Cordes et Branes: des outils pour la cosmologie primordiale

Strings & branes: tools for primordial cosmology

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Preamble

✔ Despite its exotic aspects, string theory is a *very conservative* approach to quantize general relativity
★It is expected that physics in the very early universe $t < t_{\mathsf{Pl}} \sim 10^{-43}$s can be usefully described by string theory models
★However, finding solutions of the theory is very difficult

✔ First approach: study solvable models of string theory, draw general lessons from them

✔ Second approach build models using the "ingredients" found above

➥string theory provides a toolbox for cosmology and particle physics (even without referring to string theory): supersymmetric grand unification, extra dimensions, bounce models, varying physical constants...

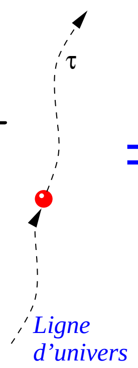
Outline

1. Very brief survey of string theory
2. String theory at large curvature and the big-bang
3. Strings and the real world
4. Branes and inflation
5. Conclusions

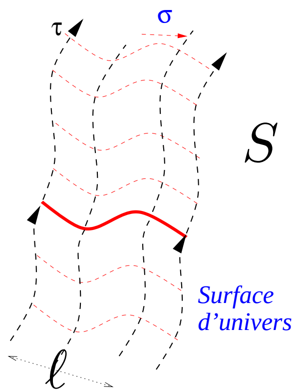
Quick overview of string theory

✔ String theory is a theory of relativistic objects extended in one spatial dimension, defined as the fundamental degrees of freedom of our universe

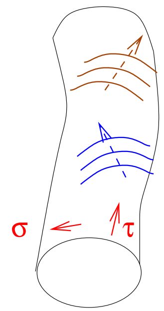
$$S = -m\int \mathrm{d}\tau$$



$\Rightarrow$



$$S = -T\int \mathrm{d}\tau\mathrm{d}\sigma\sqrt{-\mathrm{det}(g_{ab})}$$



✔ Excitations: planes waves propagating on the string worldsheet

➥ quanta: modes of an *infinite number* of harmonic oscillators of frequency N/ℓ

★Each mode N corresponds at "large" distances to a point particle of rest mass

$$\boxed{m = \sqrt{8\pi T(N-1)}}$$ *tower of Planck-mass particles*

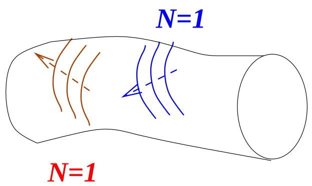
✔ Robust predictions of string theory

★Space-time has dimension 10 (9 spatial), otherwise the theory *cannot* be defined around flat Minkowski space-time (quantum mechanically)

★Supersymmetry (i.e. pairing of bosons and fermions) is a symmetry of our universe, at least at high energies, otherwise the theory is unstable *($N = 0$ mode)*.

✔ Only parameter: string tension $T > M_{\mathsf{Pl}}^2$ *(strings cannot be seen directly in experiments)*

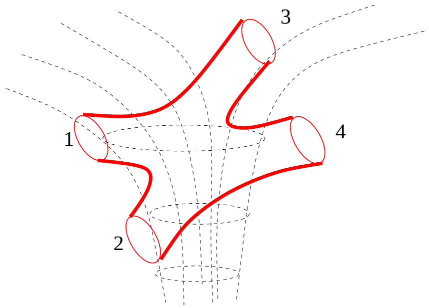
✔ Gravity (i.e. general relativity) is not a prerequisite but rather a "prediction" of the theory as it contains *always* a graviton



★The strength of gravity (i.e. the Newton constant) is a dynamical field of the theory $\phi(x^\mu)$ called *dilaton* $\boxed{G_{\rm N} = G_{\rm N}^0 e^{\phi(x^\mu)}}$ ➥ can vary with space & time !

✔ String geometry of space-time

★Only well-defined quantities: scattering amplitude of strings in a given background space-time (coherent state of strings)



$$|\eta\rangle = e^{\eta\, a^\dagger}\, |0\rangle$$

✔ Spacetime "felt" by these *probe strings* defines the *string geometry*, different from usual space-time geometry

➥ for instance, spacetime singularities may be smoothed out

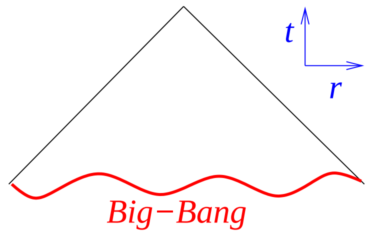
✔ What we can do

String theory in the regime of very large curvature *(up to Planck length^{-2})*

✔ **What we cannot do yet** String theory with a large coupling constant $e^{\phi(x^\mu)} \sim 1$

String theory and the big-bang singularity problem

✔ General relativity predicts that the universe began with a singularity of spacetime



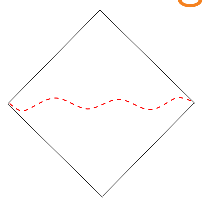
✔ Question Can string theory avoids (or put up with) the big-bang ?

★First option: near the singularity large coupling constant ⟶ pre-bigbang scenario

➥ cannot study quantitatively the strongly coupled phase

★Second option: the coupling constant (i.e. Newton's constant) remains small close to the big-bang but the curvature become large

➥ possibility of a *perturbative bounce?*



✔ String geometry from the general relativity point of view

★The space-time geometry *as seen by the strings* can be seen as corrections the the general relativity Lagrangian:

$$\mathcal{L} = \sqrt{-g}\left[\mathcal{R} + \frac{\alpha}{T}\mathcal{R}^2 + \cdots + \frac{\beta}{T^4}\mathcal{R}^4 + \cdots\right]$$

➥ Precise form of these terms completely fixed by string theory *(unitarity,...)*

★It seems that including any finite number of such terms cannot tame the singularity (classically) *[Biswas, Mazumdar, Siegel '06]*

✔ "Exact" string geometry as a loophole to this statement ?

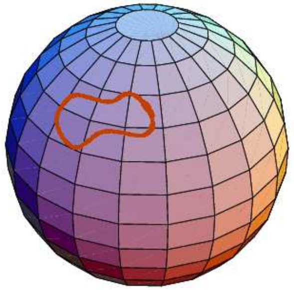
★The full range of string theory corrections to space-time geometry *cannot* be reduced to corrections of the General Relativity Lagrangian

★In certain circumstances, one can probe the "string geometry" with exactly solvable models of string theory

High curvatures in string theory

✔ Strings propagating in a space with large curvature ➥ large depletion of states

✔ Example: Strings propagating on a 3-dimensional sphere of radius ρ (space of positive curvature) ➥ what happens in the limit $\rho \to 0$? *(i.e. very large curvature)*

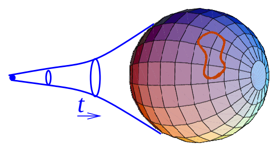


★ Instead of planes waves on the string, one has (hyper) *spherical harmonics* but with maximal spin allowed $\boxed{j < \pi T \rho^2 - 1}$

➥ minimal "wavelength" for the wave-function of the string

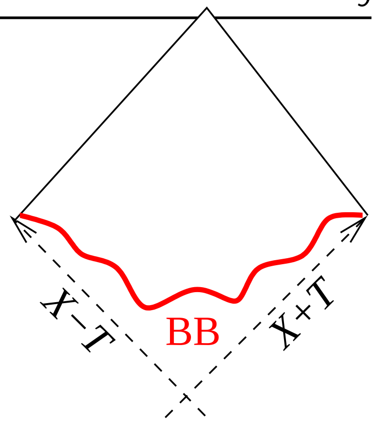
✔ Smallest radius: $\rho = 1/\pi T$ ➥ in this limit the *3-sphere* becomes a *circle* !

✔ Cosmology ? closed universe $\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}s^2(S^3)$



➥ if adiabatic evolution, may apply for $a(t) \to 0$

An anisotropic big-bang model



✔ String theory model of open universe (isotropic for late times)

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + t^2\mathrm{d}x^2 + (t^2 - 4\mu^2)(\mathrm{d}y^2 + \mathrm{d}z^2)$$

➥ in that case, apparent *strong coupling* at the big-bang

✔ Exact results from this model

★Singularity harmless for strings (vs. ordinary gravity)

★However, strings cannot go *beyond* the big-bang singularity at $t = 2\mu$

➥ "Dirichlet" boundary conditions at the singularity

✔ Main result: strings "condense" after the big-bang !

➥ String condensate of the form $\left(G_{\mathrm{N}}^{0}\right)^{-\mu^2} t^{\mu}\cosh(\mu x)$ "eats" spacetime

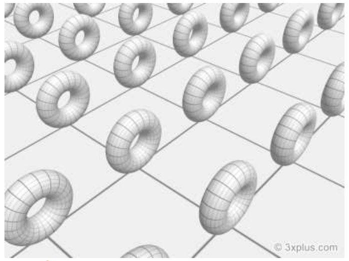
✔ Conclusions The initial conditions for which the big-bang singularity is removed correspond to a vacuum with a large production of strings

Strings and the real world (I)

✔ Is string theory good to describe the real world ?

➥ first prediction: the universe has 9 spatial dimensions

✔ Kaluza & Klein idea: extra spatial dimensions are "small" ➥ *compactification*



★Large choice of topologies leading to different 4-dimensional physics

★The continuous parameters giving the *shape* and *size* of the compact space remains dynamical massless fields (called *moduli*)

★Clearly an undesirable feature for cosmology *(decompactification problem)*

✔ Parameters can be frozen with "magnetic" fluxes turned on the compact space *(fluxes take only integer values)* ➥ price to pay is a huge number of solutions $\sim 10^{150}$!

✔ From our point of view, each such a *solution* of the same superstring theory is viewed as a *different theory* of particle physics

★What are the guidelines for the choice ? What is the predictive power of string theory ? ➥ resurgence of the anthropic principle

✔ Partial origin of the problem

String theory *needs* that each boson is paired with one fermion with similar characteristics (mass,charge...) ➥ supersymmetry *(e.g. photon* $\leftrightarrow$ *photino,...)*

★In such models the parameters of the compact space *cannot* be frozen easily because of strong constraints from supersymmetry

✔ Usual strategy *[Kachru,Kallosh,Linde, Trivedi '03]*

1- Freeze completely all parameters of the compact space *(the moduli)*

2- Only after supersymmetry is broken with extra ingredients *(as it should since supersymmetry is not realized in Nature at energies probed with experiments)*

✔ Non-supersymmetric string theories may allow to overcome this problem

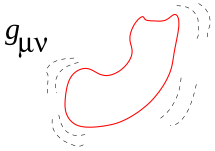
"La théorie quantique des champs est la pire des dictatures. Tout ce qui n'est pas interdit est obligatoire" J. Iliopoulos

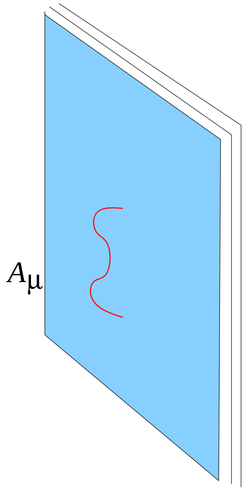
★There is room for string theories with *no supersymmetry* from the start

➥ more difficult to study but potentially promizing

Strings and the real world (II): Branes

✔ Superstrings alone only describe gravity *(& undesirable particles mentionned above)*





★String theory contains also very massive membranes, 3-branes,..
★Strings can *break* on them and become *open strings*
★Open strings attached to the brane represent quarks, gluons,... of the standard model for particle physics

✔ Branes and cosmology

★The branes probe space-time geometry on *shorter scales* than the strings
★One can imagine that the branes of the standard model are immersed in a large transverse space ➥ brane world scenarios
★Branes are also dynamical objects on their own right

Branes and inflation

✔ Inflation is a period of *accelerated expansion* in the early universe

★Explains in particular the flatness of the universe,...

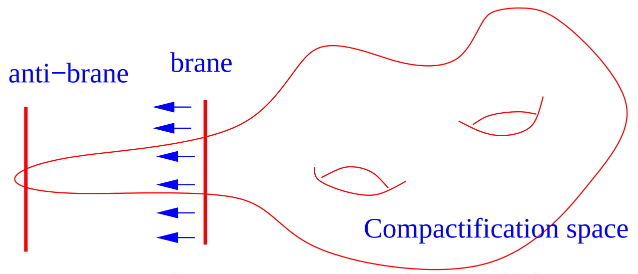
★Reproduces well the fluctuation spectrum from the CMB

➥ what is the implementation of inflation in fundamental physics ?

✔ Inflation in superstring theory

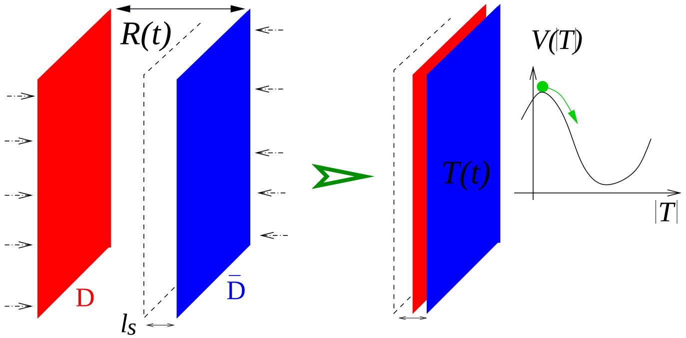
★Inflation is not natural in superstring theory (*i.e. not generic*), but possible

➥ example: brane inflation



★Brane attracted towards an anti-brane inside a "bump" of the compactification space ➥ Leads to inflation compatible with cosmological data

✔ Annihilation of brane with anti-brane *as particle with anti-particle* ➥ end of inflation



★String realization of *hybrid inflation mechanism* ➥ T is the "waterfall field"

✔ Distinctive string theory signatures of string theory inflation ?

★Inflation is possible in an "ultra-relativistic" regime with very *fast roll*

➥ only possible in string theory, predicts large grav. wave emission *[Silverstein, Tong]*

★Annihilation of branes produces generically a "dust" of Planck-mass string modes

➥ consequences not well understood *[Sen '03, Frey & al '05, D.I. Rabinovici '06,...]*

➥ Problem of reheating the universe after inflation

➥ generically predicts formation of *cosmic (super)strings* after inflation

Conclusions: string theory and the cosmology problems ?

✔ String theory at least compatible with many cosmological/particle physics data

• Inflation: seems possible, but not natural; in certain regimes, distinctive signatures
• Cosmic strings: how to cope with the cosmic superstrings apprently predicted by string theory ?
• Dark matter: as superstring theories include supersymmetry, the superparticles candidates for dark matter are *also* present in string theory
• Dark energy: positive cosmological constant hard to obtain in supersymmetric string theories
➥ in non-supersymmetric models, how to obtain such a low value ? $(10^{-47} Gev^4)$

✔ Non-perturbative string theory in the cosmological context not yet understood, may provide some guiding principles