Decoherence, Energy Conservation and Black Holes

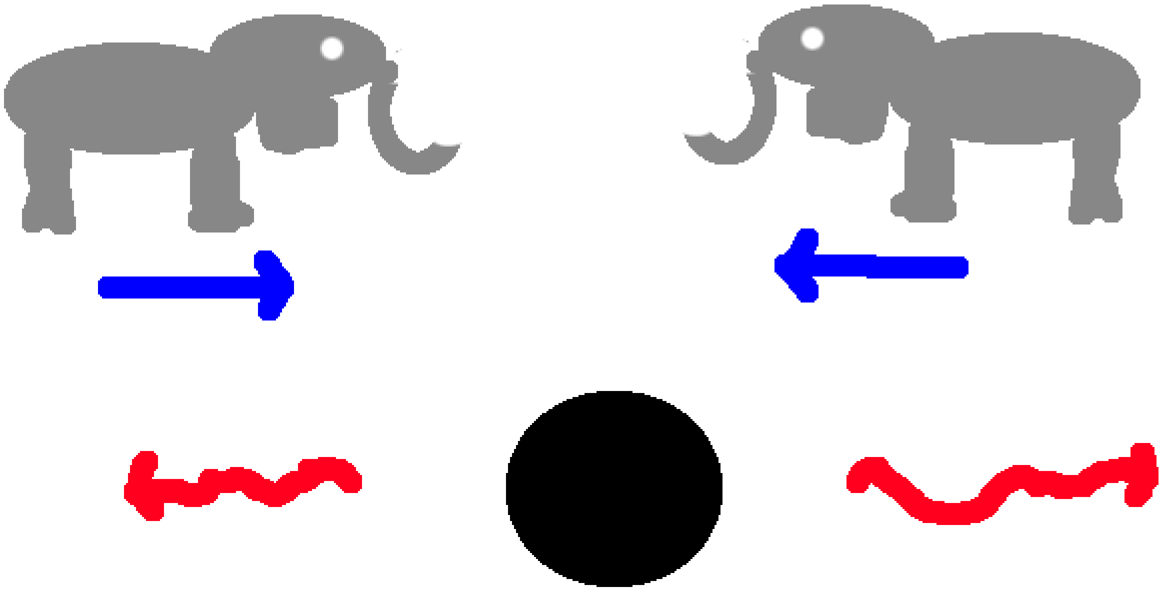
Black Hole Information "Paradox"

Hawking – 1974-- BlackHoles radiate Thermal Radiation,

$$T = \frac{1}{8\pi M}$$

Radiation Incohernet

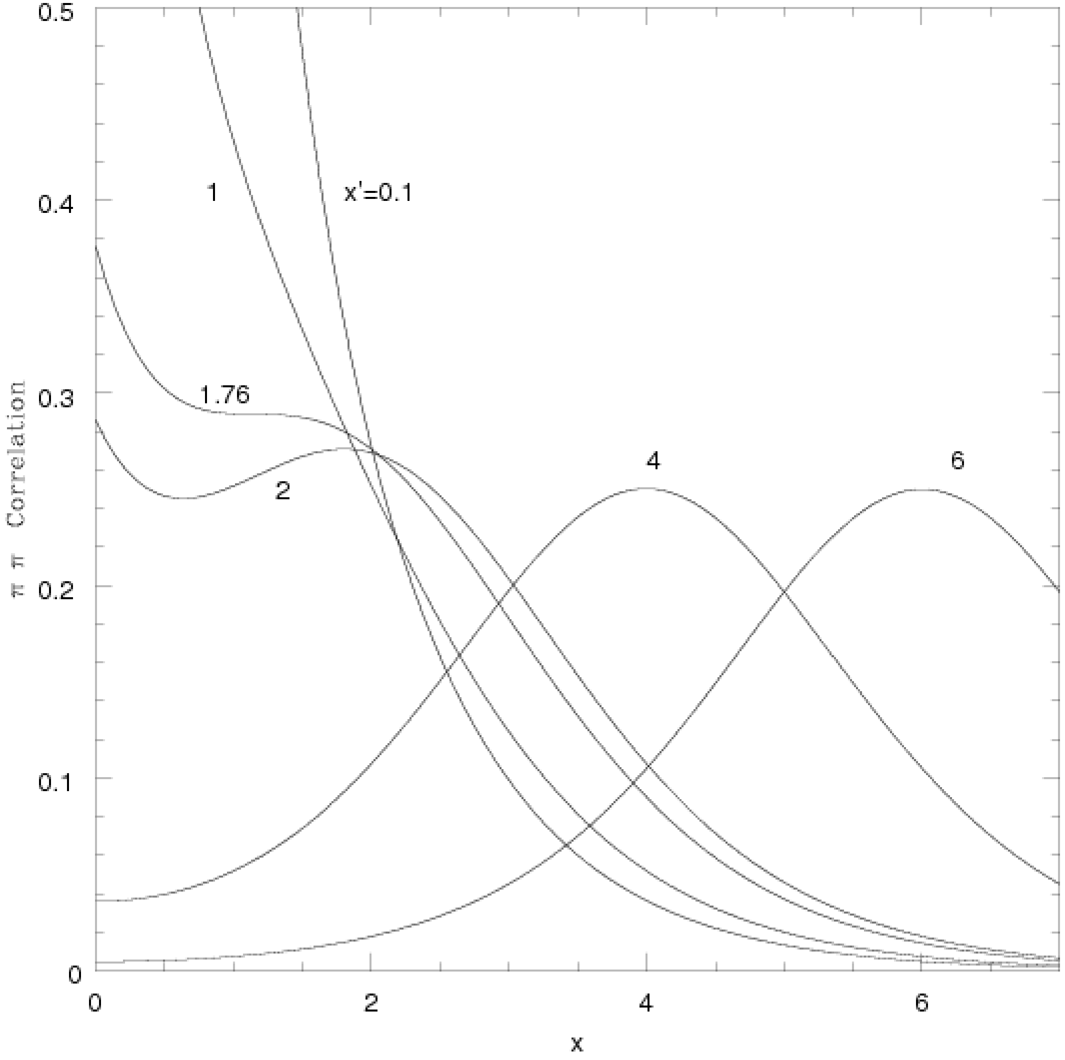
Is net output of a black hole incoherent (Independent of the initial state that formed Black hole)



Thermal Radiation outi

What is happening?

Particle pair creation at the horizon.
Schuetzhold, Unruh
Correlations of particle production at the horizon



P-P Correlation –outside to inside

Correlations robust-- Proposal to use them
to measure quantum creation at horizon
in Bose Einstein condensates.

Particles created at low energy/long wavelength
well outside the horizon.

In Regime where black hole behaves like a
classical black hole

Banks, Susskind, Peskin

Argued that if you go from coherent to decoherent

Energy conservation must be violated

Density Matrix ρ

$$\rho_{ij}(t) = \$_{ij}{}^{kl}(t,t')\rho_{kl}(t')$$

Crucial Assumption:

Evolution of $\partial_t \rho$ depends only on ρ(t)

Markovian assumption

Energy Non-conservation.

(Small (virtual) black holes should produce
Plank scale energy violation.)

Wald, Unruh in 1995 argued that their argument fails. -- either wrong or the energy violation could be pushed up to Plank scale.
(APS says that this has 24 citations.)

Despite that paper, many people keep quoting BSP as justification for black hole “paradox”

(Eg, Giddings, Colloquium at UBC in 2012)

Condensed Matter-- Caldera Leggett model of decoherence

Oscillator bath.-- Couple quantum system to a bath of Harmonic Oscillators.

-- Decoherence tends to be accompanied by energy extraction by the Harmonic oscillators (eg, Unruh, Zurek)

Stamp and Prokofev-- Spin Bath – does not need to occur Immensely controvertial, but by now supported by experiment.

Model for Black holes:

Two particles (1+1 dimensions) collide with δ

$$H = \frac{1}{2}(P_1^2 + P_2^2) + \delta(x_1 - x_2)(\sum_i \alpha_i s_i^z)$$

Momentum Conserved.
Energy Conserved.

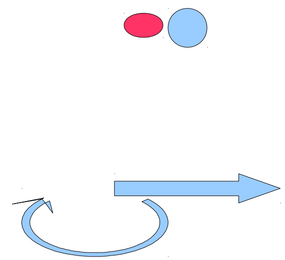
“Internal spins” represent insides of black hole

Assume spins start in s_i^x eigenstates

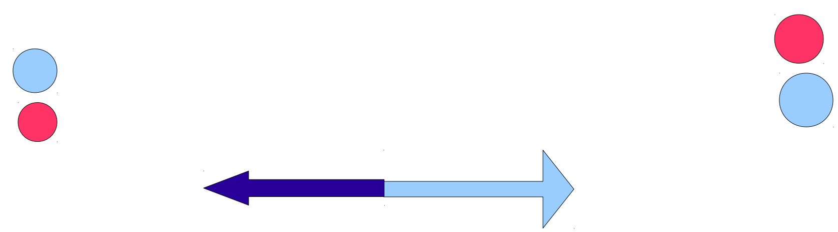
$$\Psi_+(y) = \begin{cases} e^{iky} + B_k e^{-iky} & y < 0 \\ C_k e^{iky} & y > 0 \end{cases}$$

$$\Psi_-(y) = \begin{cases} e^{-iky} + B_k e^{+iky} & y > 0 \\ C_k e^{-iky} & y < 0 \end{cases}$$

$$B_k = \frac{\sum_i(\alpha_i s_i^z)}{2ik - \sum_i(\alpha_i s_i^z)} \qquad C_k = \frac{2ik}{2ik - \sum_i(\alpha_i s_i^z)}$$



Spins rotate
Depends on state
of particles



Entangled state of spin and particles.

Trace out over spins--> The particles decohere.
Eg, higher energies reflect, lower energies go through

spin alters the phases of the outgoing modes--
destroy coherence.

Energy conserved exactly
Momentum conserved exactly.

All energy at beginning and at end is in particles.

Tracing out over the spins does not alter energy

NOT claiming that inside black hole is bunch of spins. Spins are just a simple model for “inside”

In contradiction to BSP theorem, this system conserves energy, conserves momentum, but suffers decoherence.

Violates “locality in time” assumption they made.

Evolution of density matrix depends not only on the external density matrix, but also on details of internal state of the spins (eg internal state of black hole-- especially its energy). Or on history of density matrix.

What was wrong with BSP?

Assumption-- Evolution of density Matrix depends only on the current density Matrix.
No justification in paper.

Another model

Spin 1/2 Particle at x=0
Massive scalar field coupling via σ^z

$$\mathcal{L} = \int \frac{1}{2}\left(\partial_t\phi^2 - \partial_x\phi^2 + m^2\phi^2 + 2\epsilon\phi\sigma^z\delta(x)\right)dx + \frac{1}{2}\Omega\sigma_x$$

If $\Omega << m$ State of ϕ field adiabatic

$$\phi = \phi_0 + \frac{1}{2}\epsilon\sigma^z e^{-m|x|}$$

ϕ_0 free quantum field $\int \frac{1}{\sqrt{2\pi\omega}}(a_k e^{-i\omega t}e^{ikx} + a_k^\dagger e^{i\omega t}e^{-ikx})dk$

$$\phi = \int \frac{1}{\sqrt{2\pi\omega}}((a_k e^{-i\omega t} + \epsilon\frac{2m\sigma^z}{\omega^{\frac{3}{2}}})e^{ikx} + (a_k^\dagger e^{-i\omega t} + \epsilon\frac{2m\sigma^z}{\omega^{\frac{3}{2}}})e^{-ikx})dk$$

$$\omega^2 = k^2 + m^2$$

Coherent state -- $|\alpha>$

$$a|\alpha >= \alpha|\alpha > \qquad < \alpha|\alpha' >= e^{-(\alpha-\alpha')^2}$$

The field's “vacuum” state depends on value of σ^z

If initial state of the spin is σ^z = 1 eigenstate

$$\rho_z = \frac{1}{2}\begin{pmatrix} 1+\cos(2\tilde{\Omega}t) & e^{-()\frac{\epsilon^2}{m}} sin(2\tilde{\Omega}t) \\ e^{-()\frac{\epsilon^2}{m}} sin(2\tilde{\Omega}t) & 1-\cos(2\tilde{\Omega}t) \end{pmatrix}$$

Evolution of ρ depends on history, not only on

instantaneous value of ρ

If one starts with initial ρ = $\begin{pmatrix} 1 & e^{-()\frac{\epsilon^2}{m}} \\ e^{-()\frac{\epsilon^2}{m}} & 1 \end{pmatrix}$

Evolution very different from evolution of previous from $\tilde{\Omega}t = \frac{\pi}{2}$ even though density matrix the same

Banks, Susskind, Peskin wrong in saying decoherence implies energy non-conservation.

There is no reason from energy conservation to worry about Black Holes generating entropy unless one knows much more about the exact form of the black hole decoherence.

Interior energy tied to external gravitational field. which can alter the emission process so there exists process by which energy conservation (and charge and angular momentum) can be enforced.

One would expect the BSP argument to apply to other conservation laws (eg, baryon, lepton,..)