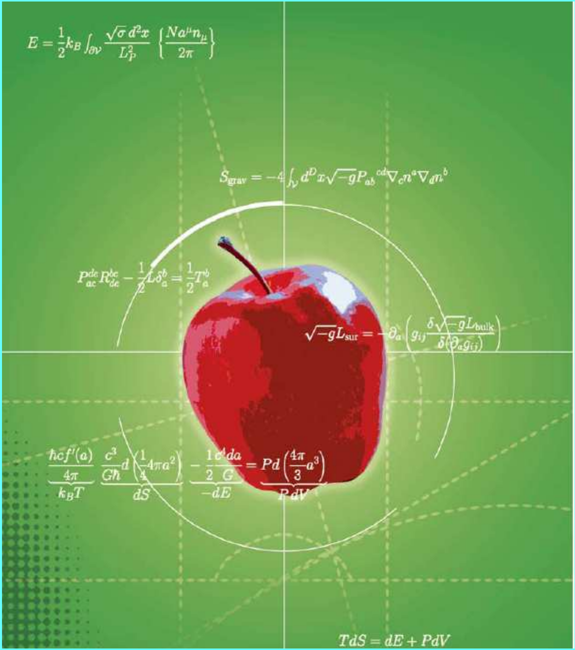

SECRET LIFE OF SPACETIME

T. Padmanabhan
IUCAA, Pune

THE PARADIGM

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I will describe (mostly) the work by me and my collaborators.

CONVENTIONAL VIEW

GRAVITY AS A FUNDAMENTAL INTERACTION

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SPACETIME THERMODYNAMICS

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GRAVITY IS AN EMERGENT PHENOMENON

NEW PERSPECTIVE

SPACETIME THERMODYNAMICS

GRAVITY IS AN EMERGENT PHENOMENON

GRAVITY IS THE THERMODYNAMIC LIMIT OF THE STATISTICAL MECHANICS OF ‘ATOMS OF SPACETIME’

PLAN OF THE TALK

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- WHY ?

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- WHY ?
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CONVENTIONAL APPROACH TO GRAVITY:
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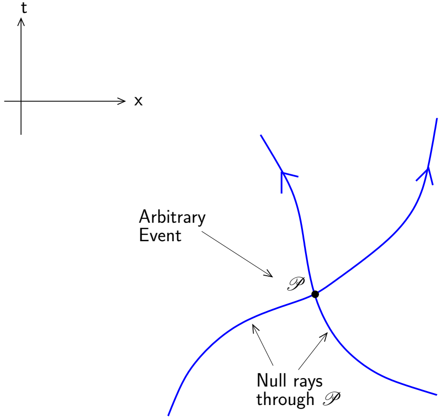
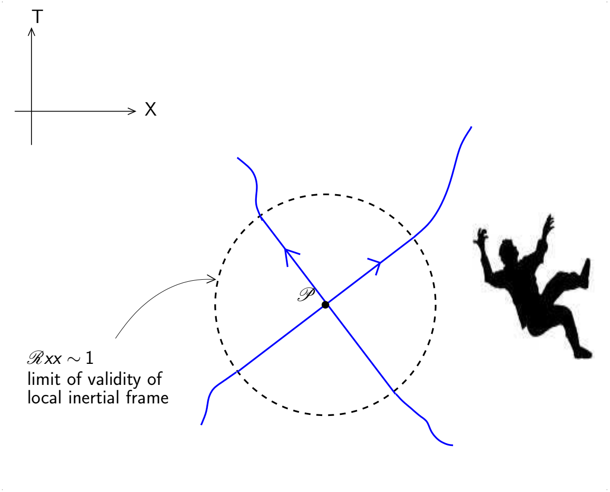
SPACETIME IN ARBITRARY COORDINATES



FREE – FALL OBSERVERS



Validity of laws of SR $\Rightarrow$ kinematics of gravity

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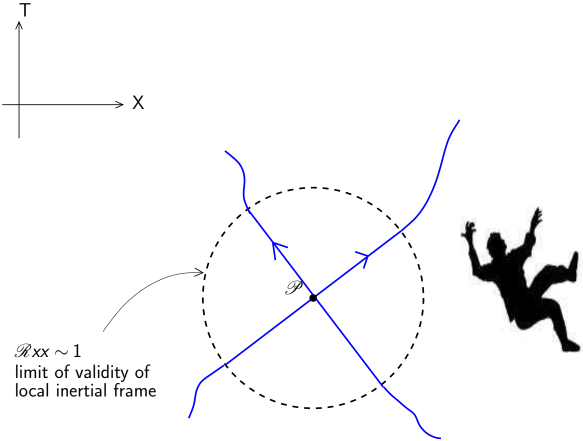

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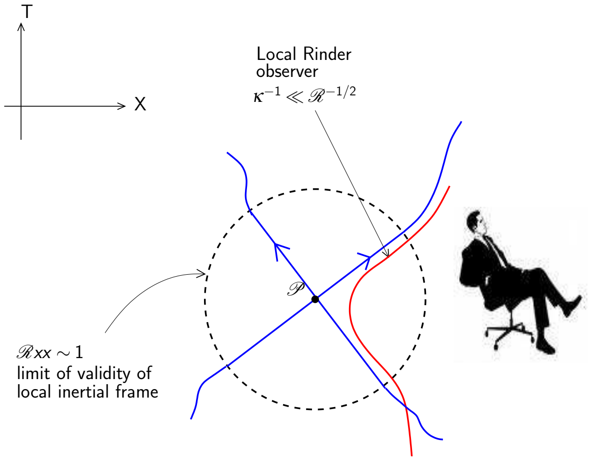

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Let us proceed, regardless ......

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- REDUCES TO EINSTEIN'S EQUATIONS IN $D = 4$; NATURAL GENERALISATION FOR $D > 4$

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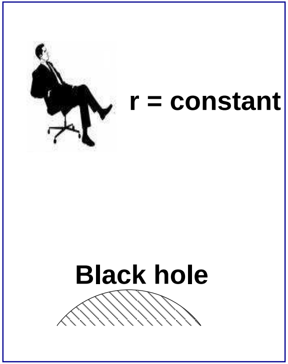
- THIS MOTIVATES US TO STUDY POINTS OF CONTACT AND CONFLICT BETWEEN QUANTUM THEORY AND GRAVITY.

Single most important result from such a study is .....

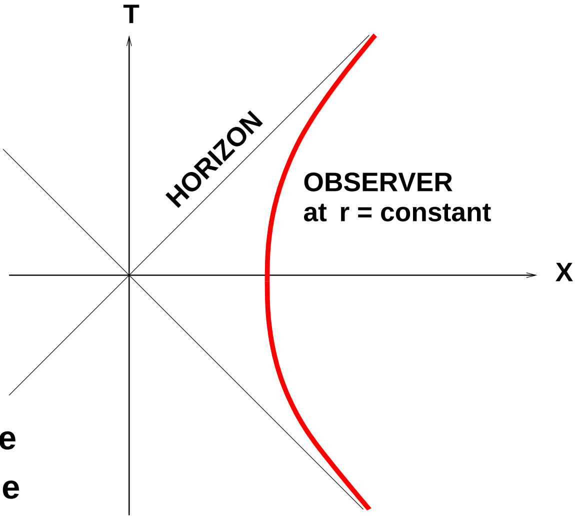
SPACETIMES, LIKE MATTER, CAN BE HOT

OBSERVERS WHO PERCEIVE A HORIZON
ATTRIBUTE A TEMPERATURE TO SPACETIME

$$k_B T = \frac{\hbar}{c}\left(\frac{g}{2\pi}\right)$$

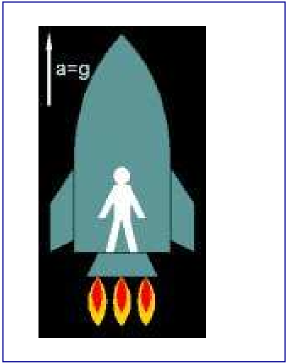


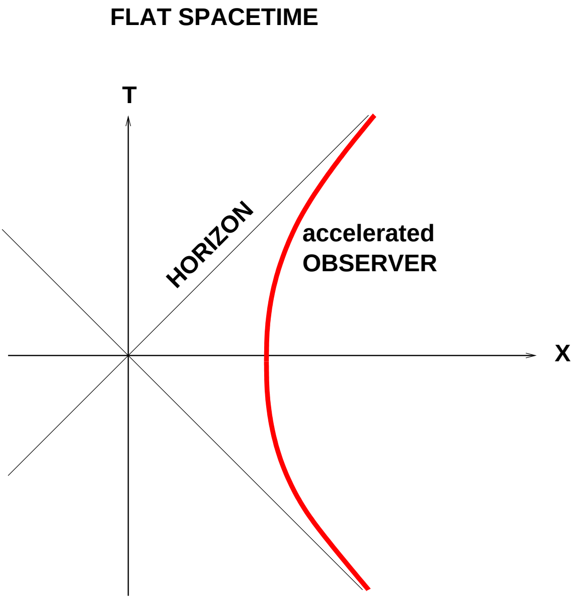
BLACK HOLE SPACETIME



Temperature

$\propto$ **acceleration due to the black hole**





Temperature
$\propto$ acceleration
of the observer

WHY ARE HORIZONS HOT ?

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$$\exp(-i\,t\,H) \qquad \iff \qquad \exp(-\beta\ H)$$

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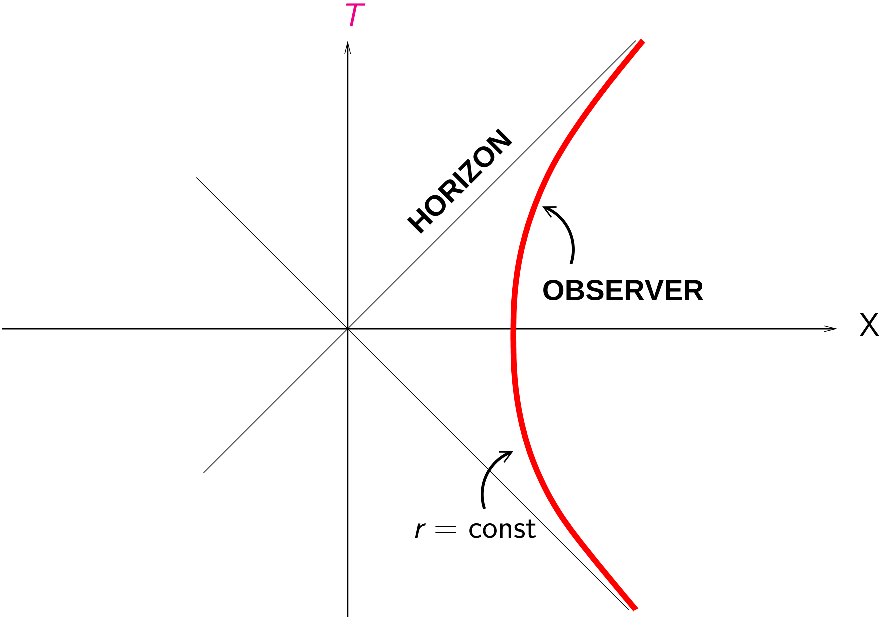
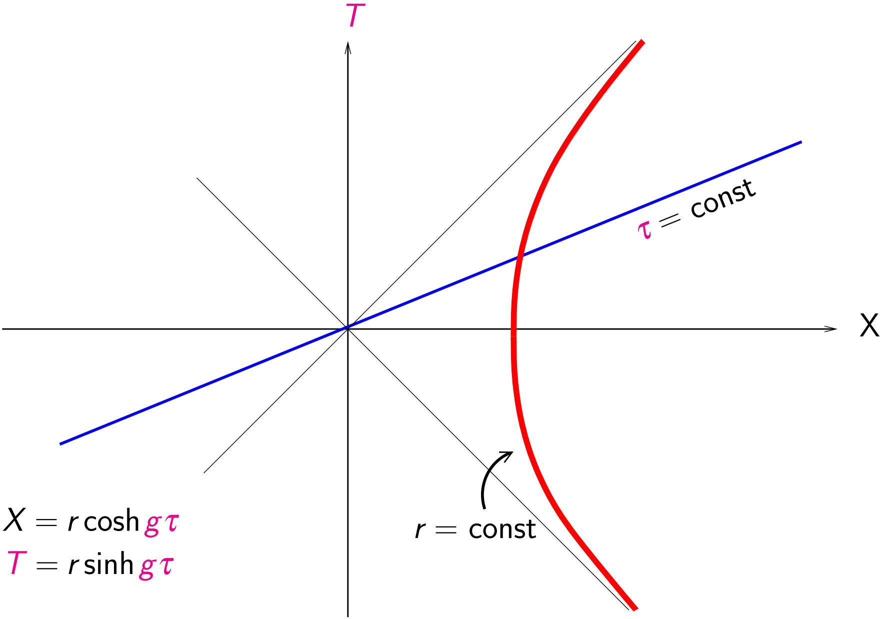
SPACETIMES WITH HORIZONS EXHIBIT PERIODICITY IN IMAGINARY TIME $\Longrightarrow$ TEMPERATURE


T
HORIZON
OBSERVER
X
$r = \text{const}$

$$ds^2 = -dT^2 + dX^2 = -g^2 r^2 d\tau^2 + dr^2$$

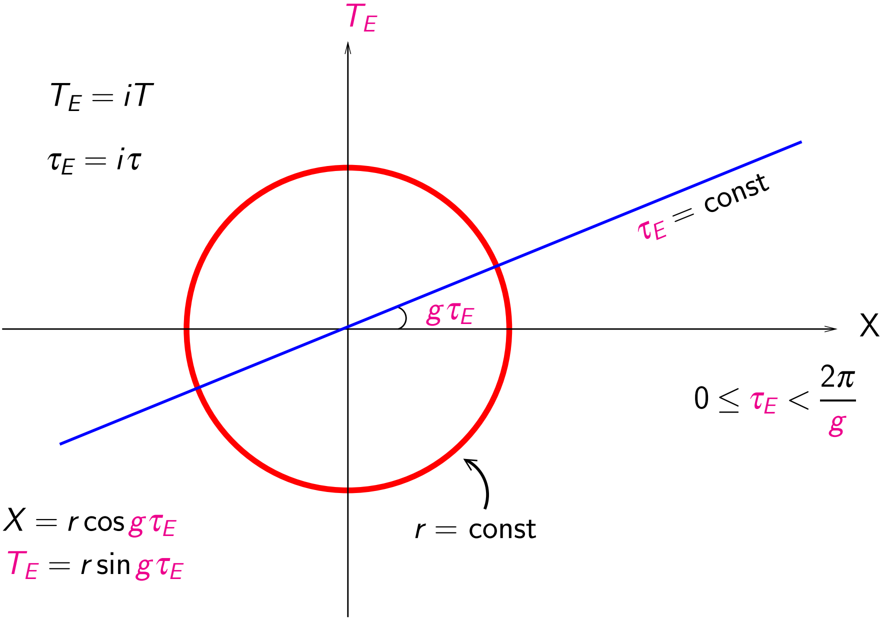


$$X = r\cosh g\tau$$
$$T = r\sinh g\tau$$

$$ds^2 = d\,T_E{}^2 + dX^2 = g^2 r^2 d\tau_E{}^2 + dr^2$$

$$T_E = iT$$

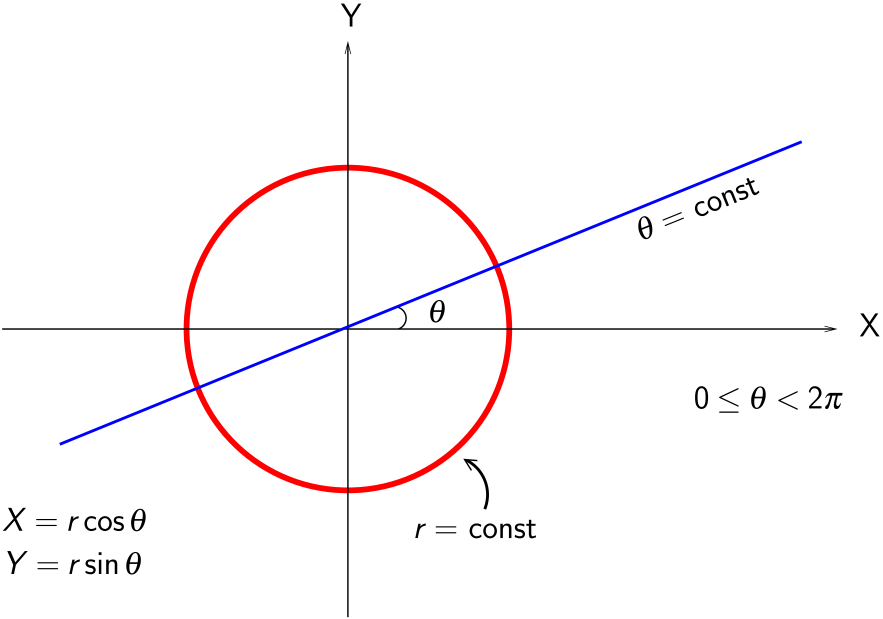
$$\tau_E = i\tau$$



$$X = r\cos g\tau_E$$

$$T_E = r\sin g\tau_E$$

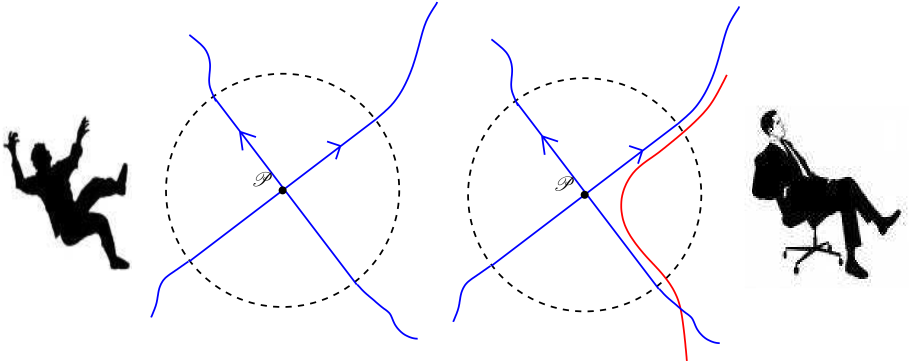
$$ds^2 = dY^2 + dX^2 = r^2 d\theta^2 + dr^2$$



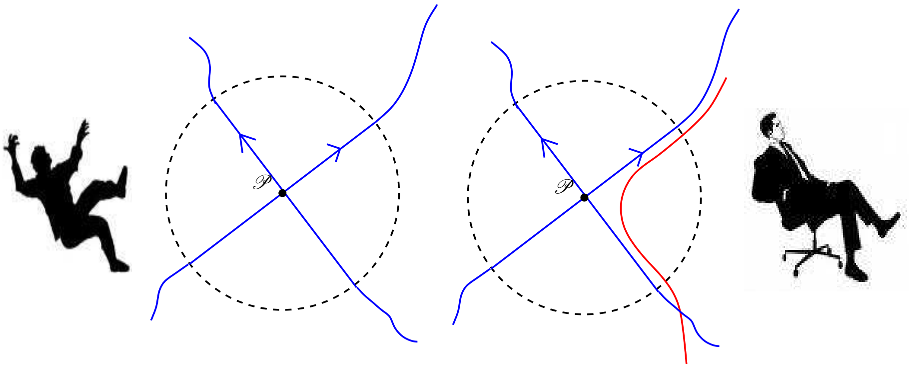
$0 \le \theta < 2\pi$

$X = r\cos\theta$

$Y = r\sin\theta$



Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations



Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations

$$ds^2 \approx -c^2 dT^2 + dX^2 \Longrightarrow ds^2 \approx -\left(1 + \frac{4\pi c (k_B T)}{\hbar} x\right) c^2 dt^2 + \left(1 + \frac{4\pi c (k_B T)}{\hbar} x\right)^{-1} dx^2$$

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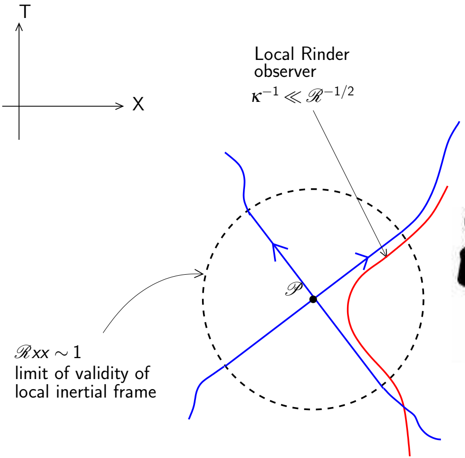
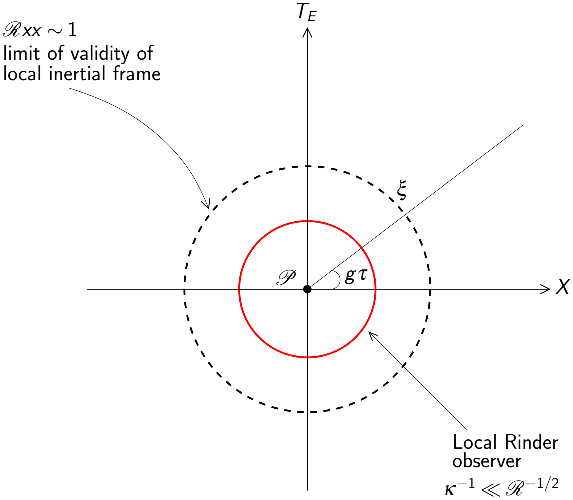
- The corresponding entropy $S = -\mathrm{Tr}\ \rho \ln \rho$ is divergent (and scales as area). QFT in CST can give temperature but not entropy!

LOCAL RINDLER OBSERVERS




T_E
$\mathscr{R}xx \sim 1$
limit of validity of
local inertial frame
ξ
$\mathscr{P}$
$g\tau$
X
Local Rinder
observer
$\kappa^{-1} \ll \mathscr{R}^{-1/2}$

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- SIMPLEST EXAMPLE OF THESE EFFECTS: BOX OF GAS IN FLAT SPACETIME! [Kolekar, TP, arXiv:1012.5421]

- Invariance under $x^a \to x^a + q^a(x)$ leads to an *off-shell* conserved current J^a in these theories.

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- The connection between $x^a \to x^a + q^a(x)$ and entropy is a mystery in the conventional approach.

SURFACE TERM IN GRAVITATIONAL ACTION – I

...another mystery in conventional approach! ...

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- The natural action principle in all Lanczos-Lovelock models have a surface and bulk term:

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- *How does the surface term know the physics determined by the bulk term?!*

SURFACE TERM IN GRAVITATIONAL ACTION-II

More Physics of the Surface Term

[T.P, 2004; A. Mukhopadhyay, T.P, 2006; S.Kolekar, T.P, 2010]

- In stationary spacetimes with horizon in any LL model,
  - Euclidean action is the free energy:

$$A_E = \underbrace{\beta E}_{\text{bulk term}} - \underbrace{S}_{\text{surface term}} = \beta F$$

SURFACE TERM IN GRAVITATIONAL ACTION-II

More Physics of the Surface Term

[T.P, 2004; A. Mukhopadhyay, T.P, 2006; S.Kolekar, T.P, 2010]

- In stationary spacetimes with horizon in any LL model,
  - Euclidean action is the free energy:

$$A_E = \underbrace{\beta E}_{\text{bulk term}} - \underbrace{S}_{\text{surface term}} = \beta F$$

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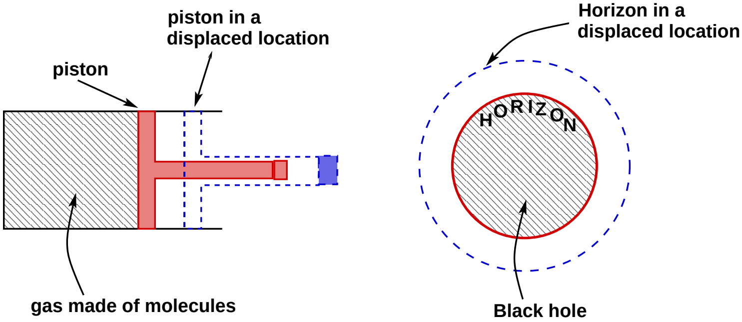
- One can obtain LL field equations from a suitable variation of the surface term [Sotiriou, Liberati, 06; TP, 06; 11]

KEY ROLE OF NULL SURFACES – I

$$TdS = dE + PdV$$

[TP, gr-qc/0204019]



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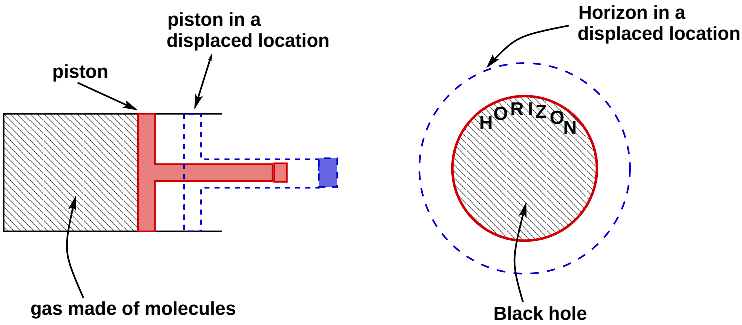

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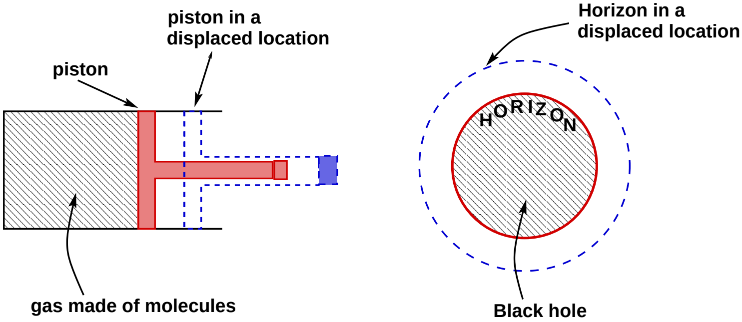

$$\frac{c^4}{G}\left[\frac{\kappa a}{c^2}-\frac{1}{2}\right] = 4\pi P a^2 \quad \Rightarrow \quad \underbrace{\frac{\hbar}{c}\left(\frac{\kappa}{2\pi}\right)}_{k_B T}\underbrace{\frac{c^3}{G\hbar}d\left(\frac{1}{4}4\pi a^2\right)}_{k_B^{-1}dS}\underbrace{-\frac{1}{2}\frac{c^4 da}{G}}_{-dE} = \underbrace{Pd\left(\frac{4\pi}{3}a^3\right)}_{P\,dV}$$

HOLDS TRUE FOR A LARGE CLASS OF MODELS!

- Stationary axisymmetric horizons and evolving spherically symmetric horizons in Einstein gravity, [gr-qc/0701002]
- Static spherically symmetric horizons in Lanczos-Lovelock gravity, [hep-th/0607240]
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IN ALL THESE CASES FIELD EQUATIONS REDUCE TO $TdS = dE + PdV$ *ON THE HORIZON!*

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- Related to, but different from, string-motivated results.

HOW COME GRAVITATIONAL DYNAMICS ALLOWS A THERMODYNAMIC INTERPRETATION ?

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GRAVITY IS THE THERMODYNAMIC LIMIT OF

THE STATISTICAL MECHANICS OF

MICROSCOPIC SPACETIME DEGREES OF FREEDOM

BOLTZMANN: IF YOU CAN HEAT IT, IT HAS MICROSTRUCTURE!

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- The density of Δn of d.o.f, needed to store energy ΔE at temperature T is given by $\Delta n = \Delta E/(1/2)k_B T$.

The equipartition law

$$E = \frac{1}{2}nk_B T \to \int dV \ \frac{dn}{dV}\frac{1}{2} \ k_B T = \frac{1}{2}k_B \int dnT$$

demands the 'granularity' with finite n; degrees of freedom scales as volume.

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EQUIPARTITION OF MICROSCOPIC DEGREES OF FREEDOM

TP, CQG, 21, 4485 (2004); MPLA, 25, 1129 (2010)[0912.3165]; PRD, 81, 124040 (2010)[1003.5665]

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- In GR, this reduces to:

$$E = \frac{1}{2} k_B \int_{\partial \mathcal{V}} \underbrace{\frac{dA}{L_P^2}}_{\text{Area 'bits'}} \underbrace{\left\{ \frac{\hbar}{k_B c} \frac{g}{2\pi} \right\}}_{\text{acceleration temperature}} \equiv \frac{1}{2} k_B \int_{\partial \mathcal{V}} dn\, T_{\rm loc}$$

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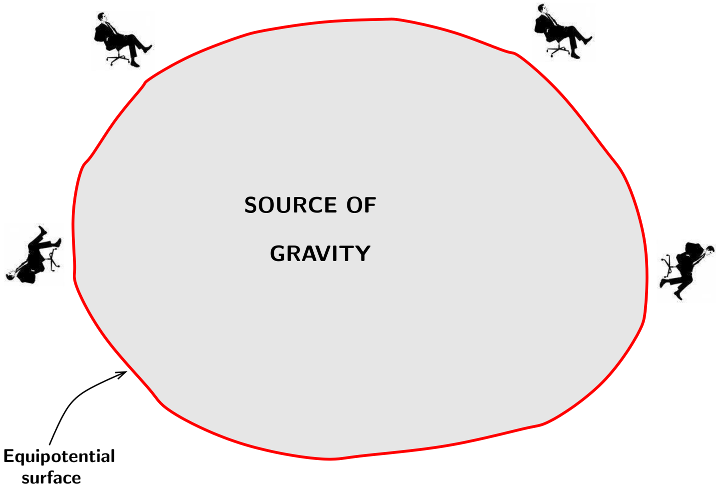

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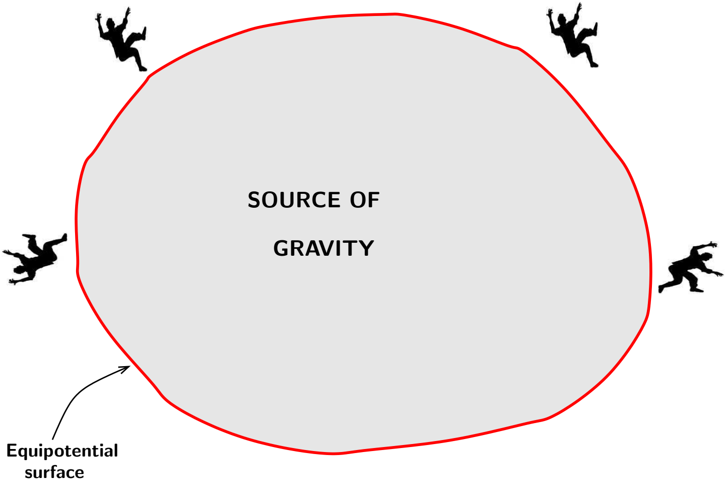

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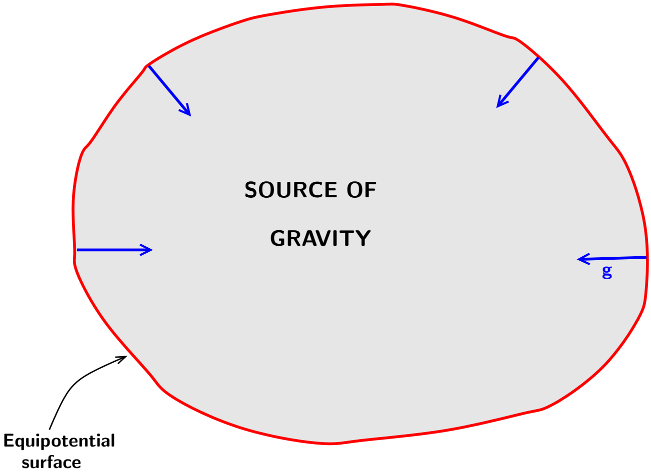

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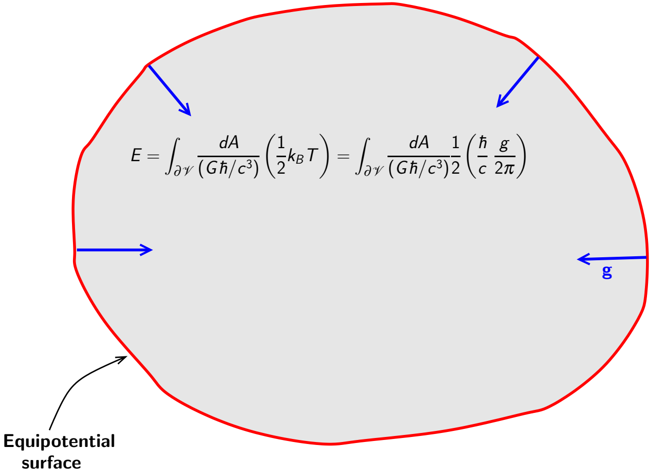

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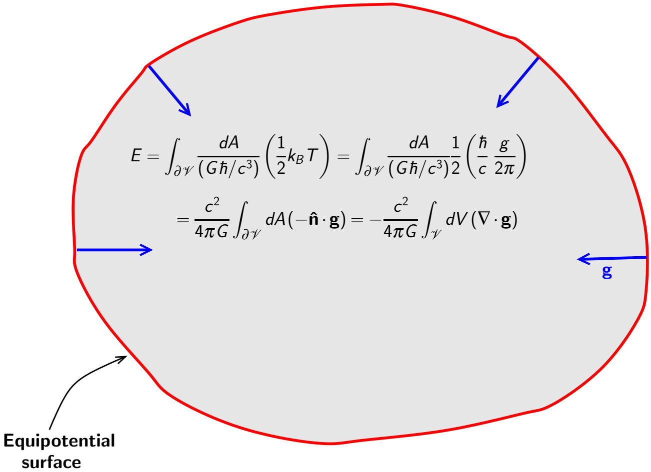

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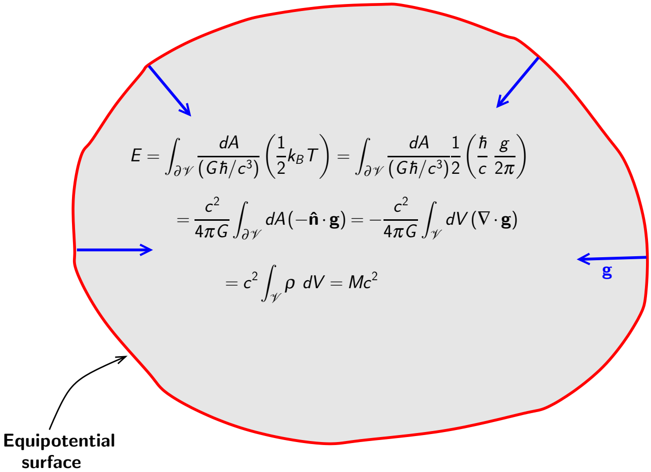
$$= c^2\int_{\mathcal{V}} \rho\;dV = Mc^2$$



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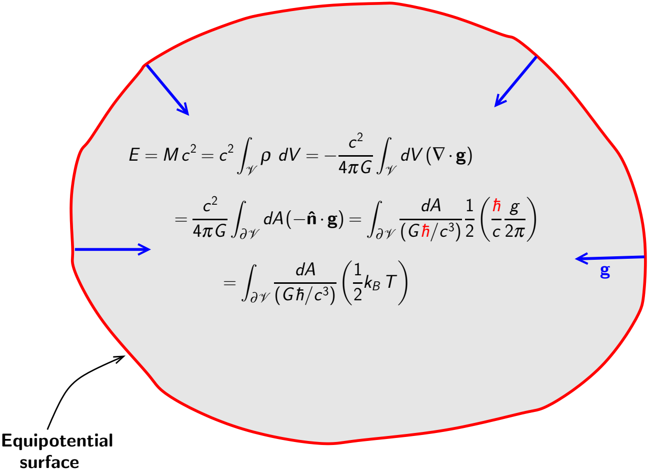

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FLUCTUATIONS AROUND EQUIPARTITION ETC.

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- In static spacetimes GR gives an exact equation: [TP,1003.5665]

$$D_\alpha a^\alpha = 4\pi[\rho_{Komar} + \rho_T]; \quad \rho_T = -\frac{a^2}{4\pi} = -\pi T_{loc}^2$$

Holographic graviton noise ? [Hogan, 08]

System	Macroscopic body	Spacetime
Can the system be hot?	Yes	Yes
Can it transfer heat?	Yes; for e.g., hot gas can be used to heat up water	Yes; water at rest in Rindler spacetime will get heated up
How could the heat energy be stored in the system?	The body must have microscopic degrees of freedom	Spacetime must have microscopic degrees of freedom
Number of degrees of freedom required to store energy dE at temperature T	Equipartition law $dn = dE/(1/2)k_B T$	Equipartition law $dn = dE/(1/2)k_B T$
Can we read off dn?	Yes; when thermal equilibrium holds; depends on the body	Yes; when static field eqns hold; depends on the theory of gravity
Expression for entropy	$\Delta S \propto \Delta n$	$\Delta S \propto \Delta n$
Does this entropy match with the expressions obtained by other methods?	Yes	Yes
How does one close the loop on dynamics?	Use an extremum principle for a thermodynamical potential $(S, F, ...)$	Use an extremum principle for a thermodynamical potential $(S, F, ...)$

THERMODYNAMIC EXTREMUM PRINCIPLE
$\longrightarrow$ FIELD EQUATIONS

Use a thermodynamical potential $\Im[q_A]$ for spacetime extremising which for all class of observers should give the field equations.

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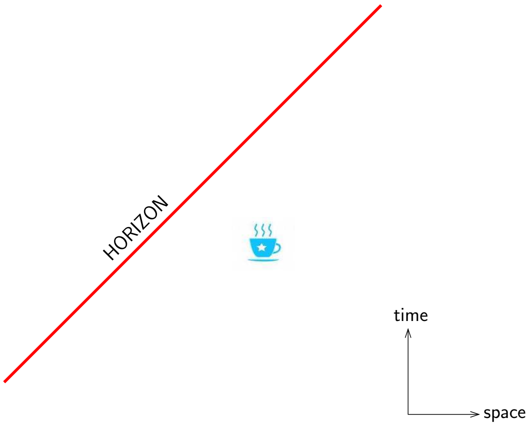

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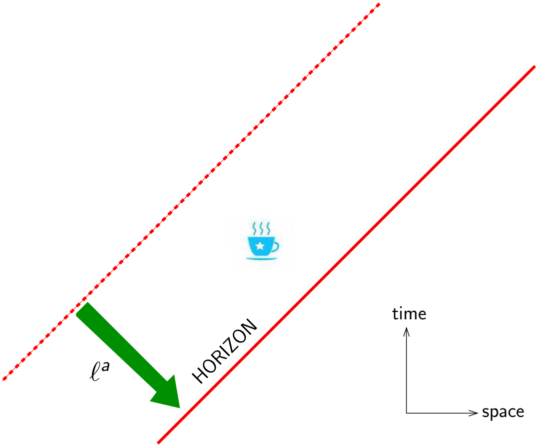

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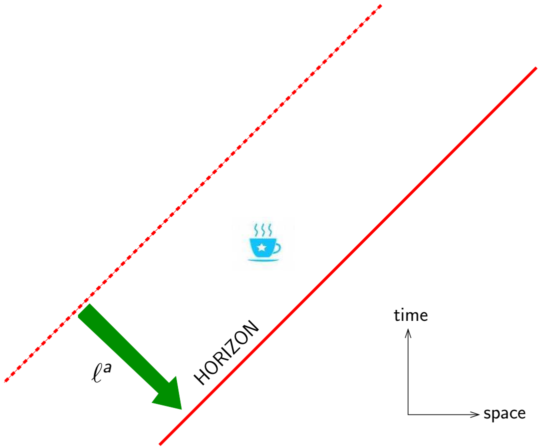
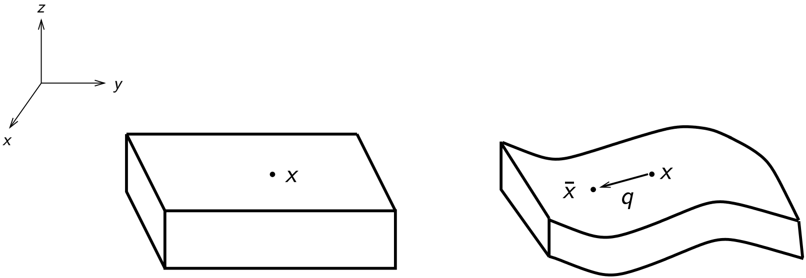


ASSOCIATE THERMODYNAMIC POTENTIALS
WITH NULL VECTORS

DEFORMING A SOLID



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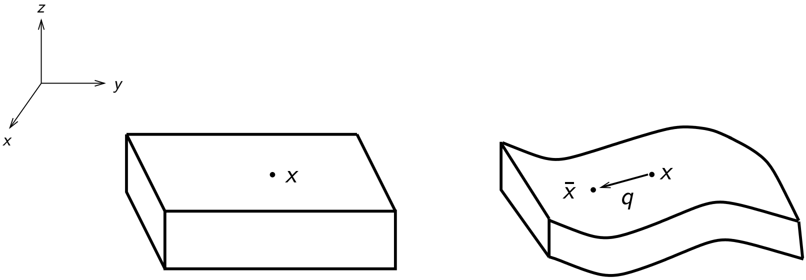

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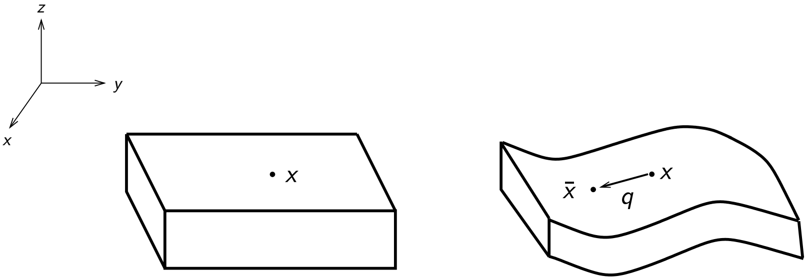

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$$\mathfrak{I} \sim A(\nabla q)^2 + Bq^2$$

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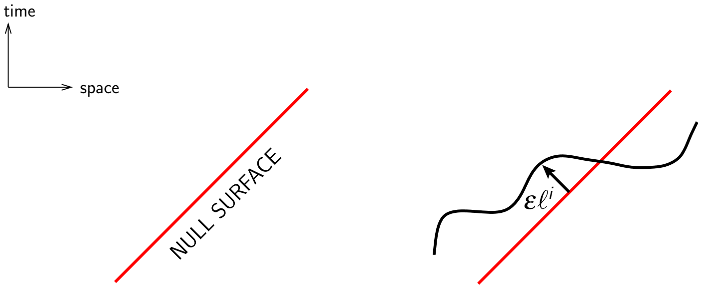

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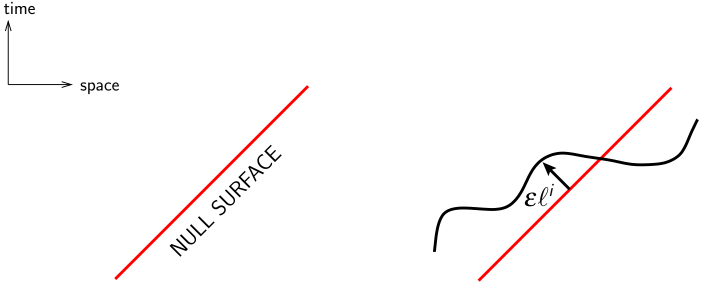

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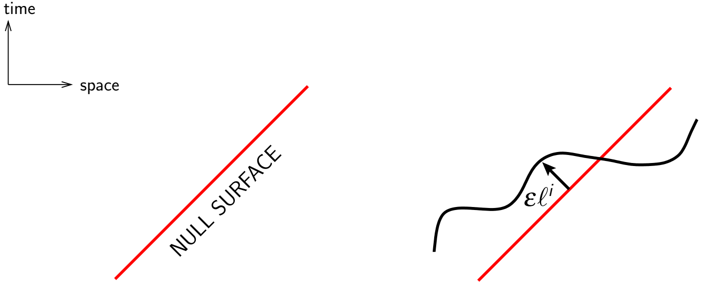

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A NEW VARIATIONAL PRINCIPLE

- Associate with the virtual displacements of null vectors ξ^a a potential $\Im(\xi^a)$ which is quadratic in deformation field:

$$\Im[\xi] \sim [A(\nabla\xi)^2 + B\xi^2] = -\left[4P^{abcd}\nabla_c\xi_a\nabla_d\xi_b - T^{ab}\xi_a\xi_b\right]$$

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- Resulting equations are the field equations of Lanczos-Lovelock theory with an arbitrary cosmological constant arising as integration constant.

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THE DYNAMICAL EQUATIONS

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- A new symmetry: Action and field equations are invariant under $T_{ab} \to T_{ab} + \rho_0 g_{ab}$. Gravity does *not* couple to bulk vacuum energy.

PRINCIPLE OF EQUIVALENCE

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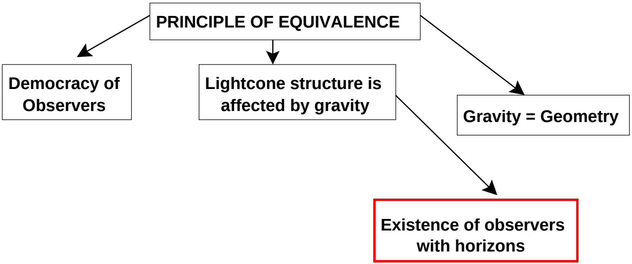
- Democracy of Observers
- Lightcone structure is affected by gravity
- Gravity = Geometry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Lightcone structure is affected by gravity
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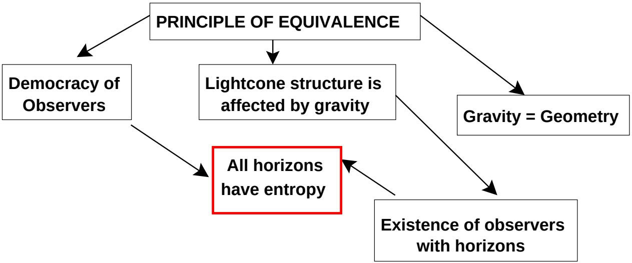
Existence of observers with horizons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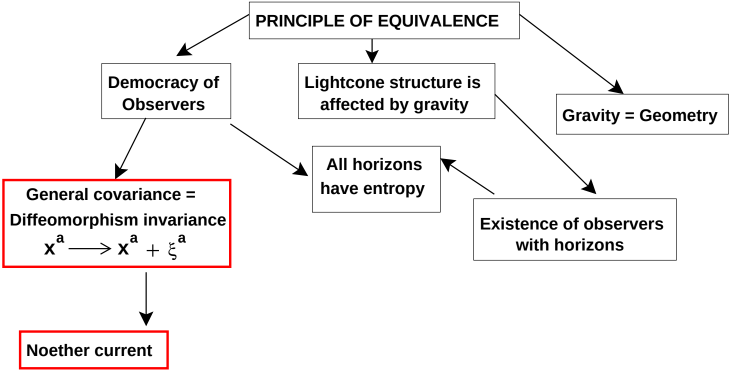
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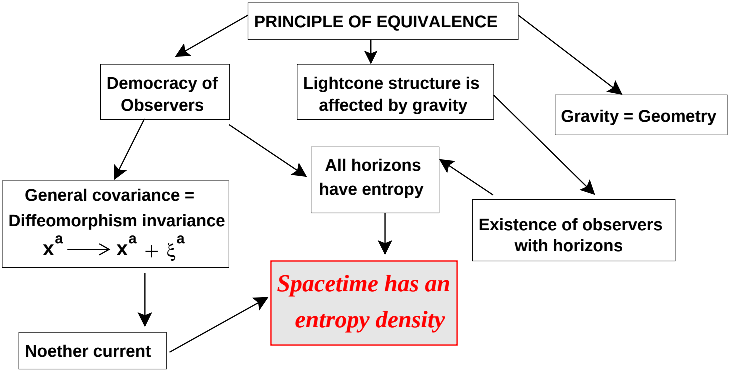
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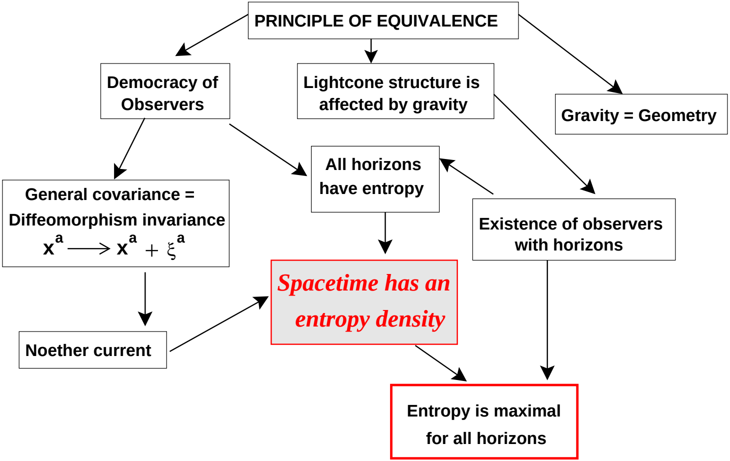
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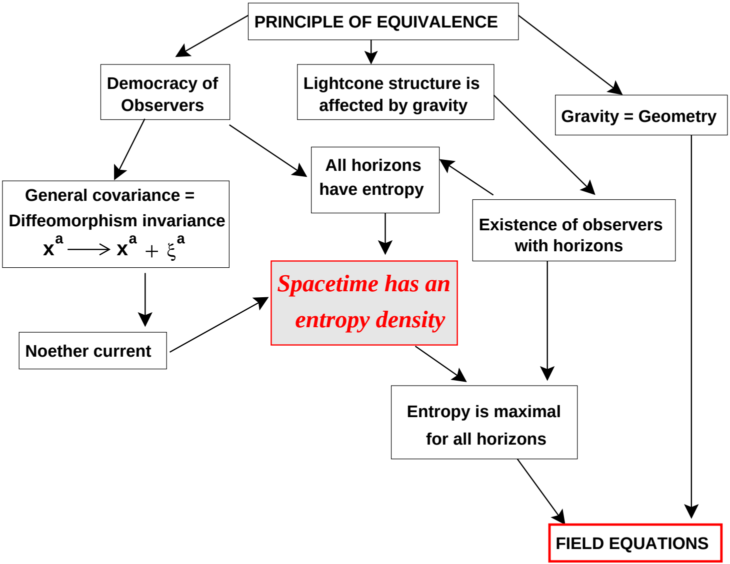
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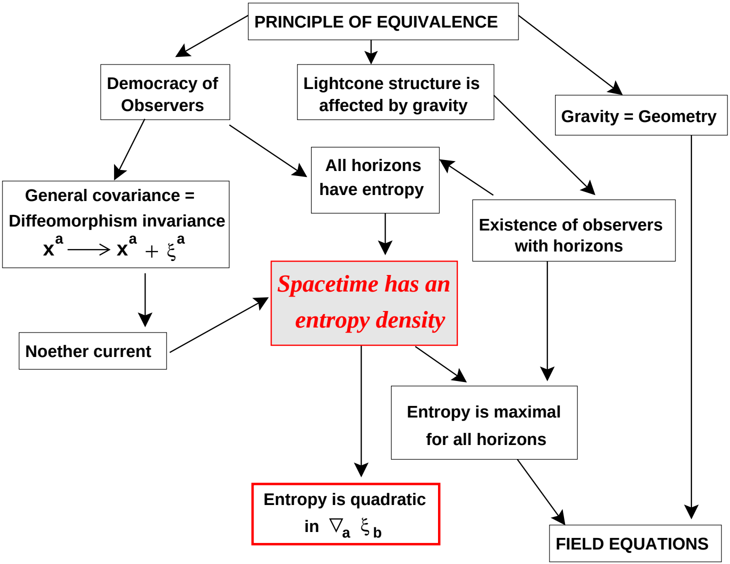

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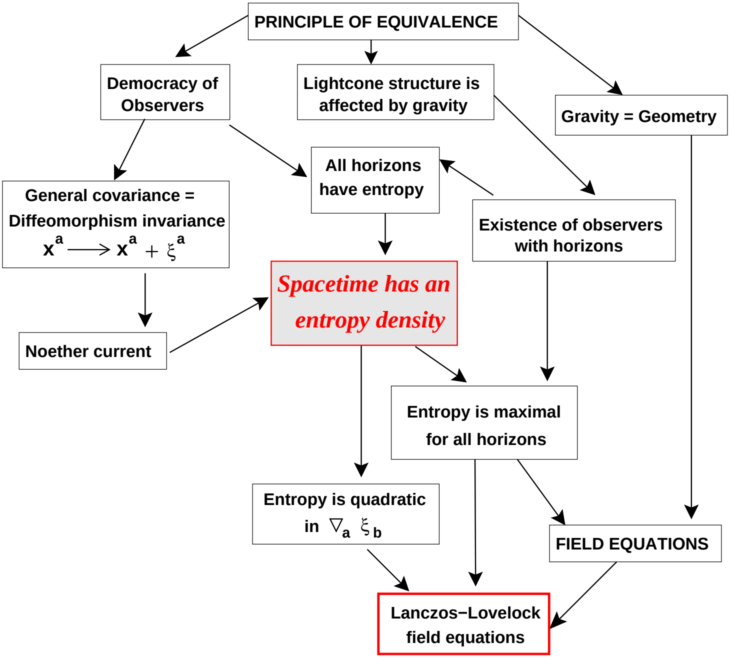
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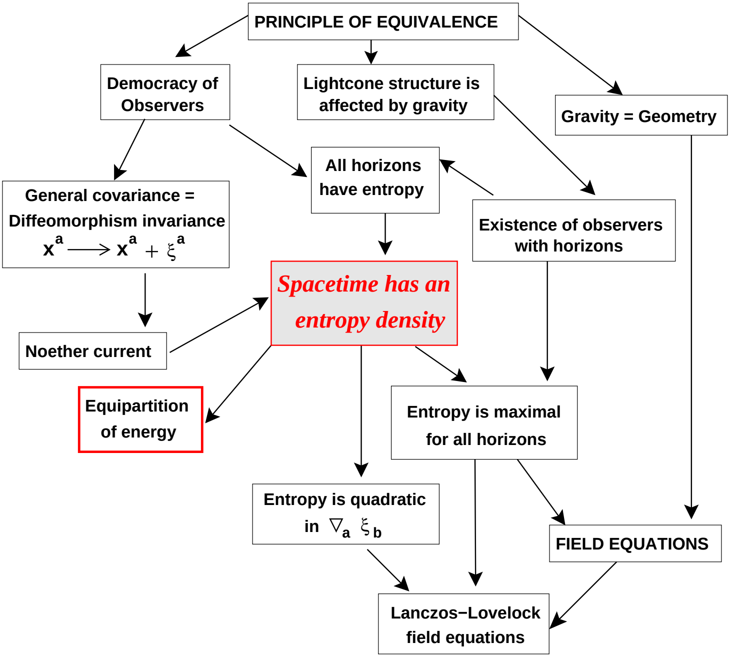
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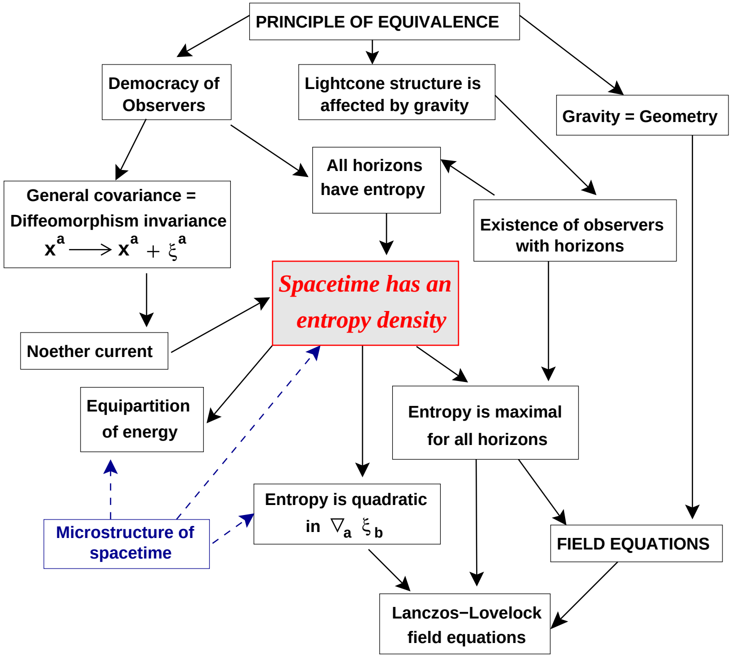

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SUMMARY - I

Emergent paradigm provides better insight into ...

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- Why does the current related to $x^a \to x^a + q^a(x)$ have anything to do with a thermodynamical variable like entropy ?
- Why do Einstein's equations reduce to a thermodynamic identity on the horizons ? And, as Navier-Stokes equations on null surfaces?
- Why does Einstein-Hilbert action have several peculiar features ? (holographic surface/bulk terms, thermodynamic interpretation ....)
- Why does the surface term in the action give the horizon entropy ? And on-shell action reduces to the free energy ?
- Why does the microscopic degrees of freedom obey thermodynamic equipartition ?
- Why does a thermodynamic variational principle lead to the gravitational field equations?
- Why do all these work for a wide class of theories?

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- Null surfaces/vectors provides an effective, collective, description of microscopic physics at large scales.
- Gravity is 'holographic' in many ways.

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- Produce a falsifiable prediction. We need to do better than other QG candidate models!

REFERENCES

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THANK YOU FOR YOUR TIME!