String theory and cosmology

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Stanford

Strings 2008, August 18, Geneva

Contents

- String cosmology: general status and new developments since Strings 07
- On a possibility of a UV finite N= 8 supergravity

String Cosmology

Standard cosmological model remains in good shape after WMAP5 release in 2008

B-mode polarization experimentalists are more optimistic about their ability to detect gravity waves from inflation

In inflationary model building:

String theory models of chaotic inflation predicting gravity waves

Stringy D3/D7 hybrid inflation with 10% of cosmic strings fitting the data

Update on the KKLMMT

Tension grows between the low scale SUSY (LHC) and the possibility of detection of gravity waves

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Standard Cosmological Concordance Model is emerging during the last 10 years

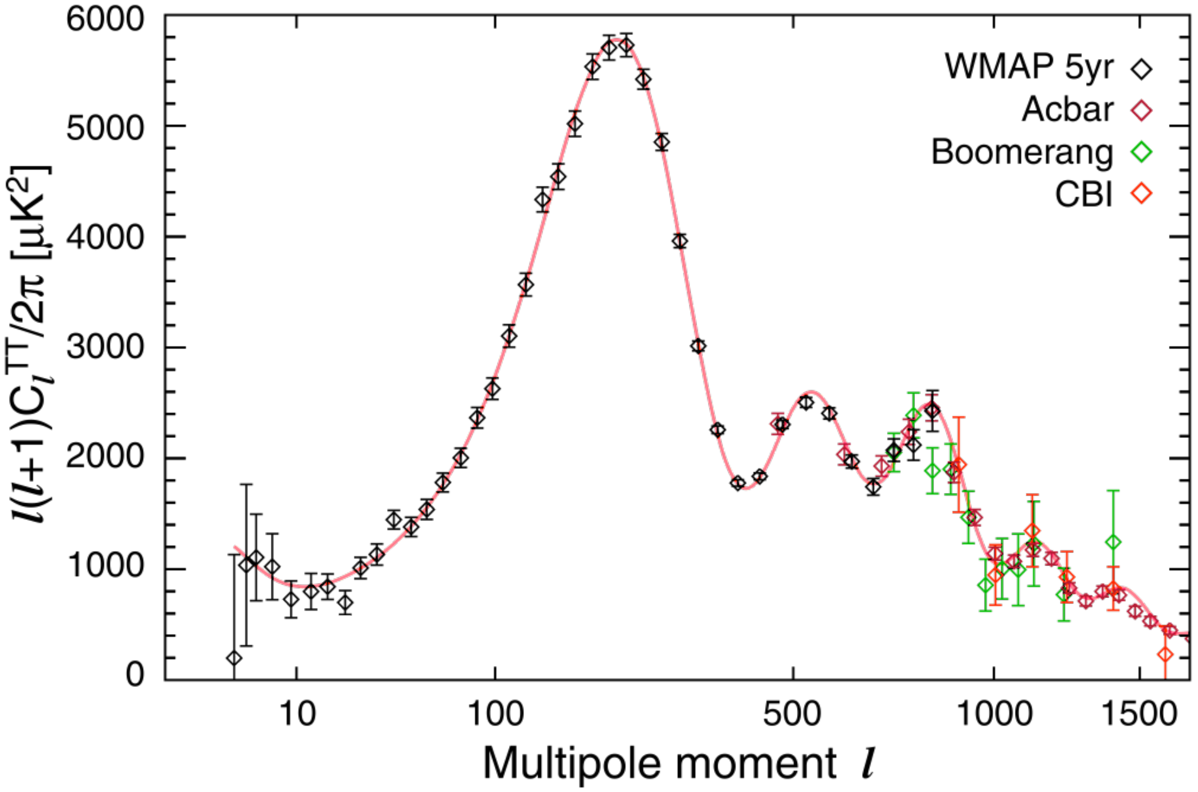
- String Theory and Particle Physics in general have to adapt to these changes

- It is now 10 years after the discovery of the Universe acceleration and the first indications of the ΛCDM model

So far 6 basic parameters are explaining all the data from the sky!

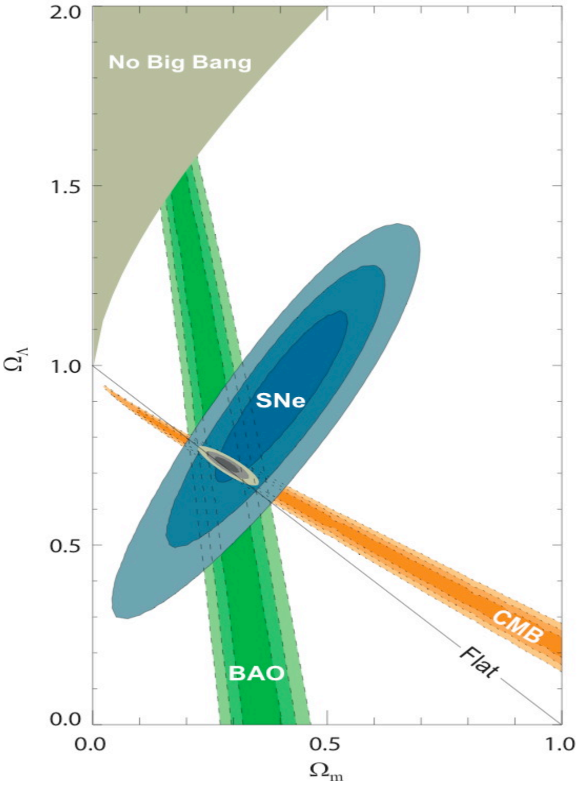
2008

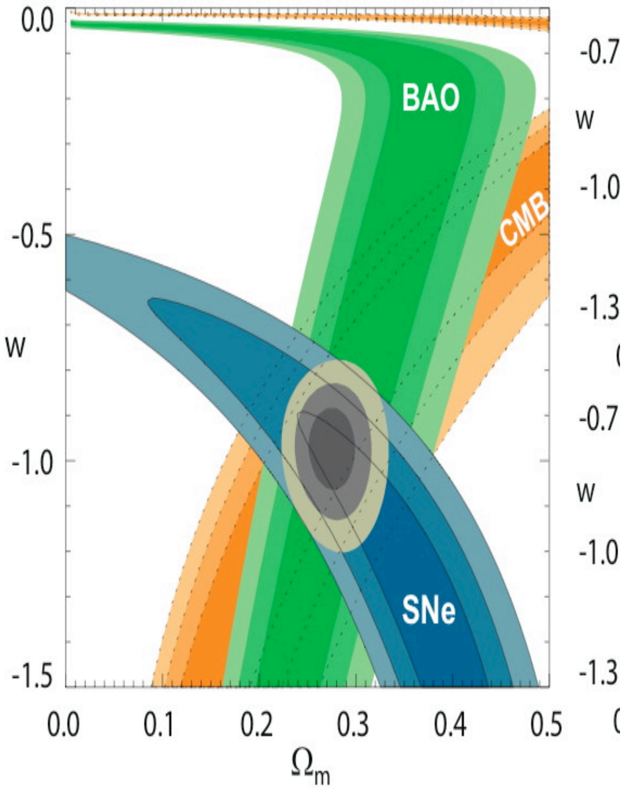
WMAP5 + Acbar + Boomerang + CBI



2008

Concordance and simplicity: $\Omega = 1,\ \omega = -1$





Stringy Landscape and Metastable dS vacua

- It is possible to stabilize internal dimensions and describe an accelerating universe. Eventually, our part of the universe will decay, but it will take a very long time.

- Vacuum stabilization can be achieved in about 10^{500} different ways. The value of CC ~ 10^{-120} in Planck units is not impossible in the context of string theory landscape with anthropic reasoning

- $\omega = -1$, CC=const, is in agreement with the data so far. No good stringy models of quintessence different from the CC=const.

- If we use string theory to understand inflation which occurs now (acceleration due to dark energy), we should also try to explain inflation in the early universe.

- We start with basic principles (string theory, inflation), develop various models, and test their predictions.

- This is how it worked for Standard Model in particle physics: the underlying principle was spontaneously broken gauge theory. A particular model, SU(3)xSU(2)xU(1) with particular field content was able to explain all data in particle physics below certain energies.

Data in cosmology and LHC ⟺ string cosmology ⟺ fundamental physics

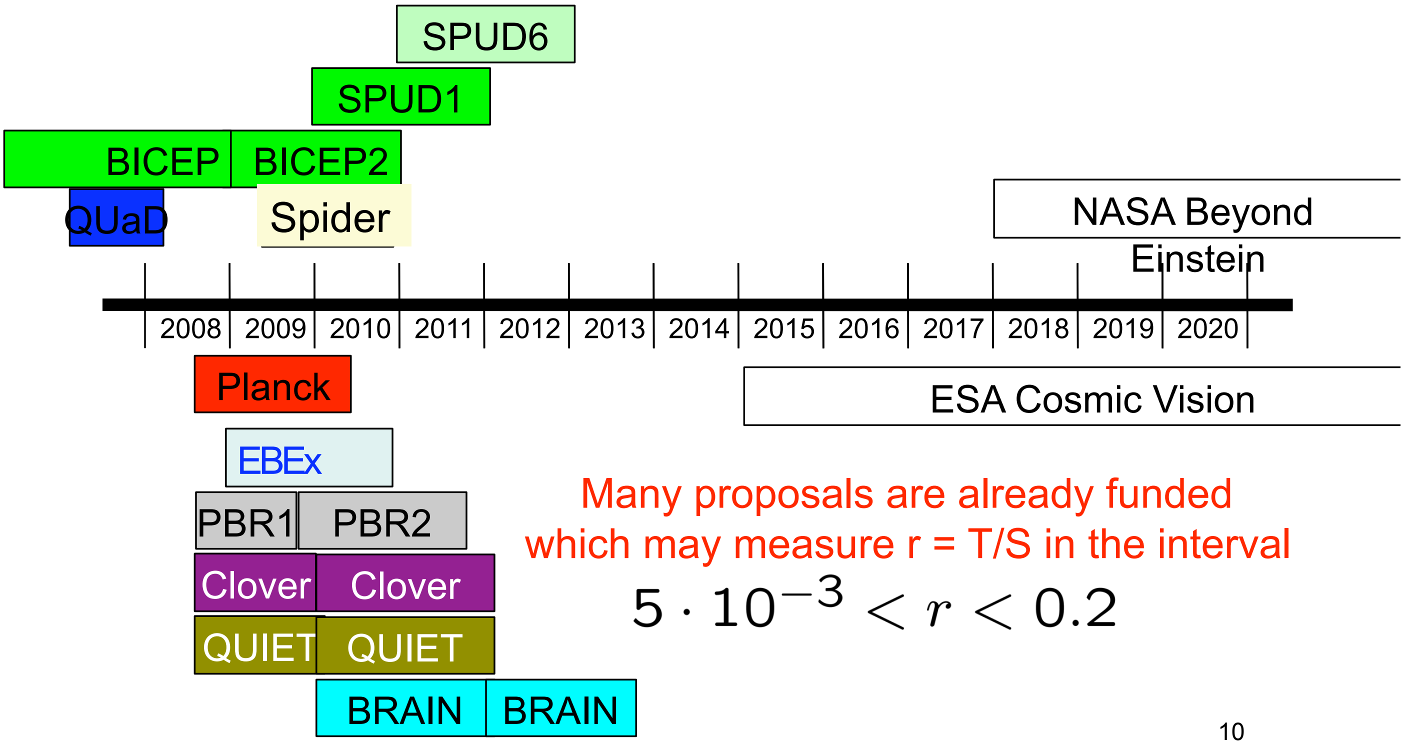
- After 2003, when string cosmology with flux compactification and moduli stabilization was developed, we are looking for inflationary models derived from string theory. There is a list of such models compatible with available data.

- We are analyzing the impact of future data and trying to work on diverse string inflation models which may be later more suitable if certain crucial discoveries are made:

- B-modes detection:
- may be of crucial importance
- Cosmic strings detection:
- very interesting for string theory and cosmology (stringy version of hybrid D-term inflation may fit the data)
- Non-gaussianity detection:
- a selection principle of cosmological models

Holy grail of observational cosmology

Calendar for B-mode detection



Many proposals are already funded which may measure r = T/S in the interval

$$5 \cdot 10^{-3} < r < 0.2$$

Important cosmological data expected soon

Planck, B-mode polarization experiments, SPT, ACT telescopes…

- Spectral Index, n_s
- Non-gaussianity, f_{NL} recent discovery/non-discovery ???
- B-modes, $r = T/S$, main news in May-June 2008: prospects for detection of B-modes from inflation in the range above r = 0.01 are excellent
- Cosmic strings, if below 10% may explain the data, requires $n_s=1$

One can view cosmological data as a test and selection principle for string theory

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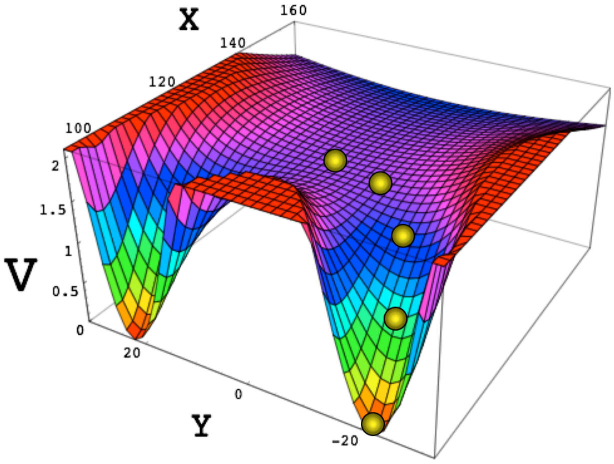
Racetrack Inflation, KKLT

A simple working model of the **moduli inflation**

Blanco-Pilado, Burgess, Cline, Escoda, Gomes-Reino, R.K., Linde, Quevedo

Superpotential: $$W = W_0 + A\,e^{-aT} + B\,e^{-bT}$$

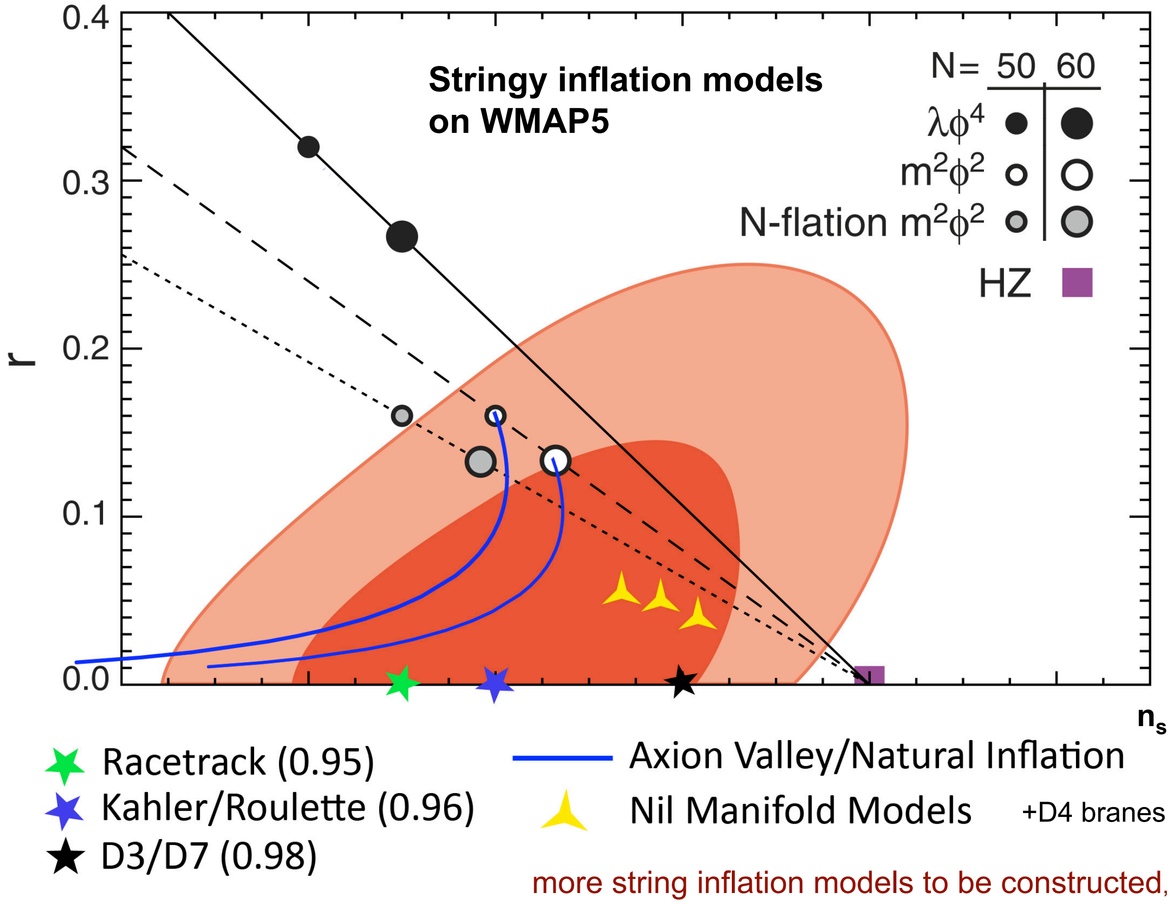
Kähler potential: $$K = -3\log(T + T^*)$$



No cosmic strings

$n_s=0.95$

No grav. waves



more string inflation models to be constructed,
e.g. Cicoli, Burgess, Quevedo, 2008

Gravity Waves from Monodromies

tensor/scalar

Silverstein, Westphal, 2008
McAllister, Silverstein, Westphal, 2008

- Lyth bound: $$\frac{\Delta\phi}{M_{\rm P}} \sim \left(\frac{r}{0.01}\right)^{1/2} \geq 1 \Leftrightarrow \begin{cases} \text{observable!} \\ \text{UV sensitive} \end{cases}$$

  chaotic inflation [Linde '83]
  natural inflation [Freese et al. '90]
  $\Rightarrow$ $\Delta\phi > M_{\rm P}$ protected by symmetry:
  Can this arise naturally in string theory?

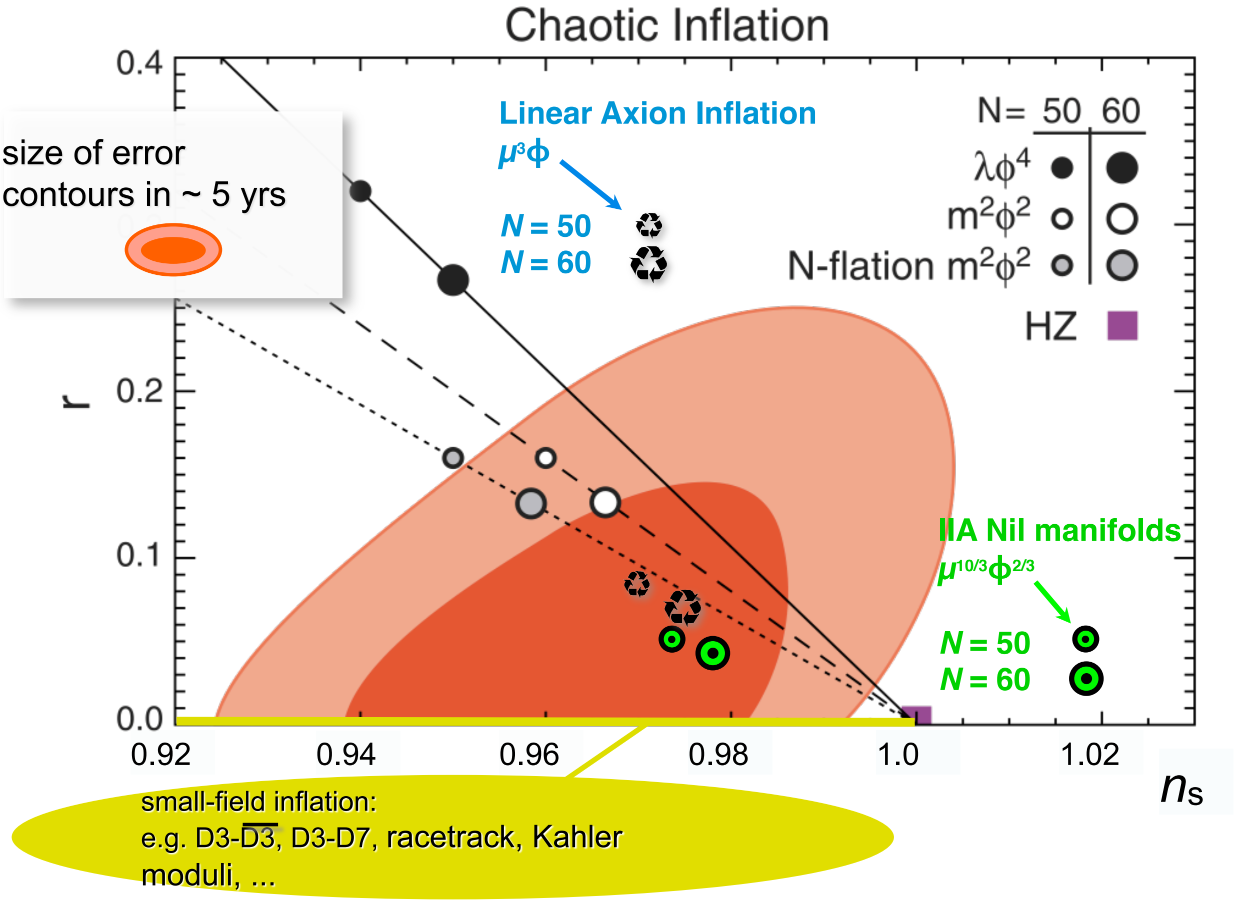
- **Yes:** Monodromy $\begin{cases} \text{would-be periodic direction (brane position, axions, ...)} \\ \textbf{not} \text{ periodic in presence of } \textbf{wrapped} \text{ brane:} \end{cases}$

  → kinematically unbounded field range; potential from brane action:

$$\mathcal{L} \sim \begin{cases} u\dot{u}^2 - \sqrt{1+u^2} \;\Rightarrow\; V(\phi) \sim \phi^\alpha\,,\ \alpha = 2/3\,, & \text{Nil manifold} \\ f_a^2\dot{a}^2 - \sqrt{\ell^4+a^2} \;\Rightarrow\; V(\phi) \sim \phi^\alpha\,,\ \alpha = 1\,, & \text{axions in e.g. CYs} \end{cases}$$

predictive: $n_s = 0.98 \quad r = 0.04$
$n_s = 0.975 \quad r = 0.07$

- Systematic control:
  shift symmetry weakly broken by V(f);
  Nil manifold case: simple & explicit construction, $O(1\%)$ tuning
  Calabi-Yau case: holomorphy & exponential suppression of instantons
  control corrections naturally for axion monodromies



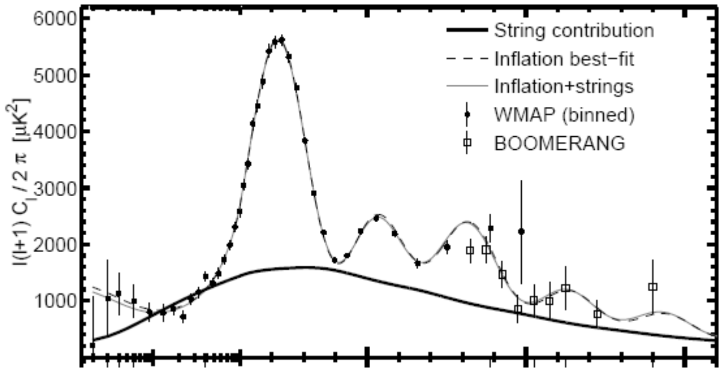
size of error contours in ~ 5 yrs

small-field inflation:
e.g. D3-$\overline{\text{D3}}$, D3-D7, racetrack, Kahler moduli, ...

Fitting CMB data with cosmic strings and inflation

Bevis, Hindmarsh, Kunz, Urrestilla

January 2008



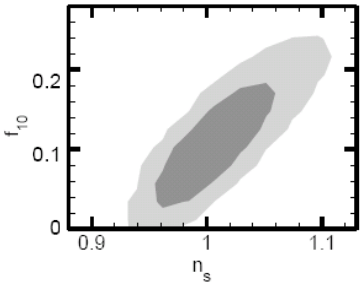
Battye, Garbrecht, Moss, 2006

WMAP3-based

10% of cosmic strings

$$G\mu < 0.7 \cdot 10^{-6}$$

Conclusion.— By including cosmic strings, we find a 6 parameter model with $n_s = 1$ that performs better than, or about as well as, the established concordance model, and that the latest data does not necessarily favor $n_s < 1$.



$$\Delta\chi^2 = -3.9$$

versus usual fit

For this model cosmic strings have to be detected!

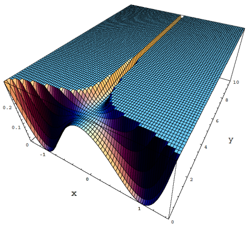
Update on D3/D7 hybrid brane inflation

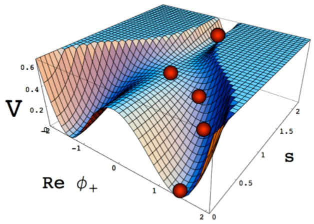
Haack, RK, Krause, Linde, Luest, Zagermann, 2008

The model is controlled by special geometry of N=2 supergravity and string compactification on K3 x $\frac{T^2}{\mathbf{Z}_2}$

Tripathy, Trivedi; Angelantonj, D'Auria, Ferrara, Trigiante
Aspinwall, RK, Bergshoeff, Kashani-Poor, Sorokin, Tomasiello

One of the goals is to use the observation by Hindmarsh et al that one can fit the data with **n_s=1** assuming **10%** contribution of cosmic strings. This is in amazing agreement with the prediction by RK, Linde and Endo, Kawasaki, Moroi (2001-2003) that in D-term inflation (Binetruy-Dvali-Halyo) one can have light cosmic strings and **n_s=1** for very small gauge couplings.



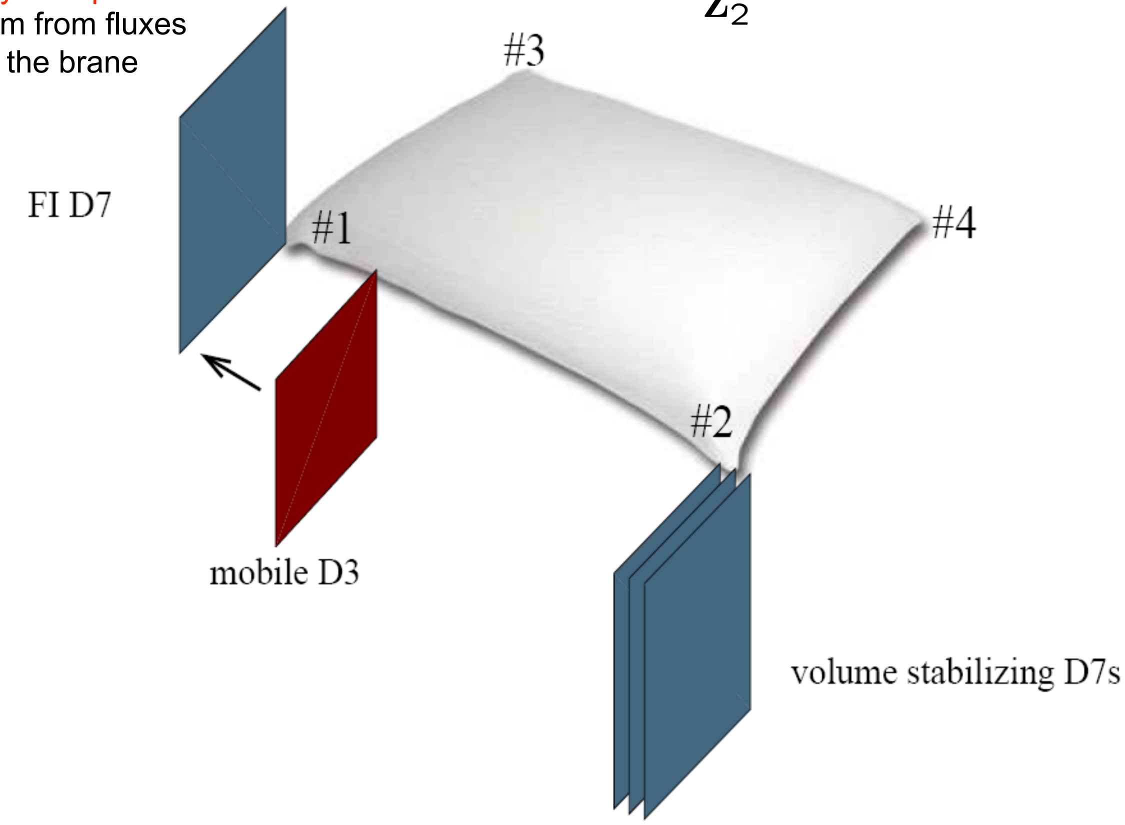


However, we did not know whether one can achieve it in D3/D7 brane inflation model

Dasgupta, Herdeiro, Hirano, RK, 2002

Effective
Fayet-Iliopoulos
term from fluxes
on the brane

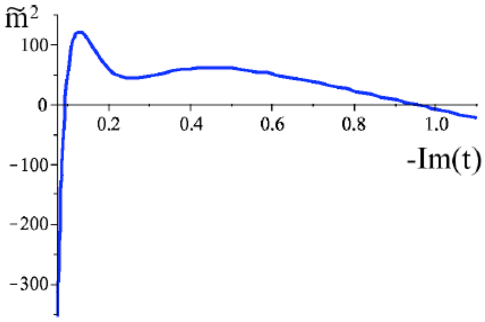
$\frac{T^2}{\mathbf{Z}_2}$ Pillow with 4 fixed points



We computed stringy corrections to the potential

they depend on the value of shape moduli, stabilized by fluxes

$$V_F = -\frac{m^2}{2}\phi^2 \,, \qquad m^2 = \frac{2|A|^2 \tilde{s}_2 e^{2a\tilde{s}_2}}{u_2}\left[3a\mathrm{Re}(\Delta) + 4t_2|\Delta|^2\right]$$



For Re t = 0.26

A stringy correction term can vanish, can be small or large, positive or negative. This depends on the choice of fluxes stabilizing the complex structure modulus t = Re t + i Im t

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In this class of models cosmic string tension is proportional to the Fayet-Illiopoulos term

$$\mu = 2\pi\xi$$

Small coupling

$$\frac{V^{3/2}}{V'} = \frac{\sqrt{2}\pi^2}{\ln 2\, g}\xi^{3/2} \approx 4.9 \times 10^{-4}$$

Usual regime of D-term inflation

$$\frac{V^{3/2}}{V'} = 2\pi\xi\sqrt{N}$$

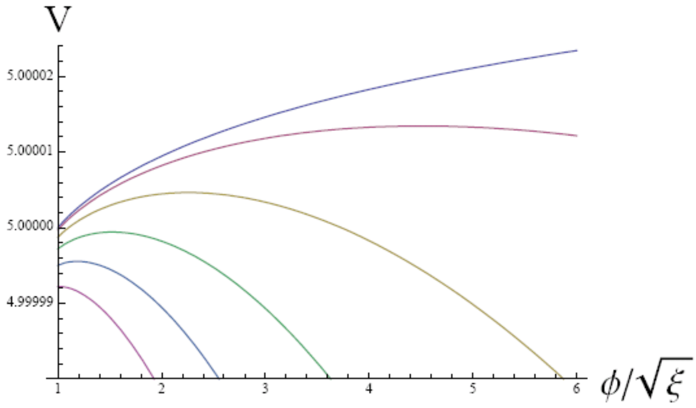
Cosmic strings are too heavy

Inflation starts close to the bifurcation point since the potential is very flat.

$$G\mu = 7 \times 10^{-7} \qquad g \approx 2.2 \times 10^{-4} \qquad n_s = 0.997$$

This numerical example is compatible with Hindmarsh *et al* fit to CMB data with 10% of cosmic strings

Flexibility with account of stringy corrections



Allows to suppress the cosmic strings tension and have a spectral index compatible with WMAP

Inflation is eternal due to the maximum which appears in the combined potential: the log ϕ term as in D-term inflation and in addition a flexible ϕ^2 from stringy corrections.

Update on KKLMMT brane inflation model:

2003

η-problem ($m^2 \sim H^2$) requires fine-tuning of terms ϕ^2

After that, the model works and has interesting properties, such as light cosmic strings

2007

Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan, Steinhardt:

Stringy corrections do not remove ϕ^2 terms as originally expected. With fine-tuning one can find an inflection point and slow-roll inflation. “Delicate inflation.”

News in 2008

Baumann, Dymarsky, Kachru, Klebanov, McAllister, to appear

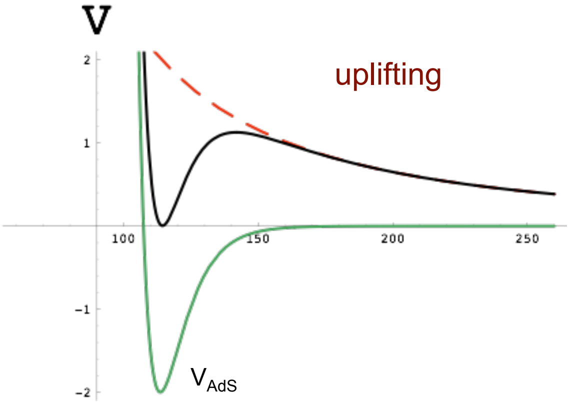
Improved understanding of quantum corrections

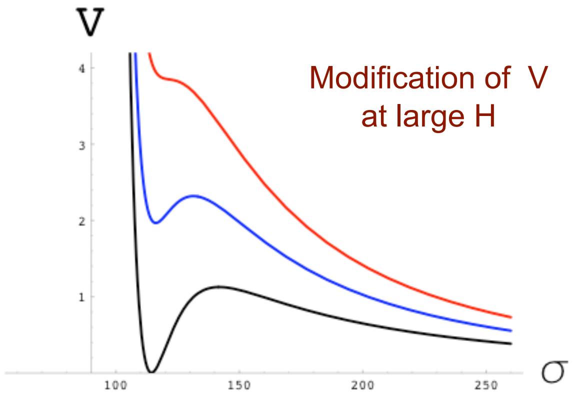
If there are some discrete symmetries, the original KKLMMT scenario with inflaton mass tuned is valid.

String Cosmology and the Gravitino Mass

Kallosh, A.L. 2004

The height of the KKLT barrier is smaller than $|V_{AdS}| = m^2_{3/2}$. The inflationary potential V_{infl} cannot be much higher than the height of the barrier. Inflationary Hubble constant is given by $H^2 = V_{infl}/3 < m^2_{3/2}$.





Constraint on the Hubble constant in this class of models: $H < m_{3/2}$

Related constraints on temperature
Buchmuller, Hamaguchi, Lebedev, Ratz 2004

Can we avoid these conclusions?

Recent model of chaotic inflation is string theory (Silverstein and Westphal, 2008) also requires $H < m_{3/2}$. For simplest models of chaotic inflation in string theory this implies that $m_{3/2} > 10^{13}$ GeV.

In more complicated theories one can have $H \gg m_{3/2}$. But this requires fine-tuning (Kallosh, A.L. 2004, Badziak, Olechowski, 2007)

In models with large volume of compactification (Quevedo et al) the situation is even more dangerous: $H < m_{3/2}^{3/2} < 1\ KeV$

It is possible to solve this problem, but it is rather nontrivial, and, once again, requires fine tuning.

Conlon, R.K., Linde, Quevedo, 2008

This is not the first time that we have cosmological problems with light gravitino: a different set of problems with light gravitino and moduli fields was known to exist for the last 25 years.

The problem which we discussed is especially difficult in the models with very light gravitino.

For example, in the conformal gauge mediation with gravitino mass O(1) eV one would need to have inflation with H < 1 eV, which is a real challenge!

From the point of view of cosmology, the price for the SUSY solution of the hierarchy problem is high, and it is growing. We are waiting for LHC...

Tensor Modes and GRAVITINO

$$r \sim 10^8 H^2$$

$$H \leq M_{3/2}$$

$$r \leq 10^8 \ M_{3/2}^2$$

R.K., Linde 2007

$r \sim 10^{-2} \longrightarrow M_{3/2} \sim 10^{13} GeV$ superheavy gravitino

$M_{3/2} \sim 1 TeV \longrightarrow r \sim 10^{-24}$ unobservable

Gravitino, string theory, B-modes and LHC

At present we are unaware of any natural way to accommodate in string theory a future detection of B-modes and, simultaneously, a possible future experimental identification of the gravitino as particles with mass much smaller than 10^{13} GeV.

Even if B-modes are not detected, there is still a tension between string cosmology and light gravitino, particularly if it forms dark matter.

New ideas are required.

Near future: theory and data LHC and COSMOLOGY:

- Supersymmetry?
- Non-gaussianity
- More on spectral index
- Cosmic strings
- B-modes ?
- Mass of gravitino ?
- Test of superstring theory?

We are waiting for LHC, dark matter and B-mode experiments data

A possibility of a UV finite N=8 SG

Recent work

- RK, The Effective Action of N=8 SG, arXiv:0711.2108
- RK, Soroush, Explicit Action of $E_{7,7}$ on N=8 SG Fields, arXiv:0802.4106
- RK, Kugo, A footprint of $E_{7,7}$ symmetry in tree diagrams of N=8 SG, in progress
- RK, On a possibility of a UV finite N=8 supergravity, arXiv:0808.2310
- RK +… work in progress

Most relevant work

- Bern, Carrasco, Dixon, Johansson, Kosower, Roiban, Three-Loop Superfiniteness of N=8 SG, hep-th/0702112
- Bianchi, Elvang, Freedman, Generating Tree Amplitudes in N=4 SYM and N = 8 SG, arXiv:0805.0757
- Drummond, Henn, Korchemsky and Sokatchev, Dual superconformal symmetry of scattering amplitudes in N=4 SYM, arXiv:0807.1095

3-loop manifestly supersymmetric linearized counterterm

(known since 1981)

RK; Howe, Stelle, Townsend

SUPERACTION: Integral over a submafifold of the full superspace

$$S^3_{UV} = A_3 \frac{\kappa^4}{\epsilon} \int d^4x \, D^{[i_1 \dots i_4][j_1 \dots j_4]} \bar{D}^{[k_1 \dots k_4][l_1 \dots l_4]} \times L_{i_1 \dots i_4, j_1 \dots j_4, k_1 \dots k_4, l_1 \dots l_4}$$

$$D^{[i_1 \dots i_4][j_1 \dots j_4]} \equiv D^{[i_1}_{(\alpha_1} \dots D^{i_4]}_{\alpha_4)} D^{[j_1}_{(\beta_1} \dots D^{j_4]}_{\beta_4)} \epsilon^{\alpha_1 \beta_1} \dots \epsilon^{\alpha_4 \beta_4}$$

$$L_{i_1 \dots i_4, j_1 \dots j_4, k_1 \dots k_4, l_1 \dots l_4} = (W_{i_1 \dots i_4} W_{j_1 \dots j_4} W_{k_1 \dots k_4} W_{l_1 \dots l_4})_{\underline{232848}}$$

$$W_{ijkl}(x, \theta, \bar{\theta}) = \frac{1}{4!} \epsilon_{ijklmnpr} \overline{W}^{mnpr}(x, \theta, \bar{\theta})$$

2007: N=8 SG is finite at the 3-loop order

A_3=0

Bern, Carrasco, Dixon, Johansson, Kosower, Roiban

L-loop counterterms

Howe, Lindstrom, RK, 1981: Starting from 8-loop order infinite # of non-linear counterterms is available. For example, in 8th loop

$$S^{L=8} \sim \frac{\kappa^{14}}{\epsilon} \int d^4x\, d^{32}\theta \;\mathrm{BerE}\; \mathrm{T}_{\mathrm{ijk}\,\alpha}(\mathrm{x},\theta)\overline{\mathrm{T}}^{\mathrm{ijk}\,\dot{\alpha}}(\mathrm{x},\theta)\mathrm{T}_{\mathrm{mnl}}{}^{\alpha}(\mathrm{x},\theta)\overline{\mathrm{T}}^{\mathrm{mnl}}{}_{\dot{\alpha}}(\mathrm{x},\theta)$$

based on Brink, Howe 1979 (on-shell covariant superspace)

Analogous candidates for the L-loop divergences, integrals over the full superspace

What could be the reason for A_L=0 for all L to provide all-loop order UV finite N=8 SG?

Possible explanations of the 3-loop computation with UV finite answer

1) It is a miracle ☺

2) Howe, Stelle, 2002: If a harmonic superspace of the type of Galperin, Ivanov, Kalitsyn, Ogievetsky, Sokatchev exists for N=8SG with manifest 7 supersymmetries, the onset of divergences will start at L=6 (this harmonic superspace is unavailable as yet).

3) Our new explanation (if it is valid for the 3–loop order, is also valid for all higher loop orders).

Main idea: a) Compare the candidate counterterms in 4+32 covariant on-shell superspace with those in 4+16 light-cone superspace.

b) Transform both results for the S-matrix into helicity formalism, which makes it easy to compare these results.

We have found a mismatch between the covariant and light-cone UV divergent answers for the S-matrix. If gauge anomalies are absent, we may apply the S-matrix equivalence theorem for different gauges. All-loop finiteness of N=8 SG follows.

Light-cone superspace

Brink, Lindgren, Nilsson, 1983
Brink, Kim, Ramond, 2007

Light-cone chiral superfield for the CPT invariant N=8

$$\phi(y,\theta) = \frac{1}{\partial^{+2}}h(y) + i\theta^m \frac{1}{\partial^{+2}}\bar{\psi}_m(y) + i\theta^{mn}\frac{1}{\partial^{+}}\bar{B}_{mn}(y) - \theta^{mnp}\frac{1}{\partial^{+}}\bar{\chi}_{mnp}(y)$$

$$-\theta^{mnpq}\phi_{mnpq}(y) + i\tilde{\theta}_{mnp}\chi^{mnp} + i\tilde{\theta}_{mn}\partial^{+}B^{mn}(y) + \tilde{\theta}_m\partial^{+}\psi^m(y) + 4\tilde{\theta}\partial^{+2}\bar{h}(y)$$

New results: Simplest example of the Lorentz covariant 4-scalar UV divergent amplitude

$$B_3\frac{\kappa^4}{\epsilon}\delta^4(p^1+p^2+p^3+p^4)\int d^8\theta\, d^8\bar{\theta}\,\phi(p_1,\theta,\bar{\theta})\,\phi(p_2,\theta,\bar{\theta})\,\bar{\phi}(p_3,\theta,\bar{\theta})\,\bar{\phi}(p_4,\theta,\bar{\theta})\,f(s,t,u)$$

This is not a complete SU(8) structure, there is another SU(8) structure. The sum of these structures is not Lorentz covariant

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Relation between 4-scalar and 4-graviton amplitudes at the tree level and for the 3-loop UV divergence

4-graviton $M_4^{tree}(1^-,2^-,3^+,4^+) = \frac{i}{\kappa^2}\frac{\langle 12\rangle^4[34]^4}{stu}$

$$M_4^{1-loop}(1^-,2^-,3^+,4^+) \sim \langle 12\rangle^4[34]^4 \times f_{box}(p_1,p_2,p_3,p_4)$$

$$M_4^{3-loop}(1^-,2^-,3^+,4^+) \sim \frac{\kappa^4}{\epsilon}\langle 12\rangle^4[34]^4 \sim \frac{\kappa^4}{\epsilon}stu\,M_4^{tree}(1^-,2^-,3^+,4^+)$$

Superfield formalism ⟺ helicity formalism

$$M_4^{3-loop}(1^-,2^-,3^+,4^+)h(p_1)h(p_2)\bar{h}(p_3)\bar{h}(p_4)$$
$$\sim \frac{\kappa^4}{\epsilon}C_{\alpha\beta\gamma\delta}(p_1)C_{\dot{\alpha}\dot{\beta}\dot{\gamma}\dot{\delta}}(p_2)C^{\alpha\beta\gamma\delta}(p_3)C^{\dot{\alpha}\dot{\beta}\dot{\gamma}\dot{\delta}}(p_4)$$
$$\sim \frac{\kappa^4}{\epsilon}\langle 12\rangle^4[34]^4 h(p_1)h(p_2)\bar{h}(p_3)\bar{h}(p_4)$$

Using a combination of the covariant superspace formalism, the light-cone formalism and the helicity formalism, we find that the UV divergent 4-particle amplitudes in the light-cone gauge are not Lorenz covariant. Therefore UV divergences in covariant gauges and in the light-cone gauge are incompatible unless their coefficients vanish.

Analogous mismatch exists for higher amplitudes and UV divergences with any number of loops.

If the equivalence theorem for the S-matrix in light-cone versus covariant gauges is valid (if there are no anomalies in the BRST symmetry of N=8 SG), we consider this result as a possible explanation of the recent 3-loop computation, as well as a prediction for the all-loop finitness of N=8 supergravity.

Any statement about the all-loop finiteness of N=8 supergravity should not be taken lightly. The theory is extremely complicated. It might happen, for example, that a more detailed investigation will reveal some additional structures in the light cone gauge, which, after being combined with the structures which we have found, will restore Lorentz covariance.

One can consider this talk as an invitation to the community to construct all possible light-cone superinvariants and compare them with the covariant ones, to study the presence/absence of anomalies, and either confirm or disprove our current conclusions.