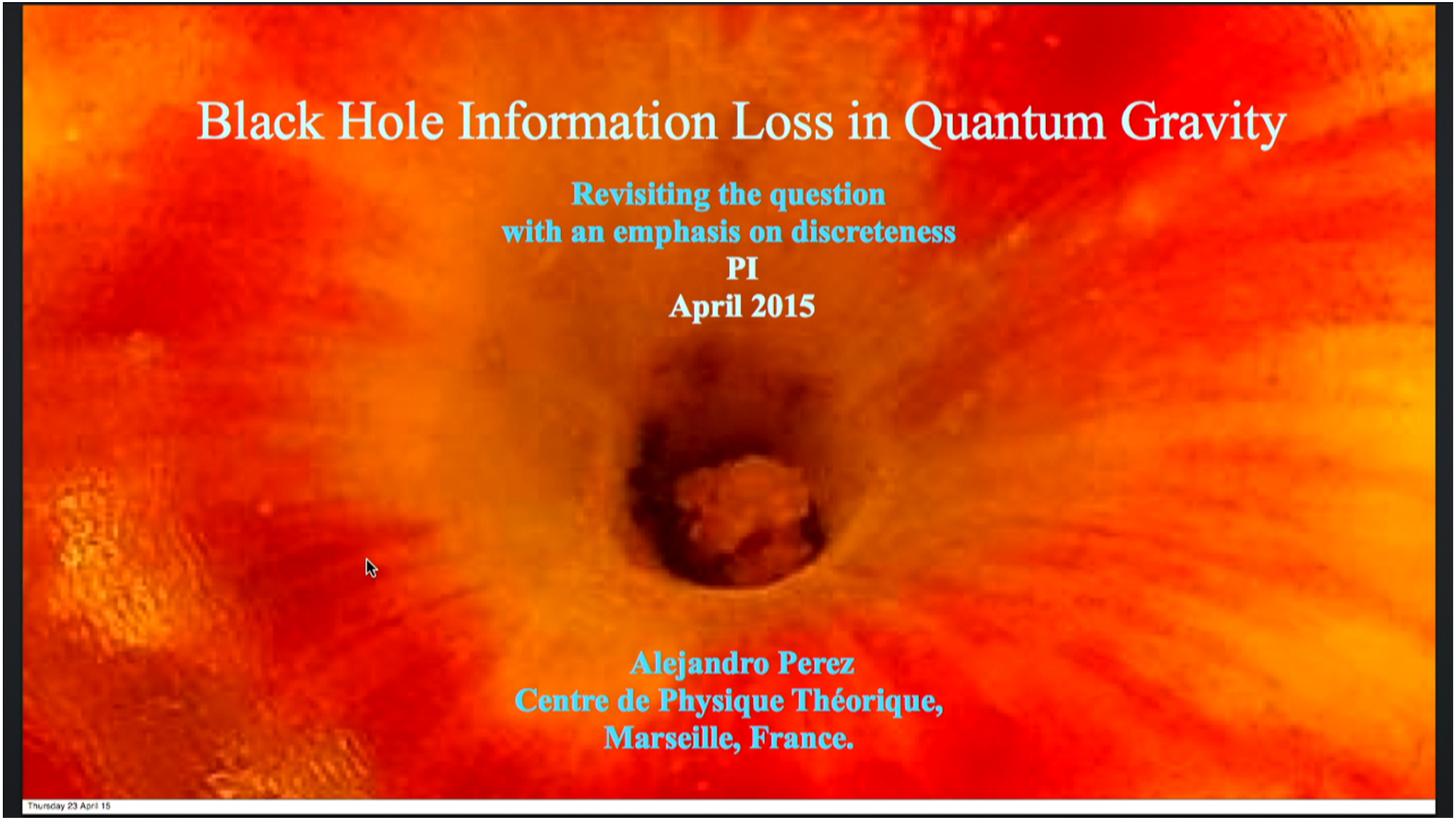
Title: Black hole information loss and discreteness of quantum geometry

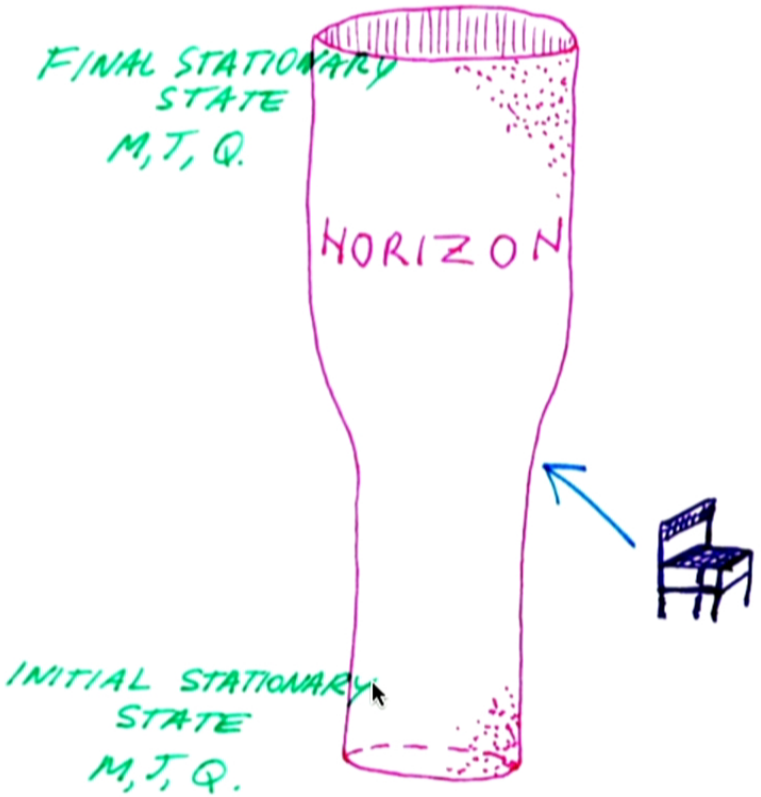
Date: Apr 23, 2015 04:00 PM

URL: http://pirsa.org/15040068

Abstract: In an approach to quantum gravity where space-time arises from coarse graining of fundamentally discrete structures, black hole formation and subsequent evaporation could be described by a unitary evolution without the problems encountered by standard remnant scenarios or the schemes where information is assumed to come out with the radiation while semiclassical evaporation (firewalls and complementarity). I point out the possibility that the final state is purified by correlations with the fundamental pre-geometric structures (in the sense of Wheeler) which are available in such approaches, and, like defects in the underlying space-time weave, can carry zero energy.


Black Hole Information Loss in Quantum Gravity
Revisiting the question
with an emphasis on discreteness
PI
April 2015
Alejandro Perez
Centre de Physique Théorique,
Marseille, France.
Thursday 23 April 15

Black hole mechanics: analogy with thermodynamics



Some definitions

- $\Omega \equiv$ horizon angular velocity
- $\kappa \equiv$surface gravity ('grav. force' at horizon) If ℓ^a =killing generator, then $\ell^a \nabla_a \ell^b = \kappa \ell^b$.
- $\Phi \equiv$electromagnetic potential.

0th law: the surface gravity κ is constant on the horizon.

1st law:
$\delta M = \frac{\kappa}{8\pi}\delta A + \underbrace{\Omega \delta J + \Phi \delta Q}_{\text{work terms}}$

2nd law:
$\delta A \geq 0$

3rd law: the surface gravity value $\kappa = 0$ (extremal BH) cannot be reached by any physical process.

Black Hole Entropy

Temperature at infinity

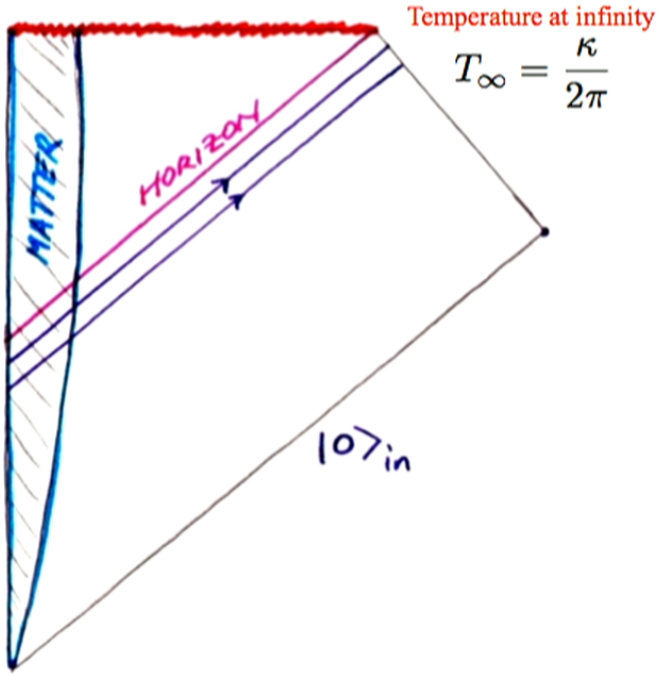
$$T_\infty = \frac{\kappa}{2\pi}$$

From the first law

$$\delta M = \frac{\kappa}{8\pi}\delta A + \Omega \delta J + \Phi \delta Q$$

One infers the ENTROPY

$$S = \frac{A}{4\ell_p^2}$$



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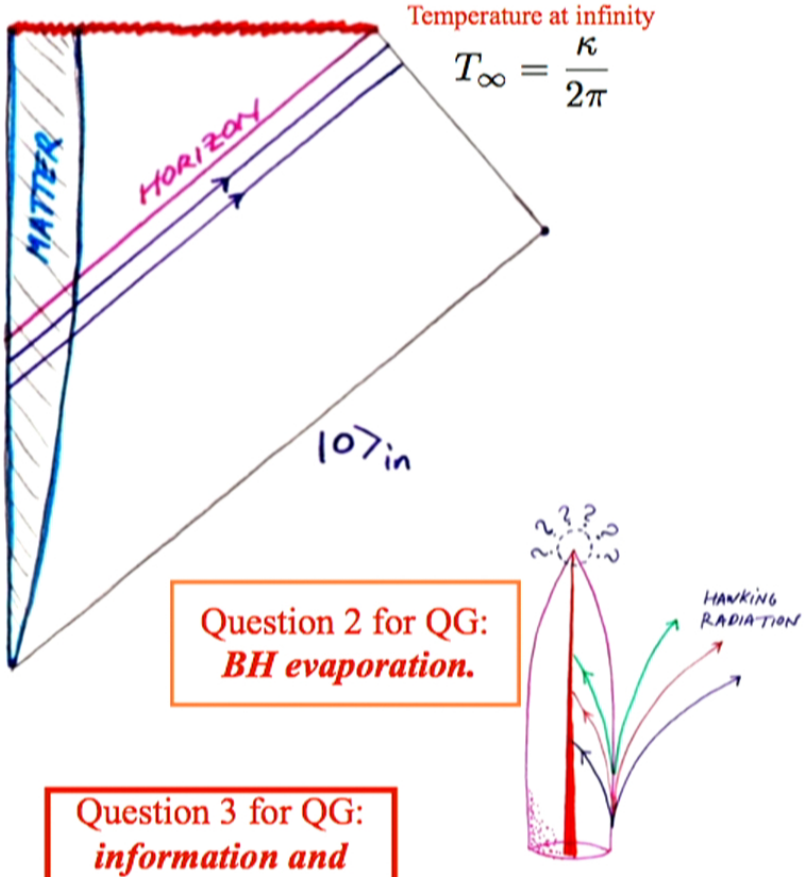
Question 1 for QG:
how to get S from statistical mechanics.



Question 2 for QG:
BH evaporation.

Question 3 for QG:
information and unitarity.

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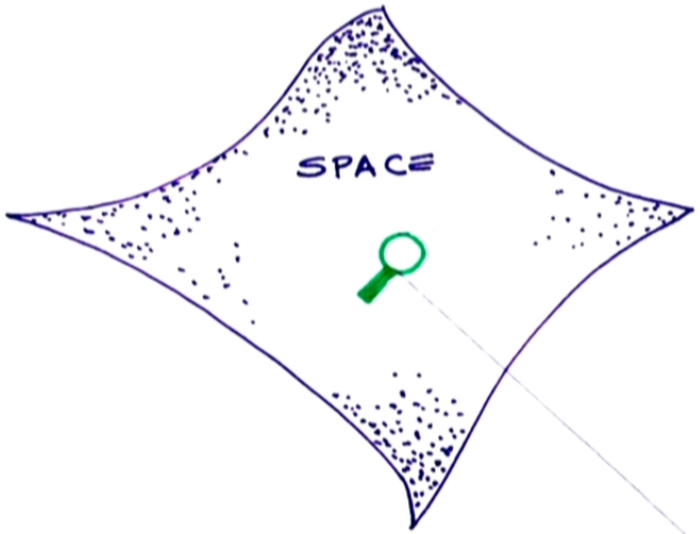
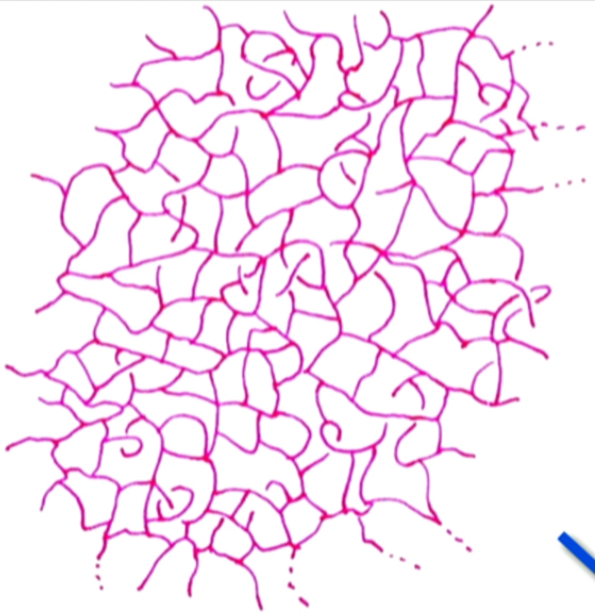
Quantum spacetime is made of discrete weave like excitations

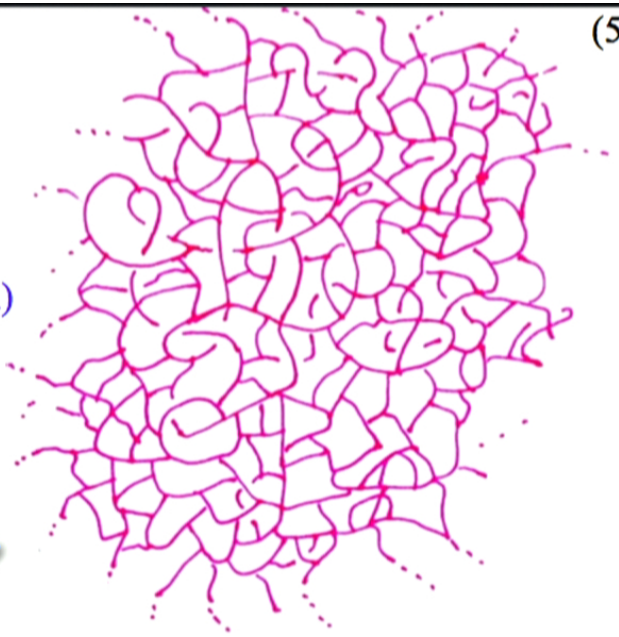
(Ashtekar-Smolin-Rovelli)

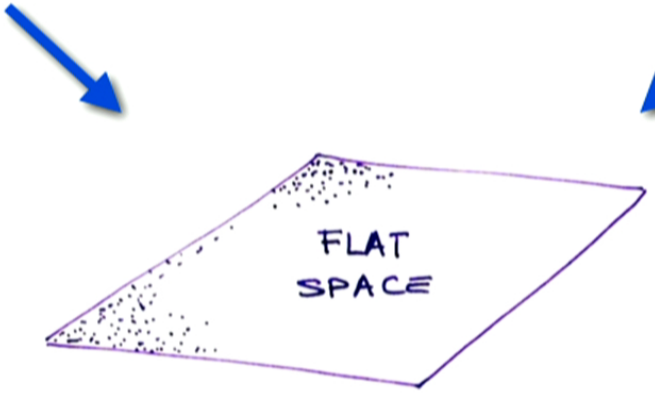


Different weave states define the same spacetime



Smooth geometry is obtained by
coarse graining (Ashtekar et al. Rovelli-Smolin)





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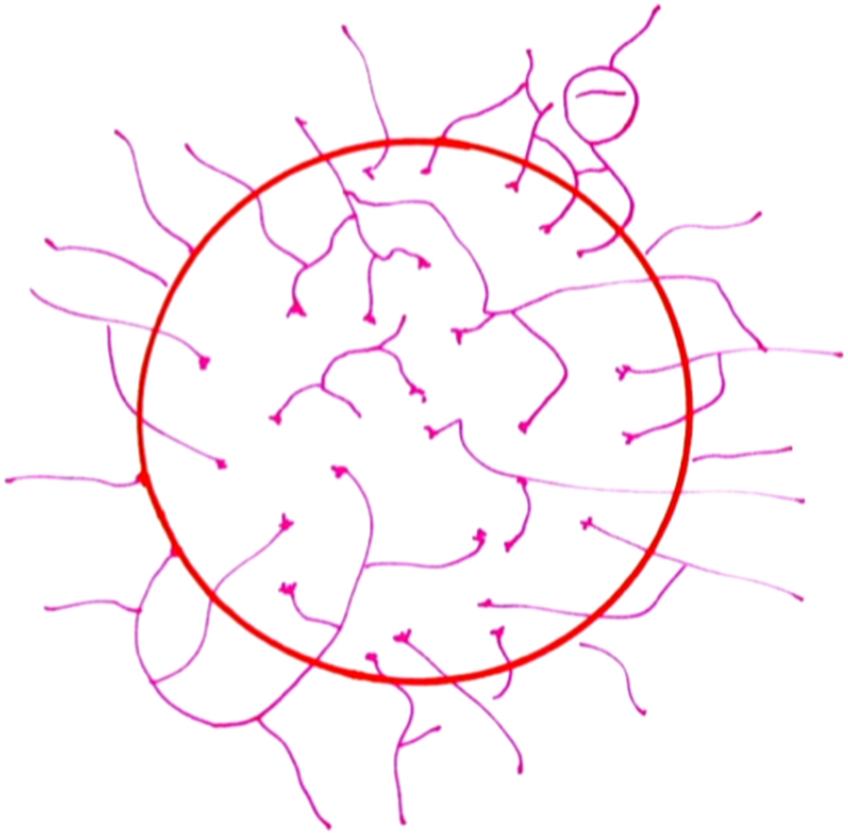
Q1: Black Hole Entropy is Horizon Entropy

$$S_{stat} = \frac{A}{4G_N\hbar} + \eta\frac{\sqrt{A}}{\sqrt{\gamma G\hbar}}$$

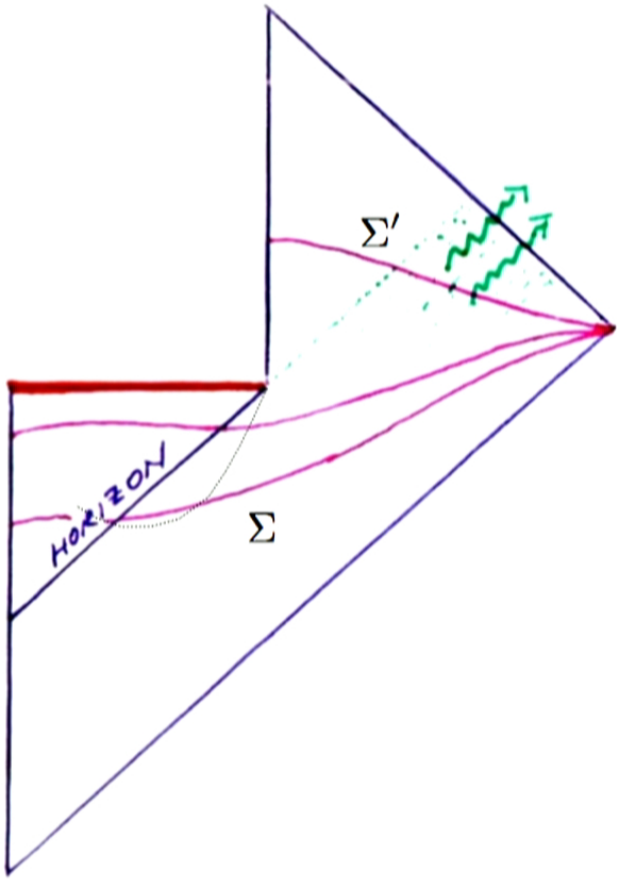
(Ghosh-Noui-AP 2014)



(Alesci, Ashtekar, Baez, Barbero, Bianchi, Borja, Corichi, Diaz-Polo, Engle, Frodden, Ghosh, Krasnov, Livine, Lewandowski, Majumdar, Mitra, Noui, AP, Pranzetti, Rovelli, Sahlmann, Terno, Thiemann, Villasenor, etc.)

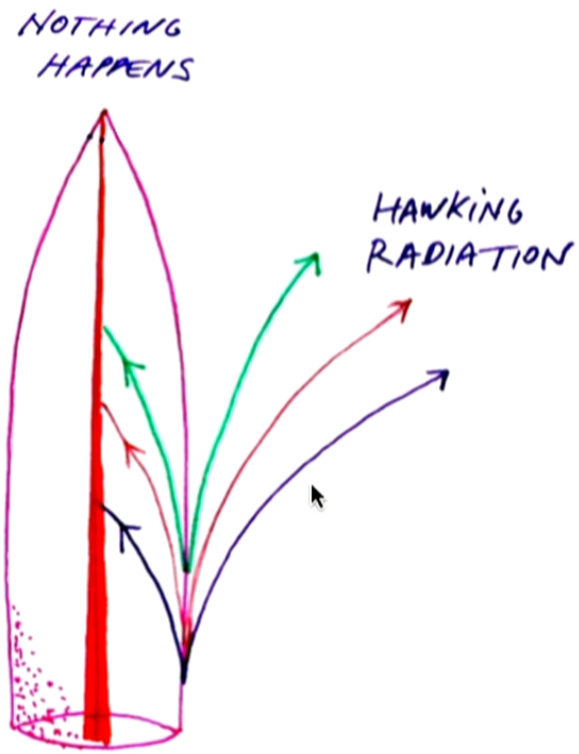
Q3: Information loss paradox

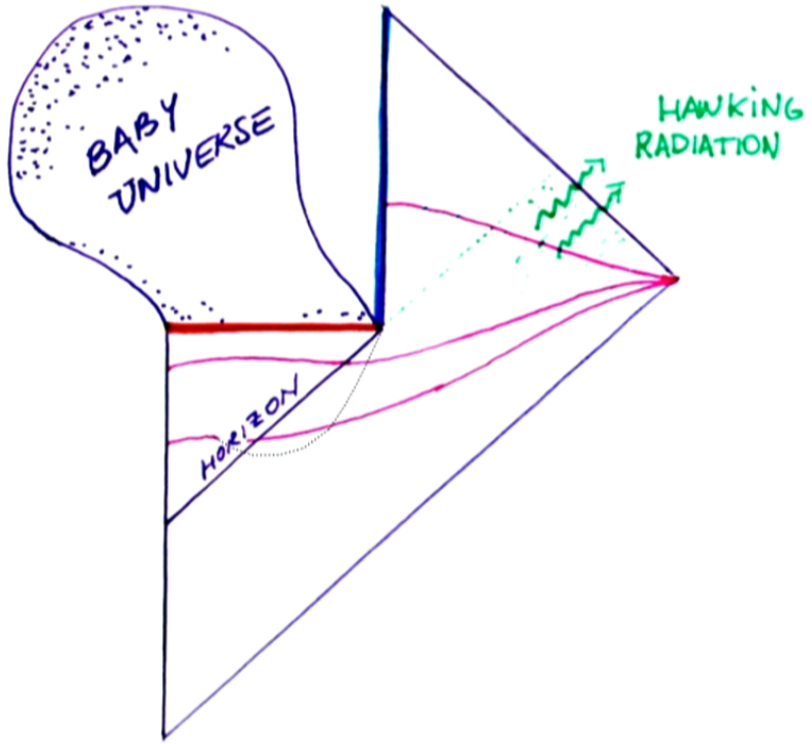
(Hawking 1976)



For a review on possibilities see
Hossenfelder-Smolin, Phys.Rev. D81
(2010) 064009

Proposal 1:
baby universe





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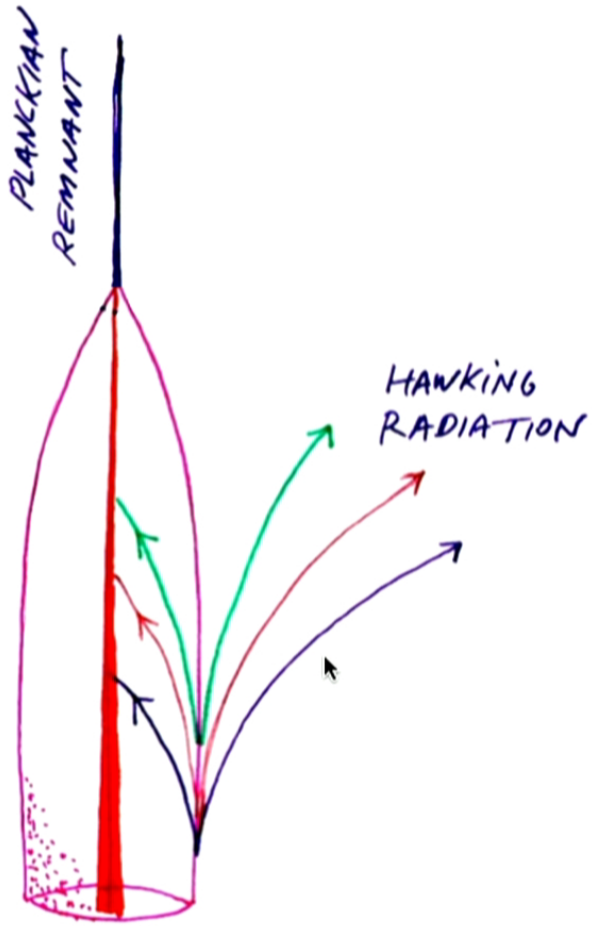
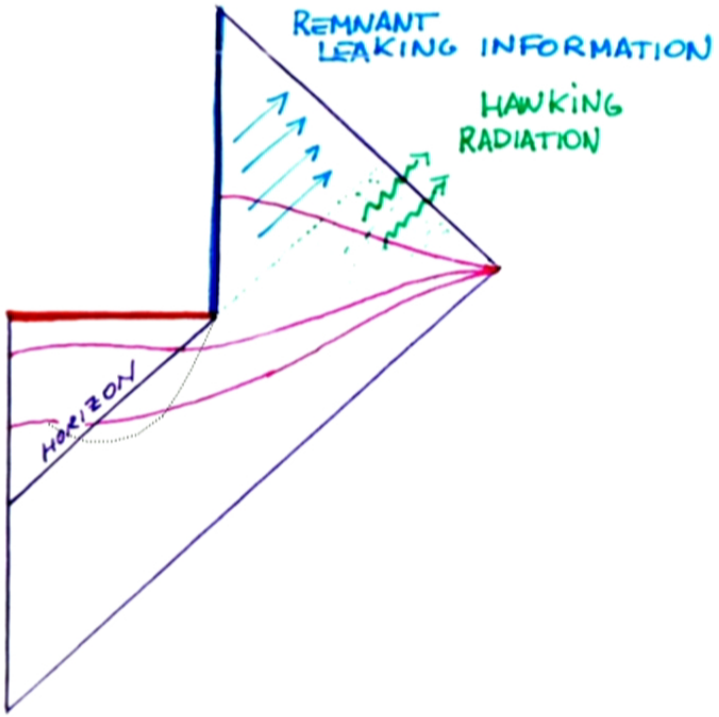
Proposal 2:
Remnants

(Giddings 94, Banks 95)



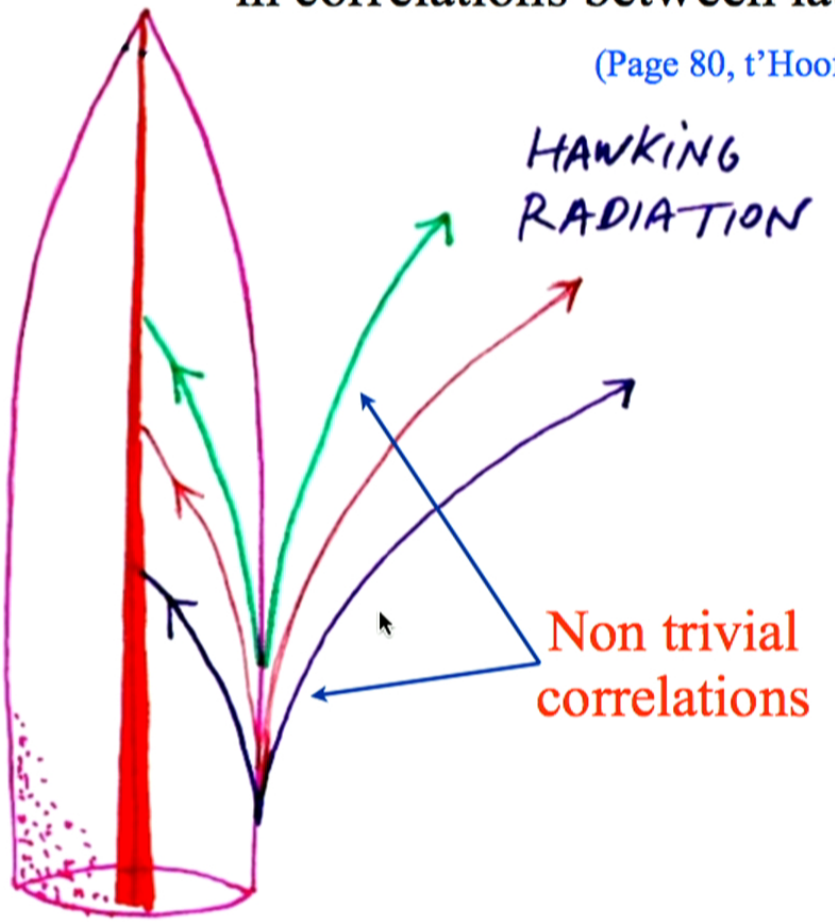


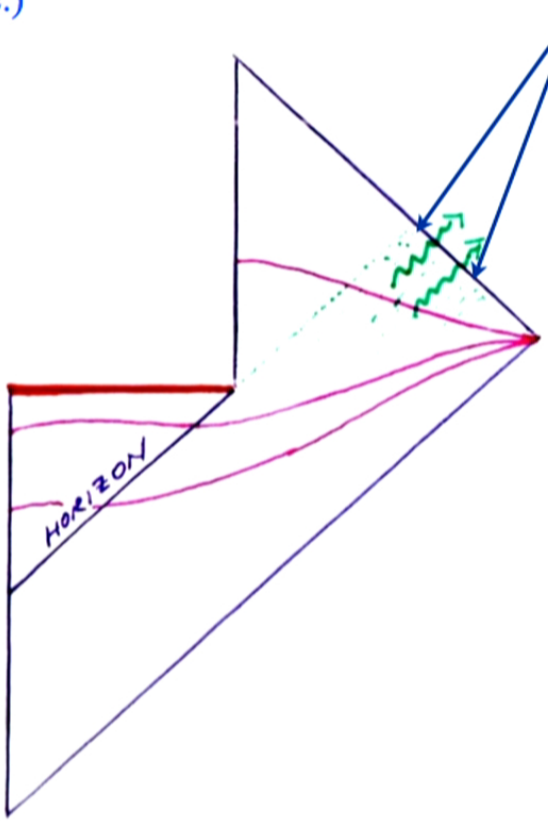
Proposal 3:

(11)

information is to be recovered
in correlations between late and early hawking radiation

(Page 80, t'Hooft 90, Susskind 93, etc.)





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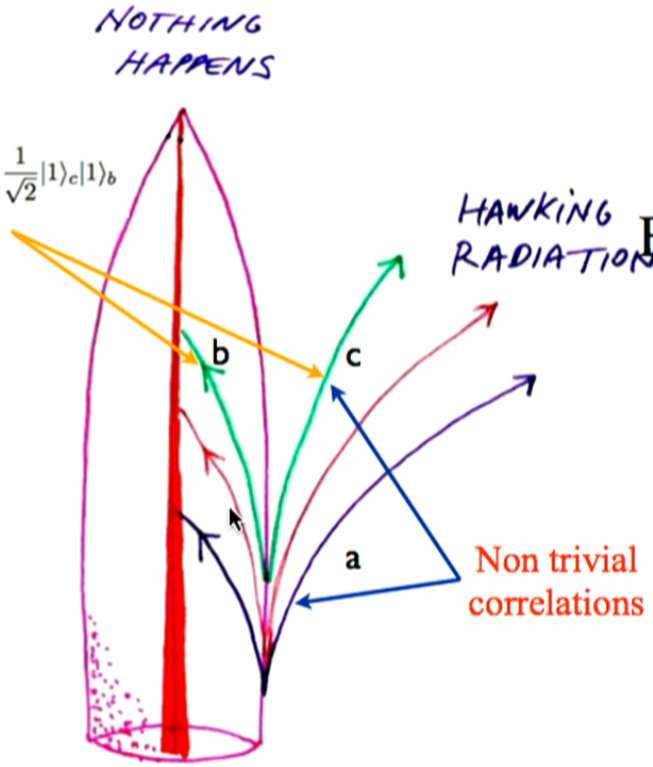
Proposal 3: information is to be recovered in correlations between late and early hawking radiation

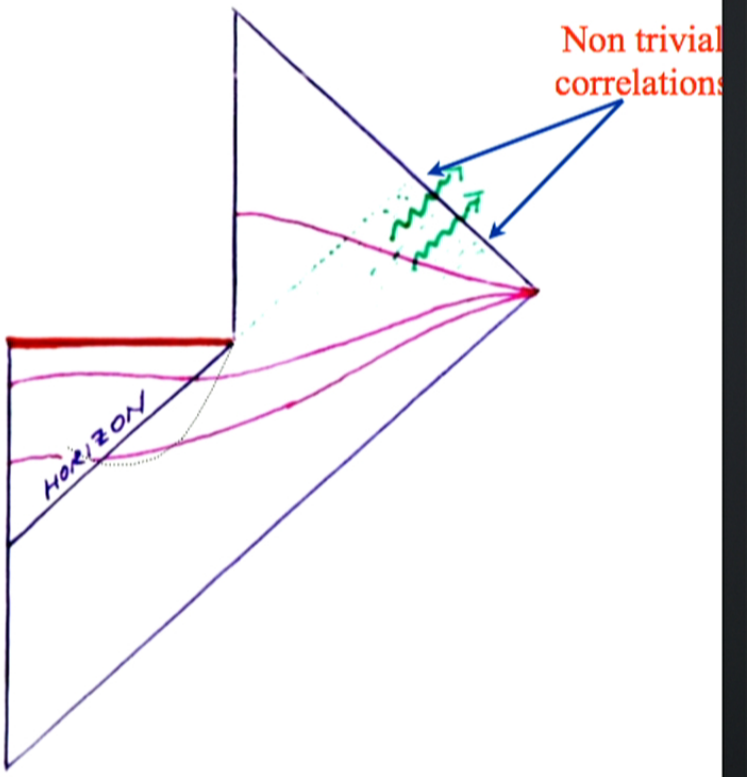
(Almeheiri-Marolf-Polchinski-Sully 2013; S. L. Braunstein, S. Pirandola, and Kyczkowski, 2013)

Maximally correlated

$$|\Psi\rangle_{\text{pair}} = \frac{1}{\sqrt{2}}|0\rangle_c|0\rangle_b + \frac{1}{\sqrt{2}}|1\rangle_c|1\rangle_b$$



Firewalls



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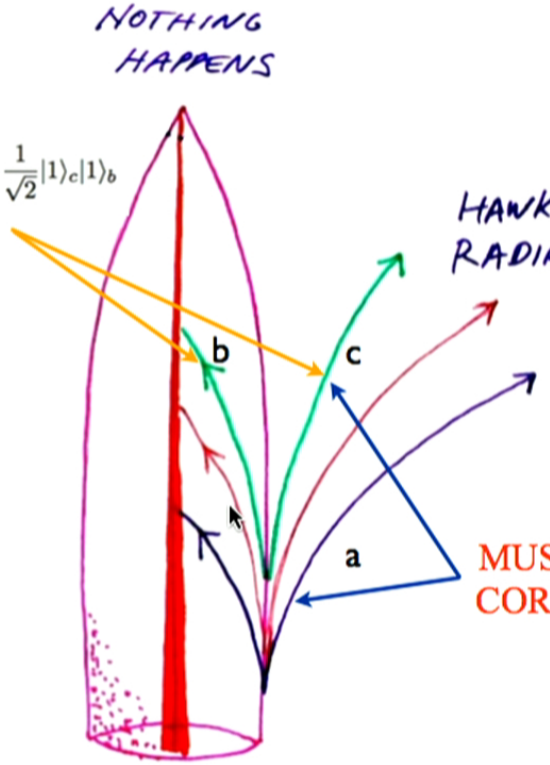
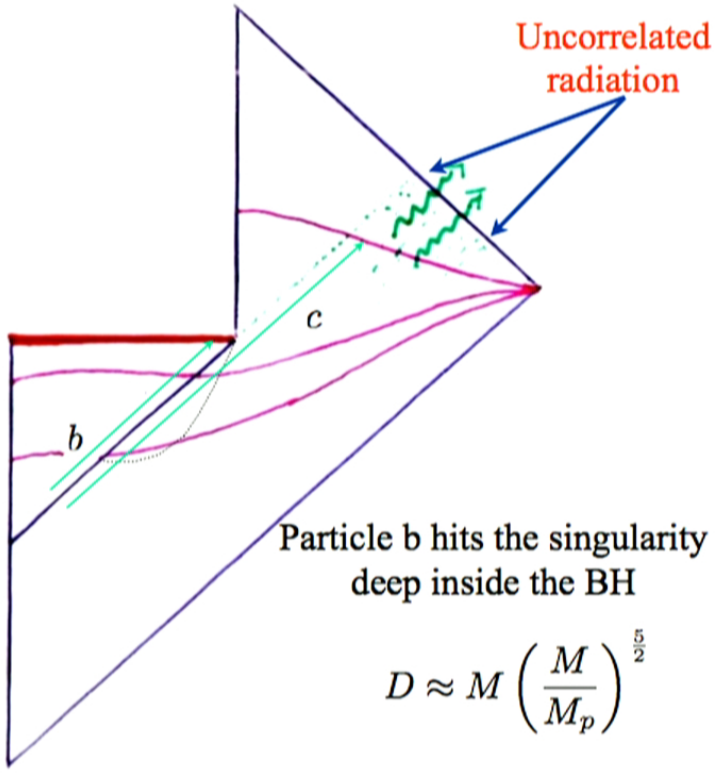


MUST HAVE NO CORRELATIONS

Firewalls



Particle b hits the singularity deep inside the BH

$$D \approx M\left(\frac{M}{M_p}\right)^{\frac{5}{2}}$$

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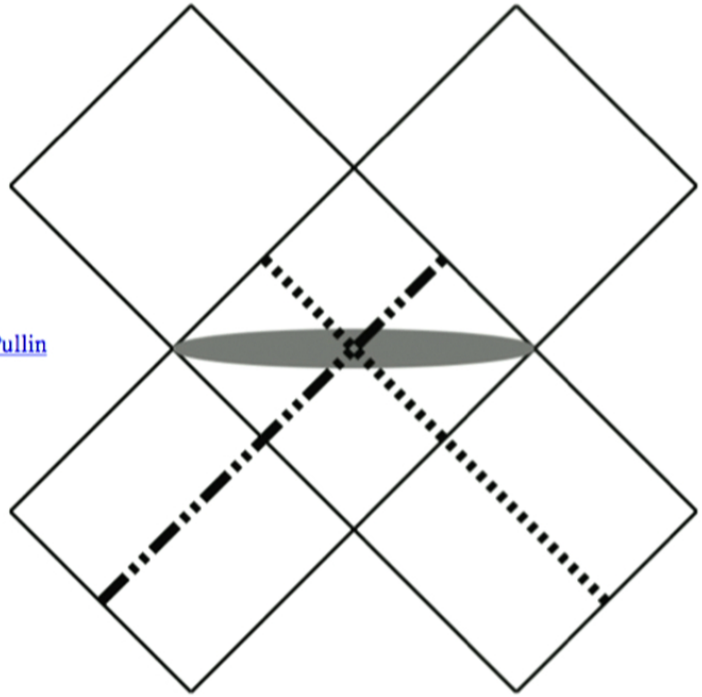
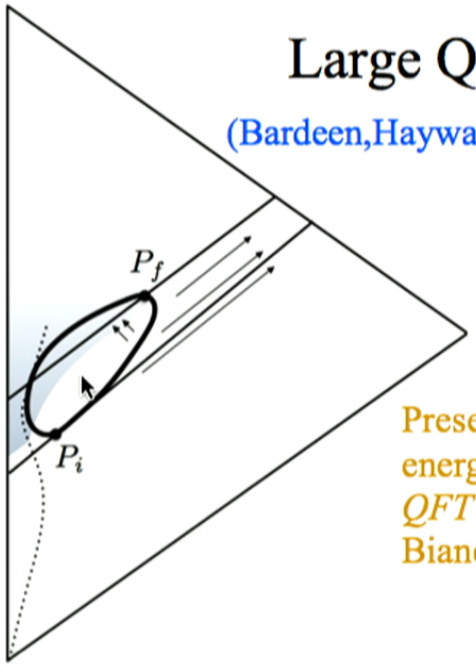
Bouncing at the singularity

Quantum shells in a quantum space-time
Rodolfo Gambini (Republica U., Montevideo), Jorge Pullin (Louisiana State U.). Aug 20, 2014. 5 pp.
Published in **Class.Quant.Grav. 32 (2015) 3, 035003**



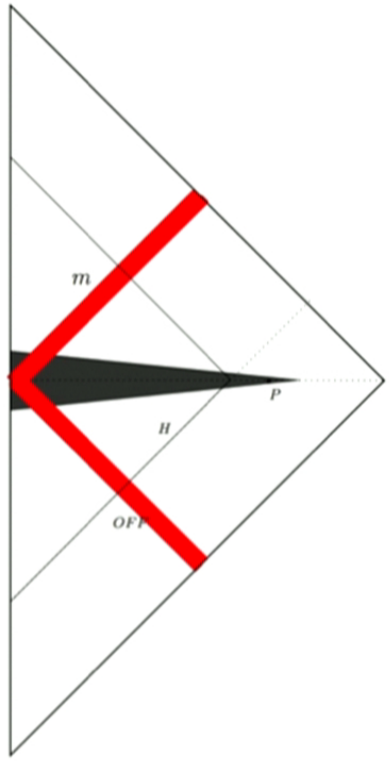
Proposal 4:
Planck Stars



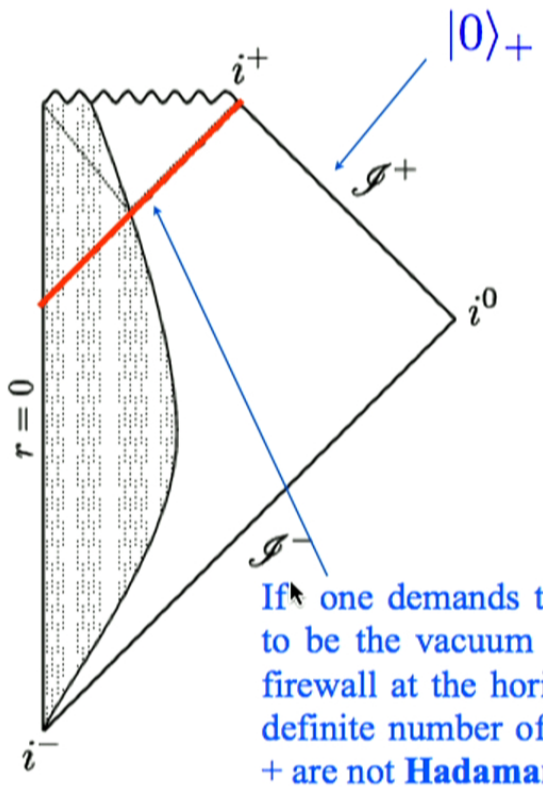
Large QG effects at low curvature

(Bardeen,Hayward, Rovelli-Vidotto, Rovelli-Haggard, etc

Present proposals are ruled out by energy conservation *if unitarity in the QFT sector holds* (**arXiv:1409.0144** Bianchi-De Lorenzo-Smerlak).

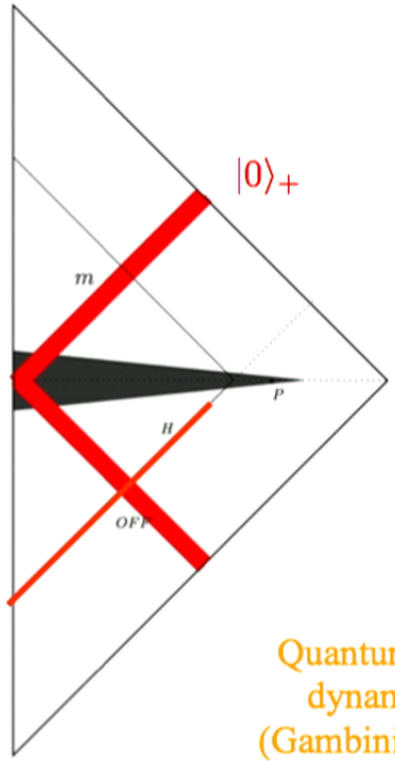


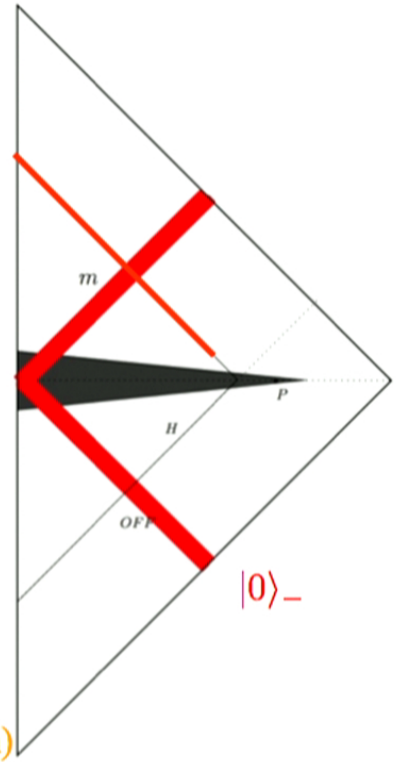
Expect modifications of the bounce scenario from back reaction



If one demands the state at scri+ to be the vacuum then there is a firewall at the horizon (states with definite number of particles at scri + are not **Hadamard** states).

Quantum effects break time symmetry of the Haggard-Rovelli's **Fireworks** framework.





Quantum shell dynamics? (Gambini-Pullin)

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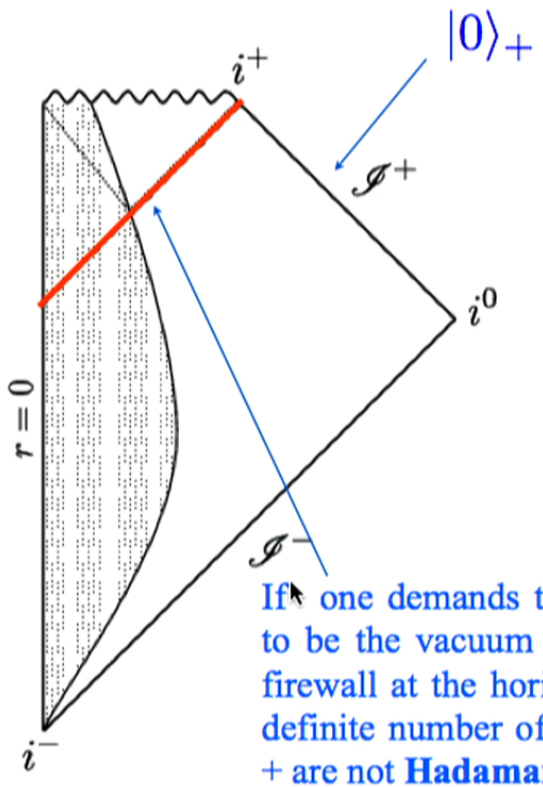

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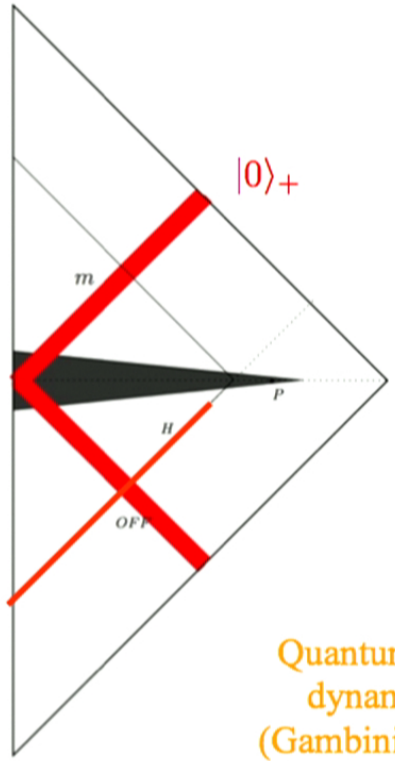

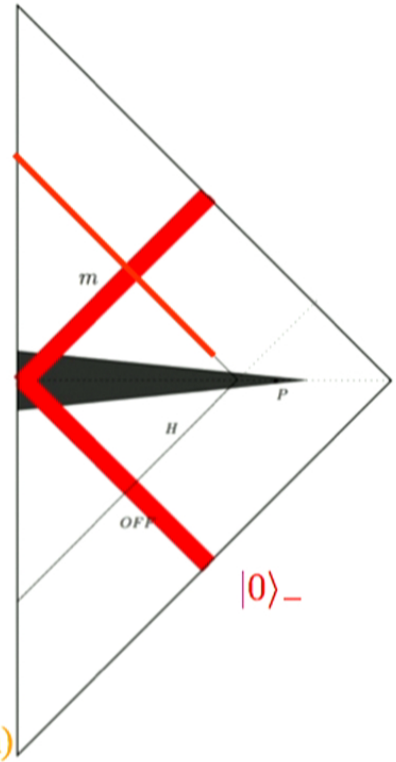

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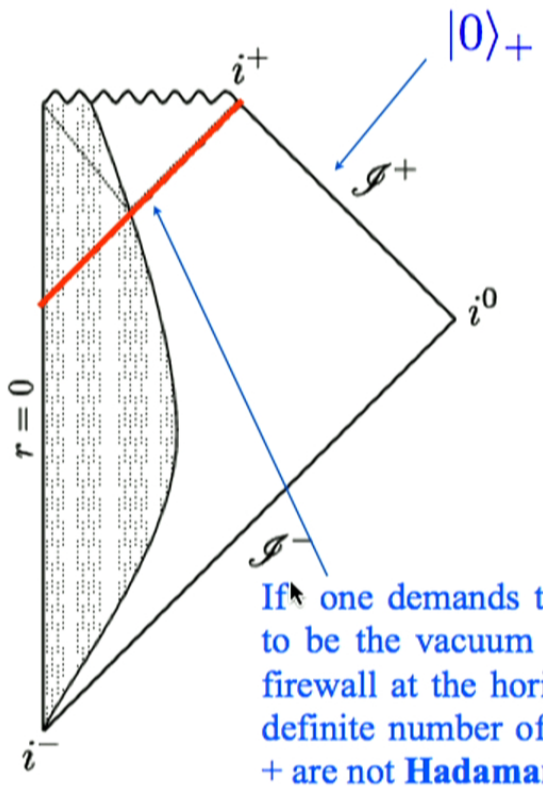

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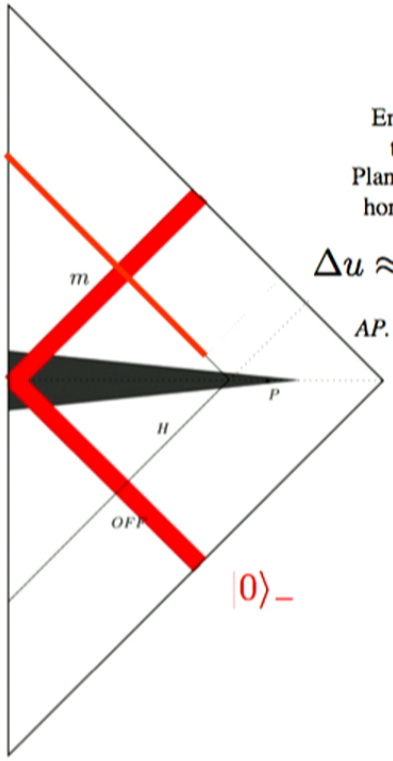
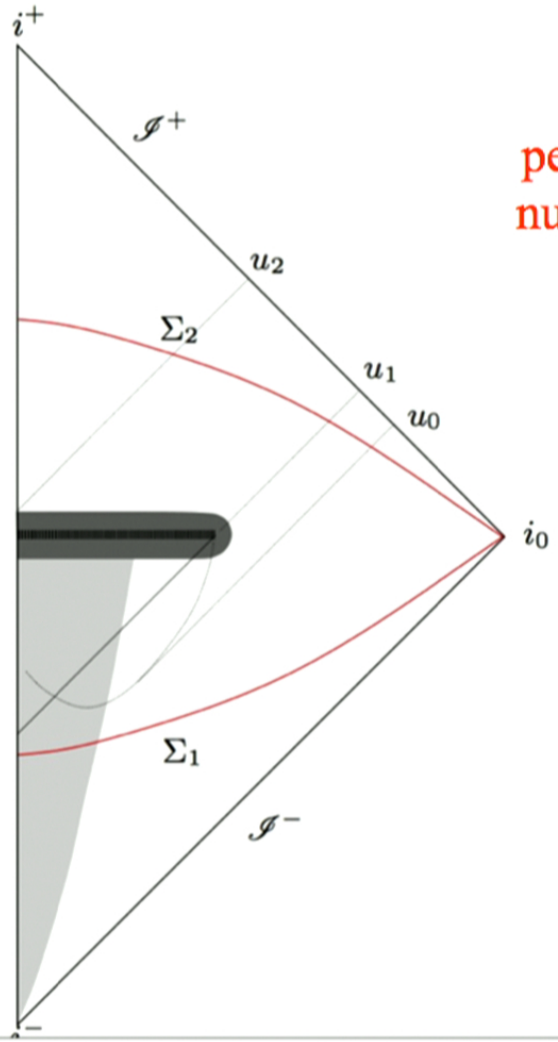


Energy momentum tensor becomes Planckian at the future horizon very quickly

$$\Delta u \approx M \log M/M_p$$

AP. and T. De Lorenzo

Revisiting the Ashtekar-Bojowald paradigm



The story told from the perspective of observers at future null infinity is a **semiclassical one**

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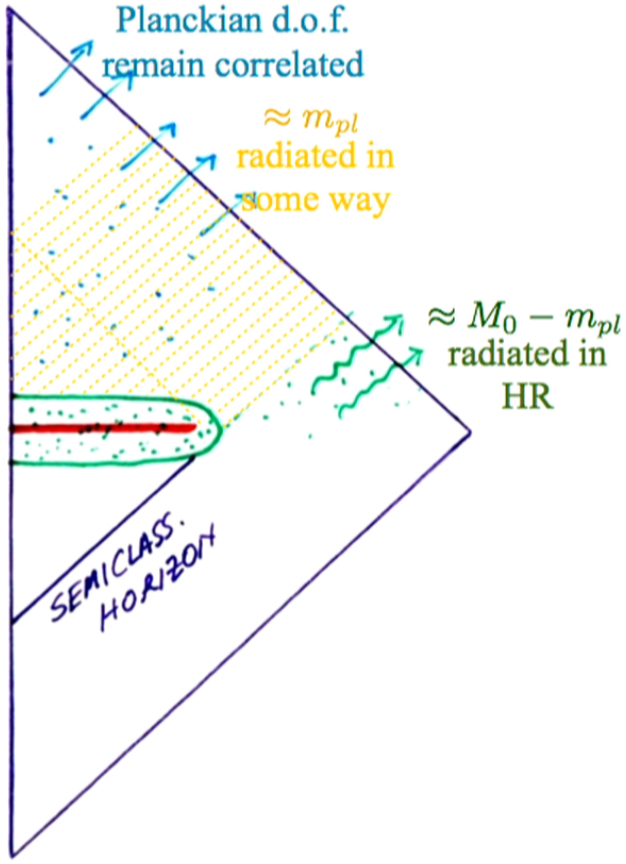
The Ashtekar-Bojowald paradigm:
Uncorrelated Hawking radiation

The constraint that a small (Planckian) amount of mass is radiated while the naked *would-be-singularity* is visible suggests **the lack of unitarity** of the EQFT degrees of freedom (arXiv:1409.0144 Bianchi-De Lorenzo-Smerlak).

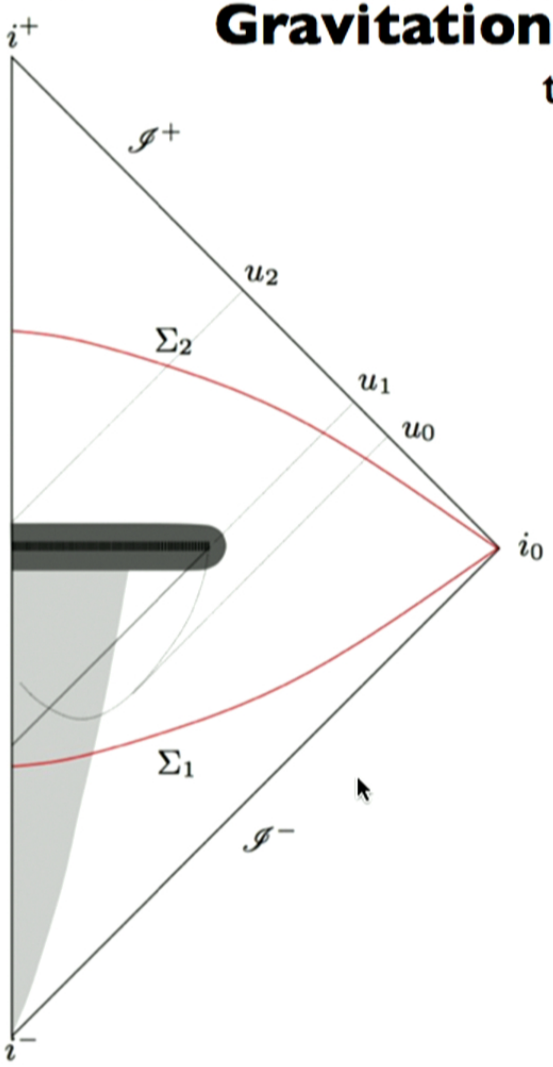
Solution: EQFT unitarity is broken while fundamental quantum gravity unitarity holds. Information is retrieved in correlations of **Planckian quantum geometry degrees of freedom** (after would-be-singularity becomes visible) that are **entangled with radiation in Hawking era.**



Gravitational collapse is highly time asymmetric

(19)

two ways of presenting the spacetime



The story told from the perspective of observers at future null infinity is a **semiclassical one**

The local version of the story must be told by **quantum gravity**

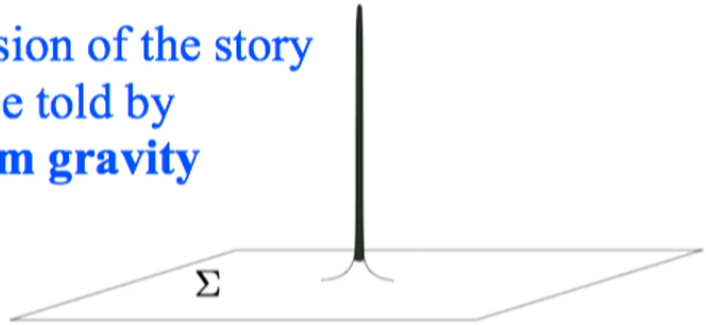


FIG. 8: A qualitative representation of the Riemannian geometry of Σ and Σ' of Fig 5. The shaded regions are those 'touching' the quantum region.

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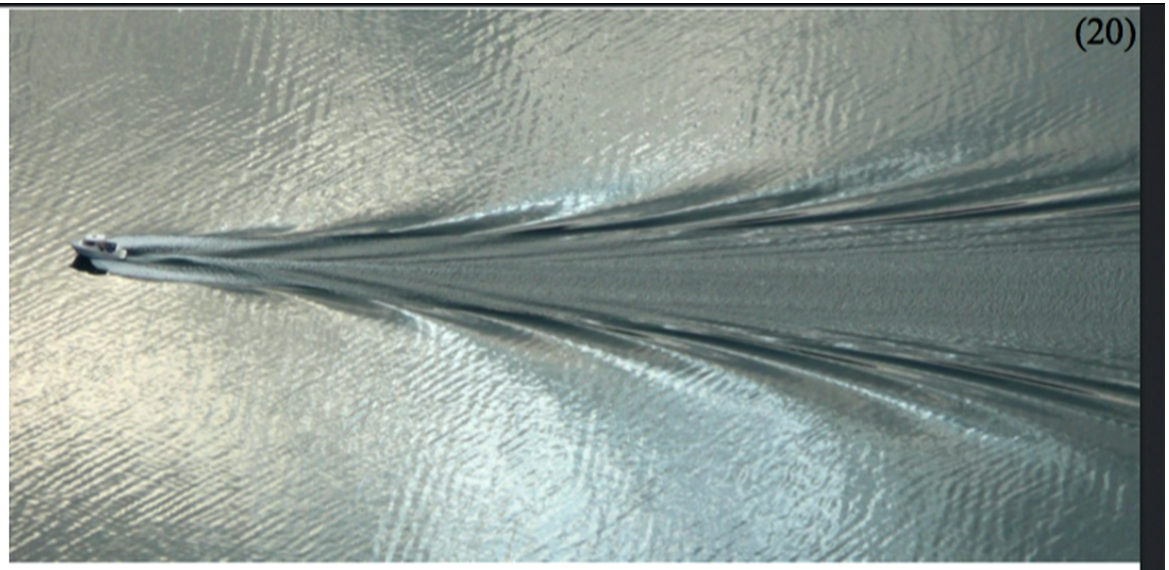

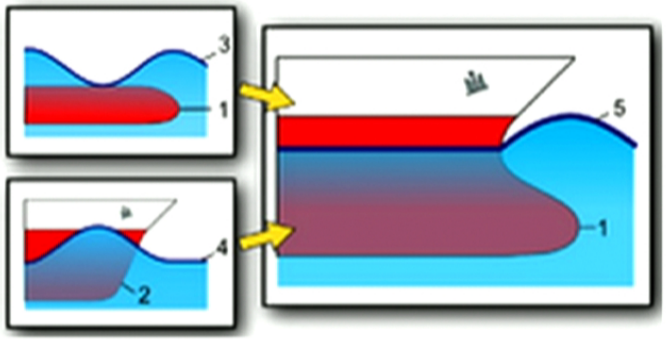

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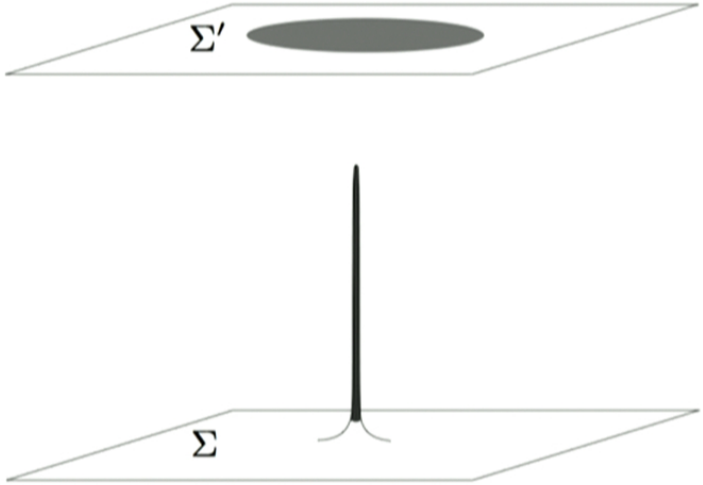
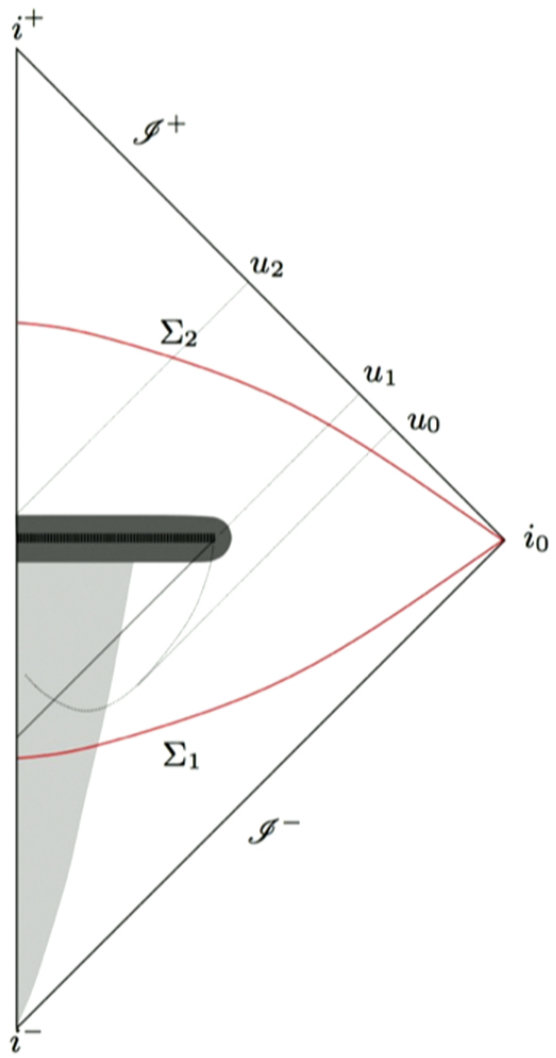


FIG. 8: A qualitative representation of the Riemannian geometry of Σ and Σ' of Fig 5. The shaded regions are those 'touching' the quantum region.

$$V(\Sigma) \propto M^3 (M/\ell_p)^\alpha. \qquad (3)$$

where the missing proportionality constant and α depend on the interior dynamics. For instance one gets $\alpha = 1/2$ if one (toy-)models the evaporation process with an advanced Vaidya metric. We can estimate the scaling of



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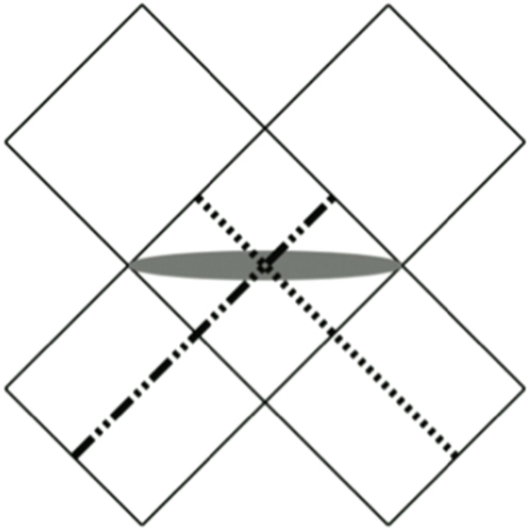

$$\langle T_{ab}u^a u^b\rangle \approx -\frac{\ell_p^2 M}{48 r^5}\left[1+\left(\frac{r}{u}\right)^4\right]$$

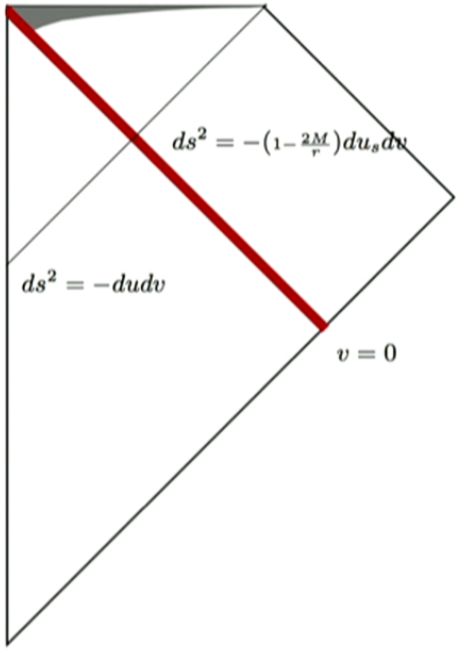

FIG. 6: 2d spherical black hole made from the gravitational collapse of a spherical pulse of energy M. The metric is flat inside the shell and Schwarzschild outside. Continuity of the metric across the shell implies the following relationship between retarded time $u = t - r$ and $u_s = t - r_*$ (for r_* the standard tortoise coordinate): $u_s = u - 4M\log(1 + \frac{u}{4M})$ and $v_s = v$. Coordinates are chosen so that the shell collapse takes place at $v = 0$. The expectation value of the energy momentum tensor in the Unruh vacuum is known in close form [65] everywhere in the spacetime. The shaded area denotes qualitatively the region where observers falling along ∂_r detect energy densities smaller than some negative fixed value.

Where does information go?

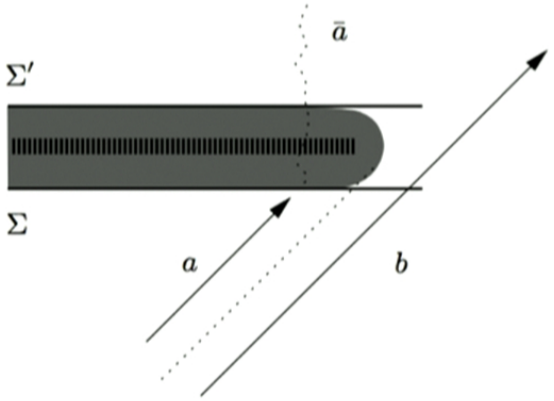

FIG. 5: Two instants of 'time' before and after the *would-be-singularity*. The spacial surface Σ is a latest surface where the space-time notion is still applicable. The surface Σ' is the earliest space-like surface in the flat emerging flat space-time across the *would-be-singularity*. The particles a and b are created close to the BH horizon. Particle b escapes to infinity as Hawking radiation. Particle a falls into the singularity, deposits its negative energy load, striped off its energy it emerges unitarily transformed into a defect $\bar{a}$ in the quantum weave state describing flat space-time to the future of the *would-be-singularity*.

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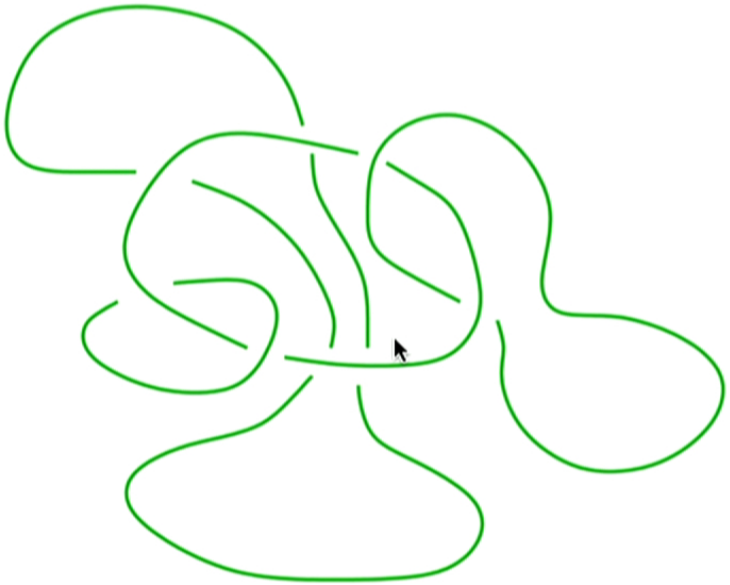
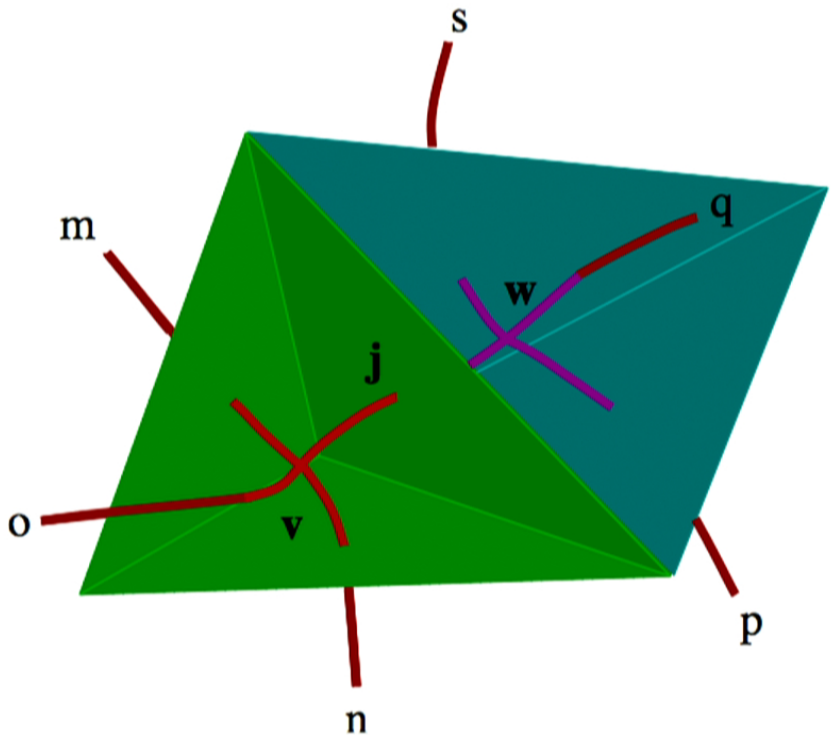
Candidates for information carriers

Degenerate geometries



The volume q-bit



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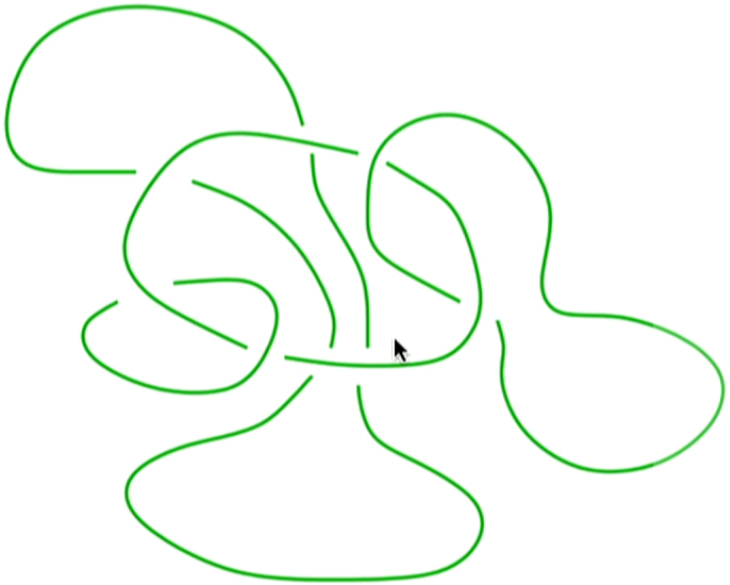
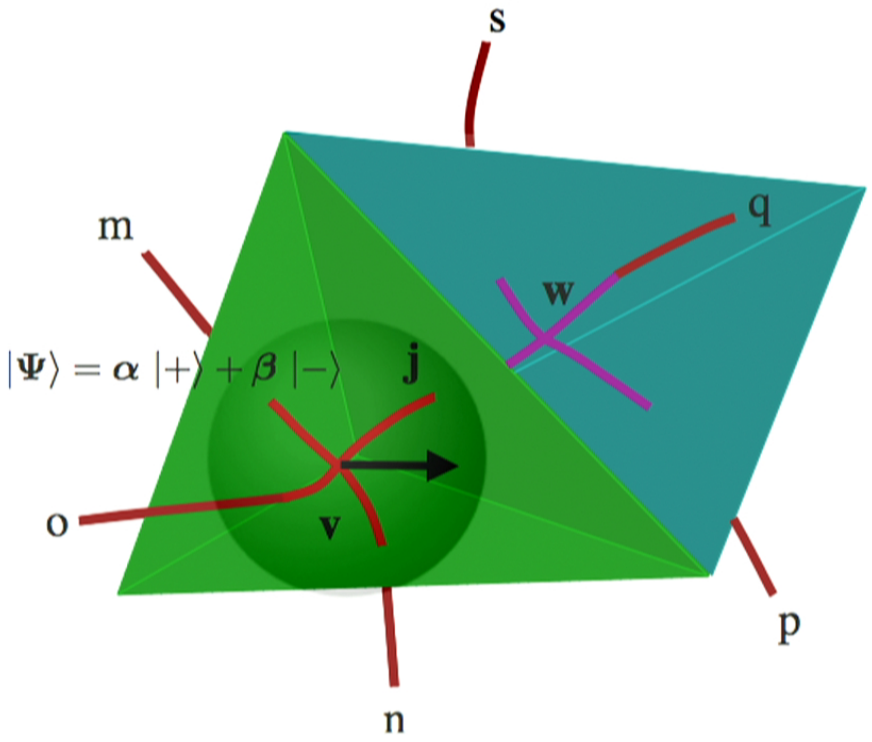
Candidates for information carriers

Degenerate geometries



The volume q-bit



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Candidates for information carriers

Independent of quantization prescriptions

T. Thiemann J.Math.Phys. 39 (1998) 3347-3371

C. Rovelli, L. Smolin. Nucl.Phys. B442 (1995) 593-622, Nucl.Phys. B456 (1995) 753

E. Bianchi, P. Dona, S. Speziale. Phys.Rev. D83 (2011) 044035

Fermions should interact with these q-bits

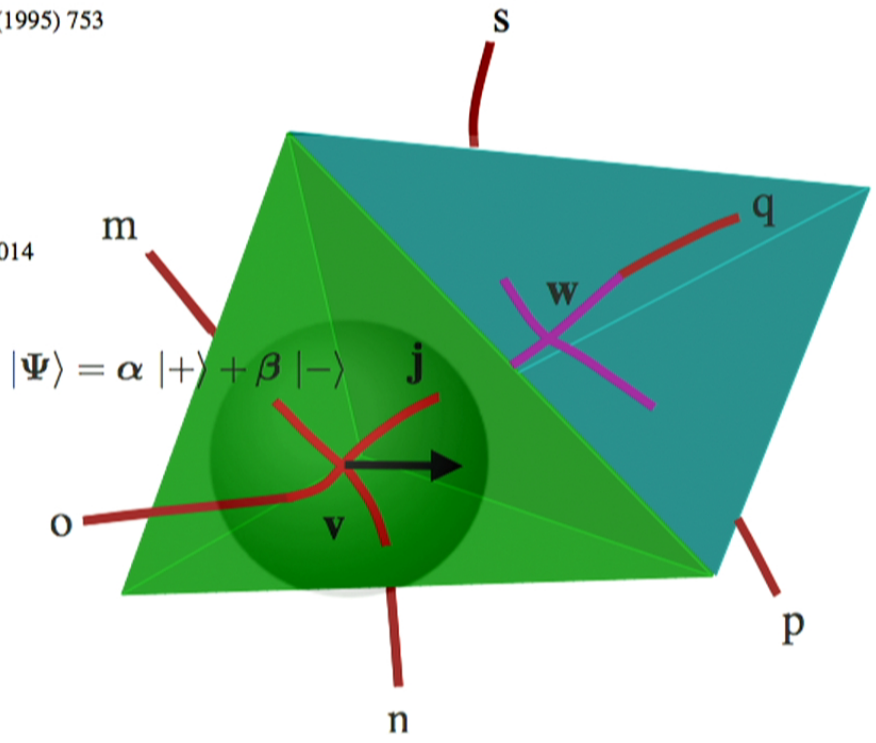
M. Christodoulou, A. Riello, C. Rovelli. Int.J.Mod.Phys. D21 (2012) 1242014

Work in progress in collaboration with Speziale and De Lorenzo

What of all this remains in physical states?

Lorentz invariance?

The volume q-bit



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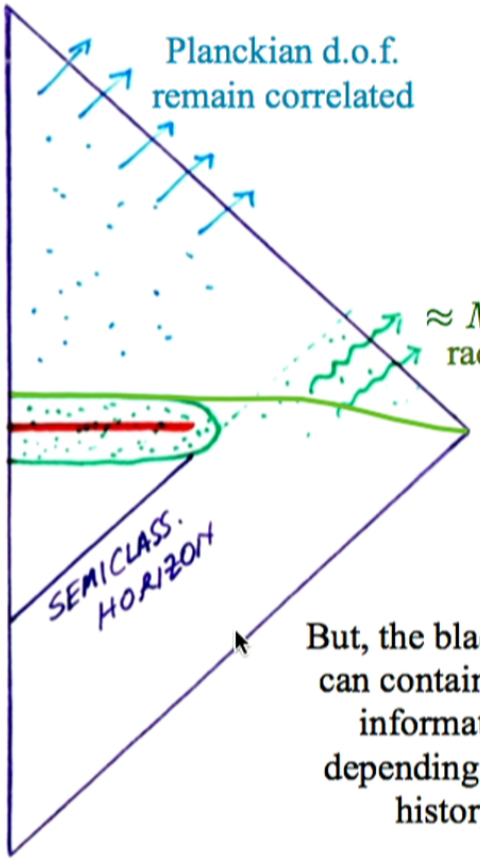
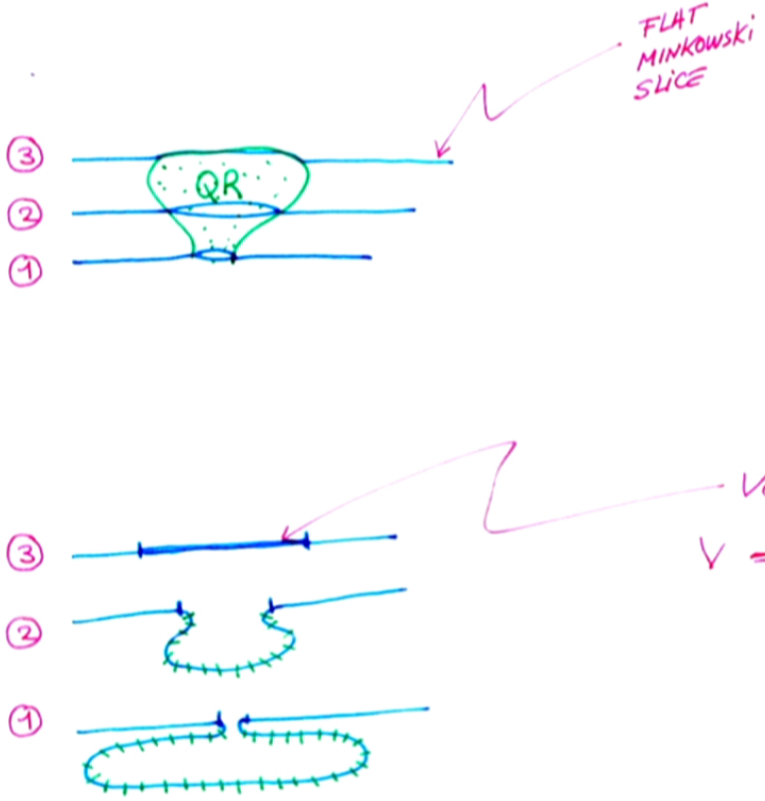
$$V \approx \frac{A_0}{4\ell_p^2} \times \ell_p^3$$



But, the black hole can contain more information depending on its history



$$L = V^{1/3} \approx \left(\frac{M_0}{M_\odot}\right)^{\frac{2}{3}} \times 10^{-11} m$$

$$L_\odot \approx 10^{-11} m$$

$$L(10^{15} g) \approx 10^{-22} m \approx 10^{-2} \ell_{LHC}$$

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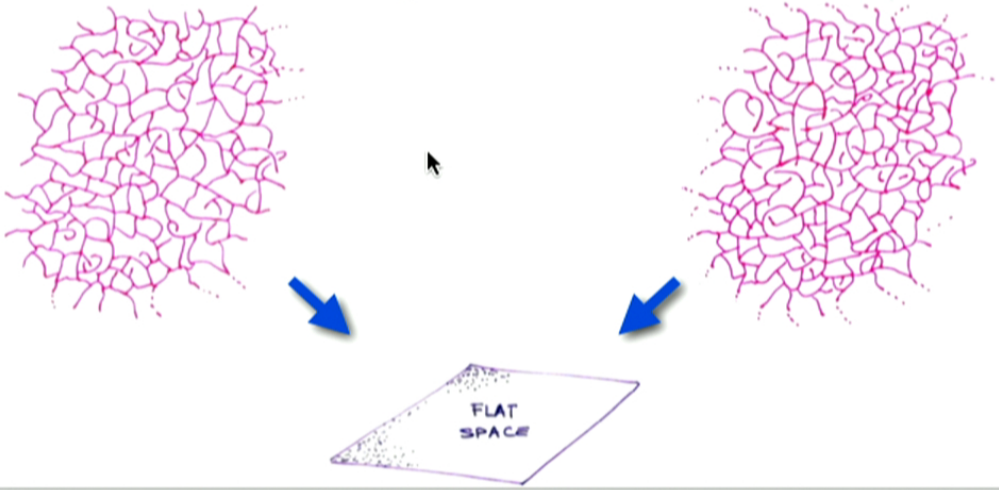
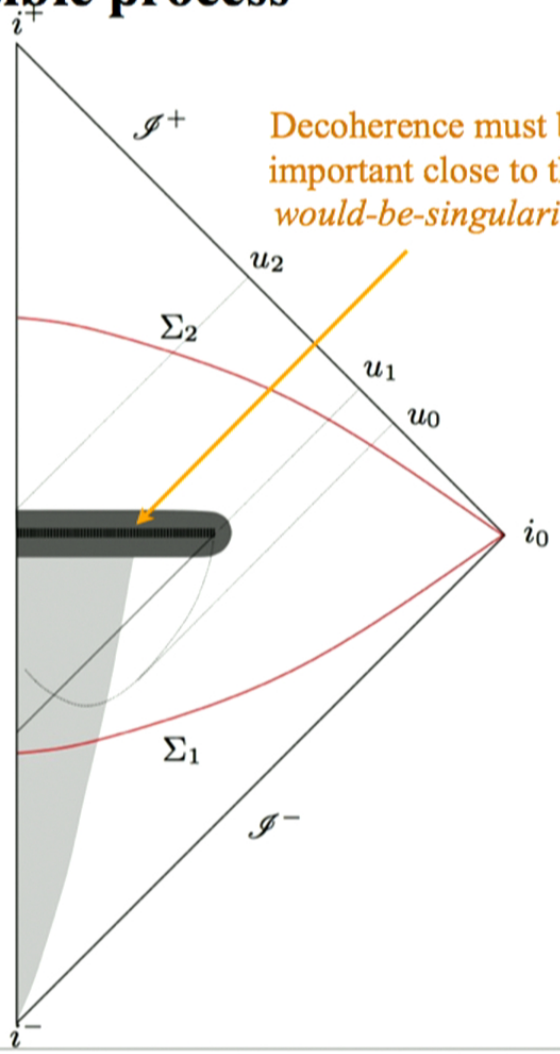
Gravitational collapse is an irreversible process

- Gravitational collapse **spacetime is highly asymmetric**.
- **Firewalls:** Purification cannot take place during Hawking era.
- Purification via EQFT degrees of freedom after Hawking era on an effective non-singular background is not possible (Hayward scenario) (from results by Bianchi-De Lorenzo-Smerlak).
- **Natural possibility:** Purification via decoherence with Planckian quantum geometry structure.
- **Initial and final "flat" space-times are not the same.**





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LQG IS NOT HOLOGRAPHIC

But what about all the holographic phenomenology? (e.g. the **Bousso bound**; a theorem by Bousso-Casini-Maldacena, Phys.Rev. D90 (2014) 4, 044002)

$$S_{\rho_0}(\rho) = -\mathrm{Tr}[\rho \log \rho] + \mathrm{Tr}[\rho_0 \log \rho_0].$$

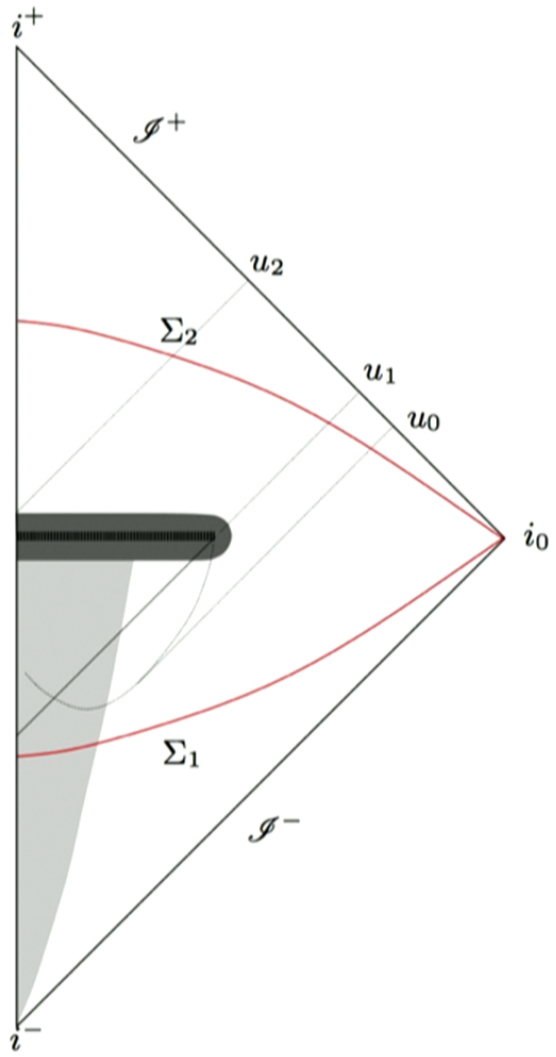
a fact about EQFT degrees of freedom that does not contradict a non-holographic fundamental framework.

Bianchi's computation of BH entropy changes (Semiclassics: Einsteins equations+QFT) **arXiv:1211.0522**

$$\delta S_{thermo} = \frac{\delta A}{4 G_N \hbar}$$

versus the computation of BH entropy in LQG (microstructure of quantum geometry)

$$S_{stat} = \frac{A}{4 G_N \hbar} + \eta \frac{\sqrt{A}}{\sqrt{\gamma G \hbar}}$$



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INFORMATION need not have WEIGHT

From Unruh 2012 "Decoherence without dissipation"

Consider two particles, which for sake of simplicity I will assume have the same mass, and live in a 1+1 dimensional spacetime. They interact only when in contact with each other, and their interaction is mediated by some hidden degrees of freedom which are represented by a number N of spin 1/2 objects, with spins operators $\vec{S}_i$. The interaction Hamiltonian is assumed to be of the form $\delta(x_1 - x_2)\sum_i S_i^3$ where $S^3 = \frac{1}{2}\sigma^3$ the third Pauli spin matrix, while the Kinetic energy is the usual $\frac{1}{2m}(p_1^2. + p_2^2)$.

$$Y = (x_1 + x_2)/2 \quad (1)$$

$$y = (x_1 - x_2) \quad (2)$$

the Schroedinger equation becomes

$$i\partial_t \Psi(t, Y, y, \{s_i\}) = -\frac{1}{m}\partial_Y^2 \Psi - \frac{1}{2m}\partial_y^2 \Psi + \mu\delta(y)(\sum_i S_i^3)\Psi \quad (3)$$

From Unruh and Wald 95

$$H = \frac{1}{2}\int \left\{[\pi(t,x) - h(x)q]^2 + [\partial_x \phi(t,x)]^2\right\} dx + \frac{\omega}{2}(p^2 + q^2 - \tfrac{1}{2})[1 + \alpha(S_z + s)] + F(S_z),$$

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Conclusions

• Quantum geometry is expected to be 'atomistic' in non perturbative QG

• Smooth spacetime arises from coarse graining.

• Discrete Planckian structure explains Hawking entropy.

• Purification via EQFT degrees of freedom does not work:

1. During Hawking era due to the **firewall problem**.
2. After Hawking era on an effective non-singular background due to **energy conservation**.

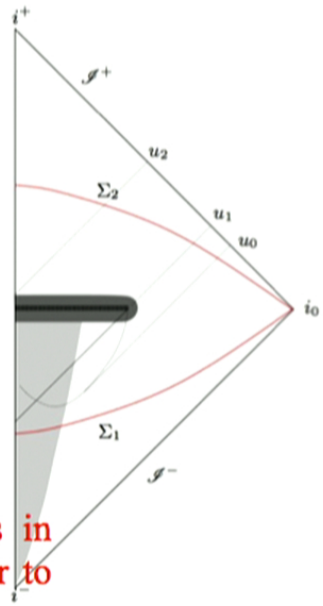
• **Natural possibility:** Purification via decoherence with Planckian quantum geometry structure (important close to the *would-be-singularity*).

• **Initial and final "flat" space-times are not the same:** EQFT scattering approach cannot describe the fundamental physics.

• The firewall argument is a problem for ADS-CFT type of scenarios not for `atomistic' QG theories.

•In this scenario the Hawking evaporation process is analogous to standard irreversible processes (breaking a glass, burning a newspaper)

Outlook



•Can one take into account non perturbative back reaction effects in spherical quantum gravity? (Gambini-Pullin theory with scalar matter to show 'time asymmetry' of *would-be-singularity*)

•Can one effectively describe the decoherence effect of EQFT? (quantum cosmology, structure formation effects, unitarity loss in QFT)

Thank you very much!

For further reading:
"No firewalls in quantum gravity: the role of discreteness of quantum geometry in resolving the information loss paradox"
arXiv:1410.7062
to appear in CQG

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