Cosmologies with Big-Bang Singularities and Their Gauge Theory Duals

K. Narayan

Chennai Mathematical Institute (CMI), Chennai

[hep-th/0610053, hep-th/0602107,
Sumit Das, Jeremy Michelson, KN, Sandip Trivedi;
arXiv:0711.2994, Adel Awad, Sumit Das, KN, Sandip Trivedi.]

- AdS/CFT with Big-Bang cosmological singularities
- Holographic gauge theory duals
- Null: towards nonsingularity, bulk point of view . . .
- Spacelike Big-Bangs, FRW cosmologies etc.

Related references:

C. Chu, P. Ho, hep-th/0602, arXiv:0710. [hep-th]: cosmological generalizations of AdS/CFT framework.

B. Craps, S. Sethi, E. Verlinde, “Matrix Big Bang” hep-th/0508, and followup work by various people: Matrix theory duals of cosmological singularities.

...

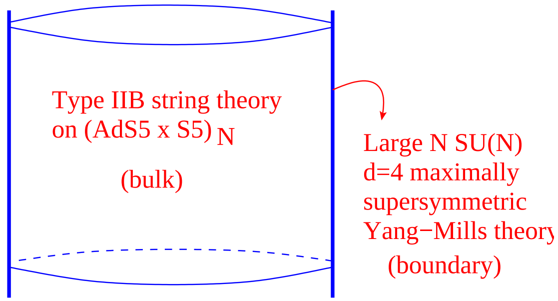
Cosmology, time dependence, ...

- Tempting to think very early Universe has deep repercussions on various aspects of physics.
- Big Bang/Crunch in string theory models? Time in string theory? Good approximations to our Universe ?
- Usually broken spacetime supersymmetry $\Rightarrow$ time dependence. Metastable/unstable stringy vacua (tachyon dynamics etc).

General Relativity breaks down at singularities: want "stringy" description. Smooth quantum (stringy) completion of classical spacetime geometry? E.g. "stringy phases" in $e.g.$ 2-dim worldsheet (linear sigma model) descriptions, dual gauge/Matrix theories, etc.

Note: Big-bang singularities somewhat different from black holes: no horizon cloaking.

AdS/CFT, modes, deformations



Nice stringy playground: AdS/CFT. Bulk string theory on $AdS_5 \times S^5$ with dilaton (scalar) $\Phi = const$, and metric

$$ds^2 = \frac{1}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2) + ds^2_{S^5} \ ,$$

(Poincare coords) with 5-form field strength, dual to boundary $d = 4$ $\mathcal{N}{=}4$ (large N) $SU(N)$ Super Yang-Mills theory.

Deformations of AdS/CFT: either growing towards boundary (non-normalizable) or subleading at boundary (normalizable). These are dual to either sources for or expectation values of CFT operators.

Time-dependent deformations: cosmologies

Start with $AdS_5 \times S^5$ and turn on non-normalizable deformations for the metric and dilaton:

$$ds^2 = \frac{1}{z^2}(\tilde{g}_{\mu\nu}dx^\mu dx^\nu + dz^2) + ds^2_{S^5}\ ,$$

$$\Phi = \Phi(x^\mu)\ , \qquad \text{also nontrivial } 5 - \text{form}\ .$$

This is a solution in string theory if

$$\tilde{R}_{\mu\nu} = \frac{1}{2}\partial_\mu\Phi\partial_\nu\Phi\ , \qquad \frac{1}{\sqrt{\tilde{g}}}\,\partial_\mu(\sqrt{-\tilde{g}}\ \tilde{g}^{\mu\nu}\partial_\nu\Phi) = 0\ ,$$

$i.e.$ if it is a solution to a 4-dim Einstein-dilaton system.

General family of solutions: ($Z(x^m)$ harmonic function)

$$ds^2 = Z^{-1/2}\tilde{g}_{\mu\nu}dx^\mu dx^\nu + Z^{1/2}g_{mn}dx^m dx^n\ , \quad \Phi = \Phi(x^\mu),$$

$g_{mn}(x^m)$ is Ricci flat, and $\tilde{g}_{\mu\nu} = \tilde{g}_{\mu\nu}(x^\mu)$. $[\mu = 0123, m = 4\ldots 9.]$

Time-dependent/Null cosmologies

Spacelike: Consider $\tilde{g}_{\mu\nu}dx^\mu dx^\nu = -dt^2 + \sum_{i=1}^3 t^{(2p_i)}dx^i dx^i$ and $e^\Phi = t^\alpha$. We obtain $e.g.$ Kasner-like cosmologies if $\sum_i p_i = 1\ ,\ \ \frac{\alpha^2}{2} = 1 - \sum_i p_i^2,$ from the R_{tt}, R_{ii}, Φ EOM. Restrictive (more later). Contain $spacelike$ cosmological singularities.

Null: Consider $\tilde{g}_{\mu\nu}dx^\mu dx^\nu = e^{f(X^+)}(-2dX^+dX^- + dx^i dx^i)$, and $\Phi = \Phi(X^+)$ [$X^+ =$ lightlike coord]. These are solutions if

$$\frac{1}{2}(\partial_+\Phi)^2 = \tilde{R}_{++} = \frac{1}{2}(f')^2 - f''\ . \qquad \left(f' = \frac{\partial f}{\partial X^+}\right)$$

Dilaton EOM $\partial_\mu(\sqrt{-\tilde{g}}\,\tilde{g}^{\mu\nu}\partial_\nu\Phi) = 0$ automatically satisfied since $\Phi = \Phi(X^+) \Rightarrow$ infinite family of solutions parametrized by $\Phi(X^+)$. $Null$ singularities here. 8 lightcone supercharges preserved.

Prototypical null example

Consider $e^f = \tanh^2 X^+$

$$ds_5^2 = \frac{1}{z^2}[\tanh^2 X^+(-2dX^+dX^- + dx_2^2 + dx_3^2) + dz^2]$$

$$e^\Phi = g_s \left|\tanh \frac{X^+}{2}\right|^{\sqrt{8}}.$$

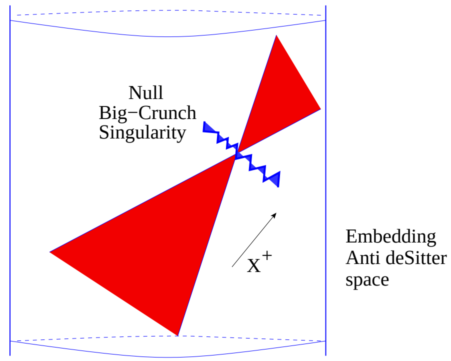
Far past/future: $AdS_5 \times S^5$ with dilaton constant. As $X^+ \to 0$, singularity (at finite affine time) as $e^f \to 0$, with $R_{++} = \frac{4}{\sinh^2 X^+}$. EOM satisfied for $X^+ \neq 0$ and continuous at $X^+ = 0$.

With g_s small, dilaton can be made small everywhere.

Note: only solution with everywhere constant dilaton is $e^f = \frac{1}{(X^+)^2}$, which is flat space $\tilde{g}_{\mu\nu} = \eta_{\mu\nu}$ using

$$x_i = X^+ Y_i, \quad X^- = Y^- - X^+(Y_2^2 + Y_3^2), \quad X^+ = -\frac{1}{Y^+}.$$

Nature of null Big-Bang/Crunch singularity



These contain null Big-Bang (Crunch) cosmological singularities when the transverse space shrinks as $e^f \to 0$, at say $X^+ = 0$. Then curvature along infalling null geodesics ξ^μ diverges

$$\tilde{R}_{ab}\xi^a\xi^b = \tilde{R}_{++}e^{-2f} \to \infty.$$

Diverging compressional tidal forces along infalling null geodesic congruence. Other invariants $R,\ R_{AB}R^{AB}$ etc as in AdS_5.

[Consider $e^f = \tanh^2 X^+$ as limit of $e^f = (|\tanh X^+| + \epsilon)^2$. Then $e^\Phi \sim g_s(\epsilon)^{\sqrt{8}}$. Curvature, affine parameter: continuous, nonsingular.]

The gauge theory duals

Conjecture: Type IIB string theory on these backgrounds dual to $\mathcal{N}=4$ $d=4$ SYM on base space $\tilde{g}_{\mu\nu}$ with time dependent gauge coupling $g_{YM}^2 = e^{\Phi}$.

- Natural extension of AdS/CFT for small perturbations $\delta\Phi,\ \delta g_{\mu\nu}$:
  $$S = \int d^4x \, [\frac{\delta\Phi(x^\mu)}{g_{\rm YM}^2} TrF^2 + \delta g_{\mu\nu} T^{\mu\nu}],$$
  $i.e.$ the dual is $\mathcal{N}=4$ SYM theory with these sources turned on.
- Analyzing the D-probe DBI action corroborates this. Imagine building up this spacetime by stacking D3-branes in a background $ds^2 = \tilde{g}_{\mu\nu} dx^\mu dx^\nu + dx^m dx_m$ and dilaton $\Phi(x^\mu)$. This gives $ds^2 = Z^{-1/2}(x) \tilde{g}_{\mu\nu} dx^\mu dx^\nu + Z^{1/2}(x) dx^m dx_m$, with dilaton and appropriate 5-form. Now take near horizon limit.

$Questions$: Vanishing absorption cross-sections (near singularity)? D-brane boundary states in time-dependent backgrounds ?

The gauge theory duals cont'd.

Reverse question: time-dependent deformations of $\mathcal{N}{=}4$ SYM ? Start in $\mathcal{N}{=}4$ vacuum in the far past; turn on time-dependent gauge coupling and a time-dependent initially flat base space. Gauge theory response ? Well-posed problem: $\Phi, \tilde{g}_{\mu\nu}$ specify gauge theory data completely.

Supergravity dual ? If the dilaton and metric are related by the (IIB) equations earlier, then a sugra dual is straightforward to identify. Nontrivial sources turned on (for operators $TrF^2, T_{\mu\nu}$) are dilaton Φ and metric $\tilde{g}_{\mu\nu}$ $\Rightarrow$ then sugra dual is this deformation of $AdS_5 \times S^5$.

Is the gauge theory $nonsingular$?
Null cosmologies special: gauge theory dual lives on base space $\tilde{g}_{\mu\nu} = e^{f(x^+)}\eta_{\mu\nu}$ conformal to flat space, and has null-time-dependent gauge coupling $g_{YM}^2 = e^{\Phi(x^+)}$.

CFT in conformally flat bgnd

Trace anomaly (ignore time-dep cplg): ${T_\mu}^\mu \propto\ -R_{\alpha\beta}R^{\alpha\beta} + \frac{1}{3}R^2$.

Null cases: only nonzero R_{ab} is $R_{++}\ \Rightarrow\ {T_\mu}^\mu = 0$ for any $f(X^+)$.

Time-varying dilaton effects: only $\partial_+\Phi$ nonzero, no tensor with two (or more) upper $+$ components $\ \Rightarrow\ $ no non-vanishing generally covariant contraction involving Φ-derivatives, and tensors made from metric.

Consider partition function $Z[g_{\mu\nu}] = \int[D\varphi]_{[g_{\mu\nu}]} e^{iS[g_{\mu\nu},\varphi]}, .$

Under Weyl rescalings of metric $g_{\mu\nu} \to e^{\delta\psi} g_{\mu\nu}$, Z changes as

$$\delta \log Z = i\langle \int d^4x\sqrt{-g}\, {T_\mu}^\mu \delta\psi\rangle.$$

Then ${T_\mu}^\mu = 0\ \ \Rightarrow\ \ \partial_\alpha Z[g_{\mu\nu}] = 0\ \ \Rightarrow\ \ Z[e^f\eta_{\mu\nu}] = Z[\eta_{\mu\nu}]$,
along 1-parameter family of metrics $\ g_{\mu\nu} = e^{\alpha f(X^+)}\eta_{\mu\nu},\ \alpha\in[0,1]$.

Correlators: $\ \langle \prod_i e^{\frac{\alpha f(x_i)\Delta_i}{2}} \mathcal{O}(x_i)\rangle_{[e^f\eta_{\mu\nu}]} = \langle \prod_i \mathcal{O}(x_i)\rangle_{[\eta_{\mu\nu}]}$.

Varying coupling effects

For our prototypical example, far past/future state is the $\mathcal{N}=4$ SYM conformal vacuum. In general, time-varying interactions lead to particle production: null backgrounds ?

Consider conformal scalar with null-dependent interaction:
$S = \int d^4x\sqrt{-g}\ \left[\frac{1}{2}(\partial\varphi)^2 + \frac{1}{6}R\varphi^2 + J(X^+)\varphi^3\right].$

Lightcone quantization: modes $e^{-i(k_i x^i + k_- X^- + \frac{k_i^2}{2k_-}X^+)}$ are positive frequency ($k_+ = \frac{k_i^2}{2k_-} > 0$) w.r.t. $X^+ \Rightarrow k_- \geq 0$.

Mode expanding in the free theory gives

$\varphi = e^{-\frac{f}{2}}\int d^2k \int_0^\infty \frac{dk_-}{\sqrt{(2\pi)^3 2k_-}}\ [a_k e^{-i(k_i x^i + k_- X^- + \frac{k_i^2}{2k_-}X^+)} + \text{c.c.}]$

Conformal vacuum: $a(k_i, k_-)|0\rangle = 0$.

General caveat: possible subtleties in $k_- = 0$ sector.

Varying coupling effects cont'd

- Vacuum of the non-interacting theory remains unchanged with a null-dependent source $\Rightarrow$ no particle production.
  Essentially, final interaction picture state
  $|s\rangle = T_+ e^{-i\int d^4x\ e^{2f(X^+)} J(X^+)\ \varphi^3} |0\rangle$ remains unchanged.
  Physically: analogous to space-varying source. X^--translation invariance means P_- conserved since source $J(X^+)$ does not break this symmetry. $Caveat$: $k_- = 0$ subtleties.

- In perturbation theory in source $J(X^+)$, correlators with interaction $\int d^4X e^{\frac{f}{2}} J(X^+) e^{\frac{3f}{2}} \varphi^3(X)$ related to free correlators, and thus to flat space $dressed$ correlators.
  Operator $\mathcal{O}(x)$ of conformal dimension Δ dressed as $e^{\frac{f\Delta}{2}}\mathcal{O}(x)$.
  For source $J(X^+)$ coupling to $\mathcal{O}(x)$, interaction damped if $J(X^+) e^{\frac{4-\Delta}{2} f(X^+)} \to 0$ as $X^+ \to 0$.

Field redefinitions: toy scalar

With varying coupling, kinetic terms of gauge fields are nontrivial.
Want redefinition to new variables with canonical kinetic terms.

$Toy\ model$: scalar field $\int d^4x\, e^{-\Phi(X^+)}(\partial\varphi)^2$. Redefine $\varphi = \epsilon(x)\tilde{\varphi}$:
$\int d^4x\, e^{-\Phi}\, \eta^{\mu\nu} \left(\epsilon^2\partial_\mu\tilde{\varphi}\partial_\nu\tilde{\varphi} + \epsilon\partial_\mu\epsilon\partial_\nu(\tilde{\varphi}^2) + (\partial_\mu\epsilon\partial_\nu\epsilon)\tilde{\varphi}^2\right)$.
Now $\epsilon(x) = e^{\Phi(X^+)/2} \Rightarrow$ first term canonical kinetic term.
ϵ null $\Rightarrow$ (i) third term vanishes, (ii) second term is total derivative
$\partial_+(\epsilon^2)\partial_-(\tilde{\varphi}^2) = \partial_-[\partial_+(\epsilon^2)\tilde{\varphi}^2]$, drop.

Consider $interactions$:
$-\int d^4x\, e^{-\Phi(X^+)}[(\partial\varphi)^2 - \lambda\varphi^4] \ \rightarrow\ -\int d^4x[(\partial\tilde{\varphi})^2 - \lambda e^{\Phi(X^+)}\tilde{\varphi}^4]$.

$\Rightarrow \tilde{\varphi}$-variables have canonical kinetic terms. $e^\Phi \rightarrow 0$ as $X^+ \rightarrow 0 \Rightarrow$
$\tilde{\varphi}$-interaction damped $\Rightarrow$ nonsingular S-matrix. Theory well-defined, transparent in $\tilde{\varphi}$-variables used to define asymptotic states.

$\mathcal{N}$=4 SYM: the tilde variables

$\mathcal{N}$=4 SYM: near singularity, $e^{\Phi} \to 0$, so kinetic terms singular: want well-defined variables $\int e^{-\Phi} \mathrm{tr} F^2 + \ldots \to \int \mathrm{tr} \tilde{F}^2 + \ldots$

For simplicity, work in lightcone gauge $A_- = 0$ (and flat metric). Define $\tilde{A}_\mu = e^{-\Phi/2} A_\mu$. Then $S_{\rm GF} = -\frac{1}{4} \int d^4x\, e^{-\Phi}\, \mathrm{Tr}[F_{\mu\nu} F^{\mu\nu}] \to$

$$- \int \frac{d^4x}{4} \left[\, \mathrm{Tr}(\partial_\mu \tilde{A}_\nu - \partial_\nu \tilde{A}_\mu)^2 - 2ie^{\Phi/2} \mathrm{Tr}\{(\partial_\mu \tilde{A}_\nu - \partial_\nu \tilde{A}_\mu)[\tilde{A}^\mu, \tilde{A}^\nu]\} \right.$$
$$\left. - e^{\Phi} \mathrm{Tr}([\tilde{A}_\mu, \tilde{A}_\nu])^2 - \partial_- \{(\partial_+ \Phi) \tilde{A}_i \tilde{A}^i\}\, \right]$$

Last term total derivative, does not affect EOM.

Other interaction terms containing the dilaton (coupling):

$\int d^4x [e^{\frac{\Phi}{2}} J^{\mu a} \tilde{A}_{\mu a} + e^{\Phi} \mathrm{Tr}([\tilde{A}_\mu, \phi^\alpha][\tilde{A}^\mu, \phi^\alpha]) + e^{\Phi} \mathrm{Tr}([\phi^\alpha, \phi^\beta][\phi^\alpha, \phi^\beta])]$,

where $J^{\mu a}$ is the gauge current from scalars ϕ^α and fermions.

Note: Dilaton couples with positive powers.

$\mathcal{N}=4$ SYM tilde variables cont'd.

We have imposed $A_- = 0$ gauge: A_+ nondynamical (also therefore $\tilde{A}_+$). The A_- EOM gives a constraint $\partial_-(\partial \cdot A) = 0$, $i.e.$ $k_-(-k_- A_+ + k_i A^i) = 0$. Thus if $k_- \neq 0$, then $-k_- A_+ + k_i A^i = 0$. Now solve for A_+ in terms of A_i , $i.e.$ $A_+ = \frac{1}{k_-}(k_i A_i)$.

Note: $\partial_-(\partial \cdot A) = 0$ means $\partial \cdot A = F(X^+, x^i)$. Residual X^--independent gauge transformations $A'_\mu = A_\mu + \partial_\mu \lambda,\ \mu \neq X^-$, can be used to fix $\partial \cdot A = 0$, for $k_- \neq 0$.
Thus for $k_- \neq 0$ modes, we can fix gauge completely $\Rightarrow$ A_+, A_i are gauge-invariant.
In a general gauge: $\tilde{A}_\mu = e^{-\Phi/2}(A_\mu + \partial_\mu \chi)$, where $\chi = -\partial_-^{-1} A_-$ is uniquely defined if $k_- \neq 0$.

$Caveat$! $k_- = 0$ subtleties of lightcone gauge.

Tilde variables cont'd.

Curved metric $\tilde{g}_{\mu\nu} = e^f \eta_{\mu\nu}$: Dilaton couples to dimension $\Delta = 4$ operators, so no dressing factors since dressed source is $Je^{\frac{4-\Delta}{2}f}$.

Interaction terms are of the form $e^{k\Phi(X^+)}\mathcal{O}(x)$. From earlier arguments, $e^{\Phi(X^+)}$ is a lightlike source $\Rightarrow$ no particle production. Dilaton couples with positive powers $\Rightarrow$ all interactions die out when the dilaton vanishes. Thus as $X^+ \to 0$, the $\tilde{A}$ theory is becoming free.

Thus the gauge theory appears nonsingular.

On dual variables

Bulk side: for operator $\mathcal{O}$ dual to bulk scalar ($e.g.$ dilaton), bulk 2-pt fn $\langle e^{\frac{f(x)\Delta}{2}} O(x) e^{\frac{f(x')\Delta}{2}} O(x')\rangle = e^{\frac{f(x)(\Delta-1)}{2}} e^{\frac{f(x')(\Delta-1)}{2}} (\frac{\Delta\lambda}{\Delta X^+})^{1-\Delta} \frac{1}{[(\Delta\vec{x})^2]^\Delta}$.
When $x \sim x'$, then $\frac{\Delta\lambda}{\Delta X^+} \sim \frac{d\lambda}{dX^+} = e^f$ giving $\frac{1}{[(\Delta\vec{x})^2]^\Delta}$.

Breaks down for singular background ($e.g.$ $X^+, X'^+ \rightarrow 0$ ambiguity).

These bulk modes, $e.g.$ dilaton, couple to operators made from A_μ. *Good gauge theory variables*: $\tilde{A}_\mu$. Bulk duals ? Hard to identify clearly. Not all operators made from $\tilde{A}_\mu$ are local in terms of $F_{\mu\nu}$. A complete set of gauge invariant operators must include these.

$\tilde{A}_\mu$ possibly nonlocal, $i.e.$ duals (good bulk variables) are stringy (recall Wilson loop). Also: in usual AdS/CFT, $\alpha' \sim \frac{1}{g_{YM}^2 N} = \frac{1}{e^\Phi N}$. Suggests α' (stringy) effects are important near singularity.

Revisiting the bulk: null case

Our analysis so far suggests gauge theory is nonsingular, living on flat spacetime with time-dependent coupling. Bulk reflection?

Consider coordinate transformation: $w = ze^{-f/2}, \quad y^- = x^- - \frac{w^2 f'}{4}$.

Then bulk $ds^2 = \frac{1}{z^2}(e^f \eta_{\mu\nu} dx^\mu dx^\nu + dz^2)$ becomes

$$ds^2 = \frac{1}{w^2}[-2dx^+ dy^- + dx_i^2 + \frac{1}{4}(\Phi')^2 w^2 (dx^+)^2] + \frac{dw^2}{w^2} \ ,$$

using $\frac{1}{2}(f')^2 - f'' = \frac{1}{2}(\Phi')^2$, the constraint on these solutions.

Now boundary at $w = 0$ manifestly flat 4D Minkowski spacetime. This gives further evidence that the gauge theory is in fact sensible.

These are $finite$ Penrose-Brown-Henneaux (PBH) transformations: subset of bulk diffeomorphisms leaving metric invariant (in Fefferman-Graham form), acting as Weyl transformation on boundary.

Revisiting bulk, cont'd

Note that the conformal factor e^f does not appear at all. This recasting of the bulk metric in terms of an arbitrary dilaton function Φ is useful. For example, in the earlier formulation, the constraint forced the dilaton to be non-analytic ($e.g.\ e^\Phi = |\tanh(\frac{x^+}{2})|^{\sqrt{8}}$) if the conformal factor were analytic ($e.g.\ e^f = (\tanh(x^+))^2$) – this is generic.

Since the dilaton is the gauge coupling $g_{YM}^2 = e^\Phi$, one might worry about possible ambiguities in time evolution via analytic continuation past $x^+ = 0$ in the gauge theory.

With the above new coordinates, one can choose the dilaton to be analytic $e.g.\ e^\Phi = (\tanh(x^+))^2$. Then the bulk has a singularity at $x^+ = 0$ but the gauge theory from our earlier arguments appears well-behaved.

Cosmologies with spacelike Big-Bang singularities

We have described cosmologies with null Big-Bang singularities so far.

We will now describe solutions with spacelike Big-Bang singularities.

More restrictive. However in addition to Kasner cosmologies earlier

$$ds^2 = \frac{1}{z^2}\ \left[dz^2 - dt^2 + \sum_{i=1}^3 t^{(2p_i)} dx^i dx^i\right] ,$$
$$e^\Phi = |t|^{\sqrt{2(1-\sum_i p_i^2)}}, \qquad \sum_i p_i = 1 ,$$

we find solutions with boundaries being FRW cosmologies with spacelike Big-Bang singularities, having metric and dilaton

$$ds^2 = \frac{1}{z^2}\ \left[dz^2 + e^{f(t)} \left(-dt^2 + \frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right)\right] ,$$
$$e^{f(t)} = c_1 \sin(2\sqrt{k}\, t) + c_2 \cos(2\sqrt{k}\, t),$$
$$e^\Phi = e^{\sqrt{3}\int dt\ e^{-f(t)}} .$$

$k = 0, \pm 1$ corresponds to flat, spherical or hyperbolic FRW universe.

Spacelike Big-Bangs cont'd

The $k = 0$ case is in fact the symmetric Kasner solution earlier

$$ds^2 = \frac{1}{z^2}\left[dz^2 + \frac{2t}{3}(-dt^2 + dx^i dx^i)\right], \qquad e^{\Phi} = |t|^{\sqrt{3}}\,.$$

Note: the $k = -1$ solution with $e^{f(t)} = \sinh(2t)$ is

$$ds^2 = \frac{1}{z^2}\left[dz^2 + \sinh(2t)\left(-dt^2 + \frac{dr^2}{1+r^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right)\right],$$

$$e^{\Phi} = |\tanh t|^{\sqrt{3}}\,.$$

Thus the dilaton is in fact bounded, approaching constant at early/late times: asymptotic spacetime is $AdS_5 \times S^5$. This gives hope that perhaps these gauge theories admit some interesting description.

Spacelike Big-Bangs cont'd

It is possible to find finite PBH transformations that transform this flat FRW case to a spacetime with flat Minkowski boundary.

For the other cases too, the boundary can be made conformally flat via further coordinate transformations. Then there are PBH transformations here too, not exact, but in an expansion about boundary.

Using these and going to the new coordinates with a flat boundary metric, we can calculate stress tensors using holographic RG tools. These generically diverge near the spacelike Big-Bang singularities.

Open questions

- Work in progress: more detailed understanding of $\mathcal{N}=4$ SYM with this time-dependent coupling, loop amplitudes, etc. Spacelike singularities ?
- What is the bulk resolution of these null singularities ? Stringy physics near these singularities ?

  D-brane dynamics in time-dependent backgrounds ?
- More severe (spacelike) cosmological singularities ? Realistic cosmologies ?