Phenomenology of Causal Set Nonlocality

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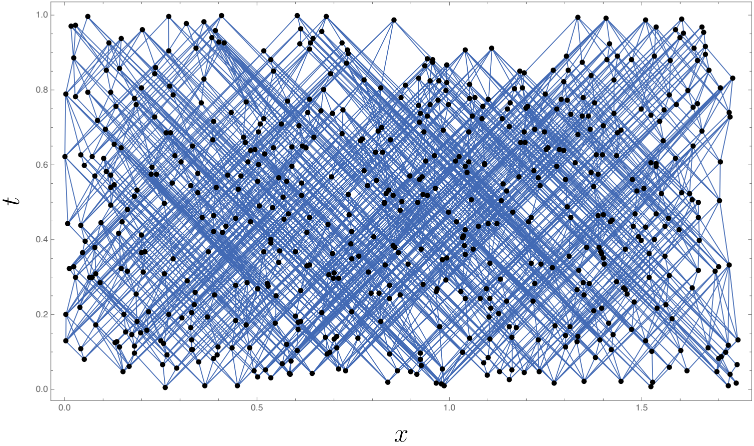
Discreteness + Lorentz Invariance ⇒ Non-locality

A **causal set** is a **locally finite, partially ordered set**. For our purposes you can think of it as a concrete model of a discrete *Lorentz invariant* spacetime.

Marrying discreteness with LI needs *kinematic randomness*. This leads to a radical form of nonlocality.



Causal Set d'Alembertians (R.Sorkin, F.Dowker, DB, L.Glaser)

A concrete example of how nonlocality may affect physics on a causet is given by discrete analogue of $\Box$:

$$\text{Lattice } \Box = \text{ finite difference equation between nearest neighbours}$$

But NN in which sense? To preserve LI need NN in all frames: treat all NN equally.

Following these guidelines one can construct (retarded) causet d'Alembertians in all dimensions

$$B^{(d)}_{xy} = \frac{1}{l^2}\begin{cases} a_d & x = y \\ b_d f_d(n(x,y)) & y \prec x \end{cases}$$

Dynamics of, say, a scalar field ϕ would then be defined by

$$B\phi_x = \sum_{y \prec x} B_{xy}\phi_y = \frac{1}{l^2}\left(a_d\phi_x + b_d \sum_{y \prec x} f_d(n(x,y))\phi_y\right) = 0.$$

Assuming fundamental dynamics given by B leads to **effective, nonlocal dynamics** in the continuum...

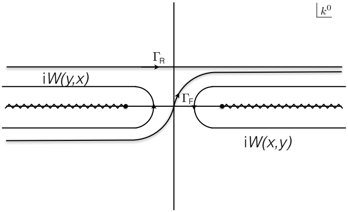
Continuum Nonlocal Field Theory (A. Belenchia, S.Liberati, DB; M.Saravani, S.Aslanbeigi)

Causet d'Alembertians lead to effective nonlocal continuum dynamics:

$$\tilde{\Box}^{(d)}\phi(x) = \frac{1}{l_n^2}\left(a_d\phi(x) + \frac{b_d}{l_n^d}\int_{J^-(x)} d^d y\sqrt{-g}\, f_d(V_{xy}/l_n^d)\, e^{-V_{xy}/l_n^d}\phi(y)\right)$$

Note: (1) $\tilde{\Box} \to \Box$ as $l_n \to 0$, (2) $l_n \geq l$.

Can construct nonlocal QFTs based on these operators. QFT properties determined by singularity structure of (momentum space) Green function.



A continuum of massive modes $k^2 < 0$ contribute to 2-point function

$$W(x-y) = W_0(x-y) + \int_0^\infty d\mu^2 \rho(\mu^2) W_\mu(x-y)$$

W_0 and W_μ are Wightman functions of local, massless and massive fields respectively. ρ is spectral density function determined by choice of $\tilde{\Box}$.

Unruh-DeWitt Detectors Coupled to Nonlocal Fields (A. Belenchia, DB, E. Martin-Martinez, M.Saravani)

Response of an UDW detector with gap $\Omega := E_2 - E_1$ coupled to a scalar field in its vacuum state is

$$\mathcal{F}(\Omega, T) = \int_{-\infty}^{\infty} d\tau \int_{-\infty}^{\infty} d\tau' e^{-i\Omega\Delta\tau} W(\Delta\tau) \chi\Big(\frac{\tau}{T}\Big) \chi\Big(\frac{\tau'}{T}\Big)$$

For a nonlocal field this picks up two contributions

$$\mathcal{F}(\Omega, T) = F_0(\Omega, T) + \int_0^{\infty} d\mu^2 \rho(\mu^2) F_\mu(\Omega, T)$$

where F_0 and F_μ are the responses for local massless and massive fields respectively.

For an inertial detector, and a field theory with $\rho(\mu^2)$ that decays exponentially fast as $\mu \to \infty$ and goes like $\rho \approx l_n^2$ as $\mu \to 0$, e.g. $\rho(\mu^2) = l_n^2 e^{-\alpha l_n^2 \mu^2}$, in the regime $\Omega < 0$, $|\Omega| T \gg 1$

$$\Delta := \frac{\mathcal{F}(\Omega, T) - F_0(\Omega, T)}{F_0(\Omega, T)} \approx |\Omega|^2 l_n^2$$

A Concrete Experimental Setup

Can this deviation from local physics be detected in a lab?

If the experimenter has the ability to repeat the experiment $\sim 10^9$times then it will be able to distinguish the two probability distributions with $\Delta \sim 10^{-10}$. For $\Omega \sim 10^{22}$Hz this would cast a bound on $l_n \lesssim 10^{-19}$m ($\sim$ LHC bound). Is this far fetched?

Since we are analysing process of spontaneous emission we could potentially have large number of events. Consider for example $^{20}_{11}$Na which has a half-life of $\sim$500ms, decays into EM excited, highly unstable $^{20}_{10}$Ne which then decays to its ground state emitting $\sim$11MeV γ-radiation, i.e. $|\Omega| \sim 10$MeV.

200g of $^{20}_{11}$Na would therefore give $N_\gamma \sim 10^{25}$ after just $t \sim 10$s. This number of events would allow for an experimentally detectable relative response of order $\Delta \sim 10^{-23}$ (assuming 0.1% detector efficiency), which in turn implies that the experiment could detect nonlocality scales $l_n \lesssim 10^{-25}$ m, many orders of magnitude better than the resolution of the LHC!!

Note: $^{20}_{11}$Na is just one example. There are more than a dozen nuclear species that provide a reliable source of spontaneous emission of gamma rays which may turn out to be better suited to concrete experimental setups...