Space-time Thermodynamics without Hidden Degrees of Freedom

Goffredo Chirco

December 16 @ DESY

Based on recent work in collaboration with H. Haggard, A. Riello, C. Rovelli

Jacobson 95, Jacobson Parentani 2003

Bianchi 2012, Bianchi Myers 2013

Engle, Pereira, Rovelli, Livine, Freidel, Krasnov, Speziale

OUTLINE

1. space-time “entanglement” thermodynamics and the Einstein’s equation of state

2. Bekenstein-Hawking entropy from entanglement thermodynamics in perturbative quantum gravity

3. space-time thermodynamics fundamental ingredients from a non perturbative LQG perspective

BLACK HOLES THERMODYNAMICS

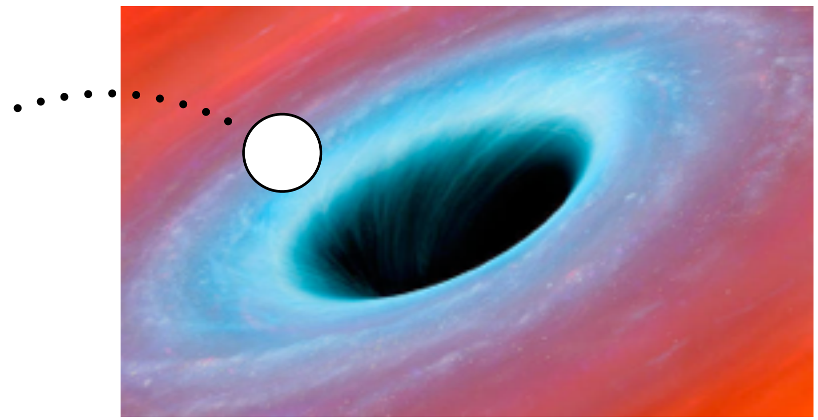
Bekenstein, Hawking 1974

BH solutions can be described as dynamical systems in terms of a small number of parameters: M, J, Qe (no hair theorem)

Israel 67, Christodoulou 71, Hawking 71, Bardeen, Carter 73

- gravity $dM = \frac{\kappa}{8\pi} dA$ + ...

+ QFT



$$M + \delta E \to A + \delta A$$

$$T_H = \frac{\kappa \hbar}{2\pi}$$ Hawking temperature

$$S_{BH} = \frac{A}{4G\hbar}$$ Bekenstein-Hawking entropy

$$k \longleftrightarrow T$$

$$A \longleftrightarrow S \quad \Rightarrow \quad dE = TdS$$

$$M \longleftrightarrow E$$

puzzling interplay between GRAVITY / QFT / THERMODYNAMICS

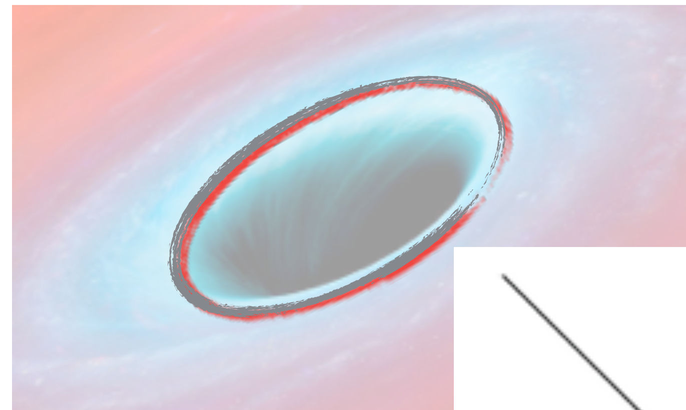
NEAR HORIZON LIMIT => LOCAL CAUSAL HORIZON THERMODYNAMICS

Schwrzschild $$d\tau^2 = (1 - \frac{2MG}{r})dt^2 - (1 - \frac{2MG}{r})^{-1}dr^2 - r^2 d\Omega^2$$

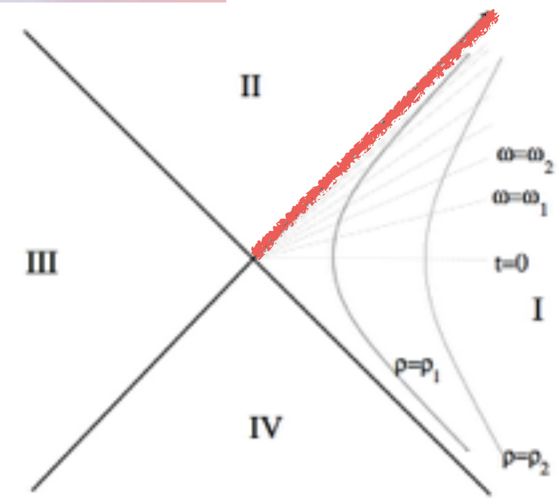
$$= g_{\mu\nu}dx^\mu dx^\nu.$$

proper distance

$$\rho = \int_{2MG}^{r} \sqrt{g_{rr}(r')}\, dr'$$



the horizon is locally non singular and for large black holes is almost indistinguishable from flat space-time



near horizon limit $$\approx 2\sqrt{2MG(r - 2MG)}$$

$$d\tau^2 \cong \rho^2 \left(\frac{dt}{4MG}\right)^2 - d\rho^2 - r^2(\rho)\, d\Omega^2 \qquad \omega = \frac{t}{4MG}$$

radial and hyperbolic angle variables for an ordinary Minkowski space

$$T = \rho\, sinh\omega$$

$$Z = \rho\, cosh\omega$$

=>

Rindler

$$d\tau^2 = dT^2 - dZ^2 - dX^2 - dY^2$$

black hole thermodynamical relations holds for the event horizon of an asymptotic uniformly accelerated observer, simply derived from local killing field

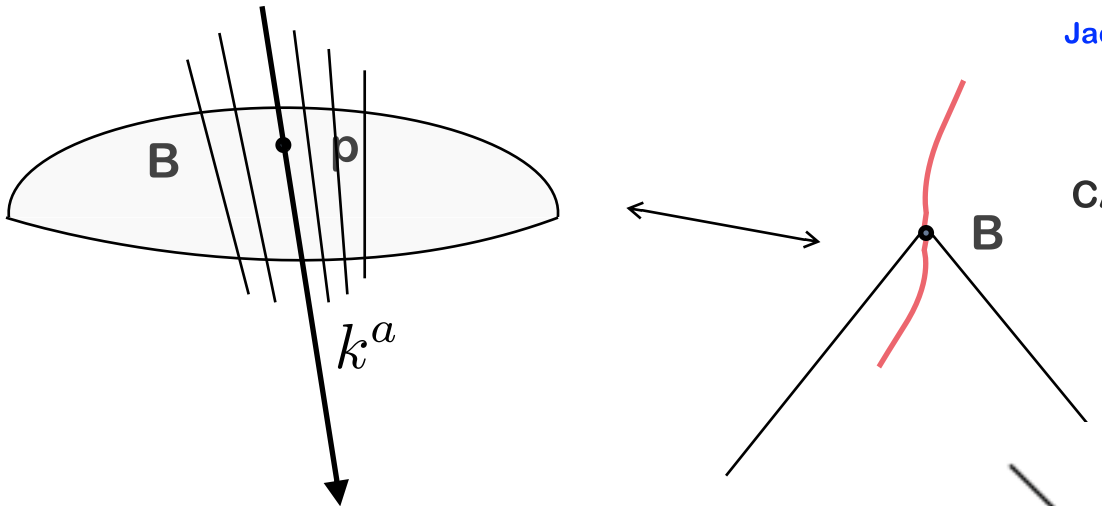
$$dM = \frac{\kappa}{8\pi}dA$$

Jacobson Parentani 03, Perez 12

FORGET BH => LOCAL CAUSAL HORIZON THERMODYNAMICS

equivalence principle : consider a local space-time space-like 2 surface patch B associated to an event p

Jacobson 95, Padmanabhan 02



CAUSAL HORIZON: boundary of the past of B = past directed null geodesic congruence normal to B

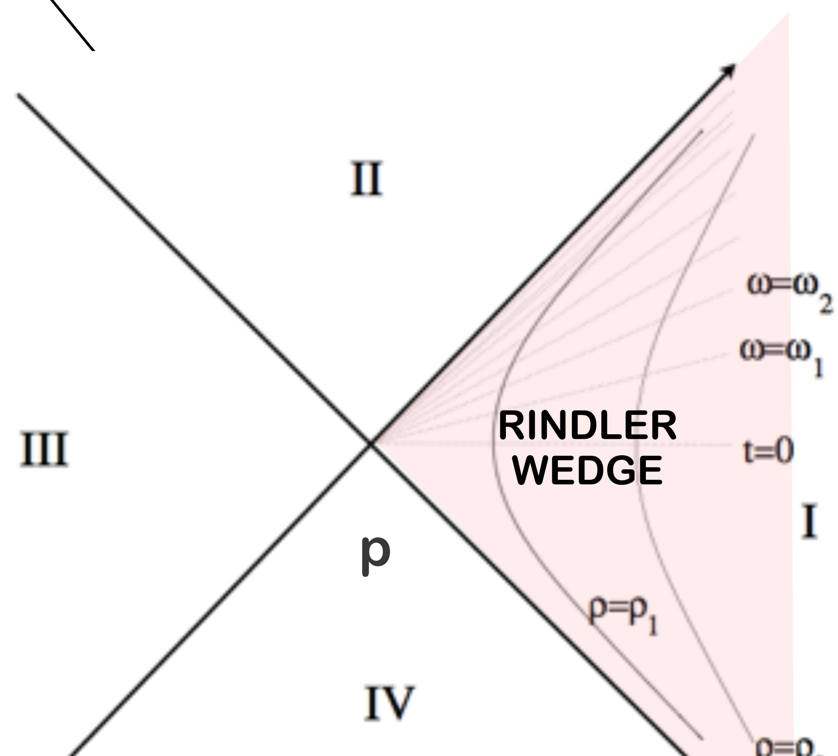
local Lorentz invariance

uniformly accelerated observer on η_{ab}

black hole thermodynamical relations holds for local causal horizon?

local quantum field theory

thermodynamical character of the LOCAL Minkowski vacuum restricted to a single Rindler wedge



local Rindler horizon as a causality barrier

ENTANGLEMENT THERMODYNAMICS

Bisognano Wichmann 76, Sorkin 1983, Sredniki 1993

- 4d Minkowski space

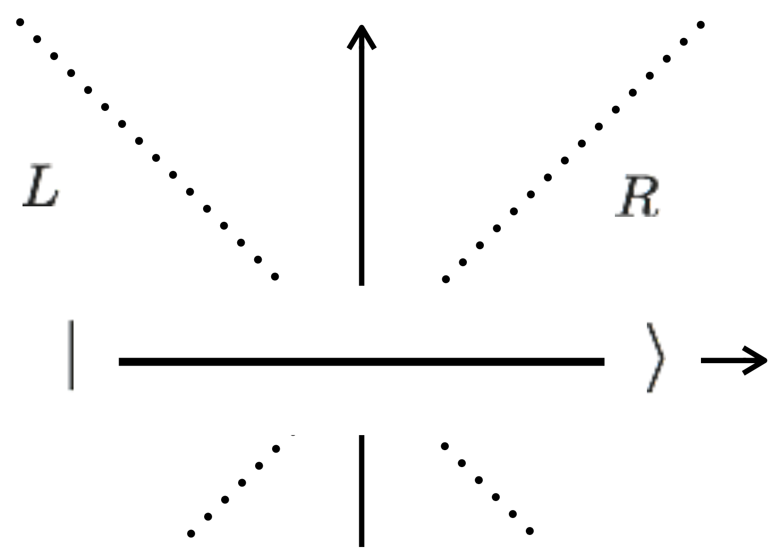
$$x^\mu = (T, Z, X, Y)$$

- two regions $\quad L = Z < |T|, \quad R = Z > |T|$

- QFT

$$\mathcal{H} = \mathcal{H}_L \otimes \mathcal{H}_R$$

- Minkowski vacuum state $\quad |0\rangle =$



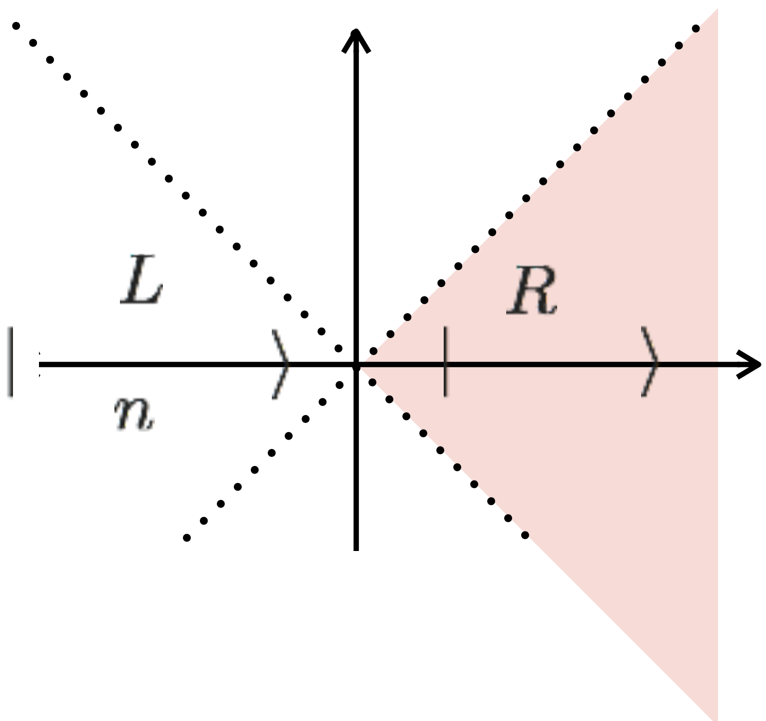
ENTANGLEMENT THERMODYNAMICS

Bisognano Wichmann ‘76

- Minkowski vacuum is not separable: highly nonlocal space like correlations, high entanglement

- restricted Minkowski vacuum state

$$|0\rangle = \sum_n e^{-2\pi\epsilon_n} |$$



- reduced density matrix

$$\rho_0 = Tr_L(|0\rangle\langle 0|)$$

$$= \sum_n e^{-2\pi\epsilon_n} |n\rangle\langle n|$$

- vacuum entanglement entropy $\quad S_{ent}(|0\rangle) = -Tr_R(\rho_0 \ln \rho_0)$ UV divergent!

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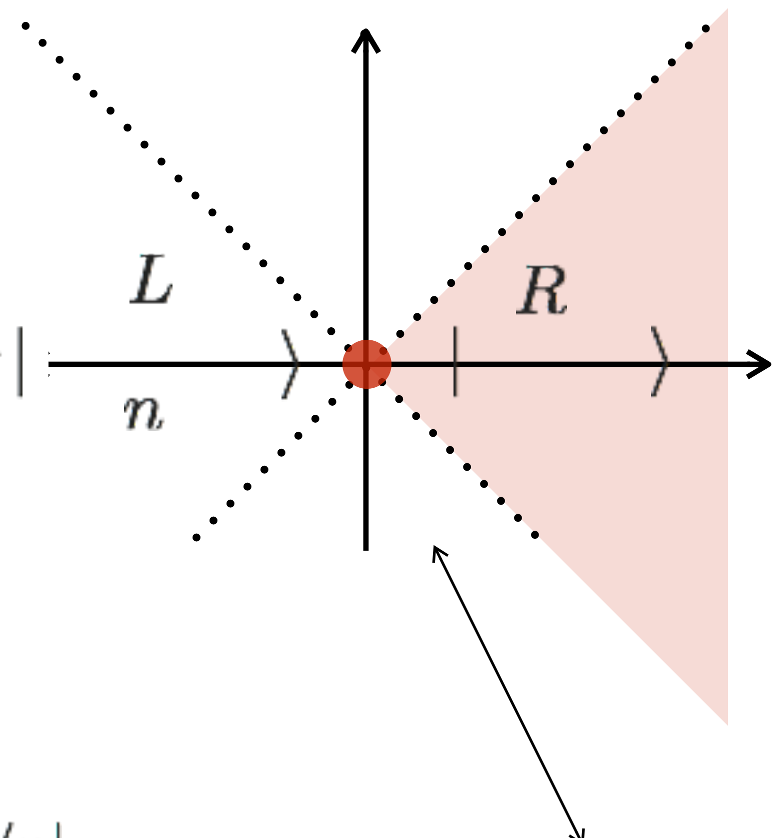


- reduced density matrix

$$\rho_0 = Tr_L(|0\rangle\langle 0|)$$

$$= \sum_n e^{-2\pi\epsilon_n} |n\rangle\langle n|$$

UV cutoff

species

- vacuum entanglement entropy

$$S_{ent}(|0\rangle) = -Tr_R(\rho_0 \ln \rho_0) = \alpha/l_p^2\, A$$

Solodukhin Liv. Rev. Rel. 2011

ENTANGLEMENT THERMODYNAMICS

- restricted vacuum is thermal: Unruh effect

$$H = \hbar K_R\, a$$

Rindler Hamiltonian

$$\rho_0 = Tr_L(|0\rangle\langle 0|) = \frac{e^{-2\pi K_R}}{Z}$$

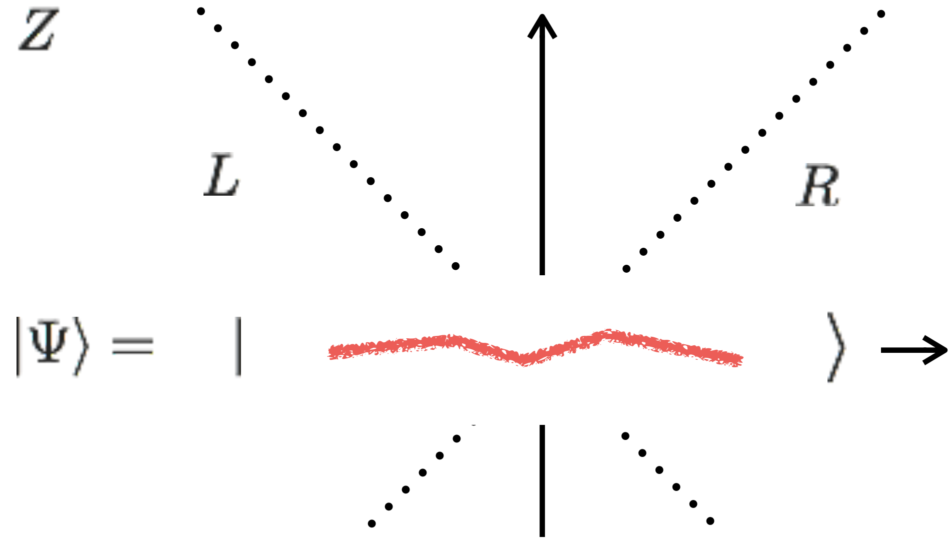
Gibbs state

$$= \frac{e^{-\frac{2\pi}{\hbar a} a\, \hbar K_R}}{Z} = \frac{e^{-H/T}}{Z}$$

T = Unruh temperature

thermodynamics?

$$\delta S_{ent} = S_{ent}(|\Psi\rangle) - S_{ent}(|0\rangle)$$



- small perturbation of the vacuum

$$\rho_1 = Tr_L(|\Psi\rangle\langle\Psi|)$$

$$\delta\rho = \rho_1 - \rho_0$$

=> entanglement perturbation

$$\delta S_{ent} = -\delta Tr(\rho \ln \rho) = -Tr(\delta\rho \ln \rho_0) - Tr(\rho_0 \frac{1}{\rho_0} \delta\rho)$$

$$= 2\pi Tr(K_R \delta\rho) + \ln Z\, Tr(\delta\rho) = \frac{2\pi}{a\hbar} Tr(\hat{H}\delta\rho) = \frac{\delta E}{T}$$

EINSTEIN'S EQUATION OF STATE

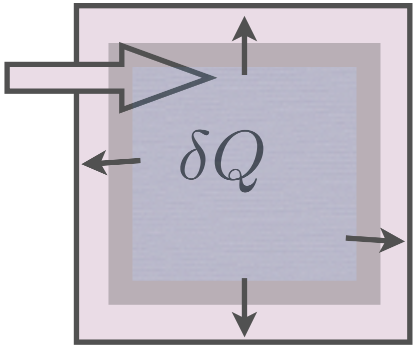
Jacobson 95

Jacobson: can we invert the logic ? QFT + THERMODYNAMICS => GRAVITY

hint:

$S(E,V)$ => $dS = (\partial S/\partial E)dE + (\partial S/\partial V)dV$

$\delta Q = dE + pdV$



equilibrium entropy balance $\delta Q = TdS$ => $T^{-1} = (\partial S/\partial E)$

$p = T(\partial S/\partial V)$

equation of state

geometric entropy functional + local matter fields energy perturbations => dynamics of space-time causal structure as an equation of state

EINSTEIN'S EQUATION OF STATE

consider physical approach for the local vacuum perturbation:

- on the horizon $\quad T = \dfrac{\hbar\kappa}{2\pi}$

$$\chi^\mu = \kappa v k^\mu$$

we know

$$E_R = E_H + E_\infty$$

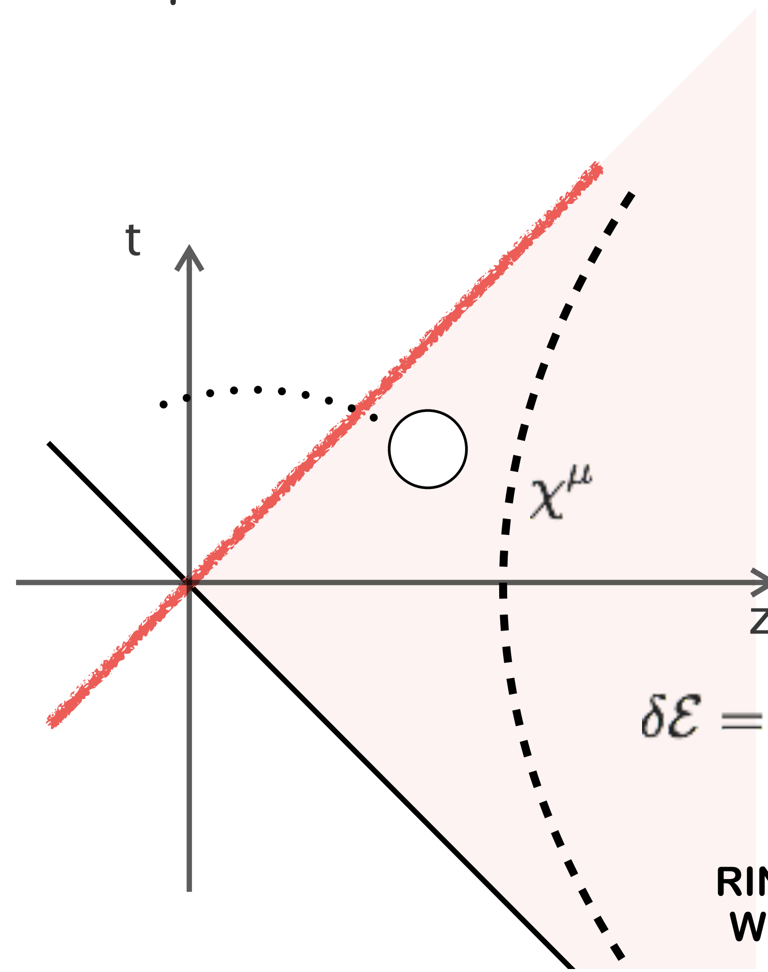
- energy flux

$$\delta E = \int_H T_{\mu\nu}\chi^\mu dH^\nu$$

- energy variation of the vacuum state

$$\delta E = Tr\left(\int_H T_{\mu\nu}\, \kappa v k^\mu dH^\nu \,\delta\rho\right)$$ (heat interpretation)

$$dH^\mu = -k^\mu dv dy_1 dy_2$$



RINDLER WEDGE

$$E_\infty = 0$$

no energy escape to future infinity

$$\delta\mathcal{E} = \int_\Sigma T_{\mu\nu}\chi^\mu d\Sigma^\nu$$

=> $$\delta E/T = -\frac{2\pi}{\hbar}\int_H \langle T_{\mu\nu}\rangle_{\delta\rho}\, v k^\mu k^\nu \, dv dy_1 dy_2$$

EINSTEIN'S EQUATION OF STATE

- entanglement area scaling

$$S_{ent}(|0\rangle) = -Tr_R(\rho_0 \ln \rho_0) = \alpha/l_p^2\, A$$

$$\delta S_{ent} = \delta(\alpha/l_p^2\, A)$$

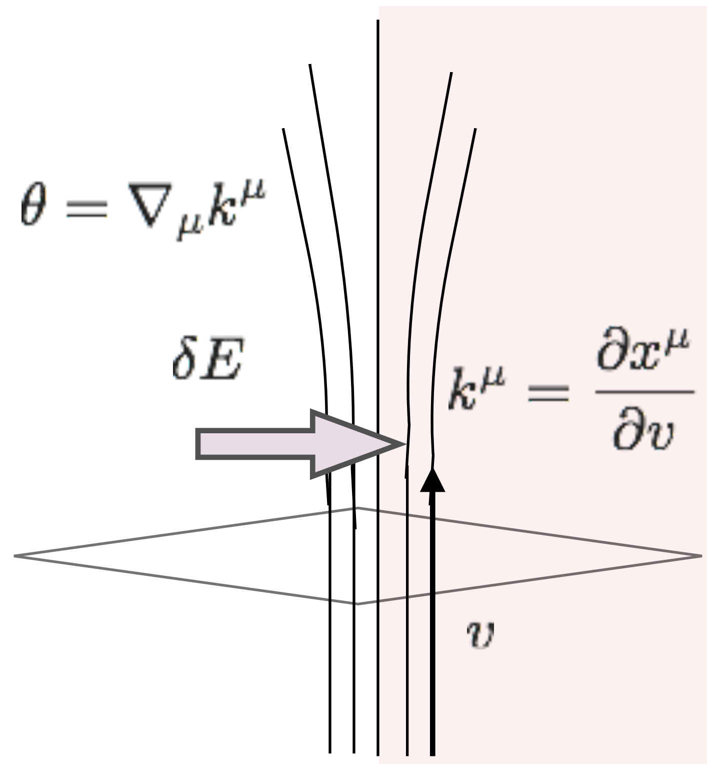
- assume universality $\delta\alpha = 0$

if $\delta S_{ent} = \delta E/T$

=> $\delta S_{ent} = \alpha/l_p^2\, \delta A$ space-time cannot be inert !

$$\Delta A = \int \theta\, dv dy_1 dy_2$$

$$\theta = \nabla_\mu k^\mu$$



- area change $\delta A = \int \delta\theta\, dv dy_1 dy_2$

$$\delta\theta = \theta_p + \frac{\partial\theta}{\partial v}|_p\, \delta v$$

- Raychaudhuri equation $\frac{\partial\theta}{\partial v} = -R_{\mu\nu}k^\mu k^\nu$

=> $$\delta S_{ent} = \alpha/l_p^2 \int_H -v\, R_{\mu\nu}k^\mu k^\nu\, dv dy_1 dy_2$$

EINSTEIN'S EQUATION OF STATE

Jacobson 95

- so $\delta S_{ent} = \delta E/T$ => $\boxed{\delta E_H = \alpha \frac{\hbar\kappa}{2\pi l_p^2} \delta A_H}$

- for all null k^a

local constitutive relation $$\frac{2\pi l_p^2}{\hbar\alpha} T_{\mu\nu} = R_{\mu\nu} + \Phi\, g_{\mu\nu}$$

- define $\Phi = -\frac{1}{2} R - \Lambda$ by

- local energy conservation $\nabla^\nu T_{\mu\nu} = 0$
- Bianchi identity $\nabla^\nu R_{\mu\nu} = \frac{1}{2} \nabla_\mu R$

=> $$\boxed{8\pi G\, T_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} - \Lambda\, g_{\mu\nu}}$$

then extended to the whole space-time via EP

if only $\alpha = 1/4$

Bekenstein-Hawking

=> $\boxed{S_{ent} = S_{BH} = A/4l_p^2}$

EINSTEIN'S EQUATION OF STATE

just an amazing
SEMICLASSICAL RESULT

LORENTIAN GEOMETRY <=> QUANTUM FIELD THEORY

inert flat space-time => • $\delta S_{ent} = \delta E/T$

space-time become dynamical ! <= • $\delta S_{ent} = \alpha/l_p^2\, \delta A$

IF Bekenstein-Hawking entropy is leading term entanglement entropy

finiteness & universality <=> QUANTUM GRAVITY

UV cut-off problems

Solodukhin Liv. Rev. Rel. 2011

a straightforward way to see it...

QUANTUM GRAVITY: PERTURBATIVE APPROACH

Bianchi 2012

- space-time explicitly dynamical but at quantum level:add the graviton to the previous picture

$$g_{\mu\nu} = \eta_{\mu\nu} + \sqrt{32\pi G} h_{\mu\nu}$$

the graviton field is defined as the perturbation of the space-time metric about the Minkowski flat metric

- at leading order in a perturbative expansion in Newton's constant G:

$$I = I_{grav}[h_{\mu\nu}] + I_{matt}[\phi] + \sqrt{8\pi G} \int d^4x h_{\mu\nu} T^{\mu\nu}$$

Fierz-Pauli action

universal coupling

- equations of motion

$$\Box h_{\mu\nu} = -\sqrt{8\pi G}(T^{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T^{\sigma}_{\sigma})$$

harmonic gauge

- look at small perturbations of the interacting Minkowski vacuum of matter fields and gravitons

- boost energy flux

$$K = \int_H T_{\mu\nu}\chi^\mu dH^\nu$$

- horizon cross section area at leading order in a perturbative expansion in Newton's constant G

$$A_H = A_0 + \sqrt{8\pi G}\int(-\Box h_{\mu\nu}k^\mu k^\nu)v dv dy_1 dy_2$$

- entropy universality recovered dynamically $\delta E = 2\pi Tr(\int_H T_{\mu\nu} v k^\mu dH^\nu \delta\rho)$

use e.o.m. $$\delta S_{ent} = \frac{2\pi}{\sqrt{8\pi G}} Tr(\int_H (-\Box h_{\mu\nu}k^\mu k^\nu)\, v\, dv dy_1 dy_2\, \delta\rho)$$

=> $$\delta S_{ent} = 2\pi\frac{1}{\sqrt{8\pi G}} Tr(A_H \delta\rho) = \frac{\delta A}{4G}$$

Bekenstein-Hawking

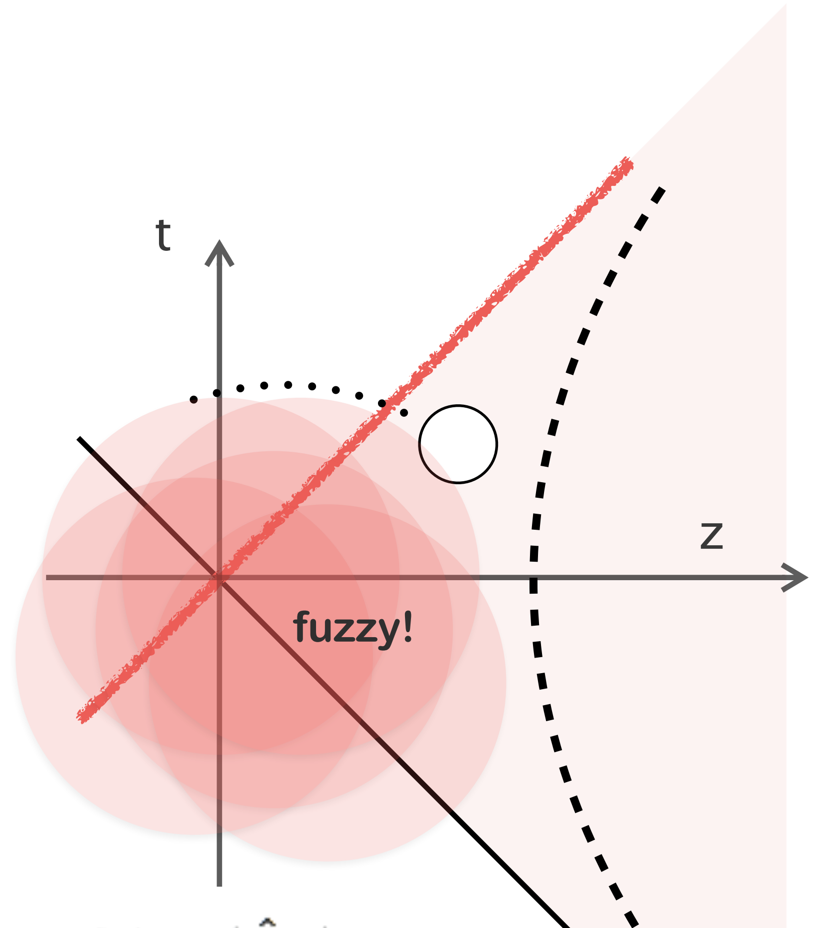
QUANTUM GRAVITY: PERTURBATIVE APPROACH

what do we learn?

$$\delta E = \frac{a}{8\pi G}\,\delta A$$

1. is not only a strict consequence of Einstein's equations, but is also a sufficient condition for the Einstein's equation to hold

2. a universal entanglement entropy area relation a la Bekenstein-Hawking requires gravity playing an active role at quantum level



$$\delta A = \langle \hat{A}_H \rangle_{\delta\rho}$$

Einstein's equations are encoded in the relation of proportionality between classical averages of quantum fluctuations of wedge fields energy and horizon area, as measured by a uniformly accelerating observer

… 3. the role of the area operator suggest to look at a non-perturbative quantum gravity scenario

A NON - PERTURBATIVE PERSPECTIVE

Ashtekar, Rovelli

our variables

- Einstein formulation

$$S[g] = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\,(R-2\Lambda)$$

the gravitational field as a peudo-riemmannian metric cannot be fundamentally correct, because it does not allow coupling to fermions

- tetrad formulation

$$S[e] = \int e^I \wedge e^J \wedge F^{KL}\varepsilon_{IJKL}$$

$$g_{\mu\nu}(x) = e^I_\mu(x)e^J_\nu(x)\eta_{IJ}$$

- Palatini: first order formulation

$$S[e,\omega] = \int e \wedge e \wedge F[\omega]^*$$

it admits a purely geometric formulation in terms of forms

Holst action

Lorentz connection is an object in the Lorentz algebra

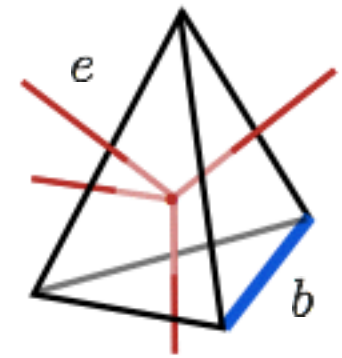
$$S[e,\omega] = \int e \wedge e \wedge F^* + \frac{1}{\gamma}\int e \wedge e \wedge F$$

the coupling constant γ is called the Barbero-Immirzi coupling constant. This is the action with which we do 4-dimensional quantum gravity, as it is the most generic one: it is polynomial and has all the relevant symmetries. The Holst term has no effect on classical physics, but plays a substantial role in the quantum theory.

A NON - PERTURBATIVE PERSPECTIVE

Rovelli

in 3D



- discretize the connection, as in Yang Mills theory, by associating an SU(2) group element U_e to each edge e of the two complex. We discretize the triad by associating a vector e^i_b of R^3 to each bone b of the original triangulation

$$\omega \longrightarrow U_e$$
$$e \longrightarrow L_f$$

holonomy of the connection along the edge, namely the matrix of the parallel transport generated by the connection along the edge

$$U_e = P\, e^{\int_e \omega} \in SL(2,C)$$

$$B_f = \int_{t_f} B \in sl(2,C)$$

- the formal relation between the continuous and the discrete variables can be taken to be the following

- the boundary variables $(L_l, \mathcal{U}_l) \in su(2) \times SU(2)$

- the algebra is also the cotangent space of the group, we can write

$su(2) \times SU(2) \sim T_* SU(2)$ => $T_* SU(2)^L$ boundary phase space

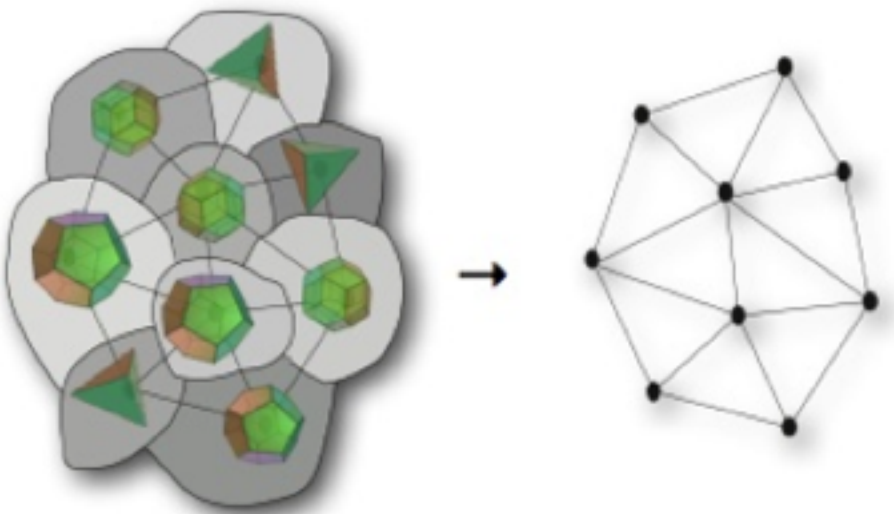
- a cotangent space carries a natural symplectic structure => quantization

analog to angular momentum

A NON - PERTURBATIVE PERSPECTIVE

Engle, Pereira, Rovelli, Livine, Freidel, Krasnov, Speziale

- Loop gravity quantum geometry



Penrose

GR on a lattice:

- Hilbert space $\mathcal{H}$
- Feynmann rules defining the transition amplitudes $\mathcal{A}_v$

BUT gravitational field forms the space-time metric: quanta of gravity are also quanta of space

boundary

$\mathcal{H}$ SU(2) spin networks $\Psi_{\Gamma_{j_l i_n}}$:

- abstract graph Γ
- SU(2) spin j_l at every link
- SU(2) invariant tensor ι_n at every node (intertwiner)

the group SU(2) encodes the symmetries of the quantized space

$\mathcal{A}_v$ SL(2,C) spin foams: quantum gravitational processes between spin network states

- interaction vertices among quanta of space

$$Z = \sum_{j_f, j_e} \prod_f (2j_f + 1) \prod_V \mathcal{A}_v(j_e, j_v)$$

- semiclassical limit of a sum over 4-geometries

=> $$Z \sim \int Dg\, e^{\frac{i}{\hbar}\int d^4x \sqrt{g}\, R}$$

A NON - PERTURBATIVE PERSPECTIVE

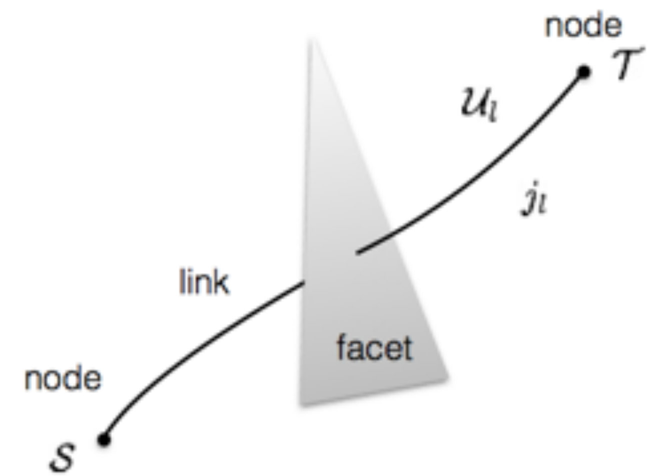
Engle, Pereira, Rovelli, Livine, Freidel, Krasnov, Speziale

- characterize the Hilbert space

consider here for simplicity a single link of the spin network. The corresponding quantum state if a function $\psi(U)$ on SU(2): a basis

$$\langle U | j, m, n \rangle = D^j_{mn}(U)$$

Wigner matrices



U has the classical interpretation of the path integral of the gravitational Ashtekar connection along the link

the state space H associated to the link decomposes as

$$\mathcal{H} = \oplus_j (\mathcal{H}^*_j \otimes \mathcal{H}_j)$$

the dynamics of the theory is obtained mapping these states to a particular subspace of unitary representations of SL(2,C)

$$Y_\gamma : \mathcal{H}^j \to \mathcal{H}_{(\gamma j),j)}$$
$$|j, m\rangle \to |(\gamma j, j); j, m\rangle$$

γ is the Immirzi parameter

- this map is associated to an embedding of our 3d-space geometry in 4d space-time
- on the image of this map the boost generator and the rotation generator satisfy

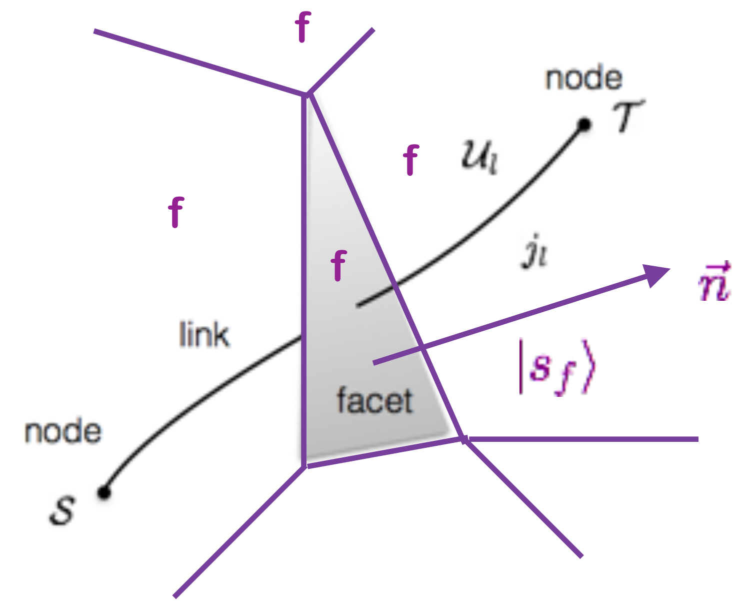
$$\vec{K} = \gamma \vec{L}$$

the spin j component of the state space live in a subspace of

$$\mathcal{H}^j_\gamma = (\mathcal{H}^j_{\gamma j, j})_\mathcal{S} \otimes (\mathcal{H}^j_{\gamma j, j})_\mathcal{T} = \mathcal{H}_\mathcal{S} \otimes \mathcal{H}_\mathcal{T}$$

A NON - PERTURBATIVE PERSPECTIVE

- describe a quantum surface $|s\rangle$ embedded in 4d



SU(2) spin-network states represent the geometry of a spatial section of space-time with normal t^μ

if we measure the geometry of a space-like surface S with a certain precision, we can describe the result of our measurements by tessellating with N facets f

each facet is going to be described by a spin network link, which we can visualise as puncturing the surface: the state describing a quantum surface of a given area and with normal in direction $\vec{n}$ has the form

$$|s\rangle = \otimes_f |s_f\rangle$$

a single puncture state $|s_f\rangle$ is an eigenstate of the area operator of the corresponding facet

$$|A_f| = 8\pi G\hbar\gamma |L_f| \quad \Rightarrow \quad A_f = 8\pi G\hbar\gamma j$$ quantised area facet

A NON - PERTURBATIVE PERSPECTIVE

- For a single puncture, the relation $|K_f| = \gamma |L_f|$ then gives
$$K_f^z = \frac{A_f}{8\pi G\hbar}$$

$K_f^z = \vec{K}\cdot\vec{n}$

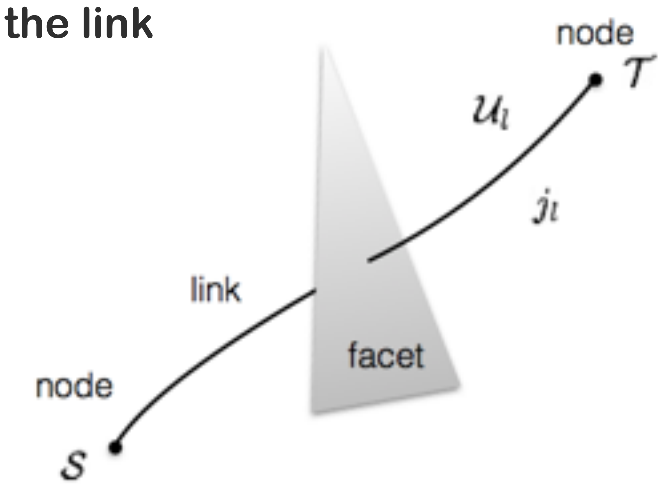
no Immirzi

This relation is the basis of the second part of Jacobson argument. From this relation we can obtain the Einstein equations. Notice that this is a relation between between the area of a space like surface (say in the x−y plane) and the boost (in the dual t − z plane).

not only ...

- the tensor product structure $\mathcal{H}^j_\gamma = \mathcal{H}_S \otimes \mathcal{H}_T$

is related to a local "partition of space" in two chunks, associated to the source and target nodes at the two ends of the link



- the short-scale correlations of the theory are then captured by the correlations between these two Hilbert states

A NON - PERTURBATIVE PERSPECTIVE

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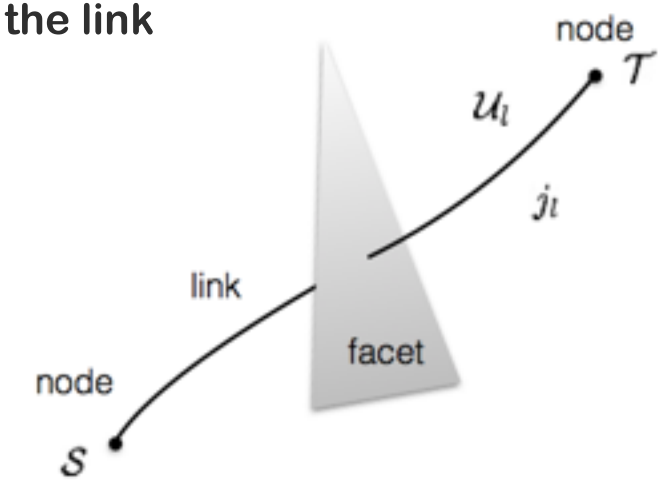

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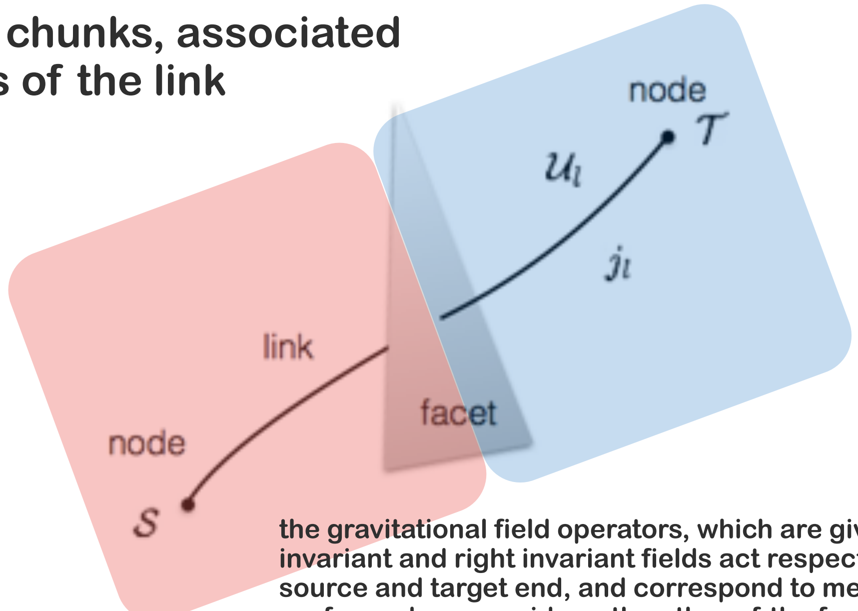
again the localization scheme…

- the short-scale correlations of the theory are then captured by the correlations between these two Hilbert states



the gravitational field operators, which are given by the left invariant and right invariant fields act respectively on the source and target end, and correspond to measurements performed on one side or the other of the facet

A NON - PERTURBATIVE PERSPECTIVE

single link entanglement thermodynamics!

- If $|\Phi\rangle \in H_\gamma^j$ is a pure state of the link, then its restriction to one half-link is the density matrix

$$\rho_T = Tr_{\mathcal{H}_S}[|\Phi\rangle\langle\Phi|]$$

measurements performed on one side only of the facet

- consider a particular family of states

$$\rho_T = e^{-2\pi K}$$

- these states have interesting properties:

$$S = -Tr[\rho_f \ln \rho_f] = 2\pi\, Tr[\rho_f K_f^z] = 2\pi \, \langle K \rangle$$

measures the entanglement across the facet

where $\langle K \rangle = \langle jf \,|K_f^Z| jf\, \rangle = \gamma\, jf$ is the expectation value of K_f^Z on $|sf\,\rangle$

- a variation $\delta\rho$ relates a change in the entropy to a change in the expectation value of K

$$\delta S = 2\pi\, \delta\langle K \rangle$$

given $\langle K \rangle = \gamma \langle L \rangle$ =>

$$\delta S = \frac{\delta A_f}{4G\hbar}$$

A NON - PERTURBATIVE PERSPECTIVE

what do we learn?

QUANTUM GEOMETRY =>

- $\vec{K} = \gamma \vec{L}$
- $A_f = 8\pi G\hbar\gamma j$

- area/energy is given by an algebraic relation at the root of quantum gravitational dynamics

$$K_f^z = \frac{A_f}{8\pi G\hbar}$$

- finiteness and universality of the entanglement entropy density per unit horizon area rely on discreteness of geometry at UV scale and on finiteness of spectrum of the area operator

$$\delta S = \frac{\delta A_f}{4G\hbar}$$

same relations we find at classical level?

basic structure of quantum theory : relations should refer to results of a measurement performed by an external system. here the quantum system is a portion of quantum space-time the external observer is an accelerated observer which can measure local aspects of the geometry

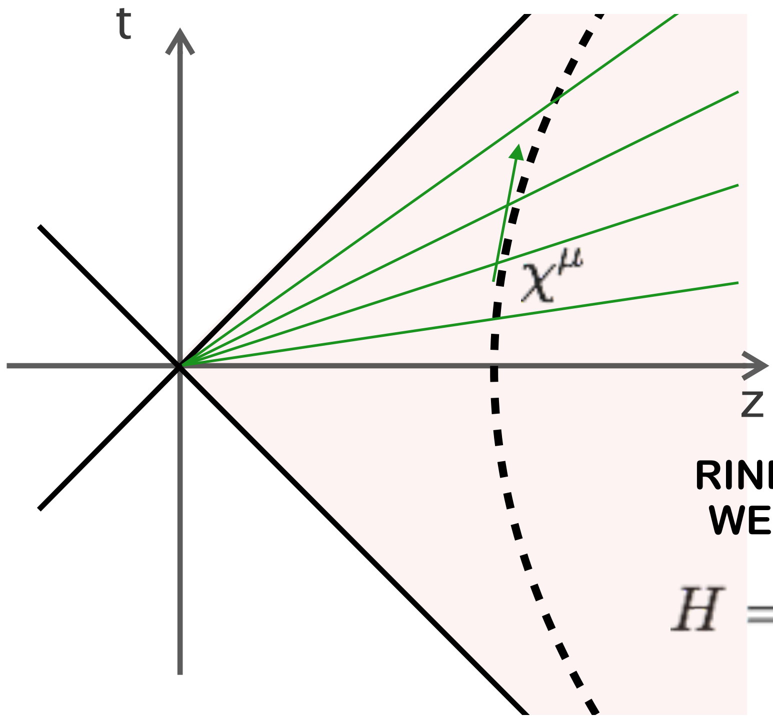
A MEASURE OF QUANTUM GEOMETRY

- the states $|s_f\rangle$ describe a portion of a quantum surface, a small facet with given area A_f and normal in direction. The evolution of the Lorentz invariant facet state in space-time as seeing by an accelerated observer is generated by the unitary operator representing a Lorentz boost

$$|s_f^t\rangle = U(t)|s_f\rangle$$

evolution of the state along a specific isometry trajectory of the boost labelled by a

This can be equally seen passively as a motion of an observer in space-time or actively as an evolution of space-time seen by an observer



$U(t) = e^{iHt}$

$$H = \hbar K_f^z\, a$$

- a classical measurement of the facet state dynamics is associated to the covariant dynamics of the trajectory of the accelerated observer

$$\rho_f = N\, e^{-\frac{2\pi}{\hbar a}H} \quad \Rightarrow \quad E = \frac{A_f\, a}{8\pi G} \qquad T = \frac{\delta E}{\delta S} = \frac{a\hbar}{2\pi}$$

ensemble of single facet states

CONCLUSIONS

1. The derivation of the Einstein's equations by Jacobson admits an interpretation different from the common one indicating the existence of microscopic states for which the Einstein equations would be an equation of state.

    - QFT entanglement thermodynamics (modular localization +KMS)
    - finiteness & universality of Bekenstein-Hawking area law from gravity
    - relevant microscopic degrees of freedom are the quanta of the gravitational field

2. the derivation requires quantum gravity: the area law indicates that there should be a physical (real) quantum mechanical cutoff at the Planck scale. This is precisely the conclusion that one obtains from a full quantum gravitational treatment of the problem in the context of loop quantum gravity, where the discreteness of the geometry at the Planck scale appears as a conventional quantization effect

3. we can identify quantum states of the semiclassical field that have a semiclassical behaviour and appears as continuous geometries when probed at large scale: in terms of these state we show that the fundamental input for the thermodynamical derivation of EE can be recovered starting from the elementary quantum dynamics of the theory

    - relation between the boost generator and the area: it contains G and gives the dynamics

thank you.