Thermal duality and gravitational collapse

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Introduction – Black holes and discrete symmetries

- The family of classical black hole solutions is parameterised by mass, charge (e.g. standard model gauge charges) and angular momentum.

- Consider the effect of discrete symmetries on them. C and P are satisfactory but T is not – time reversed BHs are not allowed.

- Radical violation of T and by extension CPT symmetry.

Introduction – Black holes and discrete symmetries

- Proposed resolution exploits thermal duality – another discrete symmetry.

- BHs can in principle be produced in scattering experiments. The highest energy cosmic rays have about enough energy to form quasi stable BHs on collision.

- Short lived BHs could be produced at LHC in some scenarios so symmetry is not entirely a theoretical question.

Time reversal and the black hole interior

- The exterior solution for a non-rotating BH is T symmetric, e.g. neutral case

$$ds^2 = (1 - \frac{R_s}{R})dt^2 - (1 - \frac{R_s}{R})^{-1}dR^2 - R^2(d\theta^2 + \sin^2\theta d\phi^2)$$

- In the rotating case, T is equivalent to P in the exterior region, so still produces a permitted state.

- Continuation inward is possible, but necessarily violates T symmetry (Finkelstein metrics).

- Time becomes correlated with topology – events inside can be LATER than those outside but not vice-versa.

T and the quantum black hole

- The quantum version of a black hole (Hawking BH) can be in thermal equilibrium with an external heat bath in what appears to be a T reversible state to an external observer.

Black holes as particle accelerators

- Black holes are the ultimate particle accelerator.

- Divergent centre of mass energy of collapsing matter – or any individual particle pair.

- Necessity of singularity (Penrose theorem) to prevent infinite energy collisions.

- Particles are isolated by hitting a space-like singularity – time must end abruptly to prevent infinite energy collisions.

- Note that a problematic situation is already set up as a horizon is formed and crossed.

Black holes and strings

- If the energy released by the gravitational accelerator were converted to strings, the possible number of states produces increases exponentially with energy (due to the string spectrum).

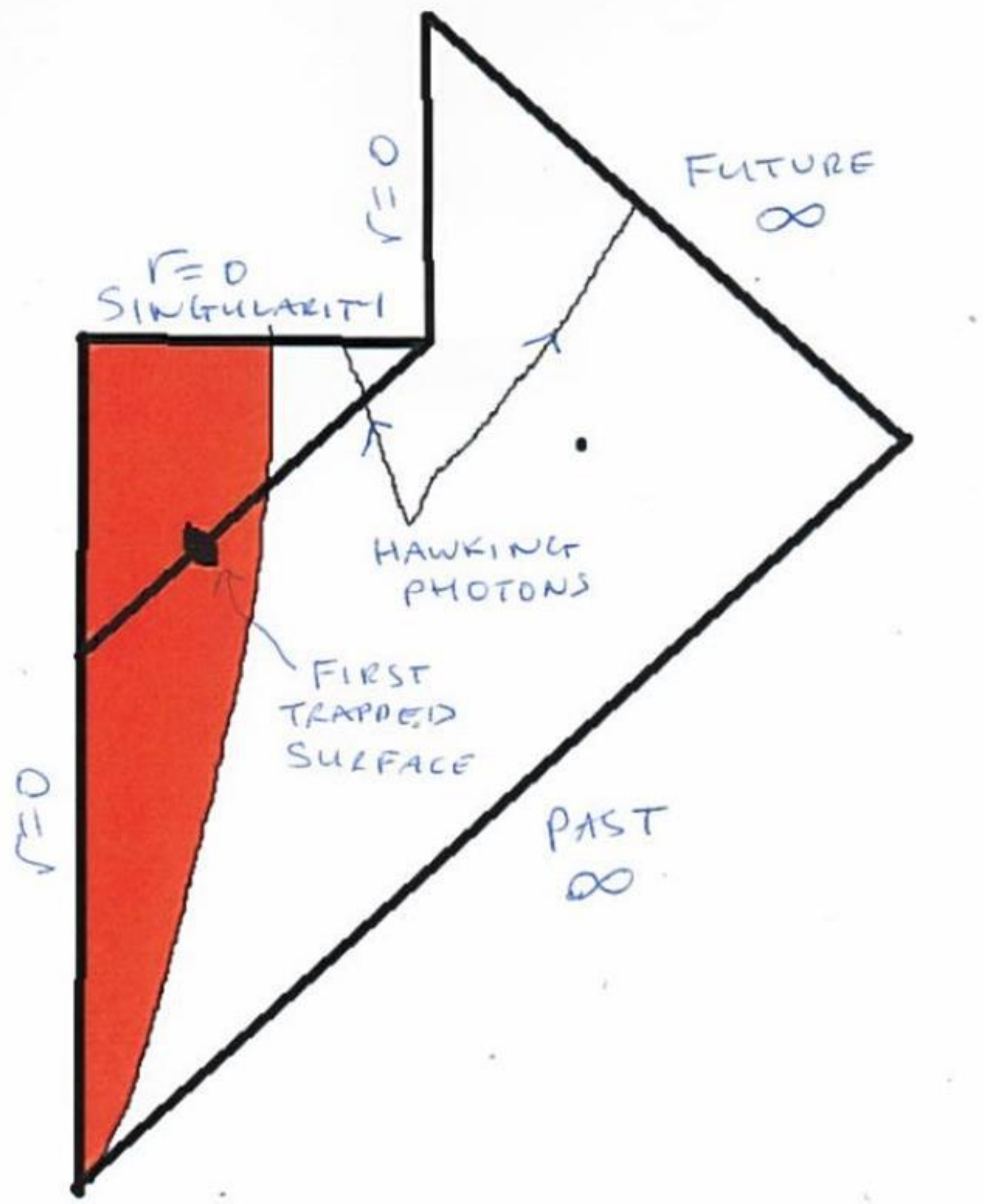
- Within a certain (fixed) distance of the horizon, the effective string entropy would match and then exceed the Hawking-Bekenstein entropy. (Hewitt, Susskind 1993)

Information problems with black holes

- Information from collapsing matter is destroyed.
- New information is randomly created in the Hawking radiation process.
- Reconciliation of information problematic due to the monogamy of entanglement.
- Divergent horizon entanglement entropy.
- Holographic limit problem.

Evaporating black hole

- Note the causal disconnection between the original information and late Hawking radiation.
- Monogamy of entanglement prevents reconciliation of 'lost' and 'found' information.



Information problems contd…

- Entangled Hawking pairs are formed close to the horizon: one is destroyed at the singularity along with infalling matter.

- Both effects inconsistent with quantum information theory.

- Both are related to T asymmetry in the BH.

- Common sense suggests some kind of re-emergence of the original information, but studies show this is difficult to achieve – this is the firewall paradox.

- Some kind of near horizon buffer apparently needed to store information.

Surface entropy

- Relationship of the Hawking entropy to entanglement entropy is unclear (both are proportional to the horizon area).
- The Hawking entropy is finite, and depends only the area.

$$S = \frac{A}{4}$$

- The thermal entanglement entropy diverges, and depends on the number of particle species.

$$s = \frac{N}{180\pi r^3} \qquad S = \frac{NR^2}{90r^2}$$

Holographic information problem

- If we accept the holographic principle, then even immediately after crossing the horizon the information density of collapsing matter exceeds the holographic bound based on the Hawking-Bekenstein entropy.

- Any holographic bound must in any case be violated in the approach to a singularity with zero surface area.

- A positive result from the Fermilab Holometer experiment (for example) would raise the status of this issue.

- This suggests that a new physical mechanism is needed to store information just OUTSIDE where a horizon would form during collapse.

Should black holes really be possible?

- Non-conservation of quantum information and infinite energy particles suggest that a true black hole may be physically impossible.

- However, it seems that the horizon neighbourhood is unremarkable unless some novel effect intervenes.

A stage illusion?

- Maybe the black hole is like a cosmic stage illusion – we are misdirected by reasonable assumptions to believe that something impossible has happened.

- How? Because our assumptions about the situation lead us to miss the possibility that the trick has ALREADY HAPPENED earlier than we think.

- In this case, the infalling matter is converted to another, radically different form BEFORE a closed horizon can form.

Assumptions

- Take thermal duality of heterotic string models seriously and look at the consequences.
- Equivalence principle valid.
- BUT: don’t assume space near collapsed object is necessarily ‘normal’.

Key features of the final state

- Thermodynamic properties of Hawking radiation are used as a guide.
- Embedded in and in equilibrium with equivalent surrounding vacuum for BH – excise the BH and replace with stringy region.
- A thermal state, close to equilibrium, which slowly evaporates if surrounded by vacuum.
- Thermal state is (statistically) T reversible.

Geometry and radiation

- Rindler vacuum for accelerated observer has depleted energy.
- Unruh radiation – the normal vacuum is a thermal excited state relative to the Rindler vacuum.
- Equivalence principle relates Unruh and Hawking radiation.
- Conjecture: Possible to excise the near horizon region of a BH and replace with a hot black body.

Proposal

- A hot string phase can replace black holes.

- A mechanism can convert collapsing matter to this hot string phase, avoiding production of BHs.

Hagedorn transition

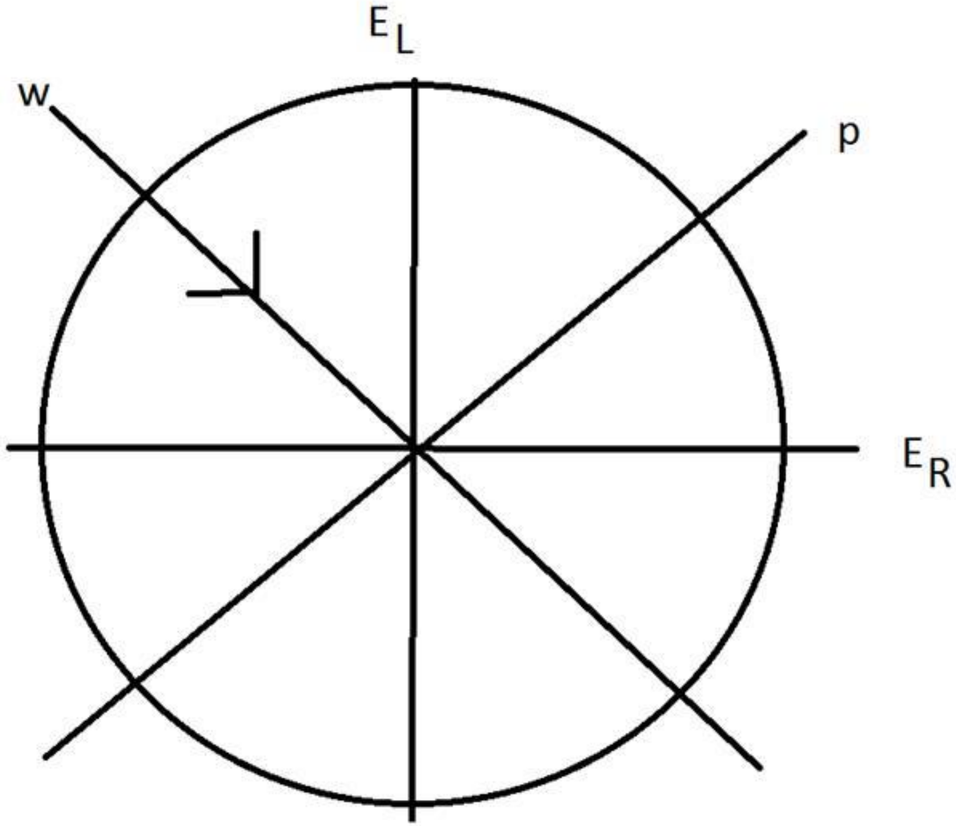
- Nature of Hagedorn transition: strings of arbitrary length form.
- Condensate formation makes sense of this as a phase transition.
- Thermalons alter the effective string tension – string thermalon coupling.
- Effective Lagrangian for hot phase is like a Ginsburg-Landau superconductor.

$$\mathcal{L} = \frac{1}{2}\sqrt{-g}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}m^2(\beta)\phi^2 + \frac{1}{4!}\lambda(\beta)\phi^4 + O(\phi^6)$$

- Distinctive feature of heterotic models: thermal duality.
- Heterotic models do not have D-branes (Polchinski) so only a string based model can work.

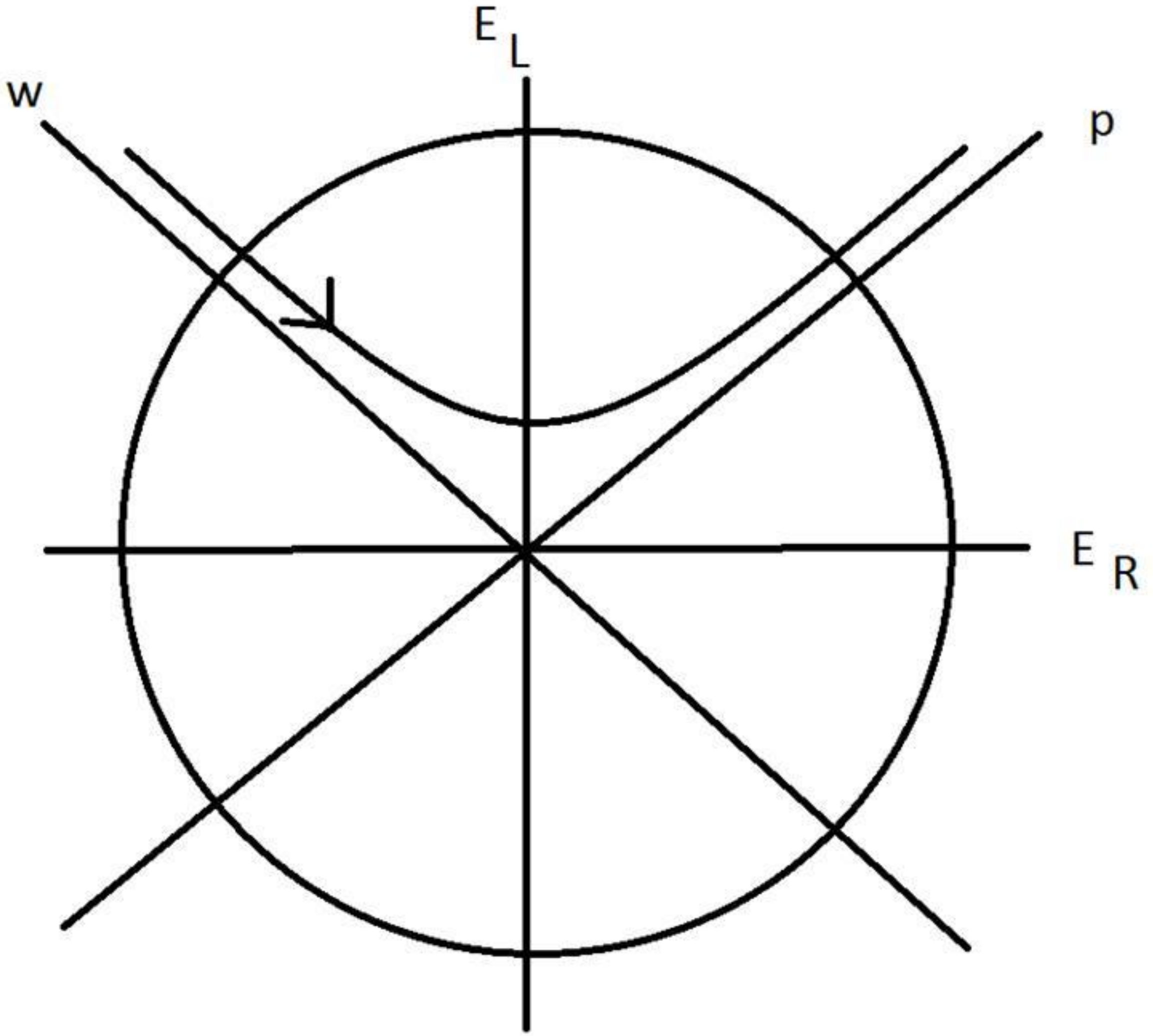
Thermalon trajectories

- Non – heterotic



$$M^2 = -8 + \frac{\beta^2}{\pi^2} = -8 + 4r^2$$

Heterotic thermalon trajectory



$$m^2(\beta) = -6 + \frac{\pi^2}{\beta^2} + \frac{\beta^2}{\pi^2}$$

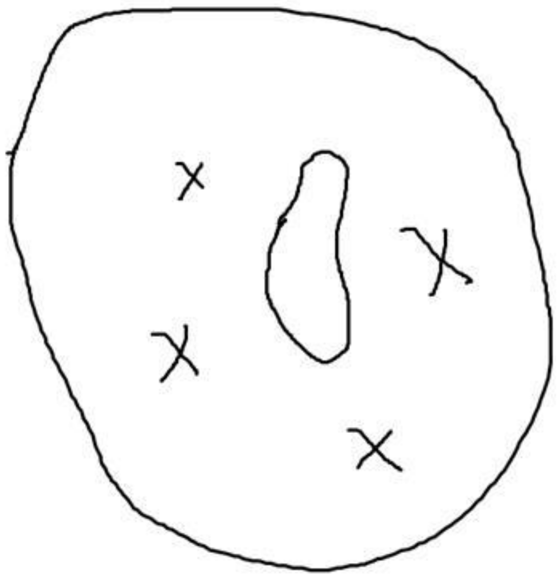
Thermalon interactions

Thermalons are expected to interact with normal matter, as they regulate the thermal string spectrum by increasing the effective string tension.

However, the thermalon mass diverges as T approaches 0, so there are no long range forces between ordinary particles associated with them.

Feynman diagrams

- Feynman diagrams: string worldsheet sphere (plus torus….) with (2,4,…) punctures for potential in the weak field limit.
- The amplitude is on shell at the upper and lower transition points.
- Off shell issue (scattering amplitude only relevant on shell) takes a full calculation out of range of these simplistic methods.
- However, we will use only qualitative properties of the couplings.



Final state

- Almost constant temperature in the bulk.
- Expulsion of gravitational gradients due to energy polarisation in a gravitational gradient is a consequence of the thermal duality of Z.
- Surface energy – positive at the outside, negative at the inside (unstable...) of a shell region.
- Hyperbolic spatial geometry

$$du^2 = \frac{dr^2}{1 + a^{-2} r^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2)$$

  makes the bulk properties AREA dependent.
- The final state is in thermal equilibrium - so has T symmetry.

Holographic properties of the final state

- Effective holography - information is conserved and stored in a quasi 2 dimensional form

- Relationship to non-commutative geometry (the fuzzy sphere)

- Differential version – shells as ‘quotients’ of fuzzy spheres.

Free energy of black holes and strings

- The free energy of black hole and that of a broken symmetry region filled with string should be the same (to first order in 1/M) as Hawking's entropy calculation applies to both.
- Free energy of a BH is half its total energy in the Schwarzschild case.
- Simple Hagedorn string as zero free energy.
- This model has positive free energy in the surface layer making agreement possible.

Thermalon weak field solutions

- Effective mass depends on distance from the horizon

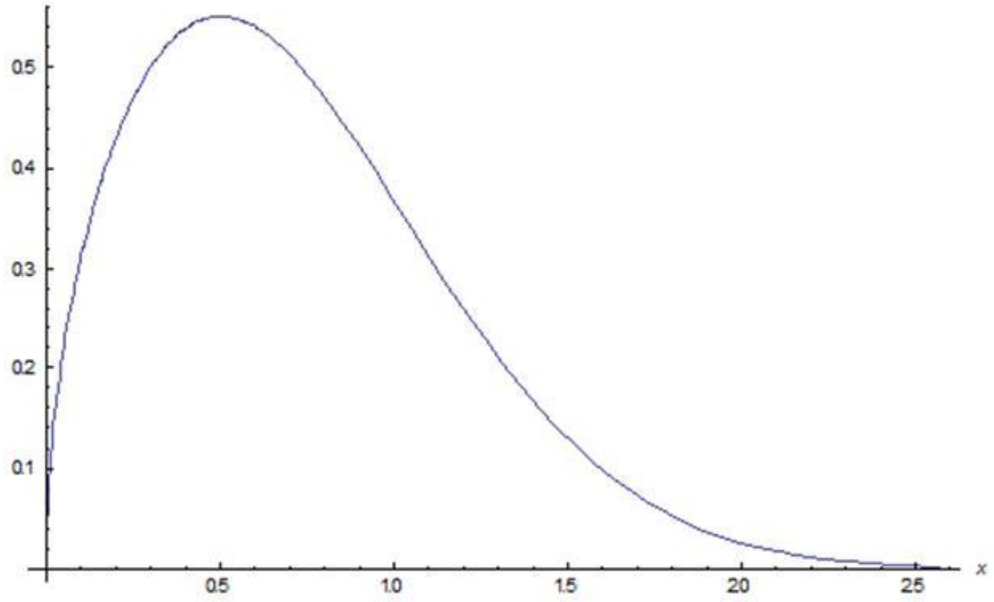
$$m^2(r) = (\frac{1}{4r^2} + 4r^2 - 6)$$

- Field equation in Rindler coordinates is

$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} = m^2(\beta(r))\phi = (\frac{1}{4r^2} + 4r^2 - 6)\phi$$

Accelerating wall solution

$$\phi = \epsilon\sqrt{r}\exp(-r^2)$$



ϕ/ϵ for the weak heterotic solution

Back reaction on metric

- The gravitational source

$$\mu = \rho + Tr(p)$$

is given by

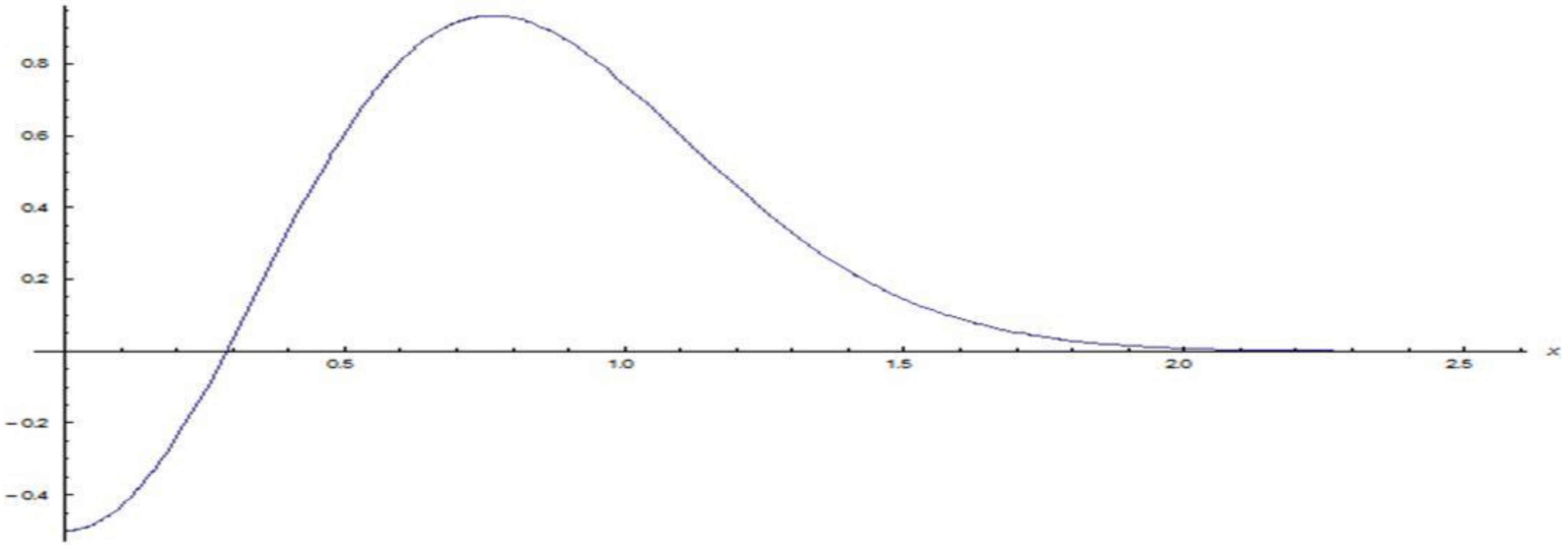
$$\mu = \frac{1}{2}\frac{\partial(\theta V)}{\partial\theta} = \frac{1}{2}\frac{\partial(yV)}{\partial y} = \frac{1}{2}(\frac{1}{4r^2} - 3)\phi^2$$

where

$$\theta = \beta^{-2} = T^2$$

Red shifted source (seen from infinity)

- Note the negative energy density close to the horizon
- Source is zero at $r = \dfrac{1}{2\sqrt{3}}$



Area difference across the wall

$$2\pi\delta A \sim 4\pi GA \int_0^\infty \mu\beta dr = 2\pi GA(\frac{\pi}{2})^{3/2}\epsilon^2$$

This can be described by a 'warp factor' w:

$$w - 1 = G(\frac{\pi}{2})^{3/2}\epsilon^2$$

Mechanics of the solution

- High pressure region squeezed between accelerating boundaries with positive (leading side) and negative (trailing side) inertia.
- Newtonian mechanics allow this configuration to undergo self sustained acceleration.

Where is a thermal deformation possible?

- Impossibility of thermalon distortions in free space, due to warp factor
- Only become possible near a collapsed object.
- This is a geometric feature which allows a conversion mechanism from matter to deformed regions only near collapsed objects.
- Accelerated thermalon modes remain unexcited in empty space.

Thermalon traps

- There can be a ‘thermalon trap’ near collapsed objects, with temperatures defined relative to a local timelike Killing vector.
- Thermalon deformation gives an interpolation between Schwarzschild solutions of different mass
- Difference in area across the deformation is related to energy.

‘Enhanced’ black hole

- The thermalon trap around a black hole could be excited (non-zero deformation).
- This would give an increased surface area and mass to the collapsed entity.
- The number of quantum states would increase – the hole would acquire ‘stringy hair’
- The entropy would increase in proportion to the area difference across the thermalon region.
- This would maintain consistency with Hawking’s law.

What does this give?

- So far have we have a possibility of thermalon energy ‘in orbit’ near horizon
-
- Dressed black hole with extra information to specify observable state.

- Still a black hole at centre, still nothing to stop particles falling in.

Space filling solution

- A solution to the thermalon 'field equation' with constant φ and constant temperature is possible at the point (β_s, ϕ_s)

  where T^2V is a minimum, so that the gravitational source vanishes.

- Such a point must exist by the mean value theorem.

- This gives a stable space filling thermalon solution.

Expelled gradients

- The London response

$$\frac{\partial \mu}{\partial \beta}$$

has opposite signs on either side of the stable temperature for the bulk region.

- This has the effect of expelling gravitational gradients from the bulk.
- The gravitational source (positive and negative) is confined close to the boundaries.

Ball solution

- Hyperbolic geometry of interior region

$$du^2 = \frac{dr^2}{1 + a^{-2}r^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$a^{-2} = -8\pi GV > 0$$

$$ds^2 = dt^2 - du^2$$

- Surface layer carries the gravitational source .
- Expelled gravitational gradients in the interior – like a gravitational magnetic superconductor .

Intermediate cases

- Transition to strong phi gives increasing nonlinearity, with increasing area difference and thickness of shell.
- Pendulum analogy, with solution in elliptic functions.
- Parameterization of shells by warp factor.
- Deviation from spherical symmetry gives non-uniform thickness and warp.
- Build of opacity as shell thickens.

Transition mechanism requirements

- Locality.
- Single particle energy conversion is possible.
- Thermalisation of kinetic energy.

Space crushing model of transition

- Infalling matter couples to thermalon traps.
- Thermalon traps contract space as the energy of decelerating particles is converted.
- Deformation of space gives a thermalisation mechanism for kinetic energy.
- The trap is analogous to a crumple zone or shock front.
- Matter bound to a trap appears almost static to an outside observer, but moving close to c to an interior one.

Trap location

- Where will a trap form during gravitational collapse?
- A spherical shell of mass m falling onto existing collapsed object of mass M will cause a trap to form at a distance $d \sim G\left(\frac{GMm}{d}\right)$ from the surface, due to the Schwarzschild neck geometry.
- A point particle of mass m falling onto existing collapsed object of mass M will increase in kinetic energy for local static observers, so that at a distance d from the surface of M it has energy $\sim\frac{GMm}{d}$.
- This will form a horizon which will meet M when $d \sim G\left(\frac{GMm}{d}\right)$ and again $d \sim G\sqrt{Mm}$

Newtonian formalism

Re-arranging the criterion for trap formation in these cases gives $\frac{GMm}{d^2} \sim 1$

At a distance d from a virtual horizon, mass scales as $\frac{GMm}{d}$ and acceleration as $\frac{1}{d}$ due to blue-shift factors.

So the effective gravitational force scales as $\frac{GMm}{d^2}$, like the classical Newton formula.

Restoring the string tension scale, the criterion for trap formation becomes $F \sim T$ i.e. that the Newtonian gravitational force is comparable to the string tension as two bodies approach.

This shows the mutual nature of the trap formation process, and that it is a kind of epiphenomenon of the gravitational interaction.

Deformation generation mechanism

- Possibility of self-consistent feed mechanism for decelerating matter to thermalons on reaching a thermalon trap.
- 4 puncture model of simplest matter- thermalon interaction.
- Larmor radiation comparison: $P \sim (\dot{J})^2$
- Thermalon couples to left-moving energy (on heterotic strings).
- E and t are ~ $\sqrt{Mm}$ and $G\sqrt{Mm}$ at a trap, so $P \sim 1/G$ here.
- This is consistent with $P \sim GP^2$
- Power may drain consistently from matter into a thermalon trap.
- Earth's magnetic field analogy for a stable self-sustaining field and current configuration.

Spontaneous deceleration

- Spontaneous deceleration gives alternative reinforcing particle trajectories, in addition to the conventional one in Feynman's picture of quantum processes.

- Decelerating trajectories can be dominant, due to a higher overall probability (the entropy is related to many possible final states in the thermalon phase).

- Reduction in free energy during conversion shows a dissipative process.

Energy and distance scales

- Apply the criterion to typical particle energies in collapse:
- Electron and 10 solar mass object case.
- Energy release: ~ 10^{26} J
- Distance scale: ~ 10^{-26}m

Spherical collapse case

- Thin spherical shell collapsing inwards.
- Partly realistic, due to extreme Lorentz contraction.
- Solution peels from the outside – mass of shell remains critical for its area as it contracts.
- Kinetic energy progressively converted to thermalon warp form.
- Space becomes longitudinally compressed.
- Similar to shock deceleration.

Single particle case

- Critical gravity surface develops ‘finger’ towards infalling particle.
- Nucleation begins as finger and particle meet.
- Similar to numerical simulations of merging BHs.
- Trap surface evolves into a spherical form (for radial collapse, zero angular momentum case).
- Energy diffuses around the thermalon trap.
- Radial compression is greatest the near particle location.

Colliding particles case

- Particle –particle collision case: both particles become string nucleation sites when their mutual gravity becomes critical (~T).

Energy propagation around a trap

- Thermalon Green's function determines transverse spread for point particle case.

- Increment of surface area is consistent with the $\sqrt{Mm}$ scale - the extra area ~ Mm is comparable to the area over which thermalons spread around the trap as the particle falls to the existing surface.

Timescales and scaling.

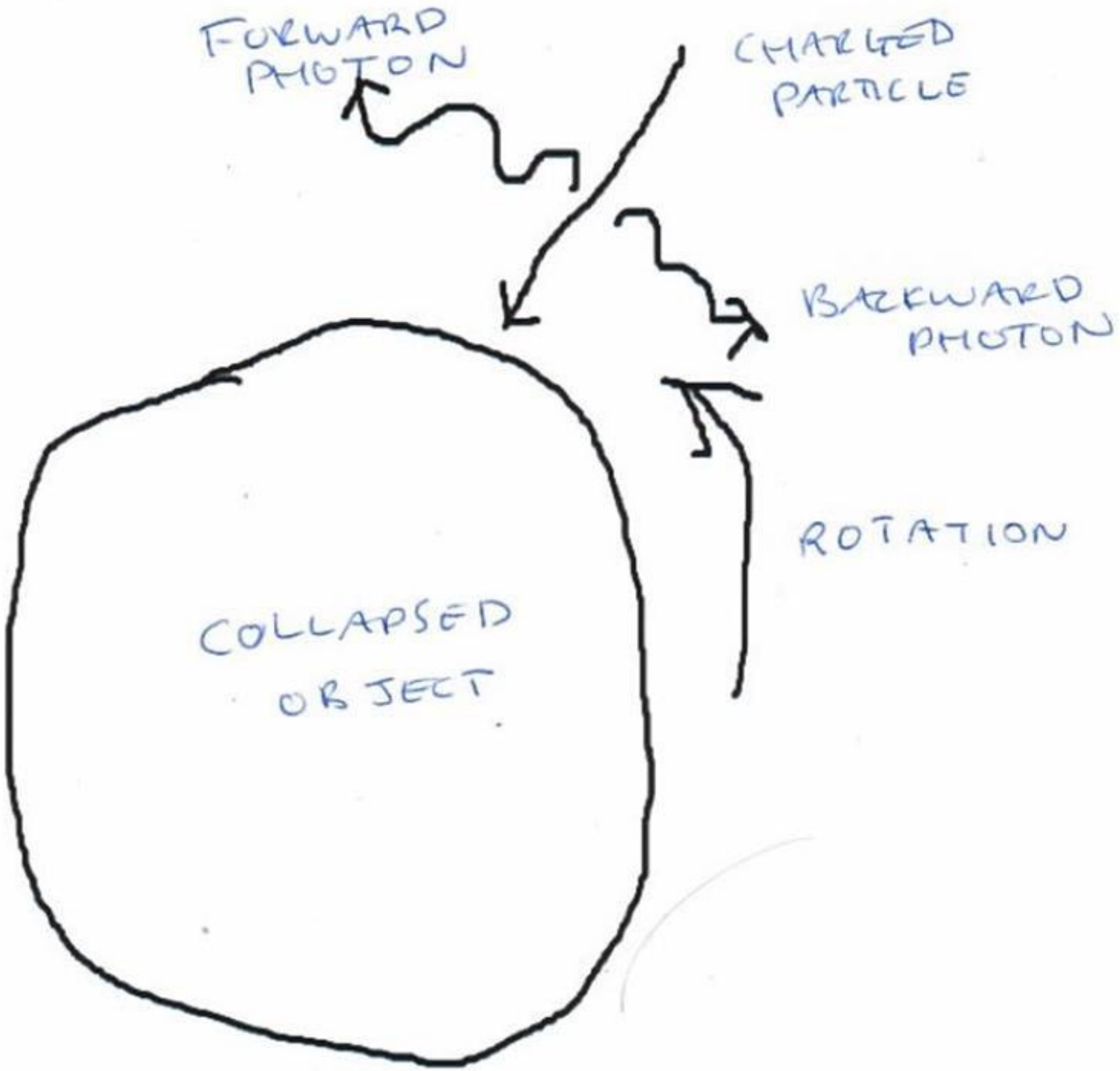
- Time for conversion $\sim M^2$
- Time for diffusion across trap $\sim M^2$
- Time for evaporation ~M^3 (as for a Hawking BH).
- Shell conversion would still be underway for collapsing astrophysical objects in their current state.
- Thickness of shells is ~ $\log(M)$– only a few hundred Planck lengths thick.
- They are effectively holograms of the collapsed objects.

Entanglement entropy

- No horizon in this model, so there is no infinite horizon entanglement.
- The Hawking entropy may be realised as an entanglement through mixing between even and odd thermal parity sectors, so that short and long string sectors become entangled.
- In this way, the field theory state is entangled with the long string sector, and has incomplete state information by itself.

Rotating black hole case

- Deceleration of charged particles should produce radiation.
- Forward and backward photons produced, relative to the direction of rotation.



Energy extraction mechanism?

$$E \sim p\frac{a}{2M}$$

for a (angular momentum per unit mass small) or

$$E \sim p$$

for near critical rotation.

Possibility of a strong Penrose mechanism and the production of high energy particles – if they can escape!