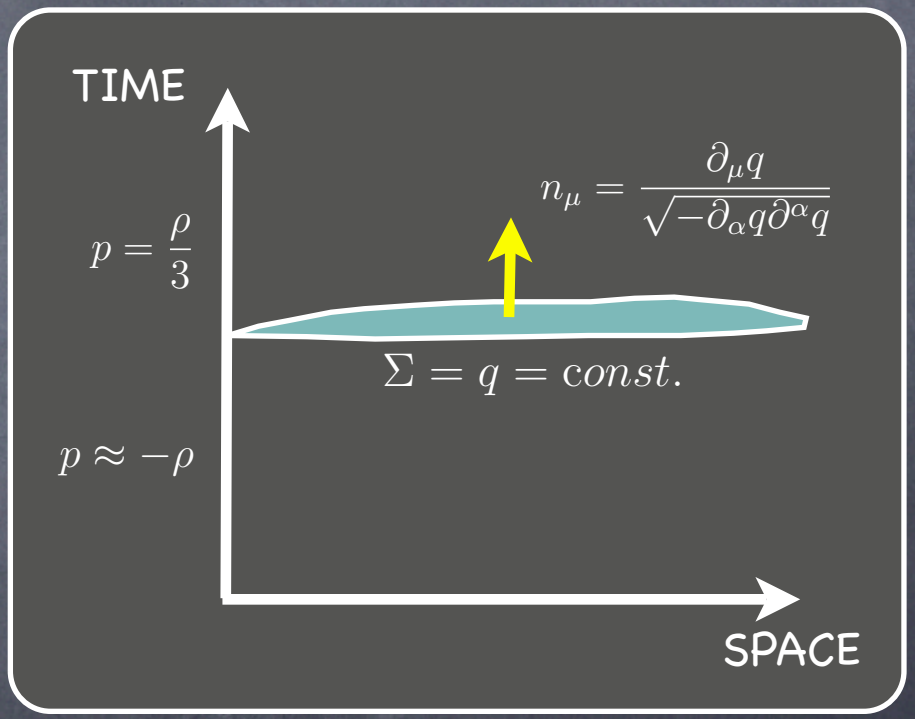


Junction Conditions

Nature of transition fixes surface

$q = \phi - \phi_c$ Hybrid inflation

$\delta q = \delta\phi$



Metric Perturbation

$$\Phi_+(t) = \Phi_-(t_*) + \left(\frac{1 - p_+/p_-}{2p_+ + 1}\right) H \frac{\delta q}{\dot{q}}(t_*)$$

$$\Phi_+(t) = \frac{2}{3\epsilon}\Phi_-(t_*)$$

Amplitude enhanced --> observable

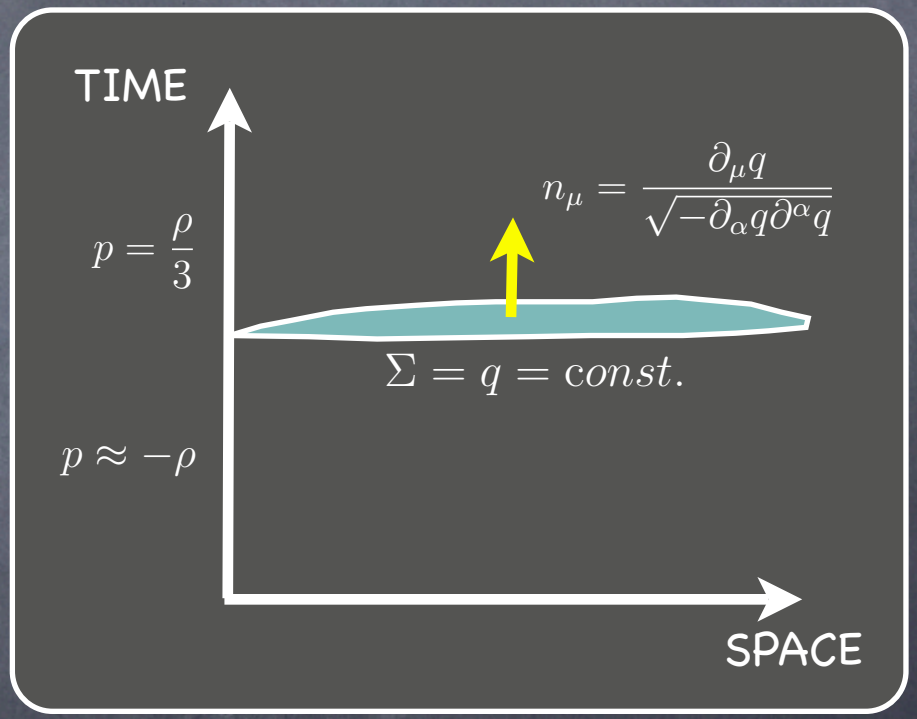
Modulated Perturbations

Nature of transition fixes surface

$$q = \phi - \phi_c(\chi)$$

Hybrid inflation
(modulated)

$$\delta q = \delta\phi - \frac{d\phi_c}{d\chi}\delta\chi$$



Metric Perturbation

$$\Phi_+(t) = \Phi_-(t_*) + \left(\frac{1 - p_+/p_-}{2p_+ + 1}\right) H\frac{\delta q}{\dot{q}}(t_*)$$

$$\Delta\Phi_+ = \frac{2}{3}\frac{\sqrt{4\pi}}{\epsilon^{1/2}}\left(\frac{d\phi_c}{d\chi}\right)\left(\frac{\delta\chi(t_*)}{M_p}\right)$$

Amplitude enhanced --> observable

Observables of Modulated fluctuations

Power Spectrum

$$P = \frac{1}{4\pi^2\epsilon}\left(\frac{H}{M_p}\right)^2 (k\eta_*)^{-2\epsilon}\left[(k\eta_*)^{2\eta-4\epsilon} + 4\pi\left(\frac{d\phi_c}{d\chi}\right)^2 (k\eta_*)^{2m^2/3H^2}\right]$$

Scalar Tilt:

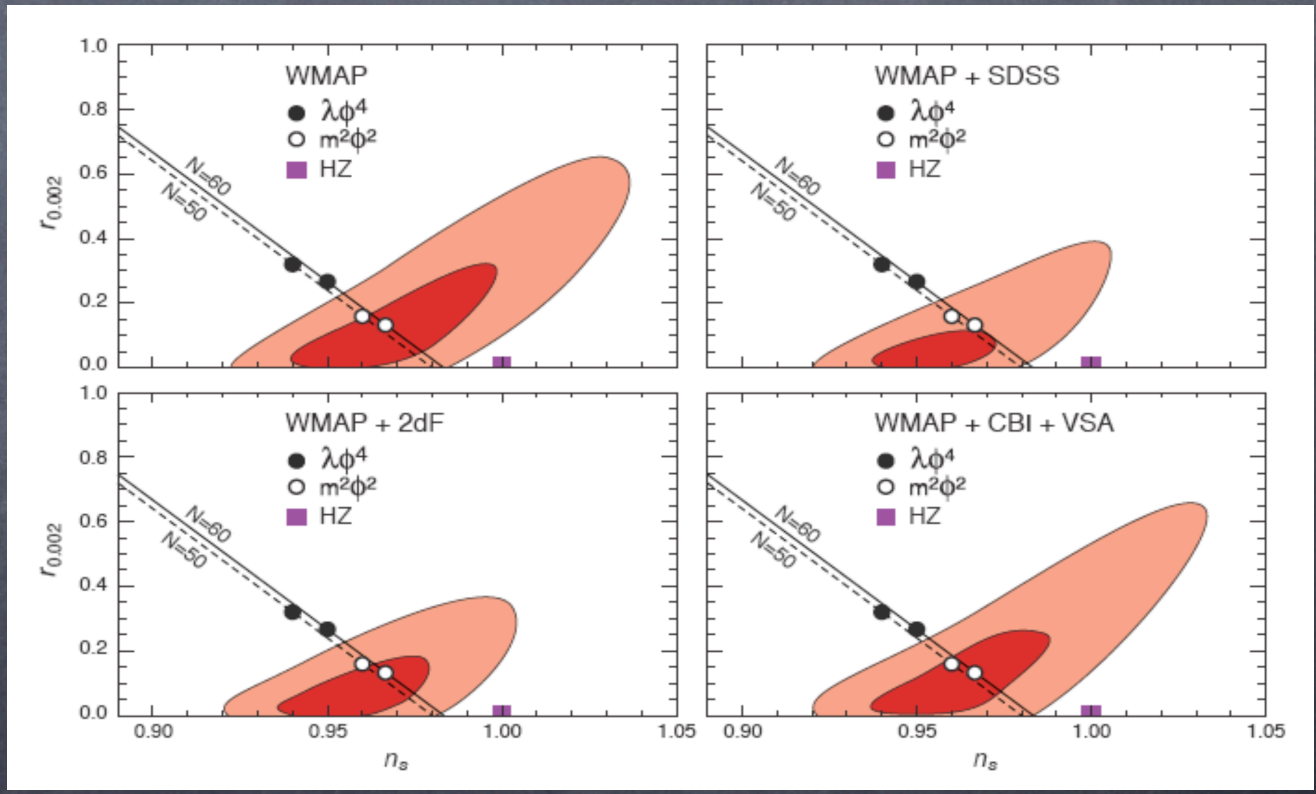
$$n_s - 1 = 2\eta - 6\epsilon$$

Modulation contribution

$$n_s - 1 = \frac{2m^2}{3H^2} - 2\epsilon$$

Tensor to Scalar ratio:

$$r = \frac{T}{S} = \frac{\epsilon}{1 + 4\pi\left(\frac{d\phi_c}{d\chi}\right)^2}$$



Single field slow-roll models

Conclusions

- Initial investigation into dynamics on landscape have interesting implications
- Moduli trapping suggests *dynamical* selection principles worth closer look
- Fluctuations of light scalars during inflation can lead to interesting phenomenology (Baryogenesis?)
- Modulated perturbations could relieve constraints on inflaton and lead to measurable r=T/S (see also curvatons and hydrodynamic models of inflation)
- Exciting time to look at String Cosmology