String Inflation

@ PONT Avignon 2008

C.P. Burgess

with N. Barnaby, J.Blanco-Pillado, J.Cline, K. das Gupta, C.Escoda, H. Firouzjahi, M.Gomez-Reino, R.Kallosh, A.Linde,and F.Quevedo



Outline

- String inflation
  - Why build models only a mother could love?
- Emerging features
  - Mechanisms and naturalness issues
  - Multiple scalars and robustness
  - Mind-broadening: *cosmic strings; reheating; …*
- Open issues
  - Scales; control of approximations; …

Outline

- String inflation
  - Why build models only a mother could love?
- Emerging features
  - Mechanisms and naturalness issues
  - Multiple scalars and robustness
  - Mind-broadening: *cosmic strings; reheating; …*
- Open issues
  - Scales; control of approximations; …

Outline

- String inflation
  - Why build models only a mother could love?
- Emerging features
  - Mechanisms and naturalness issues
  - Multiple scalars and robustness
  - Mind-broadening: *cosmic strings; reheating; …*
- Open issues
  - Scales; control of approximations; …

String Inflation

- What might one hope to learn?
  - about strings
  - about inflation
- Why is it hard?

String Inflation

- *What might one hope to learn?*
  - *about strings*
  - *about inflation*

- Why is it hard?

String Inflation

- *Wha*
  hope
  - *ab*
  - *ab*
- Why

Difficult to identify where we live within the string landscape. Seek ‘modules’ encoding low-energy features: standard model; dark energy; inflation; …

String Inflation

courtesy of Rocky Kolb

- *Wha*
  hope
  - *ab*
  - *ab*
- Why

Happy Valentine's Day !

Inflation and strings were made for each other. – *Cliff Burgess*

From *Physical Review D* Personal ads:

Mature paradigm with firm observational support seeks a fundamental theory in which to be embedded. No loop quantum gravity theories, please. Contact alan@mit.edu.

Elegant theory of everything desires to explore the landscape with a phenomenon in the hope that it will lead to a prediction. Let's get physical! Contact ed@ias.edu.

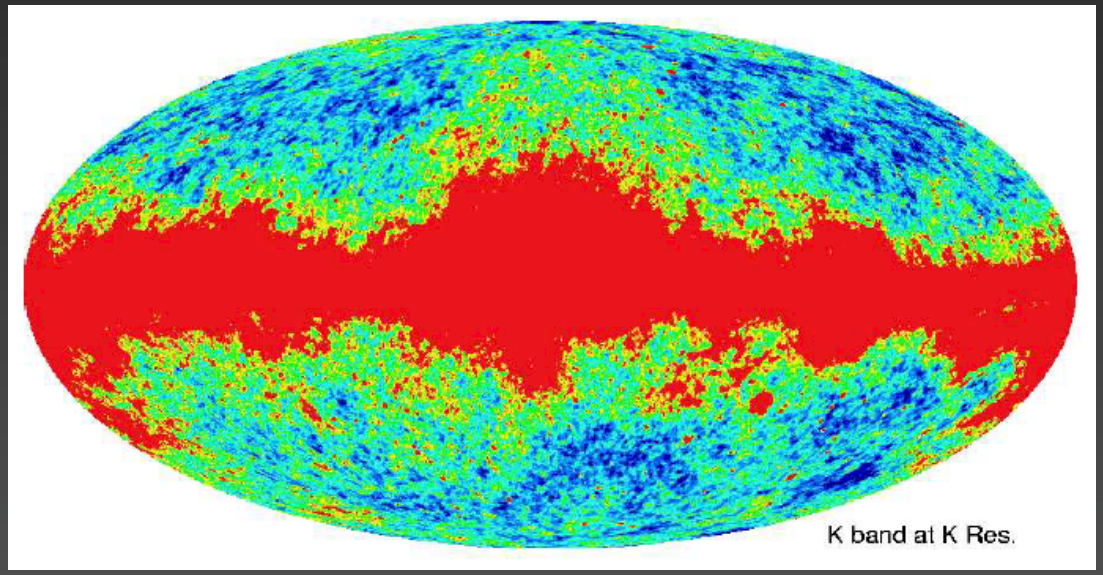
String Inflation

- *What might one hope to learn?*
  - *about strings*
  - *about inflation*

- Why is it hard?

String Inflation

- *Wha*
  hope
  - *ab*
  - *ab*
- Why



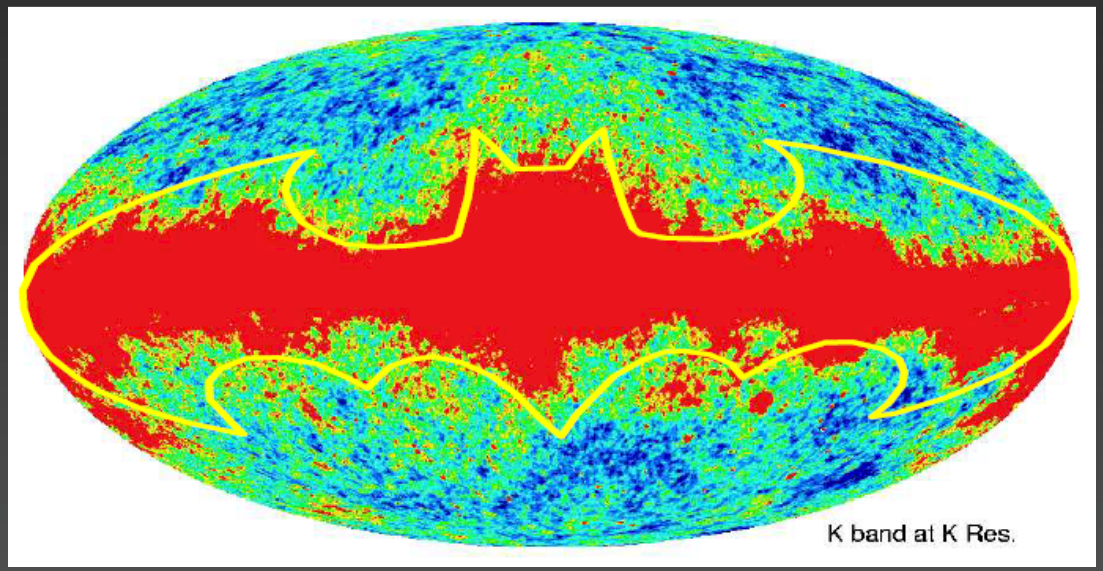
Inflation is under ever closer scrutiny due to the recent wealth of cosmological data.

What are these measurements telling us?

String Inflation

Batfit courtesy of Stephane Coutu

- *Wha*
  hope
  - *ab*
  - *ab*
- Why



Inflation is under ever closer scrutiny due to the recent wealth of cosmological data.

What are these measurements telling us?

String Inflation

- *Wha*
  hope
  - *ab*
  - *ab*
- Why

What we'd like string theory to tell us about inflation:

How generic is it in the landscape?

Initial conditions, flat potentials,

…

String Inflation

- *Wha*
  hope
  - *ab*
  - *ab*
- Why

What we'd like string theory to tell us about inflation:

How generic is it in the landscape?

Initial conditions, flat potentials, …

How does reheating work?

Does SM couple strongly enough to inflaton?

Do other channels couple even more strongly?

String Inflation

- *Wha*
  hope
  - *ab*
  - *ab*
- Why

What we'd like string theory to tell us about inflation:

How generic is it in the landscape?

Initial conditions, flat potentials, …

How does reheating work?

Does SM couple strongly enough to inflaton?

Do other channels couple even more strongly?

How robust are inflationary inferences drawn using simple single-field slow-roll models?

String Inflation

- *Wha*
  hope
  - *ab*
  - *ab*
- Why

What we'd like string theory to tell us about inflation:

How generic is it in the landscape?

Initial conditions, flat potentials, …

How does reheating work?

Does SM couple strongly enough to inflaton?

Do other channels couple even more strongly?

How robust are inflationary inferences drawn using simple single-field slow-roll models?

Are qualitatively new kinds of signatures or mechanisms possible?

Emerging Picture

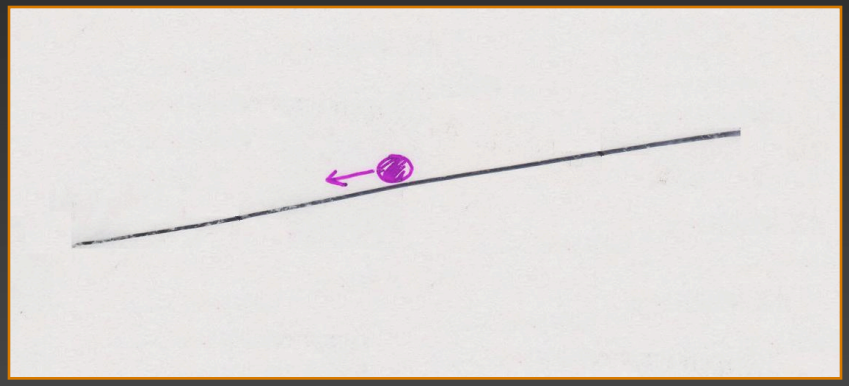
- Mechanisms
- Robustness
- Mind broadening

Emerging Picture

- *Mechanisms*
- Robustness
- Mind broadening

Emerging Picture

- *Mec*
- Robu
- Min

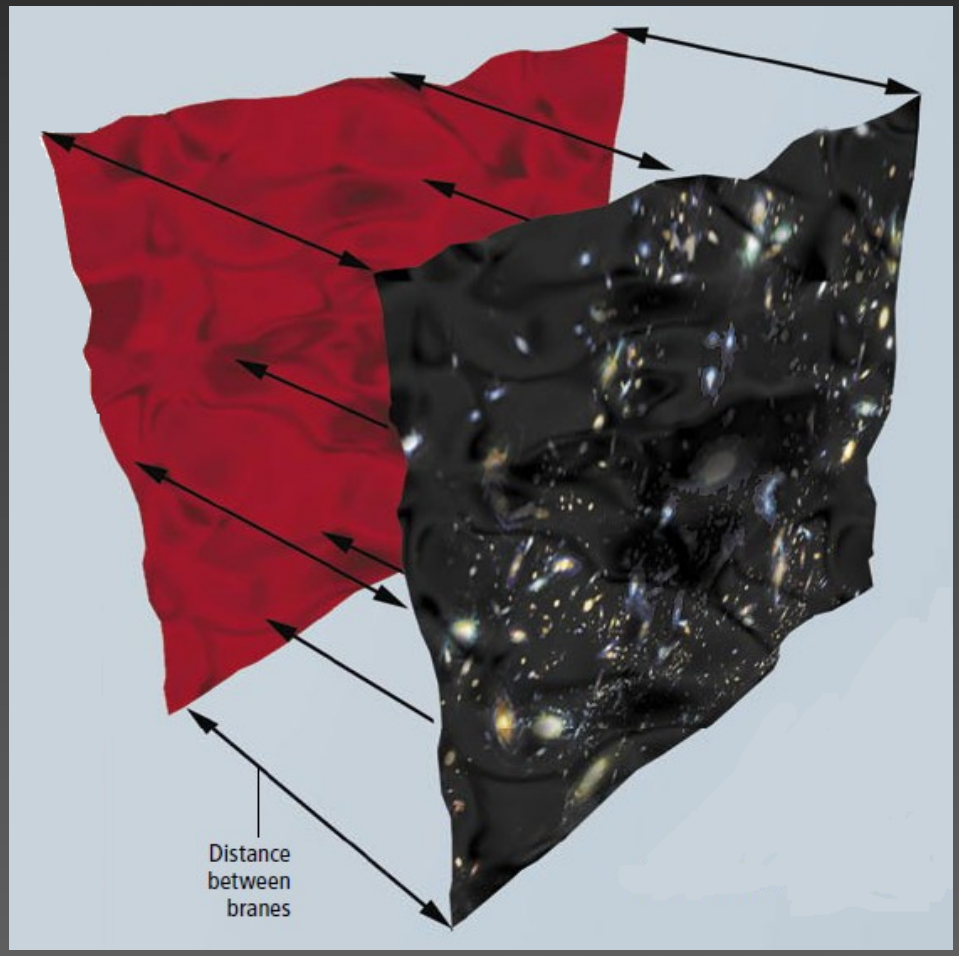


What is so hard about finding inflation in string theory?

It has many scalars.

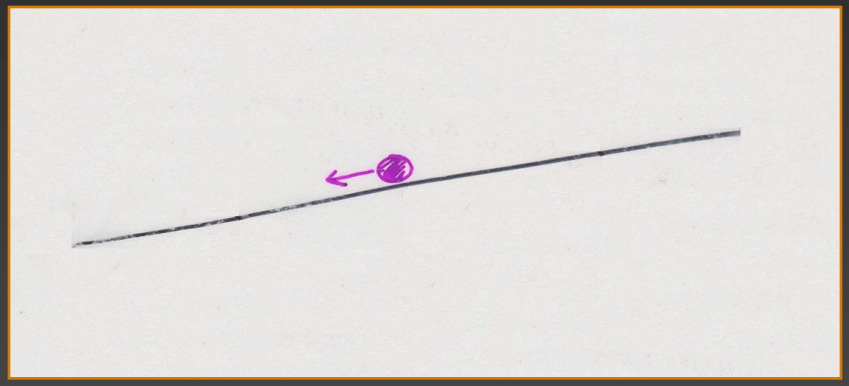
Emerging Picture

- *Mec*
- Robu
- Minc



Emerging Picture

- *Mec*
- Robu
- Min



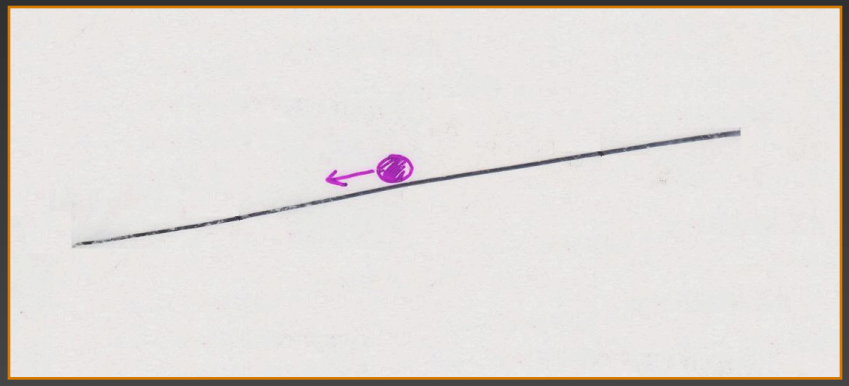
What is so hard about finding inflation in string theory?

It has many scalars, which SUSY gives flat potentials, but SUSY breaking is hard to compute reliably.

Emerging Picture

Maldacena & Nunez
Gibbons
Kachru
Wesley, Steinhardt & Turok

- *Mec*
- Robu
- Minc



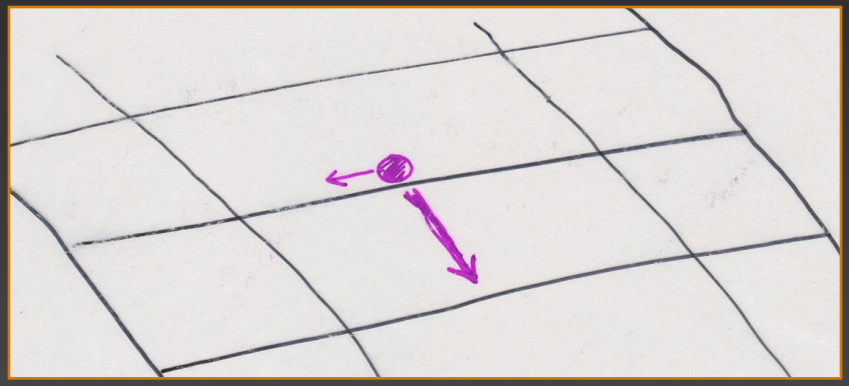
What is so hard about finding inflation in string theory?

It has many scalars, which SUSY gives flat potentials, but SUSY breaking is hard to compute reliably.

No – go theorems exist ruling out accelerated 4D expansion in the classical 10D supergravities

Emerging Picture

- *Mec*
- Robu
- Min



What is so hard about finding inflation in string theory?

It has many scalars, which SUSY gives flat potentials, but SUSY breaking is hard to compute reliably.

A convincing case for inflation requires knowing the potential for *all* of the relevant low-energy fields.

Emerging Picture

Giddings, Kachru & Polchinski
Kachru, Kallosh, Linde & Trivedi

- *Mec*
- Robu
- Min

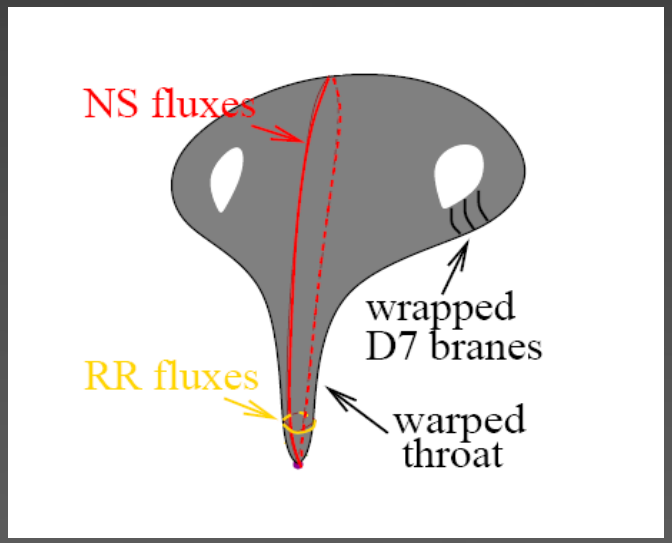
For Type IIB strings it is now known how to compute the potentials for many of these scalars, when close to an N=1 4D vacuum.

Key ingredients:

D3 and D7 branes & orientifolds

Fluxes sourced by these branes, wrapping extra dimensions

$$G_{mnp} = H_{mnp} + \tau F_{mnp}$$



Emerging Picture

Klebanov & Strassler

- *Mec*
- Robu
- Mino

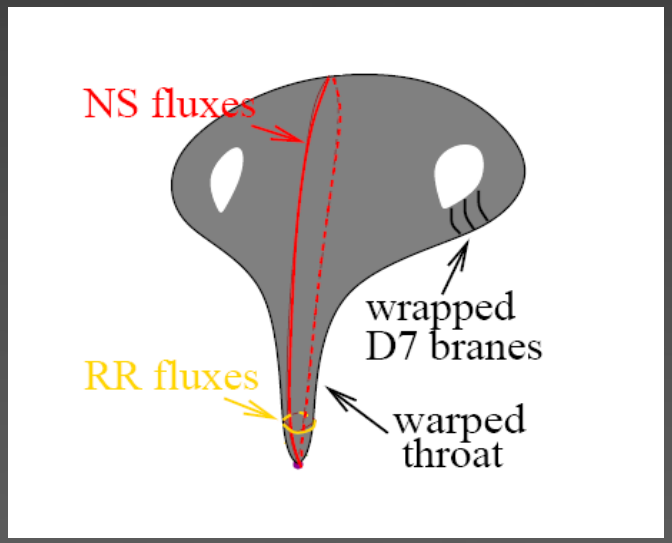
$$ds^2 = h^{-1/2}\eta_{mn}dx^m dx^n + h^{1/2}\left[dr^2 + r^2 d\Omega^2\right]$$

$$h \propto 1/r^4$$

$$ds^2 \approx r^2\eta_{mn}dx^m dx^n + \frac{dr^2}{r^2} + d\Omega^2$$

Strongly warped throats arise in response to specific flux configurations.

Warped throats strongly redshift energies *à la* Randall & Sundrum



Emerging Picture

Klebanov & Strassler

- *Mec*
- Robu
- Mino

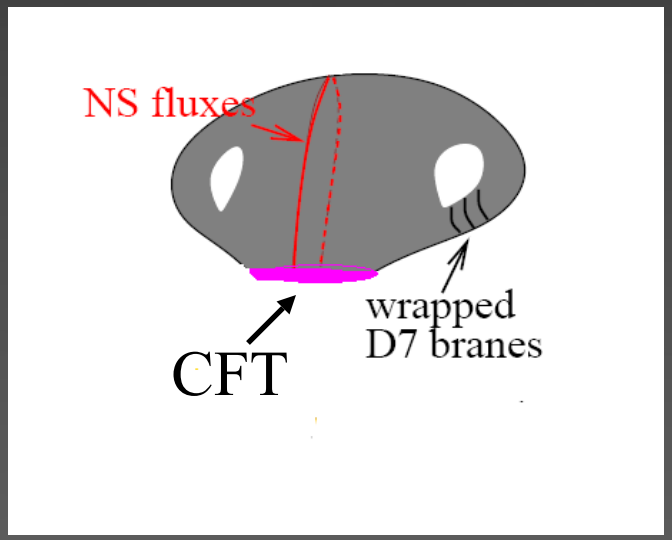
$$ds^2 = h^{-1/2}\eta_{mn}dx^m dx^n + h^{1/2}\left[dr^2 + r^2 d\Omega^2\right]$$

$$h \propto 1/r^4$$

$$ds^2 \approx r^2\eta_{mn}dx^m dx^n + \frac{dr^2}{r^2} + d\Omega^2$$

In AdS/CFT duality degrees of freedom in warped throats are dual to QCD-like approximate CFT

Eg: deconfinement phase transition = black hole formation in throat.



Emerging Picture

Denef & Douglas

- *Mec*
- Robu
- Min

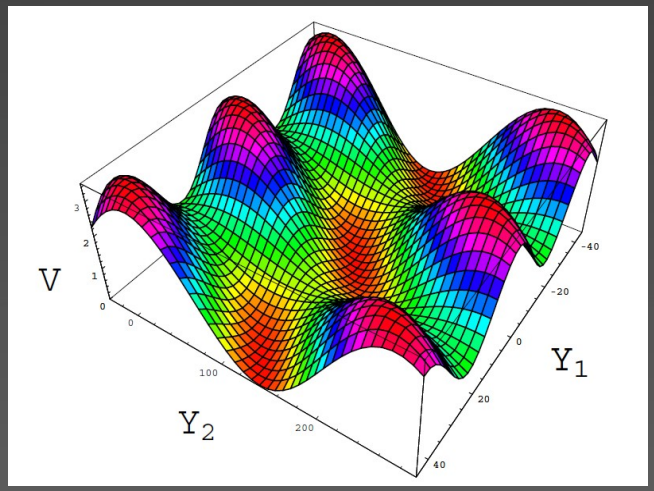
$$K = -2\ln V = -2\ln\left(\tau_1^{3/2} - \tau_2^{3/2}\right)$$

$$W = W_0 + A_1 e^{a_1 T_1} + A_2 e^{a_2 T_2}$$

$$f_i^{ab} = T_i\,\delta^{ab}$$

Low-energy dynamics of last few moduli are described by a low-energy 4D supergravity.

Inflationary solutions make sense if $H \lesssim M_{KK} \lesssim M_s$



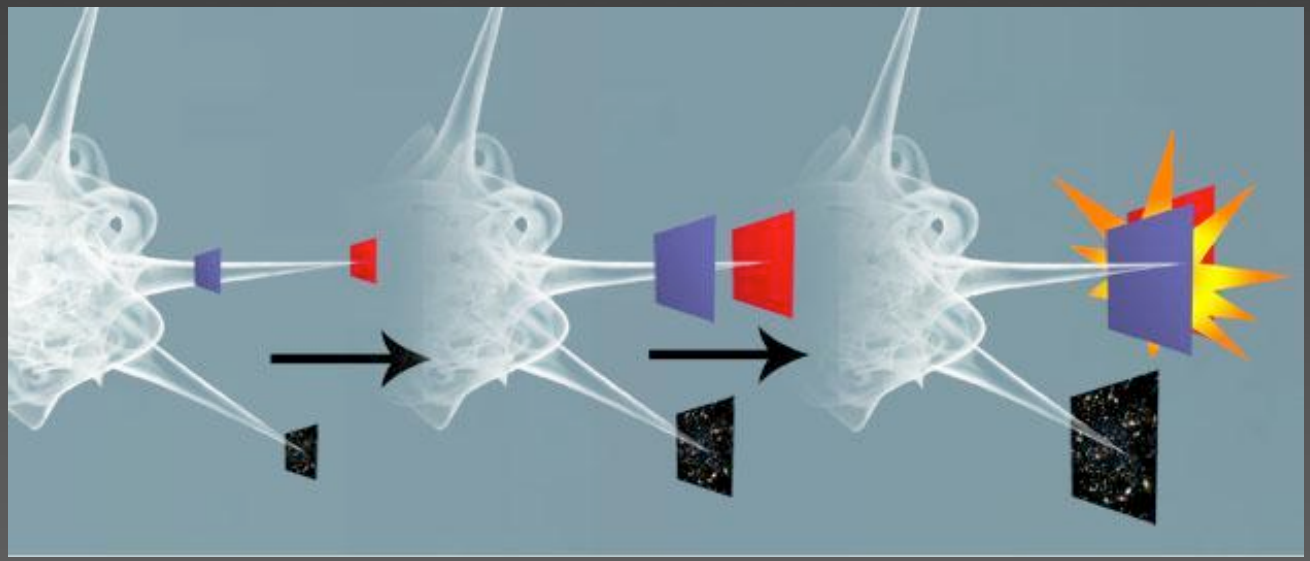
Emerging Picture

BMNQRZ
Dvali et al
KKLMMT
Silverstein & Tong
Baumann et al

- *Mec*
- Robu
- Mino

Two classes of moduli to be considered as inflatons

Open string: *eg Brane-antibrane separation*



Emerging Picture

CB, Quevedo, Rajesh & Zhang
Blanco-Pillado et al
Conlon & Quevedo
Bond, Kofman & Prokushkin

- *Mec*
- Robu
- Mino

Two classes of moduli to be considered as inflatons

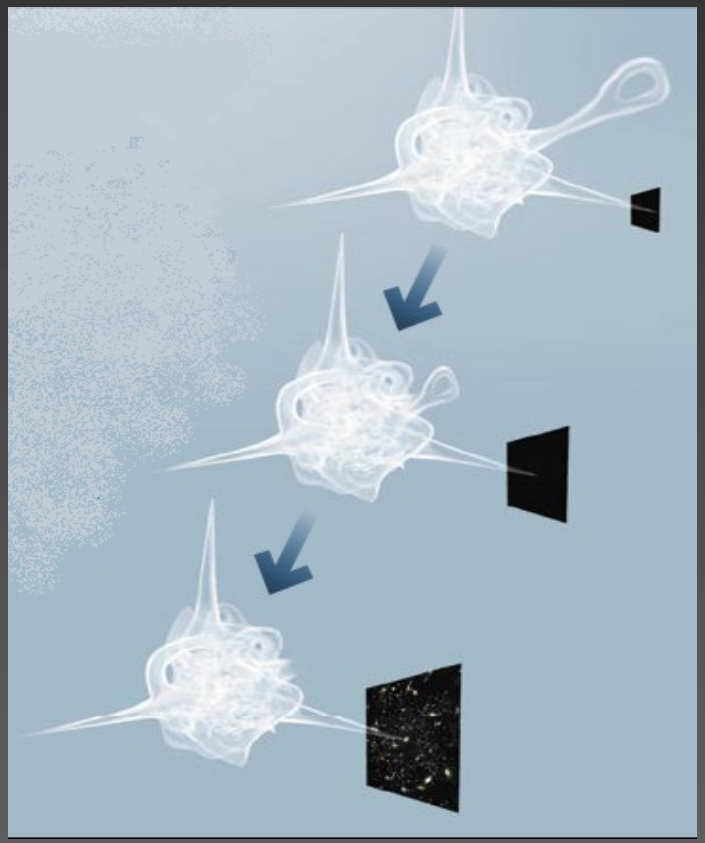
Closed string: *eg Rolling moduli (volume and shape of extra dimensions, or their superpartner axions)*

eg: Better Racetrack:

$$K = -2\ln V = -2\ln\left(\tau_1^{3/2} - \tau_2^{3/2}\right)$$

$$W = W_0 + A_1 e^{a_1 T_1} + A_2 e^{a_2 T_2}$$

$$f_i^{ab} = T_i\,\delta^{ab}$$



Emerging Picture

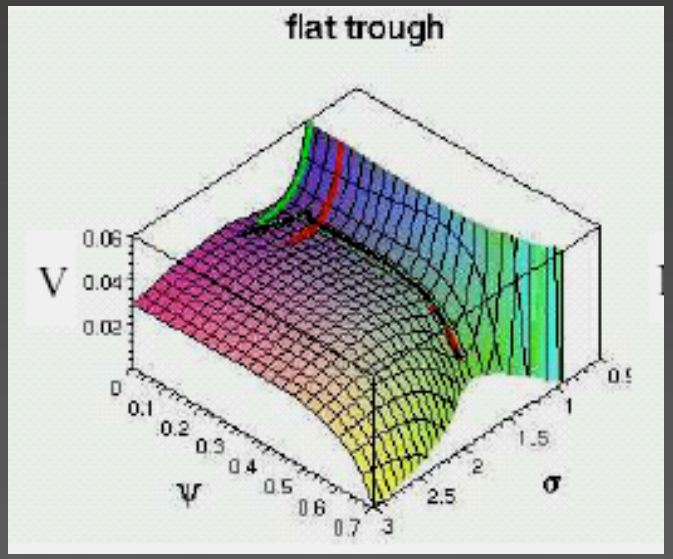
- Mechanisms
- *Robustness*
- Mind broadening

Emerging Picture

- Mec
- *Robu*
- Minc

In all cases the inflationary dynamics involves multiple fields moving in a complicated potential. Slow rolls appear not to be generic.

Warning: *It is insufficient in all known cases to fix some fields by hand, while evolving others (despite there being many papers which do so).*



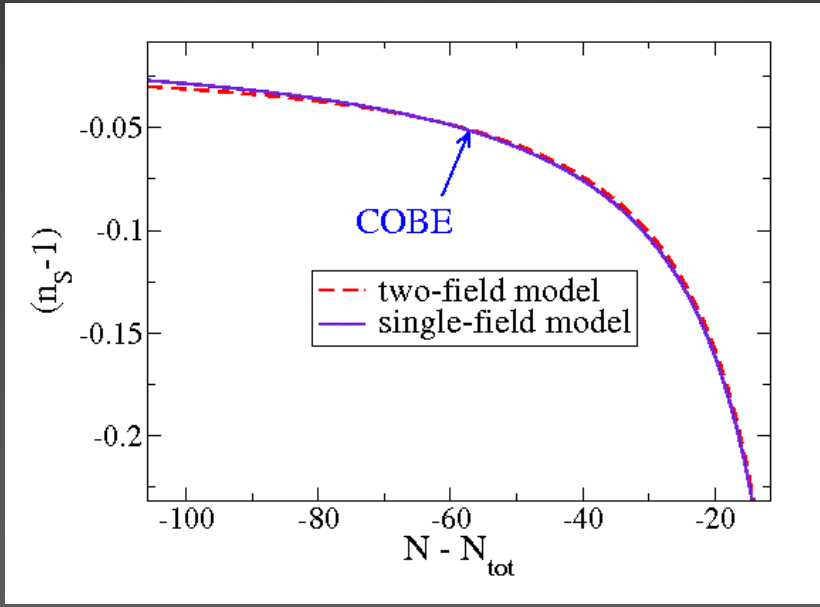
Emerging Picture

- Mec
- *Robu*
- Minc

Blanco-Pillado et al

Single-field slow-roll analyses nonetheless capture much of the generic predictions for the CMB

But must check: *The presence of multiple scalars allows in principle new features like isocurvature perturbations, etc.*



Emerging Picture

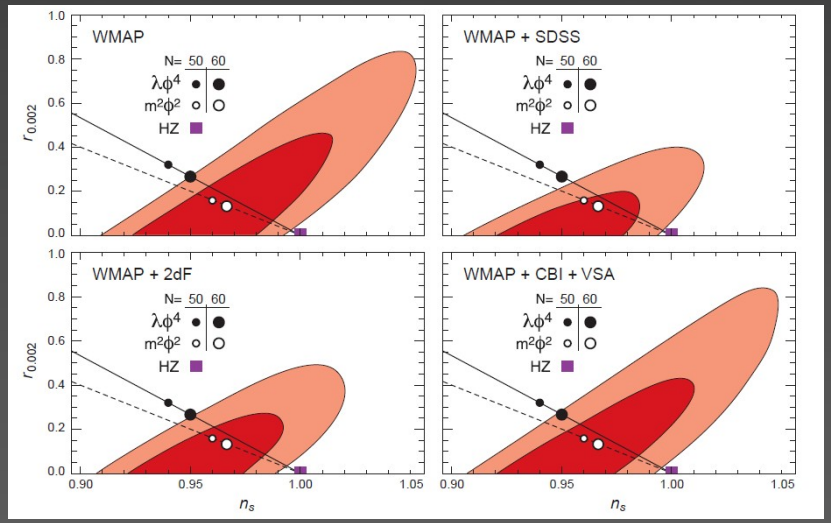
- Mec
- *Robu*
- Min

Because inflation is found in 4D effective theory, predictions tend to be contained within those of the corresponding 4D mechanism

Small-field models

Large-field models

Hybrid models



Emerging Picture

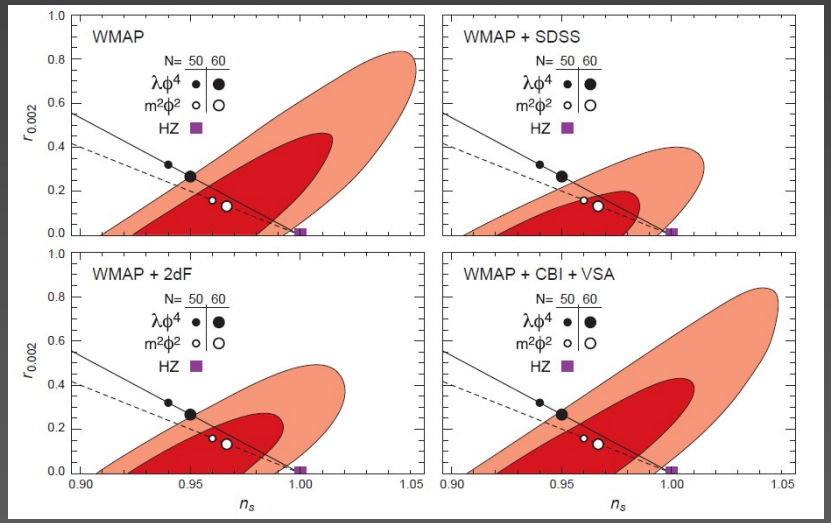
Kallosh & Linde
Baumann & McAllister

- Mec
- *Robu*
- Min

Because inflation is found in 4D effective theory, predictions tend to be contained within those of the corresponding 4D mechanism

Small-field models
Large-field models
Hybrid models

Apparently general stringy prediction: small tensor amplitude



Emerging Picture

Kaloper, Kleban, Lawrence & Shenker
CB, Cline, Holman & Lemieux

- Mec
- *Robu*
- Minc

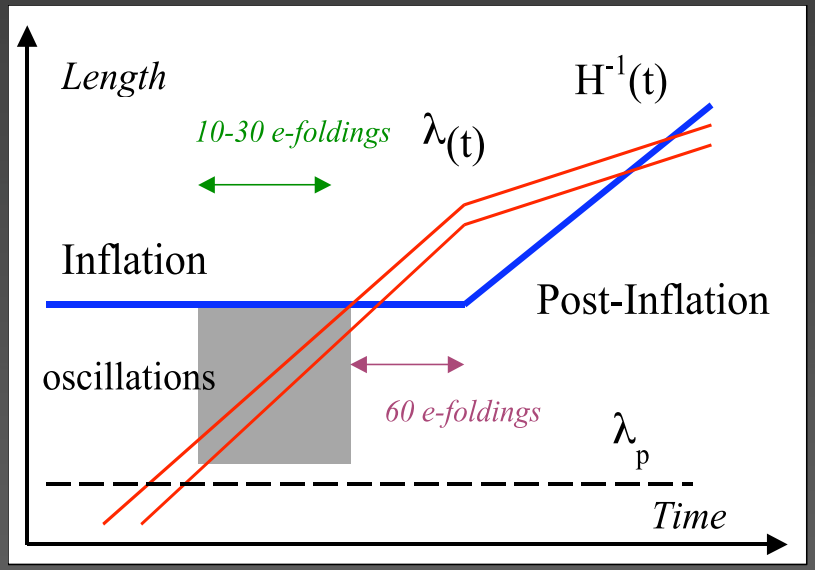
Heavy physics ($M \gg H$) decouples in string theory, and so tends not to interfere with inflationary predictions.

Two kinds of effects can be larger than the naïve H^2/M^2 suppression:

Non-adiabatic effects near horizon exit;

or

μ^2/M^2 *where* $H = \mu^2/M_p$



Emerging Picture

- Mec
- *Robu*
- Mino

Conlon & Quevedo

Inflation may be more natural in *Kahler modulus inflation*, with 3 moduli in large-volume framework.

$$K = -2\ln\left[\left(\tau_1^{3/2} - \tau_2^{3/2} - \tau_3^{3/2}\right) + \xi\right]$$

$$W = W_0 + A_1 e^{a_1 T_1} + A_2 e^{a_2 T_2} + A_3 e^{a_3 T_3}$$

$$f_i^{ab} = T_i\,\delta^{ab}$$

Slow roll relies on large field values rather than tuned parameters in the potential

$$V_{eff} \approx A - B(\phi / M)^n \exp\left[-b(\phi / M)^n\right]$$

$$\tau_3 = (\phi / M)^n \gg 1$$

Emerging Picture

- Mechanisms
- Robustness
- *Mind broadening*

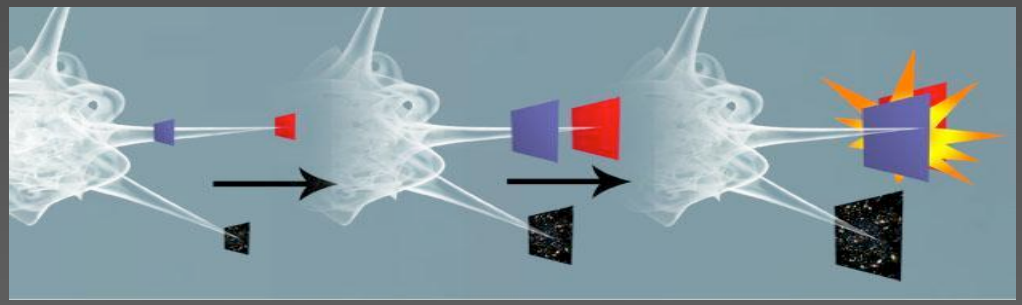
Emerging Picture

BMNQRZ
Dvali et al

- Mec
- Robu
- *Mino*

Several novel features and mechanisms have emerged

Brane-antibrane annihilation, and the absence of the inflaton in the post-inflationary low-energy theory;



Emerging Picture

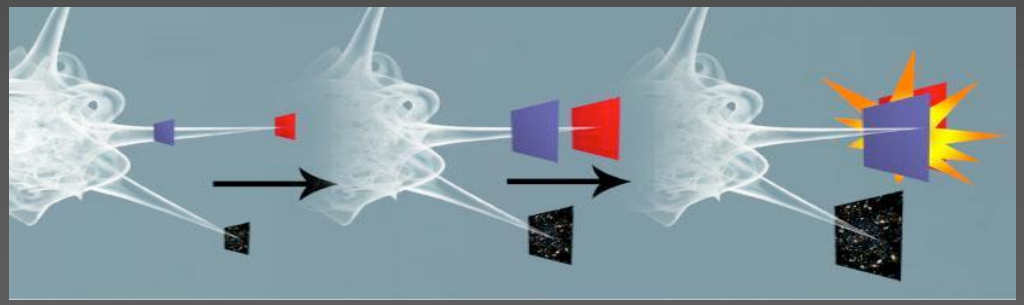
Barnaby et al
Kofman & Yi
Chialva, Shiu & Underwood
Langfelder

- Mec
- Robu
- *Minc*

Several novel features and mechanisms have emerged

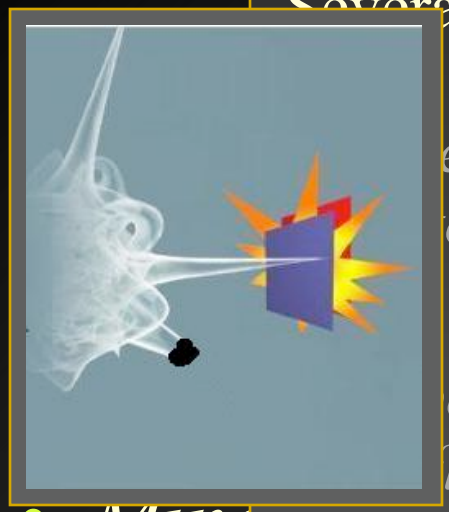
Brane-antibrane annihilation, and the absence of the inflaton in the post-inflationary low-energy theory;

Warped reheating, and the relatively efficient cascade of inflationary energy into the lowest throat.



Emerging Picture

Myers, Frey & Mazumdar
Buchel & Kofman



Several novel features and mechanisms have emerged

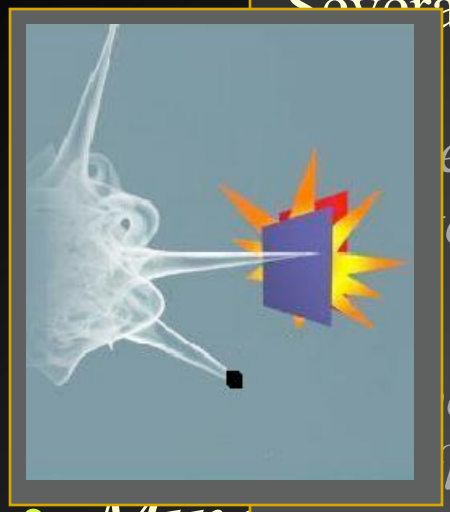
e-antibrane annihilation, and the absence of the
on in the post-inflationary low-energy theory;

ed reheating, and the relatively efficient cascade
lationary energy into the lowest throat. (Energy
dumped into throat can form evaporating BH there.)

- *Mino*

Emerging Picture

Myers, Frey & Mazumdar
Buchel & Kofman



Several novel features and mechanisms have emerged

e-antibrane annihilation, and the absence of the
on in the post-inflationary low-energy theory;

ed reheating, and the relatively efficient cascade
lationary energy into the lowest throat. (Energy
dumped into throat can form evaporating BH there.)

- *Mino*

Emerging Picture

Sarangi & Tye
BMNQRZ
Jones, Stoica & Tye
Copeland, Myers & Polchinski

- Mec
- Robu
- *Minc*

Several novel features and mechanisms have emerged

Brane-antibrane annihilation, and the absence of the inflaton in the post-inflationary low-energy theory;

Warped reheating, and the relatively efficient cascade of inflationary energy into the lowest throat.

Cosmic strings, and the leaving of inflationary relics.

Emerging Picture

Silverstein & Tong

- Mec
- Robu
- *Minc*

Several novel features and mechanisms have emerged

Brane-antibrane annihilation, and the absence of the inflaton in the post-inflationary low-energy theory;

Warped reheating, and the relatively efficient cascade of inflationary energy into the lowest throat.

Cosmic strings, and the leaving of inflationary relics.

Inflation from relativistic motion (DBI inflation)?

Emerging Picture

Veneziano et al
Khoury, Ovrut, Steinhardt & Turok

- Mec
- Robu
- *Mino*

Other ways our minds may yet broaden:

Are there stringy alternatives to inflation?

Open Issues

- Problem of scales

- Control over approximations

Open Issues

- *Problem of scales*

- Control over approximations

Open Issues

Kallosh & Linde
CB, Quevedo, Rajesh & Zhang

- *Prob*
- Cont
  appr

To address reheating issues must know where 'we' live and how we couple to the inflating sector.

Problem: *in the available models the string scale, M_s, required to obtain the right amplitude for primordial scalar perturbations gives a supersymmetry breaking scale which is too high to solve the hierarchy problem.*

eg: for warped models*: cannot make 2nd throat too deep if inflation occurs in 1st throat*

or: for large-volume models*:*

$$M_s \sim M_p/V^{1/2}; \quad m_{3/2} \sim M_p/V \sim M_s/V^{1/2}$$

Open Issues

- *Prob*
- Cont
  appr

Possible ways out:

Low-scale inflation (German, Ross & Sarkar)

Generate inflationary perturbations through other means (eg: a curvaton mechanism – nongaussianity?)

Allow M_s to roll to larger values after inflation (Conlon, Kallosh, Linde & Quevedo)

Long throats OK in dual description?

Open Issues

- Problem of scales

- *Control over approximations*

Open Issues

- Prob
- *Cont*
  appr

String inflation models are baroque in order to keep control over all approximations being used.

Some remaining weaknesses:

Size of corrections to the equations used

* *if dynamics is not given as a 4D supergravity*
* *if SUSY breaking comes from anti-branes*

Open Issues

- Prob
- *Cont*
  appr

String inflation models are baroque in order to keep control over all approximations being used.

Some remaining weaknesses:

Size of corrections to the equations used

* *if dynamics is not given as a 4D supergravity*
* *if SUSY breaking comes from anti-branes*

Inflation seekers scan through parameters of 4D action as if these are free and not calculable.

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations
  - Possible progress on fine-tunings, but not generically

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations
  - Possible progress on fine-tunings, but not generically
  - New insights on reheating (warping, cosmic strings);

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations
  - Possible progress on fine-tunings, but not generically
  - New insights on reheating (warping, cosmic strings);
  - Inflationary signals largely robust, except near horizon exit

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations
  - Possible progress on fine-tunings, but not generically
  - New insights on reheating (warping, cosmic strings);
  - Inflationary signals largely robust, except near horizon exit
  - Small tensor perturbations?

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations
  - Possible progress on fine-tunings, but not generically
  - New insights on reheating (warping, cosmic strings);
  - Inflationary signals largely robust, except near horizon exit
  - Small tensor perturbations?
- Possibly even more novel physics can arise!

Outlook

- There are plausible formulations of inflation in string theory, but still at the stage of mapping out what is possible
  - Not easy to obtain and keep control over approximations
  - Possible progress on fine-tunings, but not generically
  - New insights on reheating (warping, cosmic strings);
  - Inflationary signals largely robust, except near horizon exit
  - Small tensor perturbations?
- Possibly even more novel physics can arise!

fin