Title: Gravity waves, large-field inflation, and string theory

Date: Apr 04, 2014 04:20 PM

URL: http://pirsa.org/14040126

Abstract:

Gravity waves, Large-field inflation, and string theory

(original proof of principle)

Based on works (2008-**present**) with

simpler methods
more general understanding
new examples
...

Westphal, McAllister;
Senatore, Zaldarriaga;
Dong, Horn;
Dodelson, Torroba, Wrase
...

as well as related works by Kaloper, Sorbo, Lawrence, Flauger, Pajer, Easther, Peiris, Xu, Roberts, Dubovsky, D'Amico, Gobbetti, Kleban, Schillo, Gur-Ari; Palti, Weigand, Wenren, Berg, Sjors,,...
and the earlier N-flation scenario by Dimopoulos, Kachru, McGreevy, Wacker;...

Outline

- Intro: Large fields & QG
- Monodromy, review + new developments
- Role of mechanisms & models
  top-down, intermediate, bottom-up
- New class of large-field inflation (raised from the dead)
- Exotic sources
- Outlook: Range of theories and observational constraints

Lyth ~~"Bound"~~

$$N_e = \int \frac{da}{a} = \int \frac{da}{dt}\frac{dt}{a} = \int H dt$$

$$= \int \frac{H M_p}{\dot\phi} \frac{d\phi}{M_p} = \sqrt{8}\, r^{-\frac{1}{2}} \frac{\Delta\phi}{M_p}$$

using

$$r = \frac{\gamma\gamma}{\zeta\zeta} = \frac{\text{tensor}}{\text{scalar}} \sim \frac{\frac{H^2}{M_p^2}}{\frac{H^4}{\dot\phi^2}}$$

and assuming no strong variation of $HM_p/\dot\phi$, and no exotic sources

$r = \frac{\text{Tensor}}{\text{Scalar}}$ is related to field range in simple inflation

$$\boxed{\frac{\Delta\phi}{M_p} \sim \frac{r^{\frac{1}{2}}}{\sqrt{8}} N_e \gg 1 \; !}$$

highly UV sensitive if $\gtrsim 1$

BICEP2

- An ∞ sequence of possible terms

$$V \to V\left(1 + \sum_n c_n \frac{(\phi-\phi_0)^n}{M_p^n}\right)$$

infinitely "UV-sensitive"

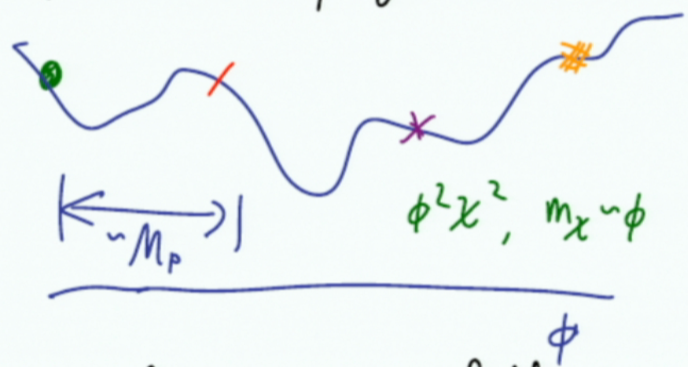
must be suppressed (e.g. symmetry)

→ Determined by Quantum Gravity theory

→ B-modes test string-theoretic large-field inflation in particular.

and falsify small-field mechanisms

A common prejudice was:



Over a large distance in field space, $V(\phi)$ could be strongly corrected by ϕ's couplings to whatever degrees of freedom UV-complete gravity.

- Can postulate a symmetry, but one wonders if QG has it; no continuous global symmetries..

Large-field inflation arises via a clear mechanism in string theory

Axions — Nflation (Dimopoulos, Kachru, McGreevy, Wacker; Wenren; Easther, McA., Liddle ...)

Monodromy — '08 ES, Westphal, McAllister

D'Amico, Gobbetti, Kleban, Schillo

Kaloper, Lawrence, Flauger, Pajer

Sorbo, Dong, Horn, Roberts ...

answering the basic yes/no question

(extra-): Arkani-Hamed et al

cf chaotic I., Linde, Natural I. 'Freese Frieman Olinto Adams Bond

These fields descend from higher-dimensional Electro-magnetic potentials

$$\hat{a} = \int_{\text{circle}} A_\mu \, dx^\mu$$

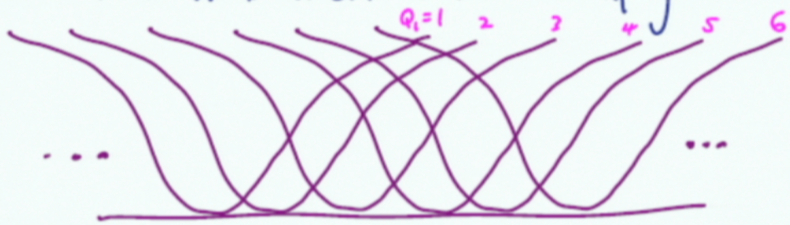
cf Les Houches Lectures '13

$$\mathcal{L}_{D>4} = F_{MN}^2 - \left(A_M + \partial_M \theta\right)^2 + \cdots$$

Gauge-Invariant $A_M \to A_M + \partial_M \Lambda$
$\theta \to \theta - \Lambda$

$$4d \quad V(\phi_a) \sim \mu^{4-p} \phi_a^p + \Lambda^4 \cos\frac{\phi_a}{f}$$

on each branch with fixed $Q_1 = \int \partial\theta$



- Full theory has underlying periodicity, with $\frac{f}{M_p} < M_p$

- Each branch has $\frac{\Delta\phi}{M_p} \gg 1$ (2008)

In string theory, the basic period $f_\theta (2\pi)^2$

a priori turns out $\ll M_p$ at weak

curvature + coupling

Banks/Dine/Fox/Gorbatov
Svrcek/Witten
cf Arkani-Hamed et al

Axions $\hat{a} = \int_{\Sigma_p} \underbrace{A_{i_1 \cdots i_p}}_{\text{potential field}} dx^{i_1} \wedge \cdots \wedge dx^{i_p}$

Σ_p: p-dim'l closed submanifold

potential field (higher-dim'l analogue of Maxwell A_μ)

$f_{\hat{a}}$ comes from kinetic term:

$$\int d^D x \sqrt{G_{(D)}}\, F_{i_1 \cdots i_{p+1}} G_{(D)}^{i_1 i_1'} \cdots G_{(D)}^{i_p i_p'} F_{i_1' \cdots i_{p+1}'}$$

$$= \int d^4 x \sqrt{g_4}\, f_{\hat{a}}^2 (\partial \hat{a})^2 = \int d^4 x \sqrt{g_4}\, (\partial \phi_{\hat{a}})^2$$

$\Rightarrow$ for all sizes $\sim R$, this yields

$$f_{\hat{a}} \sim M_p \left(\frac{\sqrt{\alpha'}}{R}\right)^p \ll M_p$$

$\sqrt{\alpha'}$ = string length

Note: this is an example of the fact that not "anything goes" in the landscape. (In same regime

$L \gg \sqrt{\alpha'}$, $g_s \ll 1$

where we control moduli stabilization & see multiple vacua, $f_{axion} \ll 1$.)

- Similar statement for certain brane collective coordinates
  (Bauman, McAllister)

- Generalization to multiple fields
  - axions: N-flation (Dimopoulos, Kachru, McGreevy, Wacker); Easther, McAllister, Grimm; Kallosh, Sivanandam, Soroush
  - branes: Becker, Leblond, Shandera; Lidsey-Huston, Ward; Kobayashi et al, ...

Kinematically extends range, but yields significant back reaction. May well be UV-completable.

But anyway, each axion direction is extended by monodromy generically.

String theory has many scalar "moduli" descending from higher dimensions $D > 4$. these must be consistently stabilized, either independently of $V_{inflation}(\phi)$ (as in original example '08, $V = \mu^3 \phi + \Lambda^4 \cos\frac{\phi}{f}$) or in a (more economical) way with $V_{inf}(\phi, \text{moduli})$ participating in moduli-stabilization.

M. Dodelson, Dong, ES, Torroba '13
cf Dong Horn ES Westphal '10

BTW, Axions are $> \frac{1}{2}$ the scalar fields in string theory :

- SUSY case $\Phi = r + i\theta$

  (and duals)

- ~~SUSY~~ limits $N_{\text{axion}} \sim 2^D$

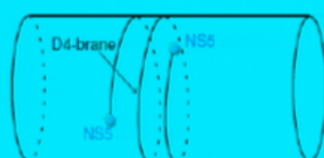
  $N_{\substack{\text{other}\\\text{moduli}}} \sim D^2$

It was a myth that string theory prefers small r, or that "most models" have that property — at least no credible argument for that.

On each branch :

$\simeq \mu^{4-p} \phi^{p} + \Lambda^{4} \cos \frac{\phi}{f}$

Large $\Delta \phi \gg M_p$, but conditions similar each time around



(T-dual of) specific example '08

Large field, $\Delta \Phi_{infl} \gg M_p$

$\Longrightarrow r \gg .01$ (BICEP '14 $r \gg .01$)

 $\sim \phi^p + osc$

Ranges of p, r?

- $p < 2$ for $(\partial\theta + A)^2 \to r \lesssim .15$
  $\overset{\shortparallel}{2 - \Delta p}$ + back reaction
  "flattening" Dong Horn ES Westphal '10

$\nearrow$ Gravity description: flattened $\phi^2 \to \phi$

e.g.  stabilized string theory example
$V = \mu^3\phi + \Lambda^4 \cos\frac{\phi}{f}$ '08 McA S W

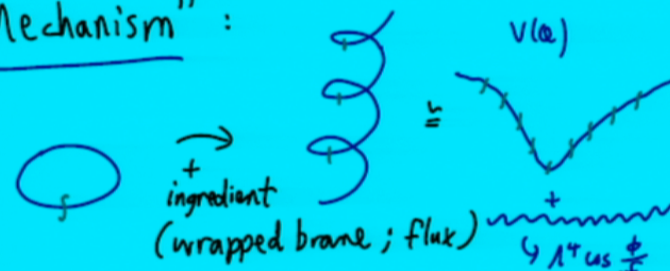
Proof of principle, not general

$\hookrightarrow$ working on more examples, systematics

- $2 < p < 4$? from $\left| f_0 A^{(1)} \wedge A^{(2)} \right|^2$ + back reaction
  (in progress)
  $\to .1 < r < .26$?

Different levels

"Mechanism" :



· "Top Down" : controlled String solution
- proof of concept, not general
↳ Now motivated to construct larger range

Intermediate :
- extract some essential features
e.g. Kaloper, Sorbo, Lawrence et al ;
+ some moduli : Dong et al (flattening) → $\phi^{2/3}$ had runaway modulus
twisted T^5, Gur-Ari $p = 1, \frac{6}{5}, \frac{4}{3}, \frac{10}{7}, \frac{3}{2}, 2$

. "Bottom up" : - Wilsonian rules,
no UV structure included

$\sim \phi^p + \text{osc}$

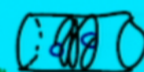
Ranges of p, r?

- $p < 2$ for $(\partial\theta + A)^2 \to r \lesssim .15$

  $\parallel$ + back reaction

  $2-\Delta p$ "flattening" Dong Horn ES Westphal '10

→ Gravity description: flattened $\phi^2 \to \phi$

e.g.  stabilized string theory example

$V = \mu^3 \phi + \Lambda^4 \cos\frac{\phi}{f}$ McA S W '08

Proof of principle, not general

↳ working on more examples, systematics

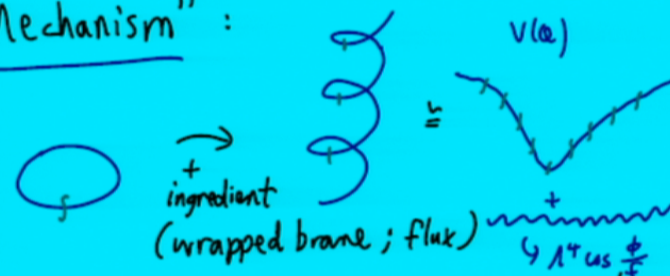
- $2 < p < 4$? from $\left| f_0 \, A^{(1)} \wedge A^{(2)} \right|^2$ + back reaction

(in progress)

$\to .1 < r < .26$?

Different levels

"Mechanism" :



- "Top Down" : controlled String solution
  - proof of concept, not general
    ↳ Now motivated to construct larger range

Intermediate :

- extract some essential features

e.g. Kaloper, Sorbo, Lawrence et al ;

+ some moduli : Dong et al (flattening) → $\phi^{2/3}$ had runaway modulus

twisted T^5, Gur-Ari $p = 1, \frac{6}{5}, \frac{4}{3}, \frac{10}{7}, \frac{3}{2}, 2$

. "Bottom up" : – Wilsonian rules,

no UV structure included

Condensed matter analogy (?)

e.g. super-conductors

UV = QED e^-, ions, lattice

somehow limits e.g. $\frac{T_c}{\mu_F}$

IR : can formulate

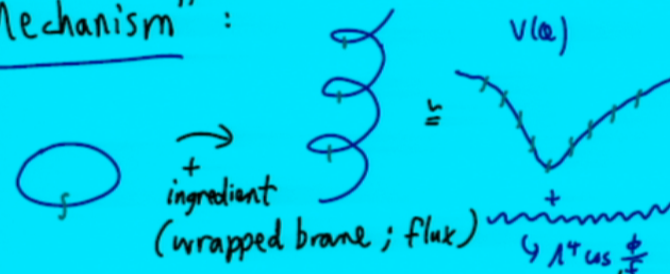
big QFT theory - space

QFT's exhibiting non-Fermi liquid behavior, anomalous transport, different $\frac{T_c}{\mu_F}$

Obviously, we don't know the UV theory of gravity, but string theory is a good candidate and pure bottom-up may miss important constraints & structures

Different levels

"Mechanism" :



· "Top Down" : controlled String solution

– proof of concept, not general
↳ Now motivated to construct larger range

Intermediate :

– extract some essential features

e.g. Kaloper, Sorbo, Lawrence et al ;

+ some moduli : Dong et al (flattening) ↗ $\phi^{2/3}$ had runaway modulus

twisted T^5, Gur-Ari $p = 1, \frac{6}{5}, \frac{4}{3}, \frac{10}{7}, \frac{3}{2}, 2$

. "Bottom up" : – Wilsonian rules,

no UV structure included

Flattening of monodromy - extended ϕ^4 (in progress w/... McAllister, Westphal, Senatore, Zaldarriaga, Wrase)

Type IIB $\mathcal{L} \supset |F_1 \wedge B \wedge B|^2$

(T-dual of $F_0\, B\wedge B$ in IIA)

To exhibit flattening effect, consider

e.g. $T^6 = T^2 \times T^2 \times T^2 = \left(L_2 \square_{L_1}\right)^3$

$$F_1 = \underset{\substack{\uparrow \\ \text{fluxes}}}{\frac{Q_1}{L_1}} \sum_{i=1}^{3} dy_1^{(i)}, \quad \underset{\substack{\uparrow \\ \text{2-form potential field}}}{B} = \sum_{i=1}^{3} \frac{b^{(i)}}{L^2}\, dy_1^{(i)} \wedge dy_2^{(i)}$$

2-form potential field → axion $b = \int_{\Sigma_2} B$

fluxes ↓

$$F_3 = Q_{31}\, dy_1^{(1)} \wedge dy_1^{(2)} \wedge dy_1^{(3)} + Q_{32}\, dy_2^{(1)} \wedge dy_2^{(2)} \wedge dy_2^{(3)}$$

$$V \sim \frac{M_p^4 g_s^4}{L^{12}}\left(\frac{Q_1^2}{L^4} u b^4 + Q_{31}^2 u^3 + \frac{Q_{32}^2}{u^3}\right)$$

where $u = \frac{L_2}{L_1}$

Inflationary potential + Q_{32} stabilizes u during inflation

fluxes stabilize u at $b = 0$

$$u \sim \frac{3^{\frac{1}{4}} L}{b}\sqrt{\frac{Q_{32}}{Q_1}} \propto \frac{1}{b}$$

$$\Rightarrow V_{eff} \propto b^3$$

Now working on this in full stabilization, e.g. (Riemann Surface)^3, ...

$\sim \phi^p + \text{osc}$

Ranges of p, r?

- $p < 2$ for $(\partial\theta + A)^2 \to r \lesssim .15$

  $+$ back reaction

  $\shortparallel$

  $2 - \Delta p$ "flattening" Dong Horn ES Westphal '10

$\nearrow$ Gravity description: flattened $\phi^2 \to \phi$

e.g.  stabilized string theory example

$V = \mu^3 \phi + \Lambda^4 \cos\frac{\phi}{f}$

M, A, S, W '08

Proof of principle, not general

↳ working on more examples, systematics

- $2 < p < 4$? from $\left| f_0 A^{(1)} \wedge A^{(2)} \right|^2$

  $+$ back reaction

(in progress)

$\to .1 < r < .26$?

Additional, Model-Dependent Structures

$$V = V_0(\phi) + \Lambda^4 \cos\frac{\phi}{f}$$

- depend on moduli
- dynamical (could evolve)

→ To do: running of f, Λ and relation to power spectrum, low ℓ, etc.

Constraints on oscillations: constant or slow-varying
Easther Flauger Peiris, Planck 13, Meerburg, Spergel, ...

Another class of Large-field inflation

New solutions with accelerated expansion in string theory

(The un-dead...)

arXiv:1310.5297v1 [hep-th] 20 Oct 2013

Matthew Dodelson[1], Xi Dong[1], Eva Silverstein[1,2,3], and Gonzalo Torroba[1]

[1] Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94306, USA

[2] SLAC National Accelerator Laboratory, 2575 Sand Hill, Menlo Park, CA 94025

[3] Kavli Institute for Particle Astrophysics and Cosmology, Stanford, CA 94025, USA

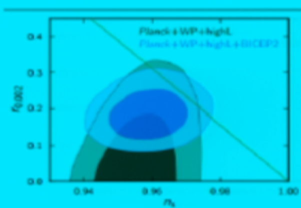
Abstract

We present concrete solutions with accelerated expansion in string theory, requiring a small, tractable list of stress energy sources. We explain how this construction (and others in progress) evades previous no go theorems for simple accelerating solutions. Our solutions respect an approximate scaling symmetry and realize discrete sequences of values for the equation of state, including one with an accumulation point at $w = -1$ and another accumulating near $w = -1/3$ from below. In another class of models, a density of defects generates scaling solutions with accelerated expansion. We briefly discuss potential applications to dark energy phenomenology, and to holography for cosmology.

4.1 Inflation, Dark Energy, Axions

In §2 we have presented new sequences of models with accelerated expansion, which come along with the large number $\sim 2^D$ of axion fields that dominate the spectrum of string theory. Accelerated expansion is well-established in the observed universe, as is dark matter. The detection of dark energy [35] is extremely significant [36], with contributions from multiple observational probes. The detection of a small tilt of the primordial power spectrum [37] and other cosmological measurements support the theory of inflation and provide some constraints on its phenomenology. In fact, power law inflation driven by a single exponential potential is ruled out observationally, so although our models are somewhat more general than that we will focus here on dark energy (it would also be interesting to explore the axion phenomenology of this type of model).

→ No longer ruled out?



Assisted (+ monodromy + N-flation)
arises in string theory, giving

$$V \sim e^{\beta_c \Phi_c}, \quad a(t) \sim t^K$$

discrete sequences of equations of
state $w = -1 + \frac{2}{3K}$

$$\begin{cases} K = 1 + \dfrac{10}{27(k-2)^2} \\ K = 4k + \dfrac{1}{64k^2 - 28k - 1} \end{cases}$$

(These are again just illustrative
examples, proofs of principle.)

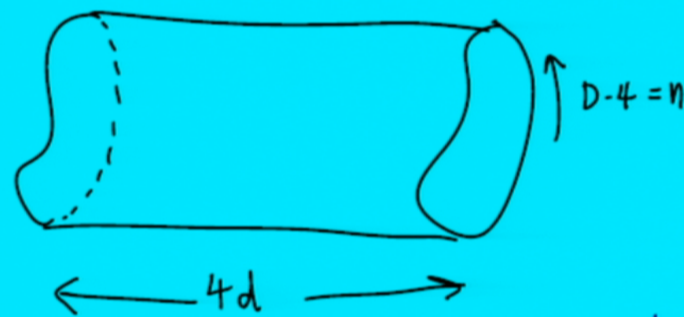
Assisted (+ monodromy + N-flation) arises in string theory, giving

$$V \sim e^{\beta_c \Phi_c}, \quad a(t) \sim t^K$$

discrete sequences of equations of state $\quad w = -1 + \frac{2}{3K}$

$$\begin{cases} K = 1 + \dfrac{10}{27(k-2)^2} \\ K = 4k + \dfrac{1}{64k^2 - 28k - 1} \end{cases}$$

(These are again just illustrative examples, proofs of principle.)



Scalar fields include string coupling

$$e^{(d-2)\hat{D}} = \frac{g_s^2}{L^n} \quad \text{and size} \quad L\sqrt{\alpha'} = e^{\phi}\sqrt{\alpha'}$$

$$S_{eff} = \frac{1}{2} M_p^2 \int d^4x \sqrt{g} \left\{ R - \sum_{i=1}^{n} (\partial \phi_i)^2 - 2(\partial \hat{D})^2 - V_{eff} + h.d. \right\}$$

Valid near appropriate weakly coupled, weakly curved solutions

Multiple terms in V can assist in generating acceleration

Liddle, Mazumdar, Schunk '98

e.g.

$$V = \sum_i V_i \, e^{\beta_i \Phi_{ci}}$$ ← canonical ⟹

$$a(t) = \left(\frac{t}{t_0}\right)^k \qquad k = \sum_i \frac{2}{\beta_i^2}$$

More generally,

$$V = \sum_i V_i \, e^{\sum_j \beta_{ij} \Phi_{cj}}$$

↳ gives assisted acceleration in string theory.

$$S_{eff} = \frac{1}{2} M_p^2 \int d^4x \sqrt{g} \left\{ R - \sum_{i=1}^{n} (\partial \phi_i)^2 - 2 (\partial \tilde{D})^2 - V_{eff} + h.d. \right\}$$

$e^{2\tilde{D}} = \frac{g_s^2}{L^n} \qquad e^{\phi} = L$

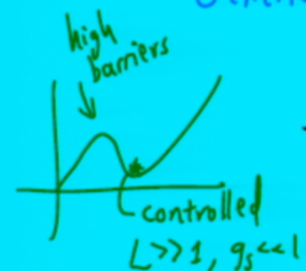
$$V_{eff} = \sum_i V_i \, e^{\alpha_i \tilde{D} + \beta_i \phi}$$

$$= M_p^2 \left\{ \underbrace{(D-10)}_{\text{Generic!}} e^{2\tilde{D}} - V_0 \, e^{3\tilde{D} + (n_0 - \frac{n}{2})\phi} + Q^2 \, e^{4\tilde{D} + (n - 2p)\phi} + \cdots \right\}$$

n_0: # internal directions wrapped

V_0: negative-tension defects (orientifolds)

Q: fluxes $\int F = Q$



New Sources of GW's

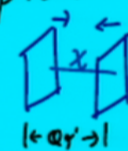
Senatore, ES, Zaldarriaga '11

The inflaton ϕ generically couples to other degrees of freedom (e.g. for reheating)

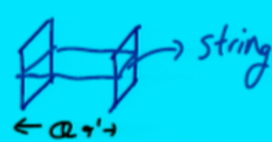
For example, (Kofman + many)

(1) $$\Delta\mathcal{L} = g^2\phi^2\chi^2 \rightarrow m_\chi^2 = m_0^2 + \phi^2(t,\vec{x})$$

$\Rightarrow$ particle production

(brane picture : )

(2) $$T_{string}^2 = T_{min}^2 + \phi^2 M_0^2$$

(brane picture : )

→ Do these Classically produce competitive GWs?

Of course inflation dilutes relics —

Produced particles, strings dilute in a Hubble time. However,

★ In e.g. monodromy, any production events are repeated many times

model-dependent

Axion monodromy → string production

cf Trapped Infl

Dong Horn Senatore ES

Kofman, Linde
Kim

→ repleshinishing supply of GWs

This, plus the more general question of B-mode degeneracy, motivates analyzing this question.

New Sources of GW's

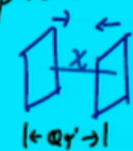
Senatore, ES, Zaldarriaga '11

The inflaton ϕ generically couples to other degrees of freedom (e.g. for reheating)

For example, (Kofman + many)

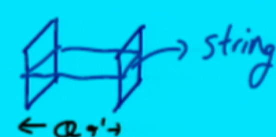
(1) $\Delta\mathcal{L} = g^2\phi^2\chi^2 \rightarrow m_\chi^2 = m_0^2 + \phi^2(t,\vec{x})$

$\Rightarrow$ particle production

(brane picture: 

)

(2) $T_{string}^2 = T_{min}^2 + \phi^2 M_0^2$

(brane picture: 

)

Result : • Easy to generate effect at $\mathcal{O}(1)$ - $\mathcal{O}(100)$ times the standard

$$\langle \gamma\gamma \rangle \sim \frac{H^2}{M_p^2}$$

• ⇒ Even within inflation, $\langle \gamma\gamma \rangle$ not automatically tied to H.
(can enhance contribution of lower V models)

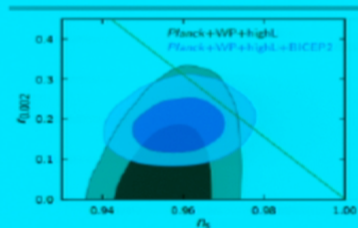
• Distinguishable? Maybe with n_T, $\langle BBB \rangle$

To Do:

There is some allowed region in theory space (UV complete)

- New examples with various r, etc. (motivated to learn more about range of possibilities)
- Systematic treatment, structural constraints?

The experimental region is rapidly shrinking...



Nonzero r at $> 5\sigma$
is a spectacular discovery

- Related to Q. Gravity / String theory in $\gtrsim \underline{2}$ ways $\left\{ \begin{array}{l} \langle \gamma\gamma \rangle \text{ Graviton} \\ \boxed{\Delta\phi \gg M_p} \end{array} \right.$
- Precise value would help e.g. determine if $\sim m^2\phi^2$ or richer dynamics
- n_T, $\langle BBB \rangle$, etc. further discrimination
- TT power spectrum, TTT NG
- Relation to GUTs, ~~SUSY~~, light (pseudo-)scalars etc. etc.