The Next Step for the LHC
Erice School for Subnuclear Physics
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Classical and Quantum Theories

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minitalk:

The Conformal Black Hole

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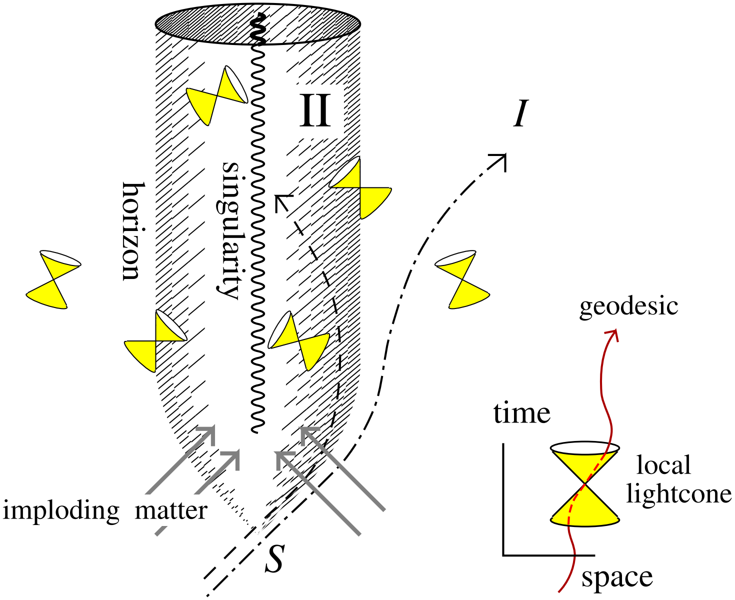
Quantum black hole physics today is in the same state of confusion as elementary particle physics before the advent of the Standard Model.


II
I
singularity
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S

Hawking's result: what is perceived as a vacuum to an observer who goes through the horizon, is a state of entangled particles for an outside observer.
Since the outside observer does not see the particles that disappeared into the black hole, the states he does observe form a *quantum mixed state*, to be described by a *density matrix*.

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A text book procedure should be found to replace that by a quantum mechanical *pure* state.
But whatever you do, you then modify the state described by the observer who went in.

Now, the observer who went in sees particles: a firewall.

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In a given coordinate frame, the metric tensor $g_{\mu\nu}(\vec{x}, t)$ has 10 independent components. One of these is the overall factor ("conformal factor"): $g_{\mu\nu} = \omega^2 \, \hat{g}_{\mu\nu}$. The light cones only depend on $\hat{g}_{\mu\nu}$, not on ω. *Our two observers disagree about ω !!*

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Indeed they do! The outside observer sees that the hole shrinks to zero; the inside observer sees a whole whose mass did not change as he passed the $t = \infty$ line (the horizon). One can write the Schw. metric as

$$\mathrm{d}s^2 = M^2(t)\Big(-\mathrm{d}t^2(1-2/r) + \frac{\mathrm{d}r^2}{1-2/r} + r^2\mathrm{d}\Omega^2\Big)$$

We promote ω to a “local gauge field”, *without modifying the physics!* The field ω always was a dynamical variable in Einstein Hilbert gravity.

Now, splitting off the field ω, it appears to behave just as a scalar “Higgs” particle, *except that it has negative energy* (It sits at the wrong end in Einstein's gravity equation: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$) .

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New observation: demand laws of nature to stay regular as $\omega \rightarrow 0$. This helps. This is great. But:

. . . it gives too strong constraints on the physics (all anomalies have to cancel, which gives too many equations for Nature's constants, and they appear to be in conflict.

The above considerations lead to a theory that has more equations than unknowns (all anomalies must cancel!) All parameters are fixed, including all *masses*, all *couplings*, *Newton's constant*, and the *cosmological constant*. Unfortunately, they all seem to become of order 1 at the Planck scale; no physically reasonable solutions were found.

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End of minitalk on black holes

Dirac's quantum notation

Axioms (*with some subtle modifications*)

- *States:* We have a vector space of bras, $\langle\psi|$, and a vector space of kets, $|\psi\rangle$ (usually infinite-dimensional). They represent physical states. ψ stands short for a description of a state.

- We have the usual operations on these states: an anti-linear mapping $|\psi\rangle \leftrightarrow \langle\psi|$, an inner product $\langle\psi_1|\psi_2\rangle$, and $\langle\psi|\psi\rangle$ is a positive norm.

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- We have the usual operations on these states: an anti-linear mapping $|\psi\rangle \leftrightarrow \langle\psi|$, an inner product $\langle\psi_1|\psi_2\rangle$, and $\langle\psi|\psi\rangle$ is a positive norm.

- *Dynamics:* There is a linear Schrödinger equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}|\psi\rangle = -iH|\psi\rangle$$

Here, H can be any hermitean operator.

Axioms that will *not* be imposed:

• The probability that any one state $|\psi_1\rangle$ is *equal* to another state $|\psi_2\rangle$ is given by $|\langle\psi_1|\psi_2\rangle|^2$.

• The expectation value for an operator X, when measured in any state $|\psi\rangle$, is given by $\langle X\rangle = \langle\psi|X|\psi\rangle$

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Instead, we will use the *weaker* conditions:

- There is an *initial condition:* The universe begins in one, given state $|\psi(0)\rangle$.

- The probability that that state coincides with a "template state" $|\psi\rangle$ is given by $|\langle\psi|\psi(0)\rangle|^2$,
  and the expectation value of an operator X in the state $|\psi(0)\rangle$ is $\langle\psi(0)|X|\psi(0)\rangle$.
  – In an other state $|\psi\rangle$, the expectation value $\langle X\rangle$ is
  $$\langle\psi|\psi(0)\rangle\langle\psi(0)|X|\psi(0)\rangle\langle\psi(0)|\psi\rangle.$$

As states $|\psi\rangle$, we may use *template states*, such as states describing single particles (photons, nucleons, etc.). In terms of these template states, $|\psi(0)\rangle$ may be *entangled*:

$$|\psi(0)\rangle = \alpha|\psi_1\rangle|\psi_2\rangle + \beta|\psi_3\rangle|\psi_4\rangle + \cdots$$

Our weakened axioms should not imply observable changes or limitations in the general concept of Quantum Mechanics.

But they open the door to "underlying theories".

Classical theories that can be mapped onto Dirac quantum systems:

Classical theory:	Quantum theory:
• Discrete periodic system	Finite number of equally spaced energy levels
• Continuous periodic system	Harmonic oscillator
• flat classical sheet	First quantized massless non-interacting fermion
• many classical sheets	Second-quantized massless fermions
• Classical string theory on a lattice (26 or 10 dimensions)	Quantum (super-) string theory on the continuum (26 or 10 dimensions)

Discrete periodic system

Classical theory:

$$(1) \to (2) \to (3) \to \cdots \to (N) \to (1)$$

Corresponding quantum states:

$$|1\rangle \to |2\rangle \to \cdots \to |N\rangle \to |1\rangle$$

Write evolution operator U : $\quad |\vec{Q}(t+\delta t)\rangle = U(\delta t)|\vec{Q}(t)\rangle$.

$$\text{Here: } U = \begin{pmatrix} 0 & 0 & \cdots & 1 \\ 1 & 0 & & 0 \\ 0 & 1 & & 0 \\ & & \cdots & \end{pmatrix}$$

Find operator H such that $U = \exp(-iH\,\delta t)$.
Make unitary transformation to *any* other basis.
One finds a "quantum mechanical" system, obeying Schrödinger equation $\frac{\mathrm{d}}{\mathrm{d}t}|\psi(t)\rangle = -iH|\psi(t)\rangle$.

$U^N = \mathbb{I}$ $\qquad$ N eigenstates:

$$\begin{aligned} U|E_n\rangle &= e^{-2\pi i\, n/N}|E_n\rangle\ , \\ H|E_n\rangle &= \frac{2\pi\, n}{N\delta t}\,|E_n\rangle \qquad . \end{aligned}$$

E_n

2

1

0

These $|E_n\rangle$ are *not* the ontological states. Those are the states $|0\rangle,\ |1\rangle,\ \cdots$, that is, (0), (1), $\cdots$.

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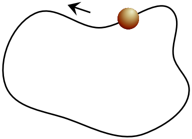
Thus, we obtain a theory that not only describes the Schrödinger equation, but also which initial state $|\psi(0)\rangle$ nature might have chosen.

Continuous periodic system

Classical theory $=$ continuum limit of the discrete theory:



(velocity $=$ constant)

$$\frac{\mathrm{d}}{\mathrm{d}t}|\psi(\varphi)\rangle = -v\,\frac{\partial}{\partial\varphi}|\psi(\varphi)\rangle\ .$$

$$H = v\,\hat{p}\ ; \qquad \frac{\mathrm{d}\varphi}{\mathrm{d}t} = -i[\varphi,\,H] = v\ .$$

$$U^N = \mathbb{I}\ , \qquad E_n = \frac{2\pi\,n}{T}\ , \qquad n = 0,\,1,\,\cdots,\,\infty\ .$$

This is the energy spectrum of the harmonic oscillator with period T.

But where are the negative values of n?

They are not there in the large N limit of the discrete theory!

Leave them out ! We can still make this mapping unitary.

Assume $T = 2\pi$. For harmonic oscillator, take
$H = \frac{1}{2}(\hat{p}^2 + \hat{x}^2 - 1)$. Vacuum energy has to be subtracted
(minus sign over one period! to be avoided).

We now *map* the "primordial" states $|\varphi\rangle$ onto the states $|x\rangle$ of the harmonic oscillator, by mapping the energy eigen states:

$$H|n\rangle = E_n|n\rangle \ , \qquad E_n = n = 0, 1, 2, \cdots, \infty \ .$$

With the proper normalization:

$$\langle\, \varphi \,|\, n \,\rangle = \tfrac{1}{\sqrt{2\pi}}\, e^{in\varphi} \ , \qquad \langle\, x \,|\, n \,\rangle = \frac{H_n(x)\, e^{-\frac{1}{2}x^2}}{2^{n/2}\pi^{1/4}\sqrt{n!}} \ .$$

Thus,

$$\langle\, \varphi \,|\, x \,\rangle = \sum_{n=0}^{\infty} \frac{H_n(x)\, e^{-\frac{1}{2}x^2}}{2^{(n+1)/2}\pi^{3/4}\sqrt{n!}}\, e^{\,in\varphi} \ .$$

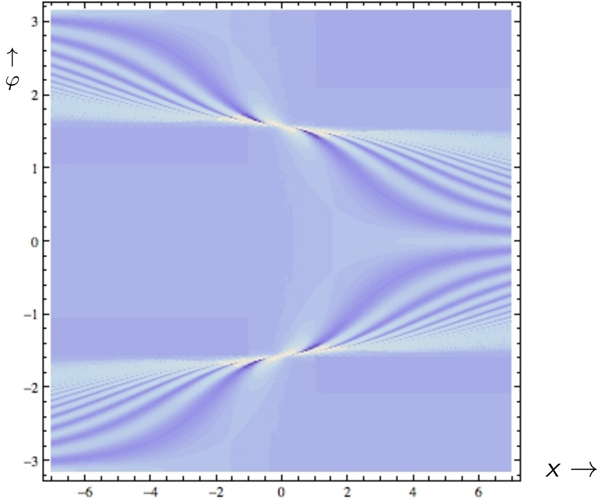
Use generating functions,

$$\sum_{n=0}^{\infty} H_n(x)\, s^n/n! = e^{-\,s^2+2sx} \;,$$

and approximation techniques,

$$\frac{\sqrt{\pi}}{2^n}\, n! = \Gamma(\tfrac{1}{2}n+\tfrac{1}{2})\,\Gamma(\tfrac{1}{2}n+1) \;\approx\; \Gamma(\tfrac{1}{2}n+\tfrac{3}{4})^2 \;,$$

(where later correction terms can be calculated), so that the functions $\langle\varphi|x\rangle$ and $\langle\varphi|p\rangle$ can be systematically approximated. Plot:



Plot of the real part of the transformation matrix $\langle \varphi \mid x \rangle$. Horizontally, x runs from -10 to 10, vertically, φ runs from $-\pi$ to π.

In the busiest parts of the picture, the rapid oscillations are no longer visible.

“Neutrinos”
(= non-interacting chiral fermions in 3+1 dimensions)

The quantum system:

$$H = m + \sigma_i p_i \ , \qquad\qquad p_i \equiv p_r\, q_i \ , \quad |q| = 1 \, , \quad p_r = \pm |p| \ .$$

$$\sigma_1\,\sigma_2 = i\sigma_3 \ , \quad \sigma_2\,\sigma_3 = i\sigma_1 \ , \quad \sigma_3\,\sigma_1 = i\sigma_2 \ ; \quad \sigma_1^2 = \sigma_2^2 = \sigma_3^2 = 1 \ .$$

Beables: $\{\mathcal{O}_i\} = \{\,\hat{q},\, s,\, r\}$, where

$$q_i \equiv \pm p_i/|p| \ , \quad s \equiv \hat{q}\cdot\vec{\sigma} = \pm 1 \ , \quad r \equiv \tfrac{1}{2}(\hat{q}\cdot\vec{x} + \vec{x}\cdot\hat{q}) \ .$$

$[\mathcal{O}_i,\, \mathcal{O}_j] = 0$, in particular: $[r,\, \hat{q}_i] = 0$, because r is $1/p_r$ times the dilaton operator in p space, while $\hat{q}_i$ is scale-invariant, since $|\hat{q}| = 1$. Furthermore,

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$$\frac{\mathrm{d}}{\mathrm{d}t}\hat q = 0 \, , \quad \frac{\mathrm{d}}{\mathrm{d}t}s = 0 \, , \quad \frac{\mathrm{d}}{\mathrm{d}t}r = s = \pm 1 \ ,$$

So, the eigen states of these $\mathcal{O}_i$ evolve classically. a SHEET !

The proof that these “neutrinos” are classical “sheets” is easy. Hilbert space can be considered as being spanned by “sheet” states, the sheet moving in one of the two orthogonal directions with the speed of light, $v_r = \pm 1$.

But the mapping between the Hilbert space of a sheet and that of a neutrino is complicated.

Need a local frame $(\hat{q}, \theta, \varphi)$ on the $\hat{q}$ sphere (coordinates (θ, φ) on the sheet):

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$$\hat{q} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} , \quad \hat{\theta} = \frac{1}{\sqrt{q_1^2 + q_2^2}} \begin{pmatrix} q_3\, q_1 \\ q_3\, q_2 \\ q_3^2 - 1 \end{pmatrix} , \quad \hat{\varphi} = \frac{1}{\sqrt{q_1^2 + q_2^2}} \begin{pmatrix} -q_2 \\ q_1 \\ 0 \end{pmatrix}$$

Define the sheet-flip operators

$$s_1 = \hat{\theta} \cdot \vec{\sigma} , \qquad s_2 = \hat{\varphi} \cdot \vec{\sigma} , \qquad s_3 = s = \hat{q} \cdot \vec{\sigma}$$

or: $\quad \sigma_i = \theta_i s_1 + \varphi_i s_2 + q_i s_3 \quad$ (orthogonal rotation Pauli matrices)

$$L_i^{\mathrm{ont}} = -i\varepsilon_{ijk} q_j \frac{\partial}{\partial q_k} \qquad \neq L_i$$

$$L_i^{\mathrm{ont}} \equiv L_i + \tfrac{1}{2}\left(\theta_i s_1 + \varphi_i s_2 - \frac{q_3\,\theta_i}{\sqrt{1-q_3^2}} s_3\right)$$

One derives for the neutrino $\vec{x}$ operator:

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One derives for the neutrino $\vec{x}$ operator:

$$x_i = q_i\,(r - \frac{i}{p_r}) + \varepsilon_{ijk}\, q_j\, L_k^{\rm ont}/p_r + \frac{1}{2p_r}\Big(-\varphi_i\, s_1 + \theta_i\, s_2 + \frac{q_3}{\sqrt{1-q_3^2}}\,\varphi_i\, s_3\Big)$$

and

$$\langle\, \vec{x},\, \alpha \,|\, \hat{q},\, r,\, s\,\rangle = \frac{i}{2\pi}\delta\,'(r - \hat{q}\cdot\vec{x}\,)\,\chi_\alpha^s(\hat{q})$$

where $\chi_\alpha^s(\hat{q})$ is defined by $(\hat{q}\cdot\vec{\sigma}_{\alpha\beta})\,\chi_\beta^s(\hat{q}) = s\,\chi_\alpha^s(\hat{q})$

Cont'd:

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What is done here is nearly quantum mechanics, except:

the expectation value of an operator is not: $\langle\,\mathcal{O}\,\rangle \stackrel{?}{=} \langle\psi|\mathcal{O}|\psi\rangle$,
but:

$$\langle\,\mathcal{O}\,\rangle = \sum_{\vec{Q}} |\langle\vec{Q}|\psi\rangle|^2\,\langle\vec{Q}|\,\mathcal{O}\,|\vec{Q}\rangle = \mathrm{Tr}\,\varrho\,\mathcal{O}\ \ ;\ \ \varrho = \sum_{\vec{Q}} \varrho_{\vec{Q}}|\vec{Q}\rangle\langle\vec{Q}|\ .$$

This means that we have to restrict ourselves to density matrices diagonal in the CA basis.

“Collapse” of the wave function can now be explained: classical states are diagonal in $|\vec{Q}\rangle$.

Work was motivated when attempting to formulate the quantum rules of compact universes.

*) SUPERSTRINGS may provide for the best scenario for
Cellular Automaton - determinism!

**) But one has to address *NO* - *GO* theorems !

Can one escape no-go theorems (Bell's inequalities)?

Theorem (Bell):
In any deterministic theory intended to reproduce quantum behavior, (for instance when Einstein-Podolsky-Rosen photons are observed through two spacelike separated filters, $\vec{a}$ and $\vec{b}$), one will have to allow superluminal signals between $\vec{a}$ and $\vec{b}$.

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> But there is no "free will" in a deterministic theory (Super-determinism).

Superdeterminism?

Theorem: even so, you cannot avoid Bell's inequalities!

unless you accept "ridiculous fine-tuning", or "conspiracy"

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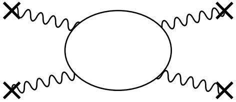
Vacuum fluctuations with spacelike separated correlations are ubiquitous in QFT vacua.

All Feynman diagrams (= all physics) can be derived from vacuum fluctuations.

$$\langle\emptyset|\phi(x^{(1)})\,\phi(x^{(2)})\,\phi(x^{(3)})|\emptyset\rangle \ =$$



$$+ \ \cdots$$

This does *still not* invalidate Bell's theorem completely: the correlations at any given Cauchy surface must "anticipate" what Alice and Bob are going to decide.

This form of superdeterminism requires: *conspiracy*.
"That's disgusting".

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But:

is "disgusting" a sound mathematical argument?

The Superstring

Superstring theory appears to be complicated and counter intuitive. Some physicists insist that physics at smaller distance scales will be strange and counter intuitive.

"*stranger even than quantum mechanics*" (D. Gross) .

should we believe this ?

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Here is the opposite theory:

Superstring theory is even simpler than classical mechanics!

(because there is not even chaos. . .)

If you understand what String Theory really is ...

this idea is conceptually simple, but mathematically hard . . .

References

arXiv: 1204.4926
arXiv: 1205.4107
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On black holes:
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