A New Cosmological Scenario in String Theory

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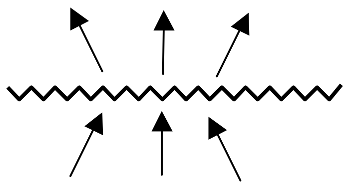
Introduction

- **Cosmological Singularity Problem**

Expansion



Contraction

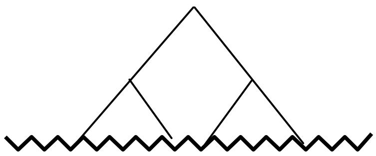
Space-like singularity
(string effects)

[Veneziano]

- **Singularity Theorems :** basic assumptions are global structure and reasonable matter $\rho + 3p > 0$
  Cannot then reverse from contraction to expansion.

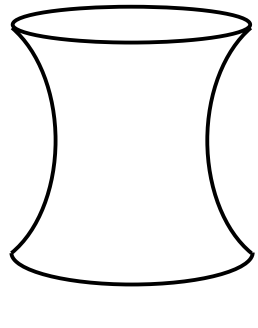
[Hawking & Penrose]

- **Space-like singularity** ⟶ **Horizon Problem**



- **DeSitter Space evades these problems with a positive cosmological constant** Λ

$$p = -\rho$$



New Space-Time Global Structure

- Consider the effective d+1-dimensional gravitational action

$$\int d^{d+1}x\sqrt{g}\left[R-\frac{\beta}{2}(\nabla\psi)^2-V(\psi)\right]$$

- General solution with a cosmological horizon at t = 0 and SO(1,d) symmetry:

Region I - Open Cosmology

$$ds^2_{d+1}=-dt^2+a_I{}^2(t)\,ds^2(H_d)$$

$$\psi=\psi_I(t)$$

Region II – ´Static` Region

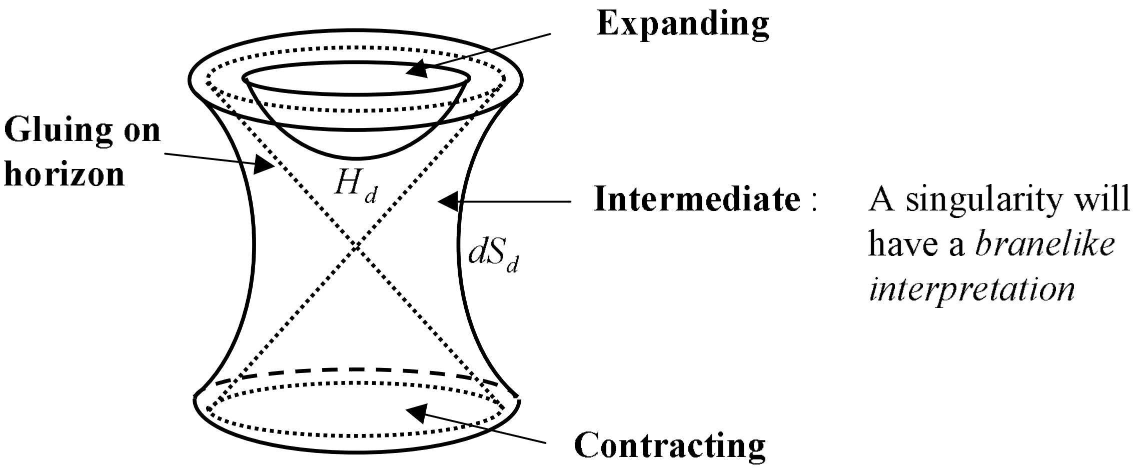
$$ds^2_{d+1}=dx^2+a_{II}{}^2(x)\,ds^2(dS_d)$$

$$\psi=\psi_{II}(x)$$

- Gluing conditions on the horizon and analytic continuation

$$a_I(t)=t+o(t^3) \qquad \psi_I(t)=\psi_0+o(t^2)$$

$$a_{II}(x)=-\,ia_I(ix) \qquad \psi_{II}(x)=\psi_I(ix)$$



Embedding in String Theory

- *Toroidal* Compactification of Type II $\quad (\tilde{d} = 9 - d)$

$$(\Lambda = e^{2\beta\psi})$$

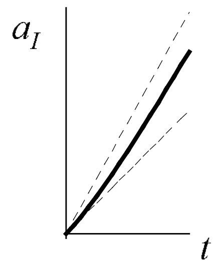
$$E^2 ds^2 = \Lambda^{-\frac{1}{2}\frac{d-1}{d-1}} ds^2_{d-1} + \Lambda^{\frac{1}{2}} ds^2(\mathbf{E}^{\tilde{d}})$$

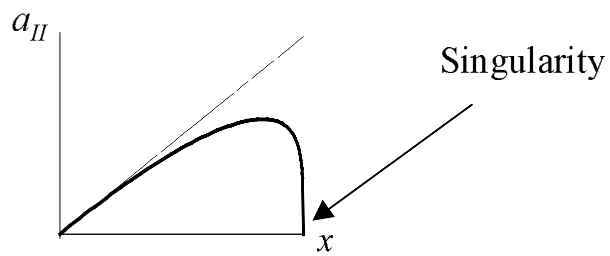
$$e^{\phi} = g_s \Lambda^{\frac{4-d}{4}} \qquad\qquad \tilde{F} = \frac{1}{g_s E^{\tilde{d}-1}} \varepsilon(\mathbf{E}^{\tilde{d}})$$

- As before d+1-dimensional action with scalar potential

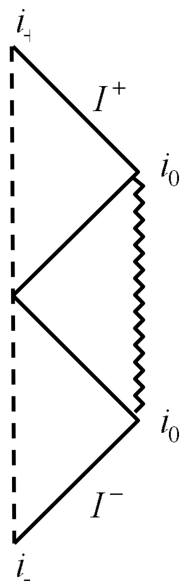
$$V(\psi) = \frac{1}{2} e^{-\psi}$$

- Behavior of scale factor

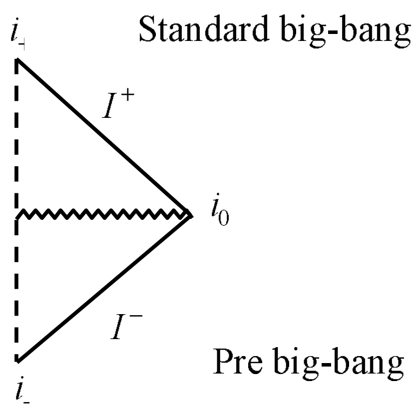




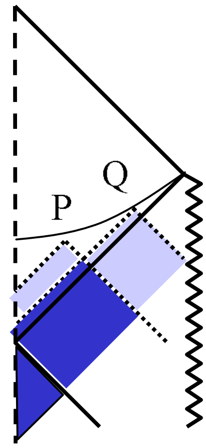
- Carter-Penrose diagram



No big-bang!



- No Horizon Problem



- Structure of the singularity

$$E^2 ds^2 \cong \Lambda^{-\frac{1}{2}}\left[\mu\, ds^2(dS_d)\right] + \Lambda^{\frac{1}{2}}\left[d\Lambda^2 + ds^2(\mathbf{E}^{\tilde{d}})\right]$$

$$e^{\phi} = g_s \Lambda^{\frac{4-d}{4}} \qquad F = \frac{1}{g_s E^d}\frac{1}{\Lambda^2} d\Lambda \wedge \varepsilon(dS_d)$$

Similar to D(d-1)-brane metric *delocalized along the* $\mathbf{E}^{\tilde{d}}$. Harmonic function

$$H(\Lambda, \mathbf{E}^{\tilde{d}}) = \Lambda$$

But

$$\text{Tension} \propto -\nabla^2 H < 0$$

Negative tension O(d-1)-plane, smeared over the transverse 9-d directions, with a deSitter world-volume.

- Solution of SUGRA with *negative tension brane source* on the O-plane world-volume Γ

$$|T|\int_{\Gamma} d^d x\, e^{-\phi}\sqrt{-\det G} \pm Q\int_{\Gamma} A$$

- Near singularity orientifold is locally near flat and BPS

- Radius $\qquad L \approx \frac{1}{E}$

- Number of O-planes per unit transverse volume $\qquad n \approx \frac{l_s E}{g_s}$

Two Dimensional Toy Model

- The case of the O-particles can be obtained as the M-theory compactification

$$\mathbf{M}^3/\Gamma \times \mathbf{E}^8$$

Other models:
[Horowitz, Steif]
[Kounnas, Lust]
[Khoury et al.]
[Nekrasov]
[Simon]
[Liu et al.]
[Elitzur et al.]
Unstable? [Lawrence]

where Γ is **Boost & Translation**.

Start with flat metric on the three dimensional space $\mathbf{M}^3$

$$ds^2 = -dX^+dX^- + dY^2$$

Then

$$\Gamma = e^{\kappa} \qquad \kappa = 2\pi i(\Delta J + RP)$$

No fixed points

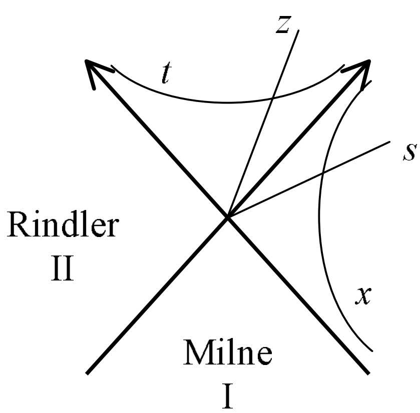
$$iJ = X^+\partial_+ - X^-\partial_- \qquad iP = \partial_Y$$

- Orientifold singularity will appear where κ becomes null

$$\kappa \cdot \kappa = 0 \quad \Rightarrow \quad X^+X^- = -\frac{1}{E^2} \qquad E \equiv \frac{\Delta}{R}$$

- Compactify to IIA theory by choosing coordinates where $\kappa = 2\pi R\partial_y$

Natural coordinates in Milne and Rindler wedges : Polar Coordinates



I: Milne

$$EX^{\pm} = te^{\pm(z+y)}, \qquad y = Y$$

II: Rindler

$$EX^{\pm} = \pm xe^{\pm(s+y)}, \qquad y = Y$$

- Background fields are:

Region I

$$E^2 ds^2 = \Lambda^{1/2}\left[-dt^2 + ds^2(\mathbf{E}^8)\right] + \frac{t^2}{\Lambda^{1/2}} dz^2$$

$$e^{\phi} = g_s \Lambda^{\frac{3}{4}} \qquad A = -\frac{1}{g_s E \Lambda} dz$$

$$\Lambda = 1 + t^2$$

Region II

$$E^2 ds^2 = \Lambda^{1/2}\left[dx^2 + ds^2(\mathbf{E}^8)\right] - \frac{x^2}{\Lambda^{1/2}} ds^2$$

$$e^{\phi} = g_s \Lambda^{\frac{3}{4}} \qquad A = -\frac{1}{g_s E \Lambda} ds$$

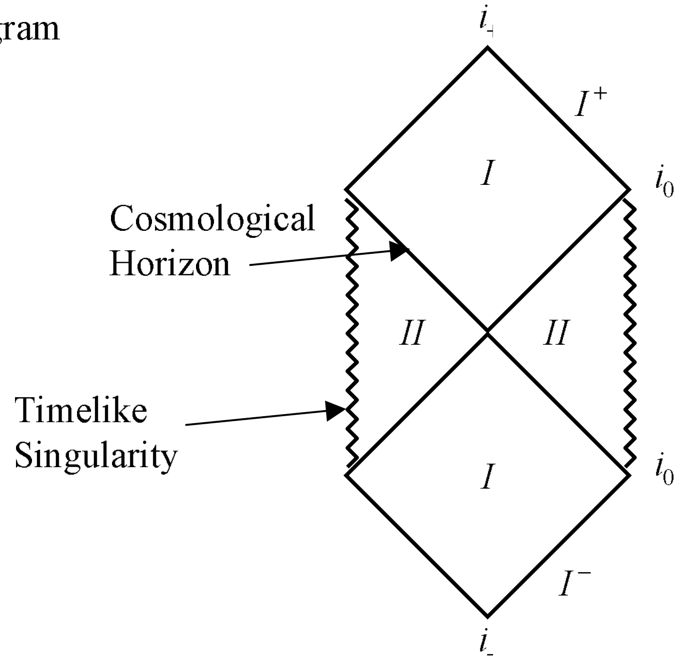
$$\Lambda = 1 - x^2$$

- 2D model with contraction for t < 0 and expansion for t > 0
- Cosmological horizons
- Singularity in Region II at $x^2 = 1$ ⇨ $O\overline{O}$ **pair delocalized on E⁸**
- T-duality along all the E⁸ directions gives a $O8$ - $\overline{O8}$ pair at a distance L

$$L \approx \frac{1}{E} \qquad 1 = N \approx \frac{l_s E}{g_s}$$

- Carter-Penrose Diagram

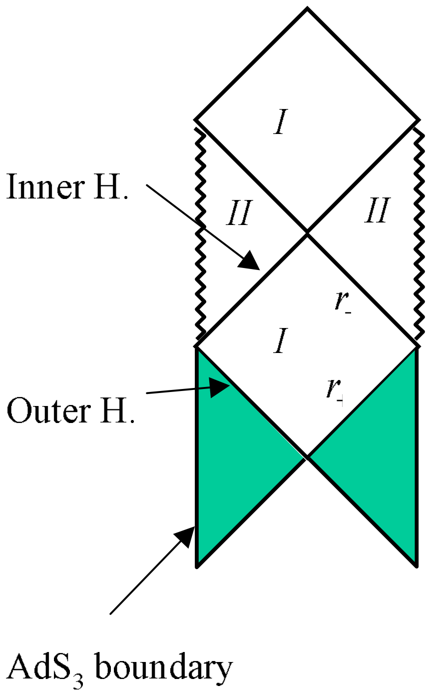
Similar 2D structure:
[Kounnas, Lust]
[Grojean et al.]



- 2D geometry as a limit of the BTZ black hole

Limit of large AdS_3 radius $L \to \infty$ such that

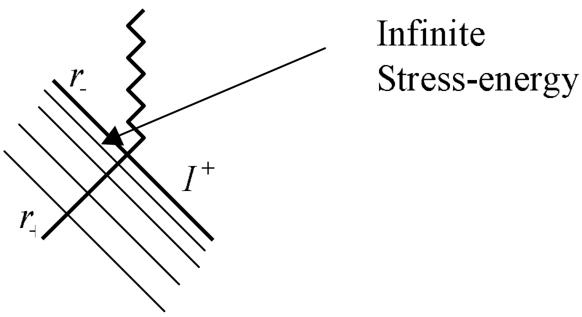
$$r_- = R \qquad\qquad r_+ = \Delta L \to \infty$$



Region *outside the black hole* is removed in the limit. We have

$$r_- \to I^-$$

- Penrose-Simpson instability of inner horizon



These modes do not exist when

$$r_- \to I^-$$

Perturbative String Description

- O8-plane BPS configuration: Type IIA on

$S^1 / I\,\Omega$ ⟵ World-sheet parity

↖ Reflection

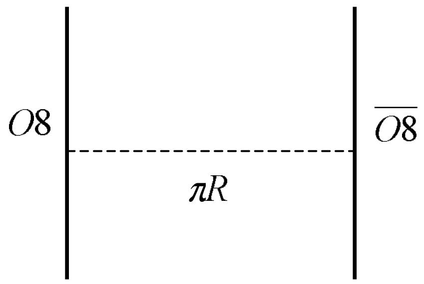
- $O8$ - $\overline{O8}$ non-BPS configuration: Type IIA on

[Antoniadis et al.]
[Kachru et al.]

S^1 / G ⟵ G generated by

$g_1 = I\,\Omega$

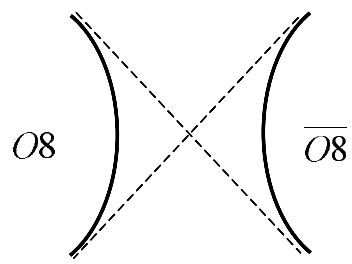
$g_2 = I\,\Omega(-)^F\,\delta$ $\delta : x \to x + \pi R$



g_1 and g_2 break the opposite half of SUSY

- Usually one adds D-branes for **Tadpole cancellation**.

- Gravity solution (tree level string theory) corresponds to the **backreaction** of closed strings to the O-planes



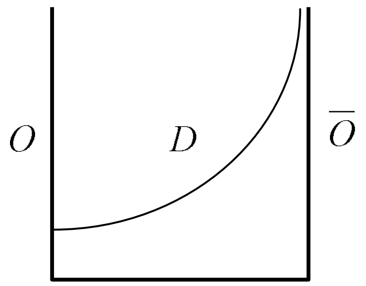
- Question: what is dynamics behind such configuration?

Orientifold Repulsion

Naïve point of view : the $O8$ - $\overline{O8}$ should ***attract and annihilate***

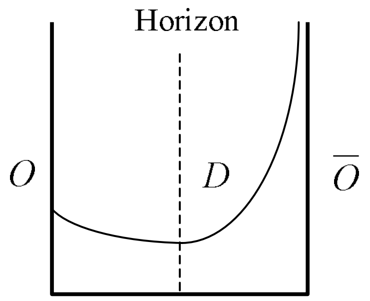
Gravity solution shows ***repulsion***

- Consider a D-brane probe between $O\bar{O}$ pair and calculate static potential.



Naïve **potential without backreaction**

- OD is SUSY
- $\bar{O}D$ repel



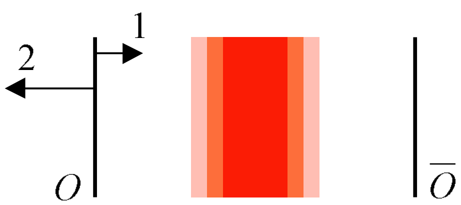
Complete potential

D-brane attracted to core of geometry

⇩

Positive energy density at the core

- Orientifolds are repelled by energy density at the core of geometry.



Energy	-	+	-
Charge	-	0	+

Two competing forces:

1. $O\bar{O}$ attraction
2. Repulsion from energy density at the core

Second force wins !

Cosmological Thermal Radiation

- Consider **minimally coupled scalar** in 2D model.

  Laplace equation $\nabla^2 \chi = 0$ gives the mode decomposition

Region I: $e^{ipz} H_p(\pm pt)$

Region II: $e^{ips} H_p(\pm ipx)$

$$H_p \propto H^{(1)}_{i|p|}$$

- Orientifold **boundary conditions** at singularity

$$\chi = 0 \qquad \text{or} \qquad \partial_x \chi = 0$$

- Assume **trivial vacuum in the far past**. From Bogobulov transformations observer in the **far future** will measure a **thermal spectrum** with

$$T \cong \frac{E}{2\pi a(t)}$$

- Temperature arises because of cosmological horizon. From surface gravity at the horizon this formula also holds in (d+1)-dimensional model.

Expected for radiation in d+1 dimensional FRW geometry

$$\rho \approx T^{d-1}$$

$$\rho \approx \frac{1}{a} \cdot \frac{1}{a^d}$$

Redshift ($\frac{1}{a}$) Expansion ($\frac{1}{a^d}$)

Conclusions

1. Gravity solutions	- Similar causal structure. How generic ?
	- Gravity + negative-tension boundary conditions ⇨ Presence of horizon ?
2. CFT	- Precise relation with a CFT description (rolling tachyon and Sen's latest work).
3. Cosmology	- Make a "realistic" model with a more complicated compactification and an exit to standard radiation domination.
	- Revisit standard literature allowing for the possibility of a cosmological horizon replacing the big-bang singularity.