Title: Emergence of (Space)-Time from Fluctuations

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Collection/Series: Lee's Fest: Quantum Gravity and the Nature of Time

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Abstract:

Based on a previously published model of a quantum gravity path integral, expressed in spectral-geometric variables (Phys. Rev. Lett. 131, 211501), co-authored with M. Reitz and A. Kempf, I study the emergence of Lorentzian signature and time dimension from quantum fluctuations, and argue the physical intuition behind it via a known condensed matter phenomenon.

Localization of Time & Emergence of Lorentz Signature

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In special relativity:

Time and space are similar enough to be mixed in Lorentz transformations,

and yet dissimilar enough to be clearly separated in the Lorentz signature.

How can it be?

Anderson Localization

Picture credit: Etera

P. Anderson, 1958: disorder localizes wavefunctions: $\left(-\frac{\hbar^2}{2m}\nabla^2 + V_{\mathrm{rand}}(\vec{r})\right)\Psi = E\Psi$

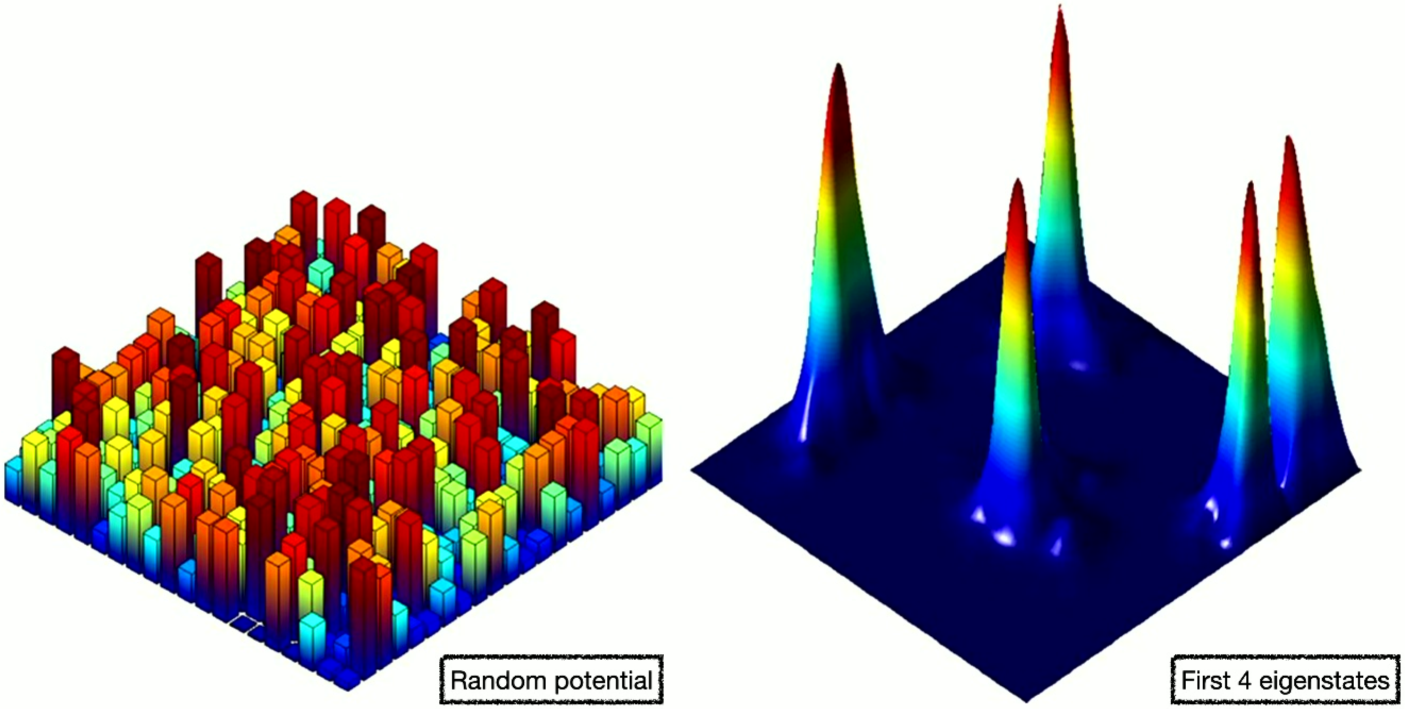
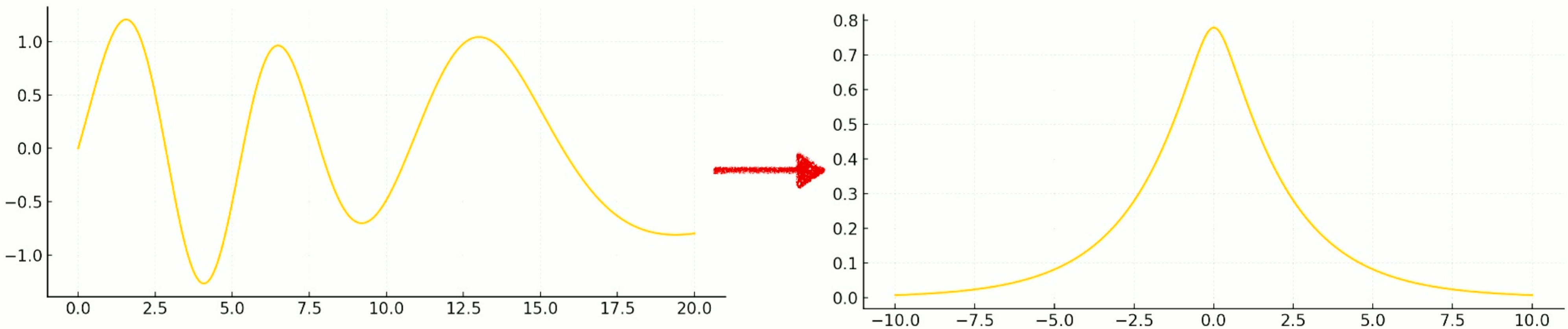


Image from: M. Filoche, S. Mayboroda, PNAS, *Universal mechanism for Anderson and weak localization, 2012*

In 1+1 and 2+1 dimensional systems any small disorder will do, in 3 and higher, a critical amount of disorder is necessary.

Presence of disorder changes the behaviour of wavefunctions:

from oscillatory to exponentially decaying.



$$\nabla^2 = -k^2,\ k \in \mathbb{R}$$

$$\nabla^2 = k^2,\ k \in \mathbb{R}$$

Sign flip!

A toy model

Assume we add disorder to only one dimension: $-\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} + V_{\mathrm{rand}}(x)$

Then, in that dimension (here, x) the wavefunctions will become localized.

Schematically: $$-\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} + V_{\mathrm{rand}}(x) \equiv +\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2}.$$

Or, if we are in 4 dimensions, we can have an effective flip of the signature from Euclidean to Lorentzian:

$$\boxed{\nabla^2 + V_{\mathrm{rand}}(t) \equiv \Box^2.}$$

Laplacian op. -> D'Alembertian op.

Time is the localized dimension, while spatial dimensions are extended.

Previous work (with M. Reitz and A. Kempf):

Path integral:

$$Z = \sum_{N=1}^{\infty} \int_{m^2}^{\Lambda} \mathcal{D}\lambda \int \mathcal{D}\phi \int \mathcal{D}\theta \mathcal{D}\bar{\theta} e^{-\beta S} \frac{\Lambda^{N(\frac{N_f}{2}-1)}}{(N-1)!}$$

Laplacian's eigenvalues

Action contains free bosons, free fermions and a gravitational action:

$$N = \frac{1}{16\pi^2} \int d^4x \sqrt{g} \left(\frac{\bar{\Lambda}^2}{2} + \frac{\bar{\Lambda}}{6} R + O(R^2) \right)$$

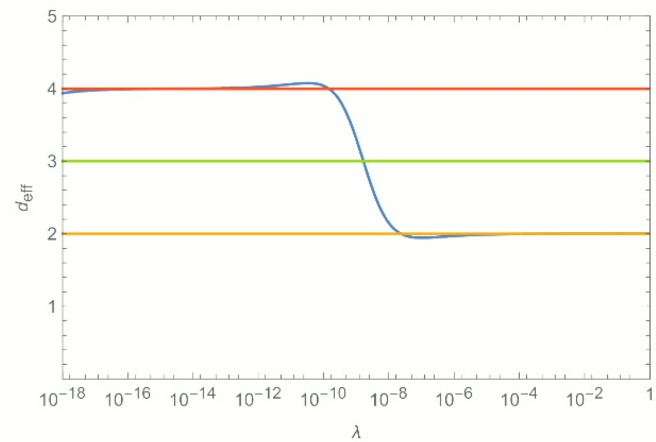
Gilkey, 1975

Fully Euclidean, most interesting result:

$$d_{\text{eff}} = d = N_f - N_b + 2.$$

Effective dimension as a difference
in number of fermion and boson species

Different effective dimension
at different energies for
non-trivial mass spectra.



New: add interactions

Add a Yukawa coupling to the action: $S_{\rm Y} = g \int d^d x \; \bar{\psi}(x)\psi(x)\,\phi(x)$

Integrating out the fields in the path integral serves as a source of disorder for the background geometry:

- Weak coupling: **does not change the sign** of the probability distribution for eigenvalues.

$$Z = \sum_{N=1}^{\infty} \frac{1}{N!} \int_0^{\Lambda} \cdots \int_0^{\Lambda} \prod_{k=1}^{N} d\lambda_k \;\; \left(\lambda_k + M_b^2\right)^{-N_b/2} \;\; \left(\sqrt{\lambda_k} + M_f\right)^{N_f} \times$$
$$\times \exp\left[\Delta S_{\rm int}(\{\lambda_k\})\right] , \quad \Delta S_{\rm int}(\{\lambda_k\}) \in \mathbb{R}$$

- Strong coupling: **changes the sign** of the probability distribution for eigenvalues.
  - As long as the coupling g is greater than a critical coupling.

Change of sign of eigenvalues indicates change of signature. Is it Lorentz or a different combination of - and + signs?

Note: it is not surprising that critical amount of disorder is necessary.

Yukawa is isotropic in the Euclidean signature, how can it single out one or more dimensions for localization?

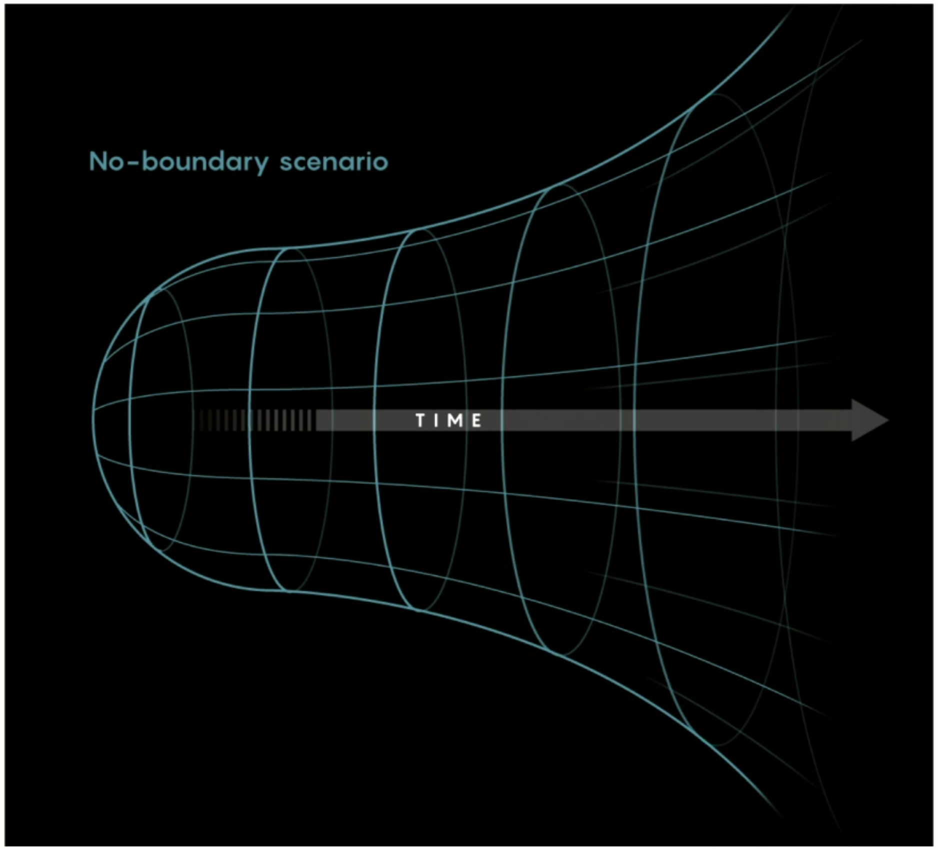
At weak disorder, still isotropic, no localized dimension.

When we increase the amount of disorder, i.e. increase coupling g, a localization happens anisotropically.

Conjecture: the time-like direction is selected as a spontaneously broken symmetry.

If we increase disorder further, possibly more dimensions become localized.

On the Hartle-Hawking no-boundary proposal:



Picture credit: Quanta

Thank you for your attention!

Happy Birthday, Lee!