Particules Élémentaires, Gravitation et Cosmologie
Année 2010-'11

Théorie des cordes: quelques applications

Cours XIII: 18 mars 2011

The unperturbed pre-big bang scenario

The pre-big bang accelerator

It looks as if we have obtained inflation for free in string theory! How is that possible with just a scalar field with vanishing potential?

The answer to this question lies in the peculiar way the dilaton appears in string theory. Recall that the exponential of the dilaton controls g_s and the ratio l_P/l_s.

Consider a post-big bang solution describing a decelerating expansion with a constant dilaton. Under SFDxT this solution goes into one describing a pre-big bang accelerating universe with a growing dilaton, hence a growing g_s and l_P/l_s.

The accelerated expansion is present in the string frame, i.e. if we measure distances in l_s-units. But the growth of l_P/l_s is so fast that the universe contracts if, instead, we measure distances in l_P-units.

Thus the answer to the question:

Is PBB a bouncing cosmology?

depends on the frame, i.e. on the meter we use to measure distances. The scale-factor may or may not bounce.

However, independently of the frame, PBB cosmology corresponds to a "curvature bounce" in that has a phase of growing curvature turning into one of decreasing curvature through an intermediate "string phase" during which the curvature is of order l_s^{-2}.

Actually, an accelerated contraction can also help solving the HBB puzzles and indeed the physical predictions are identical in the two frames.

Initial conditions & fine-tuning

So far we have assumed a "cosmological principle" for string cosmology, like it's done for the HBB scenario.
We would like instead PBB cosmology to emerge from generic (i.e. non fine tuned) initial conditions. This is possible if we make an assumption of "Asymptotic Past Triviality".
This is just the opposite of what is assumed in HBB cosmology (where everything started at a singularity).
In fact, the need for a beginning of time, is now completely removed provided we can smoothly join the pre and post bang phases.

Asymptotic Past Triviality (APT)

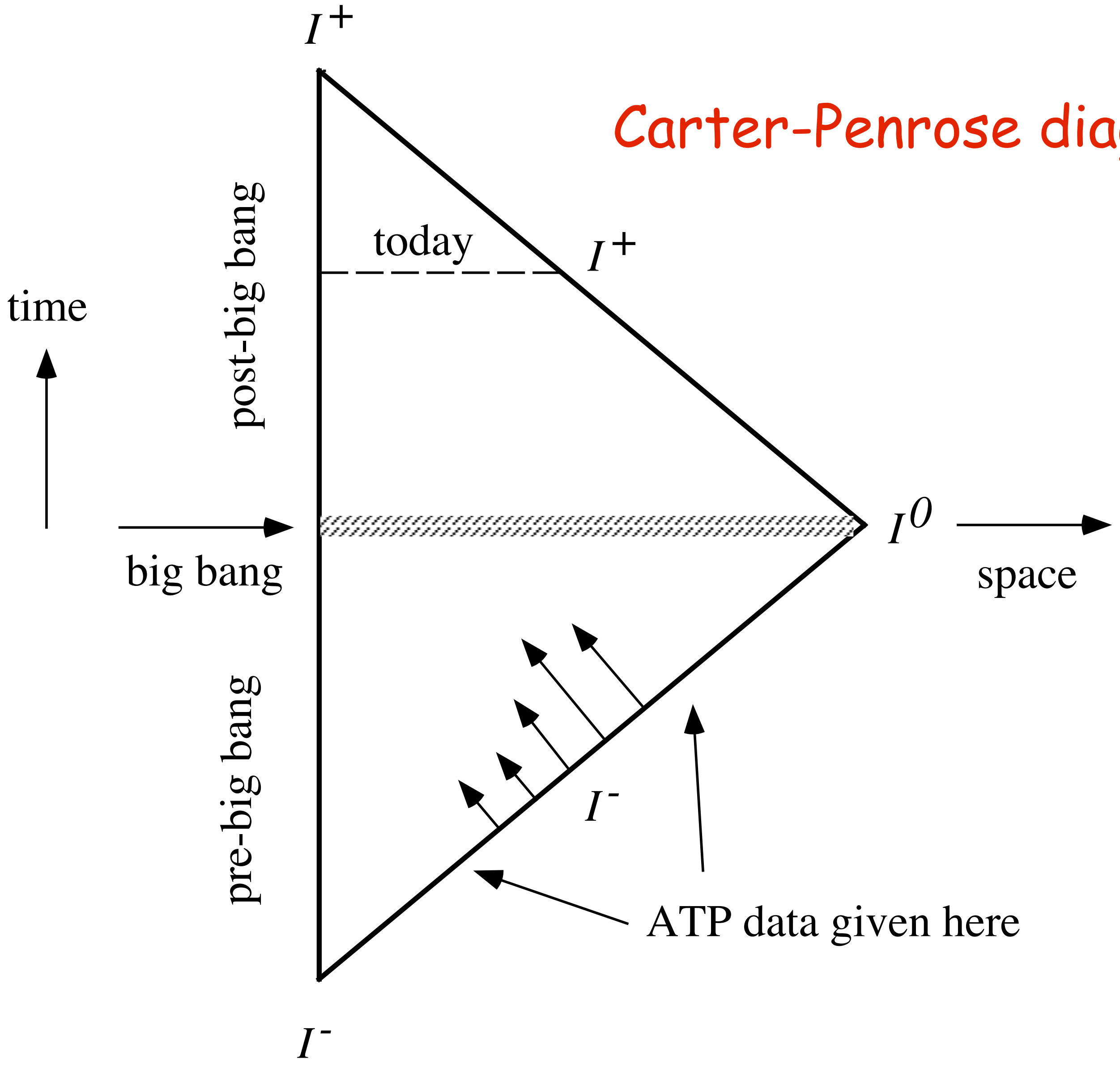
APT: As we go towards $t = -\infty$ the Universe gets closer and closer to the trivial vacuum of superstring theory (nearly flat D=10 spacetime and nearly vanishing string coupling, $e^\phi \ll 1$) but is otherwise generic (in a precise sense).

Because of SUSY, a dilatonic potential cannot be produced at any finite loop order and is therefore completely negligible as long as g_s is very small ($\phi \ll -1$).

Thanks to APT we can thus use the effective action of QST at lowest order both in the genus and in the derivative expansion:

$$\Gamma_{eff} = -\int \frac{d^{10}x}{l_s^8}\sqrt{-G}e^{-\phi}\left[R(G) - \partial_\mu\phi\partial^\mu\phi + \frac{1}{12}H^2\right]$$

Carter-Penrose diagram



$$\Gamma_{eff} = -\int \frac{d^{10}x}{l_s^8}\sqrt{-G}e^{-\phi}\left[R(G) - \partial_\mu\phi\partial^\mu\phi + \frac{1}{12}H^2\right]$$

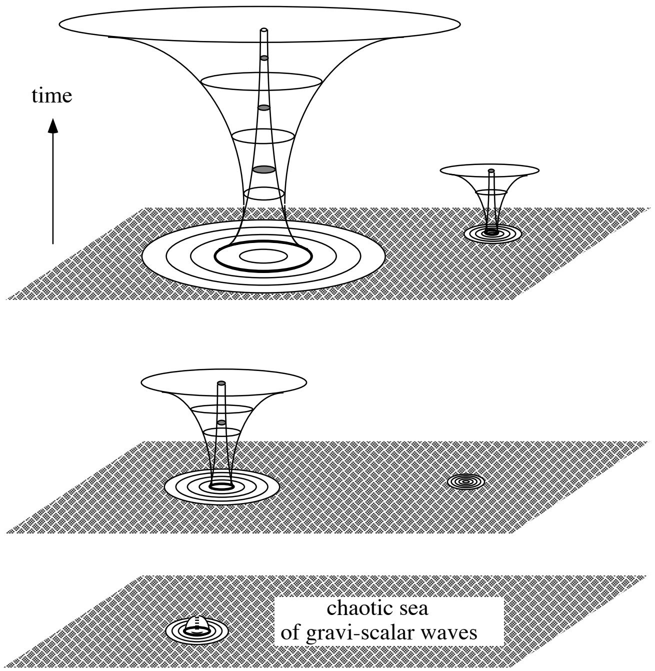
We can write down a generic solution in the far past and check that it contains the appropriate number of arbitrary functions to be called generic. It describes, physically, a chaotic superposition of gravitational and dilatonic waves.

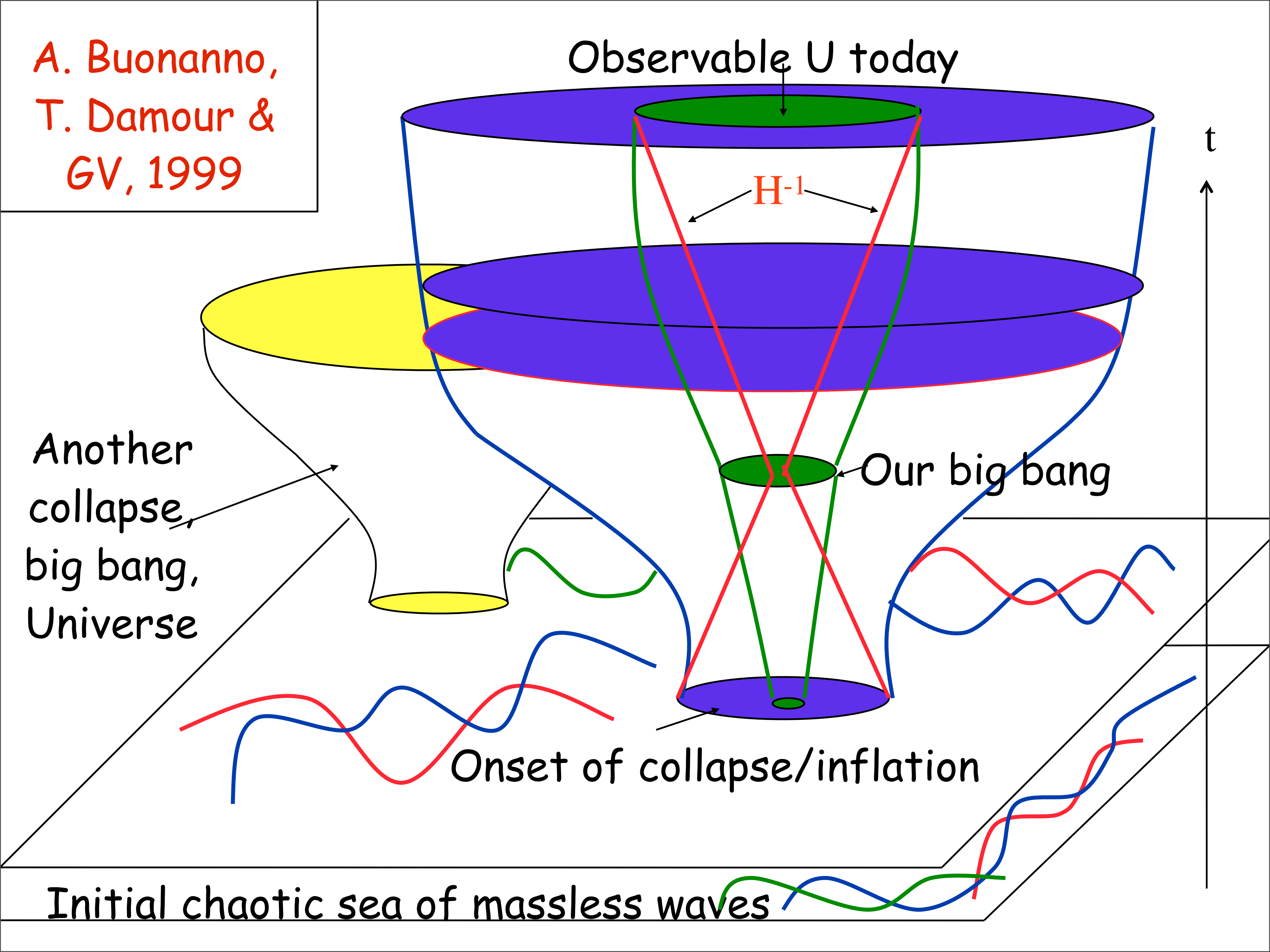
In the APT regime the field equations are invariant under a constant shift of ϕ and under a global rescaling of x. As a result, the generic initial data include, as free parameters, the initial value of the dilaton ϕ_{in} and the initial curvature scale.

Solutions that go to the trivial vacuum in the infinite past, become increasingly complicated, curved and coupled as one moves forward in time.

As a consequence of singularity theorems (Hawking, Penrose), the evolution generically brings about the formation of Closed Trapped Surfaces (CTS), i.e. of black holes in different spacetime locations with arbitrary (and randomly distributed?) values for ϕ_{CTS} and for the horizon radius R_{CTS}.

A PBB cosmology then takes place inside the CTS. How?




A. Buonanno,
T. Damour &
GV, 1999
Observable U today
H^{-1}
t
Another
collapse,
big bang,
Universe
Our big bang
Onset of collapse/inflation
Initial chaotic sea of massless waves

Models for the onset of PBB cosmology

I. Spherical symmetry (BDV 1999)

Consider spacetime around one of the CTS and approximate it by a spherically symmetric one.

By going to the Einstein frame we map the problem into one extensively studied in the GR literature, in particular by D. Christodoulou (1991, ...), the collapse of a minimally coupled massless scalar field in the case of spherical symmetry.

DC has given a quantitative criterion for the formation of a CTS and has studied the solution inside the horizon. As expected, DC's criterion is scale and dilaton-shift invariant: as usual, it has to do with some critical dimensionless ratio of incoming energy per unit advanced time (in $G = c = 1$ units).

The solution near the singularity is dominated by time derivatives with spatial gradients becoming more and more subdominant as the singularity is approached. One obtains a generalized Kasner cosmology in the Einstein frame which, in the string frame, describes a quasi homogeneous PBB cosmology:

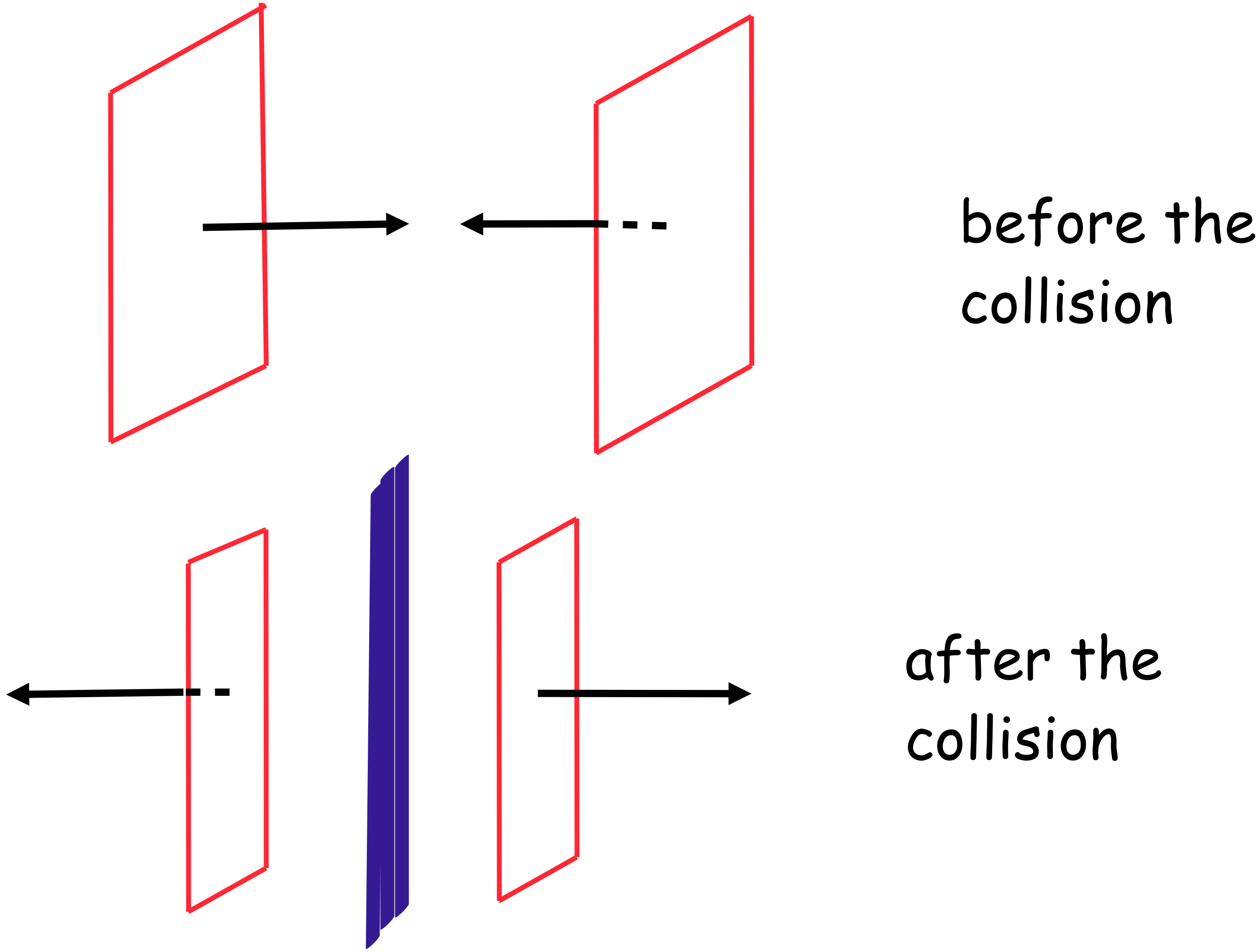
$$a_i(t) = (\pm t)^{p_i(x)} \quad ; \quad \phi(t) = -(1 - \sum_i p_i(x)) \log(\pm t) + \text{const.} \quad ; \quad \sum_i p_i^2(x) = 1$$

Near the singular hypersurface there are spatial regions that become very large (in string units) and isotropic.
In order to become sufficiently large to wash out spatial curvature we need a large-enough ratio between R_{CTS} and l_s and also a sufficiently negative ϕ_{CTS}.

II. Plane symmetry

(Feinstein, Kunze & Vasquez-Mozo '00; Bozza & GV, '00)

As another (opposite) limit we take the collision of two infinitely extended plane waves. If we assume translation invariance along the transverse plane the model is exactly soluble (reduced to quadratures).
By causality, some of the results also hold for sufficiently large wavefronts (obeying the KV criterion for CTS formation) in a spacetime region after the collision.
The metric inside the horizon is again of the generalized Kasner type and, in the string frame, it corresponds to a quasi-homogeneous PBB cosmology.



BB-like sing. formed behind wave-fronts

The fine-tuning issue

In both examples (spherical and plane symmetry) PBB inflation starts, at a curvature scale and coupling that represent two free parameters (integration constants) of the solutions.
In order to solve the HBB cosmological puzzles we need the initial coupling to be very small (say $\phi_{CTS} < -100$) and the CTS radius $R_{CTS} > 10^{-13}$ cm $\sim 10^{20}\ l_s$.
Is this fine-tuning? Given the numbers some people (like Andrei Linde) have answered: Yes! Personally I disagree: because of the chaotic nature of our scenario there will be a whole distribution of possible values for ϕ_{CTS} and R_{CTS} and at least one large smooth Universe like ours will easily emerge somewhere together with many others...

Extensions of PBB scenario

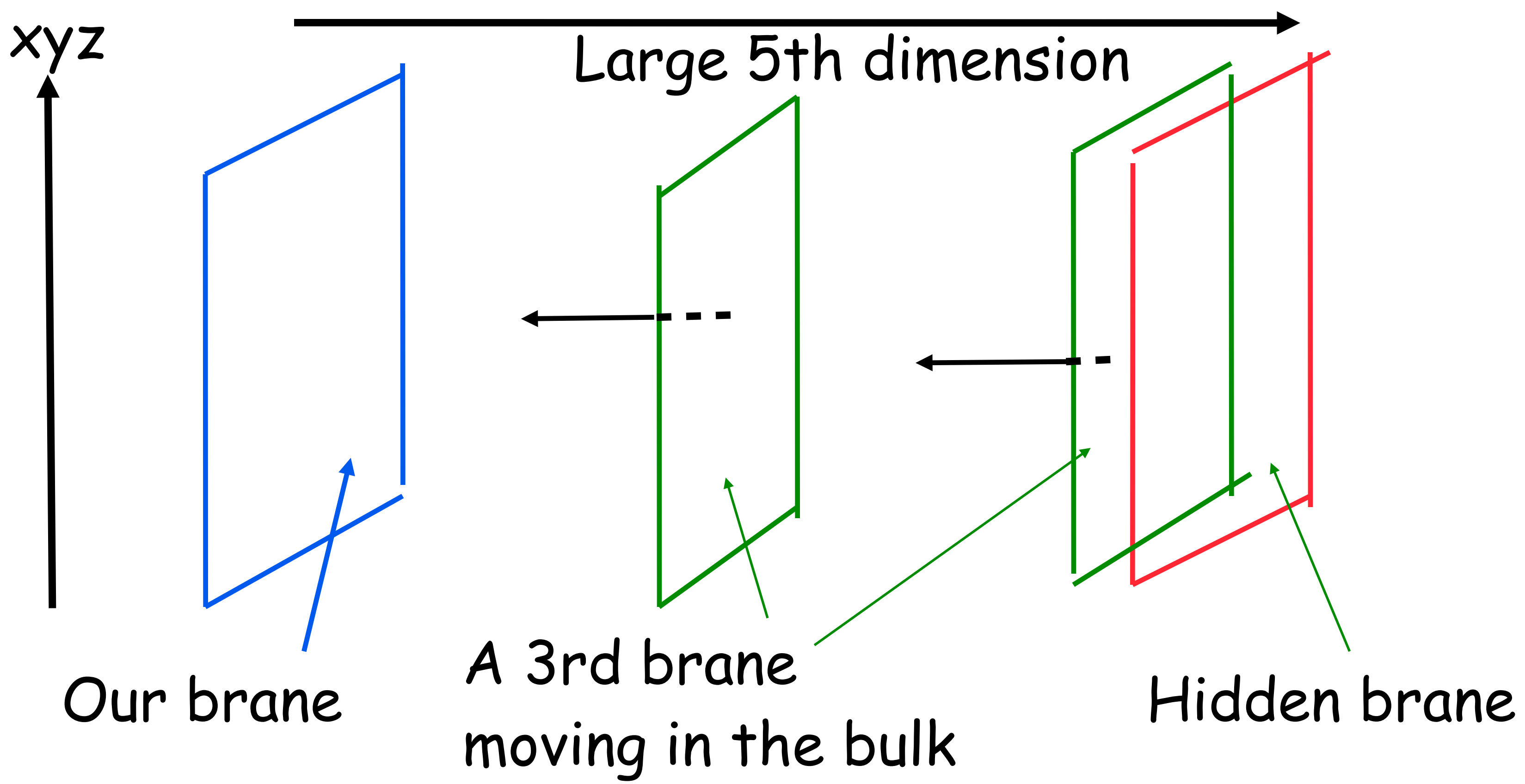
The simple PBB model can be generalized by including a non-trivial B-field and RR forms as backgrounds.
This does not seem to make the model any better.
Actually, Damour and Henneaux have shown that the addition of RR forms tends to give back the so-called BKL oscillations already known in GR as a consequence of Kasner's anisotropy.
Some spatial gradients slowly become dominant and induce a sudden jump of Kasner's $p_i(x)$. Another "velocity dominated" Kasner phase then takes place, followed by another jump of the p_i, and so on indefinitely as one approaches the singularity.
The dilaton allows for isotropic solutions without BKL oscillations, but adding other backgrounds brings them back.

Other models of a bouncing Universe

NB: other cosmologies based on extra dimensions and the brane-universe idea will be discussed next week in the two seminars given by C. Deffayet.

Ekpyrotic Universe

(Khouri, Ovrut, Steinhardt&Turok '01)

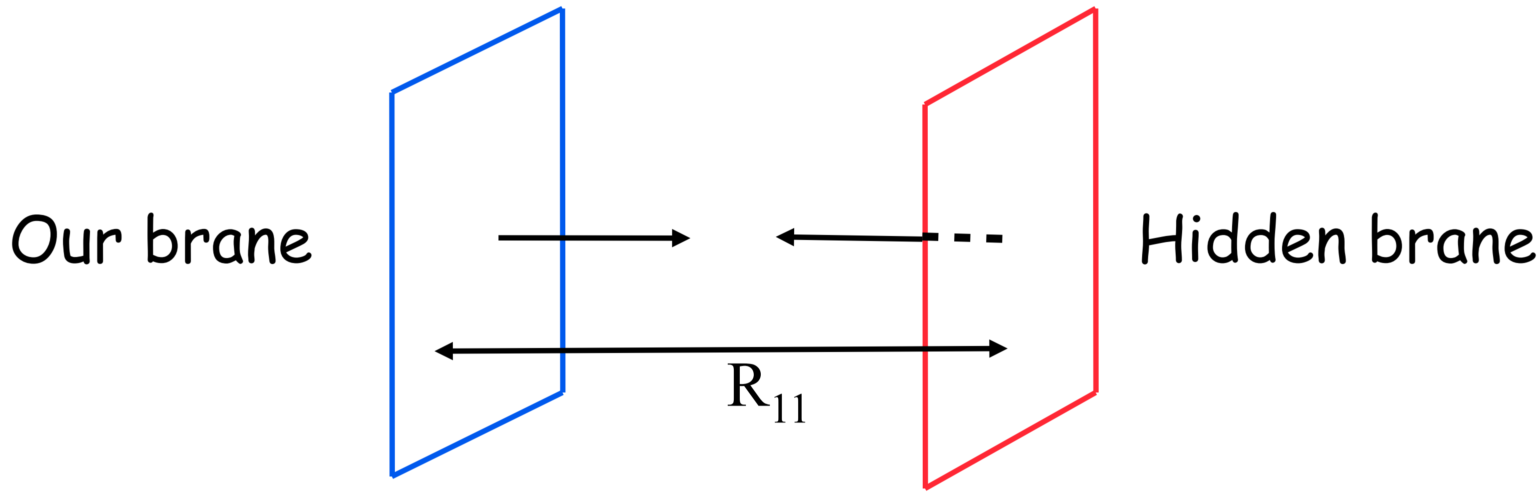


Big Bang as result of impact of 3rd brane on ours

A PBB based on Horava-Witten theory

(HW: D=11 SUGRA on S_1/Z_2 => $E_8 x E_8$)

(KOST + Seiberg)



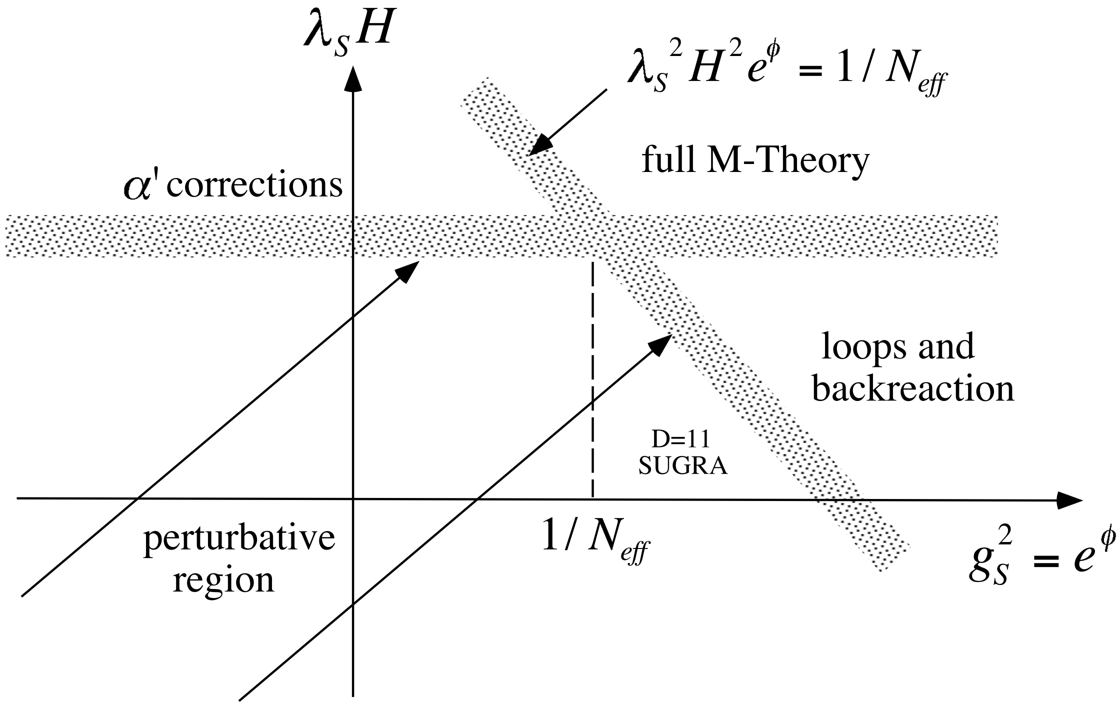
The BB is just due to the collapse of the 11th dimension to zero size. Given the relation between R_{11} and the dilaton, this means a BB at zero coupling, i.e. the opposite of what is assumed in the conventional PBB scenario.

Implementing the curvature bounce

The existence of inflationary solutions at $t < 0$ is not of much use unless we can connect this phase to a standard FLRW phase at $t > 0$.

This is the most difficult theoretical issue facing the PBB scenario (there are also, of course, phenomenological issues which I leave for the last week of this course).

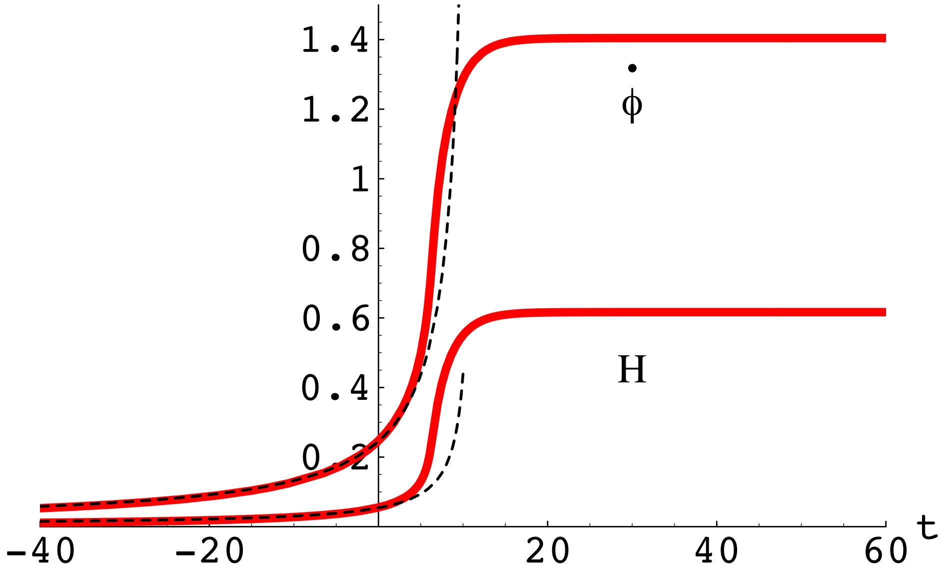
As one approaches the singularity both the curvature and the string coupling diverge. Hence describing the bounce amounts to solving string theory when the curvature approaches the string scale and/or the string coupling becomes O(1).



$\lambda_S H$
$\lambda_S{}^2 H^2 e^\phi = 1/N_{eff}$
full M-Theory
α' corrections
loops and
backreaction
D=11
SUGRA
perturbative
region
$1/N_{eff}$
$g_S^2 = e^\phi$

Strong coupling and strong curvature regimes are sometimes tractable provided the background preserves (at least part of the) supersymmetry.
Unfortunately, a time-dependent background is not supersymmetric and this makes the task very hard.
One of the very few known results concern the search for late-time de-Sitter-like (constant curvature) attractors accompanied by linear (in t) dilaton in the presence of higher derivative corrections to the tree-level effective action.
The existence of such attractors depends on the existence of real solutions to an algebraic system of n-equations in n-unknowns: generically there is a finite number of solutions.
Examples involving up to 4-derivative terms have been given but this does not prove anything because even higher order corrections cannot be neglected.

Gasperini, Maggiore, GV (1997)



If this is what really happens:
a "string phase" would follow during which the curvature is constant (and of order l_s^{-2}) while the coupling keeps growing until higher-genus corrections become important.
It is conceivable (but not yet proven) that these loop corrections complete the transition to a FLRW phase.
Since loops are related to particle production they can warm up the Universe and account for its "initial" entropy.
Entering the strong coupling region, the dilaton can develop a non-perturbative potential (as a result of SUSY breaking) and eventually get stuck in its minimum. Thereafter the dilaton would have been constant and massive thus avoiding contradiction with precision tests of GR and with the observed time independence of various constants of Nature.

Actually, in order to avoid these phenomenological problems, one has to "stabilize" also the shapes and sizes of the 6 extra dimensions of space (moduli stabilization problem) since their variation also induces variations in the constants of Nature.

We shall see that, in order to generate an interesting spectrum of cosmological perturbations it is important to let the 6 extra dimensions contract while the other 3 expand.

It is then conceivable that, at the bounce or soon after, the extra dimensions stabilize at the self-dual size (leading incidentally to the emergence of large gauge symmetries).

Only in this case the post bang (bounce) phase will be of the conventional FLRW type.