The Cyclic Universe Scenario

Erickson,Gratton,
Steinhardt & NT

* Solves horizon, flatness, homogeneity, isotropy problems using pre-bang $w>>1$ epoch instead of inflation

* Generates scale-invariant growing mode perturbations before the bang

Khoury,Ovrut,
Steinhardt &NT

* Allows for a non-anthropic, technical “solution” of cosmological constant problem, over many cycles

Steinhardt & NT

* Allows for a non-anthropic solution of the over-closure problem for axions with $f_a \sim M_S$

* Falsifiable by detection of primordial tensors

The scenario is still new and incomplete. Proposed in the spirit of trial and error: if it fails, we will learn something.

There is a profound question at stake:

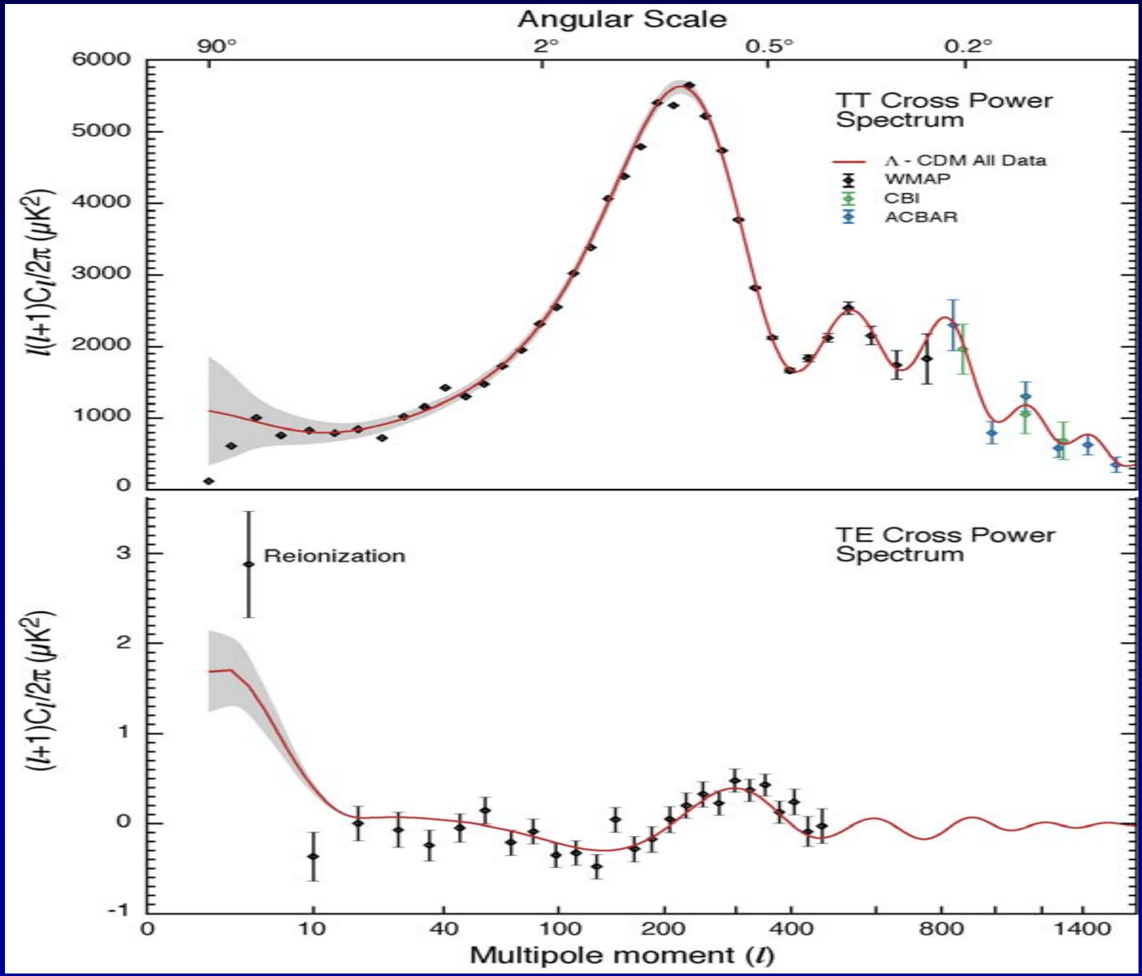
Was the big bang the beginning of time?

This talk:

Can one generate scale-invariant curvature perturbations before the big bang, within the regime of validity of 4d effective theory?

- with Jean-Luc Lehners, Paul McFadden and Paul Steinhardt

Did this prove inflation?



WMAP
2001

δT: Peebles &Yu, 1970;

Bond& Efstathiou 80's

Q δT: Coulson, Crittenden & NT, 1994

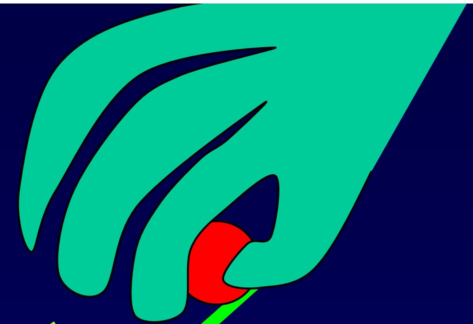
Strong evidence for:

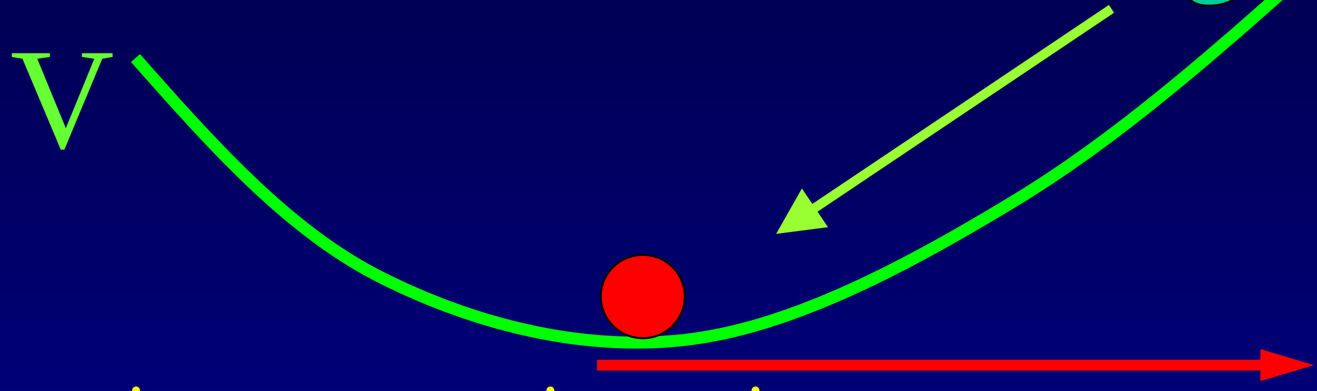
* A flat FRW Universe, with
* Simplest density perturbations: linear, growing mode/coherent, adiabatic, nearly scale-invariant, Gaussian

As predicted by simple inflationary models. But these predictions are rather generic and might be produced by different physics.

The specific signatures of inflation – tensors and non Gaussianity, have not yet been seen
($\lambda\ \phi^4$ inflation ruled out because over-predicts tensors)

Puzzles of standard inflation





* Assumes universe sprang into existence in a super-dense, inflating state: why?
* Cosmic singularity left unresolved
* Requires finely tuned potentials:

couplings $<10^{-10}$ and $\rho_\Lambda \sim 10^{-100}\ \rho_{Inf}$

* Strange vacuous future
* Canonical measure on final state gives $P(N) \sim e^{-3N}$ Gibbons &NT

(see Thursday talk …)

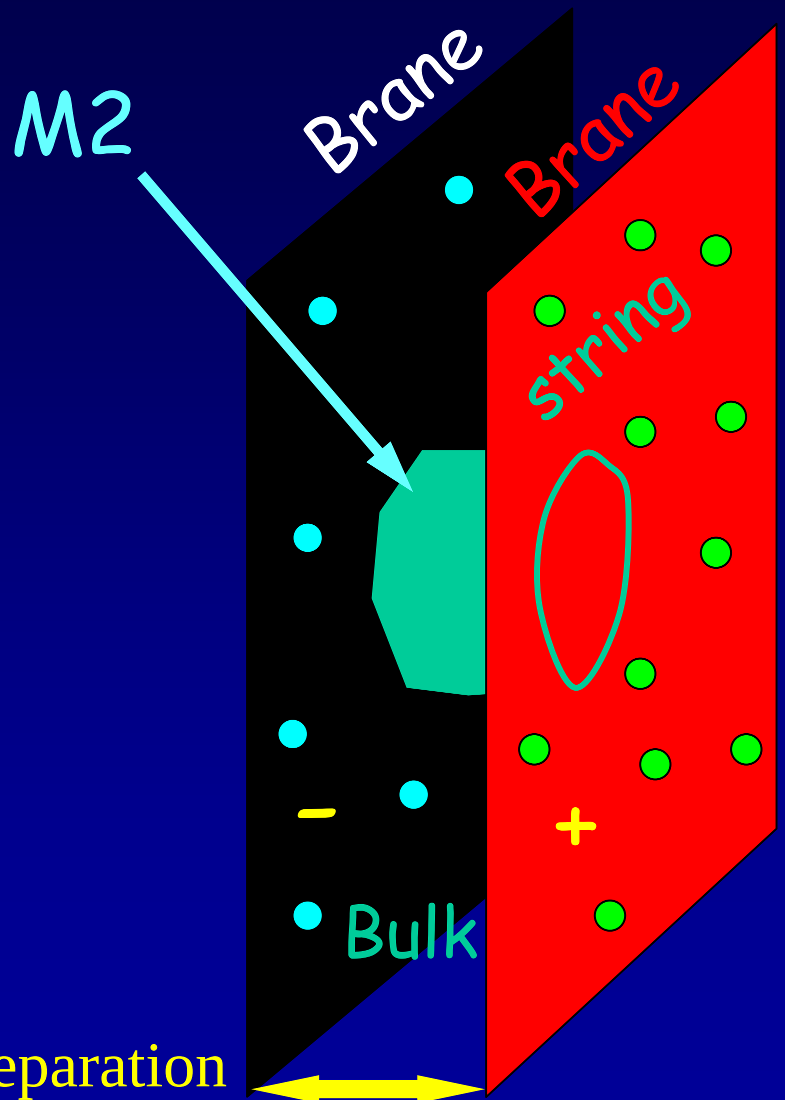
Can we do better?

Heterotic M Theory

Horava-Witten

Lukas,Ovrut, Waldram, Stelle

Hull, Townsend



separation parameterized by scalar ϕ

* chirality

* M_{Pl} ~1000 M_{GUT}

* spectrum of observed particles fits neatly in $E_8 x E_8$

* KOST,KOSST: density of matter finite at the bang

$$a_{\pm} = a_4 \begin{cases} \cosh(\phi) \\ \sinh(-\phi) \end{cases}$$

finite at collision, even though this IS the big bang in 4d desc^n;

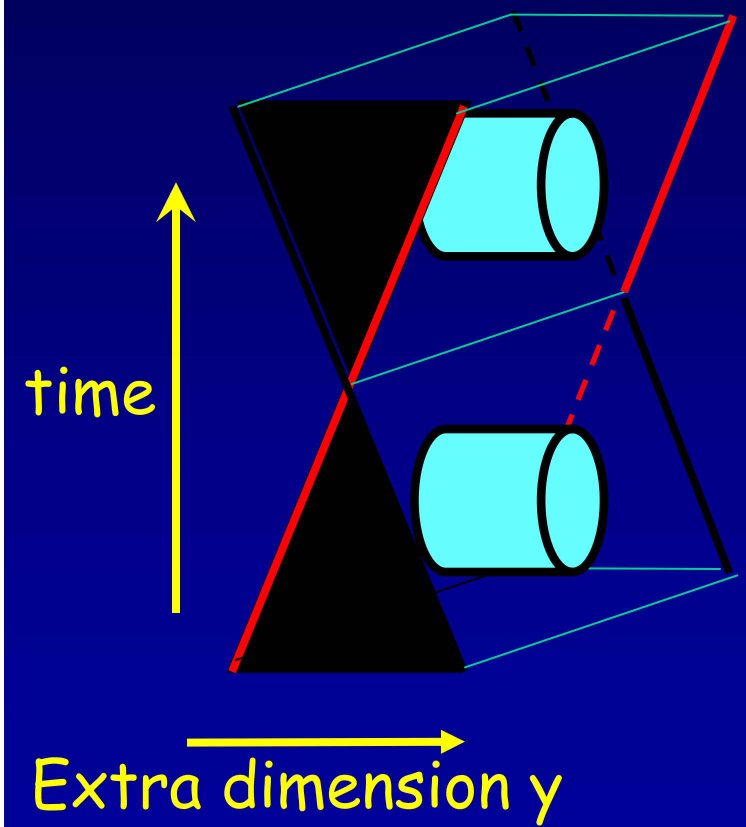
$a_4 \rightarrow 0$, $\phi \rightarrow -\infty$,

kinetic-dominated

M-theory model for the bang

Perry, Steinhardt & NT, 2004
Berman & Perry, 2006

Winding M2 branes=Strings:



No blue-shift for winding membranes: describe perturbative string states including gravity

String coupling ➡ 0 at singularity

Classical evolution of string is regular across t=0, unambiguous propagation across the singularity

Calculable T_{HBB} due to string creation

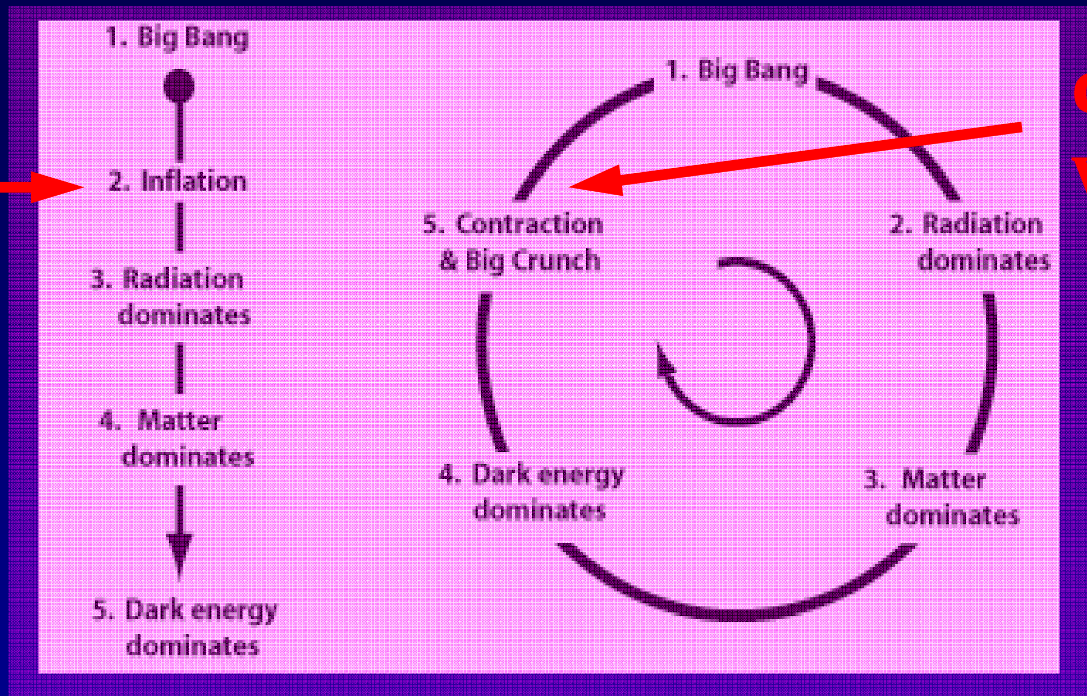
Near collision, $ds^2 \sim -dt^2+t^2dy^2+dx^2$: locally flat

4d effective descriptions

Inflation | Cyclic

expanding
w≈ -1 phase

contracting
w>>1 phase



$a \sim e^{Ht}$

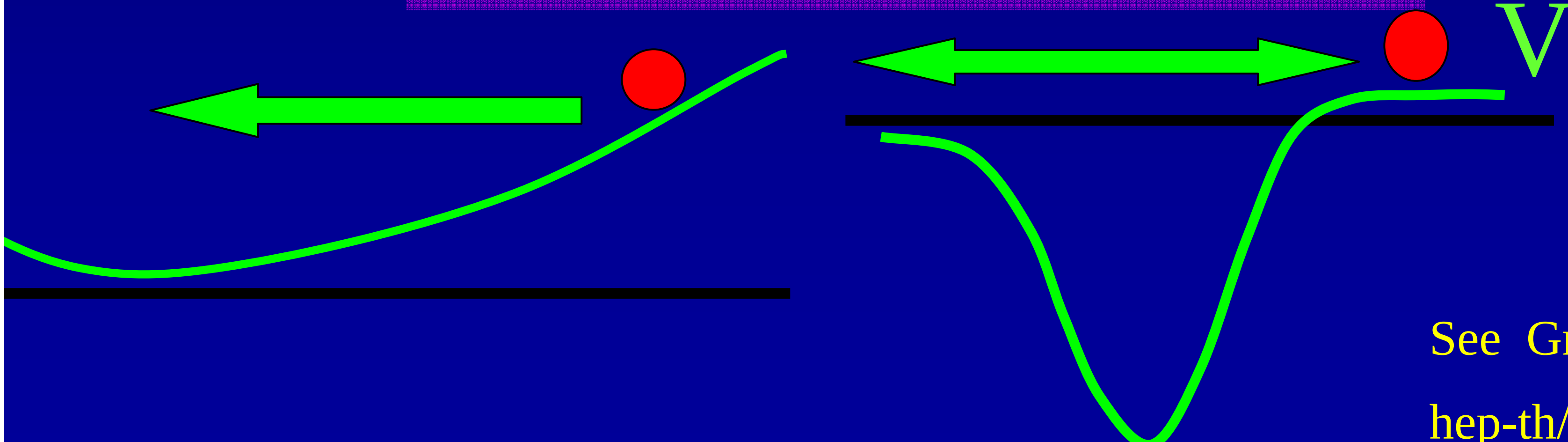
$H^2 \sim V$

$\lambda \sim H^{-1}$

$a \sim |t|^{(2/3w)}$

$\lambda \sim |t|$

$\dot{\phi}^2, |V| \sim |t|^{-2}$

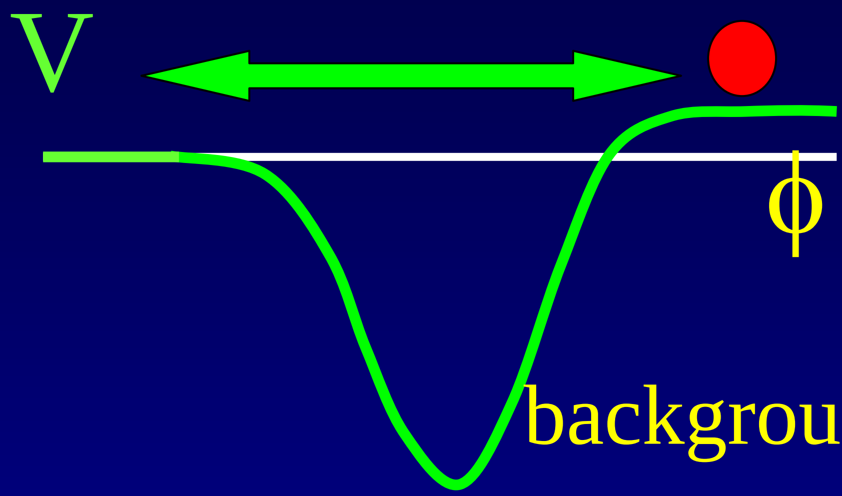


See Gratton et al

hep-th/0607164

Ekpyrotic perturbations

KOST



Assume: steep, negative potential,

$$V = -V_0 e^{-c\phi}$$

background $E \approx 0,\ \phi = (2/c)\ln(-At)$

Fluctuations: (neglect gravity) $(\partial_t^2 - \nabla^2)\delta\phi = -V_{,\phi\phi}\delta\phi.$

$$\delta\phi = \sum_{\mathbf{k}} \left(\chi_{\mathbf{k}}(t) e^{i\mathbf{k}\cdot\mathbf{x}} a_{\mathbf{k}} + h.c.\right) \Rightarrow \ddot{\chi}_{\mathbf{k}} = -k^2 \chi_{\mathbf{k}} + \frac{2}{t^2}\chi_{\mathbf{k}}$$

- Just as for a scalar field in de Sitter spacetime

Scale-invariance

Assume incoming adiabatic vacuum

$$\chi_{\mathbf{k}}^{in} \approx e^{-ikt}(2k)^{-\frac{1}{2}}$$ $$|kt| \gg 1$$

Growing-mode is local time delay

$$\approx Ck^{-\frac{1}{2}}(-kt)^{-1}$$ $$|kt| \ll 1$$

$$\langle \delta\phi^2 \rangle = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{C^2}{k^3 t^2}$$

Now include gravity

$$ds^2 = -dt^2(1+2\Phi) + a^2(t)\mathbf{dx}^2(1-2\Phi)$$

Long λ,

$$\delta t = \frac{\alpha_1(\mathbf{x})}{a} - \frac{\alpha_2(\mathbf{x})}{a}\int^t dt' a(t'), \qquad \delta x^i = (1+\alpha_2(\mathbf{x}))\, x^i$$

Quasi-gauge modes

$$\Phi = \alpha_1(\mathbf{x})\frac{\dot{a}}{a^2} + \alpha_2(\mathbf{x})\left(1 - \frac{\dot{a}}{a^2}\int^t dt' a(t')\right)$$

	Local time delay	Local dilatation: "Curvature pertn. *R*"
Expanding U	Decaying	Growing
Contracting U	Growing	Decaying

Important Question

How can 4d growing mode perturbations pre-bang match to 4d growing mode perturbations post-bang, when their geometrical character is so different?

Creminelli et al + earlier work by many others

1. If 4d effective description breaks down near brane collision, at $O(v^2/L^2)$

Brane collision speed

Warp length scale

Tolley et al., Battefield et al., McFadden et al.

2. This talk: if extra, light degrees of freedom are driven unstable in ekpyrotic phase

Lehners, Steinhardt, NT, to appear

Basic idea: consider two scalar fields, both with steep negative potentials

e.g. $$V = -V_1 e^{-c_1\phi_1} - V_2 e^{-c_2\phi_2}$$

$8\pi G=1$

$c_i>>1$

Scaling solution $$a \propto (-t)^p, \qquad \phi_i = \frac{2}{c_i}\ln(-A_i t), \qquad p = \sum_i \frac{2}{c_i^2}.$$

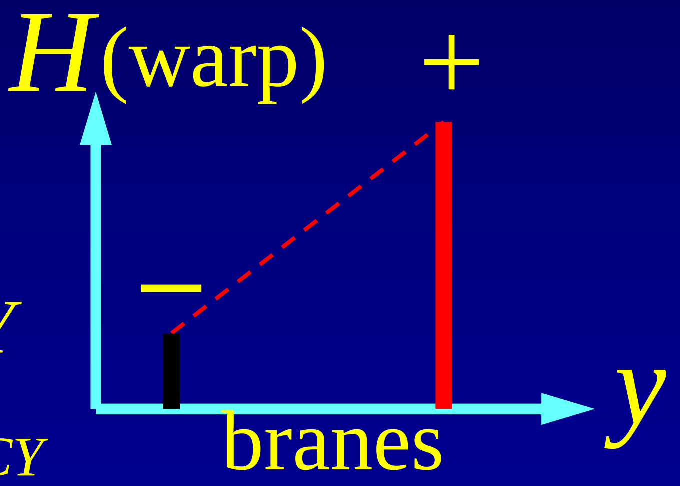
➡ entropy perturbation $$\frac{\delta\phi_1}{\dot\phi_1} - \frac{\delta\phi_2}{\dot\phi_2}$$ nearly scale-invariant

But this converts easily to *R*

Heterotic M Theory

5d descn. $$\int_5 \left(\frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - Ce^{-2\phi} \right) - \sum_i \mu_i \int_4 e^{-\phi}$$

$$ds_5^2 = H(y)\eta_{\mu\nu}dx^\mu dx^\nu + H^4(y)dy^2$$



Static soln $H^3(y) = e^{\phi} = V_{CY}$

Two scalar fields: radion and V_{CY}

Claim: before and after boundary brane collision, minus brane hits zero of H and bounces back. This bounce converts entropy to curvature!

4d effective theory

$$S_4 = \int_4 \frac{1}{2}\left(R - (\partial\phi_1)^2 - (\partial\phi_2)^2\right)$$

Geometrical quantities
(11d metric)

$$a_\pm = a_4 e^{-\sqrt{3}\phi_1/2} \begin{cases} (\cosh 2\phi_2)^{\frac{1}{4}} \\ (-\sinh 2\phi_2)^{\frac{1}{4}} \end{cases}$$

$$V_{CY,\pm} = e^{\sqrt{3}\phi_1} \begin{cases} (\cosh 2\phi_2)^{\frac{3}{2}} \\ (-\sinh 2\phi_2)^{\frac{3}{2}} \end{cases}$$

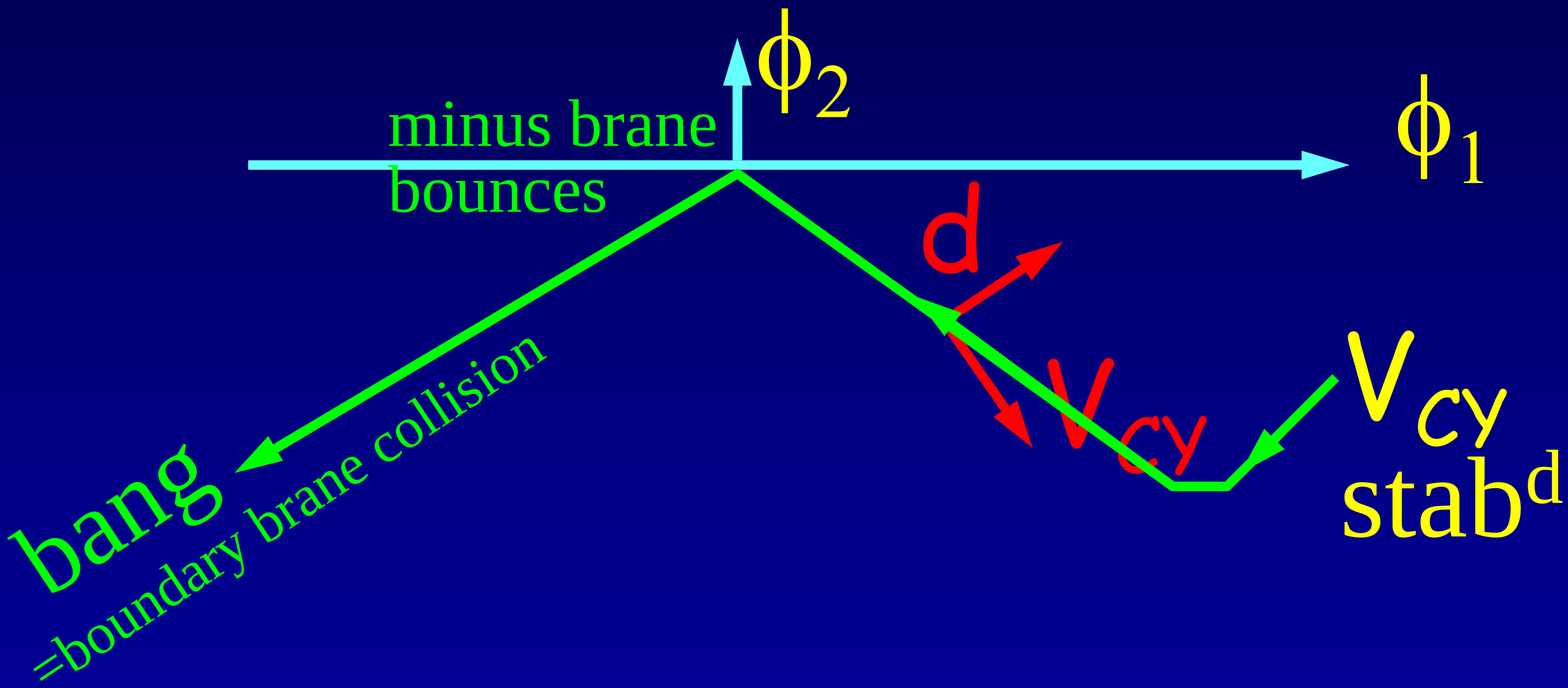
$$d = e^{-3\phi_2 + \sqrt{3}\phi_1}\left[(1+e^{4\phi_2})^{\frac{3}{2}} - (1-e^{4\phi_2})^{\frac{3}{2}}\right]$$

$$-\infty < \phi_1 < \infty \text{ and } -\infty < \phi_2 < 0$$

* at large negative ϕ_2, d and V orthogonal

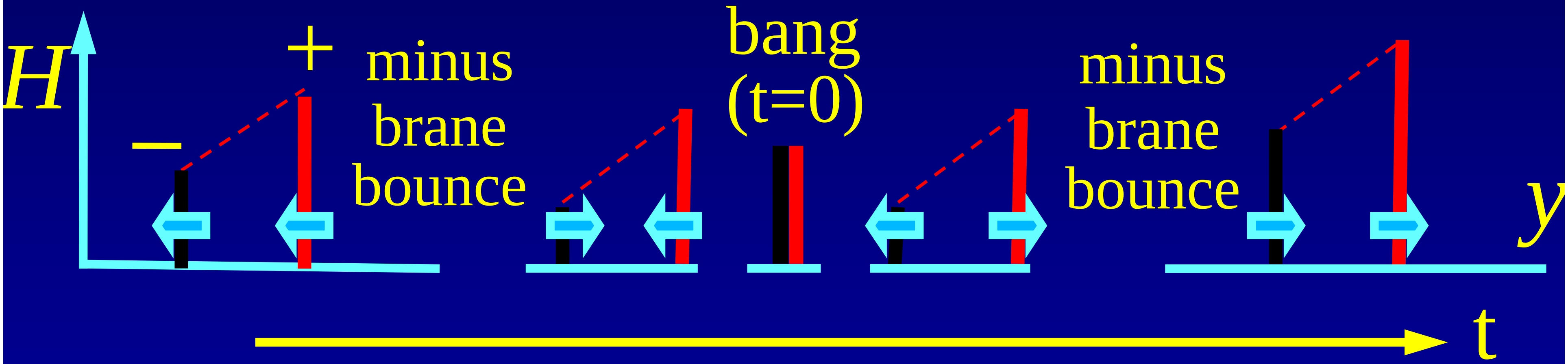
* if $V_{CY,+}$ fixed at large brane separation, $a_+ \sim a_4 \cosh(2\phi_2)$, then ϕ_2 decouples as in Randall-Sundrum model

4d scalar field description:



e.g. $V(\phi_1,\phi_2) \sim -e^{-d} - e^{-V} + (V_{cy}-V_0)^2\, e^d$

Full 5d story of boundary brane collision



Lehners, McFadden, Steinhardt &NT, 2006

cf : Lukas et al, Chamblin&Reall; Lehners&Stelle; Lu,Pope&Gibbons

Creation of curvature perturbation

General formula:

$$\dot{\mathcal{R}} = -\frac{H}{\dot{H}} g_{IJ}(\phi) \frac{D^2 \phi^I}{Dt^2} s^J + \frac{H}{\dot{H}} \frac{k^2 \Psi}{a^2}$$

entropy perturbation:

$$s^I = \delta\phi^I - \dot{\phi}^I \frac{g_{JK}(\phi)\dot{\phi}^J \delta\phi^K}{g_{LM}(\phi)\dot{\phi}^L \dot{\phi}^M}$$

Sources of curvature:

i) Trajectory-bending due to departure from scaling soln, or $V(\phi_1)$ turning off before/after $V(\phi_2)$

ii) Bounce of negative tension boundary brane

ii) is model indept: $\mathcal{R} \sim H_{bounce}/M_{Pl}$

generically small

Note:

Potential has to be chosen to ensure solution heads from Λ domination to a regular bounce: this is a selection principle which involves essentially all the cosmological properties of the model.

Background solution has $w \gg 1$. It is an attractor in all directions except the entropy direction.

Scalar Spectral Index

Special case: if V(d) and V(V_{CY}) are the same function V(ϕ), get

$$n_s = 1 + 8\left(\frac{V}{V_{,\phi}}\right)^2 - 4\left(\frac{V}{V_{,\phi}}\right)_{,\phi}$$

Second term dominates if V steep and falls faster than an exponential at large ϕ. Leads to a slightly red spectrum.

For example, V ~ - exp(C $\phi^{4/3}$) as in Conlon/Quevedo hep-th/0509012 for Kahler moduli.

Matching across t=0

If 4d effective theory is an exact truncation then

i) Analytic continuation of pos/neg freq modes,

or

ii) Geometrical matching of local brane collision rapidity and Kasner exponents

are equivalent (and gauge invariant), and amount to matching long-wavelength part of 4d curvature perturbation $\mathcal{R}$ (actually, $\mathcal{R} \to -\mathcal{R}$) across the singularity

Cyclic Predictions:

* Red Tilt

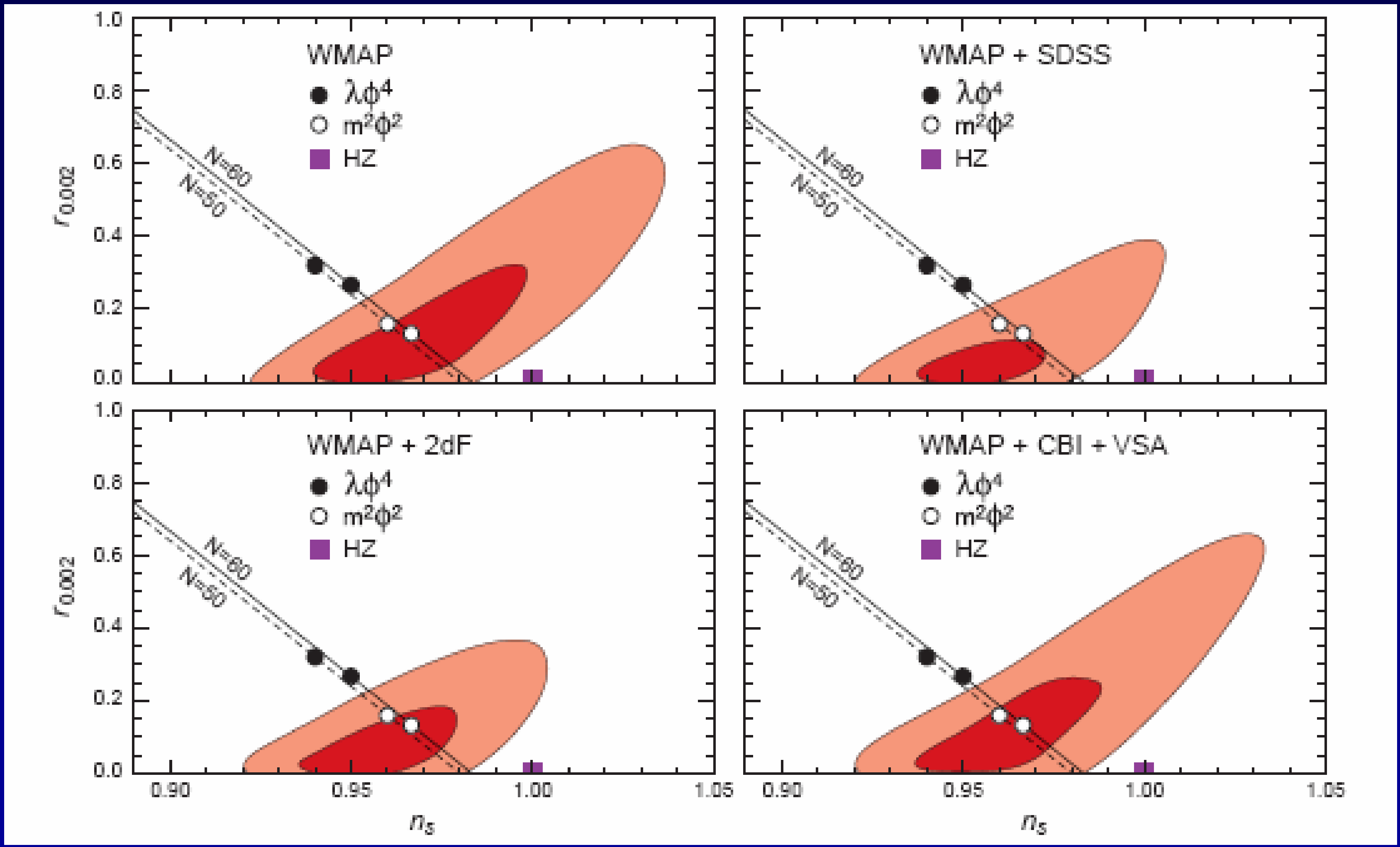
* No Tensors

* Far more Gaussian than inflation

n_s, tensors

W-MAP 2006

Ratio tensor/scalar pertns



Spectral index

Conclusions

Many cosmological puzzles can be solved by a pre-bang epoch of dark energy domination followed by its decay into a $w \gg 1$ phase

Main theoretical challenge is to show that a crunch/bang transition is allowed

A detection of primordial long wavelength gravitational waves would disprove this idea