# $G_N, \hbar, c$ :An Eternal Golden Braid

## *(a.k.a. The Quantum Dynamics of GR)*


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# A Ninety Year Journey

- *Quantum Gravity as a Quantum Field Theory?*
  *(The Limitations of Imitations)*
- *String Theory - Infancy and Early Successes*
  *(How to sensibly scatter gravitons)*
- *String Theory - Addressing the Puzzles of Black Holes (How to account for BH entropy)*
- *Quantum Gravity as a Quantum Field Theory!*
  *(Onwards to a quantum understanding of spacetime)*

# Gravity as Classical Field Theory

- *The metric* $g_{\mu\nu}(x)$ *a generalisation of EM field* $A_\mu(x)$.
- *Einstein's eqns. a nonlinear version of Maxwell eqns.*
- *Linear approximation* $g_{\mu\nu}(x) \approx \eta_{\mu\nu} + h_{\mu\nu}(x)$
- *Wave equation admitting plane wave solutions*

$$\partial^2 h_{\mu\nu} = 0$$

- *Two independent polarisations like EM but now* $\epsilon_{\mu\nu}$ *tensorial, not vectorial (spin two instead of spin one).*
- *Natural to consider quanta of these waves - gravitons.*

# A Quantum Spin Two Field

- *Treat gravity as a theory of a massless spin two field.*
- *Unique Fierz-Pauli quadratic Lagrangian with gauge invariance:* $h_{\mu\nu}(x) \to h_{\mu\nu}(x) + \partial_\mu \xi_\nu(x) + \partial_\nu \xi_\mu(x)$.
- *Coupling to energy-mom. via* $h_{\mu\nu}(x) T^{\mu\nu}(x)$.
- *But this is not a consistent theory - forgotten energy-mom. of gravity itself!* ( $T^{FP}_{\mu\nu} \propto h^2$ )
- *But then a cubic self coupling correction to FP theory.*
- *Leads to a cubic term in* $T_{\mu\nu}(x)$ *—> quartic coupling.*
- *Iterates to Einstein theory (arbitrary order couplings).*

# Quantum Problems

- *This approach seems successful in describing gravity without committing to a geometric interpretation.*
- *Together with success of QED, appeared as if quantum gravity might be similarly tackled.*
- *However, at energies* $M_P \propto \sqrt{\frac{1}{G_N}}$ *, significant corrections to Einstein theory with undetermined coefficients. Four graviton amplitude not calculable.*
- *Situation similar to that in pion physics. Good low energy effective theory below scale set by* $f_\pi$ *.*
- *But eventually, need QCD and full meson spectrum.*

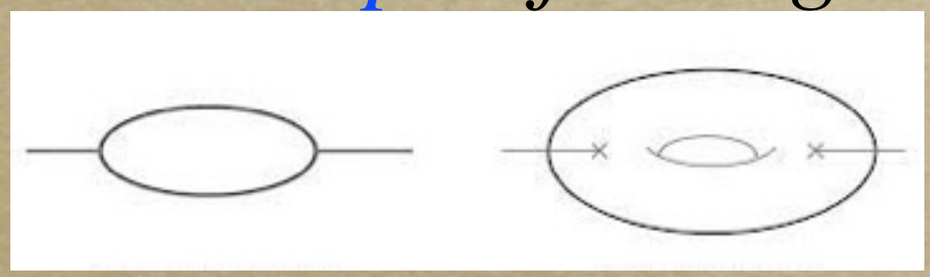
# A New Dramatis Personae: Strings

- *Remarkable fact: The lowest excitation of a closed (super-)string is a massless spin 2 particle - graviton!*
- *In addition, a full tower of massive states* ($m_n^2 \propto nT$ ).
- *For energies lower than "tension" T, recovers Einstein theory. (Yoneya; Scherk-Schwarz)*
- *Like in the pion eff. field theory. But now, precise set of classical corrections in* $\frac{E^2}{T}$ .
- *Higher derivative or higher order terms in curvature correct Einstein theory. Precisely determined coeffs.*

# Scattering Strings

- *Thus $R^4$ term gives the leading correction to the scattering of two gravitons.*

- *What about the quantum corrections which brought the QFT approach to grief?*
- *Comes from virtual loops of strings.*



- *Suppressed w.r.t tree by factors of $g_s^2$ - string coupling.*
- *Finite quantum contributions (e.g. to $R^4$) because of lack of point like interactions - smeared out.*

# Taking Stock

- *Thus string theory gives computable classical and qtm. corrections to Einstein's theory.*
- *Similar to the QCD completion of pion physics by addition of massive states.*
- *So what's the downside?*
- *Comes with additional baggage - SUSY, extra dim.*
- *SUSY: Attractive but remains to be seen at LHC.*
- *Extra Dim.: Predates string theory as a popular way of unifying non-gravitational interactions.*

# String Theory and Spacetime

- *More serious criticism: string theory had ignored the link to spacetime geometry - focussed on gravitons.*
- *Conundrums associated with black holes and cosmological singularities are non-perturbative.*
- *Would not encounter them by expanding around Minkowski spacetime.*
- *Analogy: Schwinger effect of pair production of charge particles in a constant electric field.*
- *Would not see from Feynman diagrams of QED.*

# Black Hole Puzzles

- *Bekenstein-Hawking's discovery: BHs are thermodynamic objects -w/ Entropy and temperature.*

$$S_{BH} = \frac{A_H}{4G_N\hbar} \qquad T_H = \frac{\hbar}{8\pi G_N M}$$

- $A_H$ *is the area of the horizon.*
- *Two-fold puzzle here.*
- *A) BHs are unique configurations in GR - no hint of any substructure. Classically entropy is zero.*
- *B) Even assuming there was some entropy of quantum origin - why is it not extensive? like volume?*

# (Ac)countability

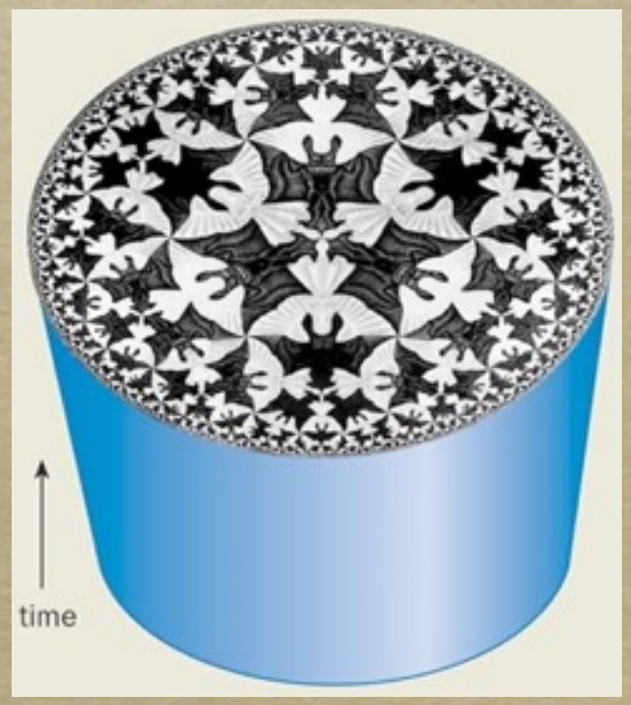
- *String theory in mid-90's could account precisely for the entropy of a large class of BHs.*
- *By understanding certain solitonic objects (like $g_s^{-1}$) in closed string theory - D-branes - in a dual way.*
- *In terms of open string excitations - Yang-Mills +massive spectrum. (Polchinski)*
- *Counting the latter gave an accounting of the entropy of the former - which are often charged BHs.*
- *First example:* $S_{SV} = 2\pi\sqrt{Q_1 Q_5 N_L}$ *(Strominger-Vafa) and non-extremal generalisation* $S'_{SV} = 2\pi\sqrt{Q_1 Q_5}(\sqrt{N_L} + \sqrt{N_R})$

# Refined Counting

- *Not some lucky fluke! Many diverse examples.*
- *Moreover, $S_{BH}$ has corrections from the (classical) higher derivative additions to Einstein: Wald entropy.*
- *Subleading in the charges. Can be matched in many cases to microscopics (De Wit et.al….Dabholkar et.al).*
- *$S_{BH}$ also has quantum corrections (in $G_N$). For a class of BHs, the log corrections can also be strikingly matched with one loop in gravity. (Sen et.al.)*
- *Gives confidence in the robustness of this accounting - very nontrivial agreement of functional dependence.*

# Qtm. Spacetime: A Concrete Case

- *Black Hole success led to precise proposal by Maldacena for quantum behaviour of gravity in a large class of spacetimes.*
- *Arises from the two pictures of D-branes.*
- *Gravity/Strings in (asymptotically) Anti de-Sitter (AdS) spacetime equivalent to a QFT (Gauge Theory) on boundary.*
- *Dictionary between "bulk" and "boundary" observables - holography.*
- *Questions in QFT* $\leftrightarrow$ *Gravity ! (See Shiraz' talk)*
- *Black holes are thermal states in QFT.*
- *Quantum Gravity (in AdS) is a QFT!!*



# The Next Century

- *Makes verifiable/falsifiable predictions about frameworks that existed before strings were even dreamt of. Highly nontrivial !*
- *Need to decipher what is behind this miraculous connection.*
- *Seems to be very general - for various kinds of gauge theories (not just Yang-Mills) and various theories of gravity (like higher spin Vasiliev theories). Does not need SUSY.*
- *Picture of continuum classical spacetime emerging from a more microscopic quantum description to be fleshed out.*
- *Extend to more general spacetimes - cosmological?*
- *Plenty of work for theorists for the next hundred years.*

# The Years….

"The years of searching in the dark for a truth that one feels but cannot express, the intense desire and the alternations of confidence and misgiving until one breaks through to clarity and understanding are known only to one who has experienced them."

- Albert Einstein