The Quantum and the Continuum : Einstein's Dichotomous Legacies

Talk at : Current Trends in Modern Physics, IISER Kolkata

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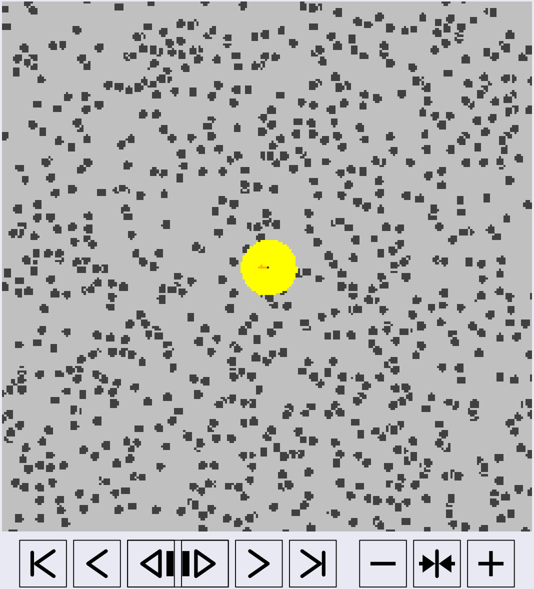
Legacy of the Quantum : Brownian Motion



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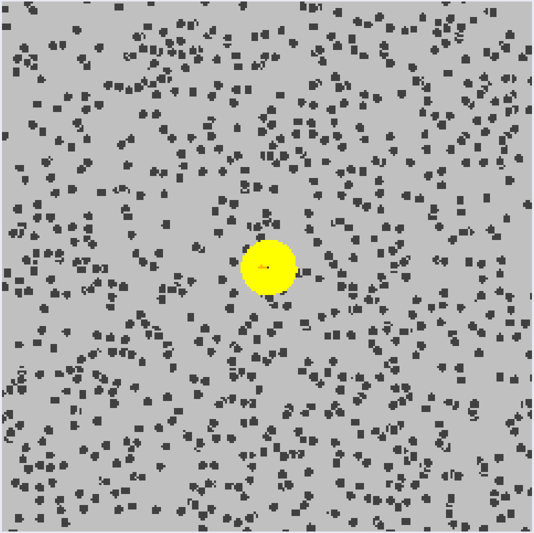

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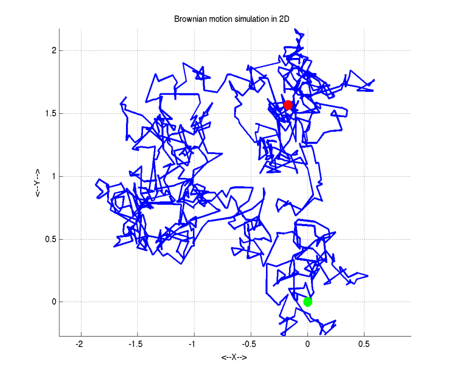

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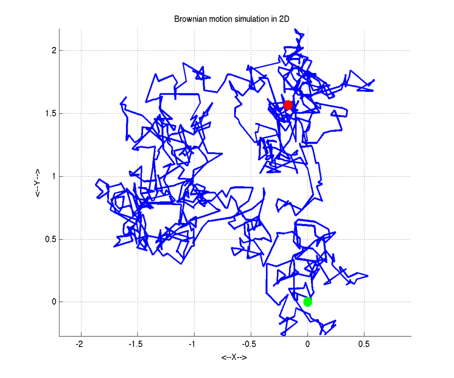
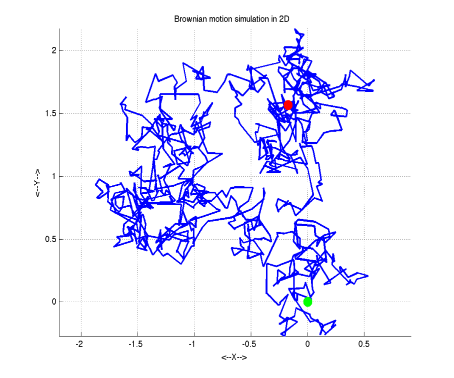


Einstein's formula



Einstein's formula

$$\langle x^2 \rangle_t = \frac{kT}{3\pi\eta r}\, t$$

Implications

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- Boltzmann : entropy (irreversibility) $\rightarrow$ probability $\leftrightarrow$ countability
- Einstein : Explicit proof of existence of discreteness of matter (molecules) and their statistical behaviour

Legacy of the Quantum : Light Quantum Hypothesis

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Maxwell equations

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$$\nabla \cdot \vec{E} = \sum_{I=1}^{N} e_I \; \delta^{(3)}(\vec{r} - \vec{\vec{r}}_I(t))$$

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Einstein :

"... we make use of continuous spatial functions to determine the electromagnetic state of space, so that a finite (countable) number of quantities (charges) cannot be considered as sufficient for the complete determination of the electromagnetic state of space."

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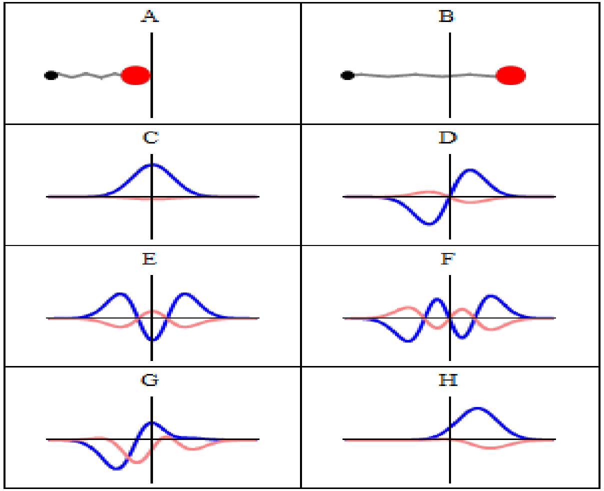
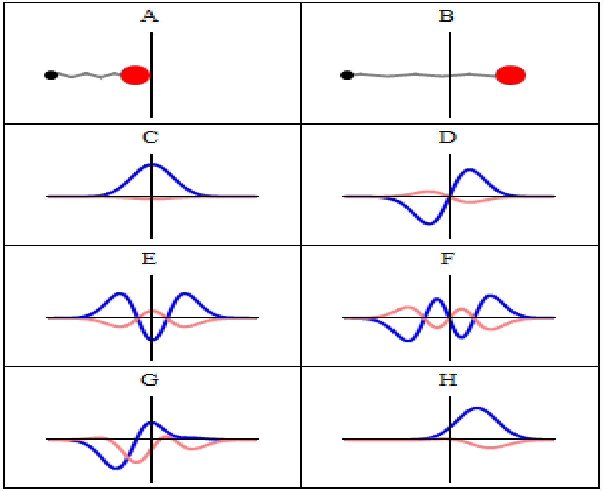
$$\mathcal{E} = \hbar\,\omega\ ,\ \vec{p} = \hbar\,\vec{k}$$

Quantum Electrodynamics : in a flash



Quantum Oscillator



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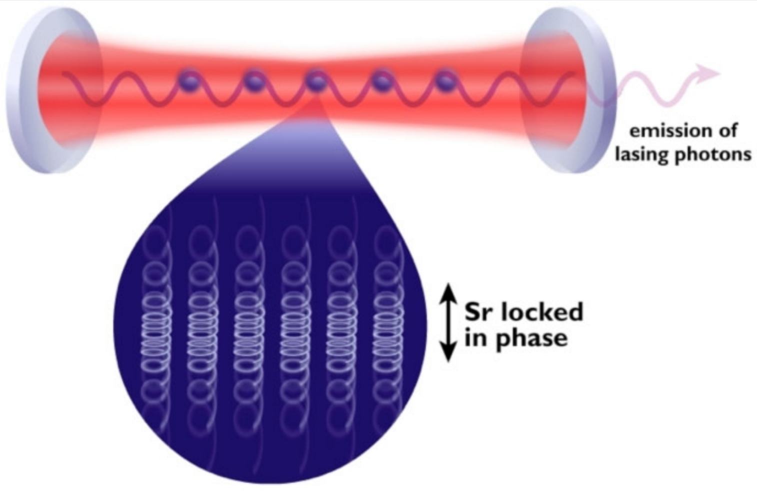

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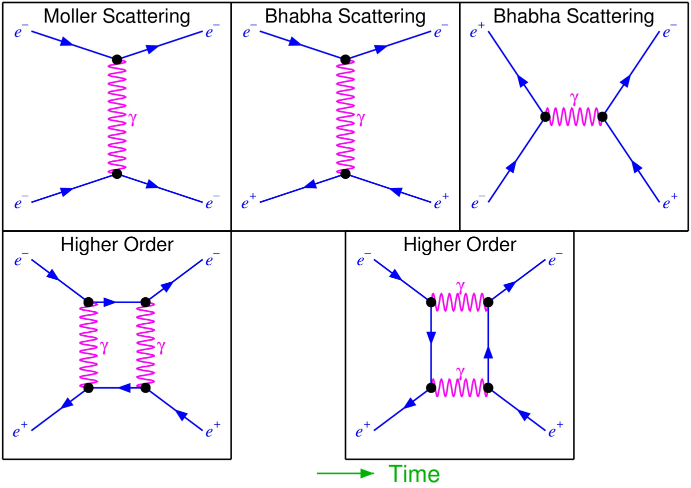

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$$a_e \equiv \left(\frac{g-2}{2}\right)_e^{QED} = 0.5\frac{\alpha}{\pi} - 0.32848\left(\frac{\alpha}{\pi}\right)^2 + 1.19\left(\frac{\alpha}{\pi}\right)^3 \cdots$$

$$= (1159652.4 \pm 0.4) \times 10^{-9}$$

$$a_\mu \equiv \left(\frac{g-2}{2}\right)_\mu^{QED} = 0.5\frac{\alpha}{\pi} + 0.76578\left(\frac{\alpha}{\pi}\right)^2 + 24.45\left(\frac{\alpha}{\pi}\right)^3 \cdots$$

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Major success of perturbative QFT

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But how do we recover Classical **E** and **B** fields ?

Quantum to classical oscillator : coherent states

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$$\begin{aligned}\hat{a}|\alpha\rangle &= \alpha|\alpha\rangle \\ |\alpha, t\rangle &= \sum_{n=0}^{\infty} \frac{\alpha^n e^{-[i(n+\frac{1}{2})\omega t + (|\alpha|^2/2)]}}{\sqrt{n!}} |n\rangle \\ \langle\alpha, t|\hat{x}(t)|\alpha, t\rangle &= x_0 \cos\omega t\end{aligned}$$

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Minimum uncertainty states

$$\Delta x \; \Delta p = \hbar$$

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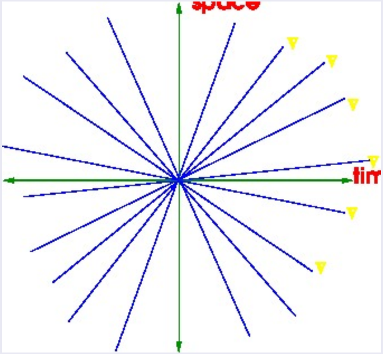
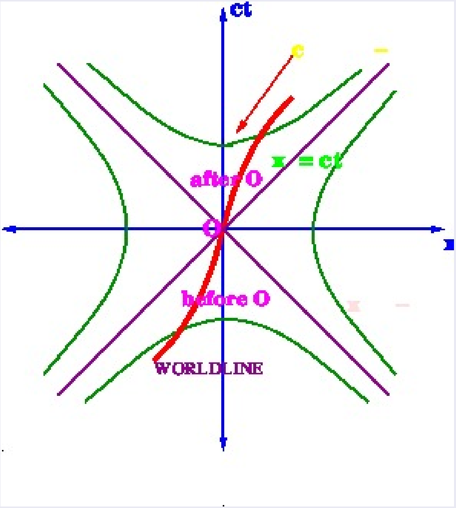
Continuum fields & classical electrodynamics emerge from QED in the semicl approximation

Legacy of the Continuum : Galilean Sptm (1+1 dim)



Equivalence class of positions for each instant of time

Chasing Light : Sp Rel Sptm continuum (1+1 dim)



Hyperboloid : Equivalence class of events

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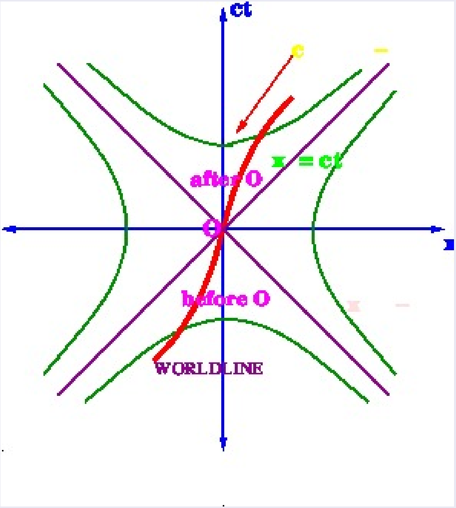

Hyperboloid : Equivalence class of events

Sptm geometry : non-Euclidean but flat (global)

Chasing Light : under Gravity (using Principle of Equivalence)

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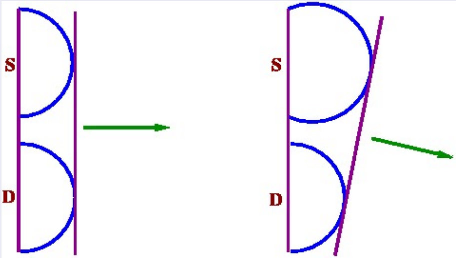

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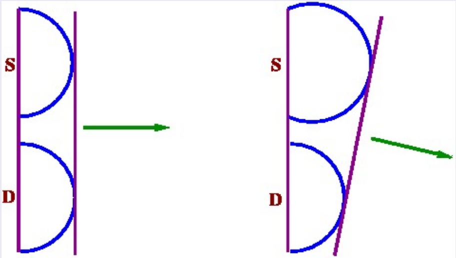

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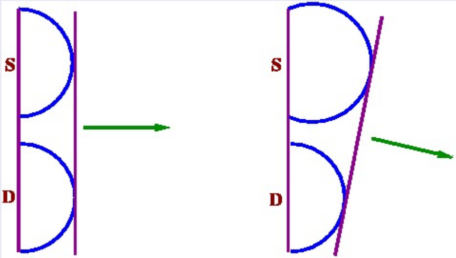

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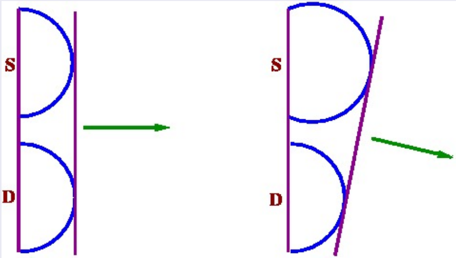

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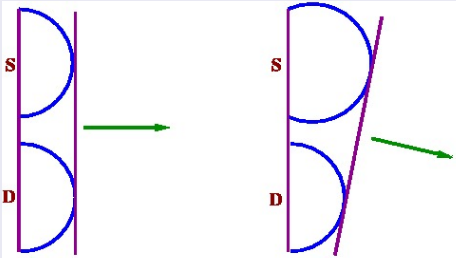

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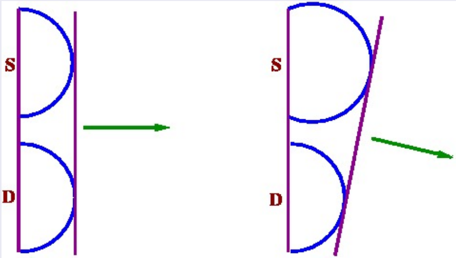

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- → **Spacetime is locally flat but globally curved**

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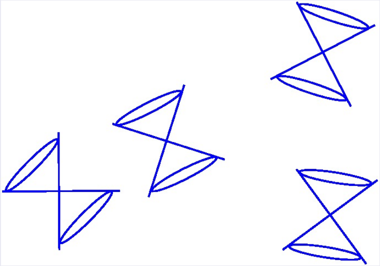

Spacetime : Pseudo-Riemannian Geometry

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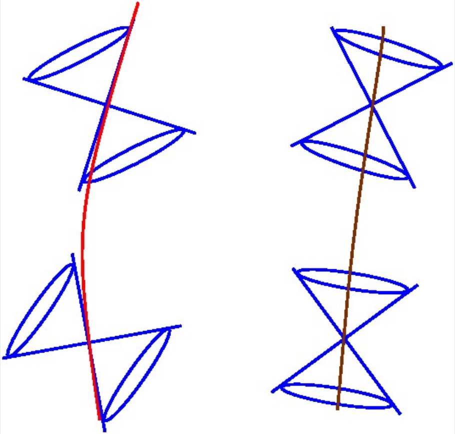

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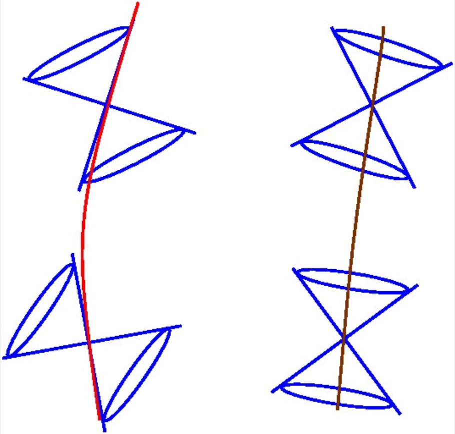

Gravitational Force originates from Curved Sptm

What causes Sptm to curve ? Einstein's equation

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Evidence of Dynamical Sptm : Gravitational waves, Expanding Universe, Black Holes

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N SR Point particle energy momentum tensor (classical)

$$T^{ab}(x) = \sum_{I=1}^{N} m_I \int d\tau u_I^a u_I^b \; \delta^{(4)}(x - \bar{x}_I(\tau))$$

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Both are examples of **Sptm singularities** in GR !

Sptm Singularities : Gravitational Collapse

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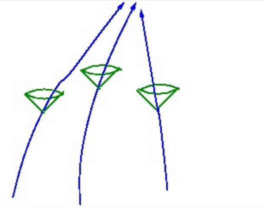

CONVERGENCE OF TIMELIKE GE

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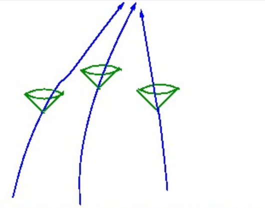

CONVERGENCE OF TIMELIKE GE

Raychaudhuri Eq : Sptm geometry illdefined at singularity

Further Conundrum : Black Hole Horizon

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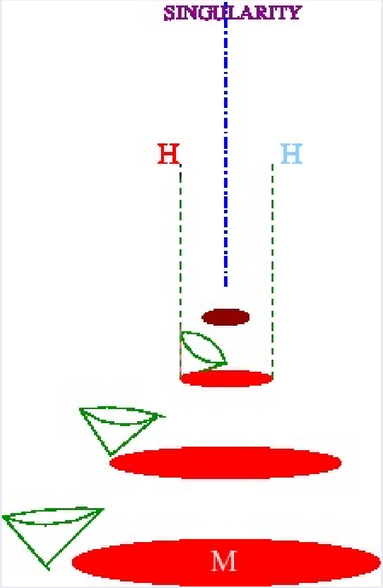

Area Increase Theorem

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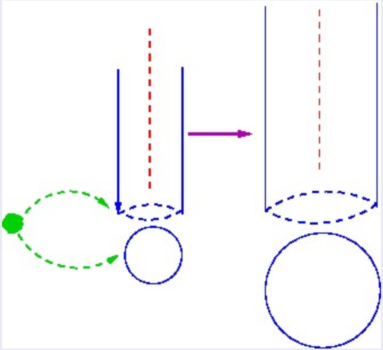

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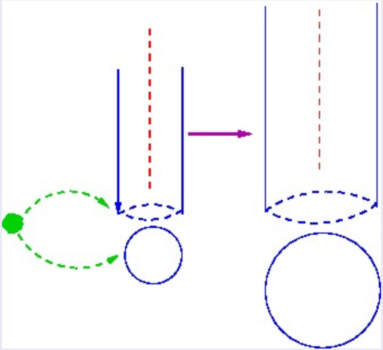

Horizon area can never decrease : Hawking

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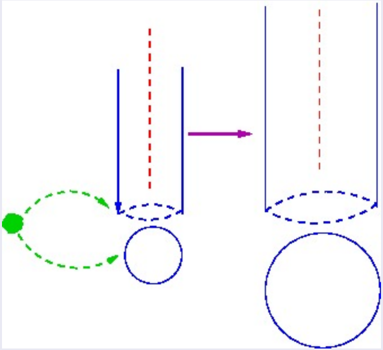

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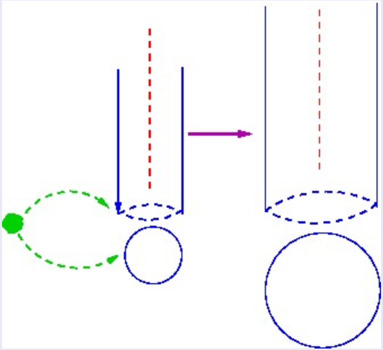

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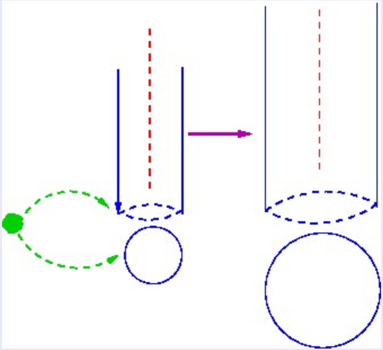

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Black hole : exact solution of Einstein eq. !

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Strengthens thermodyamic analogy : $\kappa_{hor} \leftrightarrow T$, $M \leftrightarrow U$

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Bekenstein : Microstates necessary for Black Hole Entropy must originate from quantum GR !

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Concrete proposals : Loop Quantum Gravity, Causal Dynamical Triangulations, Spin Foams, ...

LQG and Black Hole Entropy : Resolution of the Dichotomy

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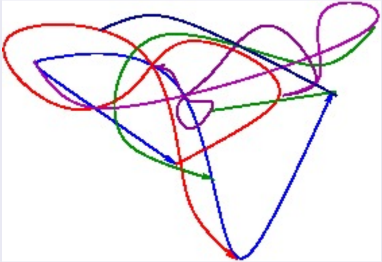

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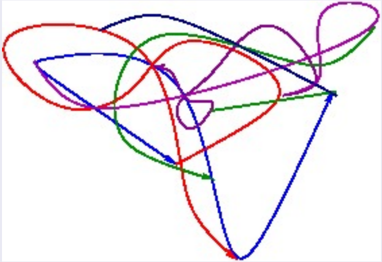

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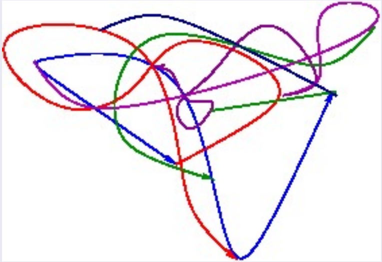

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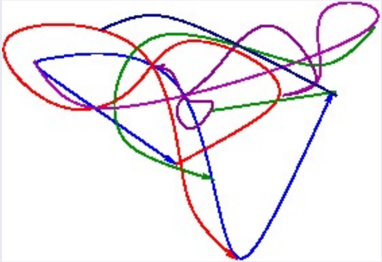

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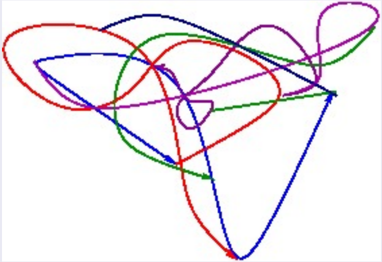

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- **Geom observables : bounded, discrete spectra**

Area Spectrum

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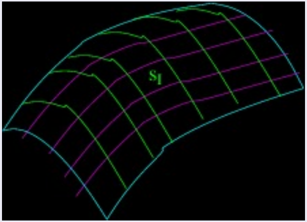

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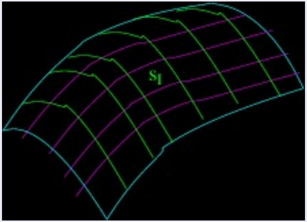

$$\hat{\mathcal{A}}_S \equiv \sum_{I=1}^{N} \int_{S_I} \det{}^{1/2}[{}^2g(\hat{E})]$$

$$a(j_1, \ldots, j_N) = 8\pi\gamma l_P^2 \sum_{p=1}^{N} \sqrt{j_p(j_p+1)}$$

$$\lim_{N\to\infty} a(j_1, \ldots j_N) \leq \mathcal{A}_{cl} + O(l_P^2) \text{ for } j_p \leq \frac{k}{2}$$

Equispaced $\forall j = 1/2$

Quantum Black Hole (non-rotating)

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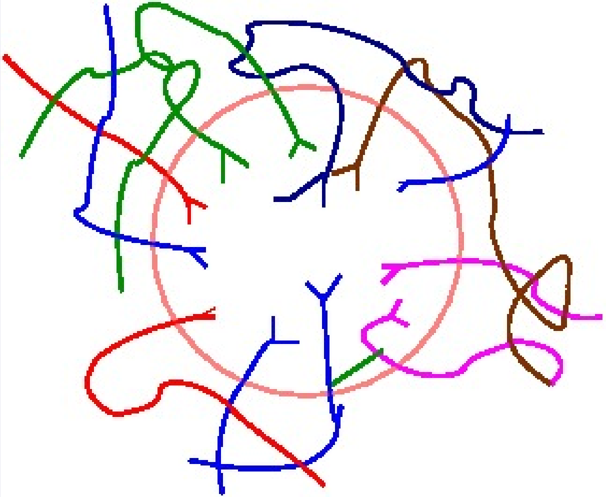

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Systematic, finite corrections to Bekenstein-Hawking entropy : signature of LQG

It from Bit

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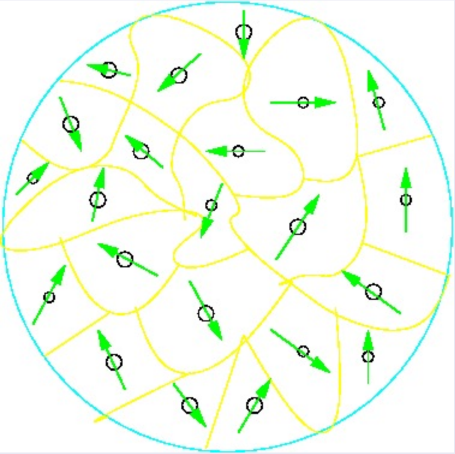

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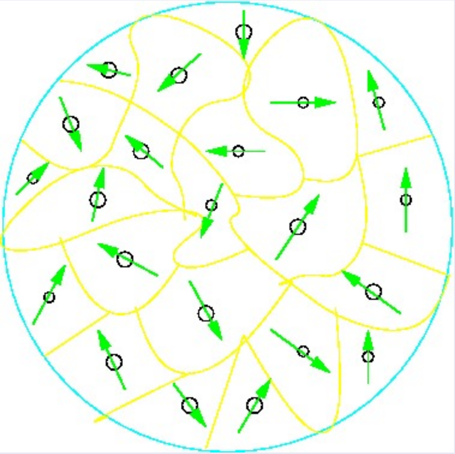

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$$\mathcal{N} = \frac{N_H!}{((N_H/2)!)^2} - \frac{N_H!}{(N_H/2+1)!(N_H/2-1)!}$$

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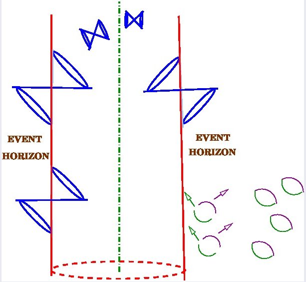

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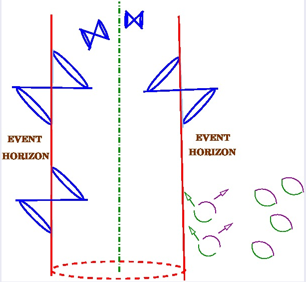

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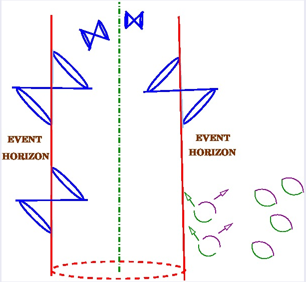

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Hawking's treatment : **Semiclassical !** i.e., sptm classical, matter-radiation quantal

If sptm is also quantized, is b h radiation still thermal ?

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- **What about a formula involving $G, c, \hbar, \Lambda_{QCD}$? Does this occur in Physics ?**

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Current Interest : Black hole entropic approach to critical NS mass

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