Title: A Non-Local Reality: Is there a Phase Uncertainty in Quantum Mechanics?

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Abstract: A century after the advent of Quantum Mechanics and General Relativity, both theories enjoy incredible empirical success, constituting the cornerstones of modern physics. Yet, paradoxically, they suffer from deep-rooted, so-far intractable, conflicts. Motivations for violations of the notion of
relativistic locality include the Bell's inequalities for hidden variable theories, the cosmological horizon problem, and Lorentz-violating approaches to quantum geometrodynamics, such as Horava-Lifshitz gravity. Here, we explore a recent proposal for a ``real ensemble'' non-local description of<br>quantum mechanics, in which ``particles'' can copy each others' observables AND phases, independent of their spatial separation. We first specify the exact theory, ensuring that it is consistent and has (ordinary) quantum mechanics as a fixed point, where all particles with the same observables have the same phases. We then study the stability of this fixed point numerically, and
analytically, for simple models. We provide evidence that most systems (in our study) are locally stable to small deviations from quantum mechanics, and furthermore, the phase variance per observable, as well as systematic deviations from quantum mechanics, decay as ~ (EnergyXTime)^{-n}, where n > 2. Interestingly, this convergence is controlled by the absolute value of energy (and not energy difference). Finally, we discuss different issues related to this theory, as well as potential implications for early universe, and the cosmological constant problem.

Motivation

We study a hidden variable model, the so-called real ensemble model recently introduced by Smolin

- A hidden variable theory, extended outside the quantum mechanical regime, may allow non-local signalling in the early universe, creating correlations in the CMB.
- A real ensemble model is a non-local hidden variable theory, as an alternative to quantum mechanics, and so can potentially possess this type of non-local signalling.
- To be viable, however, quantum mechanics must be an attractor, such that the non-quantum mechanical theory becomes quantum mechanics at later times, consistent with present-day experiments.

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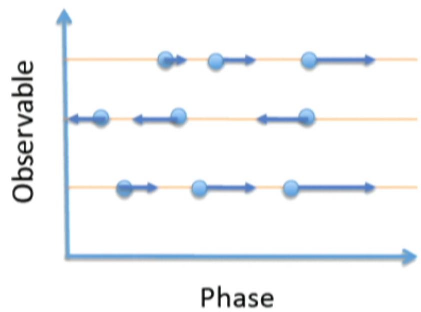
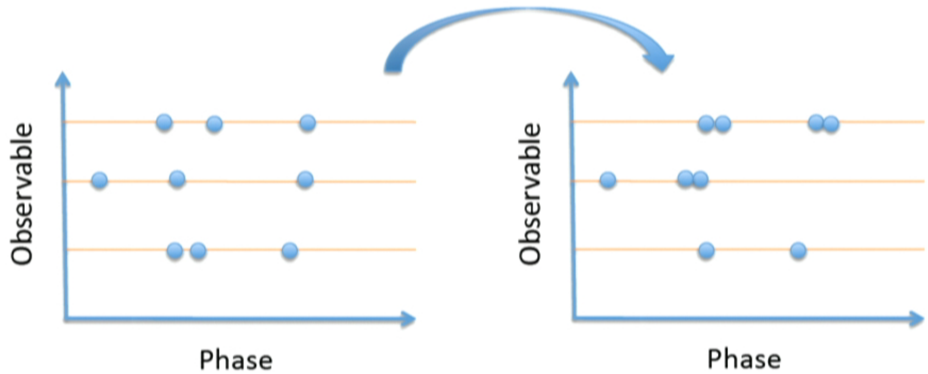


Continuous Evolution Rule



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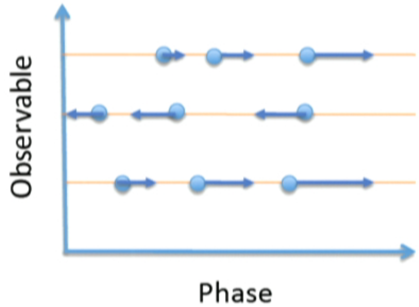


Continuous Evolution Rule

Equations - QM

The equations which reproduce quantum mechanics are:

$$\dot{\phi}(a,t) = \sum_b \sqrt{\frac{\rho(b,t)}{\rho(a,t)}} R(a,b) \cos\left[\phi(a,t) - \phi(b,t) + \delta(a,b)\right],$$

$$\dot{\rho}(a,t) = \sum_b 2\sqrt{\rho(a,t)\,\rho(b,t)} R(a,b) \sin\left[\phi(a,t) - \phi(b,t) + \delta(a,b)\right],$$

with

$$H/\hbar = \begin{matrix} R(1,1)\,e^{i\delta(1,1)} & R(1,2)\,e^{i\delta(1,2)} & \dots \\ R(1,2)\,e^{-i\delta(1,2)} & R(2,2)\,e^{i\delta(2,2)} & \\ \dots & & \dots \end{matrix} .$$

Equations - With Weight Function

$$\dot{\phi}(a_i, \phi_i, t) = \sum_{a_j}\sum_{\phi_j} w(a_j, \phi_j, t)\sqrt{\frac{\rho(a_j, t)\sum_{\phi_k} w(a_j, \phi_k, t) F(\phi_j - \phi_k)}{\rho(a_i, t)\sum_{\phi_k} w(a_i, \phi_k, t) F(\phi_i - \phi_k)}}$$
$$\times R(a_i, a_j)\cos[\phi_i(t) - \phi_j(t) + \delta(a_i, a_j)]$$

$$\dot{\rho}(a_i, \phi_i, t) = 2w(a_i, \phi_i, t)\sum_{a_j}\sum_{\phi_j} w(a_j, \phi_j, t)$$
$$\times\sqrt{\rho(a_i,t)\left[\sum_{\phi_k} w(a_i,\phi_k,t)F(\phi_i-\phi_k)\right]\rho(a_j,t)\left[\sum_{\phi_k} w(a_j,\phi_k,t)F(\phi_j-\phi_k)\right]}$$
$$\times R(a_i, a_j)\sin[\phi_i(t) - \phi_j(t) + \delta(a_i, a_j)].$$

Outline

The System

- This case involves two possible values of a, spin up or spin down, simplifying the analysis since there are only two states to sum over.
- For each case, 3 phases are chosen
- a FORTRAN numerical code using GNU (c) scientific library numerically evolves sample such systems according to the known equations

The Sample F Functions

The function F will have one of a few predefined values.

- $c = 0$: $F(d\phi) = 1$. This corresponds to the case when the densities under the square roots are independent of phase.
- $c = 1$: The smooth cosine type function is a simple case that is sensitive to the phase differences, while still creating an influence from the variation in the phases of the different particles. This would appear as

$$F(d\phi) \equiv \frac{1}{2} + \frac{1}{2}\cos(d\phi) = \cos^2\left(\frac{d\phi}{2}\right). \tag{1}$$

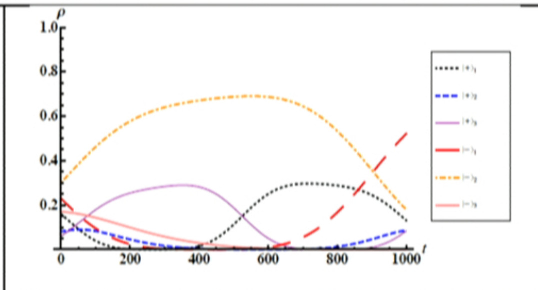
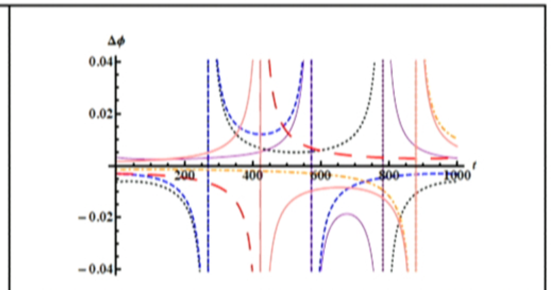
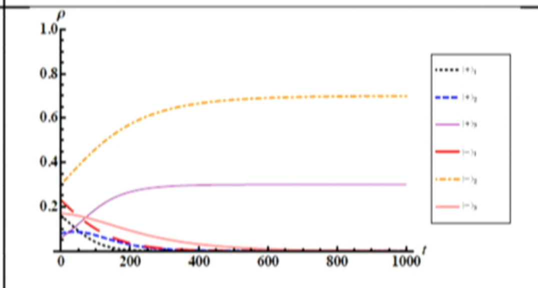
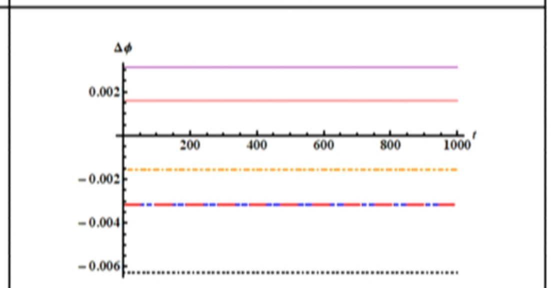
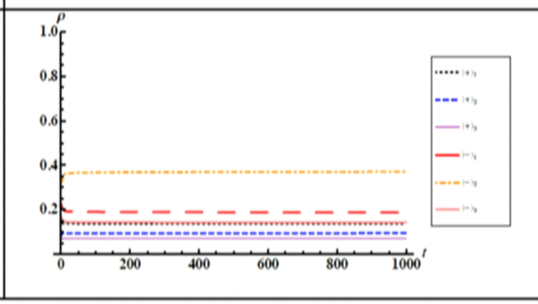
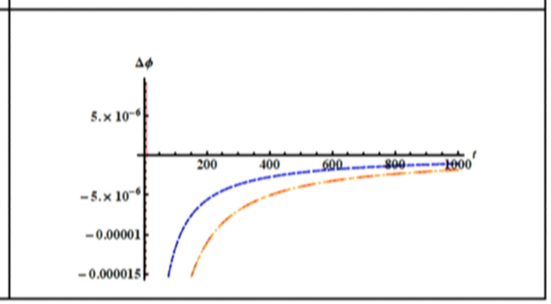
- More generally:

$$F_c(d\phi) \equiv \cos^2\left(\frac{c\ d\phi}{2}\right)\Theta[\cos(d\phi) - \cos(\pi/c)],$$

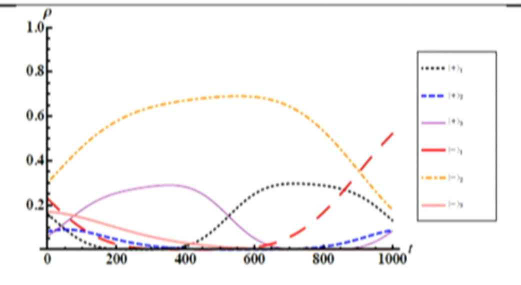
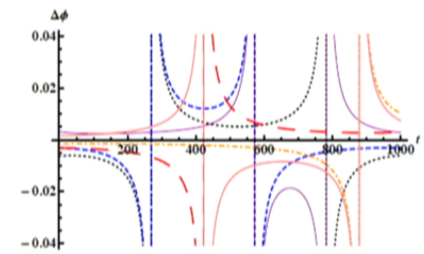
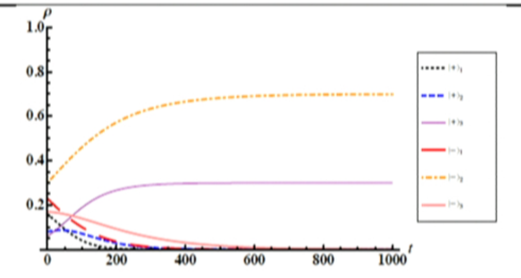
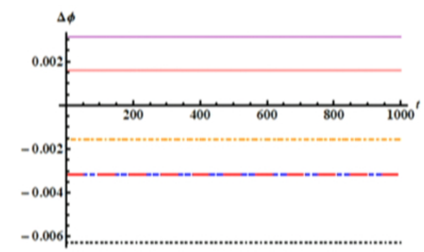
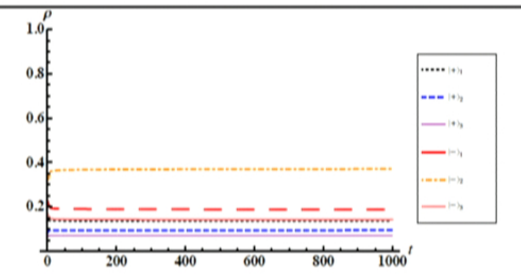
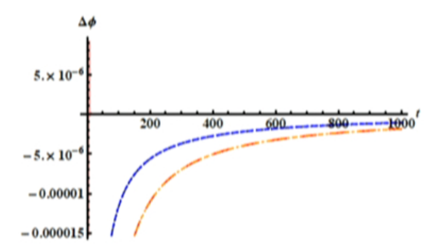
Initial Conditions

The initial conditions for shown plots are
$\rho(0) = \{\{0.16, 0.08, 0.06\}, \{0.23, 0.3, 0.17\}\}$ and
$\phi(0) = \left\{\{0, \delta\phi, 2\delta\phi\}, \left\{\frac{\pi}{2} + \delta\phi, \frac{\pi}{2}, \frac{\pi}{2} + \frac{\delta\phi}{2}\right\}\right\}$. The Hamiltonian is
$H = \omega_0 \hbar (2\sigma_z)$ or $H = \omega_0 \hbar (2I)$. $\hbar \equiv 1$ and ω_0 determines the units for t.

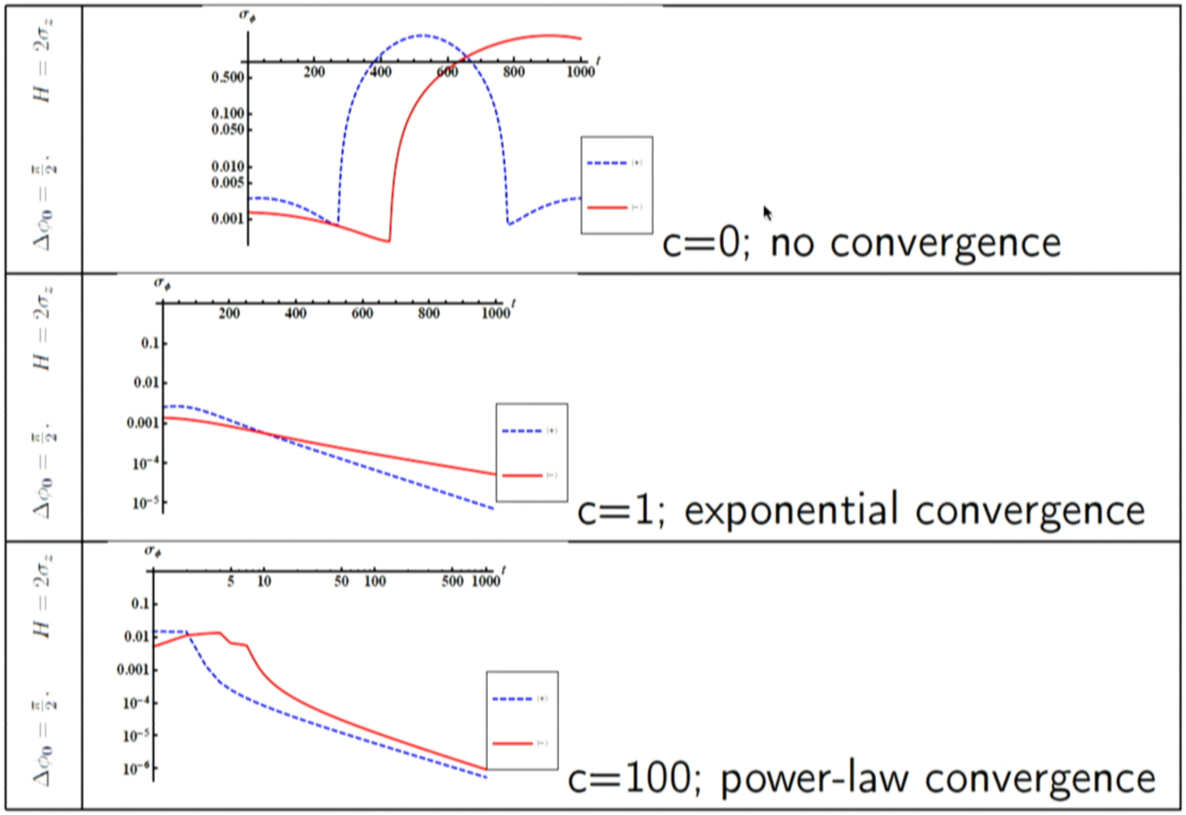
Simulated Dynamics for $c = 0, 1, 100$

	Probability vs Time	Phase Difference vs Time
$\Delta\varphi_0 = \frac{\pi}{2}; \quad H = 2\sigma_z$		
$\Delta\varphi_0 = \frac{\pi}{2}; \quad H = 2\sigma_z$		
$\Delta\varphi_0 = \frac{\pi}{2}; \quad H = 2\sigma_z$		

Simulated Dynamics for $c = 0, 1, 100$

	Probability vs Time	Phase Difference vs Time
$\Delta\phi_0 = \frac{\pi}{2}$; $H = 2\sigma_z$		
$\Delta\phi_0 = \frac{\pi}{2}$; $H = 2\sigma_z$		
$\Delta\phi_0 = \frac{\pi}{2}$; $H = 2\sigma_z$		

Standard Deviation of Phases for $c = 0, 1, 100$



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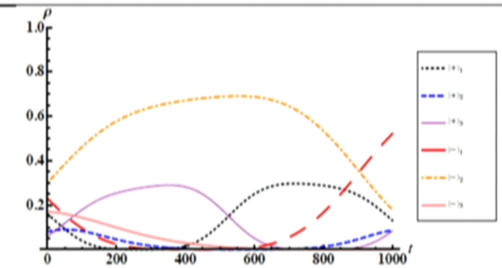
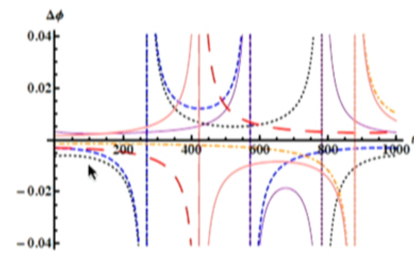
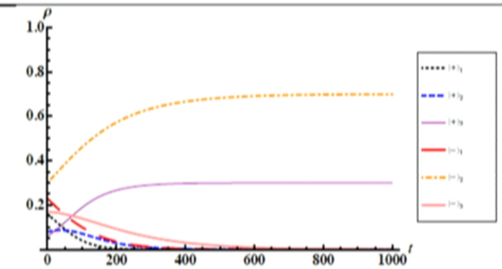
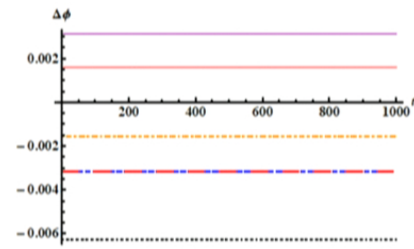
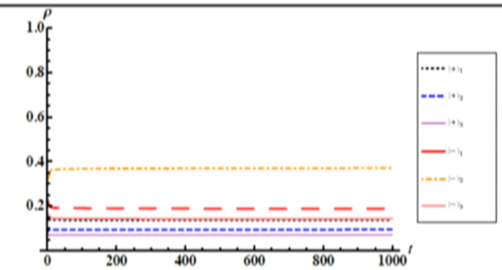
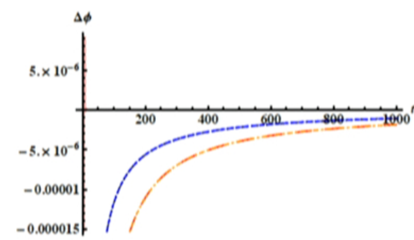
$\Delta\varphi_0 = \frac{\pi}{2}; \quad H = 2\sigma_z$		
$\Delta\varphi_0 = \frac{\pi}{2}; \quad H = 2\sigma_z$		
$\Delta\varphi_0 = \frac{\pi}{2}; \quad H = 2\sigma_z$		

Equations - Non-Equilibrium with Weight Function

$$\dot{\phi}\left(a_i,\phi_i,t\right)=\sum_{a_j}\sum_{\phi_j} w\left(a_j,\phi_j,t\right)\sqrt{\frac{\rho\left(a_j,t\right)\sum_{\phi_k} w\left(a_j,\phi_k,t\right)F\left(\phi_j-\phi_k\right)}{\rho\left(a_i,t\right)\sum_{\phi_k} w\left(a_i,\phi_k,t\right)F\left(\phi_i-\phi_k\right)}}$$
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Perturbation Theory near Equilibrium

For diagonal Hamiltonians, we can perturb equations close to Quantum Equilibrium:

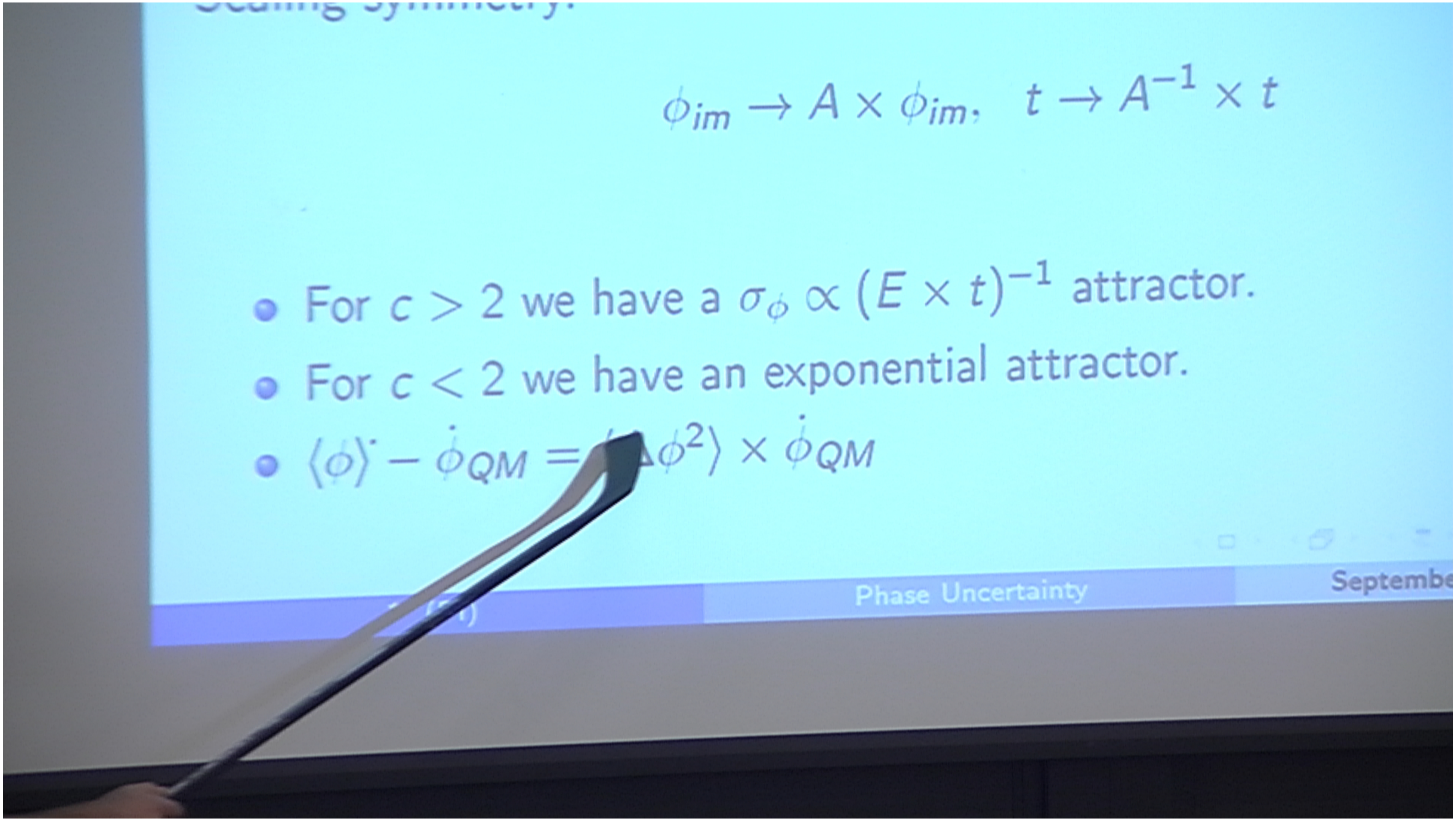
$$\dot{\phi}_{im} = \dot{\phi}_i - \dot{\phi}_m = (\frac{1}{c} - \frac{1}{2}) \left[(\phi_i - \langle\phi\rangle)^2 - (\phi_m - \langle\phi\rangle)^2\right] + \mathcal{O}(\Delta\phi^4),$$

$$\dot{w}_i = 2w_i(\phi_i - \langle\phi\rangle) + \mathcal{O}(\Delta\phi^3)$$

Scaling symmetry:

$$\phi_{im} \to A \times \phi_{im}, \quad t \to A^{-1} \times t$$

- For $c > 2$ we have a $\sigma_\phi \propto (E \times t)^{-1}$ attractor.
- For $c < 2$ we have an exponential attractor.
- $\langle\phi\rangle^{\cdot} - \dot{\phi}_{QM} = \langle\Delta\phi^2\rangle \times \dot{\phi}_{QM}$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Phase Uncertainty

Final Remarks

- Smolin's Real Ensemble model is a hidden variable theory that adds Phase Uncertainty to Quantum Mechanics.
- Dynamics consists of Continuous Evolution and Copy Rules, which we specified for the first time
- We established that Quantum Mechanics is an attractor fixed point for a range of parameters and initial conditions
- Convergence to Quantum Mechanics is faster than $(\text{Energy}\times\text{Time})^{-2}$.
- Satisfactory interpretation still missing
- Potential Applications to Early Universe, and Cosmological Constant Problem