

CLASSICAL AND QUANTUM DYNAMICS OF
HIGHER-DERIVATIVE SYSTEMS

or

LIVING WITH GHOSTS

Valparaiso, January 11, 2018

based on

A.S., Int. J. Mod. Phys. A32 (2017) no.33,
1730025 [arXiv:1710.11538]

MOTIVATION:

... To myself, I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary whilst the great ocean of truth lay all undiscovered before me.

Isaac Newton

- The ocean is now charted up to $E \lesssim 10^3$ GeV, $l \gtrsim 10^{-17}$ cm.
- But it extends up to $M_P \approx 10^{19}$ GeV. We have now explored its 10^{-16} -th part.

PROBLEMS IN QUANTUM (AND CLASSICAL) GRAVITY:

- Nonrenormalizability
- Non-causality. Closed time loops. Paradoxes.

TOE = strings?

- No fundamental quantum string theory
- No phenomenological successes.

An alternative (dream) solution: [A.S., 2005]

Our Universe as a soap film in a flat higher dimensional bulk. The TOE is a field theory in this bulk. Gravity etc is an effective theory living on the film, like

$$H_{\text{soap}} = \sigma \mathcal{A} = \sigma \int d^2x \sqrt{g}$$

TRY

$$S = -\frac{1}{2h^2} \int \text{Tr}\{F_{MN}F_{MN}\} d^6x,$$

in $D = 6$, $M, N = 0, 1, 2, 3, 4, 5$.

- Dimensionful coupling constant, nonrenormalizable
- Includes higher derivatives

A SECOND TRY

$$\mathcal{L}^{D=6} = \alpha \text{Tr}\{F_{\mu\nu} \square F_{\mu\nu}\} + \beta \text{Tr}\{F_{\mu\nu} F_{\nu\alpha} F_{\alpha\mu}\}$$

- α, β are dimensionless, renormalizability

But GHOSTS appear

- In a ghost system the Hamiltonian has no ground state. No vacuum in field theory. It is inherent for all higher-derivative theories.

OSTROGRADSKY HAMILTONIAN

M. Ostrogradsky [1801-1862] is known by

- Ostrogradsky theorem from vector analysis
- Ostrogradsky method for calculating $\int P(x)/Q(x) dx$.
- Ostrogradsky Hamiltonian

In the paper

[M. Ostrogradsky, *Mémoire sur les équations différentielles relatives au problème des isopérimètres*, Mem. Ac. St. Petersbourg **VI** 4 (1850) 385.]

he reinvented the Hamiltonian formalism and applied it to higher-derivative theories.

- Consider $L(x, \dot{x}, \ddot{x})$.
- **Equation of motion:**

$$\frac{d^2}{dt^2} \left(\frac{\partial L}{\partial \ddot{x}} \right) - \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{x}} \right) + \frac{\partial L}{\partial x} = 0.$$

- **Conserved energy:**

$$E = \ddot{x} \frac{\partial L}{\partial \ddot{x}} + \dot{x} \left(\frac{\partial L}{\partial \dot{x}} - \frac{d}{dt} \frac{\partial L}{\partial \ddot{x}} \right) - L.$$

- Treat $v = \dot{x}$ as an independent variable and define

$$p_v = \frac{\partial L}{\partial \dot{v}} = \frac{\partial L}{\partial \ddot{x}},$$

$$p_x = \frac{\partial L}{\partial \dot{x}} - \dot{p}_v,$$

- Canonical Hamiltonian:

$$H(p_v, p_x; v, x) = p_v \dot{v} + p_x \dot{x} - L =$$

$$p_v a(p_v, x, v) + p_x v - L[a(p_v, x, v), x, v],$$

where $a(p_v, x, v)$ is the solution of the equation $\partial L(x, v, a)/\partial a = p_v$.

- Linear term $p_x v \longrightarrow$

Theorem 1: [Woodard, 2015] *The classical energy of a nondegenerate higher-derivative system can acquire an arbitrary positive or negative value.*

also

Theorem 2: [Raidal + Veermae, 2017] *The spectrum of a Hamiltonian of a higher-derivative system is not bounded neither from below, nor from above.*

- This phenomenon is sometimes called “Ostrogradsky instability”, but it is not an instability.

Arnold’s principle: *If a notion bears a personal name, then this name is not the name of the discoverer.*

(self-referential).

PAIS-UHLENBECK OSCILLATOR [1950]

Consider

$$L = \frac{1}{2} [\ddot{x}^2 - (\omega_1^2 + \omega_2^2)\dot{x}^2 + \omega_1^2\omega_2^2x^2]$$

- Ostrogradsky Hamiltonian:

$$H = p_x v + \frac{p_v^2}{2} + \frac{(\omega_1^2 + \omega_2^2)v^2}{2} - \frac{\omega_1^2\omega_2^2x^2}{2}$$

- Canonical transformation:

$$X_1 = \frac{1}{\omega_1} \frac{\hat{p}_x + \omega_1^2 v}{\sqrt{\omega_1^2 - \omega_2^2}}, \quad \hat{P}_1 \equiv -i \frac{\partial}{\partial X_1} = \omega_1 \frac{\hat{p}_v + \omega_2^2 x}{\sqrt{\omega_1^2 - \omega_2^2}},$$

$$X_2 = \frac{\hat{p}_v + \omega_1^2 x}{\sqrt{\omega_1^2 - \omega_2^2}}, \quad \hat{P}_2 \equiv -i \frac{\partial}{\partial X_2} = \frac{\hat{p}_x + \omega_2^2 v}{\sqrt{\omega_1^2 - \omega_2^2}}.$$

($\omega_1 > \omega_2$ was assumed).

- In these variables,

$$H = \frac{\hat{P}_1^2 + \omega_1^2 X_1^2}{2} - \frac{\hat{P}_2^2 + \omega_2^2 X_2^2}{2}.$$

The spectrum is

$$E_{nm} = \left(n + \frac{1}{2}\right) \omega_1 - \left(m + \frac{1}{2}\right) \omega_2$$

with positive integer n, m .

- All states are normalizable (“pure point”). Infinite degeneracy if ω_1/ω_2 is rational. Everywhere dense if ω_1/ω_2 is irrational.

UNUSUAL BUT NOT SICK!

UNITARITY CONFUSION

Consider

$$\hat{H} = \omega_1 a_1^\dagger a_1 - \omega_2 a_2 a_2^\dagger.$$

- Ordinary “vacuum” $|\Phi\rangle$ with $a_1|\Phi\rangle = a_2|\Phi\rangle = 0$ is in the middle of the spectrum.
- Introduce the state $|\tilde{\Phi}\rangle$ satisfying

$$a_1|\tilde{\Phi}\rangle = a_2^\dagger|\tilde{\Phi}\rangle = 0$$

and consider the tower of states

$$|n\rangle = \frac{a_2^n}{n!}|\tilde{\Phi}\rangle$$

Then $\hat{H}|\tilde{\Phi}\rangle = 0$,

$$\hat{H}|1\rangle = \hat{H}(a_2|\tilde{\Phi}\rangle) = -\omega_2 a_2 a_2^\dagger a_2 = \omega_2 a_2|\tilde{\Phi}\rangle = \omega_2|1\rangle$$

and $\hat{H}|n\rangle = n\omega_2|n\rangle$.

- The spectrum is positive definite. One can rename $a_2 \rightarrow b_2^\dagger$, $a_2^\dagger \rightarrow b_2$.

THE PRICE

- $[b_2, b_2^\dagger] = -1$ and hence $|1\rangle = b_2^\dagger|\tilde{\Phi}\rangle$ has a **negative norm**:

$$\langle 1|1\rangle = -\langle\tilde{\Phi}|b_2b_2^\dagger|\tilde{\Phi}\rangle = -\langle\tilde{\Phi}|\tilde{\Phi}\rangle = -1.$$

-

$$|\tilde{\Phi}\rangle = \exp\left\{-\frac{\omega_1}{2}X_1^2\right\}\exp\left\{\frac{\omega_2}{2}X_2^2\right\}$$

and the whole tower $|n\rangle$ are not in \mathcal{L}_2 .

IT IS BETTER NOT TO THINK IN THESE TERMS!

BENDER AND MANNHEIM PROPOSAL

Consider

$$H = \frac{\hat{P}_1^2 + \omega_1^2 X_1^2}{2} - \frac{\hat{P}_2^2 + \omega_2^2 X_2^2}{2} .$$

and assume X_1 to be real and X_2 purely imaginary.

Then the **normalizable** wave functions involve a factor

$$\exp \left\{ -\frac{\omega_1}{2} X_1^2 \right\} \exp \left\{ \frac{\omega_2}{2} X_2^2 \right\} .$$

and the spectrum is positive definite.

- This is a **different** spectral problem.
- Just no need to do this.

PATH INTEGRAL CONFUSION [Hawking + Hertog, 2002]

- A Lagrangian path integral

$$\sim \int \prod_t dx(t) \exp \left\{ i \int dt L(\ddot{x}, \dot{x}, x) \right\} \quad (1)$$

- The corresponding Hamiltonian path integral

$$\sim \int \prod_t dx(t) dv(t) dp_x(t) dp_v(t) \exp \left\{ i \int dt [p_v \dot{v} + p_x \dot{x} - H(p_v, p_x; v, x)] \right\}. \quad (2)$$

Substitute here the Ostrogradsky Hamiltonian and integrate over $\prod_t dp_x(t)$. We obtain the factor

$$\prod_t \delta[v(t) - \dot{x}(t)].$$

Integrating further over $\prod_t dv(t) dp_v(t)$, we derive (1).

- The Euclidean rotation $t \rightarrow -i\tau$ in the Hamiltonian integral (2) is **impossible**. The integral

$$\prod_\tau \int_{-\infty}^{\infty} dp_x(\tau) \exp \left\{ \int d\tau p_x(\tau) \left[i \frac{dx(\tau)}{d\tau} - v(\tau) \right] \right\}$$

diverges.

- Euclidean rotation $t \rightarrow -i\tau$ in the Lagrangian integral (1) is possible, the integral may converge, but its analytic continuation into Minkowski space does not give a unitary evolution.

CONCLUSION:

Euclidean path integrals (in contrast to Minkowski ones) are not defined for higher-derivative systems.

INCLUDING INTERACTIONS

Consider the Lagrangian [A.S., 2005]

$$L = \frac{1}{2} [\dot{x}^2 - 2\omega^2 x^2 + \omega^4 x^4] - \frac{1}{4} \alpha x^4.$$

Equation of motion:

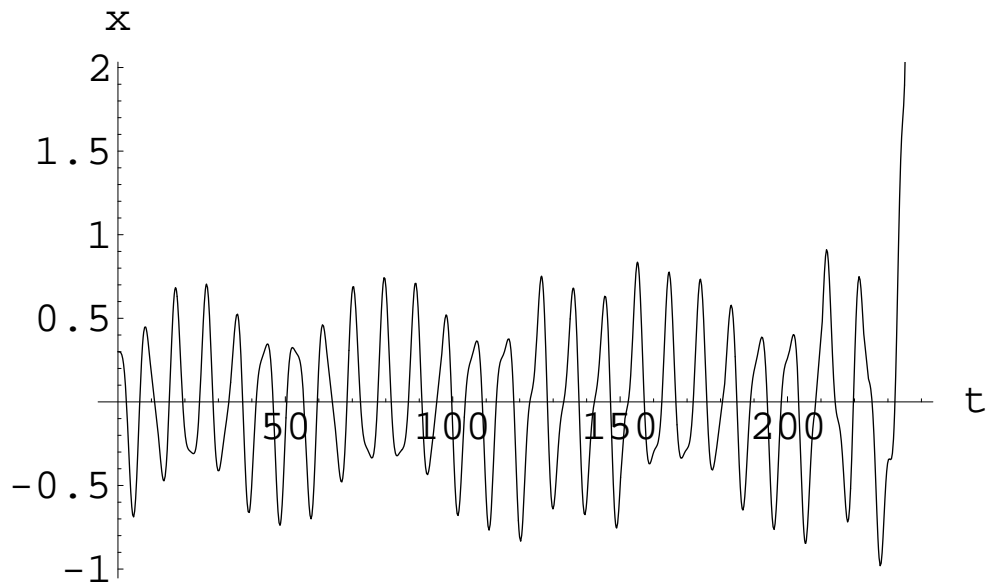
$$\left(\frac{d^2}{dt^2} + \omega^2 \right)^2 x - \alpha x^3 = 0.$$

fixed point:

$$x(0) = \dot{x}(0) = \ddot{x}(0) = x^{(3)}(0) = 0.$$

- **Stable trajectories** for small deviations (the island of stability).
- **Collapse** (the system runs to the infinity at finite time) for large enough deviations.

ON THE SHORE OF THE STABILITY ISLAND



A similar stability island for another HD system in

[S.N. Carrol, M. Hoffman, and M. Trodden,
PR **D68** (2003) 023509]

AN EXAMPLE OF COLLAPSE: FALLING TO THE CENTER

Consider

$$V(r) = -\frac{\kappa}{r^2}$$

with $m\kappa > 1/8$.

- Spectrum is not bounded from below.
- Schrödinger problem is not well defined.

If one smoothes the singularity,

$$V(r) = -\frac{\kappa}{r^2}, \quad r > a,$$
$$V(r) = -\frac{\kappa}{a^2}, \quad r \leq a,$$

the spectrum is bounded, but depends on a .

- Violation of unitarity (probability “leaks” into the singularity).

AN OBSERVATION:

- **If** quantum theory is sick, **so** is its classical counterpart. If classical theory is benign, **so** is its quantum counterpart.

INTERACTING SYSTEMS WITH BENIGN GHOSTS

[D. Robert + A.S., 2006]

Consider the Hamiltonian

$$H = pP + DV'(x)$$

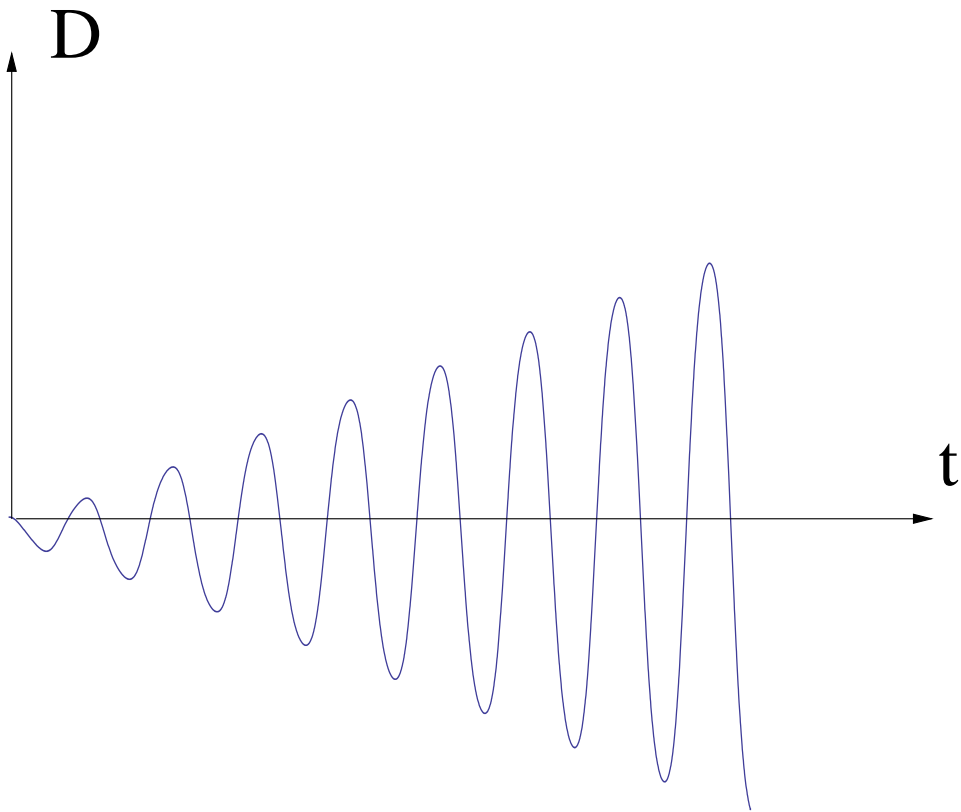
with

$$V(x) = \frac{\omega^2 x^2}{2} + \frac{\lambda x^4}{4}, \quad \lambda > 0.$$

- Not positive definite \longrightarrow **ghosts**.
- 4-dimensional phase space $(p, x), (P, D)$.
- Two integrals of motion: H and

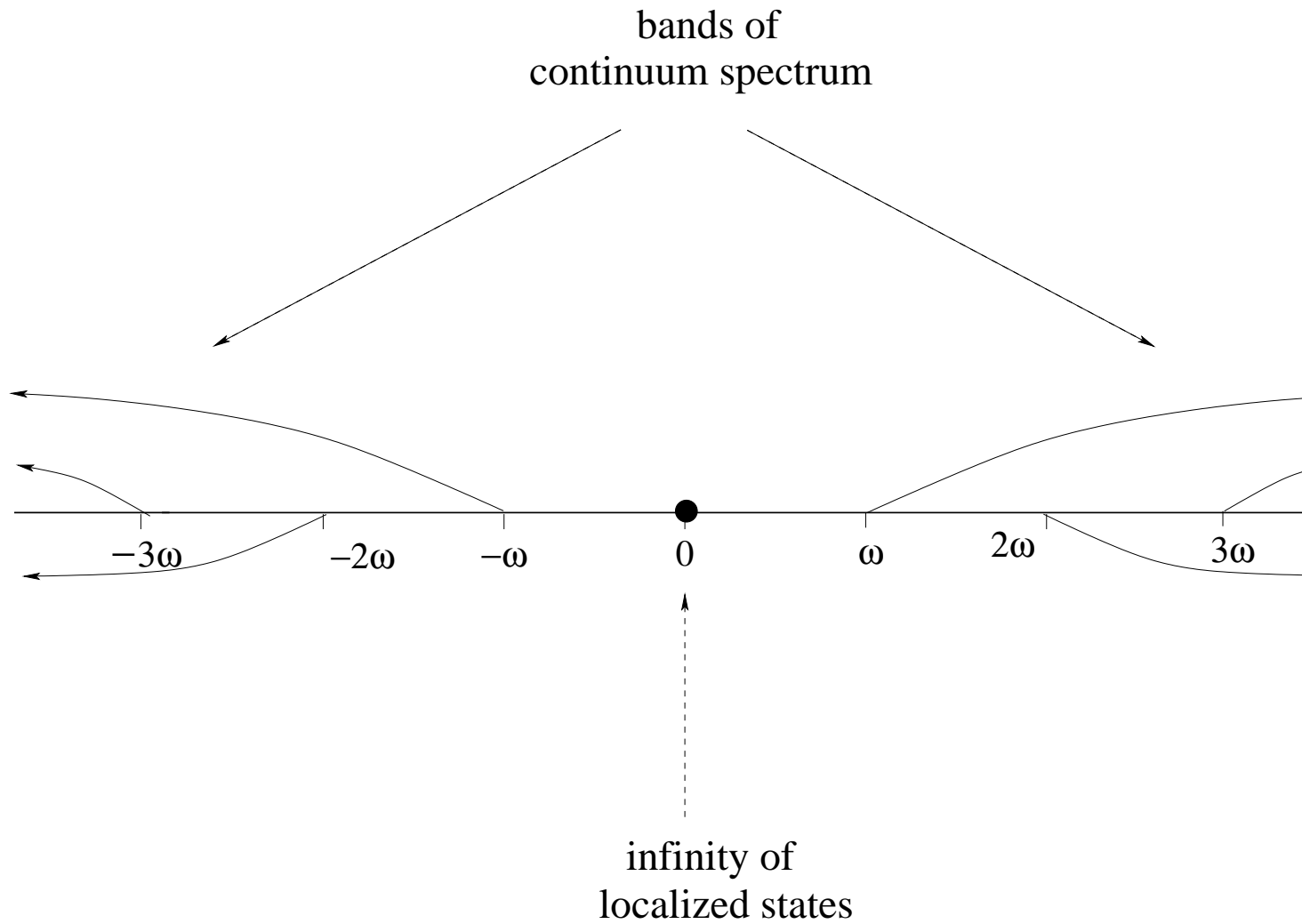
$$N = \frac{P^2}{2} + V(x).$$

- Exactly solvable.
 - The solutions to the classical equations of motion are expressed via elliptic functions.



- Linear growth for $D(t)$; $x(t)$ is bounded. No collapse.
- Other benign ghost systems:
[Pavšič, 2013; Ilhan+Kovner, 2013]

QUANTUM PROBLEM
is also exactly solvable.



Spectrum of the Hamiltonian $H = pP + DV'(x)$.

(1+1) FIELD THEORY

$$S = \int [\partial_\mu \phi \partial_\mu D - DV'(\phi)] dxdt,$$

with

$$V(\phi) = \frac{\omega^2 \phi^2}{2} + \frac{\lambda \phi^4}{4}, \quad \lambda > 0.$$

Equations of motion:

$$\begin{aligned} \square \phi + \omega^2 \phi + \lambda \phi^3 &= 0 \\ \square D + D(\omega^2 + 3\lambda \phi^2) &= 0. \end{aligned} \quad (3)$$

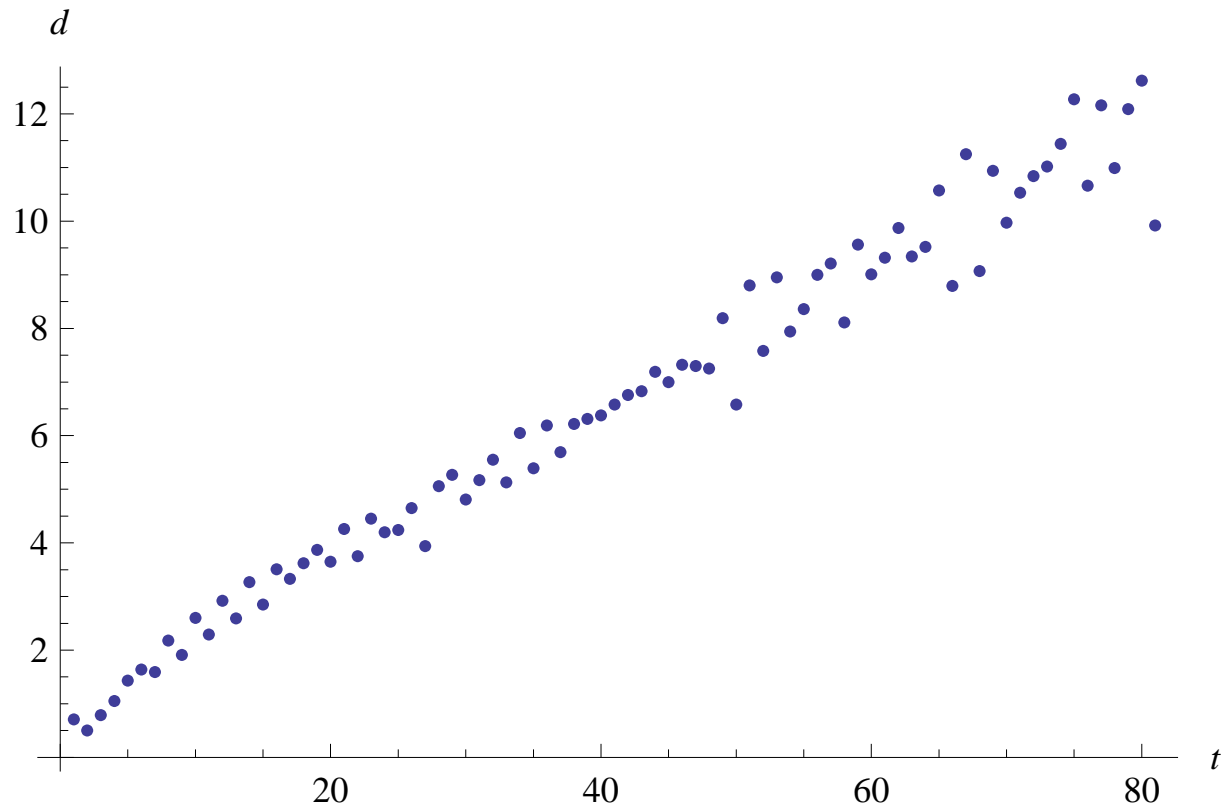
- Only two integrals of motion: the energy and

$$N = \int dx \left\{ \frac{1}{2} \left[\dot{\phi}^2 + (\partial_x \phi)^2 \right] + \frac{\omega^2 \phi^2}{2} + \frac{\lambda \phi^4}{4} \right\}.$$

- Not exactly solvable.

- **Stochasticity**. Solved **numerically**.
- Finite spatial box. Different initial conditions.

TYPICAL BEHAVIOR:



Dispersion $d = \sqrt{\langle D^2 \rangle_x}$ as a function of time.

SWEET DREAM

The TOE is a higher-derivative field theory with benign ghosts living in a higher-dimensional flat space-time. Our Universe represents a 3-brane — a solitonic solution extended in three spatial and the time directions and localized in the extra dimensions. Gravity arises as effective theory on the world volume of this brane.