Title: IR effects, semiclassical relations, and perturbative limitations in inflationary spacetimes

Date: Jun 18, 2010 12:15 PM

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Abstract: TBA

the infrared limit...

the infrared limit...

of inflationary spacetimes

IR effects, semiclassical relations, and perturbative limitations in inflationary spacetimes

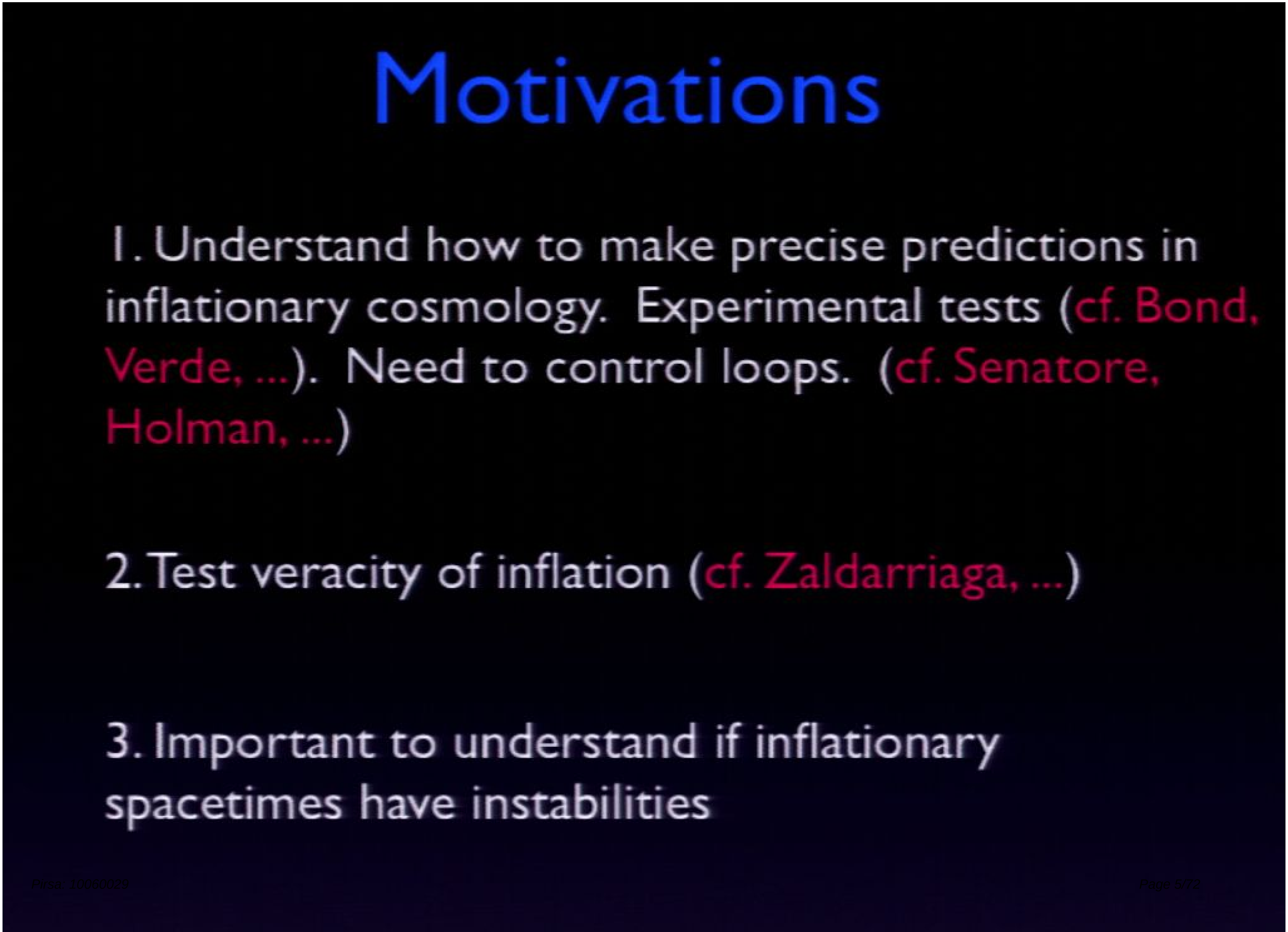
Based on:

arXiv: 1005.1056 "Semiclassical relations and IR effects in de Sitter and slow roll spacetimes,"

arXiv: 1005.3287 "Cosmological diagrammatic rules,"

work in progress

... w/ Martin Sloth



Motivations

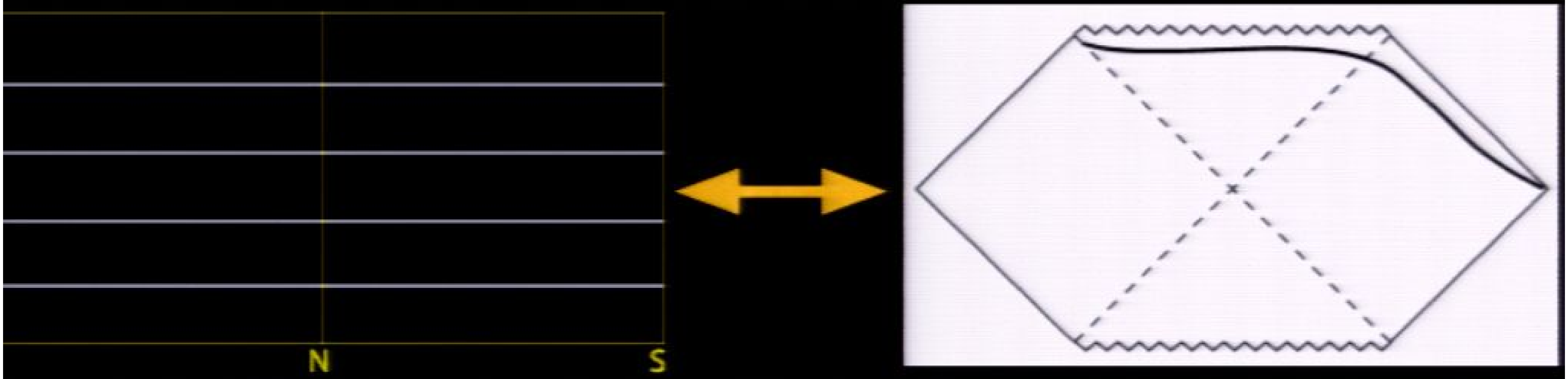
1. Understand how to make precise predictions in inflationary cosmology. Experimental tests (cf. Bond, Verde, ...). Need to control loops. (cf. Senatore, Holman, ...)

2. Test veracity of inflation (cf. Zaldarriaga, ...)

3. Important to understand if inflationary spacetimes have instabilities

Motivations

4. Connections to quantization of black holes

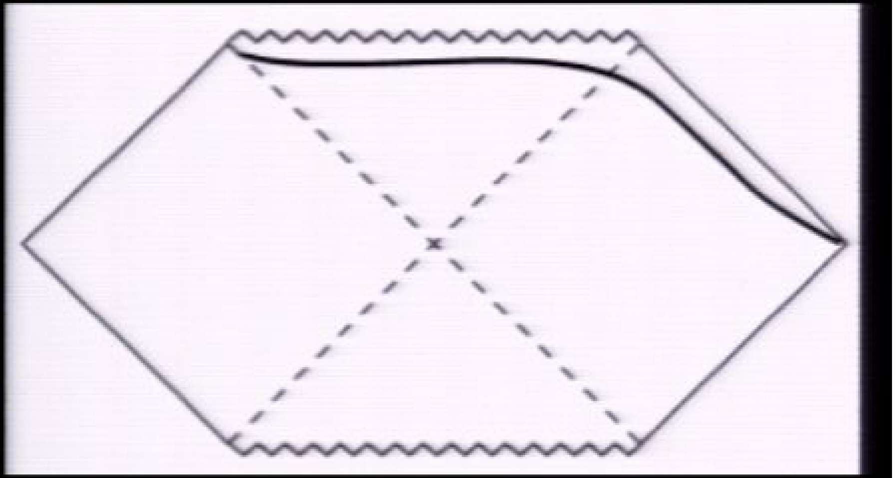


e.g. Arkani-Hamed -String Pheno 2006

SBG hep-th/0703116

Arkani-Hamed et al 0704.1814

The black hole case leads to the "information paradox"



hep-th/0703116 proposal to avoid the contradiction leading to paradox:

nice slice state not well defined (for long times)
(e.g. large fluctuations/perturbative breakdown)

(an information problem would remain: what nonperturbative mechanisms unitarize theory?)

A basic theme

Rapid expansion produces accumulation of long-distance fluctuations of light fields. These can produce large IR contributions -- how do these affect physical quantities?

An essential mechanism

dS: $$ds^2 = -dt^2 + e^{2Ht} dx_3^2$$

(flat slicing throughout)

Consider a massless scalar field:

$$\langle \sigma(x,t) \sigma(x,t) \rangle = \int \frac{d^3k}{(2\pi)^3 2k} \left(\frac{H^2}{k^2} + e^{-2Ht} \right)$$

k - comoving momentum

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usual
UV div

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How is this regulated?

1) Add a mass: $m \ll H$

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$$\langle \sigma^2(x,t) \rangle \to \frac{3H^4}{8\pi^2 m^2}$$ for $t \to \infty$

2) Finite duration inflation

$$\langle \sigma^2(x,t) \rangle = \int_{a_i H}^{aH} \frac{d^3k}{(2\pi)^3 2k} \frac{H^2}{k^2} = \left(\frac{H}{2\pi} \right)^2 2H(t - t_i)$$

largest wavelength

$Ht_i = -\log(\Lambda_{IR})$

True for other light fields:

True for other light fields: e.g. gravity

$$ds^2 = -dt^2 + a^2(t)(dx_3^2 + \gamma_{ij} dx^i dx^j) \qquad a(t) = e^{Ht}$$

TT gauge: $\gamma_{ii} = 0 \qquad \partial_i \gamma_{ij} = 0$

$$\langle \gamma^2(x) \rangle = \frac{1}{4} \langle \gamma_{ij}(x) \gamma_{ij}(x) \rangle = \int \frac{d^3k}{(2\pi)^3 k} \left(\frac{H^2}{k^2} + a^{-2}(t) \right)$$

$$= 2 \langle \sigma^2(x) \rangle$$

... same IR div

(also true for global slicing - Higuchi)

Are these effects physical?

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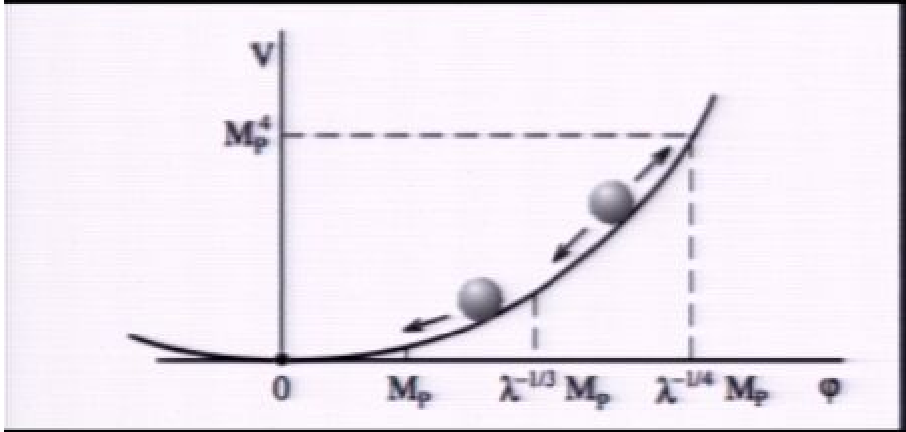
An example - self reproduction:



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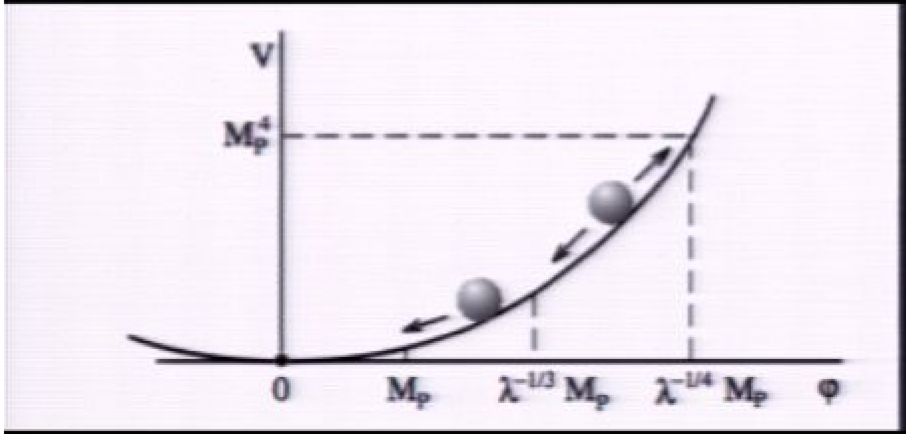
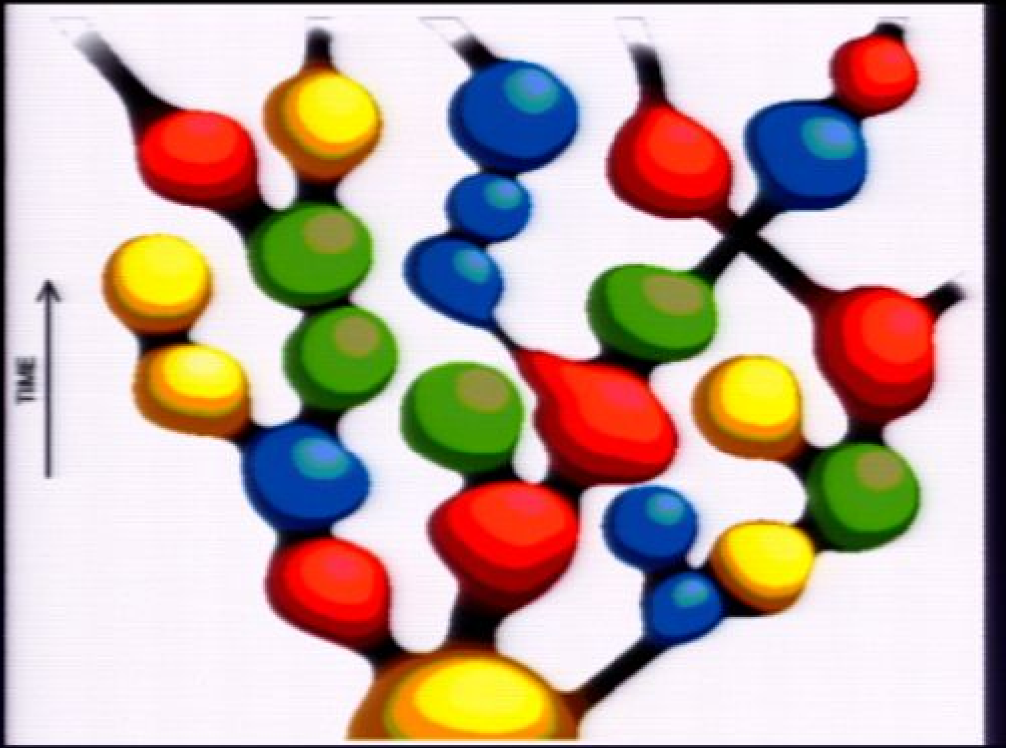


Linde:



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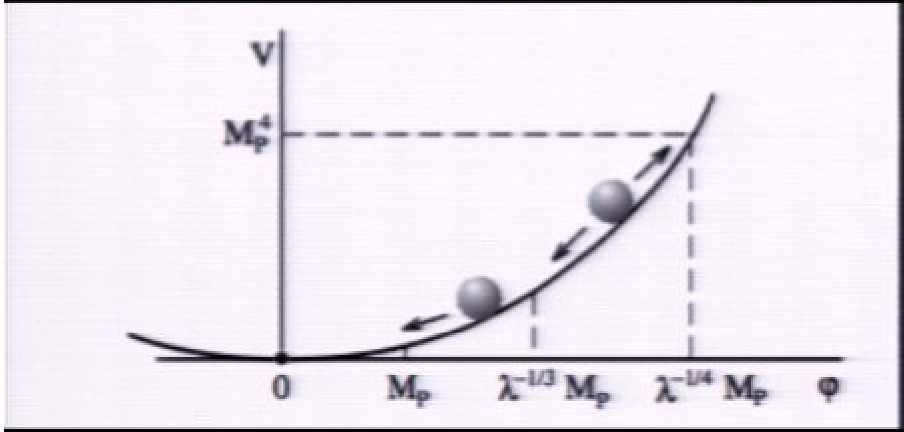

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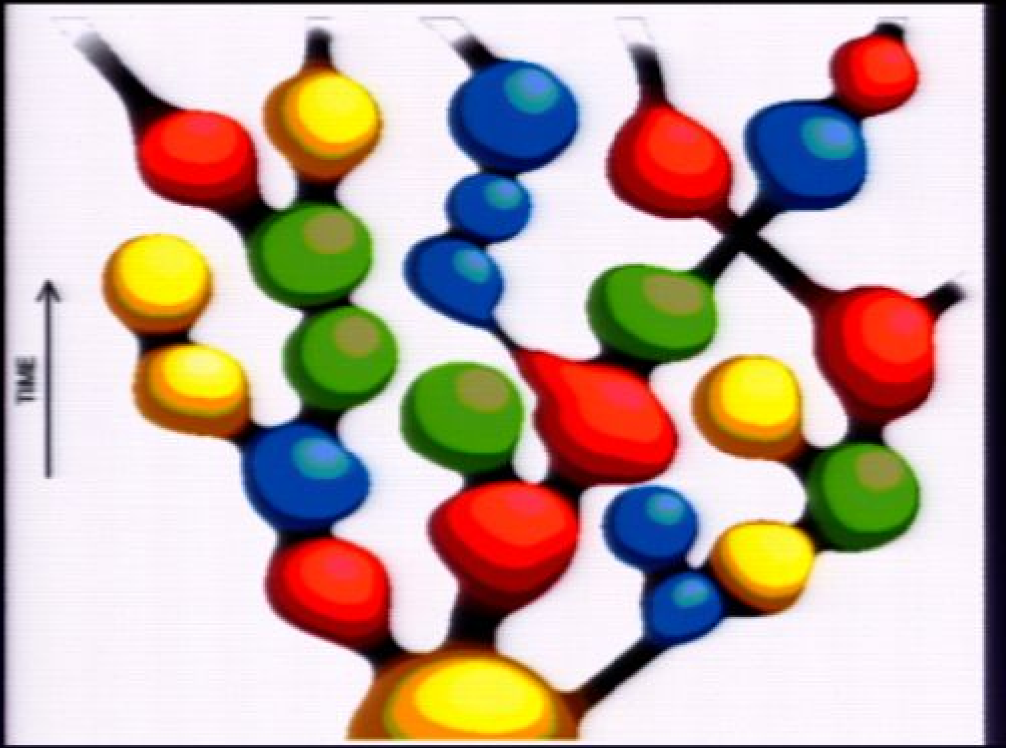

Fluctuations in background get large.

How general is this?

To properly study, need appropriate observables

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No local diff-invt observables in gravity

Relational approach: Leibniz, Einstein, DeWitt, ...

Important puzzle: proper quantum implementation

e.g. in “wavefunction of universe”

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For example, hep-th/0512200 w/ Marolf and Hartle: recover local observables, in an approximation, from “proto-local” observables

Some progress in dS: arXiv: 0705.1178 w/ Marolf

Important puzzle: proper quantum implementation

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serious potential pitfalls: Boltzmann brains, measure paradoxes and quandries ... (c.f. Freivogel, Susskind,...)

Might expect large IR contributions to amplitudes

e.g. loop corrections, trispectrum, ...

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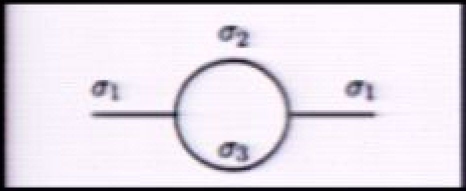
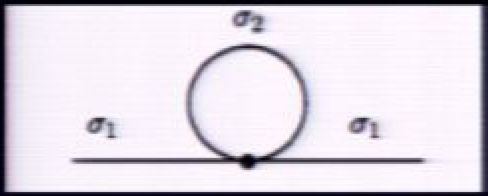
Loops: toy model -- scalars



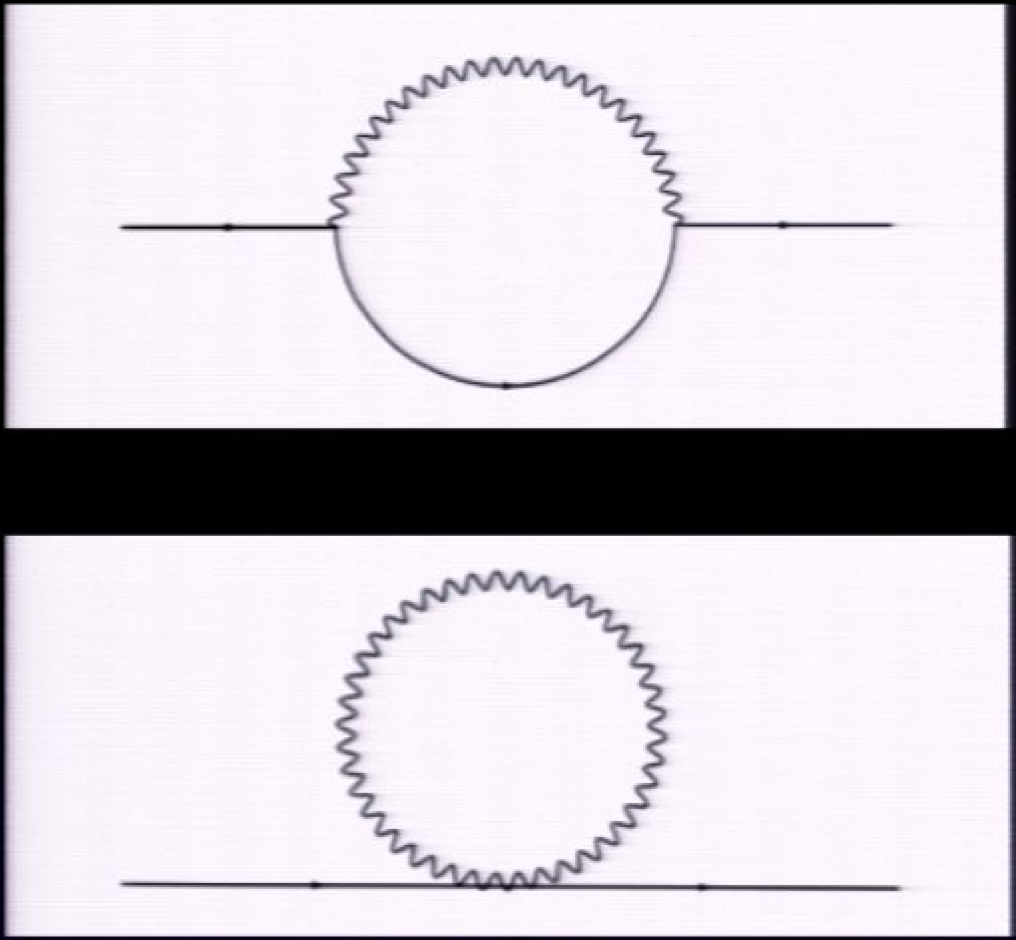
Marolf and Morrison



Burgess et al
(+many others)

More generic: Gravity

e.g.



Calculation: (see e.g. Maldacena, ...)

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1) Action $S = \frac{1}{2}\int \sqrt{-g}\,[R - \partial_\mu\sigma\partial^\mu\sigma - 2\Lambda]$

2) ADM

$$ds^2 = -N^2dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

3) Gauge $h_{ij} = a^2(t)(e^\gamma)_{ij}$ $det(e^\gamma) = 1$

$\partial_i\gamma_{ij} = 0$

Action:

$$S_2 = \frac{1}{2}\int d^3x\,dt\,a^3\left[\frac{1}{4}(\dot{\gamma}_{ij}\dot{\gamma}_{ij} - a^{-2}\partial_k\gamma_{ij}\partial_k\gamma_{ij}) + \dot{\sigma}^2 - a^{-2}\partial_i\sigma\partial_i\sigma\right]$$

$$S_3 = \int d^3x\,dt\,\frac{a}{2}\gamma_{ij}\partial_i\sigma\partial_j\sigma$$

$$S_4 = -\int d^3x\,dt\,\frac{a}{4}\gamma_{il}\gamma_{lj}\partial_i\sigma\partial_j\sigma$$

+... $(\sigma^4\ ,\ \text{etc.})$

Want corrections to in-in correlator, e.g.

$\langle \sigma_{k_1}(t_0)\sigma_{k_2}(t_0)\rangle \quad \sim$

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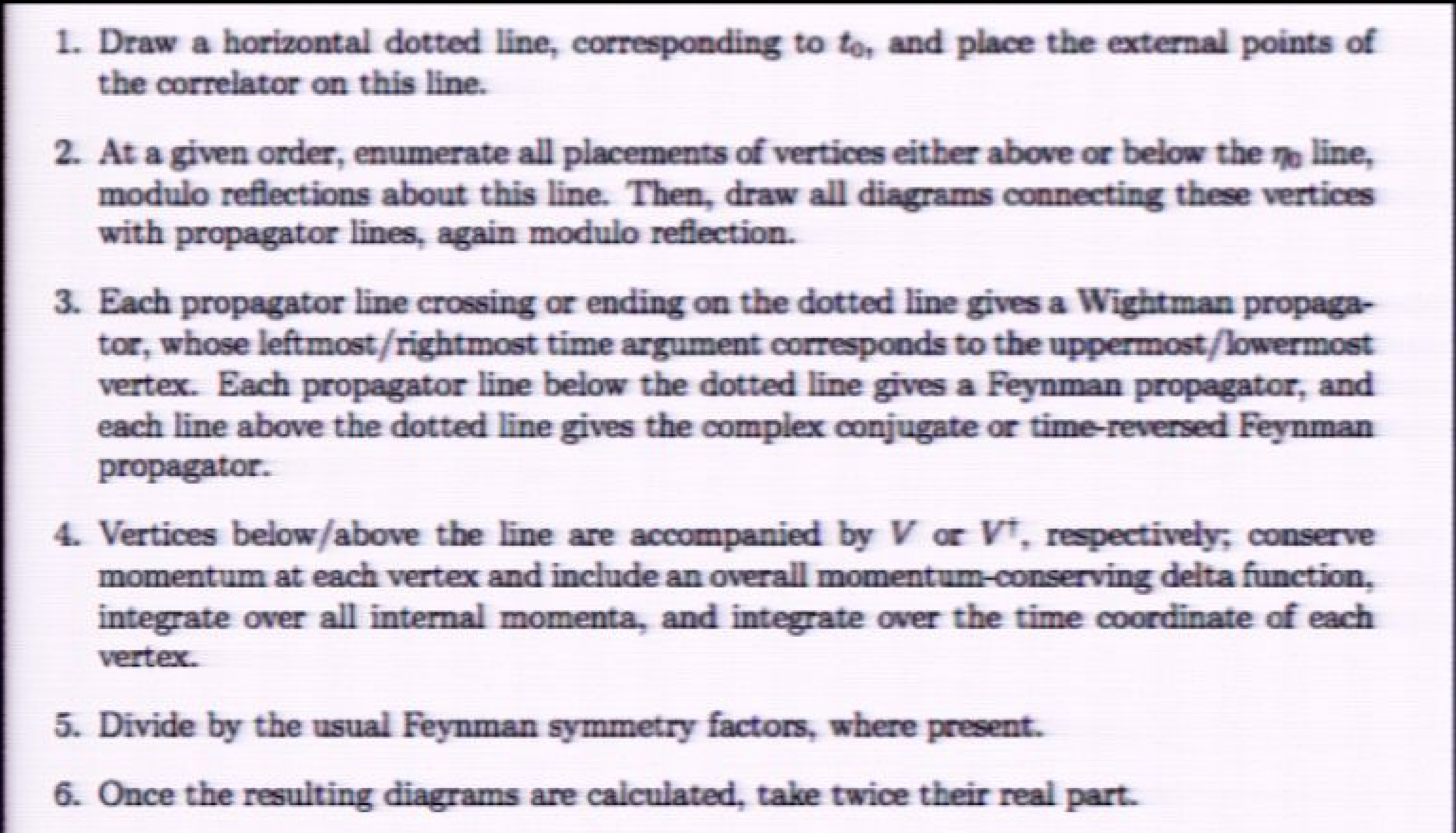
"Cosmological diagrammatic rules:"

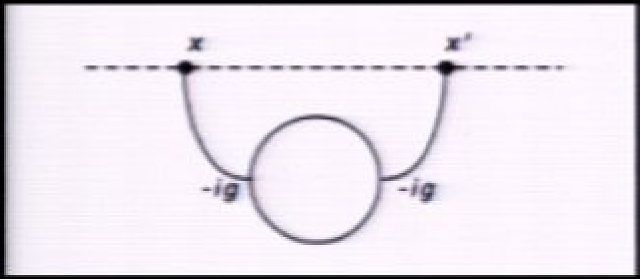
arXiv: 1005.3287



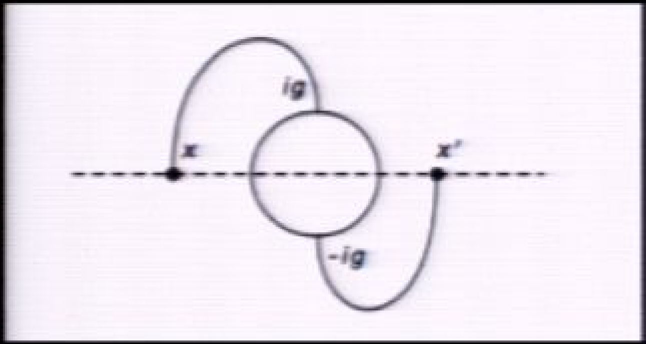
1. Draw a horizontal dotted line, corresponding to t_0, and place the external points of the correlator on this line.
2. At a given order, enumerate all placements of vertices either above or below the η_0 line, modulo reflections about this line. Then, draw all diagrams connecting these vertices with propagator lines, again modulo reflection.
3. Each propagator line crossing or ending on the dotted line gives a Wightman propagator, whose leftmost/rightmost time argument corresponds to the uppermost/lowermost vertex. Each propagator line below the dotted line gives a Feynman propagator, and each line above the dotted line gives the complex conjugate or time-reversed Feynman propagator.
4. Vertices below/above the line are accompanied by V or $V^\dagger$, respectively; conserve momentum at each vertex and include an overall momentum-conserving delta function, integrate over all internal momenta, and integrate over the time coordinate of each vertex.
5. Divide by the usual Feynman symmetry factors, where present.
6. Once the resulting diagrams are calculated, take twice their real part.

Our example: Three diagrams (scalar analogs shown)

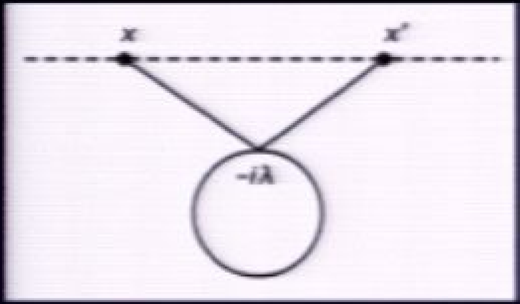
A



B



C



(+... -- not IR divergent)

E.g. results:

$$A_k(\eta) + B_k(\eta) = \frac{H^2}{2k^3}\frac{H^2}{(2\pi)^2}\left[2\log(k/\Lambda_{IR}) + \frac{2}{3}\log(\Lambda_{UV}/k) \right.$$
$$\left. + \frac{101}{90} + \mathcal{O}(k^2\eta^2, \Lambda_{IR}^2, 1/\Lambda_{UV}^2)\right]$$

$$C_k(\eta) = \frac{H^2}{2k^3}\frac{H^2}{(2\pi)^2}\left[2\log(\Lambda_{IR}/\Lambda_{UV}) + \mathcal{O}(k^2\eta^2, \Lambda_{IR}^2, 1/\Lambda_{UV}^2)\right]$$

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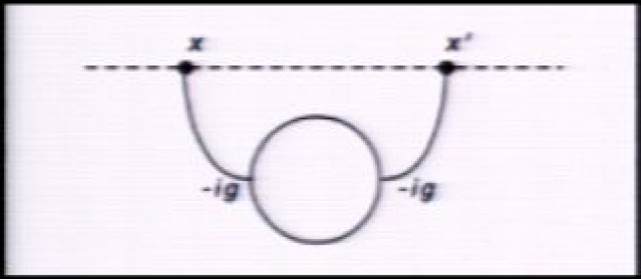

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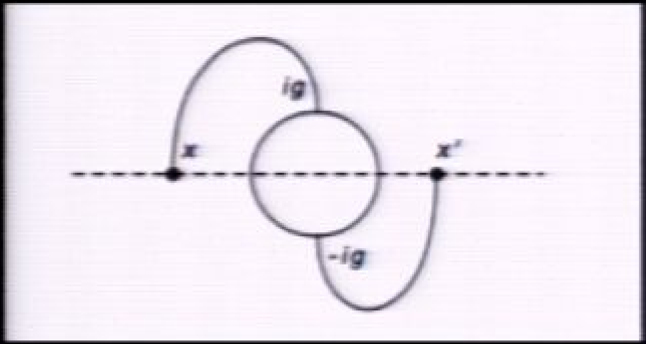

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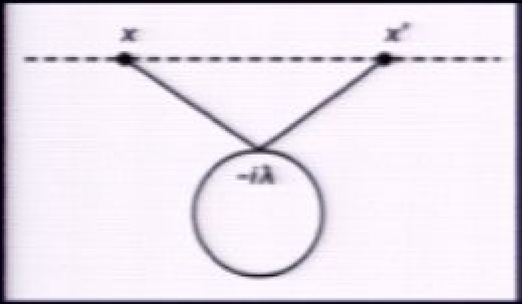

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Calculation hard, even in pure dS, much less slow roll.

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And, can we understand the IR behavior?

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Observation: the long wavelength fluctuations “freeze” and behave ~ classical background

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E.g. consider $\langle \sigma_{k_1} \sigma_{k_2} \rangle_\gamma$ ← "background"

$$k^2 = k_i k_i - k_i (e^{-\gamma})_{ij} k_j = k_i k_i - \gamma_{ij} k_i k_j + \frac{1}{2} \gamma_{il} \gamma_{lj} k_i k_j + \cdots$$

$$\begin{aligned} \langle \sigma_{k_1} \sigma_{k_2} \rangle_\gamma \; &= \; \langle \sigma_{k_1} \sigma_{k_2} \rangle_0 \\ &+ \; \left(-\gamma_{ij} k_i k_j + \frac{1}{2} \gamma_{il} \gamma_{lj} k_i k_j \right) \frac{\partial}{\partial k^2} \langle \sigma_{k_1} \sigma_{k_2} \rangle \Big|_0 + \frac{1}{2} (\gamma_{ij} k_i k_j)^2 \left(\frac{\partial}{\partial k^2} \right)^2 \langle \sigma_{k_1} \sigma_{k_2} \rangle \Big|_0 + \cdots \end{aligned}$$

Next, average over fluctuations:

$$
\begin{aligned}
\left\langle (\sigma_{k_1}\sigma_{k_2})_{\gamma} \right\rangle &= (\sigma_{k_1}\sigma_{k_2}) \\
&+ \frac{1}{2} k_i k_j (\gamma_{ij}\gamma_{ij}) \frac{\partial}{\partial k^2} (\sigma_{k_1}\sigma_{k_2}) + \frac{1}{2} k_i k_j k_k k_l (\gamma_{ij}\gamma_{kl}) \left(\frac{\partial}{\partial k^2}\right)^2 (\sigma_{k_1}\sigma_{k_2})
\end{aligned}
$$

$$\left\langle \langle \sigma_{k_1}\sigma_{k_2}\rangle_\gamma \right\rangle = \langle \sigma_{k_1}\sigma_{k_2}\rangle + \frac{1}{2}k_i k_j \langle \gamma_{il}\gamma_{jl}\rangle \frac{\partial}{\partial k^2}\langle \sigma_{k_1}\sigma_{k_2}\rangle + \frac{1}{2}k_i k_j k_k k_l \langle \gamma_{ij}\gamma_{kl}\rangle \left(\frac{\partial}{\partial k^2}\right)^2 \langle \sigma_{k_1}\sigma_{k_2}\rangle$$

Use:

$$\langle \gamma_{ij}(x)\gamma_{kl}(x)\rangle = \sum_s \int \frac{d^3k}{(2\pi)^3 k}\left[\frac{H^2}{k^2} + a^{-2}(t)\right]\epsilon^s_{ij}(k)\epsilon^{s*}_{kl}(k)$$

$$\Rightarrow \quad \left\langle \langle \sigma_{k_1}\sigma_{k_2}\rangle_\gamma \right\rangle = \left\{1 + \frac{2}{3}\langle \gamma^2(x)\rangle_* \left[\frac{2}{5}k^4\left(\frac{\partial}{\partial k^2}\right)^2 + k^2\frac{\partial}{\partial k^2}\right]\right\}\langle \sigma_{k_1}\sigma_{k_2}\rangle$$

$$\left\langle (\sigma_{k_1}\sigma_{k_2})_\gamma \right\rangle = \langle\sigma_{k_1}\sigma_{k_2}\rangle$$
$$- \frac{1}{2}k_i k_j \langle\gamma_{il}\gamma_{jl}\rangle \frac{\partial}{\partial k^2}\langle\sigma_{k_1}\sigma_{k_2}\rangle + \frac{1}{2}k_i k_j k_k k_l \langle\gamma_{ij}\gamma_{kl}\rangle \left(\frac{\partial}{\partial k^2}\right)^2 \langle\sigma_{k_1}\sigma_{k_2}\rangle$$

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$$\langle\gamma^2(x)\rangle_* \approx -2\frac{H^2}{(2\pi)^2}\log(\Lambda_{IR}/a_* H)$$

Exactly reproduces
IR divergence

Toy example: cf Marolf-Morrison, ϕ^3

(similar exp. for Burgess et al -- cf Holman's talk)

$$\mathcal{L} = -\frac{(\partial\phi)^2 + m^2\phi^2}{2} + \frac{g}{3!}\phi^3 \; ;$$

$$\left\langle (\sigma_{k_1}\sigma_{k_2})_\gamma \right\rangle = \langle \sigma_{k_1}\sigma_{k_2} \rangle - \frac{1}{2}k_i k_j \langle \gamma_{il}\gamma_{jl} \rangle \frac{\partial}{\partial k^2}\langle \sigma_{k_1}\sigma_{k_2} \rangle + \frac{1}{2}k_i k_j k_k k_l \langle \gamma_{ij}\gamma_{kl} \rangle \left(\frac{\partial}{\partial k^2}\right)^2 \langle \sigma_{k_1}\sigma_{k_2} \rangle$$

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$$\mathcal{L} = -\frac{(\partial\phi)^2 + m^2\phi^2}{2} + \frac{g}{3!}\phi^3 \; : \qquad \phi = \varphi + \bar{\phi}$$

"background"

$$\mathcal{L} = -\frac{1}{2}\left[(\partial\varphi)^2 + (m^2 - g\bar{\phi})\varphi^2\right] + \cdots$$

$$\delta\langle\varphi\varphi\rangle_{\bar{\phi}} = \frac{1}{2}g^2\bar{\phi}^2\left(\frac{\partial}{\partial m^2}\right)^2\langle\varphi\varphi\rangle$$

$$\langle\delta\langle\varphi\varphi\rangle_{\bar{\phi}}\rangle = \frac{1}{2}g^2\langle\bar{\phi}^2\rangle\left(\frac{\partial}{\partial m^2}\right)^2\langle\varphi\varphi\rangle \qquad \langle\bar{\phi}^2\rangle \sim \frac{3H^4}{8\pi^2 m^2}$$

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$$\langle\bar{\phi}^2\rangle \sim \frac{3H^4}{8\pi^2 m^2}$$

$$\sim \frac{3g^2H^4}{32\pi^2 m^6}\langle\varphi\varphi\rangle$$

(small m:
large correction!)

Apply to slow roll: $h_{ij} = a^2(t) e^{2\zeta} (e^{\gamma})_{ij}$

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$$\langle\langle \zeta_{k_1}\zeta_{k_2}\rangle\rangle = \langle \zeta_{k_1}\zeta_{k_2}\rangle_0 \left[1 + \frac{1}{2}(n_s-1)^2\langle\zeta^2(x)\rangle_* + \frac{n_s-1}{3}\frac{n_s-1}{5}\langle\gamma^2(x)\rangle_*\right]$$

scalar fluctuations

tensor fluctuations

Apply to slow roll: $h_{ij} = a^2(t)e^{2\zeta}(e^{\gamma})_{ij}$

$$\langle\langle\zeta_{k_1}\zeta_{k_2}\rangle\rangle = \langle\zeta_{k_1}\zeta_{k_2}\rangle_0\left[1+\frac{1}{2}(n_s-1)^2\left\langle\zeta^2(x)\right\rangle_* + \frac{n_s-1}{3}\frac{n_s-1}{5}\left\langle\gamma^2(x)\right\rangle_*\right]$$

scalar fluctuations   tensor fluctuations

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Can give large shifts to: $r \propto \frac{\langle\gamma^2\rangle}{\langle\zeta^2\rangle}$ f_{NL} ...

Large when?

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scalar fluctuations tensor fluctuations

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Can give large shifts to: $r \propto \frac{\langle\gamma^2\rangle}{\langle\zeta^2\rangle}$ f_{NL} ...

Large when? $\langle\gamma^2\rangle \sim H^3 t \sim 1 \quad \Leftrightarrow \quad t \sim 1/H^3$

general dimension: t~RS

(Studying other observables ...)

Can resum/absorb into background?

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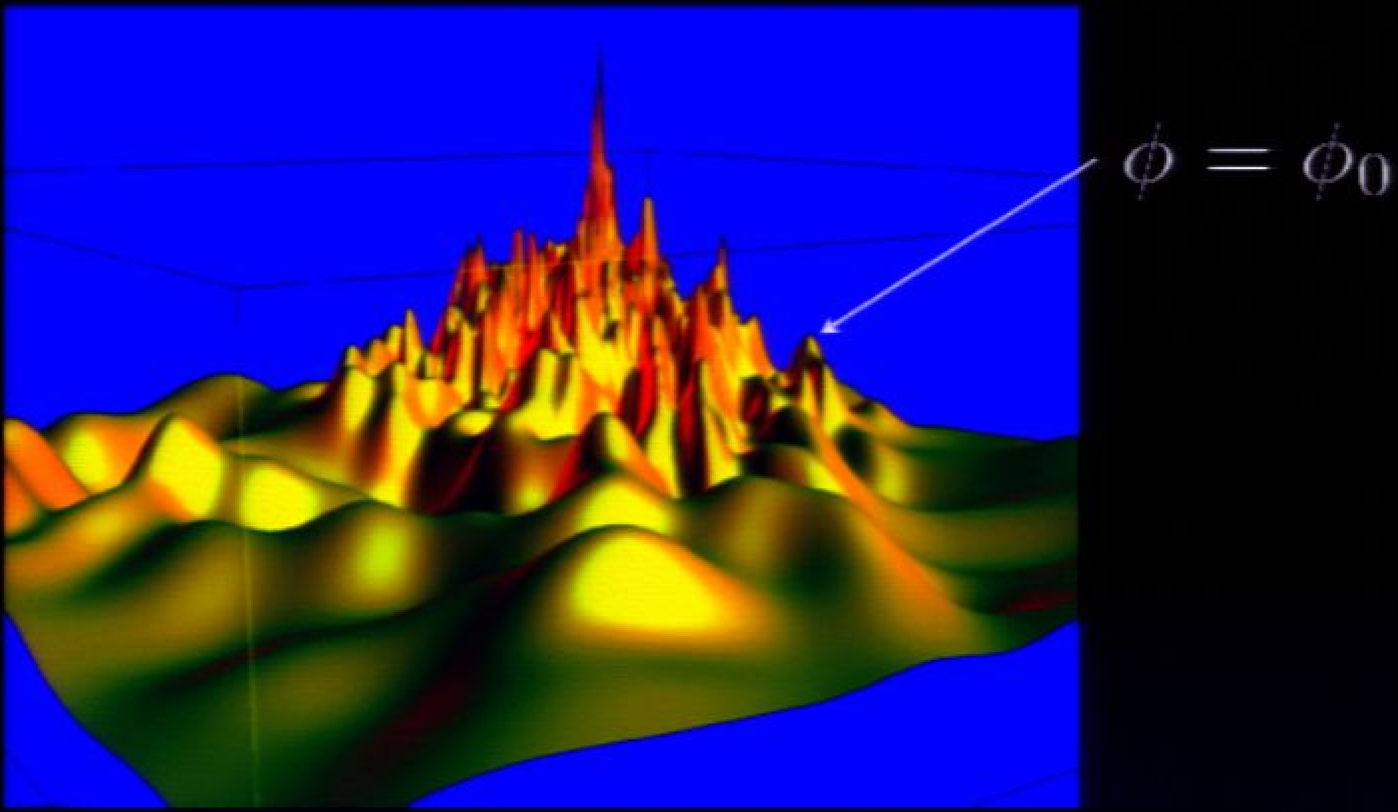
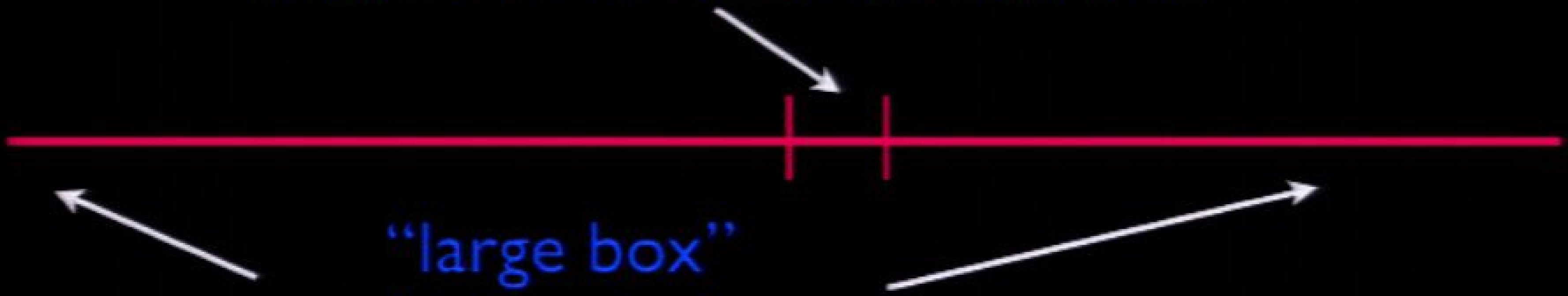
E.g. self-reproducing universe



Expect can make predictions about local observables, with appropriate conditionals ...

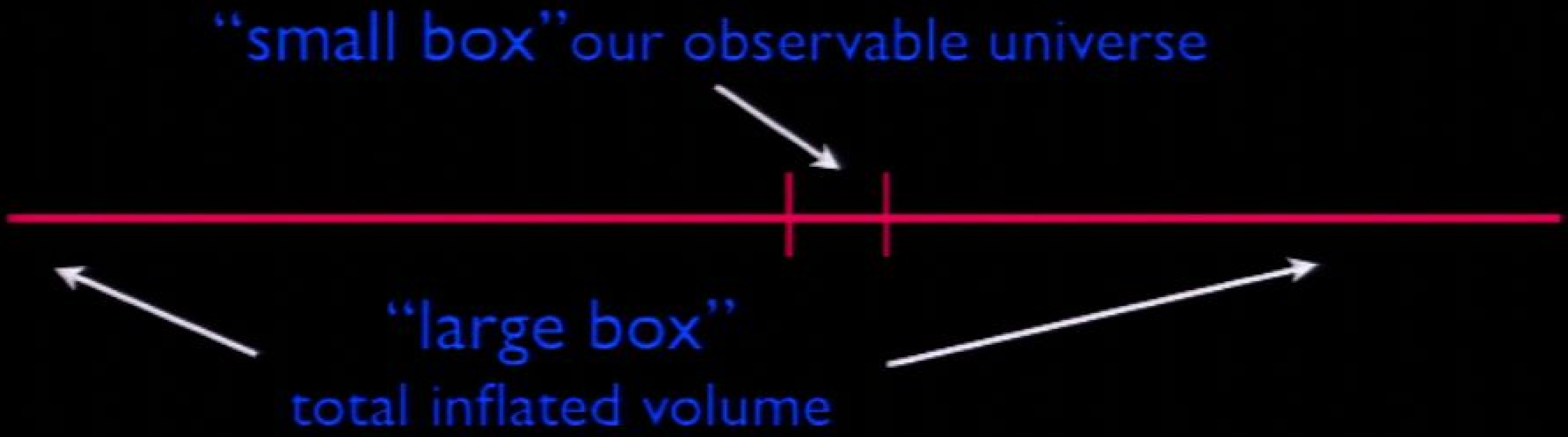
But can one calculate a "wavefunction of the universe"?



“small box”our observable universe

“large box”

total inflated volume



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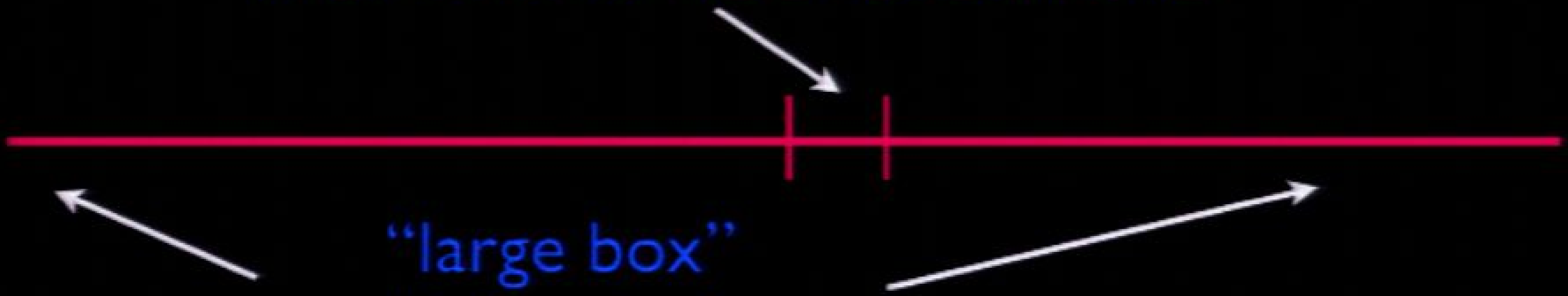
total inflated volume

- plausibly can resum to eliminate large $\langle\zeta^2\rangle$ corrections for observables in small box

(e.g. ~DRG ... Burgess, et al;
δN - Byrnes et al 1005.3307)

small region -- short time



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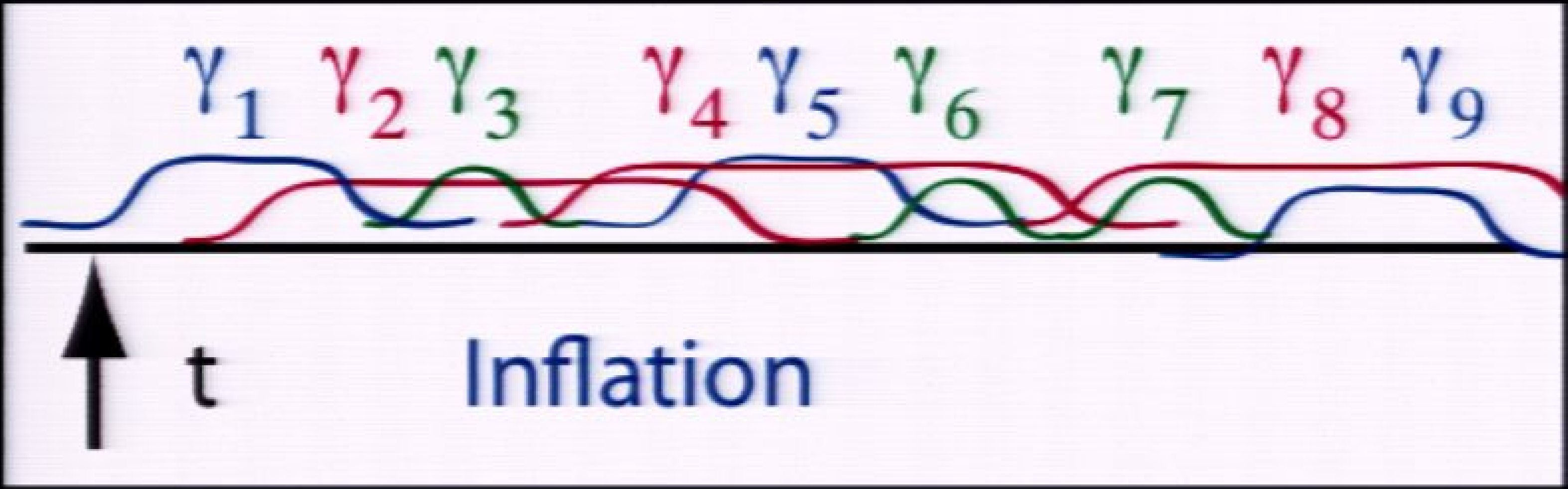
e.g. self-repro regime

stochastic, "Mandelbrot" (c.f. Susskind), $\rho(V)$ (c.f. Senatore)

... capture certain gross features

but: quantum wavefunction of the universe??

have lost perturbative control



$\langle\gamma^2\rangle \propto H^3 t$

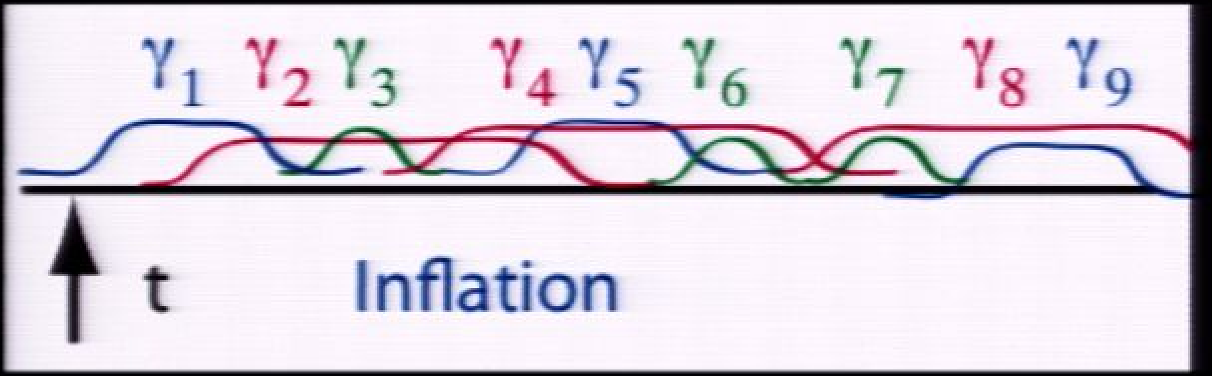
"spacetime foam, writ large"

(cf Masui)

Plausible story (under investigation):

- ~local observables: resum - eliminate large effects
- but globally?? plausibly can't eliminate (instability of dS?)

What observables?



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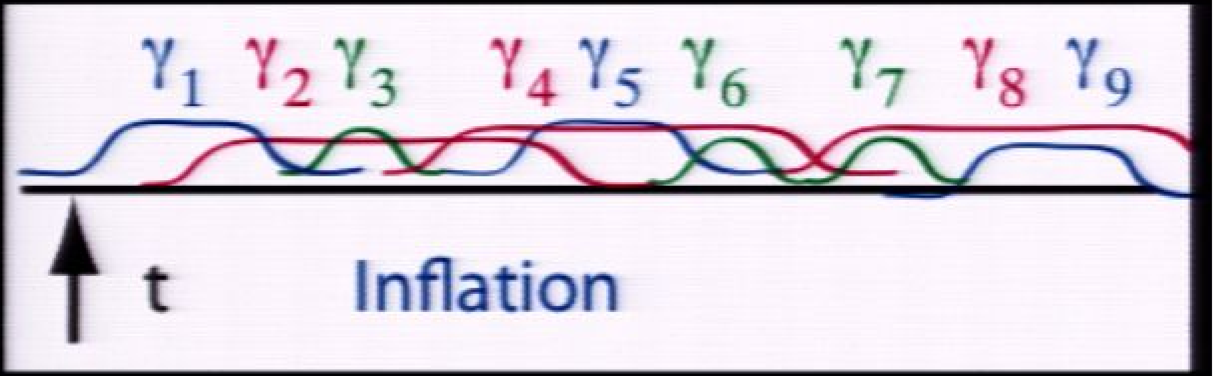

Compare self reproduction: (Creminelli et al -- c.f. Senatore)

$\rho(V)$ $\quad V = \int d^3x\sqrt{h}$ (or: fluctuations in V)

sensitive to ζ fluctuations

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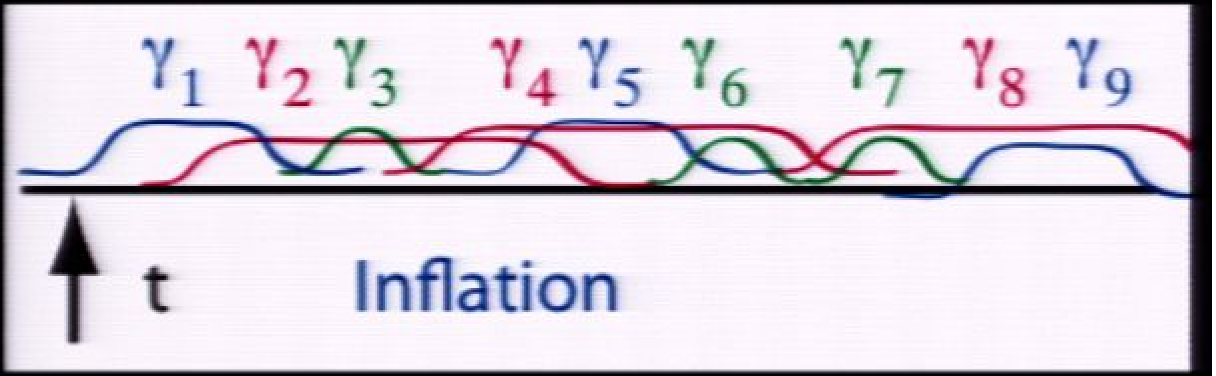

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sensitive to ζ fluctuations

γ fluctuations: volume preserving

So try:

$\int_\Gamma ds$ $\quad \Gamma$:

- Curve between comoving point masses
- Nontrivial holonomy -- e.g. on T^3

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t~RS (possibly times couplings)

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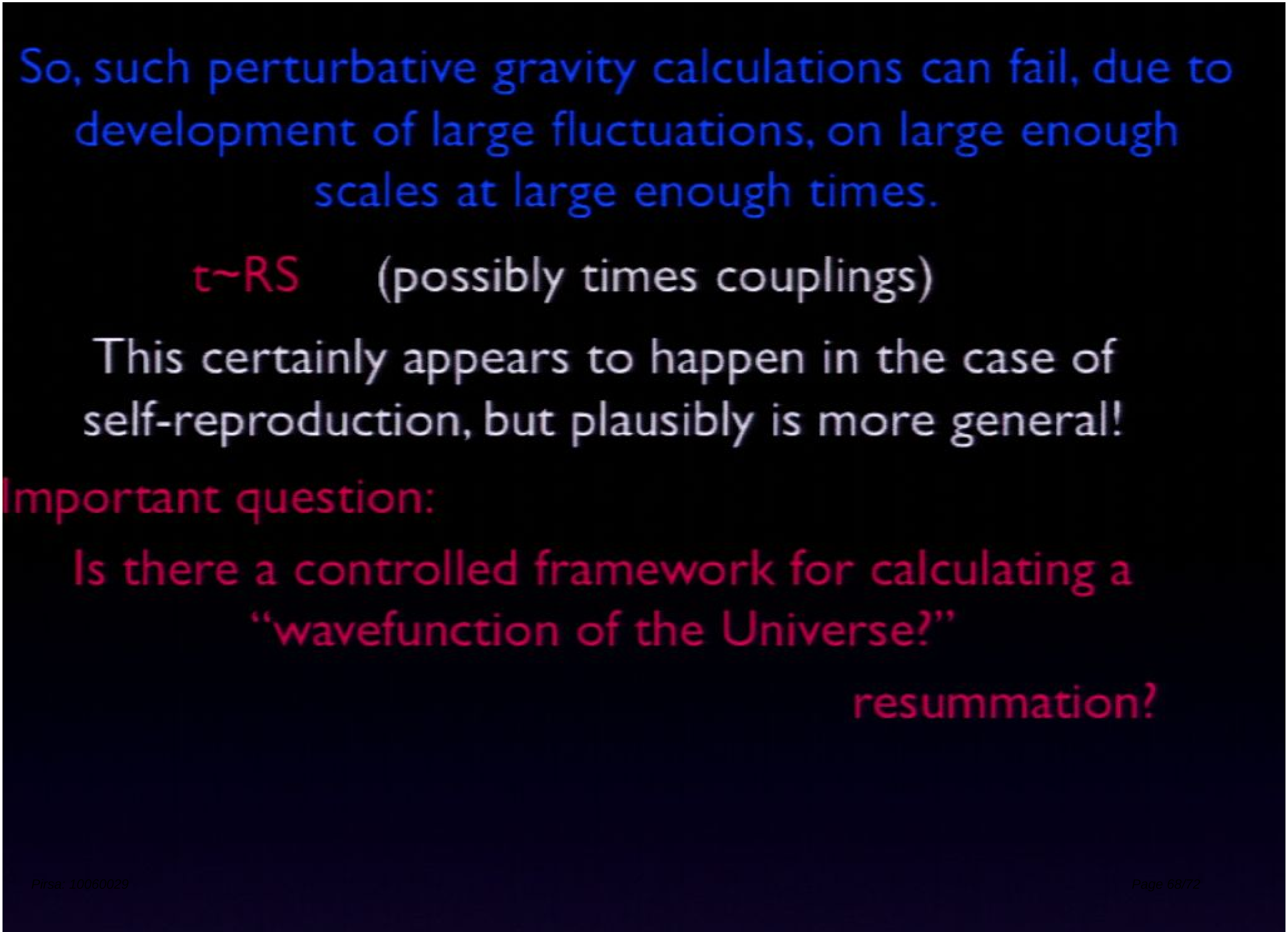

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Important question:

Is there a controlled framework for calculating a "wavefunction of the Universe?"

resummation?

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Important question:

Is there a controlled framework for calculating a "wavefunction of the Universe?"

resummation?

(And compare the analogous statements made for "nice slice" state of black hole ... there we need the state on the full slice!)

on behalf of all participants

including those past the horizon

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THANKS!

to the organizers for a very stimulating and enjoyable conference