String condensation and high energy graviton scattering

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Hagedorn transition and gravity

- Initial interpretation – a maximum temperature, number of states vs energy from partition function for single string increases exponentially – cancels Boltzmann factor at limiting temperature
- Same temperature appears as zero mass for single winding mode in Euclidean time. Suggests a phase transition with formation of condensate. Properties can be modelled using thermalon field as an order parameter.
- Thermalon condensate represents a micro-canonical ensemble [MVZ]. Complex field charge is related to string B-dual pseudo-scalar charge for heterotic strings.

Rindler solutions

- Introduce a gravitational field. In equilibrium, local temperature varies due to gravitational red shift – Killing vector does not have constant norm.
- Rindler solutions for thermalon [MH, MVZ] using Unruh temperature - related to thermal duality. Weak deformation solutions need only a free thermalon approximation. Solutions exist for all superstring theories.
- Mechanics – negative energy on inside, pressure gradient. Self-supporting hot shell.

Combining BHs with condensate

- Back reaction: Warp factor and energy. No embedding is possible in flat space by minimum principle, but is possible near a BH.
- Continuous family of combined BH and string solutions parametrized by thermalon field or micro-canonical energy or warp factor of string condensate.
- Consistency with Hawking thermodynamic values follows from original argument – the same temperature vs mass relationship (to leading order in $1/M$)

BH string hybrids

- Could progressively replace BH interior with string condensate – limiting case a hyperbolic space filled with string condensate.
- Limiting case would have string condensate on inside, gravitational field (gravitons) on outside.
- BH is no longer the unique possibility for endpoint of gravitational collapse – a relationship to the firewall paradox is evident.

BH states

- Counting black hole states – well known how many states a BH SHOULD have: from
- 1. Hawking evaporation
- 2. State counting of possible precursors for extremal BHs [SV, M].
- Often ASSUMED that BHs would have this number of states – but these are elusive to identify!
- Instead, if #BH =1 or 0, conversion to string is thermodynamically favourable. Complete conversion is possible, giving ‘correct’ number of states for a BH replacement

BUT

- Appears that condensate could only be produced by a delicate process of injection near a horizon. Very thin layer of condensate could be formed near horizon.
- Before condensate forms – nothing there. Riemannian tidal curvature small, so string effects apparently not relevant.

Nucleation condition

- Constant area Hagedorn acceleration surface (relative to timelike vector field). (also [GI].)
- Critical surface a ‘string regulated’ version of a Penrose trapped null surface.
- Note the LOCALITY of the properties. Irrelevant to field theory but may be important in string theory.

Condensation horizon

- Close to horizon, conditions are CLOSE to being fulfilled – constant area surfaces with close to critical acceleration. Infalling particle could tip this over and begin a condensation process.
- WHERE this happens (condensation horizon) is significant. Infalling shell (Lorentz contraction) gives ΔA proportional to d^2 also to Mm (global case). M = collapsed mass, m = particle mass
- Gives $\sqrt{Mm}$ scale for distance to the condensation horizon.
- LARGE compared to 1 for astrophysical BHs – this gives a conversion region for infalling particles. Gives adequate space for conversion

Origin of Hawking entropy

- Field entropy is generated in time during conversion
- Due to fields becoming an open system in contact with string sector (entropy of entanglement between fields and strings).

Thermalons and frames

- Thermalon order parameter defined relative to the timelike vector field defining a critical surface giving constant area and critical acceleration at the outer boundary.
- Further in, a static frame is defined with respect to the thermalon Wick rotation frame (thermalon is not a simple scalar). Defines local rest frame of the string fluid.

Inductive conversion

- Conversion is an inductive process – the particle sheds energy as needed to continue matching critical conditions at the inner boundary.
- Space contracts radially – the particle produces a ‘stern shock’ – eventually produces a hyperbolic geometry with volume proportional to surface area.

Particle dynamics

- Local energy of particle in thermalon frame (TF) proportional to distance from existing (condensation) horizon.
- Area increment available from spherical section salient to condensation horizon – depends on d^2 only (elementary geometry).
- Position of condensation horizon is similar to global case.
- Universal model approximates behaviour of nucleating particle and can be easily translated to QM

Effective gauge field

- Single particle case – equivalent to constant abelian gauge field (independent of particle mass) between old and new condensation horizons. Couples via i of QM
- Effective thermalon force in the static thermalon frame = -2 * (apparent) gravitational force – both constant and related to string tension.

Graviton scattering

- Compare this model to a very different regime – ultra high energy particle collisions e.g. gravitons.
- Violation of unitarity at $s = M_P^2$ is expected in quantum gravity
- Black holes to the rescue?

Classicalization hypothesis

- Amplitudes are unitarized by BH formation.
- N-portrait: Quantum BH = Bose –Einstein condensate of N gravitons (Dvali et al)
- Collective coupling λ= $^{N}/_{R^2}$

Quantum critical point

- Quantum critical point at λ = 1
- M_{BH}= $\sqrt{N}$,   S ~N
- Constituent gravitons have energy scale corresponding to size of BH i.e. 1/M

Connection with BHs

- Scattering probability $(\lambda/N)^N * N! \sim e^{(-N)}$ from Stirling's formula at $\lambda = 1$

- Requires multiplicity of BH states consistent with Bekenstein-Hawking formula ($S \sim N$) to compensate and get BH formation to just dominate.

BUT

- Multiplicity of BH states is put in by hand!
- Relies on BHs rather than strings for unitarity at high energy.

String theory

- 2 regions for collision energy
- E/N < M_S,   λ < N g^2 field and string theory agree
- E/N > M_S, λ > N g^2 gives hard final gravitons with Regge behaviour (well behaved amplitudes).

Critical point

- Role of gravitational blue shift as critical point is approached – collision energy is enhanced.
- Quantum critical point and string transition point coincide at the condensation horizon.
- N gravitons each with E = M_S locally: indicative of phase transition to string condensate at quantum critical point.

Role of condensation

- Condensation allows strings to provide necessary multiplicity of states, instead of BHs. High multiplicity of states is also invoked to give dominant probability for string condensation.
- String states are available to observation as the horizon is eliminated.
- Allows subsequent stage of Hawking evaporation to be consistent with QM (enough matching states are available here)
- Collapsed object has string condensate on inside, gravity field on outside – formation of both components is at quantum critical point, but relies on condensate for dominant number of states.

Conclusions

- String condensation may occur during gravitational collapse and avert closed event horizon formation
- String condensation offers a microscopic completion of the N-portrait, and resurrects string theory as the essential component of quantum gravity that underwrites good behaviour at high energy.

Thanks

- Many thanks for listening!