The Abdus Salam
International Centre for Theoretical Physics

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*SPRING SCHOOL ON SUPERSTRING THEORY
AND RELATED TOPICS*

22 - 30 March 2007

Brane Inflation
PART 1 & 2

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Brane Inflation : I & II String theory viewed from the Cosmos

Henry Tye

Cornell University

Gia Dvali, Nick Jones, Louis Leblond, Horace Stoica,
Gary Shiu, Levon Pogosian, Sash Sarangi, Sarah Shandera,
Ira Wasserman, Mark Wyman, Ben Shlaer, Hassan Firouzjahi, Girma Hailu, Xingang Chen, Jiajun Xu, Rachel Bean

ICTP Trieste 3/22/07

Recent reviews

- Cliff Burgess, “Strings, branes and cosmology”, hep-th/0606020
- H. Tye, “Brane Inflation : string theory viewed from the cosmos”, hep-th/0610221
- Jim Cline, “String cosmology”, hep-th/0612129
- Renata Kallosh, “On inflation in string theory”, hep-th/0702059

Plan

- Inflation and brane inflation
- Brane inflation confronts data
- Cosmic strings
- A variation (detail) of the KKLMMT scenario, where gauge/gravity duality plays a key role.

Inflationary Universe

10^{-30} m $\qquad$ 10^{-34} s

- solves a number of outstanding cosmological problems : flatness, horizon, defects, angular momentum etc.
- generated all matter-radiation in our universe from the inflaton potential.
- started the hot big bang universe.
- generated the density perturbation that seeded the structure formation.
- generated the temperature fluctuation observed in COBE, WMAP, ...

Inflation

- $$H^2 = \Lambda + \frac{k}{a^2} + \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4}$$
- a(t) = the cosmic scale factor ~ size of universe
- H = Hubble constant =(da/dt)/a
- Λ = dark energy = inflaton potential ~V
- k = curvature
- ρ_m = matter density at initial time
- ρ_r = radiation density at initial time
- H = constant $\Rightarrow$ a = exp(Ht)

Evolution of the inflaton

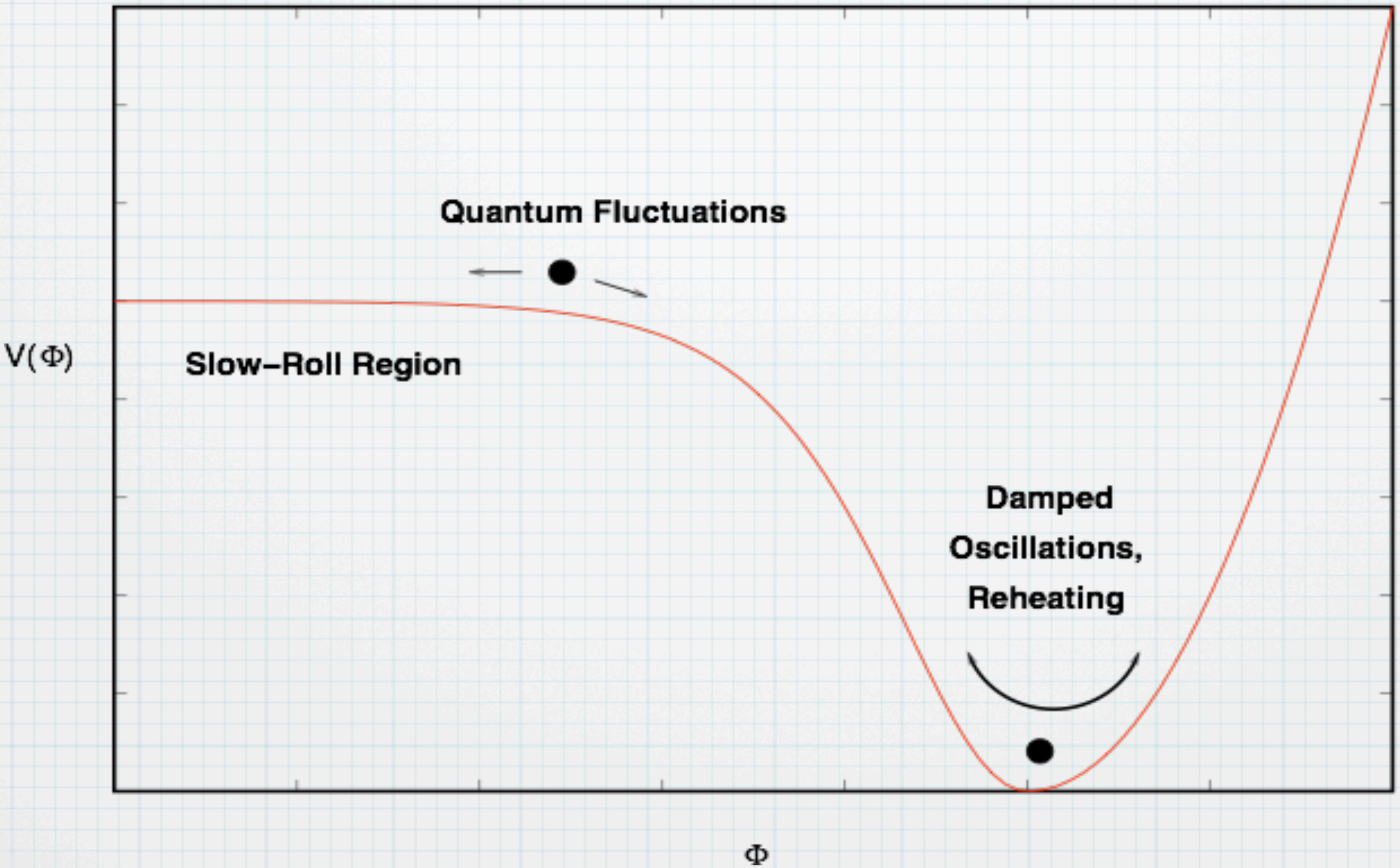
$$H^2 = \frac{V(\phi)}{3M_{Pl}^2}$$

$$\cancel{\ddot{\phi}} + 3H\dot{\phi} = -\frac{\partial V}{\partial \phi}$$

$$\frac{\dot{a}}{a} = H$$

$$a(t) \simeq e^{Ht} \rightarrow e^{N_e}$$

Vacuum energy comes from the inflaton potential



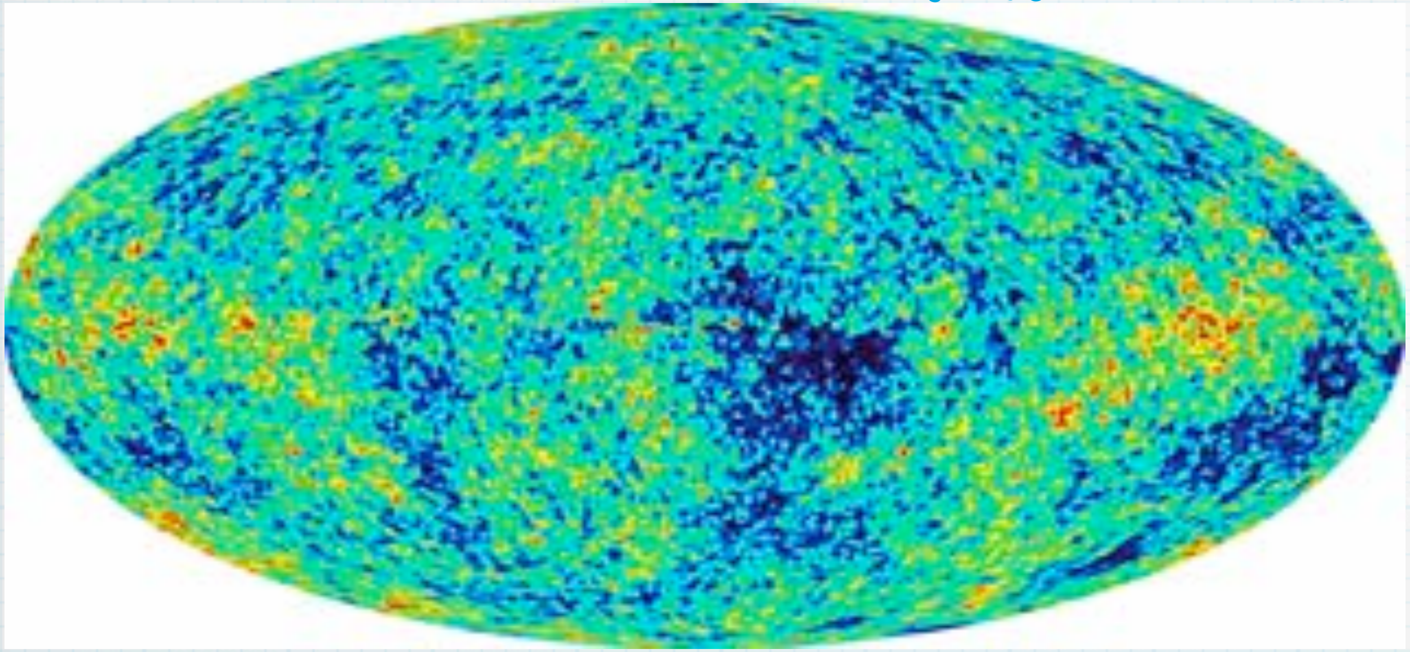
Density fluctuation generated during inflation :

$$\frac{\delta\rho}{\rho} \simeq 10^{-5} \qquad\qquad \frac{\delta\rho}{\rho} \simeq \frac{H^2}{2\pi\dot{\phi}}$$

which is roughly scale-invariant, led to structure formation in our universe

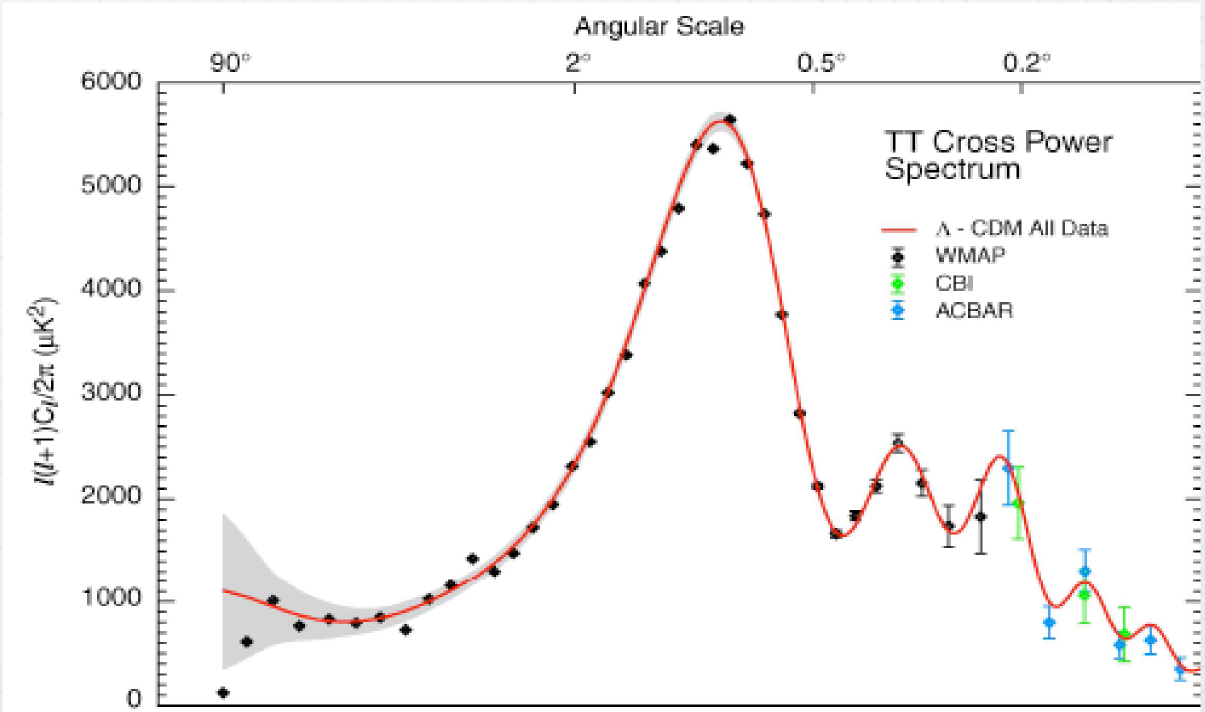
It also led to temperature fluctuation that was seen in the cosmic microwave background radiation.

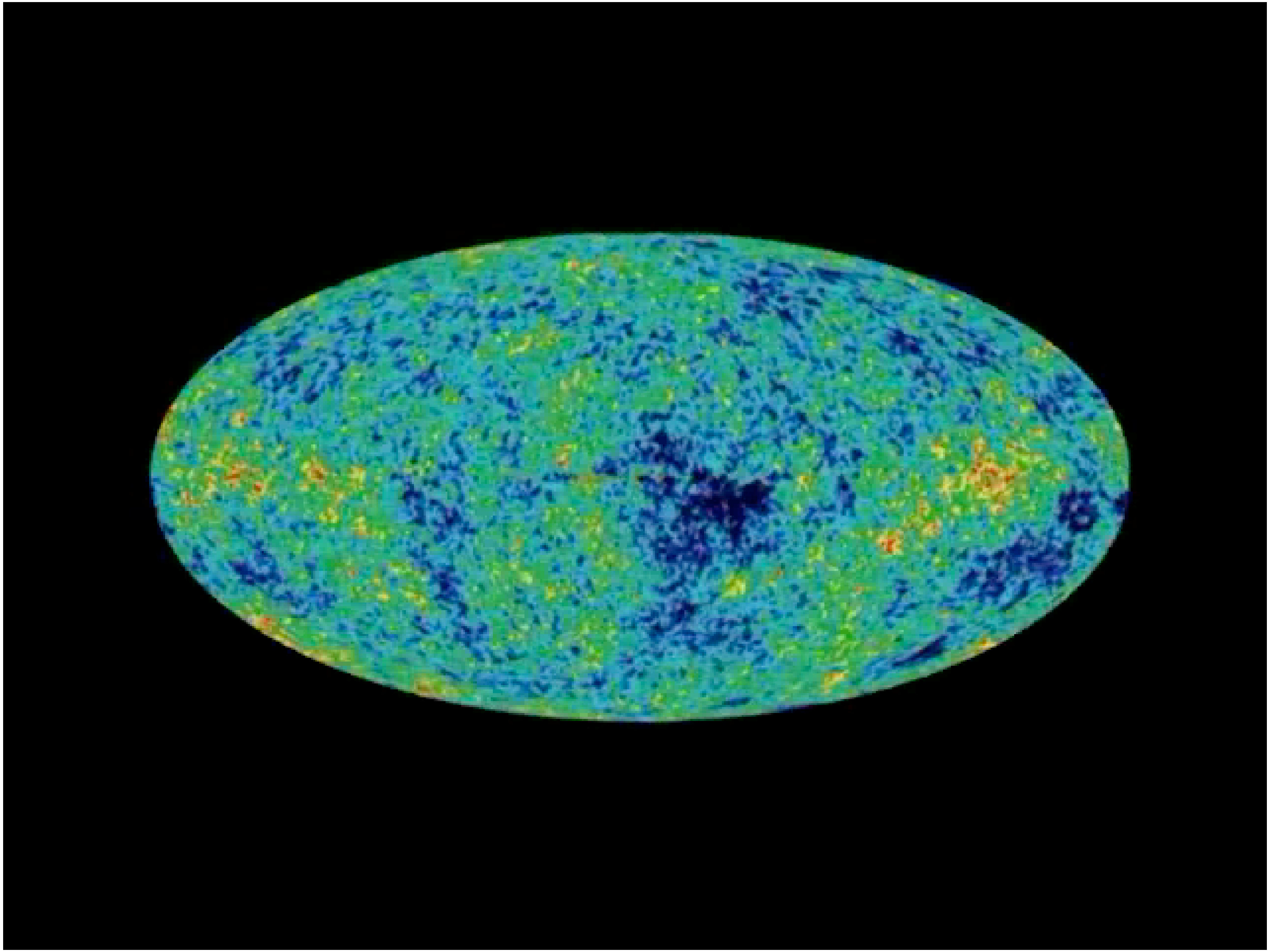
WMAP 2003, 2006



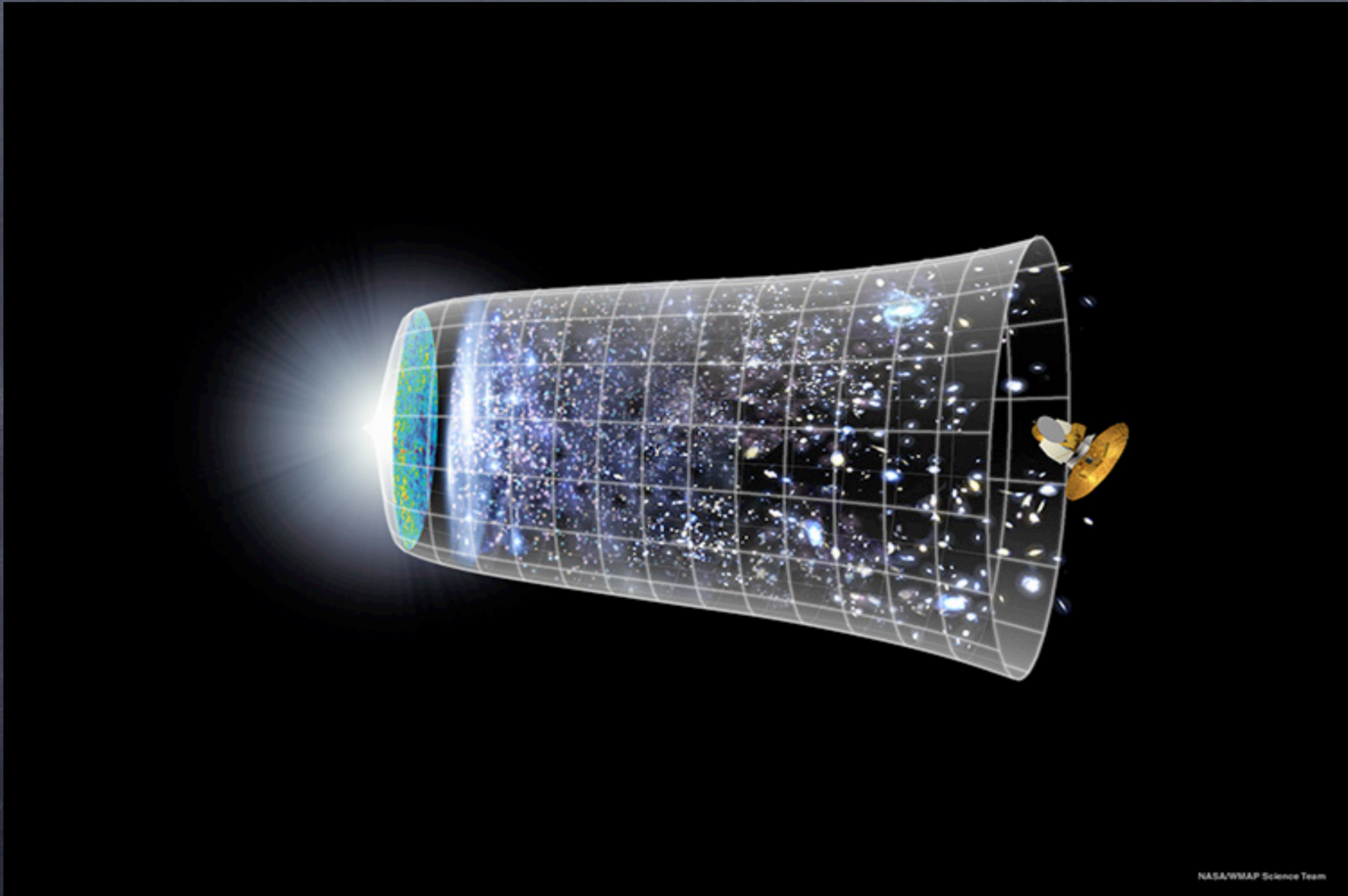
T=2.725⁰K

Data strongly supports inflation





The cosmological evolution of the density perturbation


NASA/WMAP Science Team

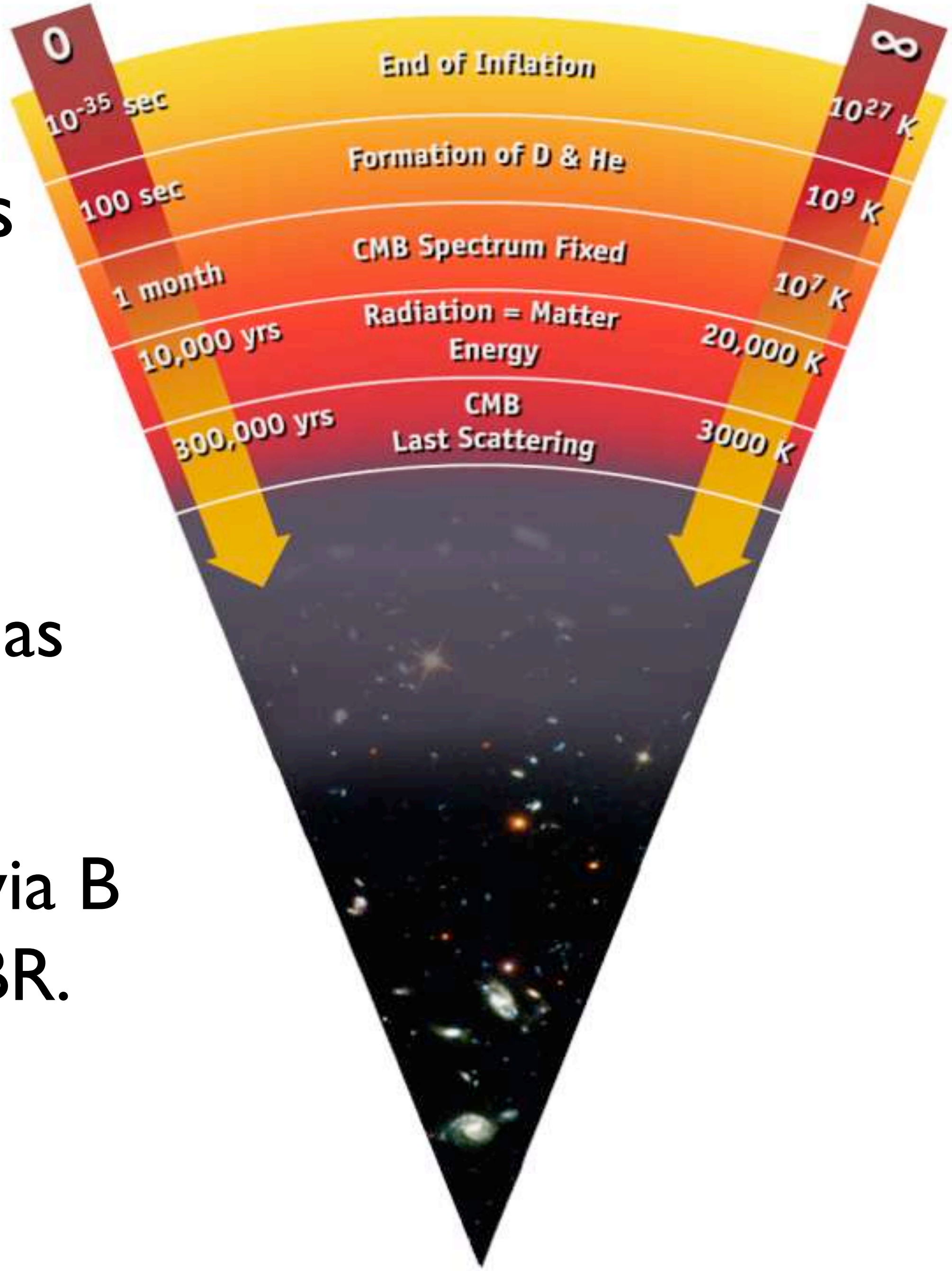
Tensor Mode

Metric perturbation evolves undisturbed since the inflationary epoch.

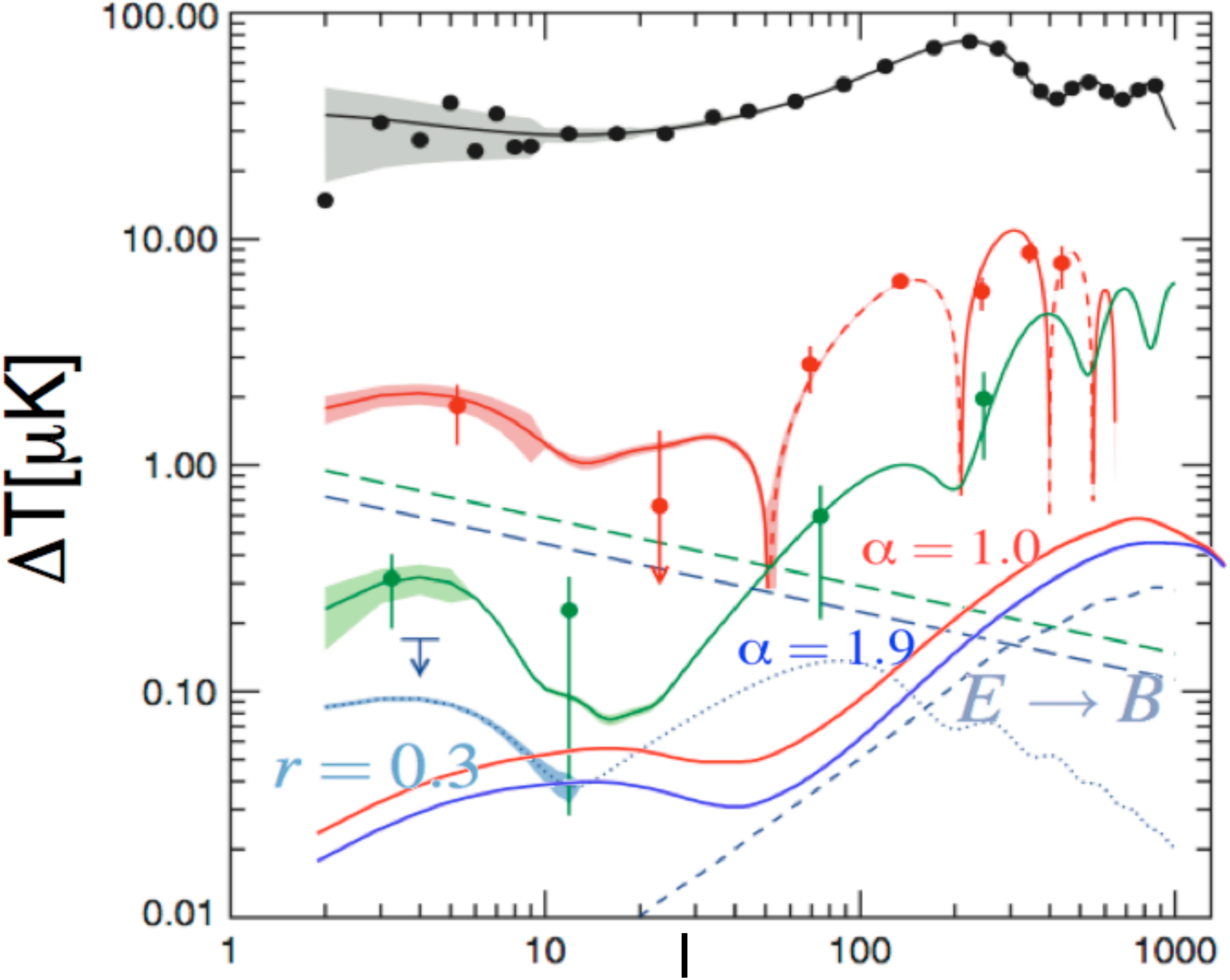
This may be detected by gravitational wave detectors as stochastic background.

This may also be detected via B mode polarization in CMBR.

$$r = \frac{P_t(k)}{P_s(k)}$$



Temperature Fluctuation and Polarization



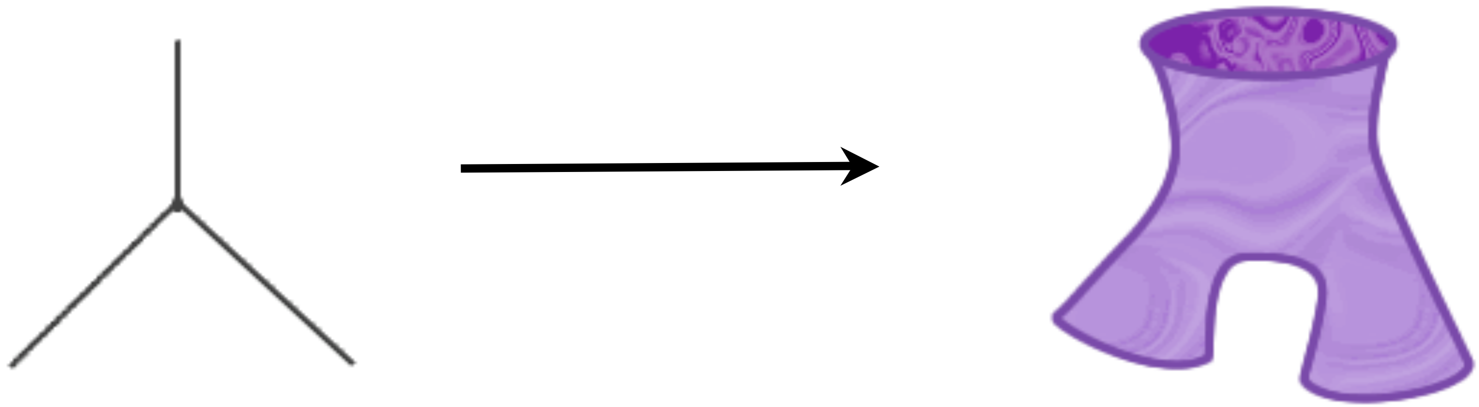
Motivation for Stringy Inflation

- Recent CMBR observations strongly support inflation as the origin of hot big bang and the structure formation in the Universe.
- However, the origin of inflation is not known from a fundamental theory point of view.
- String theory, on the other hand, is a consistent theory of gravity and is expected to provide the standard model of the strong and electroweak forces.
- Since the scale of inflation is very high, probably around GUT scale, it is natural to expect that string theory was relevant in explaining the origin of inflation.
- This would provide a unique chance to test the relevance of string theory to the real world.
- One may pinpoint distinct stringy signatures, which helps to solidify the inflationary scenario.

String Theory

- A consistent theory of quantum gravity. It contains the graviton in its spectrum.

- All known particles are low-lying string vibrations.



It has 10 spacetime dimensions

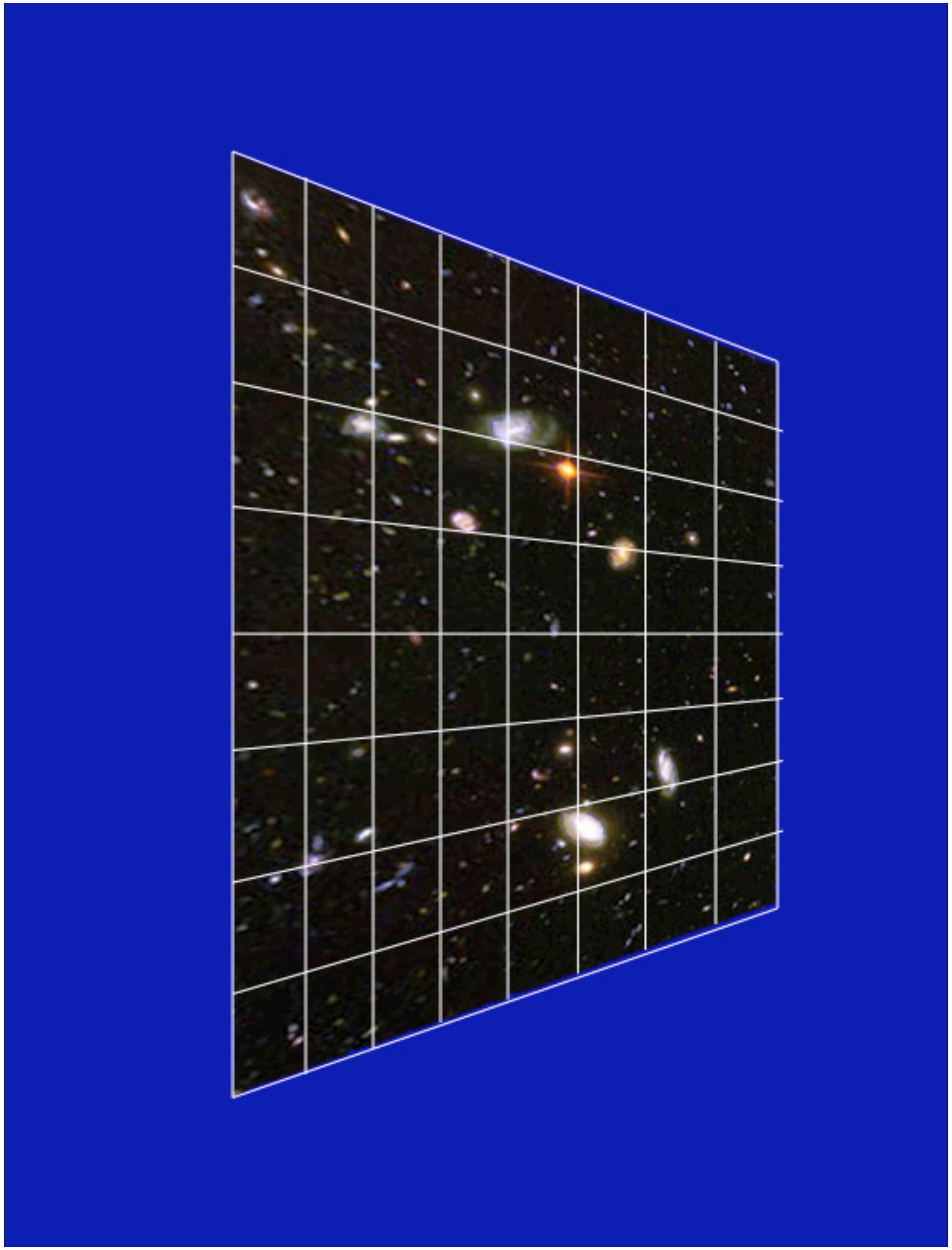
Superstring theory contains Dp-branes

A p-brane has p spatial dimensions:
a point particle is like a 0-brane;
a string is like a 1-brane;
a membrane is a 2-brane

We are living inside a D3-brane
(or a Dp-brane wrapping a p-3 cycle)

Outside our branes is the bulk,
which is compactified.

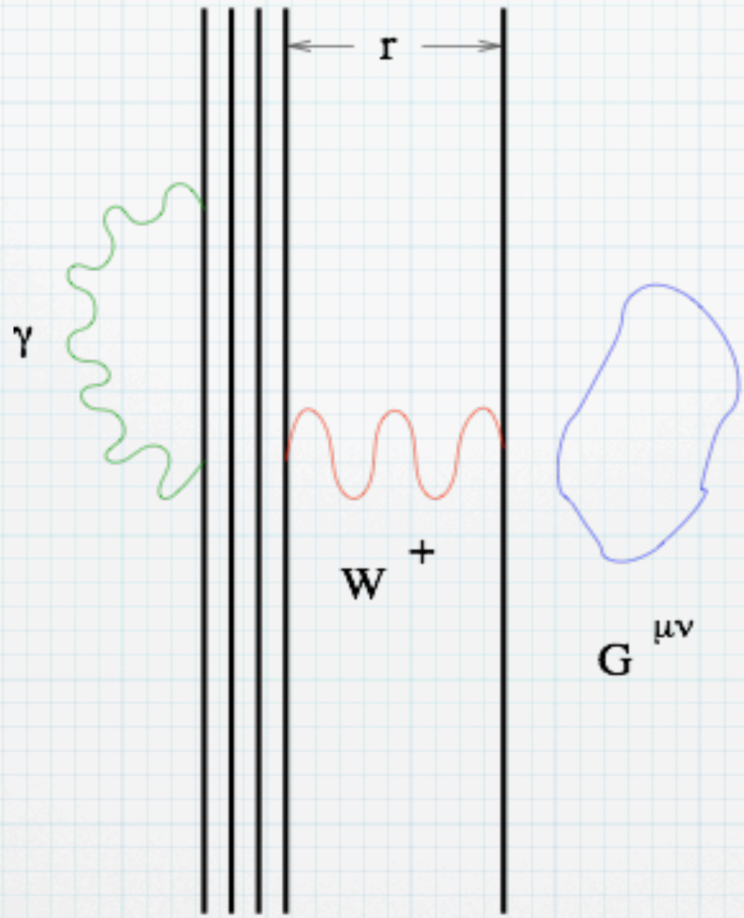
Brane World



Aaron
Miller

Brane world

10^{-30} m

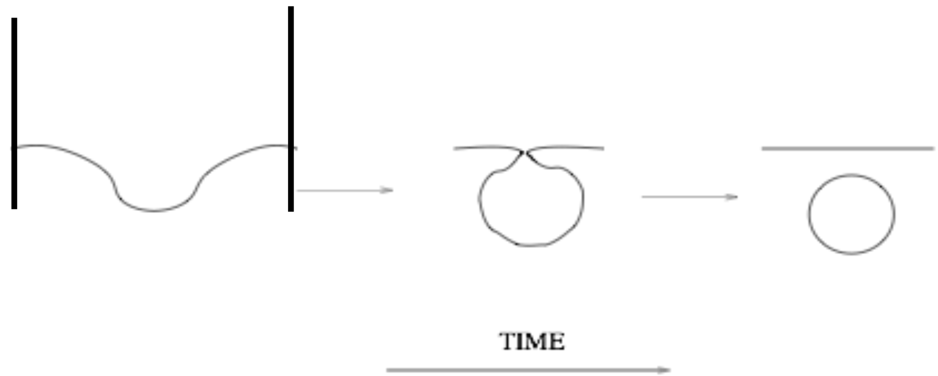


How to test this picture ?

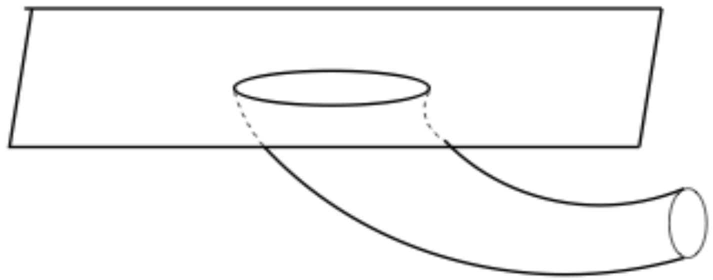
Z boson emitting a graviton

open string closed string

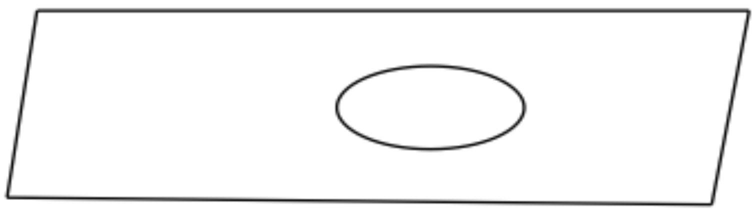
field theory
point particle



string theory



open string one-loop
=
closed string tree
diagram



How is inflation realized in the brane world ?

Light scalar field :

- Closed string mode : modulus
- Open string mode : tachyon, brane position etc.

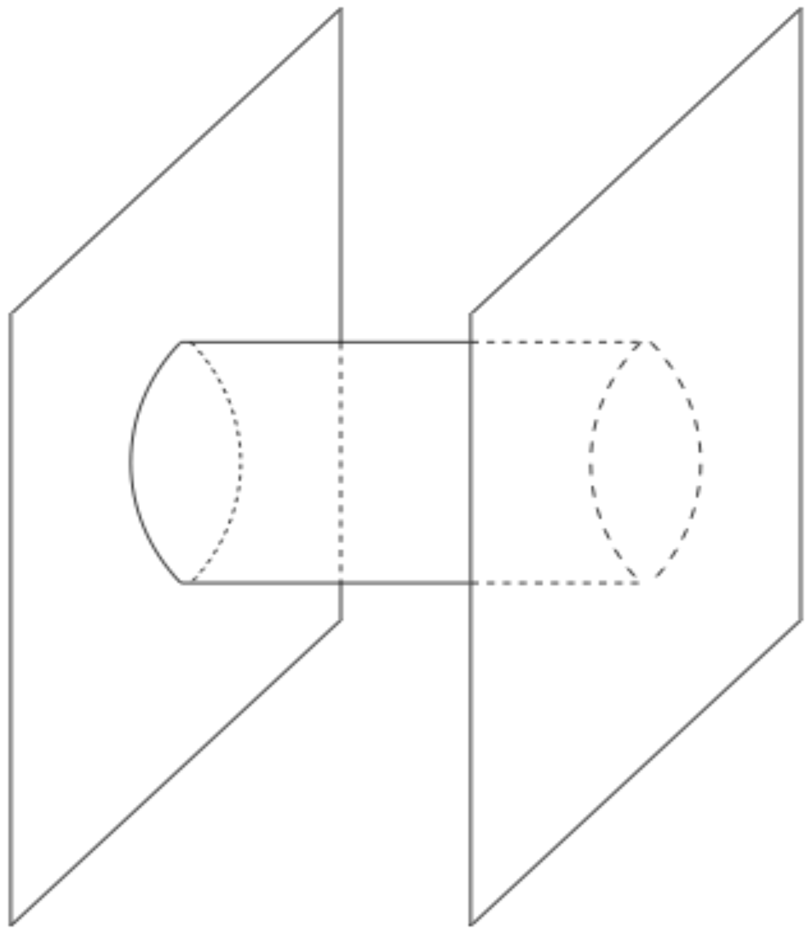
Typical flux compactification involves dozens to hundreds of moduli, so their potential V generically would have some flat directions.

Special stringy signatures ?

Brane inflation

Inflaton is an open string mode

Inflaton potential comes from the closed string exchange

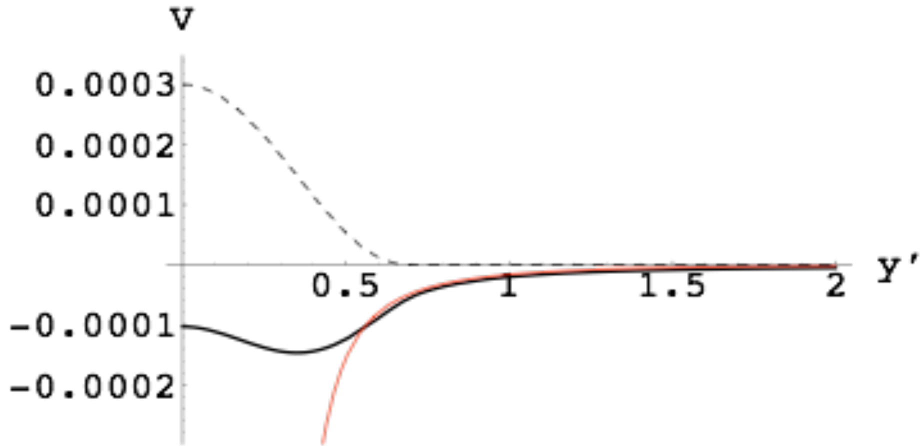


G. Dvali and H.T. , hep-ph/9812483

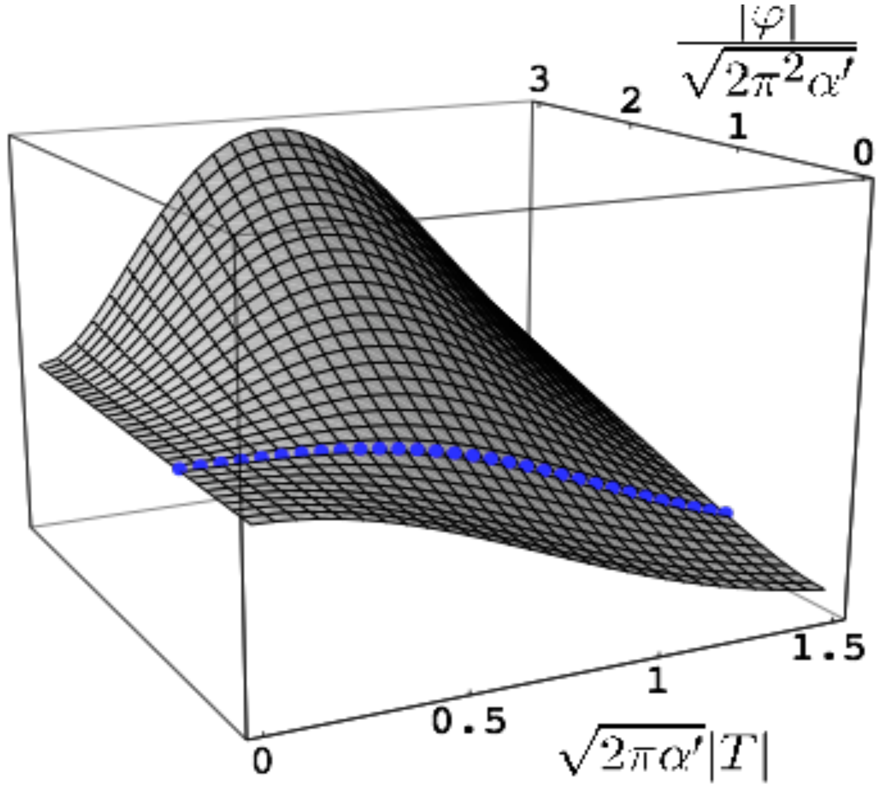
D3-anti-D3 brane inflation

C.P. Burgess, M. Majumdar, D. Nolte, F. Quevedo, G. Rajesh, R. Zhang, hep-th/0105204
G. Dvali, Q. Shafi and S. Solganik, hep-th/0105203

Inflaton Potential (like hybrid inflation)



$$\sum_i (-1)^F m_i^{2n} = 0, \qquad n = 1, 2, 3$$

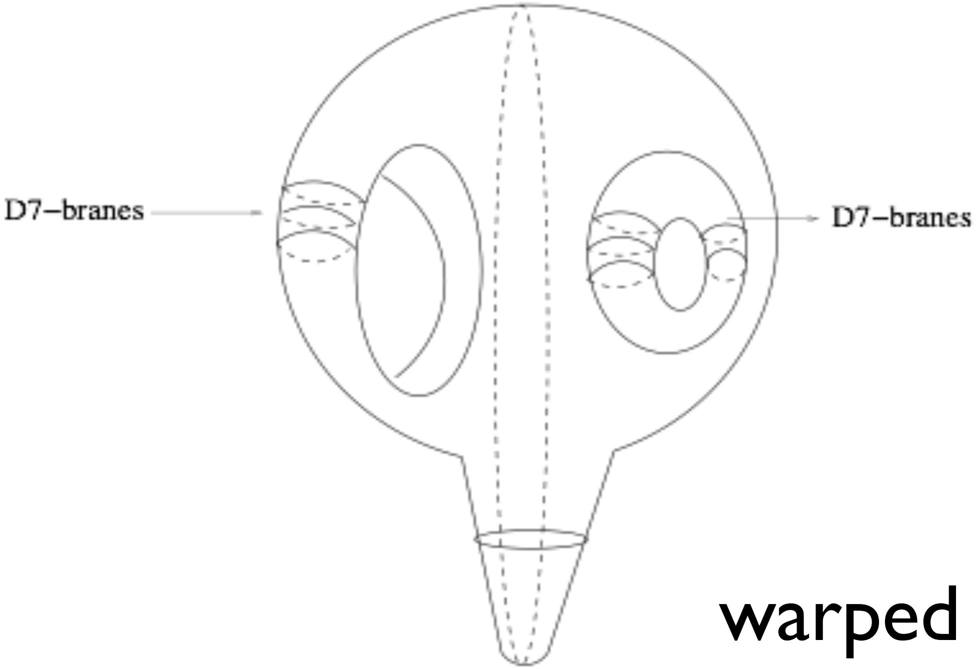


J. Garcia-Bellido, R. Rabadan, F. Zamora, hep-th/0112147
S. Sarangi and H.T., hep-th/0307078

N. Jones and HT, hep-th/0211180

Flux compactification

where all moduli of the 6-dim. “Calabi-Yau” manifold are stabilized



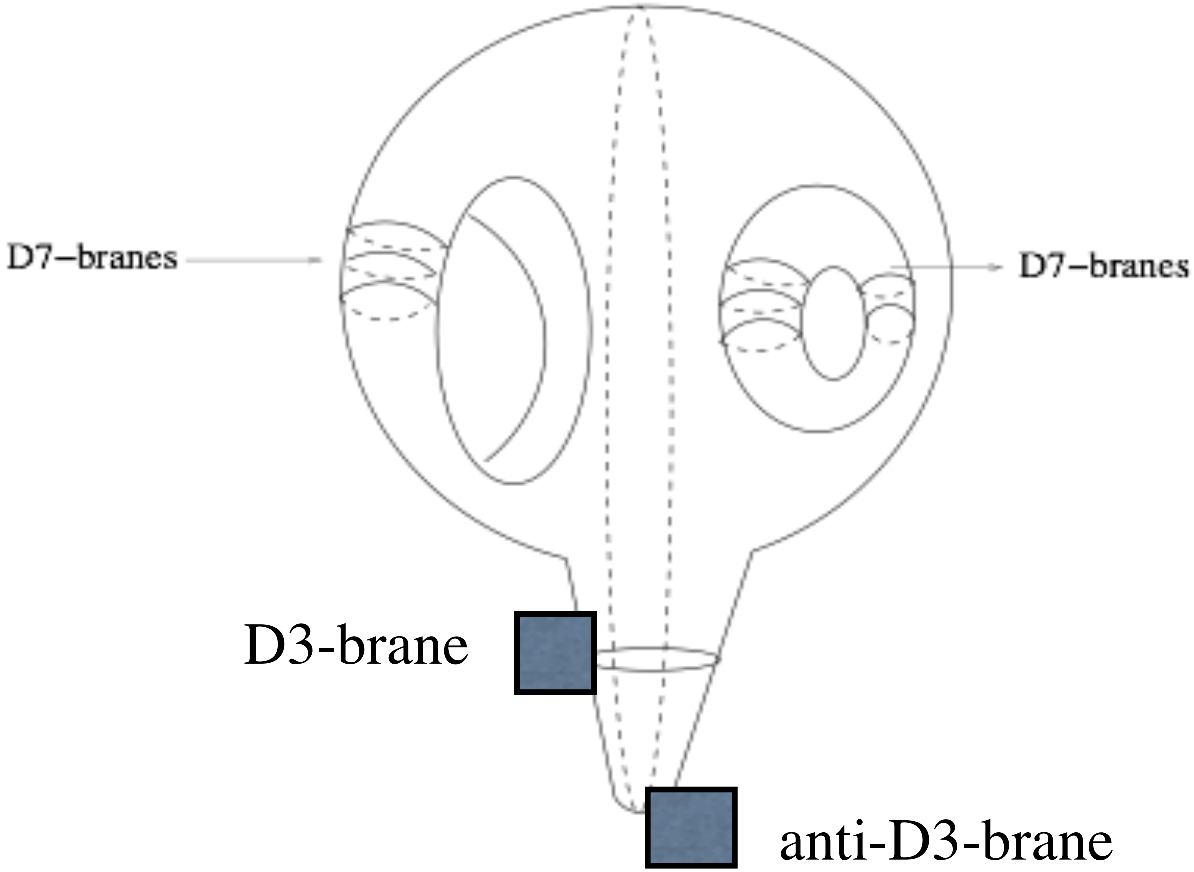
warped deformed throat

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

and many others, 2001....

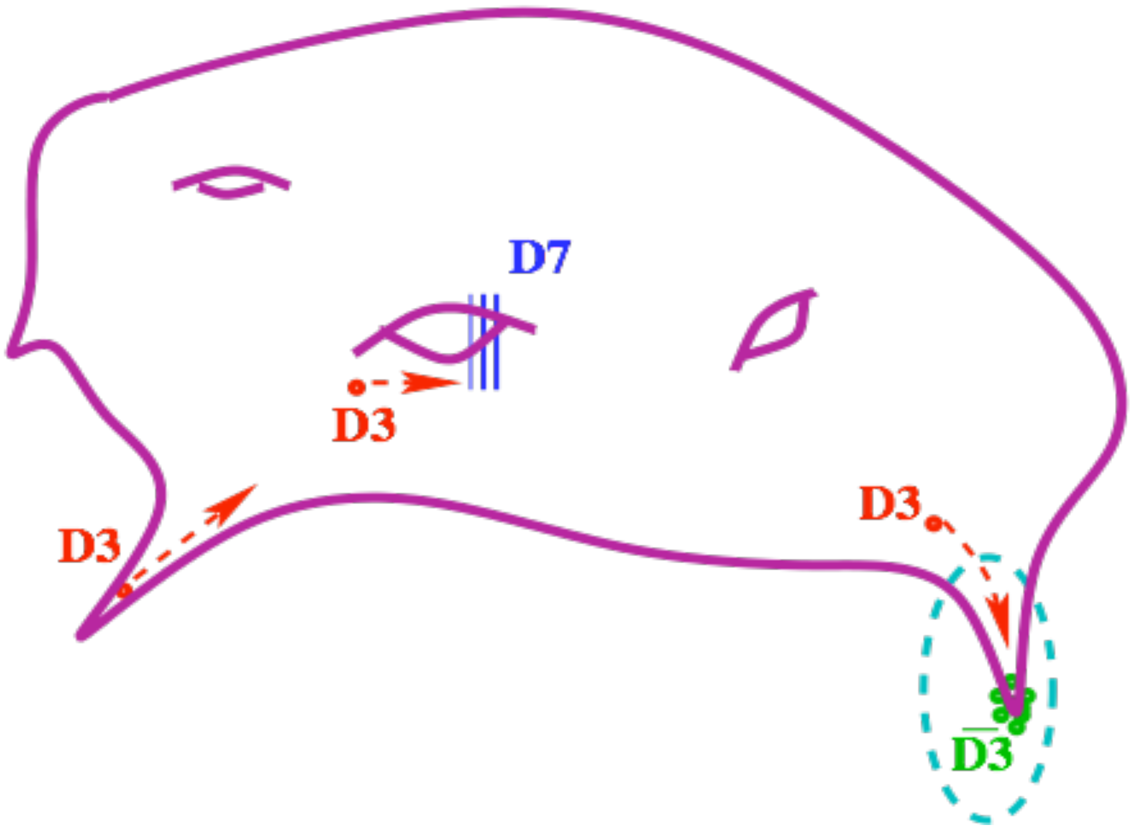
KKLT vacuum

KKLMMT Scenario



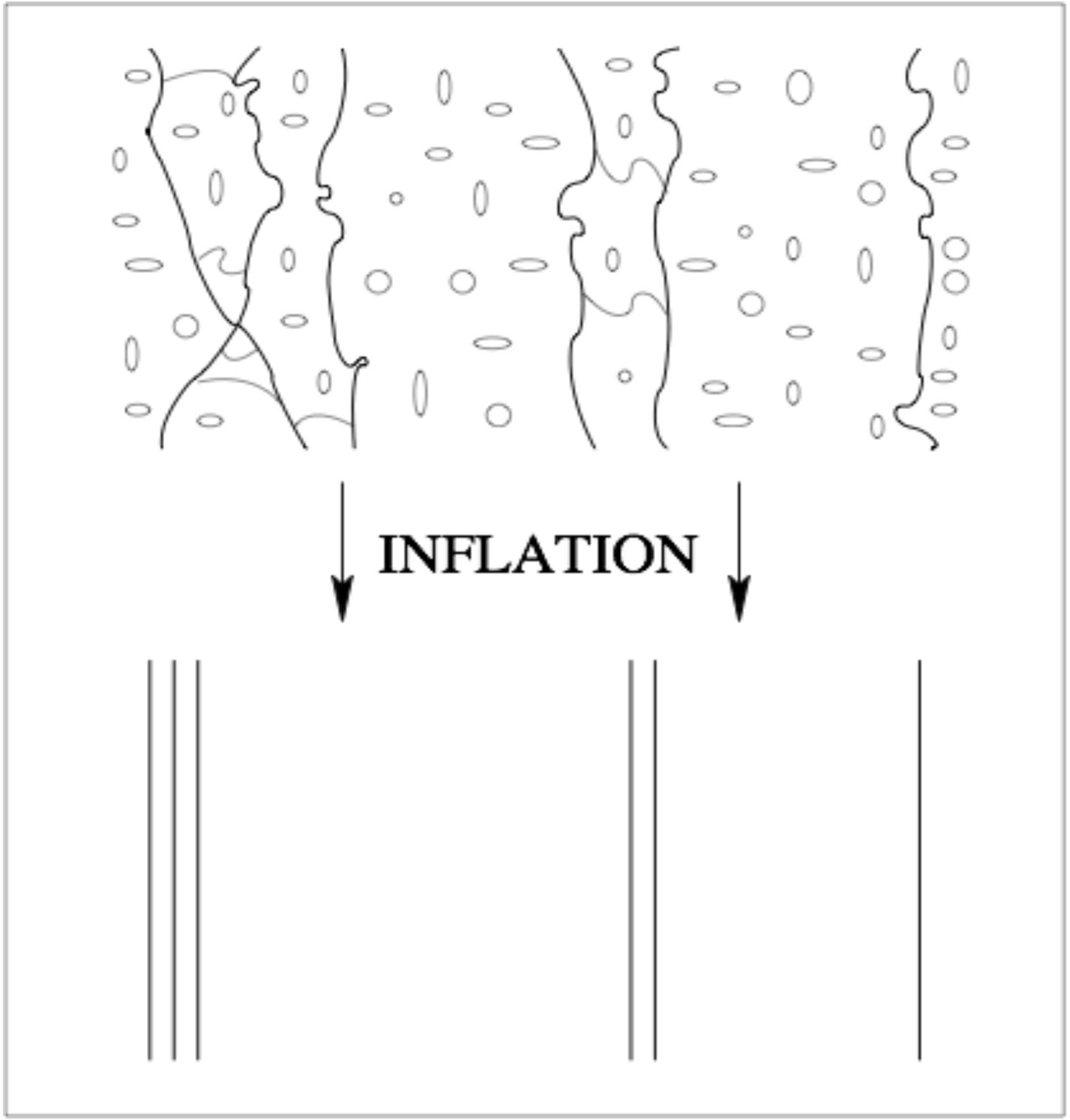
Kachru, Kallosh, Linde, Maldacena,
MacAllister, Trivedi, hep-th/0308055

Some simple scenarios

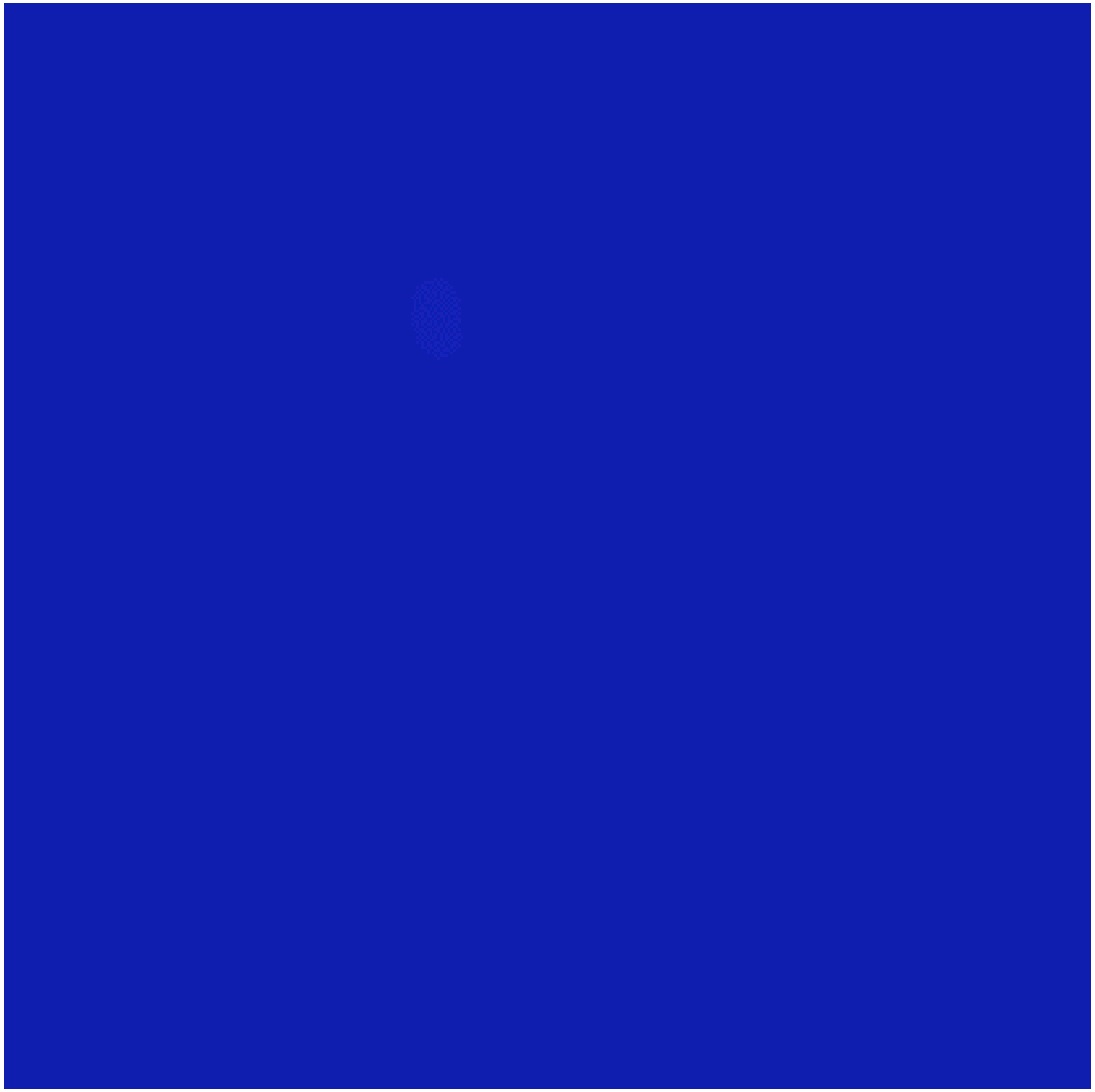


- Features:
  - Mobile D3s
  - warped throats
  - anti-D3s in throats
  - Wrapped D7s

Brane inflation



Brane Inflation and Collision



A. Miller

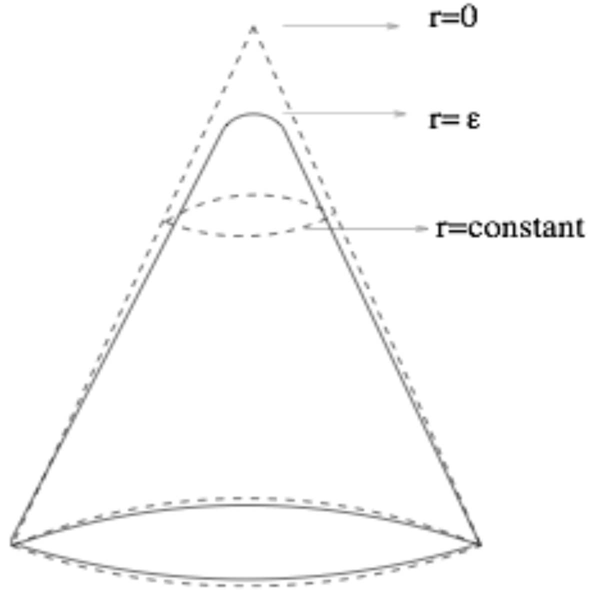
Klebanov-Strassler Throat

$$ds_{10}^2 = h^2(r)[-dt^2 + a(t)^2 dx^2] + h^{-2}(r) ds_6^2$$

$$h(r) \simeq r/R(\ln r/r_0)^{1/4}$$

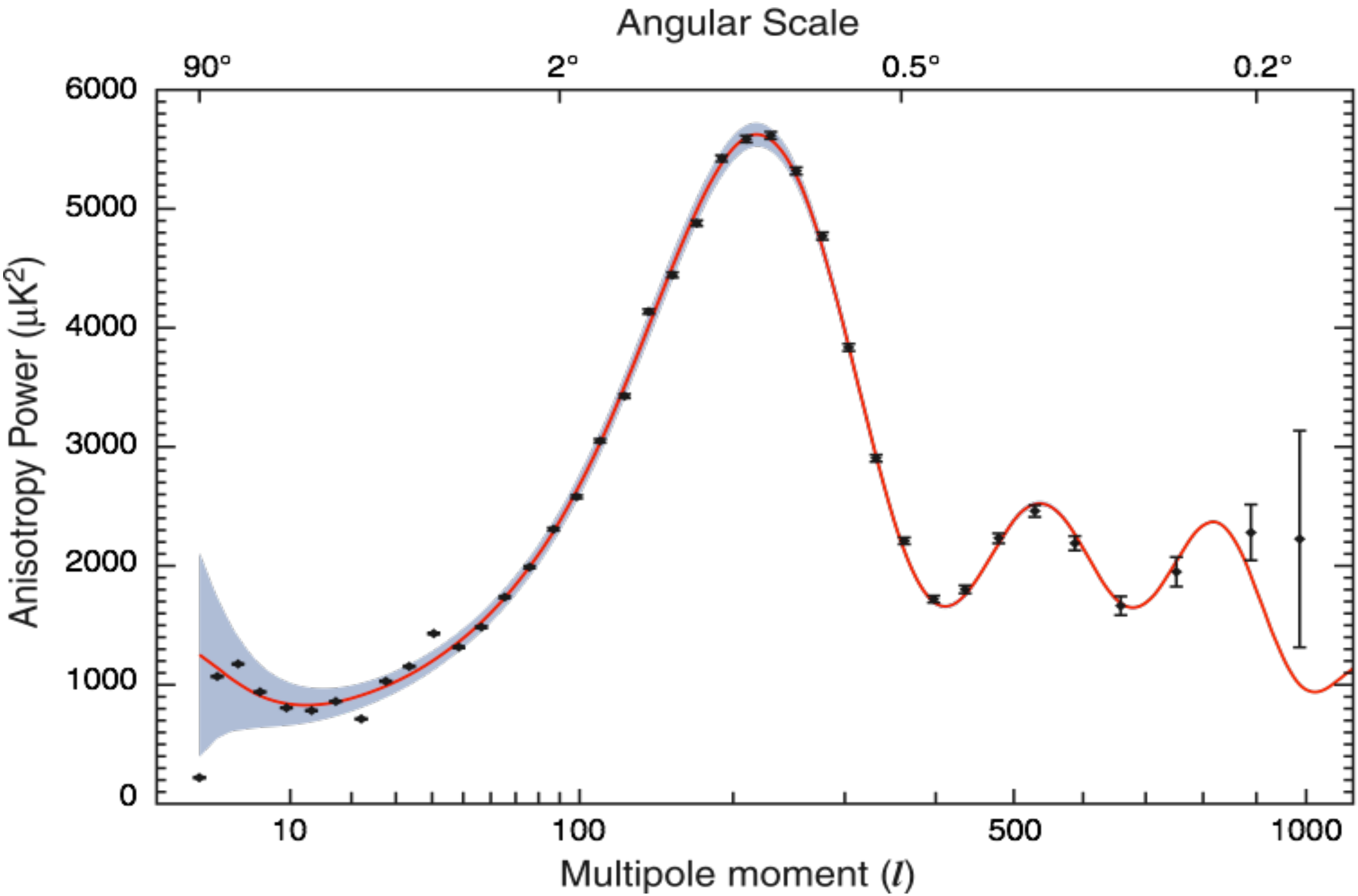
$$ds_6^2 = dr^2 + r^2 ds_{T^{1,1}}^2$$

$$ds_{T^{1,1}}^2 = \frac{1}{9}(\, d\psi + \sum_{i=1}^{2} \cos\theta_i \, d\phi_i \,)^2 + \frac{1}{6}\sum_{i=1}^{2}(\, d\theta_i^2 + \sin^2\theta_i \, d\phi_i^2 \,)$$



$$\sum_{i=1}^{4} w_i^2 = \epsilon^2$$

WMAP 2006



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (l)

Inflaton potential

$$V(\phi) = V_K(\phi) + V_0 + V_C(\phi) \simeq \frac{m^2}{2}\phi^2 + V_0\left(1 - \frac{vV_0}{4\pi^2}\frac{1}{\phi^4}\right)$$

$$V_0 = 2T_3 h_A^4 = 2T_3 h(\phi_A)^4$$

KKLMMT scenario

$$h_A(\phi) \simeq \phi_A$$

SLOW-ROLL : $\frac{\delta\rho}{\rho} \simeq \frac{H^2}{2\pi\dot{\phi}}$

mass and additional terms to the potential :

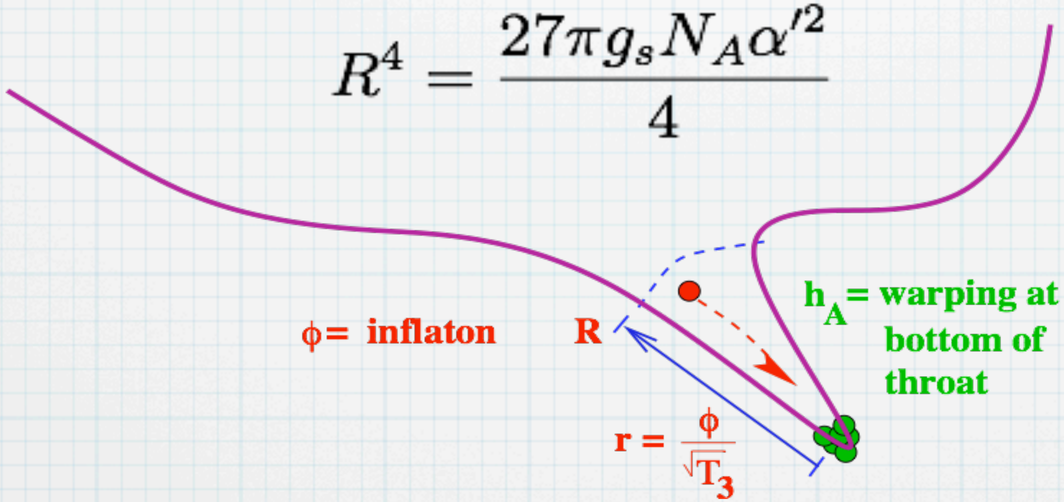
Baumann, Dymarsky, Klebanov, Maldacena McAllister, Murugan, hep-th/0607050

Burgess, Cline, Dasgupta, Firouzjahi, hep-th/0610320

Slow-Roll-KKLMMT

$$V = V_K + V_A + V_{D\bar{D}} = \frac{1}{2}\beta H^2\phi^2 + 2T_3 h_A^4 (1 - \frac{1}{N_A}\frac{\phi_A^4}{\phi^4}) + \ldots$$

$$R^4 = \frac{27\pi g_s N_A \alpha'^2}{4}$$



$$\beta < 1/5 \rightarrow m/m_0 < 1/2$$

$\beta \sim 1 \rightarrow$ no slow roll

During inflation

$$\eta = 0$$

Inflaton is an open string mode :

$$S = -\int d^4x\, a^3(t) \left[T\sqrt{1-\dot{\phi}^2/T} + V(\phi) - T \right]$$

$$\rightarrow \int d^4x\, a^3(t) \left[\frac{\dot{\phi}^2}{2} - V(\phi) \right]$$

Dirac-Born-Infeld action yields Lorentz factor :

$$\phi = \sqrt{T_3} r$$

$$\gamma = \frac{1}{\sqrt{1-\dot{\phi}^2/T}} \quad \rightarrow \quad \dot{\phi}^2 < T(\phi)$$

$$T(\phi) \sim \phi^4 \rightarrow \quad \text{exponentially small}$$

Silverstein, Tong, hep-th/0404084

Alishahiha, Silverstein, Tong, hep-th/0404084

Properties

For $n_s = 0.95 \pm 0.03$, there are 4 allowed regions :

* (1) Slow-roll KKLMMT, hep-th/0308055
* (2) relativistic, where tensor mode can be very large S. Shandera and HT, hep-th/0601099
* (3) ultra-relativistic, where non-Gaussianity can be very large Alishahiha, Silverstein, Tong, hep-th/0404084
* (4) Chen scenario X. Chen, hep-th/0408064

3 regions with red tilt

* 1 Slow-roll : $\gamma_{55} \simeq 1 \quad \gamma_1 \simeq 1$
* 2 Intermediate : $\gamma_{55} \simeq 1 \quad \gamma_1 \gg 1$
* 3 DBI/ultra-relativistic :

  $$\gamma_{55} \gg 1 \quad \gamma_1 \gg 1$$

What data can measure :

Angular power spectrum :

$$P_s(k) \sim k^{n_s - 1}$$

$$\frac{\partial n_s}{\partial \ln k}$$

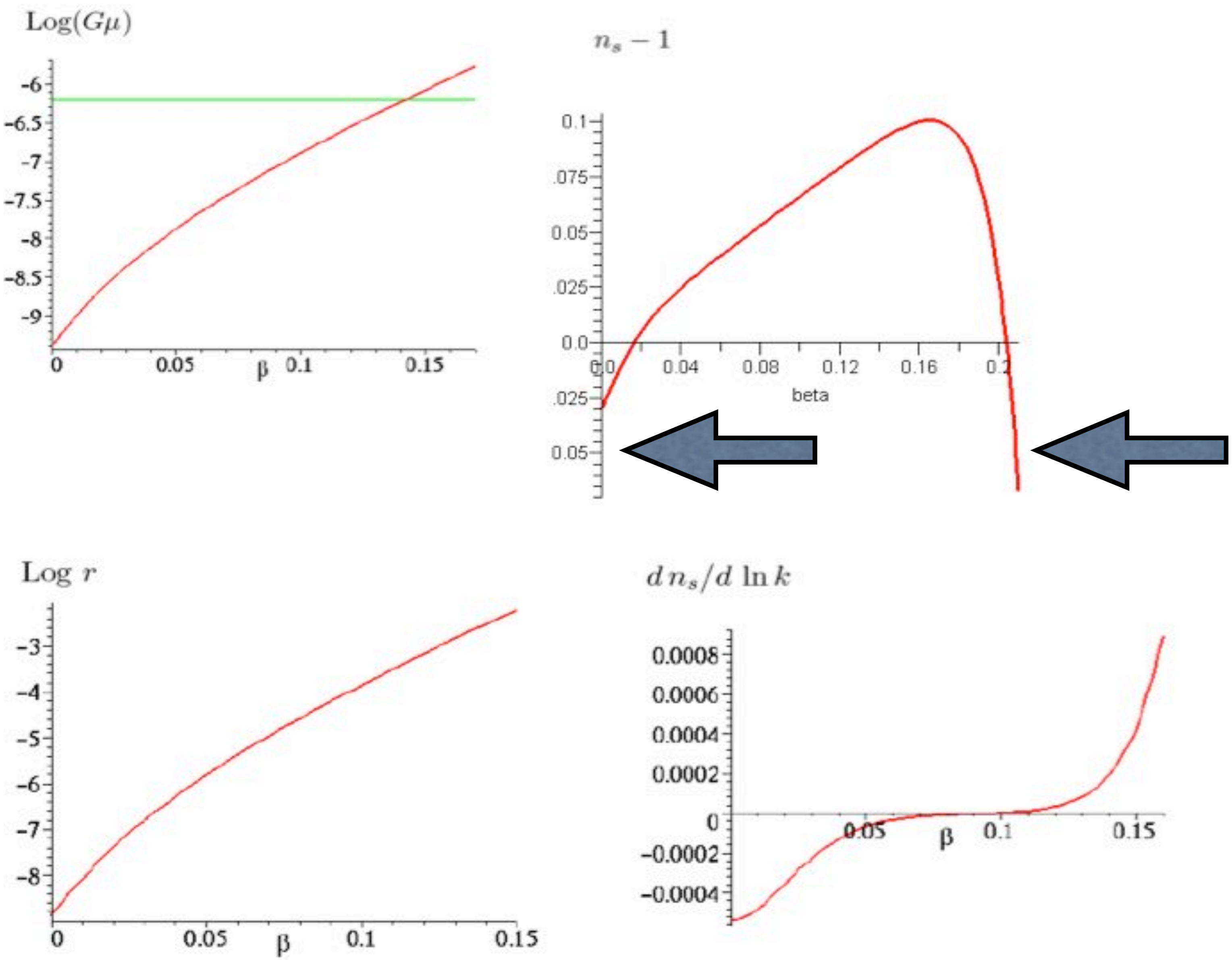
$$r = P_t(k)/P_s(k) \qquad\qquad n_t$$

f_{NL} measures 3-point function

$$f_{NL} = 0.32\gamma^2 < 300$$

P. Creminelli, A. Nicolis, I. Senatore, M. Tegmark, M. Zaldarriaga astro-ph/0509029

Extending KKLMMT slightly



H. Firouzjahi and H.T., hep-th/0501099

WMAP + ...

SLOW-ROLL

$$0 \leq \beta \leq 0.05$$

$$n_s \sim 0.98 + \beta \qquad \rightarrow n_s \leq 1.03$$

$$\log r \sim -8.8 + 60\beta$$

$$\log G\mu \sim -9.4 + 30\beta$$

U. Seljak and A. Slosar, astro-ph/0604143

DBI

$$\ddot{\phi} - \frac{3T'}{2T}\dot{\phi}^2 + T' + \frac{3H}{\gamma^2}\dot{\phi} + \left(V' - T'\right)\frac{1}{\gamma^3} = 0$$

$$\cancel{\ddot{\phi}} - \cancel{\frac{3T'}{2T}}\dot{\phi}^2 + \cancel{T'} + \frac{3H}{\cancel{\gamma^2}}\dot{\phi} + \left(V' - \cancel{T'}\right)\frac{1}{\cancel{\gamma^3}} = 0$$

$$\Longrightarrow \qquad \dot{\phi} = -V'/3H$$

It is convenient to use the inflaton field as the clock.

Some useful parameters

$$\frac{\ddot{a}}{a} = H^2(1 - \epsilon_D)$$

$$\epsilon_D \equiv \frac{2M_p^2}{\gamma}\left(\frac{H'(\phi)}{H(\phi)}\right)^2$$

$$\eta_D \equiv \frac{2M_p^2}{\gamma}\left(\frac{H''(\phi)}{H(\phi)}\right)$$

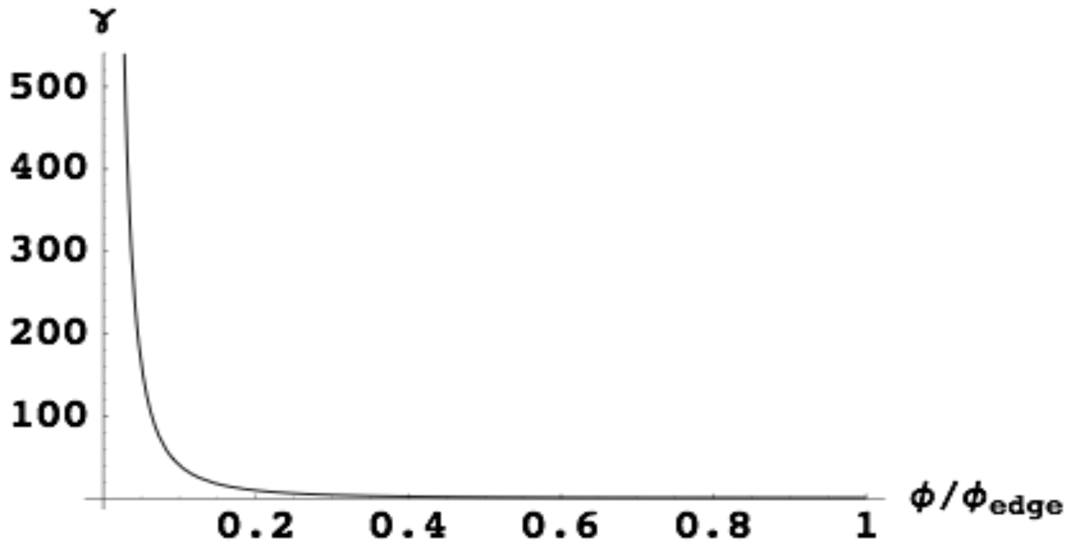
$$\kappa_D \equiv \frac{2M_p^2}{\gamma}\left(\frac{H'}{H}\frac{\gamma'}{\gamma}\right)$$

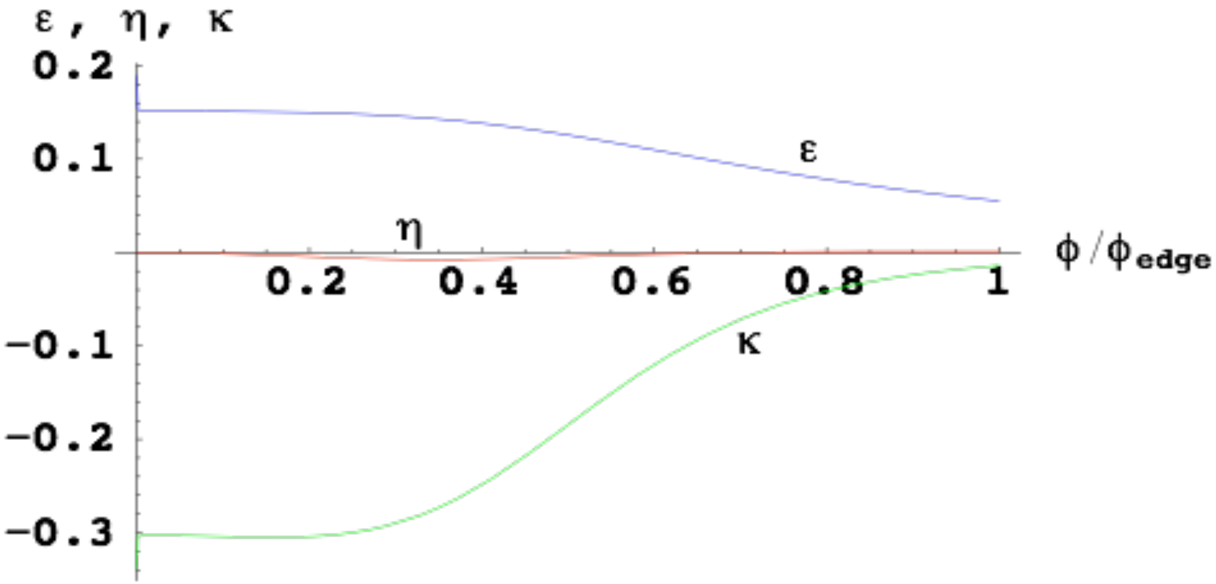
$$r = \frac{16\epsilon_D}{\gamma}$$

$$f_{NL} \leq 0.3\gamma^2$$

$$n_s - 1 \sim (1 + \epsilon_D + \kappa_D)(-4\epsilon_D + 2\eta_D - 2\kappa_D)\,.$$

If r saturates the observational bound,
non-Gaussianity is small.

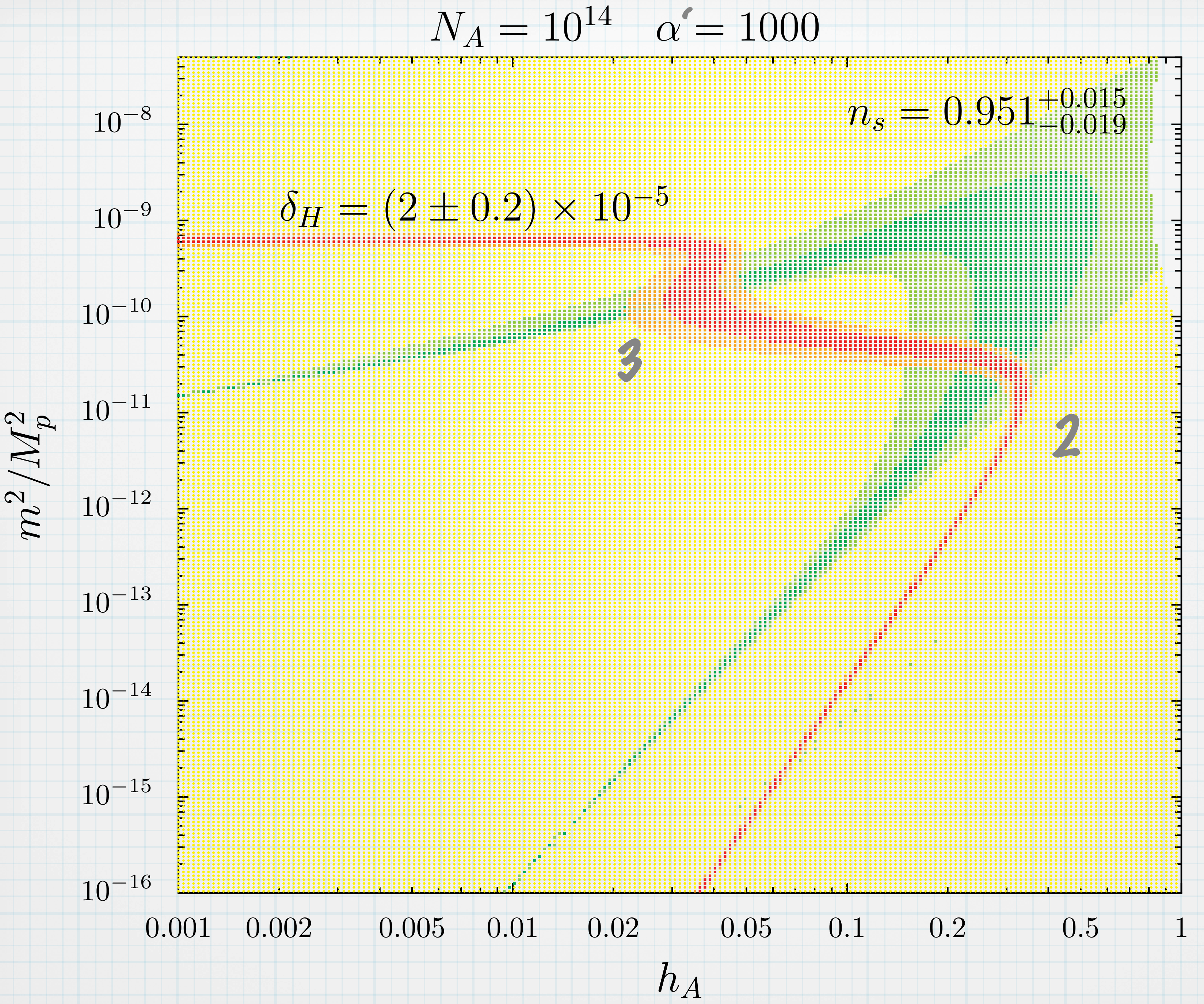




$$\epsilon \longrightarrow \epsilon_{SR}$$

$$\eta \longrightarrow \eta_{SR} + \epsilon_{SR}$$

$$\kappa \longrightarrow 0$$



$N_A = 10^{14}$ $\alpha' = 1000$
$n_s = 0.951^{+0.015}_{-0.019}$
$\delta_H = (2 \pm 0.2) \times 10^{-5}$
3
2
m^2/M_p^2
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
0.001
0.002
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
h_A

Jiajun Xu

Intermediate region

$$\gamma_{55} \simeq 1 \quad \gamma_1 \gg 1$$

$$r = 16\epsilon/\gamma < 0.3$$

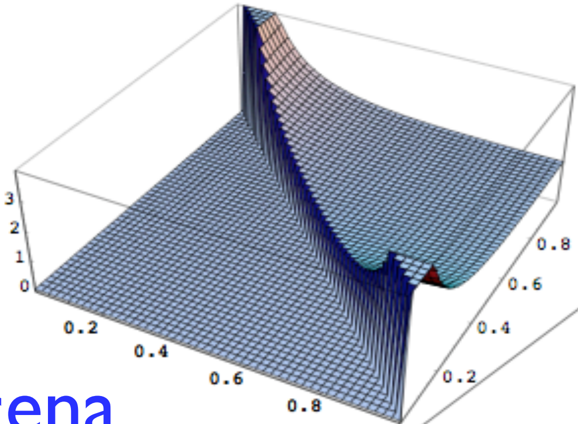
$$n_t = -\frac{r}{8}\left(\frac{\gamma}{1-\epsilon-\kappa}\right)$$

$$\frac{1}{M_p}\Delta\phi = \sqrt{\frac{r}{8}}\,\Delta N_e$$ Lyth bound

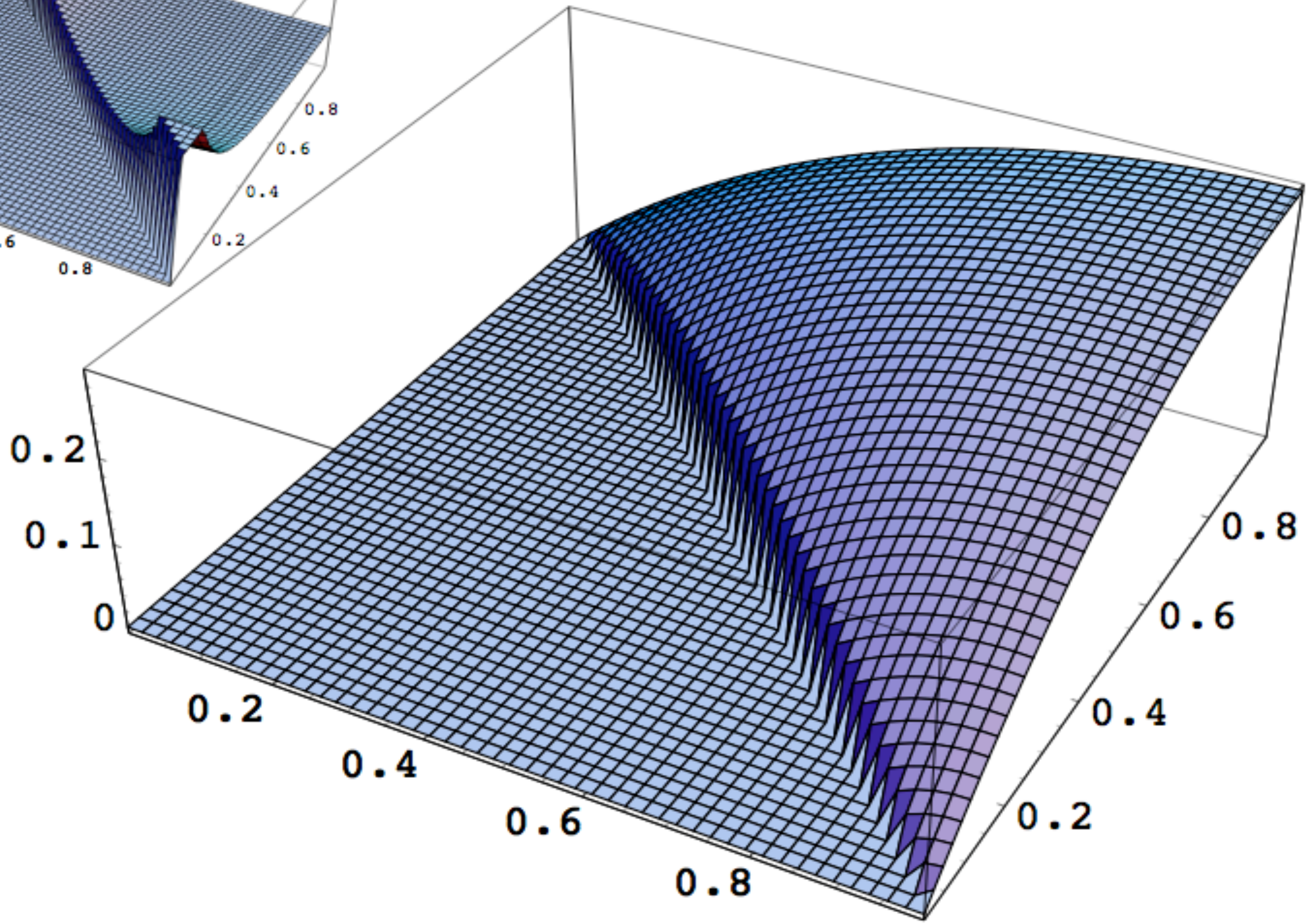
Tensor mode measures the metric perturbation.

It is the GOAL of CMBR cosmologists.

Non-Gaussianity



Maldacena



X. Chen, M.X. Huang, S. Kachru, G. Shiu, hep-th/0605045

String model Parameters

* string scale $M_s^2 = 1/\alpha'$
* string coupling g_s
* warp factor h_A
* Number of D3 flux N_A
* inflaton mass m
* When r saturates the observational bound, non-Gaussianity is small, and vice versa.

Cosmological parameters :

$$\delta_H, n_s, dn_s/d\ln k, r, n_t, f_{NL}, G\mu$$

DBI ultra-relativistic region

$$f_{NL} \simeq \left(\frac{m}{M_p}\right)^2 \left(\frac{M_p}{m_s h_A}\right)^4 \simeq 10^{-12} \frac{1}{(G\mu_s)^2}$$

$$\frac{m_s}{M_p} > 10^{-2} \qquad N_A \sim 10^{14}$$

$$\frac{m}{M_p} \simeq 10^{-6} \qquad h_A \sim 10^{-1} - 10^{-2}$$

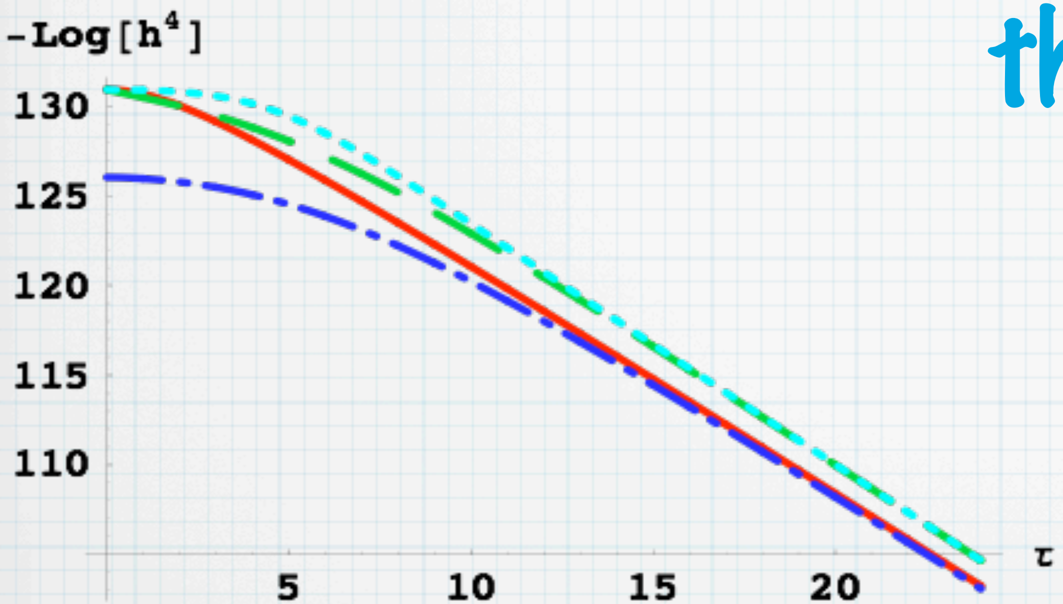
To fit a KS-like throat inside the bulk : $\frac{m_s}{M_p} \sim 10^{-12}$

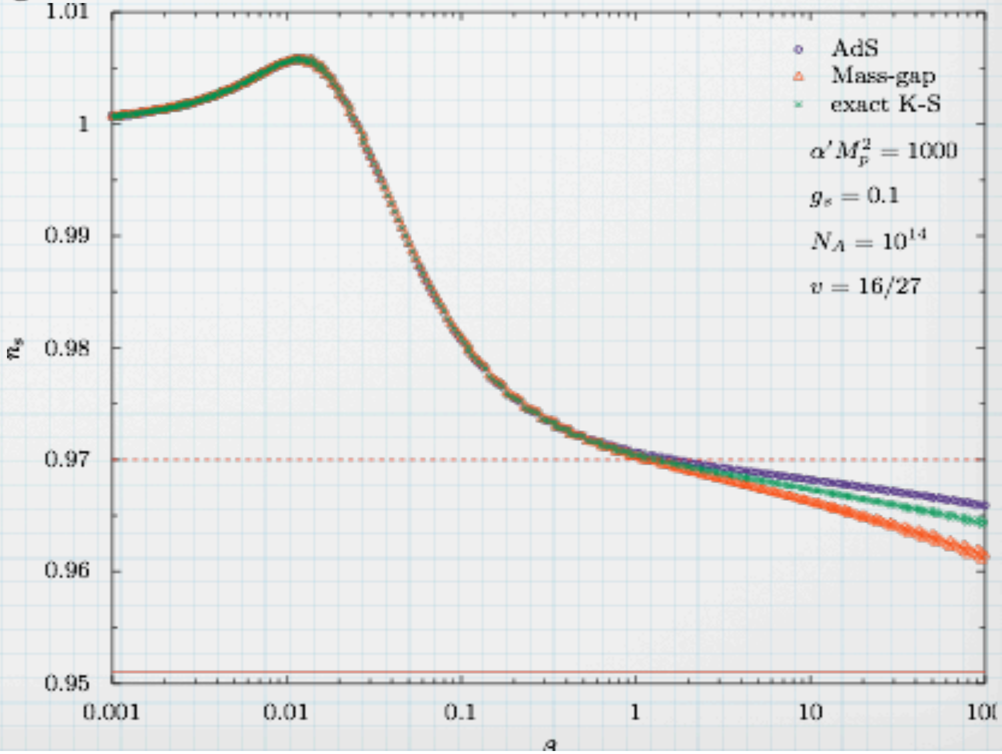
Need a long narrow throat :

Z_p -orbifold the KS-like throat

M. Alishahiha, E. Silverstein and D. Tong, hep-th/0404084
S. Kecskemeti, J. Maiden, G. Shiu, B. Underwood, hep-th/0605189

Various approximations to the KS throat





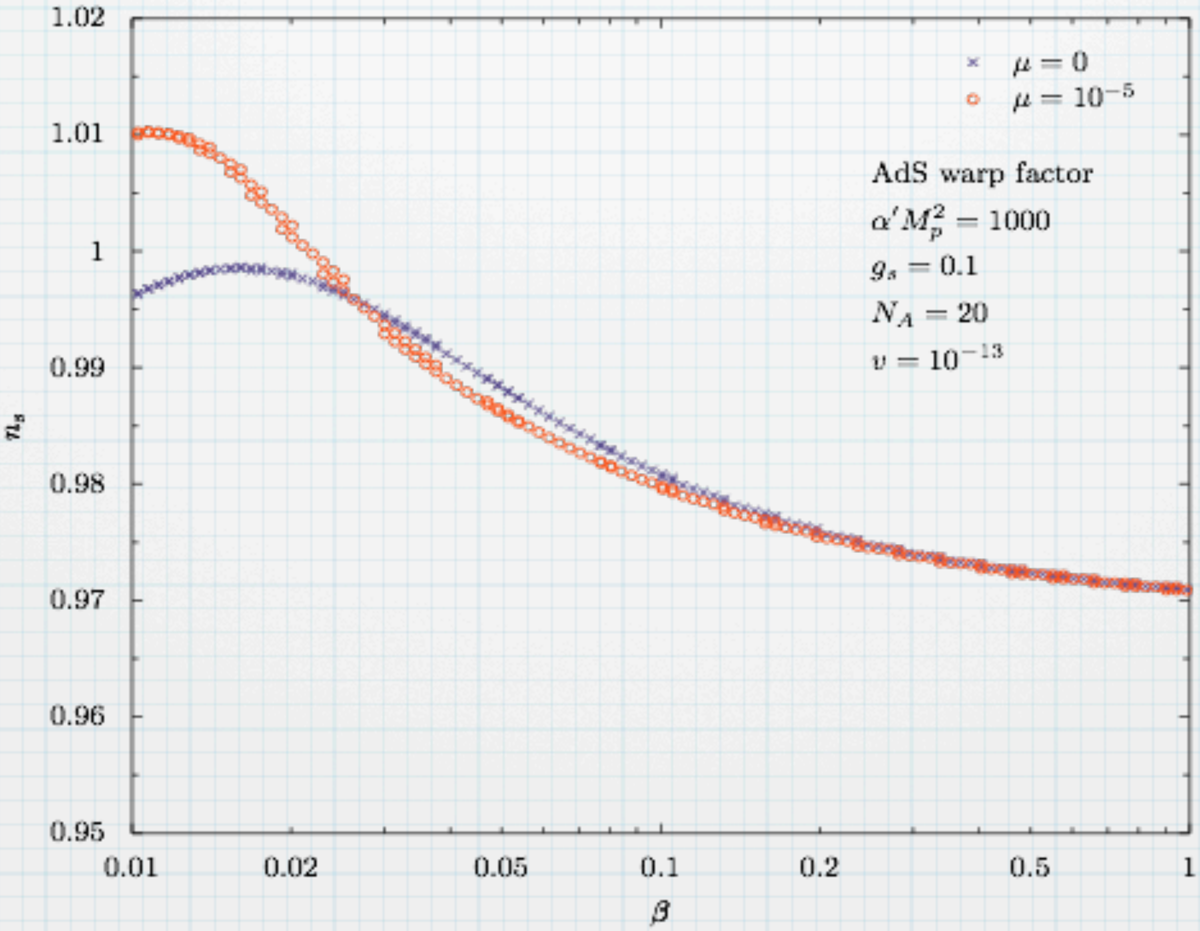
Shiu and Underwood

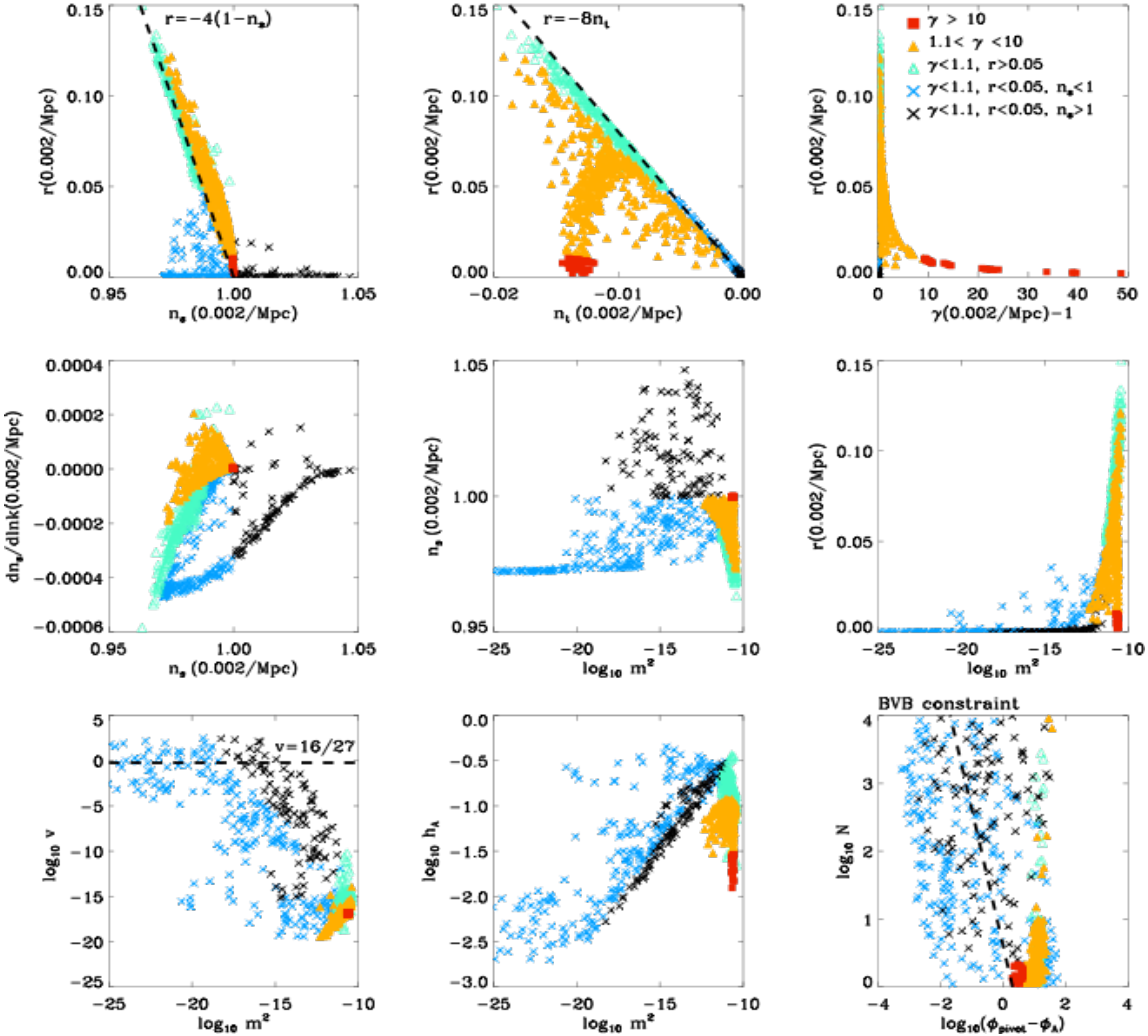
Bean, Shandera, HT and Xu

CMBR data is sensitive to the shape/structure of the throat and flux compactification

* warped resolved conifold
- Klebanov and Murugan, hep-th/0701064
- (p,r) throats etc.......

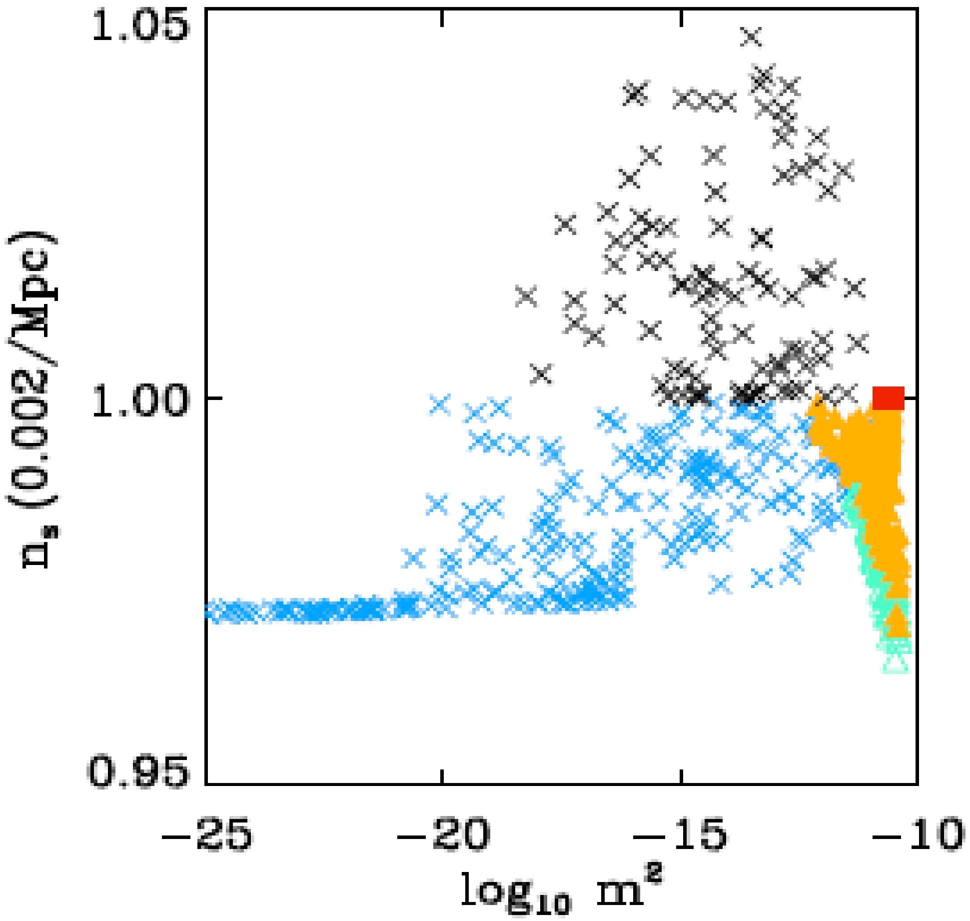
Turning on a quartic term

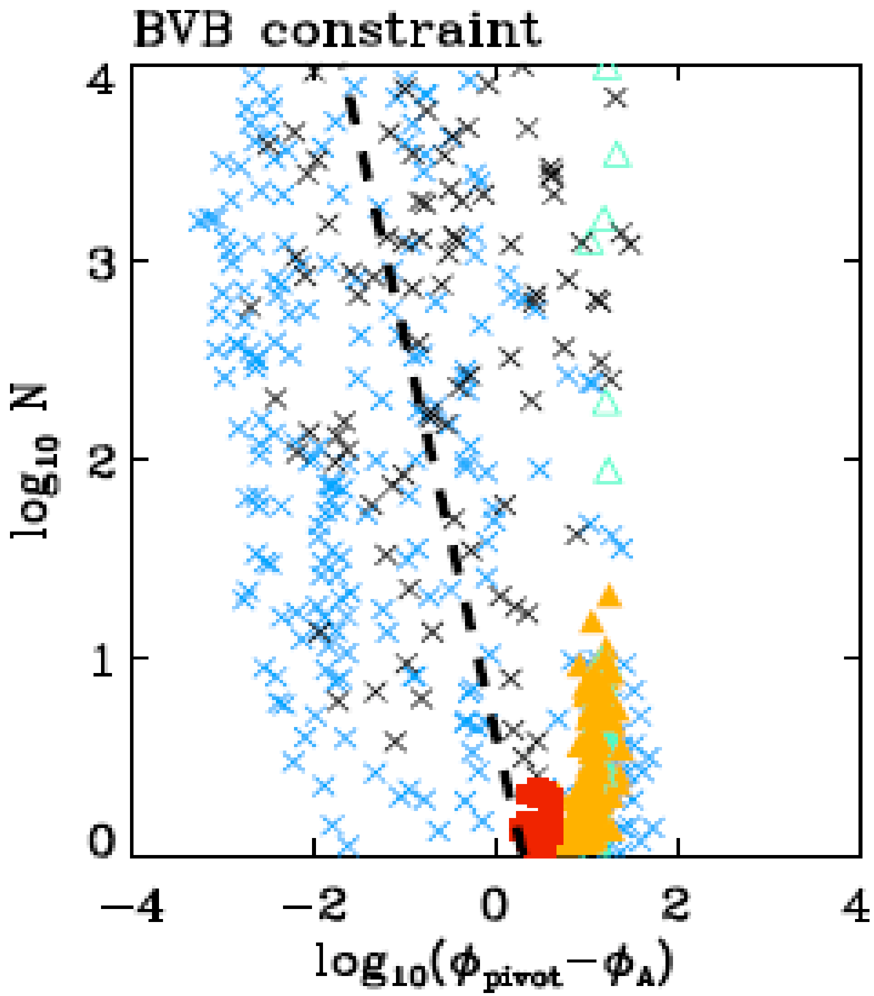




r=−4(1−n_s)
r(0.002/Mpc)
n_s (0.002/Mpc)
r=−8n_t
n_t (0.002/Mpc)
γ > 10
1.1< γ <10
γ<1.1, r>0.05
γ<1.1, r<0.05, n_s<1
γ<1.1, r<0.05, n_s>1
γ(0.002/Mpc)−1
dn_s/dlnk(0.002/Mpc)
n_s (0.002/Mpc)
log10 m²
v=16/27
log10 v
log10 h_A
BVB constraint
log10 N
log10(φ_pivot − φ_A)

Comparing to WMAP, SDSS, HST/GOODS





D. Baumann and L. McAllister, hep-th/0610285

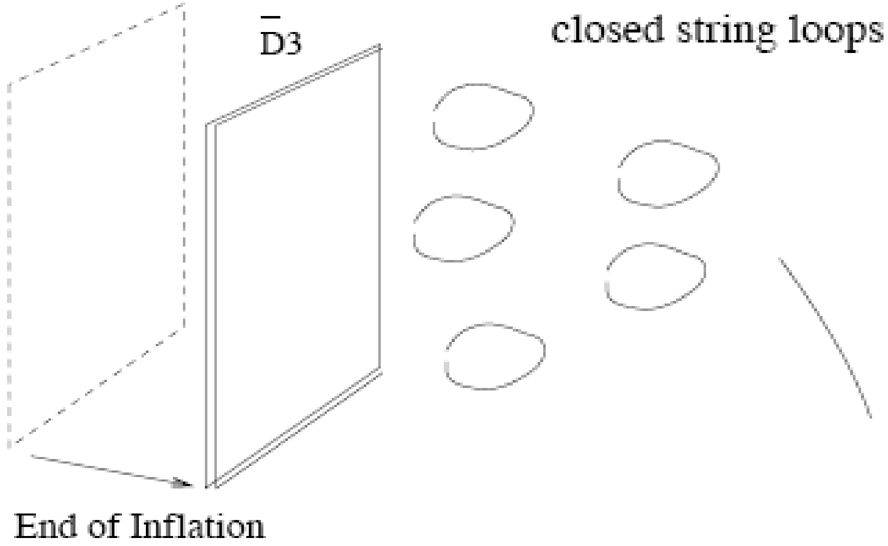
R. Bean, S. Shandera, H. T. and J. Xu, hep-th/0702107

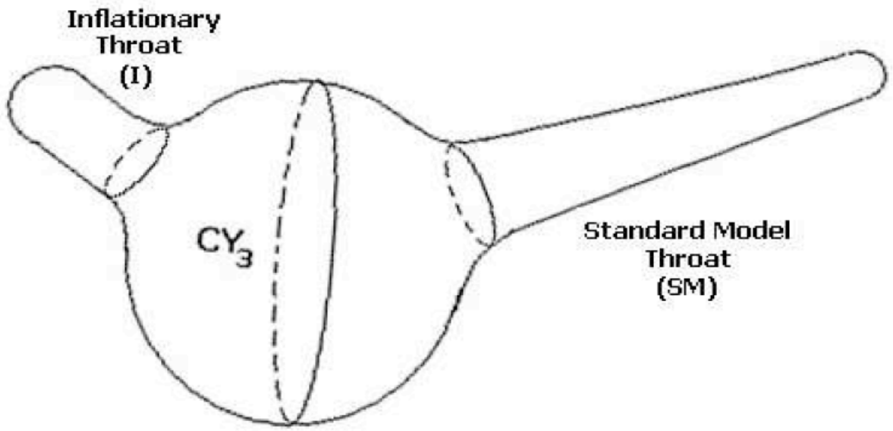
summary on constraints from data

- For the simplest version, only the original slow-roll KKLMMT region is allowed.
- Large tensor, or large non-Gaussianity regions are ruled out.
- Variations of the model may still allow large tensor or large non-Gaussianity.

Heating in Brane Inflation

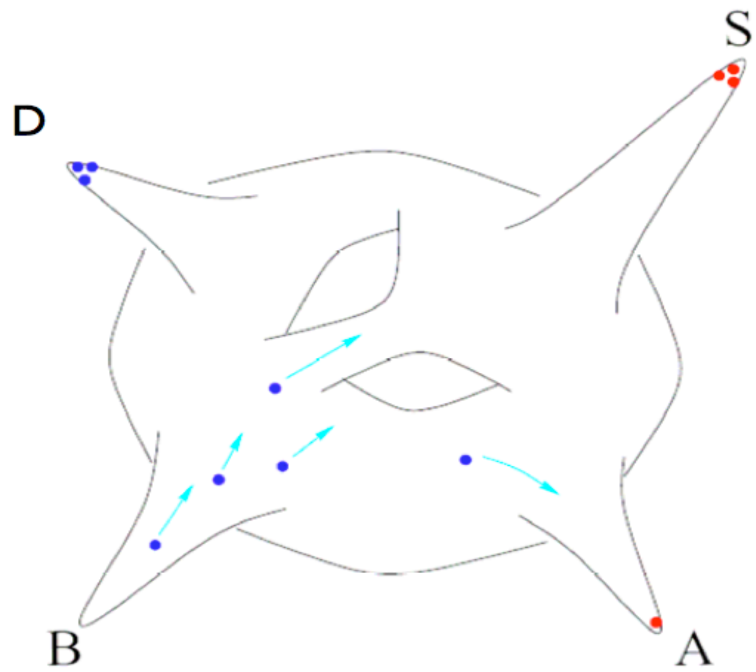
- At the end of brane inflation all energy stored in brane-anti-brane system is transferred to closed string modes.
- In the brane world picture, it is assumed that the Standard Model of particle physics is confined on some D3-branes.
- Heating Problem: There should exist a mechanism to channel the energy from the closed strings modes to the SM fields.
- Multi-throat compactification: Usually one can create many warped throats in CY. Different throats can have different energy scales. In one throat the inflation can take place while in another throat the SM fields are located.





Kofman and Yi

Heating after brane inflation



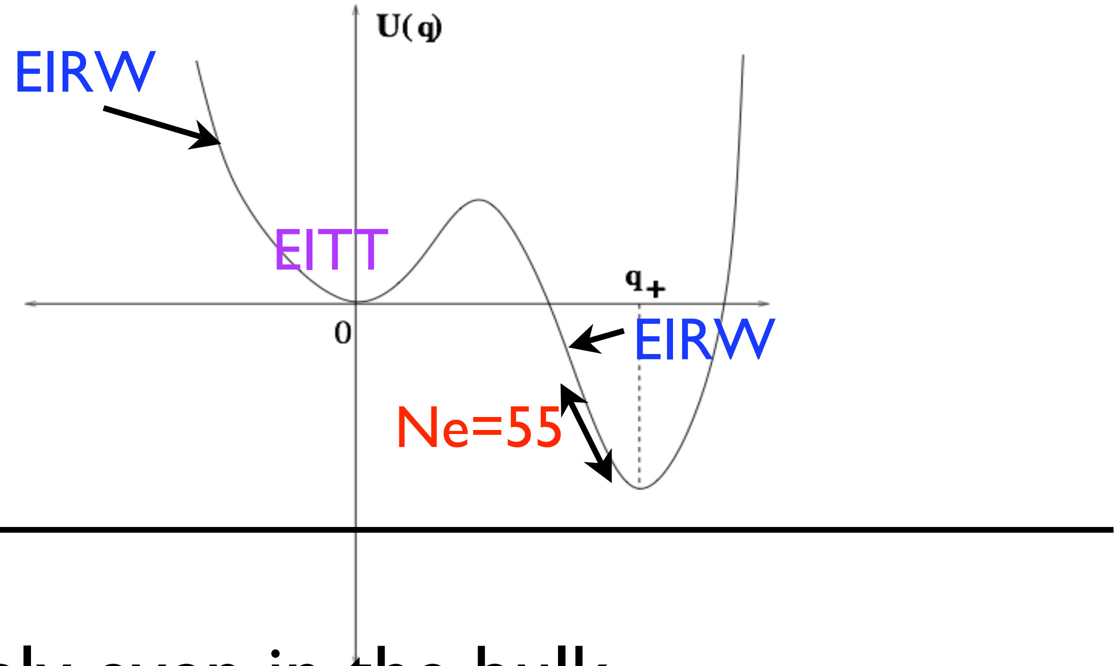
KK
$$\sigma \sim \left(\frac{L}{R}\right)^6 \frac{1}{M_P^2 h^2} \qquad \Gamma_{A\to S} \sim h_A^9/R \gg h_A^{17}/R$$

KK modes in D throat as hidden dark matter.
There was a matter-dominated period where a(t) can grow by a big factor.

X. Chen and H.T., hep-th/0602136

Is brane inflation eternal ?

- Eternal Inflation of the Random Walk type
- Eternal inflation of the Tunneling Type



EIRW is unlikely even in the bulk.

The possibility of EITT depends on the initial condition.

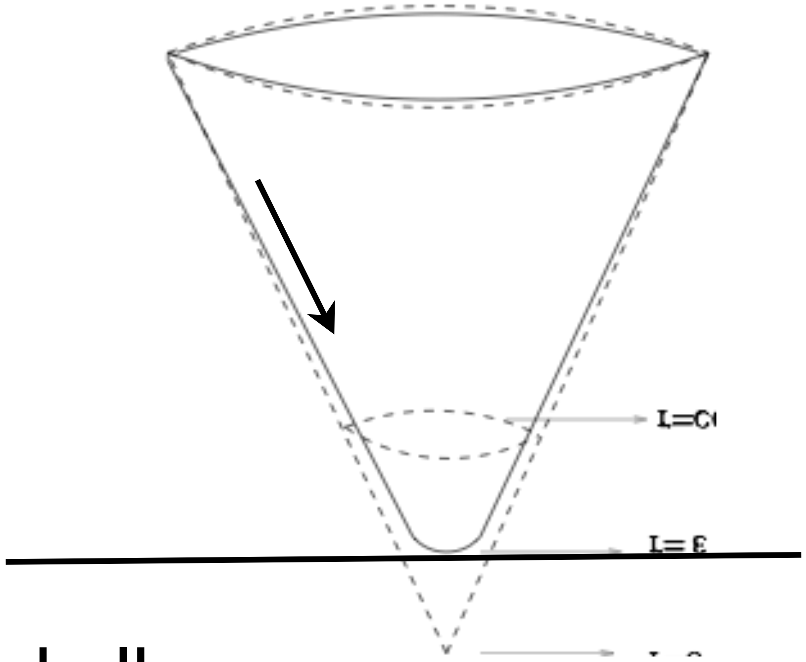
X. Chen, S. Sarangi, H.T. , J. Xu, hep-th/0608082

Is brane inflation eternal ?

Eternal inflation of the random walk type is absent as the inflaton is moving down the throat.

$$\delta\phi = \frac{H}{2\pi} \qquad \Delta\phi = |\dot{\phi}\Delta t| = \frac{|\dot{\phi}|}{H}$$

$$\frac{\delta\phi}{\Delta\phi} = \frac{H^2}{2\pi|\dot{\phi}|} > 1$$



EIRW is unlikely even in the bulk.

The possibility of EITT depends on the initial condition.

X. Chen, S. Sarangi, H.T. , J. Xu, hep-th/0608082

Conclusions and Remarks

- Brane inflation is robust : the picture looks better as one tries to be more realistic.
- It may allow large tensor-to-scalar ratio r, or large non-Gaussianity.
- It may yield distinctive string theory signatures in CMBR.
- It may yield a cosmic string tension spectrum, with tension within the present observational bound and may be tested in the near future, $10^{-11} \leq G\mu \leq 10^{-8}$
- Heating (pre(re)heating) towards the end of inflation looks reasonable.
- Many possible scenarios.
- Large influx of data coming.