Title: Time and the big bang

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Abstract: The evidence for the big bang is now overwhelming. However, the basic question of what caused the bang remains open. One possibility is that time somehow \'emerged,\' placing the universe in an inflationary state. Another, perhaps more conservative possibility, is that the big bang was a violent event in a pre-existing universe. I will describe model calculations employing the AdS/CFT correspondence which show how this is possible, and which point to a new explanation for the origin of large scale structure in the universe.

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# Time and the Big Bang

Neil Turok, PI

work in progress w/ B. Craps, T. Hertog

* the big question
* AdS/CFT
* Dual description
* Quantum resolution
* Particle creation + backreaction
* GLASSy perturbations
* Outlook + problems

Was the big bang the beginning? ②

YES → seem to require inflation to smooth, flatten universe, generate density variations

NO → inflation not needed, epoch of slow contraction $w \gg 1$ can play the same role
- ekpyrotic/cyclic cosmology

Can we learn something from string theory?

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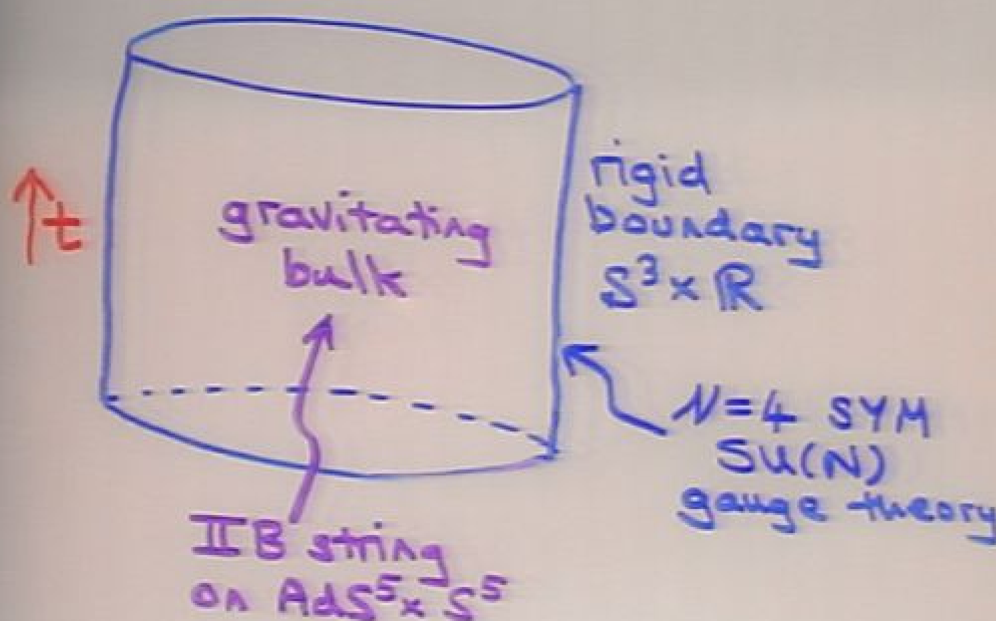
string theory?

AdS/CFT : a powerful tool for quantum gravity (Maldacena, Witten...) 3

conformal picture :




$$g_s \longleftrightarrow \frac{1}{N}$$

$$\left(R_{AdS}\right)^4$$

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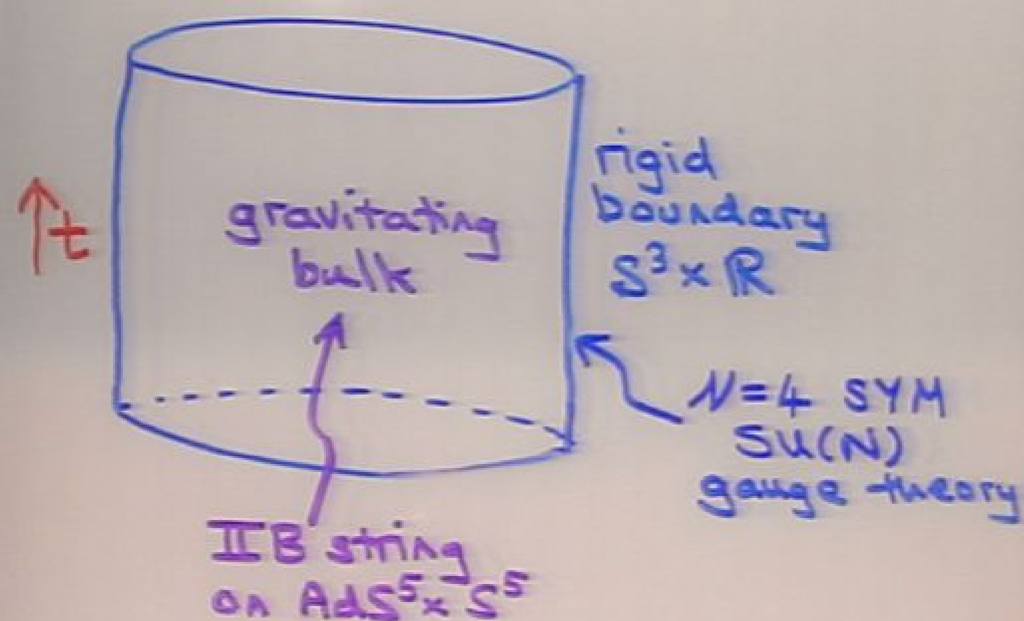


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④

Idea:

bulk cosmology $\leftrightarrow$ boundary dual

Caveat:

dual theory tractable for $g_t \ll 1$.

stringy corrections to Einstein gravity are large in this limit

not yet clear how to extend to $g_t \gg 1$

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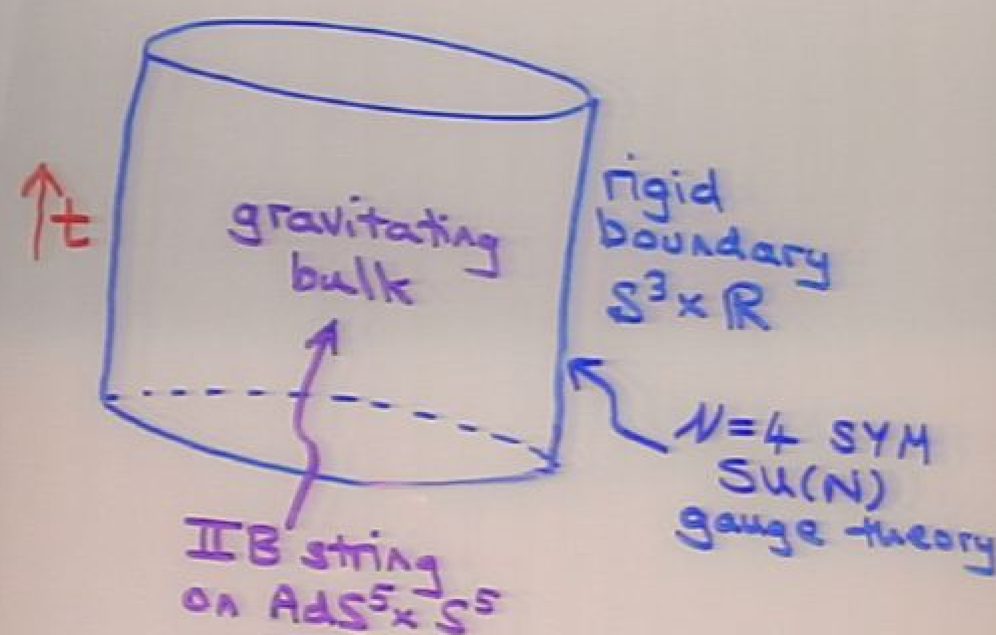


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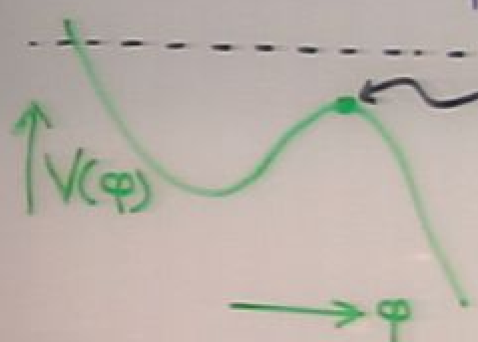
truncate to just one scalar $\varphi$ –

a particular quadrupole dist$^n$ of $S^5$

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<u>just</u> stabilised by SUSY b.c.s

AdS: $ds^2 = R_{AdS}^2\left[-(1+r^2)dt^2 + \frac{dr^2}{1+r^2} + r^2 d\Omega_3^2\right]$

$r \to \infty \qquad \varphi \sim \alpha r^{-2} \ln r + \beta r^{-2}$

$\alpha, \beta$ fns on $\mathbb{R} \times S^3$

SUSY b.c.s $\alpha = 0 \to$ <u>stable</u>

Generalised b.c.s $\alpha = f\beta$, $f > 0 \Longrightarrow$ cosmological dynamics

$\to$ big crunch : what ...?

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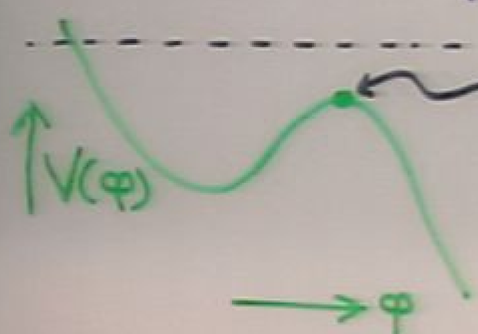


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$\rightarrow$ big crunch : what next? Hertog + Horowitz

Dual theory:

AdS/CFT dictionary

$$\varphi \longleftrightarrow \mathcal{O} = \frac{1}{N} \mathrm{Tr}\left[\Phi_1^2 - \frac{1}{5}\sum_{i=2}^{6} \Phi_i^2\right]$$

$$\beta \longleftrightarrow \langle \mathcal{O} \rangle$$

$$\alpha \longleftrightarrow \text{source for } \mathcal{O}$$

$$S_{SYM} \to S_{SYM} + \int d^4x\, f\, \mathcal{O}^2$$

$$f > 0 \longrightarrow \underline{V \sim -f\phi^4}, \quad \phi^2 \equiv \mathcal{O}$$

General feature:

Cosmological Dynamics $\longleftrightarrow$ Unbounded negative scalar potential

→ no ground state, nevertheless, theory is * perturbatively renormalisable

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* perturbatively renormalisable
* asymptotically free

renormalized potential ⑦

$$V_{ren} \sim -\frac{1}{N^2} \frac{\phi^4}{\ln(\phi^2/M^2)}$$

exact at large N → quantum corrections do not turn potential around.

Can we make sense of this theory?

$V \sim -\lambda\phi^4$ : homogeneous mode on $S^3$, $\bar{\phi}$ runs to infinity in finite time (agrees w/ bulk cosmology for $\alpha, \beta$).

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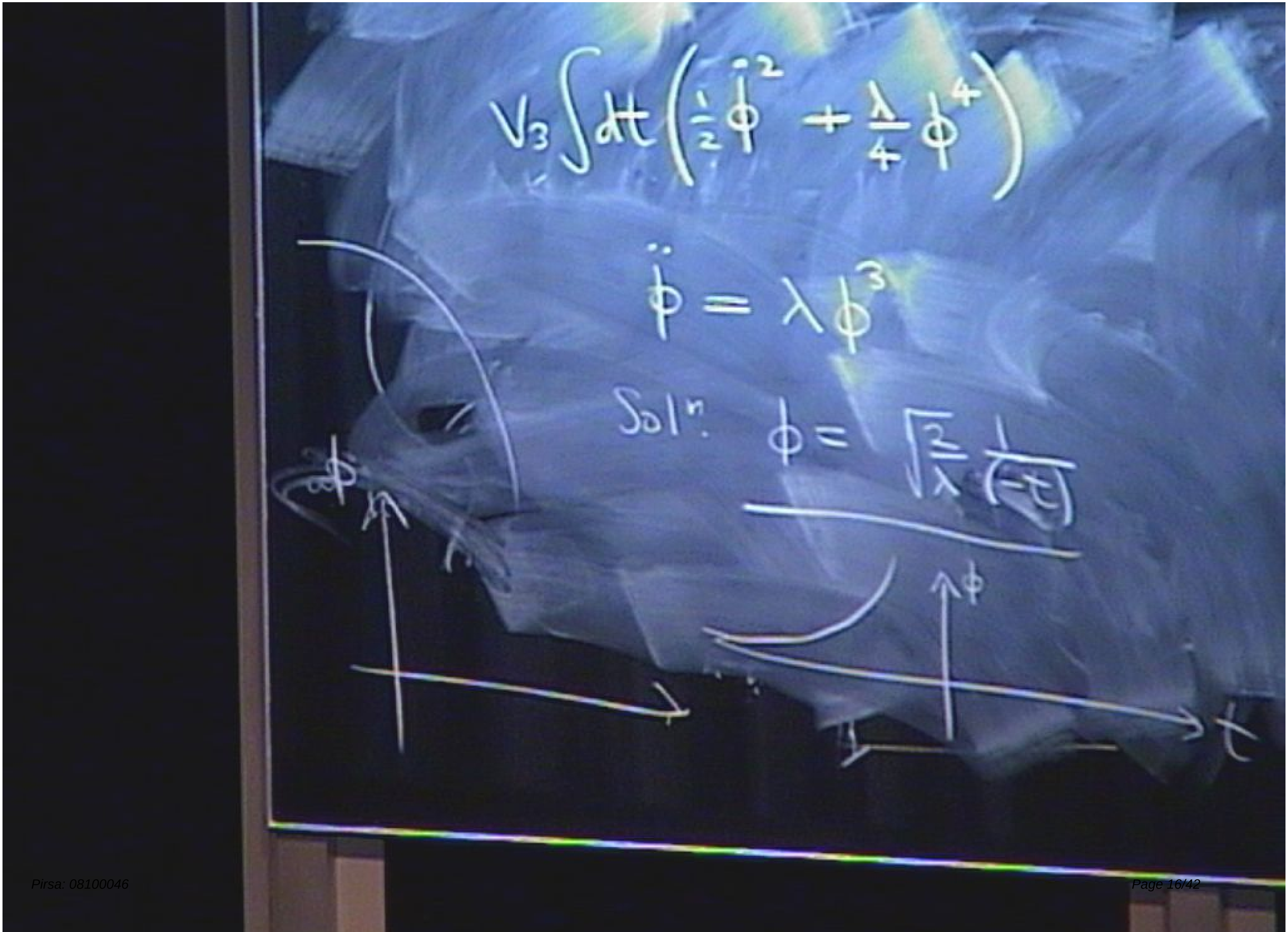
$V_3 \int dt \left( \frac{1}{2}\dot{\phi}^2 + \frac{\lambda}{4}\phi^4 \right)$
$\ddot{\phi} = \lambda \phi^3$
Sol$^n$: $\phi = \sqrt{\frac{2}{\lambda}} \frac{1}{(-t)}$
$\phi$
$t$

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e.g. energy eigenstates

$$\Psi_E^{\pm} \sim \frac{e^{\pm i\sqrt{\lambda}\,\bar{\phi}^3}}{\bar{\phi}}$$

WKB becomes exact as $\bar{\phi} \to \infty$

- Hamiltonian is self-adjoint if restrict Hilbert space to

$$\Psi_E^{+} + e^{i\alpha}\Psi_E^{-},$$

with $\alpha$ independent of $E$.

Key point: spread in wf$^n$ keeps you away from the singularity e.g. energy eigenstates

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Note:

(9)

non-positivity of gravitational KE, $S_{EH} \sim -\int dt\, a\dot{a}^2$

$\Longleftrightarrow$ non-positivity of dual PE

$$S_\phi \sim \int dt \left(\tfrac{1}{2}\dot{\phi}^2 + \lambda\phi^4\right)$$

i.e. negative V

<u>but</u> dual theory has no ordering problems, and role of time is completely conventional

— space is "emergent"

— time is not !

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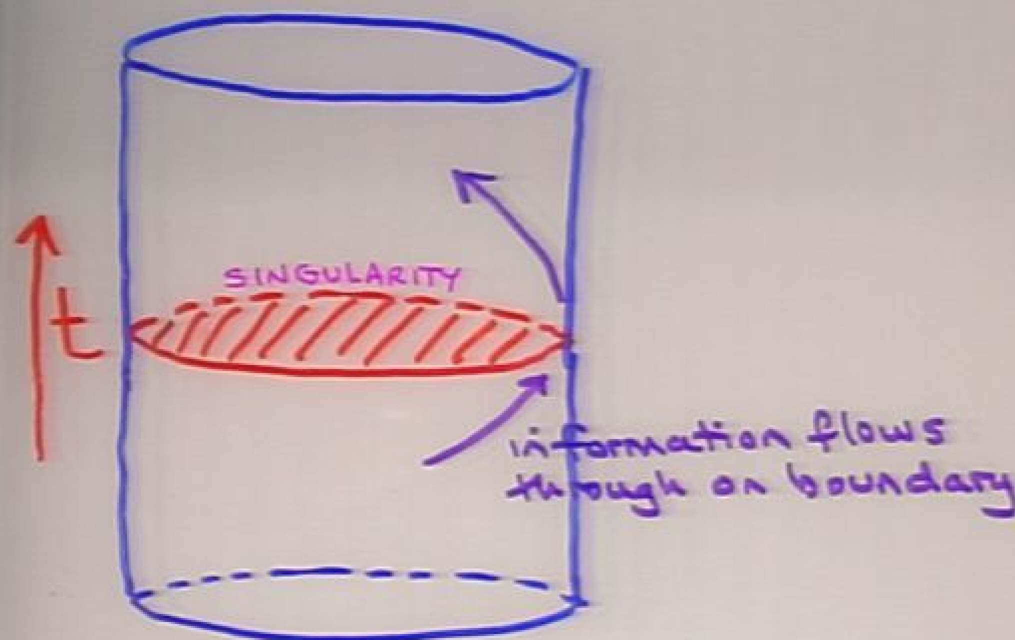
General idea:



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Note': unconventional features

* Field theory has no ground state

* Canonical ensemble doesn't exist

* Expectation values generally ill-defined $\Psi \sim \frac{1}{x}\cos(x^3)$

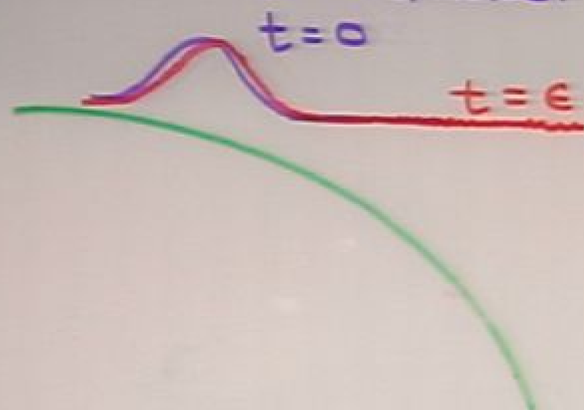
$$\langle x \rangle = \int dx \, \frac{1}{x^2} \cos^2(x^3) \cdot x = \infty \, !$$

Note:

quantum <u>premonition</u>

due to <u>nonlocality</u> (omni-science!)

eg. localised wavepacket




feels singularity at arb'y short times

- the universe knows the singularity is coming!
- <u>have</u> to impose BC there, at <u>all</u> times

Key points

* Semiclassical approx$^n$ becomes exact as $x \to \infty$ $\quad (x = \sqrt{V_3}\,\bar{\phi})$
* Field evolution becomes <u>ultralocal</u> near singularity - spacelike separated points decouple

- these allow us to solve the quantum dynamics of $\phi$.

# Complex Classical Solutions

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Semiclassical ($\hbar$) expansion $\quad \Psi = A e^{iS/\hbar}$ $\quad$ $A, S$ series in $\hbar$

leading order $\quad S = S_{cl}$

$$S_{cl}(x,t) = \int_{t_i, x_i}^{t, x} (p\dot{x} - V)\, dt + \frac{\hbar}{i} \log \Psi(x_i)$$

e.g. Gaussian wpkt

$$x + 2i\frac{pL^2}{\hbar} = x_c + 2i\frac{p_c L^2}{\hbar} \qquad t = t_i$$

$$\left(\rightarrow \Psi \sim e^{ip_c x}\, e^{-(x-x_c)^2/4L^2}\right)$$

$$x = x_f \qquad t = t_f$$

– line in complexified phase space

Note: two limits in which solution is real: $L = 0$ and $L = \infty$

Generically solution is complex

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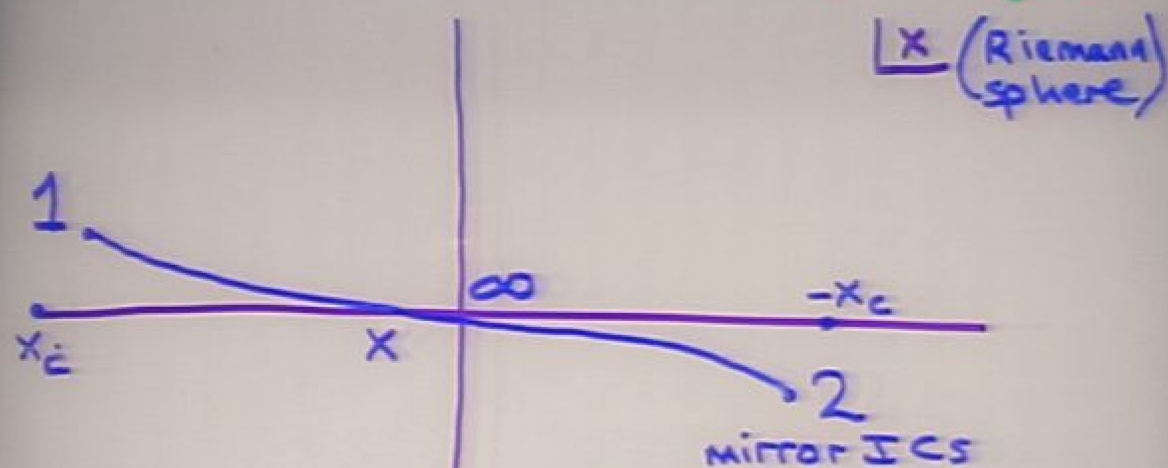
We can implement SA bc at $x \to \infty$ via method of images:

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Symm $x \to -x$ guarantees no flux through $x = \infty$.

13a

$\Rightarrow$

$$\Psi \sim \frac{1}{x}\left( e^{ix^3}\, e^{-¢^2\left(\frac{1}{x}+t\right)^2} + e^{i\alpha}\, e^{-ix^3}\, e^{-¢^2\left(\frac{1}{x}-t\right)^2} \right)$$

Gaussian running past $x=\infty$

$x \to \infty$

Gaussian entering at $x=\infty$

$$¢ = \frac{1}{L t_i^2}\,\frac{1+iL^2/\hbar t_i}{1+6iL^2/\hbar t_i}$$

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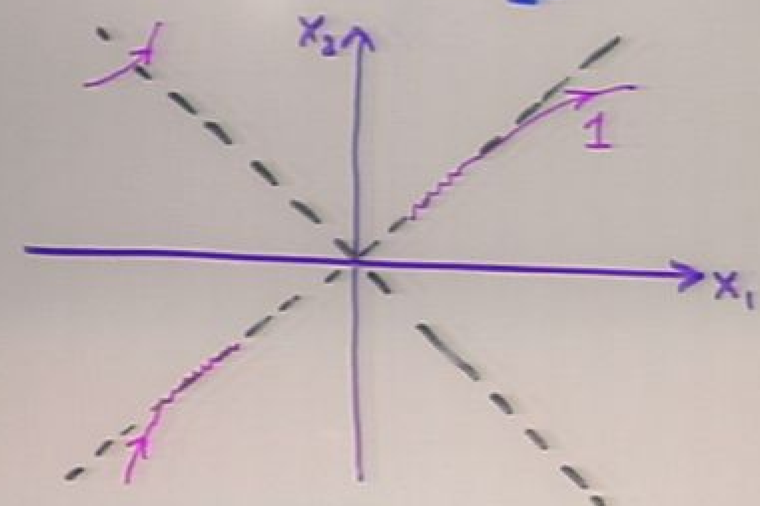
# 2 site model

$$S = \int \tfrac{1}{2}\dot{x}_1^2 + \tfrac{1}{2}\dot{x}_2^2 - \frac{(x_1 - x_2)^2}{\Delta^2} + \lambda x_1^4 + \lambda x_2^4$$




$$\Psi = \Big(A_1 e^{iS_1/\hbar} + \underbrace{e^{i\alpha} A_2 e^{iS_2/\hbar}}_{\text{IC}:\, x_1 \to -x_1}\Big) + e^{i\beta}\Big(\underbrace{A_3 e^{iS_3/\hbar}}_{x_2 \to -x_2} + \underbrace{A_4 e^{iS_4/\hbar}}_{x_1 \to -x_1,\; x_2 \to -x_2}\Big)$$

ignore coupling $\frac{1}{\Delta^2}$ → sat SA bcs exactly

$\frac{1}{\Delta^2}$ small → need to adjust ICs for 2,3 to ensure SA bcs satisfied

Note: new phase for each site: transl^n

2 site model

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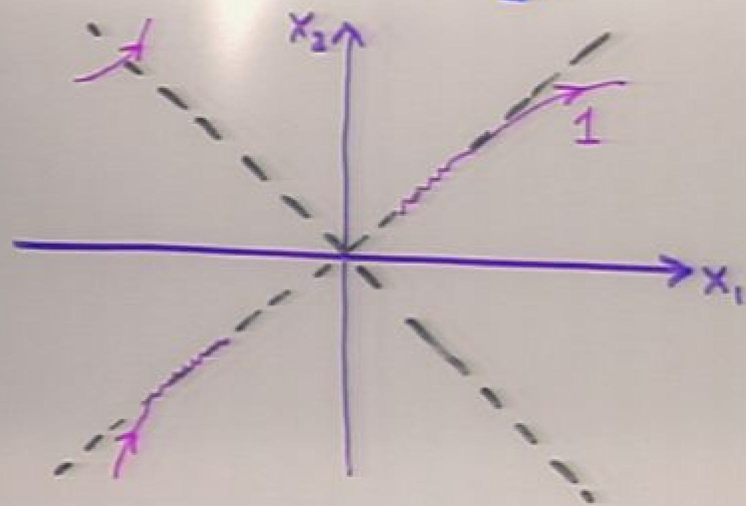


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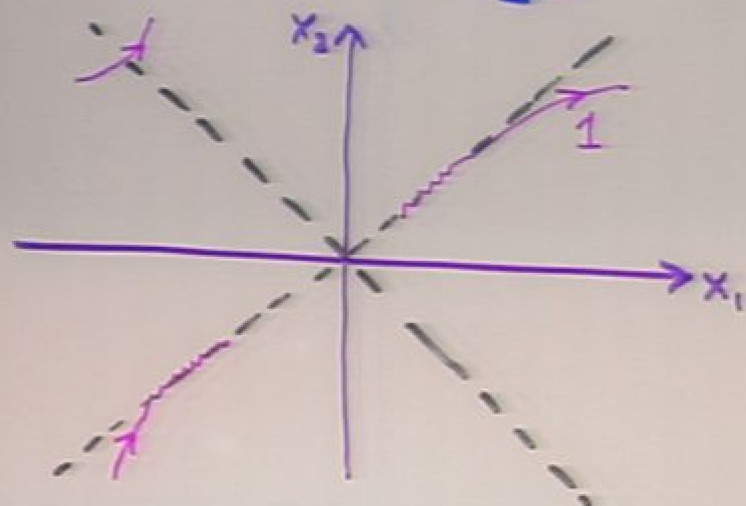


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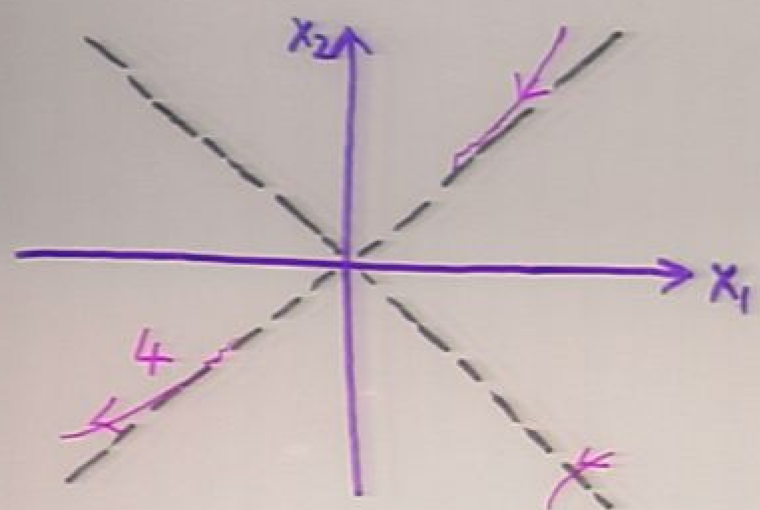
(15)

Upshot: sol$^{n}$ 4 dominates well after the bounce:



# Particle Creation

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homog. mode $\quad \bar{x} = x_1 + x_2$

pert$^n$ $\quad \delta x = x_1 - x_2$

ICs : at $t = t_i$ $\quad \boxed{\bar{x} + 2i\frac{\bar{p}L^2}{\hbar} = x_c + 2i\frac{p_c L^2}{\hbar}}$

– gaussian wpkt centred on $x_c = -\frac{1}{t\sqrt{\lambda}}$

and $\quad \boxed{\delta x + \frac{i}{\omega}\delta\dot{x} = 0} \quad (\omega^2 = 2/\Delta^2)$

– $\delta x$ in its adiabatic vacuum $\quad \delta x \sim e^{i\omega t}$ pos. freq.

$$S = \int \dot{\bar{x}}^2 + \delta\dot{x}^2 + \lambda\bar{x}^4 + \lambda\bar{x}^2\delta x^2 + \lambda\delta x^4 - \frac{2}{\Delta^2}\delta x^2$$

background $\quad \ddot{\bar{x}} = \lambda\bar{x}^3 \rightarrow \bar{x} \sim -\frac{1}{\sqrt{\lambda}(t-i\epsilon)}$ near $t=0$

pert$^n$s $\quad \delta\ddot{x} = \lambda\bar{x}^2\delta x - \frac{2}{\Delta^2}\delta x + o(\delta x^3).\lambda$

$$= \frac{6}{(t-i\epsilon)^2}\delta x - \omega^2\delta x + o(\lambda).$$

$\epsilon$ related to

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$\epsilon$ related to $L, x_f, = 0$ if bg sol$^n$ is real homog. mode $\quad \bar{x} = x_1 + x_2$

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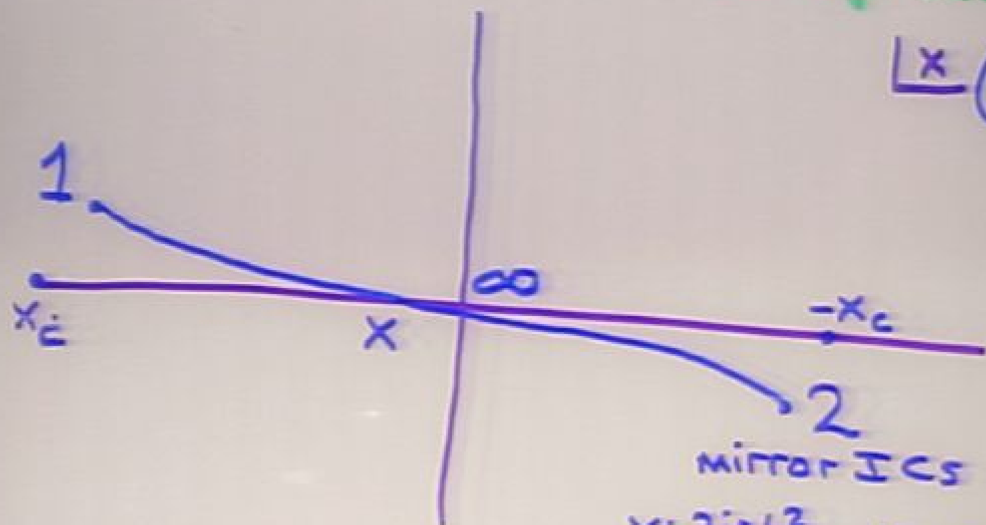
$\underline{\lfloor x}$ (Riemann sphere)




mirror ICs

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# Par.. .cle Creation

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$\epsilon$ related to ... $x_1$ = 0 if bg sol$^n$ is real

(17)

Solution: Hankel : pos. freq in
$\rightarrow$ pos. freq out

$\rightarrow$ no particle production at lowest order !

(cf Tolley +NT)

Full nonlinear treatment:

conclusion remains, particle production very small, back-reaction negligible at small $\lambda$.

— this is a result of the coupling $\lambda$ being constant, in turn a result of classical scale-invariance

BUT: (18)

in QFT for $AdS^5 \times S^5$, $\lambda$ runs

$$\rightarrow \omega^2 = k^2 - \frac{6}{(t-i\epsilon)^2}\left(1 + \frac{5}{12}\frac{1}{\log(Mt)} + o\left(\frac{1}{\log^2}\right)\cdots\right)$$

particle production

Bogoliubov $\beta \sim \frac{1}{\log(k/M)} e^{-2k\epsilon}$

$$\Rightarrow \rho_{particles} \sim \int d^3k \cdot k \frac{1}{\log^2(k/M)} e^{-4k\epsilon}$$

$$\sim \frac{1}{\epsilon^4}\frac{1}{\log^2(k\epsilon)}$$

Est $\epsilon \sim \frac{R_{Ads}}{\sqrt{\log(MR_{Ads})}}$ (minimal sprd wpkt, typical $x_f$)

$\rightarrow \rho_{particles} \sim \frac{1}{R_{Ads}^4}$ c.f $\rho_{class} \sim \frac{\log(MR_{Ads})}{R_{Ads}^4}$

– backreaction small

N-dependence

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$\rho_{\text{pticles}} \sim N^5 \qquad \rho_{\text{class bg}} \sim \lambda^{-1} N^2$

BR small if $\lambda < N^{-3}$, but $V(\phi)$ isnt under control there (yet!)

$V_{1\text{-loop}} \sim \lambda^2 \qquad$ large N corr$^{n}$s $\sim \frac{\lambda g_t^2}{N^2}$ (?)

- can neglect if $g_t^2 < 1/N$, but this is getting further from gravity regime

Models with UV fixed point at $\lambda < 0$ may bounce in a calculable regime

e.g. Dymarsky, Klebanov, Roiban : quiver gauge theories obtained by orbifolding $S^5$

# Origin of Perturbations (20)

Observations: perts are approx:

G aussian
L inear
A diabatic : GLASSy.
S calar
S cale-invariant

– a prediction of simple inflation models, but perhaps more generic?

Here, bulk curvature pert$^{n}$s $\delta h_{\mu\nu}$ are related via AdS/CFT to boundary stress-tensor correlators

$$\langle \delta T_{\mu\nu}(x)\, \delta T_{\rho\lambda}(x') \rangle \text{ etc.}$$

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Straightforward calculations show these are scale-invariant up to log corrections e.g.

$$\langle \delta T_{00}(r,t)\, \delta T_{00}(0,t) \rangle \sim \frac{1}{r^6 t^2} \frac{\ln\left(\frac{1}{\mu t}\right)}{\ln(\mu r)^2}$$

– and slightly red due to asympt. freedom.

Conjecture: observed GLASSy pert$^{n}$s due to asymptotic conformal invariance of dual field theory

# Outlook + Problems

(22)

* AdS/CFT with generalised BCs + deformed dual theory provide a laboratory for studying cosmic sing$^y$'s

* Simplest model doesn't bounce, but more realistic models might → selection on the 'landscape'?

* Need model with UV fixed point – asymptotic conformal invariance

* Need to translate boundary correlators into the bulk

* Need to extend this to large $g_t$