Title: On the Perturbative Stability of Quantum Field Theories in de Sitter Space

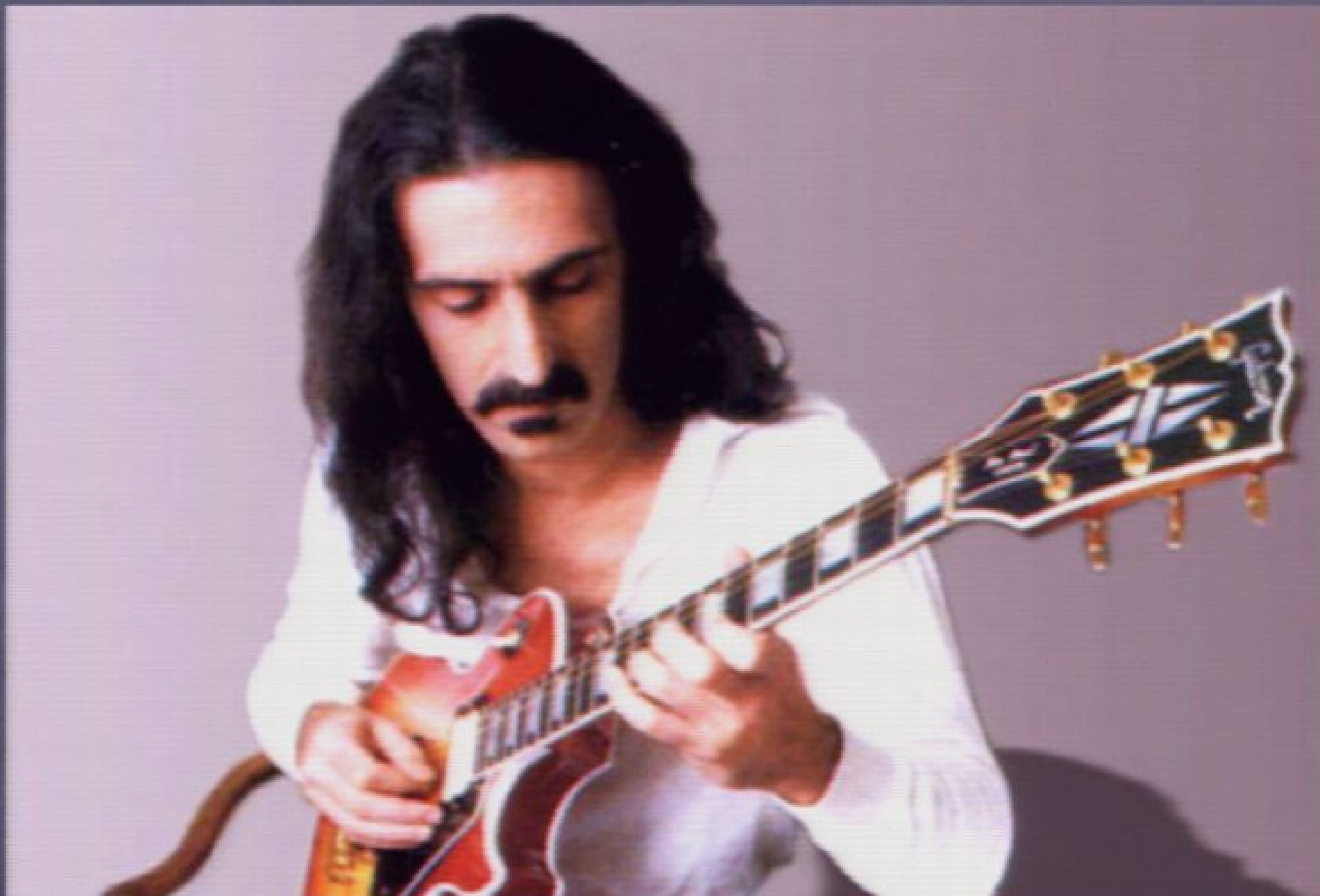
Date: Apr 20, 2011 11:00 AM

URL: http://pirsa.org/11040068

Abstract: We use a field theoretic generalization of the Wigner-Weisskopf method to study the stability of the Bunch-Davies vacuum state for a massless, conformally coupled interacting test field in de Sitter space. A simple example of the impact of vacuum decay upon a non-gaussian correlation is discussed. Single particle excitations also decay into two particle states, leading to particle production that hastens the exiting of modes from the de Sitter horizon resulting in the production of \emph{entangled superhorizon pairs} with a population consistent with unitary evolution. We find a non-perturbative, self-consistent "screening" mechanism that shuts off vacuum decay asymptotically, leading to a stationary vacuum state in a manner not unlike the approach to a fixed point in the space of states.

On the Perturbative Stability of deS QFT's

D. Boyanovsky, R.H. arXiv:1103.4648



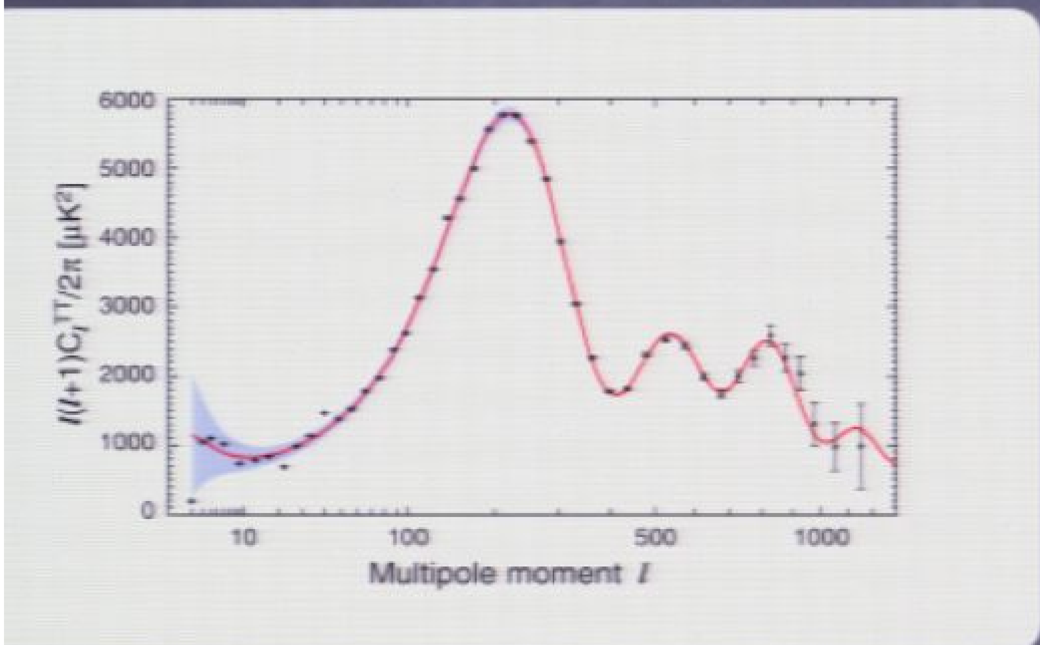
Shut up and play your guitar!

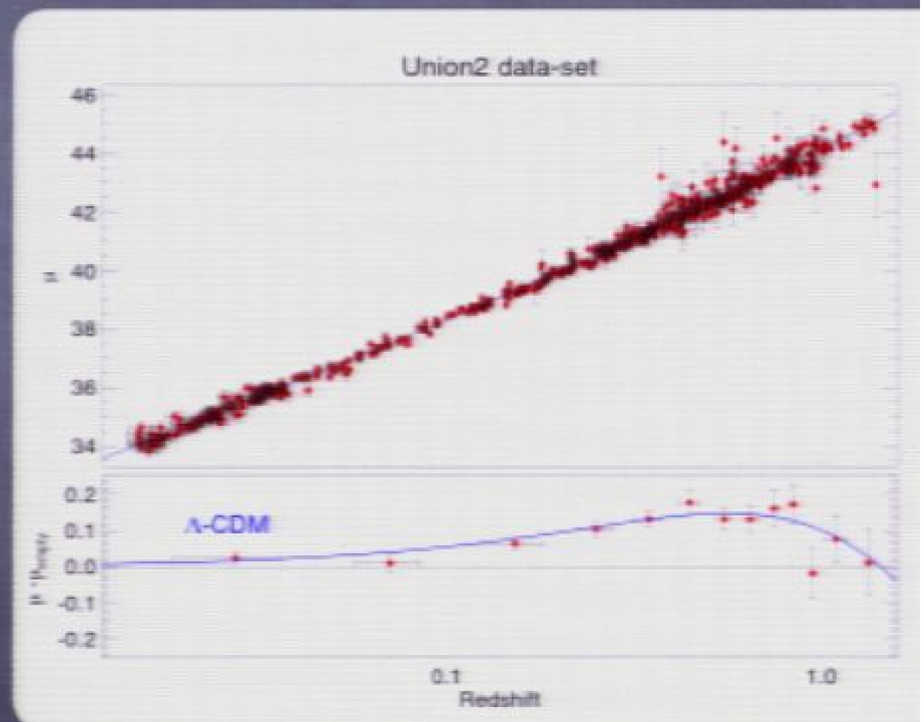
Outline

- Is de Sitter space stable? Polyakov's views
- Some quantum Mechanics: The Wigner-Weisskopf Method
- WW in de Sitter Space
- Non-Perturbative Screening? A Conjecture
- Conclusions and Further Directions

Is de Sitter Space Stable?

Why worry?





Why wouldn't de Sitter space be stable?

Polyakov: IR behavior of QF's is such that interactions produce so many particles that the in and out vacua become inequivalent. This is the "adiabatic catastrophe"

There are some calculations that claim to bear this out. ALL use some kind of S-matrix type argument:

$$\langle \text{many particles} | H_I | \text{vacuum} \rangle \neq 0 \Rightarrow \text{vacuum decay rate}$$

But is this how it works out?

The Wigner-Weisskopf Method: QM and QFT

If you want to know what happens to a quantum state, do quantum mechanics!

$$H = H_0 + H_I$$

$$i\frac{\partial}{\partial t}|\psi(t)\rangle_I = H_I(t)|\psi(t)\rangle_I$$

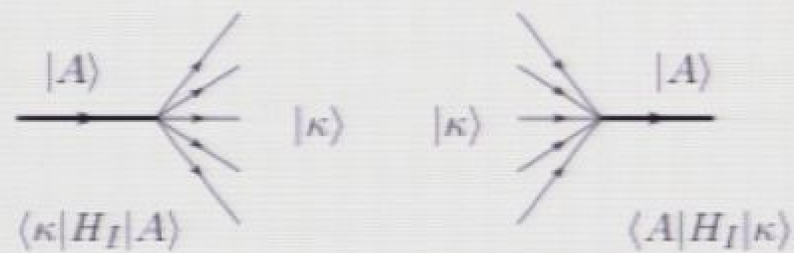
$$|\psi(t)\rangle_I = \sum_n C_n(t)|n\rangle$$

$$i\dot{C}_n(t) = \sum_m \langle n|H_I(t)|m\rangle C_m(t)$$

In general, an infinite dimensional mess!

$$|A\rangle \leftrightarrow \{\kappa\}$$

But s'pose that at some order in the interaction one state is only connected to a subset of states.



Then we can restrict ourselves to this sector and set up a simpler set of equations

$$C_\kappa(t) = -i\int_0^t \langle\kappa|H_I(t')|A\rangle\, C_A(t')\, dt'$$

$$\dot{C}_A(t) = -\int_0^t \Sigma(t,t')\, C_A(t')\, dt'$$

$$\Sigma(t,t') = \sum_\kappa \langle A|H_I(t)|\kappa\rangle\langle\kappa|H_I(t')|A\rangle$$

$$C_A(0) = 1, \quad C_\kappa(0) = 0$$

How do we solve this integro-differential equation?

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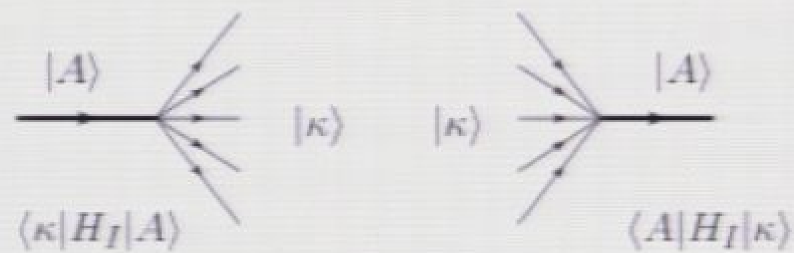

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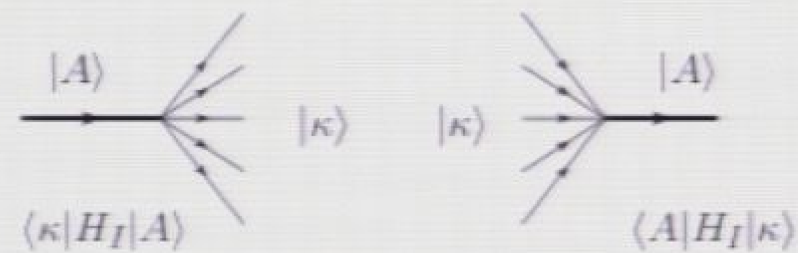

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The Markovian Approximation

The kernel is perturbatively "slow". S'pose it's mostly constant over the time range under consideration.

$$\int_0^t dt'\;\Sigma(t,t')C_A(t') = 0 \approx \left(\int_0^t dt'\;\Sigma(t,t')\right) C_A(t)$$

$$\Rightarrow C_A(t) \approx C_A(0)\exp\left(-\int_0^t dt'\;\Sigma(t,t')\right)$$

We can systematize this approximation as a consistent expansion in derivatives of the coefficient of A

$$W_0(t,t') = \int_0^{t'} \Sigma(t,t'')dt'' \Rightarrow \Sigma(t,t') = \frac{d}{dt'}W_0(t,t'), \quad W_0(t,0)=0$$

$$\int_0^t \Sigma(t,t')\,C_A(t')\,dt' = W_0(t,t)\,C_A(t) - \underbrace{\int_0^t dt'\,W_0(t,t')\,\frac{d}{dt'}C_A(t')}_{4'\text{th order}}$$

$$W_1(t,t') = \int_0^{t'} W_0(t,t'')dt'', \quad W_1(t,0)=0$$

$$\int_0^t W_0(t,t')\,\frac{d}{dt'}C_A(t')\,dt' = W_1(t,t)\,\dot{C}_A(t) + \cdots$$

$$\int_0^t \Sigma(t,t')\,C_A(t')\,dt' = W_0(t,t)\,C_A(t) - W_1(t,t)\,\dot{C}_A(t) + \cdots$$

Finally

$$\dot{C}_A(t)\left[1 - W_1(t,t)\right] + W_0(t,t)C_A(t) = 0 \Rightarrow$$

$$C_A(t) = e^{-i\int_0^t \mathcal{E}(t')dt'}, \quad \mathcal{E}(t) = \frac{-i\,W_0(t,t)}{1 - W_1(t,t)} \simeq -i\,W_0(t,t)\left[1 + W_1(t,t) + \cdots\right]$$

In the Markovian approximation

$$C_\kappa(t) = -i\int_0^t dt'\;\langle\kappa|H_I(t')|A\rangle\exp\left(-i\int_0^{t'} dt''\;\mathcal{E}(t'')\right)$$

1st order PT matrix elt

$$C_\kappa(t) = -i\int_0^t dt'\;\langle\kappa|H_I(t')|A\rangle$$

WW goes beyond PT and is valid at LATE times

Does this actually work? Look at case where interaction is time independent.

$$C_A(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi i} \frac{e^{i\omega t}}{\omega - I(\omega) - i\epsilon}$$

$$I(\omega) = \int_{-\infty}^{\infty} d\omega' \frac{\rho(\omega')}{\omega + \omega' - E_A - i\epsilon}$$

$$C_\kappa(t) = -i\langle\kappa|H_I|A\rangle \int_0^t e^{i(E_\kappa - E_A)t'}\, C_A(t')$$

$$\Sigma(t,t') = \sum_\kappa |\langle A|H_I|\kappa\rangle|^2 e^{i(E_A - E_\kappa)(t-t')}$$

$$\equiv \int_{-\infty}^{\infty} d\omega'\, \rho(\omega')\, e^{i(E_A - \omega')(t-t')}$$

$$\rho(\omega') = \sum_\kappa |\langle A|H_I|\kappa\rangle|^2 \delta(E_\kappa - \omega')$$

ate time evolution determined by pole nearest the real axis. With no interaction, pole is at origin.

$$I(\omega) \simeq -\Delta E_A - z_A\omega + i\frac{\Gamma_A}{2}$$

$$\Delta E_A = \mathcal{P}\int_{-\infty}^{\infty} d\omega' \frac{\rho(\omega')}{E_A - \omega'}$$

$$z_A = \mathcal{P}\int_{-\infty}^{\infty} d\omega' \frac{\rho(\omega')}{(E_A - \omega')^2}$$

$$\Gamma_A = 2\pi\rho(E_A)$$

$$C_A(t) \simeq \mathcal{Z}_A\, e^{-i\Delta E_A^r t}\, e^{-\frac{\Gamma_A^r}{2} t}$$

$$\mathcal{Z}_A = \frac{1}{1 + z_A} \simeq 1 - z_A$$

$$\Delta E_A^r = \mathcal{Z}_A\, \Delta E_A$$

$$\Gamma_A^r = \mathcal{Z}_A\, \Gamma_A$$

How does the Markovian approximation do in this case?

$$\mathcal{E}(t) = -i\int_0^t dt'\,\Sigma(t,t') = \int_{-\infty}^{\infty} d\omega' \frac{\rho(\omega')}{E_A-\omega'}\left[1-e^{i(\omega'-E_A)t}\right]$$

$$\int_0^t dt'\,\mathcal{E}(t') = tA(t) - i\,B(t)$$

$$A(t) = \int_{-\infty}^{\infty} d\omega'\,\frac{\rho(\omega')}{(E_A-\omega')}\left[1-\frac{\sin(\omega'-E_A)t}{(\omega'-E_A)t}\right]\xrightarrow[t\to\infty]{}\mathcal{P}\int_{-\infty}^{\infty} d\omega'\,\frac{\rho(\omega')}{(E_A-\omega')}$$

$$B(t) = \int_{-\infty}^{\infty} d\omega'\,\frac{\rho(\omega')}{(E_A-\omega')^2}\left[1-\cos(\omega'-E_A)t\right]\xrightarrow[t\to\infty]{}\pi t\rho(E_A) + \mathcal{P}\int_{-\infty}^{\infty} d\omega'\,\frac{\rho(\omega')}{(E_A-\omega')^2}$$

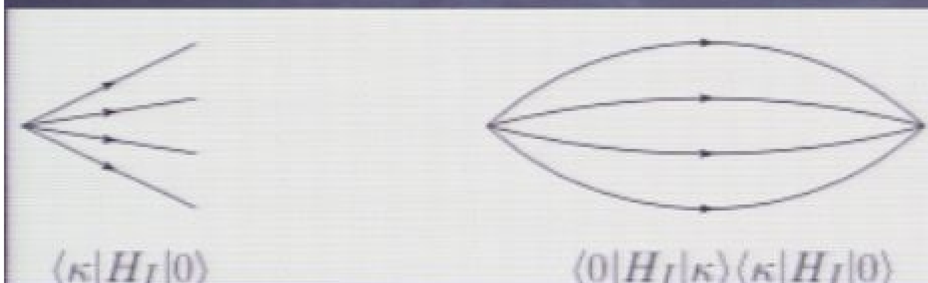
This gives the same result as the exact answer!

Some Flat space QFT results

ex 1.

$$H_I(t) = \lambda \int d^3x \; :\phi^4(\vec{x},t):$$

Normal ordering connects vacuum to 4-particle state at leading order



$$\Sigma(t,t') = \int_{-\infty}^{\infty} d\omega' \rho(\omega') e^{-i\omega'(t-t')}$$

$$\rho(\omega') = \lambda^2 V \prod_{i=1}^{3} \int \frac{d^3k_i}{(2\pi)^3} \frac{\delta(\sum_{i=1}^{3} k_i + |\vec{k}_{\rm tot}| - \omega')}{16\, k_1 k_2 k_3 |\vec{k}_{\rm tot}|}$$

$$C_0(t) = e^{-z_0}\, e^{-i\Delta E_0\, t}$$

$$\Delta E_0 = -\lambda^2 V \int \prod_{i=1}^{3} \frac{d^3k_i}{(2\pi)^3} \frac{1}{16\left(k_1k_2k_3|\vec{k}_{\rm tot}\right)} \frac{1}{\left(\sum_{i=1}^{3} k_i + |\vec{k}_{\rm tot}|\right)}$$

$$z_0 = \lambda^2 V \int \prod_{i=1}^{3} \frac{d^3k_i}{(2\pi)^3} \frac{1}{16\left(k_1k_2k_3|\vec{k}_{\rm tot}|\right)} \frac{1}{\left(\sum_{i=1}^{3} k_i + |\vec{k}_{\rm tot}|\right)^2}$$

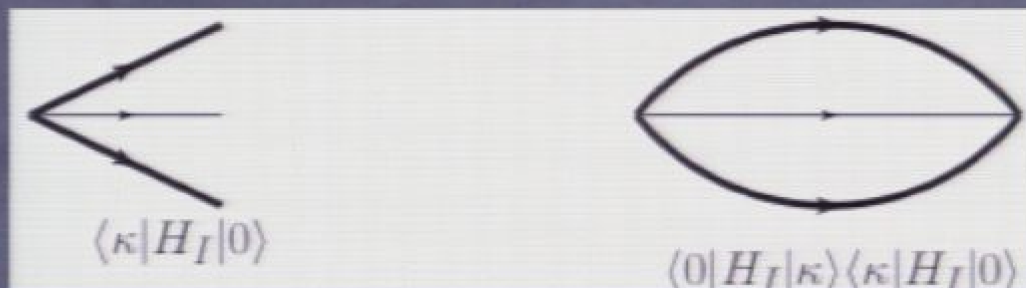
$$\Gamma_0 = 2\pi\rho(\omega'=0) = 0$$

Note that vacuum is stable, as Nature intended!

ex 2.

$$H_I(t) = M \int d^3x \, \varphi(\vec{x},t)\, \chi^2(\vec{x},t)$$

Take phi to be massive and chi massless



$$C_0(t) = e^{-z_0} e^{-i\Delta E_0 t}$$

$$\Delta E_0 = -\mathcal{P} \int_{-\infty}^{\infty} d\omega' \, \frac{\rho_{\rm vac}(\omega')}{\omega'}$$

$$z_0 = \mathcal{P} \int_{-\infty}^{\infty} d\omega' \, \frac{\rho_{\rm vac}(\omega')}{\omega'^{\,2}}$$

$$\Sigma_{\rm vac}(t,t') = \int_{-\infty}^{\infty} d\omega' \; \rho_{\rm vac}(\omega')$$

$$\rho_{\rm vac}(\omega') = V M^2 \int \frac{d^3p}{(2\pi)^3} \int \frac{d^3k}{(2\pi)^3} \, \frac{\delta(\omega' - E_p - k - |\vec{k}+\vec{p}|)}{2E_p \, 2k \, 2|\vec{k}+\vec{p}|}$$

Suppose we take all fields massless

$$\Sigma_0(t,t') = \frac{i\, M^2 V}{(4\pi)^4 \, (t - t' - i\epsilon)^3}, \quad \epsilon \to 0^+$$

$$\Delta E_0 = -\frac{M^2 V}{2(4\pi)^4 \, \epsilon^2}, \quad z_0 = \frac{M^2 V}{2(4\pi)^4 \, \epsilon}$$

WW in de Sitter Space

Consider CONFORMALLY COUPLED scalar in (Poincare patch of) DeS

Do the conformal rescaling of the field to make it look like flat space QFT

$$\chi(\vec{x},\eta) = a(\eta)\phi(\vec{x},\eta)$$

$$S = \frac{1}{2}\int d^3x\, d\eta \left\{ \frac{1}{2}\left[\chi'^2 - (\nabla\chi)^2 - \mathcal{M}_\chi^2(\eta)\,\chi^2 + \right] - g\, a^{(4-p)}(\eta)\,\chi^p \right\}$$

Now quantize using BD mode functions in a comoving box

$$\chi(\vec{x},\eta) = \frac{1}{\sqrt{V}}\sum_{\vec{k}}\left[a_{\vec{k}}\, g_\nu(k;\eta)\, e^{i\vec{k}\cdot\vec{x}} + a^\dagger_{\vec{k}}\, g^*\nu(k;\eta)\, e^{-i\vec{k}\cdot\vec{x}}\right]$$

$$g_\nu(k;\eta) = \frac{1}{2}\, i^{-\nu-\frac{1}{2}}\sqrt{\pi\eta}\, H^{(2)}_\nu(k\eta) \qquad a_{\vec{k}}|0\rangle_{BD} = 0$$

Interaction Hamiltonian is

$$H_I(\eta) = \frac{g}{(-H\eta)^{4-p}}\int d^3x\; :\chi^p(\vec{x},\eta):$$

Now just use the WW formalism as in flat space, now using BD Fock space states

$$C_\kappa(\eta) = -i\int_{\eta_0}^{\eta} d\eta' \langle\kappa|H_I(\eta')|A\rangle C_A(\eta')$$

$$\partial_\eta C_A(\eta) = -\int_{\eta_0}^{\eta} d\eta'\ \Sigma(\eta,\eta')$$

$$\Sigma(\eta,\eta') = \sum_\kappa \langle A|H_I(\eta)|\kappa\rangle\langle\kappa|H_I(\eta')|A\rangle$$

$$C_A(\eta_0) = 1,\ C_\kappa(\eta_0) = 0$$

Markovian Approximation

$$C_A(\eta) = e^{-\int_{\eta_0}^{\eta} W_0(\eta',\eta')\,d\eta'}$$

$$W_0(\eta',\eta') = \int_{\eta_0}^{\eta'} \Sigma(\eta',\eta'')d\eta''$$

Now go back and revisit our previous examples ex 1. $H_I(\eta) = \lambda \int d^3x \;:\chi^4(\vec{x},\eta):$

Just like flat space in terms of rescaled field. Vacuum is stable, just as in flat space

Disagrees with Higuchi who uses 1st order PT to calculate decay rate.

Resolution: Having a non-zero matrix elt of interaction between vacuum and 4-particle state does NOT mean vacuum decays. It gets dressed up instead!

Adiabatic turn on gives exact ground state

$$|\tilde{0}\rangle = U_\epsilon(0,-\infty)|0\rangle =$$
$$= |0\rangle - i\int_{-\infty}^{0} \sum_\kappa |\kappa\rangle\langle\kappa|H_I(t)|0\rangle\, e^{-\epsilon|t|}dt$$
$$z_0 = \sum_\kappa |\langle\kappa|\tilde{0}\rangle|^2$$

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$$H_I(\eta) = \frac{M}{(-\eta H)} \int d^3x \; \chi^3(\vec{x},\eta)$$

$$\Sigma_0(\eta,\eta') = \frac{M^2 V}{H^2 \eta \eta'} \int \frac{d^3p}{(2\pi)^3} \int \frac{d^3k}{(2\pi)^3} \frac{e^{-i(p+k+|\vec{k}+\vec{p}|)(\eta-\eta')}}{2p\,2k\,2|\vec{k}+\vec{p}|}$$
$$= \frac{i\,M^2 V}{(4\pi)^4 H^2 \eta \eta'} \frac{1}{\left[\eta - \eta' - i\epsilon\right]^3}$$

$$C_0(\eta) \simeq e^{-i\Delta_0(\eta)}\, e^{-z_0(\eta)}$$
$$\Delta_0(\eta) = -\frac{M^2 V}{2(4\pi)^4 H^2(-\eta)\,\epsilon^2}\left[1 - \frac{2}{3}\frac{\epsilon^2}{\eta^2}\ln\left(\frac{-\eta}{\epsilon}\right)\right]$$
$$z_0(\eta) = \frac{M^2 V}{2(4\pi)^4 H^2 \eta^2 \epsilon}\left[1 + \frac{\pi\,\epsilon}{3\,\eta}\right]$$

Now there IS vacuum decay; wave function renormalization is time dependent and grows as we go into the far IR

We can make contact with the flat space case here in a particular renormalization scheme where UV cutoff is constant in PHYSICAL coords.

$$\tilde{\epsilon} \equiv \frac{\epsilon}{(-H\eta)} = \text{constant}$$
$$z_0 = \frac{M^2 V_{\text{phys}}(\eta)}{2(4\pi)^4 \tilde{\epsilon}}$$

It gets harder and harder to overlap dressed state with the bare one as the universe expands

Non-Pertubative Screening Mechanism?

Recall

$$C_0(\eta) = e^{-i\int_{\eta_0}^{\eta} d\eta' \; \mathcal{E}(\eta')}, \; \mathcal{E}(\eta) = \frac{-iW_0(\eta,\eta)}{1 - W_1(\eta,\eta)}$$

Can $W_1(\eta,\eta)$ become secular?

If it did, maybe it could cancel late time behavior of the wavefunction renormalization.

This would be like finding a dressed state with very small, but NON-ZERO overlap with the bare state; no adiabatic catastrophe.

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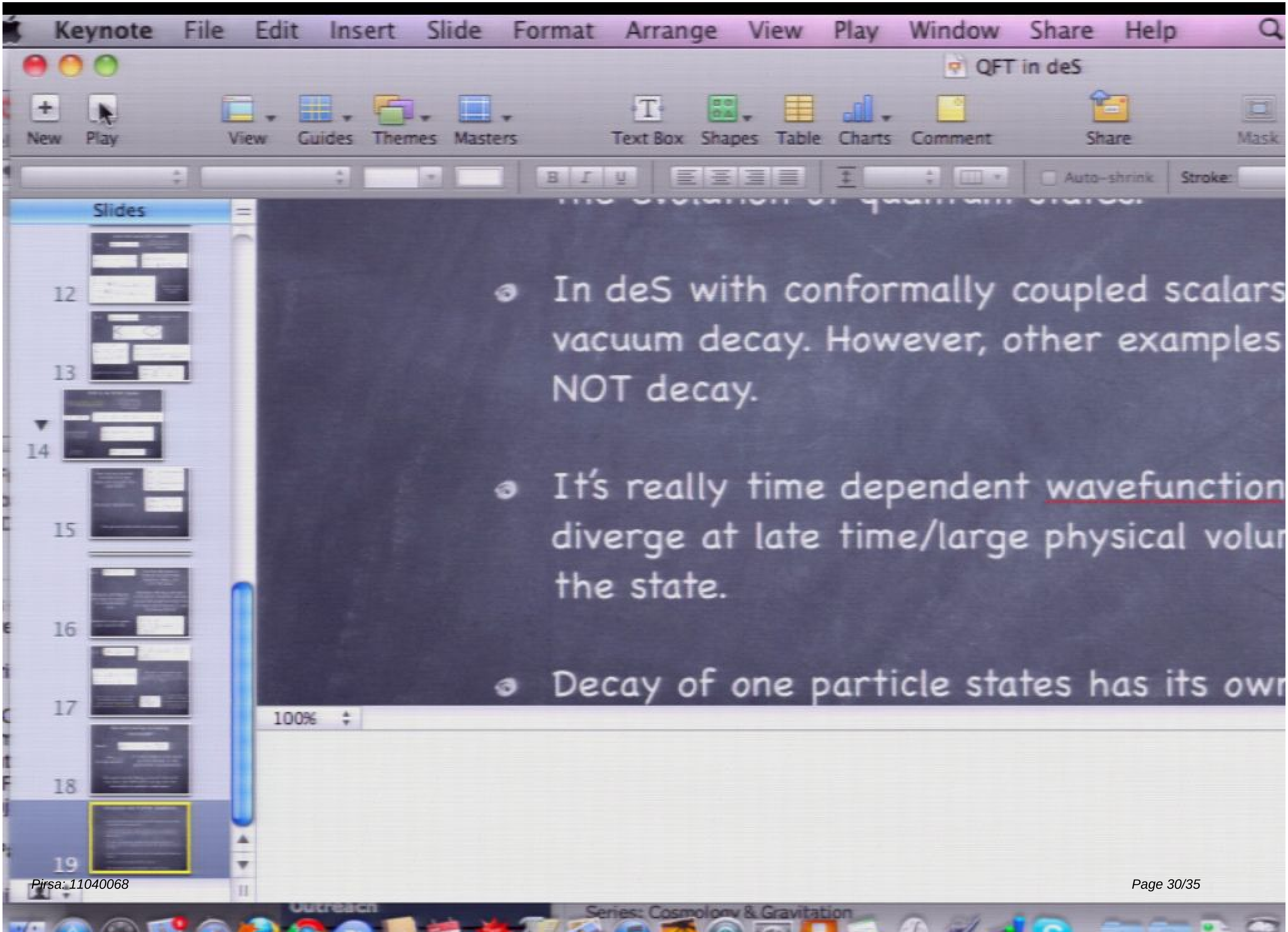
Discussion and Further Questions

- We have a formalism that resums late time behavior and can track the evolution of quantum states.
- In deS with conformally coupled scalars, we can see examples of vacuum decay. However, other examples just show state dressing, NOT decay.
- It's really time dependent wavefunction renormalizations that diverge at late time/large physical volume that drive the decay of the state.
- Decay of one particle states has its own interesting story (Read our paper!)
- How to go beyond leading Markovian approx?
- Mass generation in massless MINIMALLY coupled theory?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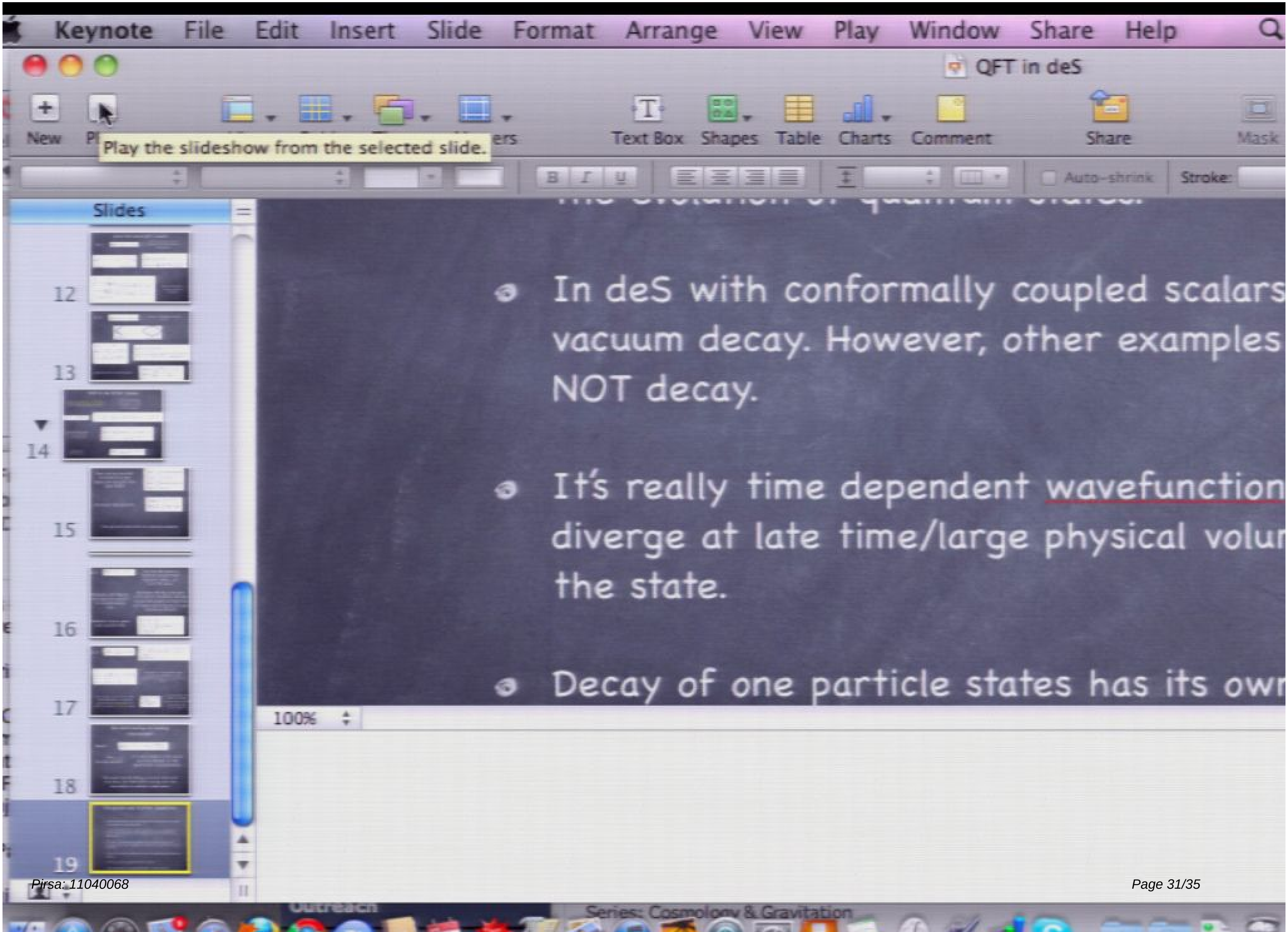
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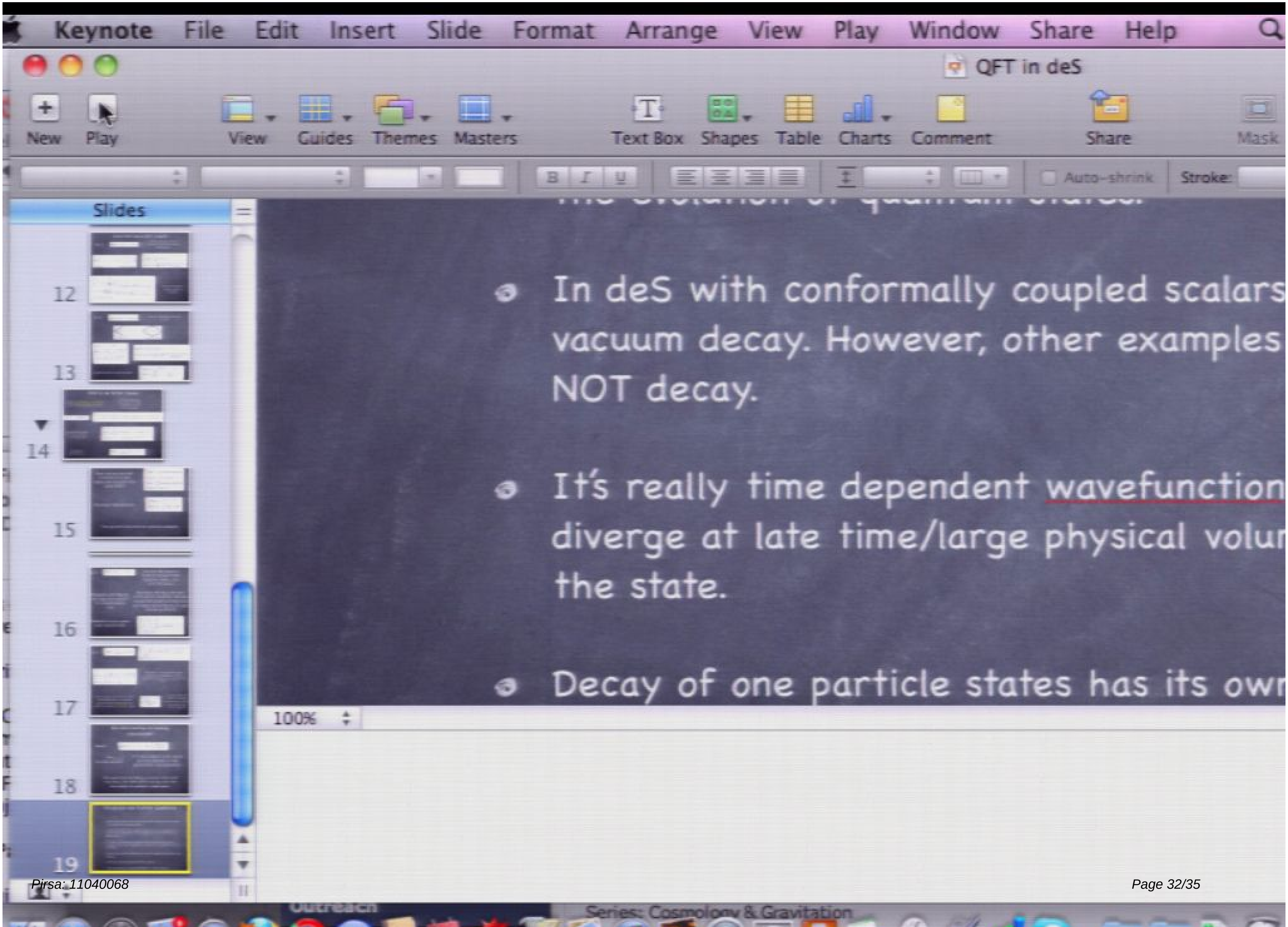
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Discussion and Further Questions

- We have a formalism that resums late time behavior and can track the evolution of quantum states.
- In deS with conformally coupled scalars, we can see examples of vacuum decay. However, other examples just show state dressing, NOT decay.
- It's really time dependent wavefunction renormalizations that diverge at late time/large physical volume that drive the decay of the state.
- Decay of one particle states has its own interesting story (Read our paper!)
- How to go beyond leading Markovian approx?
- Mass generation in massless MINIMALLY coupled theory?

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