GRAVITY FROM SPACETIME THERMODYNAMICS

Goffredo Chirco

UNIVERSITEIT VAN AMSTERDAM

@ CENTRA - IST

Lisboa - June 25th

based on collaborations with: Liberati - SISSA, Eling, Sindoni,Oriti - AEI, Vitagliano - IST/CENTRA

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OUTLINE

- introduction and motivation
  - BH thermodynamics => local spacetime thermodynamics
  - GR from thermodynamics of local horizons
  - non-equilibrium & dissipation
- from GR to higher order gravity theories
  - f(R) and generalized Brans-Dicke gravity
  - Higher cuvature and Entanglement Entropy and Noether charge
- summary: thermodynamical equilibrium as a general principle of gravitational dynamics?

A - the Einstein equation of state

- **black hole thermodynamics**

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

- **mathematical analogy \to physical identity**

from classical level + quantum level

0th	κ	constant along the horizon
1st	$dM = \frac{\kappa}{8\pi G} dA + \Omega dJ + \Phi dQ$	
2nd	$dA \geq 0$	
3rd	κ = 0 unattainability	

=>

QM+SM $S = \frac{A}{l_p^2}$

Bekenstein 73

QFT Hawking 75

$T = \frac{\hbar\kappa}{2\pi}$ => $S = \frac{A}{4G}$

interplay

- **how does GR know about T-k and S-A ?**

Jacobson 95

A - the Einstein equation of state

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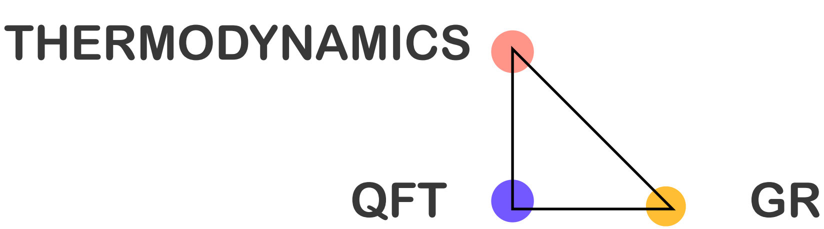
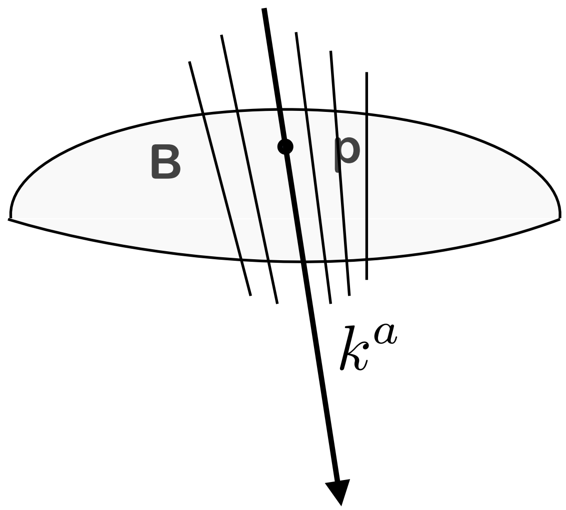


semiclassical picture

thermodynamics as a premise ?

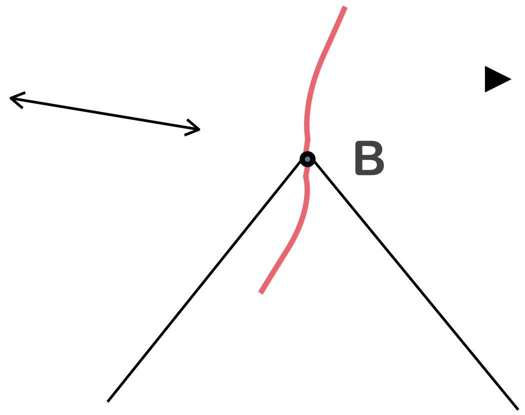
from BH to local horizon thermodynamics

LOCAL CAUSAL HORIZON



- consider a local spacetime spacelike 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

- at p the 2 surface can be characterized by the kinematical d.o.f. of the bundle of null geodesics: expansion, shear...

not enough...

- QFT & THERMO extended to local horizon physics

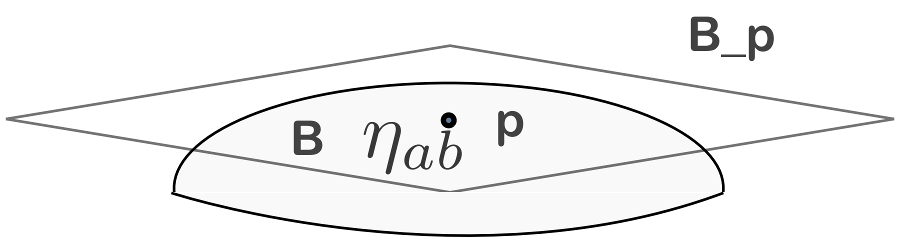
basic ingredients:

- stationarity : ∃ time Killing vectors
- non inertial frames : Unruh effect
- horizon area-entropy relation

local horizon thermodynamics

STATIONARITY - LOCAL KILLING HORIZON

- introduce a local inertial frame at p (local Lorentz symmetry)



- consider an approximate Killing field χ^a generating boosts orthogonal to B

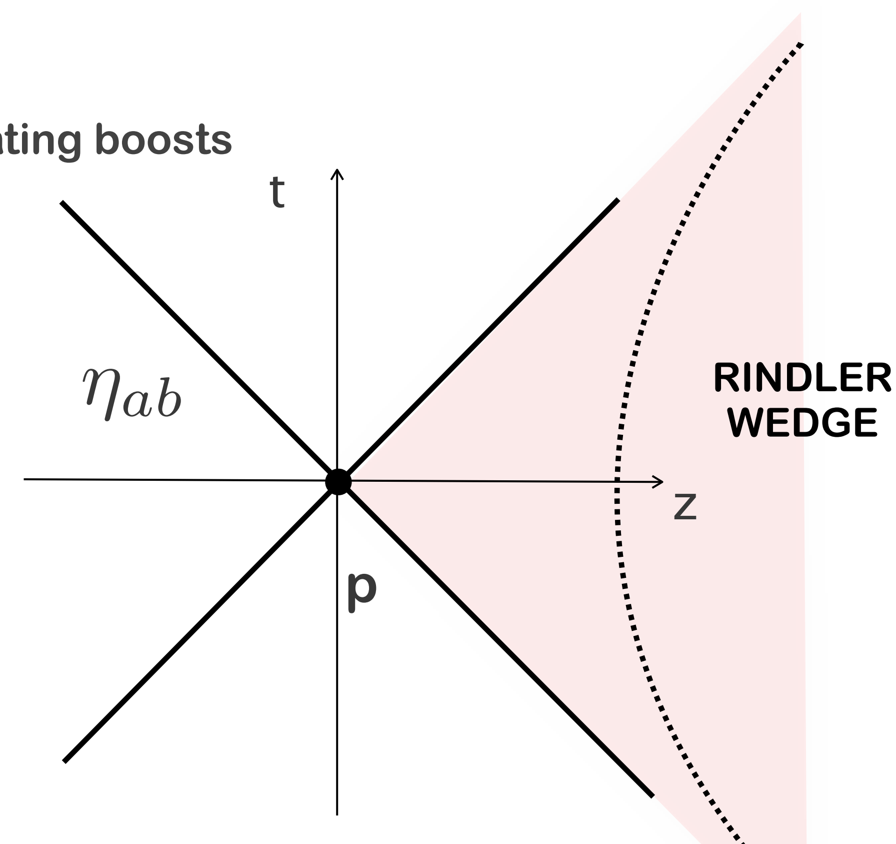
- Lorentz boost introduces a local Rindler frame

=> LOCAL RINDLER HORIZON

- arrange χ^a so that : $\chi^a = -\lambda k^a$

+ boost isometry => Killing horizon stationarity

uniformly accelerated frame....



local Rindler horizon as a causality barrier

local horizon thermodynamics

UNRUH EFFECT

- assume locally Minkowski vacuum
- given local Lorentz symmetry + stability of the vacuum

=> when restricted to the Rindler wedge, the usual global Minkowski vacuum state $|0\rangle$ in quantum field theory turns out to be equivalent to a Gibbs thermal state with an Unruh-Tolman temperature

Unruh 76

- H operator generating Lorentz boost on the quantum fields

noninertial frame traslations in hyperbolic angle

$$\beta^{-1} \rightarrow T = \frac{1}{2\pi}$$

RINDLER WEDGE thermal system

$$\rho = \exp(-\beta H)/Z$$

$$\langle E\rangle = Tr(\rho H)$$

$$S = -Tr(\rho ln \rho)$$

for $\delta\rho \ll \rho$

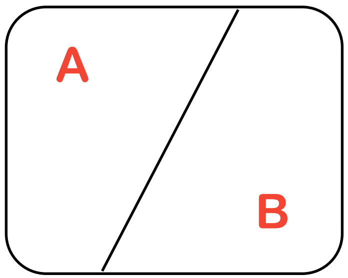
=> $\delta S = \beta\delta\langle E\rangle$ ✓

EQUILIBRIUM

local horizon thermodynamics

HORIZON AREA - ENTROPY RELATION some holographical assumption

▶ L



$\rho_L = |\Psi\rangle\langle\Psi|$ pure

$\rho_A = tr_B\, \rho$ mixed

missing information - von Neumann entropy

entanglement entropy

$$S(\rho_A) = -tr\, \rho_A\, ln\, \rho_A$$

+ Rindler horizon => entanglement entropy = thermal entropy

▶ the entanglement entropy scales with the area but is infinite. need UV regulation

$$S = \alpha A$$ => S = f (geometry)

we get horizon thermodynamics without any help from GR....

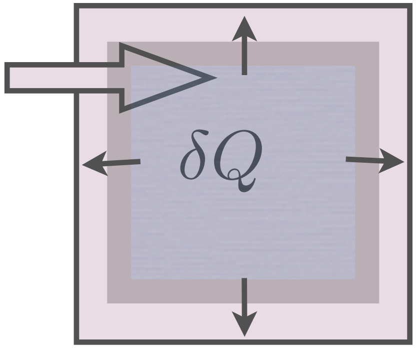
MEM the entropy density depends on the nature of the quantum fields and their interactions and can be some complicate function of the position in spacetime

GR from local horizon thermodynamics

Einstein equation of state: ANALOGY

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

$\delta Q = dE + pdV$

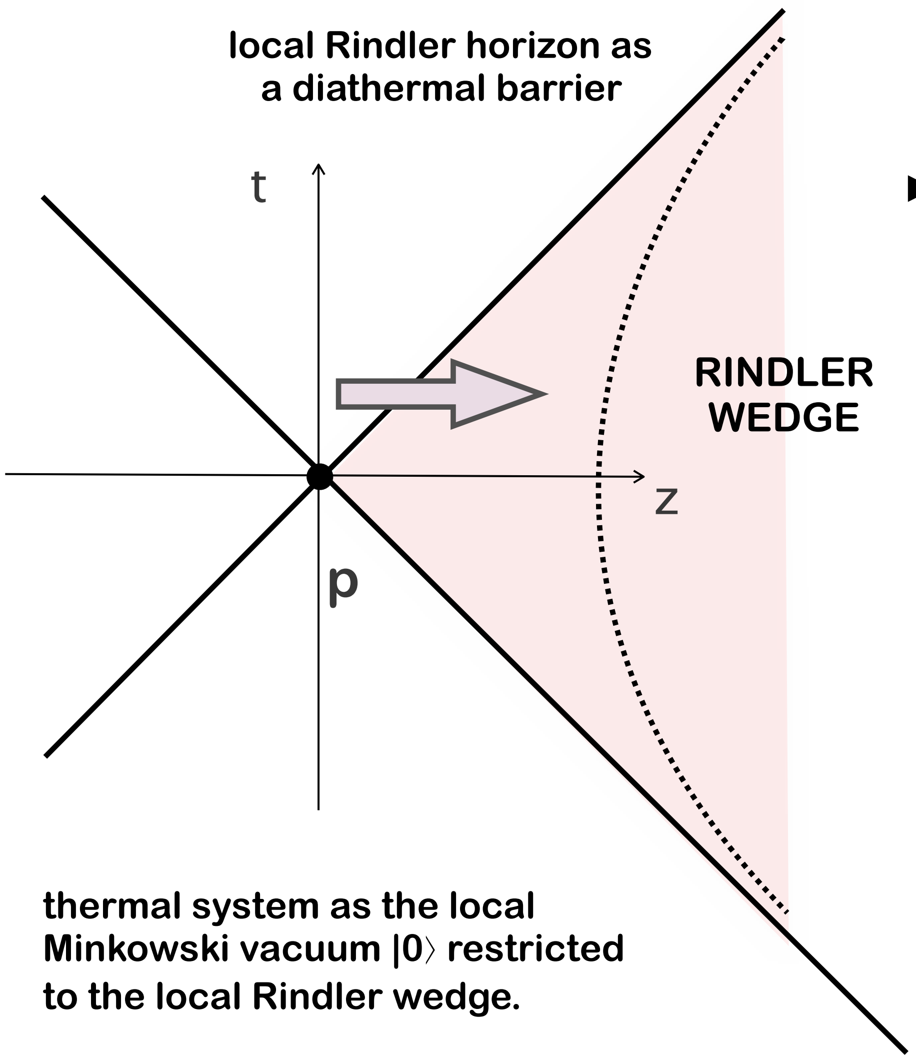


equilibrium entropy balance $\delta Q = TdS$ **=>** $T^{-1} = (\partial S/\partial E)$, $p = T(\partial S/\partial V)$

equation of state

IDEA	geometric entropy functional	+	local matter-energy perturbations	=>	Einstein eq. as equation of state

GR from local horizon thermodynamics



- for the horizon system the heat flow is the energy current of the matter as measured with respect to the boost Hamiltonian for which the state is thermal

$$\delta Q = \delta \langle E \rangle = \int T_{ab} \chi^a d\Sigma^b$$

energy crossing the horizon = **vacuum perturbation**

for $\delta\rho \ll \rho$ => $\delta S = \beta \delta \langle E \rangle$ => $T \delta Q = \delta(\alpha A)$

- then the assumption of entropy balance (Clausius law) provides a **local matter/geometry constitutive relation**

GR from local horizon thermodynamics

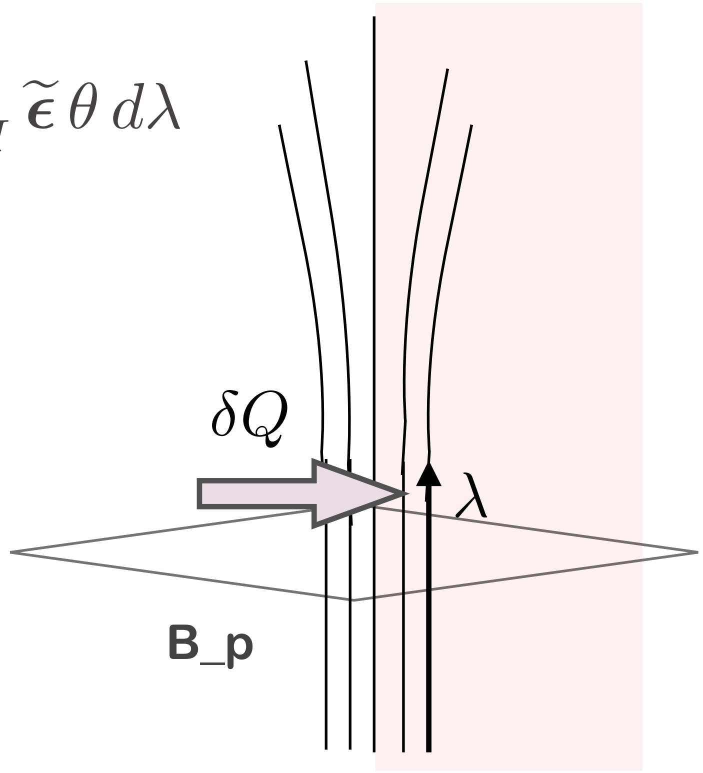
- assume α constant => $\delta S = \alpha\, \delta A \quad \delta A = \int_H \tilde{\epsilon}\, \theta\, d\lambda$

- equilibrium = Rindler horizon bifurcation surface

$$\delta S = \alpha\, \delta A = 0 \quad \Rightarrow \quad \theta_p = 0$$

- perturbation via heat flux

$$\theta \approx \theta_p + \lambda\, \frac{d\theta}{d\lambda}\Big|_p + \mathcal{O}(\lambda^2)$$ by Raychaudhuri



=> $$dS = \alpha \int_H \tilde{\epsilon}\, d\lambda [\theta - \lambda(1/2\,\theta^2 + \|\sigma\|^2 + R_{ab} l^a\, l^b)]_p$$

- equilibrium recovery via entropy balance law $\delta Q = T dS$

$$T dS = \alpha \frac{\kappa \hbar}{2\pi} \int_H \tilde{\epsilon}\, d\lambda [\underbrace{\theta - \lambda(1/2\,\theta^2}_{=0} + \|\sigma\|^2 + R_{ab} l^a\, l^b)]_p =$$

$$= \int_H \tilde{\epsilon}\, d\lambda\, (-\lambda\kappa) T_{ab} l^a l^b = \delta Q$$

δA has local and non-local contributions

GR from local horizon thermodynamics

LOCAL LEVEL:

for all null k^a $\quad \frac{2\pi}{\hbar\alpha} T_{ab} = R_{ab} + \Phi\, g_{ab}$ local constitutive relation

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

- local energy conservation $\nabla^b T_{ab} = 0$
- Bianchi identity $\nabla^b R_{ab} = \frac{1}{2}\nabla_a R$

=> $$8\pi G\, T_{ab} = R_{ab} - \frac{1}{2} R\, g_{ab} - \Lambda\, g_{ab}$$

if only $\alpha = \frac{1}{4G}$

Jacobson 95

UV cutoff <=> G
INDUCED GRAVITY

the equation is then extended to the whole spacetime via EP

NON-LOCAL LEVEL: $$dS_i = -\alpha \int_H \tilde{\epsilon} d\lambda \lambda \|\sigma^2\|$$

How to get rid of the non local terms ?

Eling 2006

B - the non-equilibrium regime

non-equilibrium horizon thermodynamics

- **impossible!** it is associated to an arbitrary kinemaical d.o.f. of the null congruence, associated to the arbitrary choice of B

- the non-local entropy term can be written as an **internal entropy production** term

=>

$$dS = dS_{eq} + dS_i$$

LOCAL = EQUILIBRIUM

NON-LOCAL = NON-EQUILIBRIUM

GENERALIZED CLAUSIUS EQUATION Eling 2006, Chirco 2009

- to recover the eom for GR one needs a generalization of the entropy balance relation where the non-local entropy term is interpreted as **unmatched heat**

$$dS = \frac{\delta Q}{T} + \delta N$$

irreversible processes

=> microscopic level ?

non-equilibrium horizon thermodynamics

- the unmatched heat for GR coincides with the expression for the tidal heating dissipation in BH (Hawking-Hartle)

Chirco 2009

internal entropy production term must be associated to some horizon viscosity

membrane paradigm : horizon congruence dynamics is well described by 2+1 viscous fluid equations Damour 79, Thorne 86

$$dS_i = \frac{2\eta}{T}\hat{\sigma}_{\mu\nu}\hat{\sigma}^{\mu\nu} + \frac{\xi_B}{T}\hat{\theta}^2$$

$$TdS_i = 2\eta \int_H \tilde{\epsilon} dv ||\sigma^2|| = \frac{1}{8\pi G}\int_H \tilde{\epsilon} dv ||\sigma^2||$$

- spacetime viscosity will be related to the UV cut-off scale of the theory, through the entropy density

=> introduce a horizon viscosity coefficient

$$\eta = \frac{T\alpha}{2} = \frac{\hbar\alpha}{4\pi} = \frac{1}{16\pi G}$$

> as for BH, the shear viscosity to entropy density ratio for the Rindler horizon sistem saturate the Kotvun Son Starinet bound

$$\eta/\alpha = \frac{1}{4\pi}$$

focussing on the irreversible sector

- in AdS/CFT the KSS bound is interpreted as a universal lower bound for all strongly coupled field theories with gravity dual

Policastro 2001, Starinets, Kotvun 2003

INTERESTING...

KSS ratio seem to be rooted in gravitational physics, but the Rindler wedge is a subregion of Minkowski space time: **NO GRAVITY AT ALL**

- interpretation of dissipative effects as a consequence of an underlying fluctuating behaviour of spacetime at the UV cut-off scale (Candelas-Sciama and AdS/CFT)

> **ENTANGLEMENT VISCOSITY**

Chirco 2010

if one could calculate η directly from the fluctuations of the matter fields in the thermal vacuum, that would **characterize the KSS bound as a fundamental property of quantum entanglement and its associated holography**

entanglement viscosity

PROBLEM

how to relate a phenomenological transport coefficient η from a fluid-wise description (membrane) of the horizon to the quantum vacuum state on the bulk ??

MAIN IDEA

(AdS/CFT)

- on large spatial and time scale the thermal vacuum can be effectively described by hydrodynamics
- calculate the hydrodynamics transport coefficient from microscopic theory using KUBO FORMULA involving the Green's function of the energy momentum tensor for the matter fields in the wedge

Kotvun 03, Son 07, Starinets 09

- no holographic duality like AdS/CFT in Rindler wedge ... but PRE-HOLOGRAPHY

area scaling behaviour of entanglement entropy : quantum degrees of freedom of the wedge seem to be packed on the stretched horizon surface > TRY a lower dimensional description of the vacuum fields associated to the horizon

lower dimensional description of bulk fields

WHAT WE WANT:

dual lower dimensional description of the vacuum state in terms of a strongly coupled thermal CFT effectively living on a (D-1) Minkowski (horizon membrane)

RECEIPT

- start with the canonical energy momentum tensor for the Rindler wedge

$$T_{(R)}{}^{\mu}_{\nu} = \frac{\partial L_R}{\partial(\partial_\mu)\psi}\partial_\nu\psi - \delta^\mu_\nu L_R \qquad \text{where} \quad L_R = \sqrt{-g}L_M$$

ANSATZ: on large scales, the holographic vacuum state is described by a conserved lower dimensional SET

$$\langle\hat{T}^{(D-1)}_{\mu\nu}\rangle = Z^{-1}Tr(\rho\,\hat{T}^{(D-1)}_{\mu\nu}) = \langle 0|\hat{T}^{(D-1)}_{\mu\nu}|0\rangle$$

Minkowski vacuum expectation value

thermal average at Tolman-Unruh temperature $\quad T_{(R)}{}^{\mu}_{\nu} = \kappa\xi T_{(M)}{}^{\mu}_{\nu}$

- **DIMENSIONAL REDUCTION**

$$\langle\hat{T}^{(D-1)}_{\mu\nu}\rangle = \int_{lc}^{\infty} d\xi\,\langle\hat{T}^{(R)}_{\mu\nu}\rangle = \int_{lc}^{\infty} d\xi\,\kappa\xi\,\langle\hat{T}^{(M)}_{\mu\nu}\rangle$$

Kubo like formula for the horiizon viscosity

II

apply the formalism of viscous hydrodynamics and calculate the shear viscosity through a **Green-Kubo approach** in terms of the effective lower dimensional SET

- consider a metric perturbation $h_{\mu\nu}$ associated to the bulk vacuum perturbation $\delta\langle E\rangle$ as source for the (D-1) field theory operator $\hat{T}^{D-1}_{\mu\nu}$

- assuming the perturbation is small, from **linear response theory**, one can calculate the change of the expectation value of $\hat{T}^{D-1}_{\mu\nu}$

$$< \delta\hat{T}^{D-1}_{\mu\nu}(k^0,\vec{k}) >= G_R(k^0,\vec{k})\, h_{\mu\nu}(k^0,\vec{k})$$

where G_R is the retarded 2-point thermal Green's function of $\hat{T}^{D-1}_{\mu\nu}$

$$G_R(k^0,\vec{k}) = \int d\tau d^{D-2}x\, e^{ik^0 t}\, e^{-i\vec{k}\vec{x}} < [\hat{T}^{D-1}_{\mu\nu}(x)\hat{T}^{D-1}_{\mu\nu}(0)] >$$

- in the limit $(k^0,\vec{k}) \to 0$ $\quad < \hat{T}^{D-1}_{xy}, \hat{T}^{D-1}_{xy} > (k^0,\vec{k}\to 0) = i\eta k^0 - P + \mathcal{O}(\omega^2)$

from which one gets the quantitative expression for the shear viscosity

$$\eta = \lim_{k^0\to 0} \frac{1}{k^0}\, G_R^{xy,xy}(k^0,0)$$

KSS bound for the Rindler horizon

- in our particular case we have

$$\eta = \lim_{k^0 \to 0} \frac{1}{k^0} \int_{l_c}^{\infty} \xi' \int_{l_c}^{\infty} \xi \int d\tau d^{D-2}x \, e^{ik^0\tau} \theta(\tau) \kappa^2 \xi \xi' < [T^D_{xy}(\tau, x, y, \xi), T^D_{xy}(0, \xi')] >$$

where $< [T^D_{xy}(\tau, x, y, \xi), T^D_{xy}(0, \xi')] >$ is the Minkowski 2-point correlator of the bulk field theory

Chirco 2010

THEN

for a free minimally coupled scalar field in 4D Rindler spacetime is

$$\eta = \frac{1}{1440\pi^2 l_c^2}$$

AREA SCALING ENTANGLEMENT VISCOSITY

- from the thermal description of the dimensionally reduced vacuum fields

$$\epsilon = \frac{\pi^2 T^4}{30} = \frac{1}{480\pi^2 \xi^4} \quad \text{--->} \quad \epsilon_r = \frac{\kappa}{960\pi^2 l_c^2}$$

$$s = \frac{2\pi^2}{45} T^3 = \frac{1}{180\pi \xi^3} \quad \text{--->} \quad s = \frac{1}{360\pi l_c^2}$$

all area scaling quantities

4D - Planckian form : massless free scalar field = ultrarelativistic boson gas $\epsilon = 3P$

$$> \quad \eta / s = \frac{1}{4\pi}$$

KSS bound satisfied by just entanglement quantities !!!

KSS bound for the Rindler horizon

NON equilibrium thermodynamical description:

- propagation of purely gravitational dof associate with macro dissipative effects

- a microscopic description for the macro shear viscosity in terms of the fluctuations of the Rindler wedge thermal state in a finite temperature QFT

KSS ratio from entanglement:

local Rindler horizon system | NO GRAVITY
NO HOLOGRAPHIC DUALITY LIKE ADS/CFT

GOAL: KSS ratio may be a fundamental holographic property of spacetime and quantum entanglement

support for the hypothesis that semi-classical gravity on macroscopic scales is induced as an effective theory of some lower dimensional strongly coupled quantum system with a large number of degrees of freedom

Does it work for generalizd gravity theories ?

interestingly successful enough to try to go from GR to higher order gravity theories...

Is themo a eneral principle for gravitational dynamics ?

Discriminant facor for gravity theory: a metatheory of grvaity ?

extension to generalized gravity theories

GR is effectively purely geometrical. very special.

RATIO the entropy functional may be constrained by the different formulations of the equivalence principle

no scalar d.o.f. => no extra dynamical gravitational fields <=> constant entropy density $G_N = const$

mediated

propagating tensorial d.o.f. => gravitational waves <=> non-local heat flow

<=> SEP

- EEP => | extra d.o.f => extra dynamical gravitational fields <=> entropy density is a general function of spacetime

  scalar-tensor theories of gravity — scalar heat flows ?

=> **changing the assumed entropy functional would change the associated gravitational field equation**

How does the thermodynamical derivation work in the case ?

extension to generalized Brans-Dicke gravity

ENTROPY

- promote the entropy density to be an independent field

$$\alpha \to \phi(x) \qquad \Rightarrow \qquad S = \int d^4x\sqrt{h}\phi(x)$$

- again, consider the variation of S along the horizon geodesic bundle

$$\delta S = \int \sqrt{h}\left(\phi\theta + \frac{d\phi}{d\lambda}\right) d\lambda d^2x$$

- Taylor expand around p ($\lambda = 0$)

Raychaudhuri

$$\delta S = \int \sqrt{h}\left[\left(\theta\phi + \frac{d\phi}{d\lambda}\right) + \lambda\left(\theta\frac{d\phi}{d\lambda} + \phi\frac{d\theta}{d\lambda} + \frac{d^2\phi}{d\lambda^2} + \phi\theta^2 + \theta\frac{d\phi}{d\lambda}\right)\right]_p$$

- equilibrium $\mathcal{O}(\lambda^0)$ => $\theta_p = -\phi^{-1}\frac{d\phi}{d\lambda}$

the kinematical d.o.f. θ_p is linked to the derivative of the spacetime scalar field

- at $\mathcal{O}(\lambda)$

$$\delta S = \int \sqrt{h}d\lambda d^2x\lambda(-\phi R_{\mu\nu}k^\mu k^\nu + k^\mu k^\nu\nabla_\mu\nabla_\nu\phi - \frac{3}{2}\phi\theta^2 - \phi\sigma_{\mu\nu}\sigma^{\mu\nu})$$

extension to generalized Brans-Dicke gravity

EXTRA ENTROPY

- new non-equilibrium contributions?

$$\delta S = \int \sqrt{h} d\lambda d^2 x \lambda (-\phi R_{\mu\nu} k^\mu k^\nu + k^\mu k^\nu \nabla_\mu \nabla_\nu \phi - \frac{3}{2}\phi\theta^2 - \phi\sigma_{\mu\nu}\sigma^{\mu\nu})$$

$$dS_i = \frac{2\eta}{T}\hat{\sigma}_{\mu\nu}\hat{\sigma}^{\mu\nu} + \frac{\xi_B}{T}\hat{\theta}^2$$

the additional scalar d.o.f.may appear as a new gravitational channel for dissipating energy

- not correct: given the equilibrium condition

$$\frac{3}{2}\phi\theta^2 = \frac{3}{2\phi} k^\mu k^\nu \nabla_\mu \phi \nabla_\nu \phi$$

=> unlike the shear term, the bulk term is LOCAL

- after the k^μ are peeled of, local terms at p are frame independent

PUZZLE !! Jacobson, Padmanabhan

these terms exist for any observer in the local spacetime patch => they will end up describing the dynamics of the global spacetime

extension to generalized Brans-Dicke gravity

HEAT

- principle of **background independence** => $\phi(x)$ must be varied like other fields

- must contribute to the total Lagrangian

$$L_{matt}(g_{\mu\nu}, \psi) + L_{scalar}(g_{\mu\nu}, \phi) \quad \Rightarrow \quad \delta Q \sim k^\mu k^\nu (T^M_{\mu\nu} + T^\phi_{\mu\nu})$$

most general contribution to the heat flux:

assume the action constructed out of first dervatives of the scalar field

$k^\mu k^\nu$ projection => no relevant contribution from interaction terms

$$\Rightarrow \quad \delta Q_{scalar} \sim \frac{\Omega(\phi)}{\phi} k^\mu k^\nu \nabla_\mu \phi \nabla_\nu \phi$$

- restricting to $\Omega(\phi) \equiv \Omega$ constant, for simplicity:

$$\Rightarrow \quad \frac{\delta Q}{T} = -\int d^4x \sqrt{h} \lambda \left(2\pi T^M_{\mu\nu} k^\mu k^\nu + \left(\frac{\Omega}{\phi}\right) k^\mu k^\nu \nabla_\mu \phi \nabla_\nu \phi\right)$$

extension to generalized Brans-Dicke gravity

ENTROPY BALANCE

- at local level:

$$\phi R_{\mu\nu} - \nabla_\mu \nabla_\nu \phi + \left(\frac{3/2 - \Omega}{\phi} \right) \nabla_\mu \phi \nabla_\nu \phi + \Phi g_{\mu\nu} = 2\pi T^M{}_{\mu\nu}$$

=> by defining the Dicke constant $\omega = \Omega - 3/2$ one obtains the constitutive relations capturing any Brans-Dicke theory

- Φ come from local matter-energy conservation + Bianchi identity + ...

$$\nabla_\nu \Phi = \nabla_\nu \left(\Box\phi - \frac{1}{2}\phi R + \frac{\omega}{2\phi} \nabla_\mu \phi \nabla^\mu \phi \right) + \\ + \left(\frac{1}{2} R + \frac{\omega}{2\phi^2} \nabla_\mu \phi \nabla^\mu \phi + \frac{\omega}{\phi} \Box\phi \right) \nabla_\nu \phi$$

... plus an integrability condition on the last term $(\ldots)\nabla_\nu \phi = \nabla_\nu V(\phi)$

then $$\frac{dV}{d\phi} = R + \frac{\omega}{\phi^2} \nabla_\mu \phi \nabla^\mu \phi + 2\frac{\omega}{\phi} \Box\phi$$

=> $$\Phi = \Box\phi - \frac{1}{2}\phi R + \frac{\omega}{2\phi} \nabla_\mu \phi \nabla^\mu \phi + \frac{1}{2} V(\phi)$$

extension to generalized Brans-Dicke gravity

... therefore: from $S = \int d^4x \sqrt{h}\phi(x)$

=> $$I_{gen} = \frac{1}{4\pi}\int \sqrt{-g}\, d^4x[(\phi R - \frac{\omega}{\phi}\nabla_\mu\phi\nabla^\mu\phi + V(\phi)) + L_{matt}]$$

- the entropy functional holds for the general Brans-Dicke theory
- **IMPORTANT:** the information about the dynamics of the scalar d.o.f. is encoded in the integrability condition together with the trace of the metric field equation

$\omega = 0$ => metric $F(R)$

$$3\Box\phi + 2V(\phi) - \phi\frac{dV}{d\phi} = (2\pi)\, T^{M\,\mu}_{\ \ \mu}$$ => propagating scalar sourced by matter

$\omega = -3/2$ => Palatini $F(R)$

$$2V(\phi) - \phi\frac{dV}{d\phi} = (2\pi)\, T^{M\,\mu}_{\ \ \mu}$$ => scalar and matter in algebraic relation: non propagating scalar

summary

- the thermodynamical derivation works for the simplest cases of scalar tensor higher order gravity, naturally providing the dynamics for the extra dynamical scalar d.o.f.
- but... f(R) is still special since they are trivially related to GR coupled to a scalar field by a field dependent conformal rescaling of the metric: no new lesson

MAIN POINT can we capture higher curvature corrections to GR with the local thermodynamic reasoning ?

NO no clear thermodynamical interpretation for higher curvature corrections to entanglement and high: thermal derivation from entanglement is limited to theories where $S \sim A$

Fursaev, Solodukhin

YES Noether charge entropy functional naturally brings the extra information about curvature currections (e.g. Lovelock gravity): it works!

Parikh 98, Padmanabhan, Jacobson 2011

summary

For stationary horizons, Wald entropy for L= R + aR^2 + ... is

$$S_{bh} = \frac{A}{4\hbar G_N} + curvature\ terms = \frac{2\pi}{\hbar}\int_\Sigma Q^{ab}[\chi] N_{ab} dA$$

$$Q^{ab}[\chi] = W^{abc}\chi_c + X^{abcd}\nabla_c \chi_a$$

Noether potential for the horizon generating Killing flow

For $L = L[g_{ab}, R_{abcd}]$, can choose $X^{abcd} = \frac{\partial L}{\partial R_{abcd}}$

and $W^{abc} = 2\nabla_d X^{abcd}$

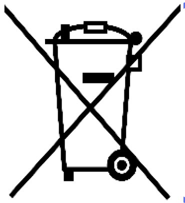
Cardoso 99

but...

- not complete thermodynamical interpretation : problems with 2nd Law
- the causal structure of higher curvature theories is generally not the metric light cone
- Noether charge is associated to a gravitational Lagrangian: Entropy loses its statistical interpretation

it seems that the local thermodynamical derivation can only capture the leading order area term in the entropy....

thermodynamical equilibrium as a general principle ?



in fact the local character makes the derivation very general: can we consider the entropy balance equation as a general principle for deriving the gravitational dynamics ??

further investigations :

- confirm the validity of the approach at the GR level in a different formalism => Plebanski formulation of GR in terms of self dual forms
  > BF theory with constraints

- extend the approach with more classical geometric variables: new degrees of freedom =>
  - metric affine theories
  - non zero torsion: Einstein-Cartan
  > Poincare' gauge gravity

=> characterize possible continuous limits in an emergent geometry perspective

thermodynamical equilibrium as a general principle ?

interesting relations and
hints :

- fluid/gravity duality in flat spacetime

Bredberg 2011, Compere 2011, Chirco 2011

- holographic entanglement entropy and spacetime reconstruction

Raamsdonk 2012, Takayanagi 2012

=> provide a dynamical principle for the geometry 'emerging' from some holographic quantum theory

intrinsic local character:

just a failure or telling something deep on the holographic principle ...?

obrigado !