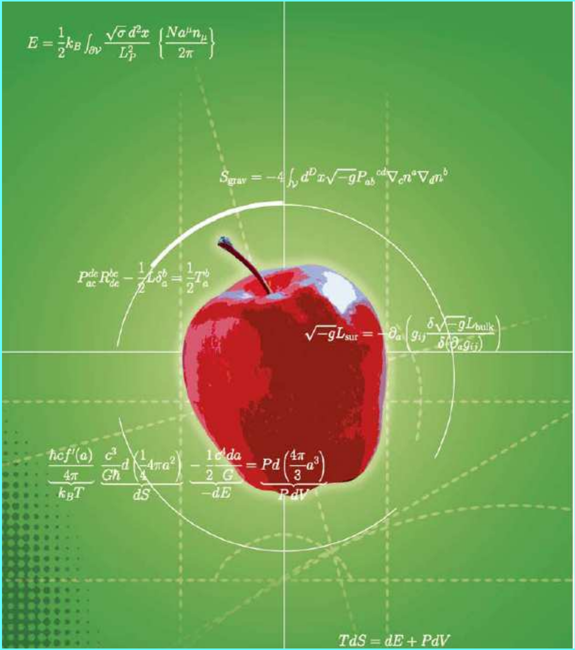

SECRET LIFE OF SPACETIME

T. Padmanabhan

IUCAA, Pune

EVERYBODY WANTS TO QUANTIZE GRAVITY!

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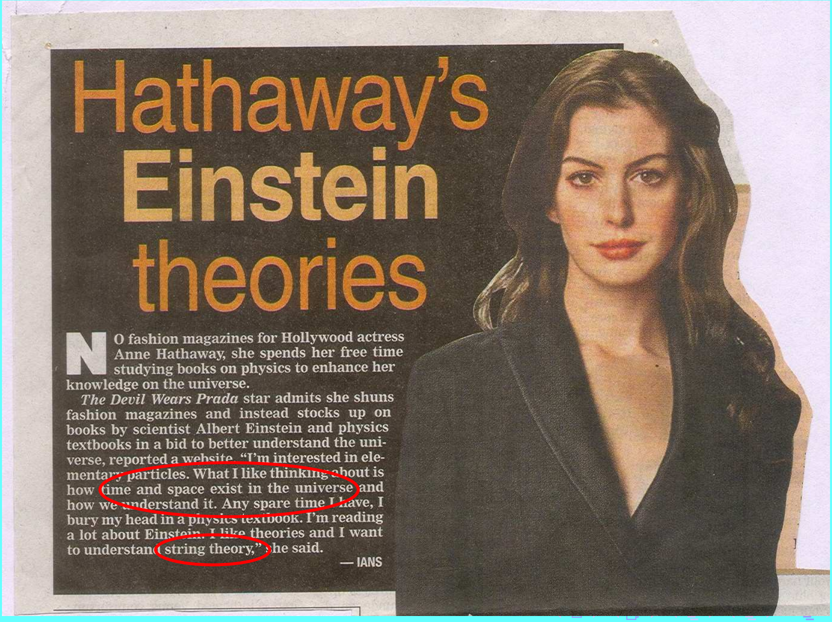

Hathaway's Einstein theories

NO fashion magazines for Hollywood actress Anne Hathaway, she spends her free time studying books on physics to enhance her knowledge on the universe.

The Devil Wears Prada star admits she shuns fashion magazines and instead stocks up on books by scientist Albert Einstein and physics textbooks in a bid to better understand the universe, reported a website. "I'm interested in elementary particles. What I like thinking about is how time and space exist in the universe and how we understand it. Any spare time I have, I bury my head in a physics textbook. I'm reading a lot about Einstein. I like theories and I want to understand string theory," she said.

— IANS

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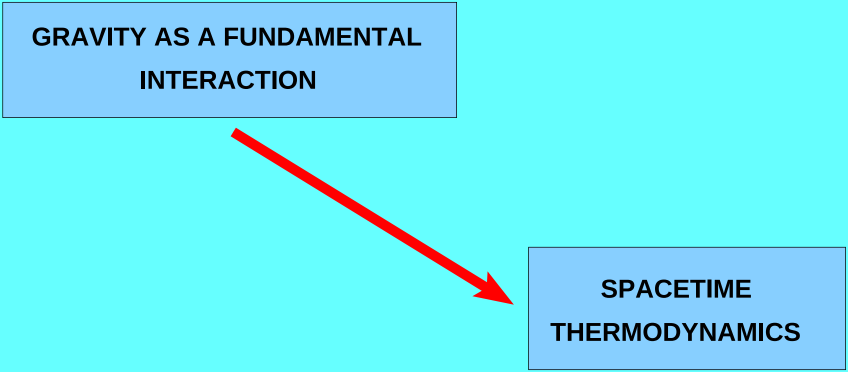
CONVENTIONAL VIEW

GRAVITY AS A FUNDAMENTAL INTERACTION

CONVENTIONAL VIEW



NEW PERSPECTIVE

SPACETIME THERMODYNAMICS

GRAVITY IS AN EMERGENT PHENOMENON

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

BOTTOM-UP: MICRO to MACRO

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- *But what if we do not know the microscopic theory ?*

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- Very similar things happen for equations governing spacetime!

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THE PARADIGM

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

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HORIZON THERMODYNAMICS $\Leftrightarrow$ GRAVITY

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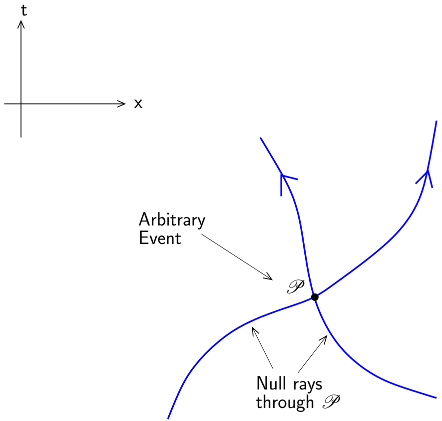
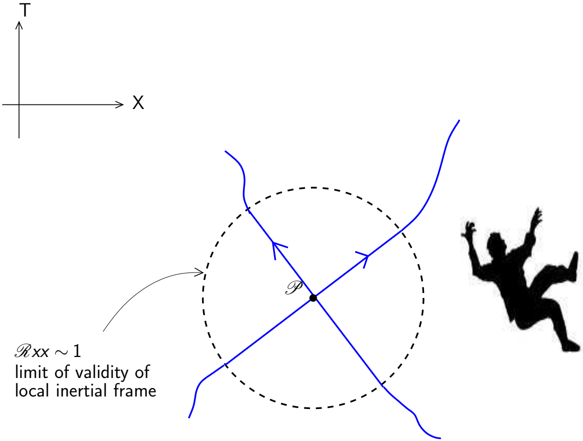
SPACETIME IN ARBITRARY COORDINATES



FREE – FALL OBSERVERS



Validity of laws of SR ⇒ kinematics of gravity

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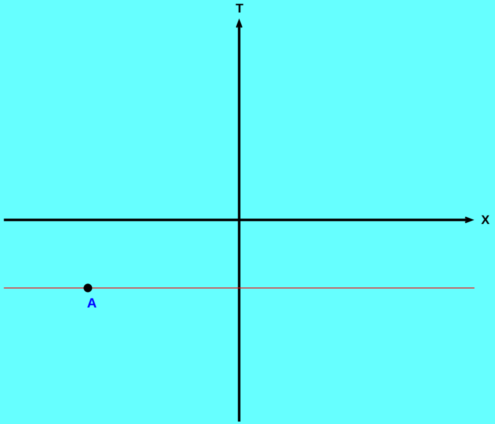

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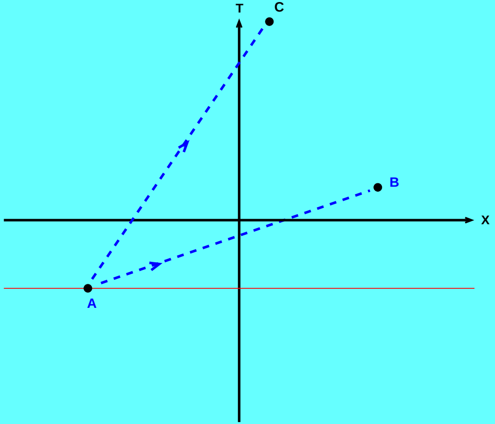
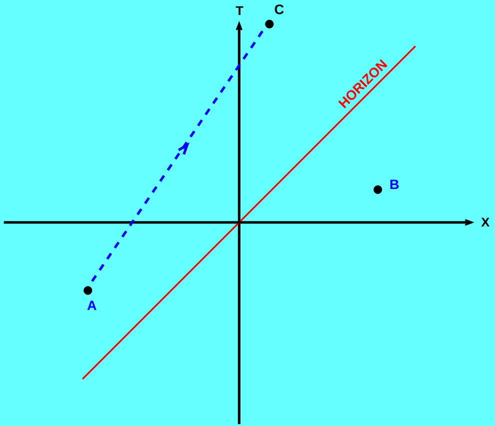


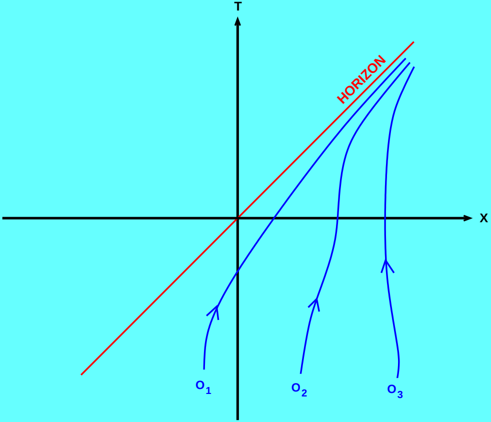
Newtonian physics: A can communicate with B and C.

SPACETIME AND CAUSAL STRUCTURE



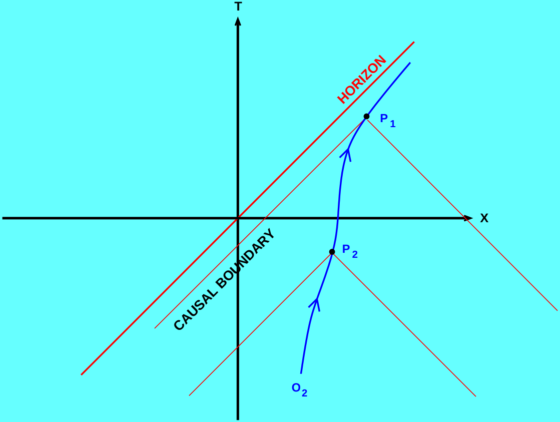
Special Relativity introduces a causal horizon;
A cannot communicate with B.

SPACETIME AND CAUSAL STRUCTURE



A family of observers $(O_1, O_2, O_3, ...)$ have a causal horizon

SPACETIME AND CAUSAL STRUCTURE



Boundary of union of backward light cones can be used to define causal horizon.

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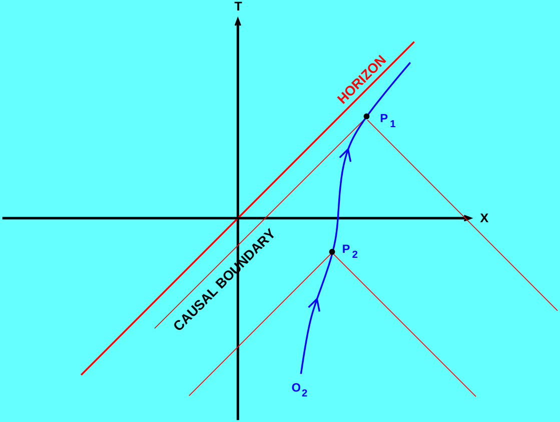
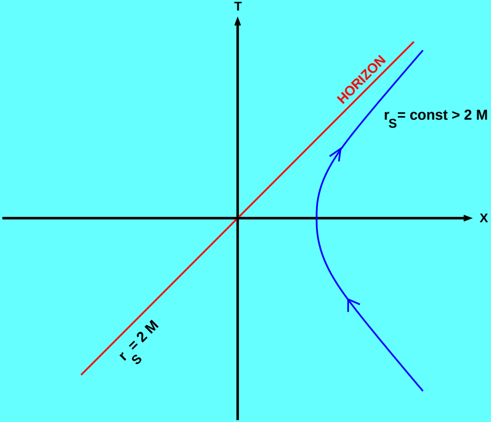


Boundary of union of backward light cones can be used to define causal horizon.

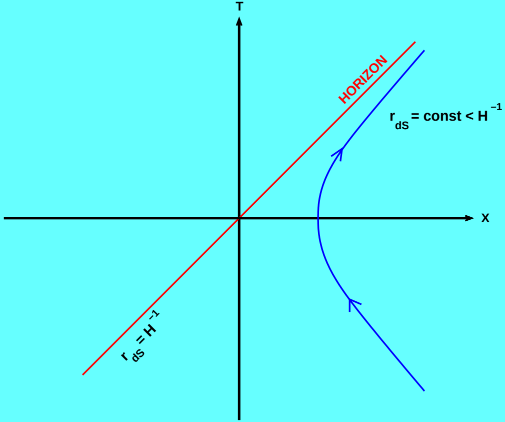
Family of observers with causal horizon exists in any spacetime.

SCHWARZSCHILD SPACETIME



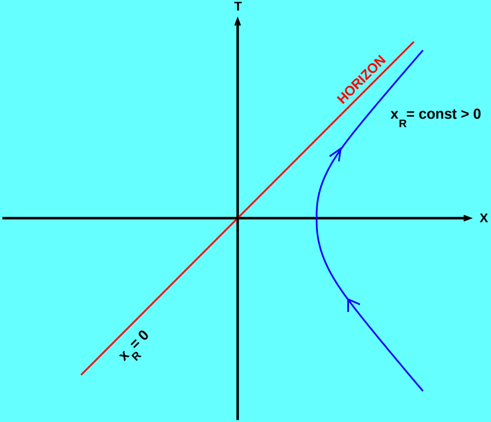
$$ds^2 = -\left(1-\frac{2M}{r_S}\right)dt_S^2+\left(1-\frac{2M}{r_S}\right)^{-1}dr_S^2$$
$$= Q_S^2(T,X)(-dT^2+dX^2)$$

DE-SITTER SPACETIME



$$
\begin{aligned}
ds^2 &= -\left(1 - H^2 r_{dS}^2\right) dt_{dS}^2 + \left(1 - H r_{dS}^2\right)^{-1} dr_{dS}^2 \\
&= Q_{dS}^2(T, X)(-dT^2 + dX^2)
\end{aligned}
$$

RINDLER (FLAT!) SPACETIME



$$
\begin{aligned}
ds^2 &= -2\kappa x_R \, dt^2 + (2\kappa x_R)^{-1} \, dx_R^2 \\
&= -dT^2 + dX^2
\end{aligned}
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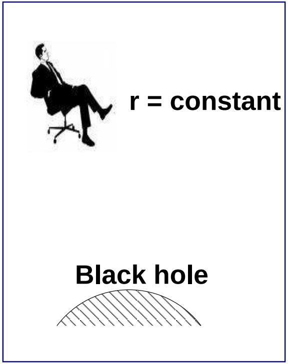
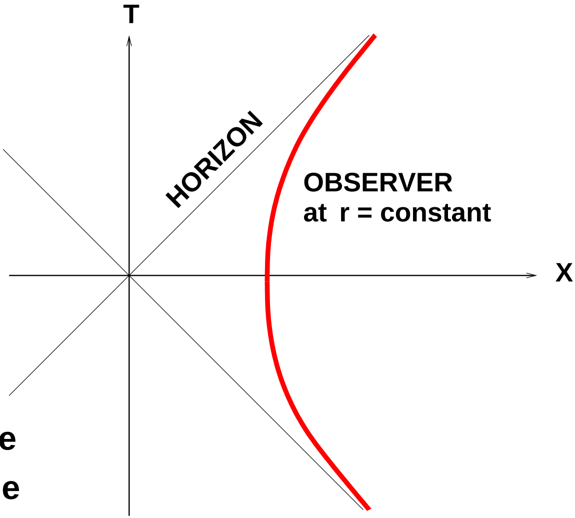
SPACETIMES, LIKE MATTER, CAN BE HOT

OBSERVERS WHO PERCEIVE A HORIZON
ATTRIBUTE A TEMPERATURE TO SPACETIME

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

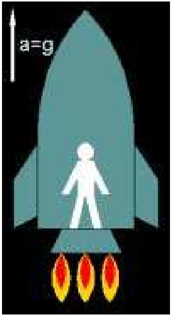
BLACK HOLE SPACETIME



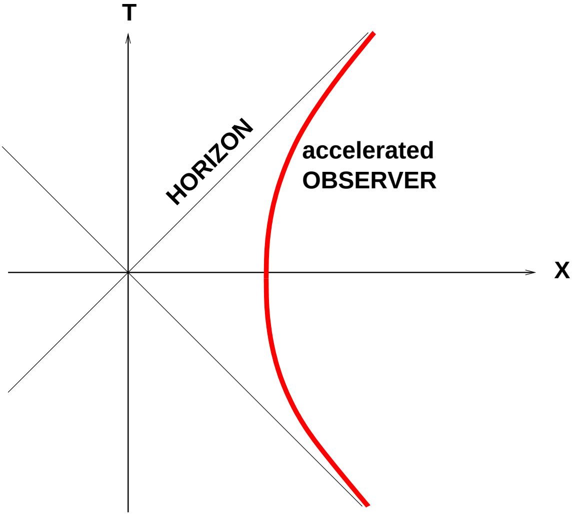


Temperature

$\propto$ acceleration due to the black hole



FLAT SPACETIME



Temperature
$\propto$ acceleration
of the observer

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

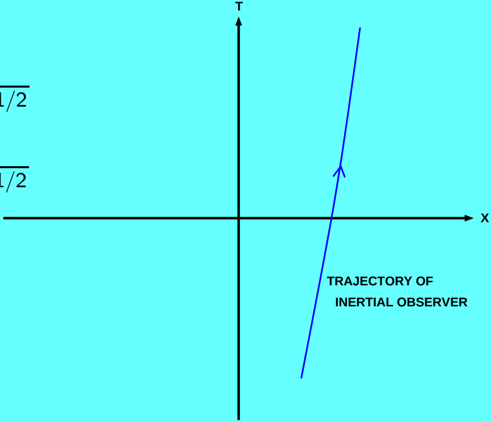
WHY ?

WHERE DOES TEMPERATURE SPRING FROM?!

Plane wave viewed by inertial observers

$$T = \frac{\tau}{(1 - v^2)^{1/2}}$$

$$X = \frac{v\tau}{(1 - v^2)^{1/2}}$$



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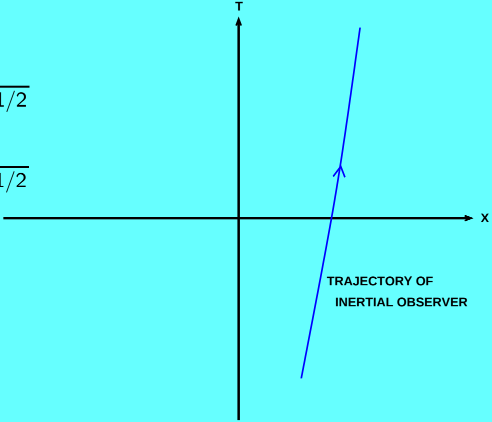

$$\phi(T, X) = \exp[-i\Omega(T - X)]$$

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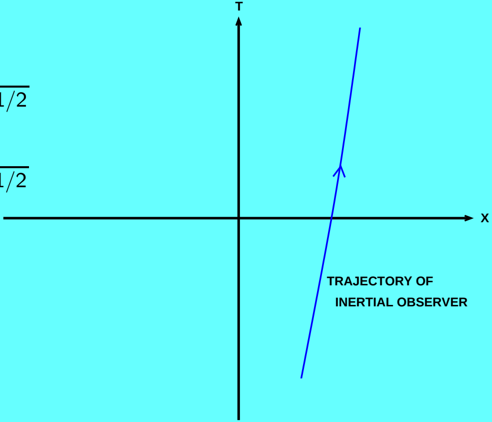


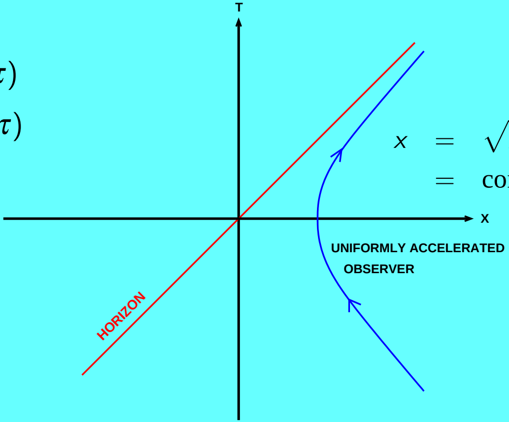
$$\phi(T, X) \equiv \phi\left(T(\tau), X(\tau)\right) = \exp - i\Omega \left(\frac{1 - v}{1 + v}\right)^{1/2} \tau$$

Doppler effect: $\Omega' = \Omega \left(\frac{1 - v}{1 + v}\right)^{1/2}$

Plane wave viewed by Rindler observers

$$T = x \sinh(\kappa\tau)$$

$$X = x \cosh(\kappa\tau)$$



$$x = \sqrt{X^2 - T^2} = \text{constant}$$

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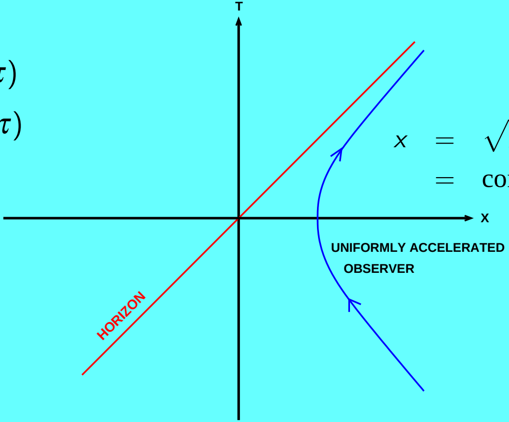

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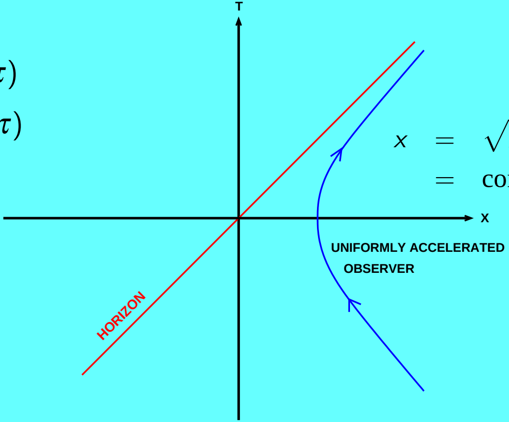

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$$\phi(\tau) = \phi(T(\tau), X(\tau)) = \exp i \overbrace{\left[\frac{\Omega}{\kappa} e^{-\kappa\tau}\right]}^{\text{exponential redshift!}}$$

TEMPERATURE OF THE HORIZON

- A mode $\phi(T,X) = \exp[-i\Omega(T-X)]$ frequency Ω will lead to

$$\phi(\tau) = \exp[i\Omega\kappa^{-1}\exp(-\kappa\tau)] = \int_0^\infty d\nu[A(\nu)e^{-i\nu\tau} + B(\nu)e^{i\nu\tau}]$$

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- Ratio of the coefficients is the Boltzmann factor: $\exp -\beta\nu$; determines the equilibrium level population of a detector.

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- In frequency space the result is purely classical (no $\hbar$ anywhere!):

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- Exponential redshift occurs near any horizon with κ determined by surface gravity at the horizon.

WHY ARE HORIZONS HOT ?

$$\left.\begin{array}{r}\text{PERIODICITY IN}\\ \text{IMAGINARY TIME}\end{array}\right\} \Longleftrightarrow \left\{\ \text{FINITE TEMPERATURE}\right.$$

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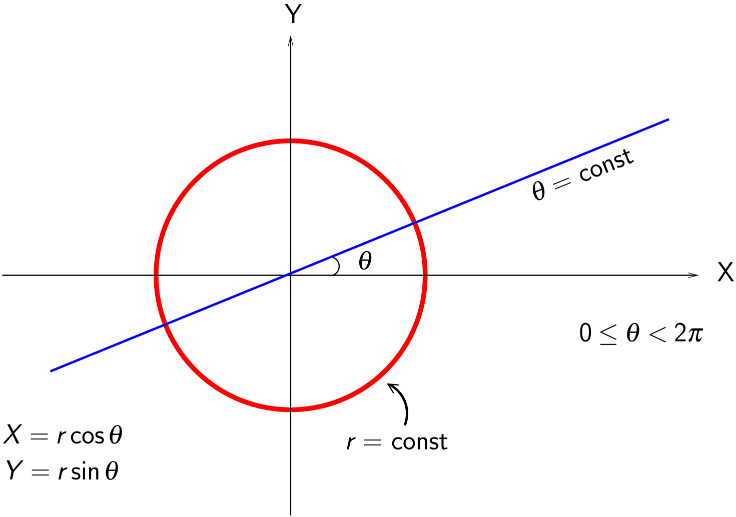
SPACETIMES WITH HORIZONS EXHIBIT PERIODICITY IN IMAGINARY TIME $\Longrightarrow$ TEMPERATURE

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



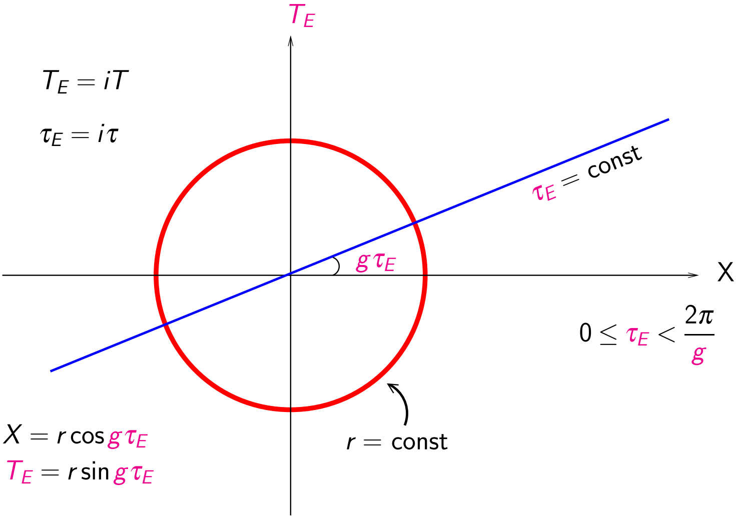
$$0 \leq \theta < 2\pi$$

$$X = r\cos\theta$$
$$Y = r\sin\theta$$

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

$T_E = iT$

$\tau_E = i\tau$



$$0 \le \tau_E < \frac{2\pi}{g}$$

$X = r\cos g\tau_E$

$T_E = r\sin g\tau_E$

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

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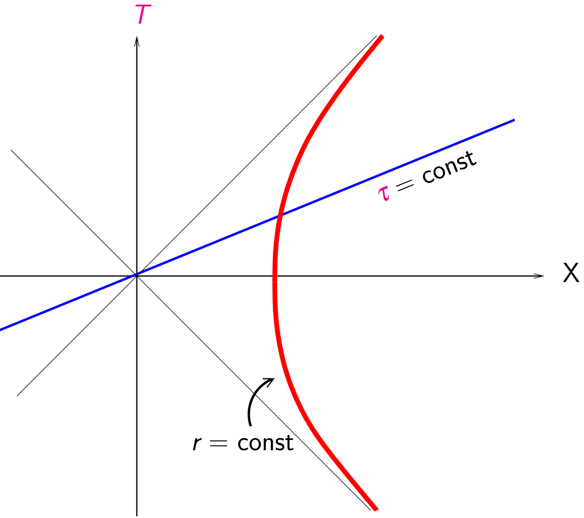

$$X = r\cosh g\tau$$
$$T = r\sinh g\tau$$

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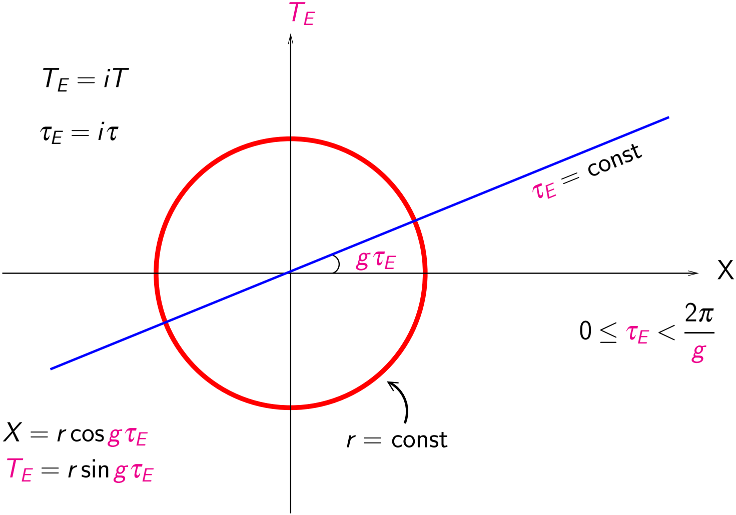

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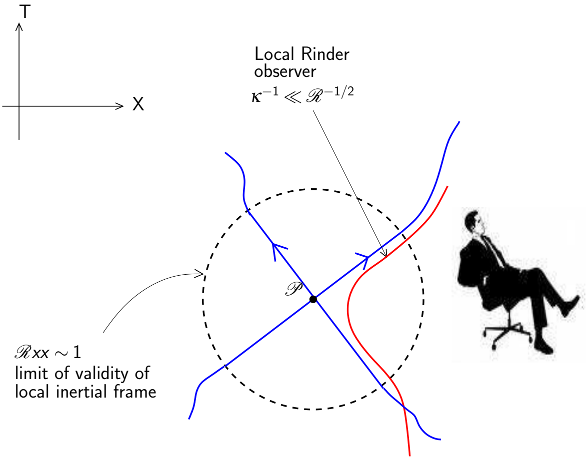
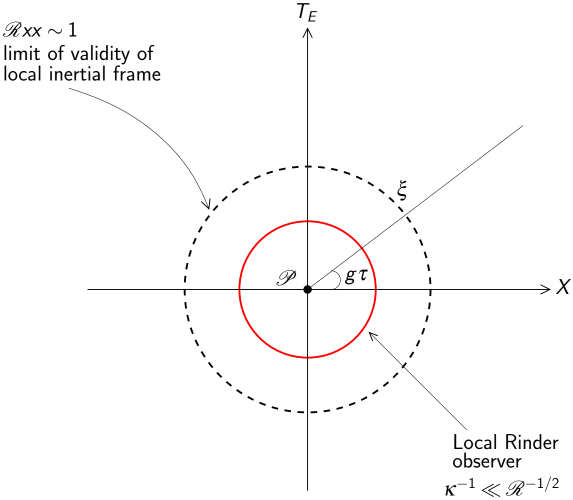
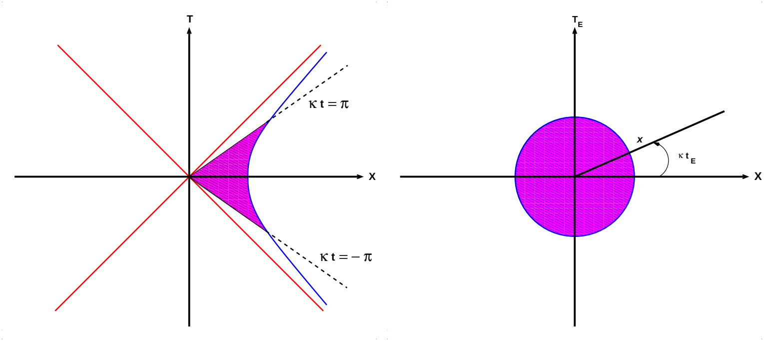
LOCAL RINDLER OBSERVERS




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

PERIODICITY IN THE EUCLIDEAN TIME



$T = x \sinh \kappa t, \; X = x \cosh \kappa t$ $\qquad$ $T_E = x \sin \; \kappa t_E, \; X = x \cos \; \kappa t_E$

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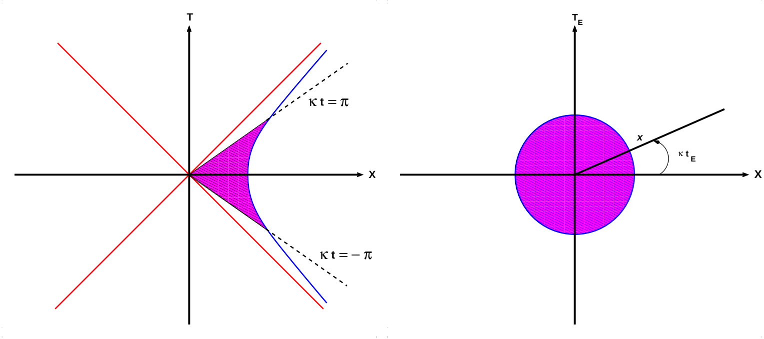

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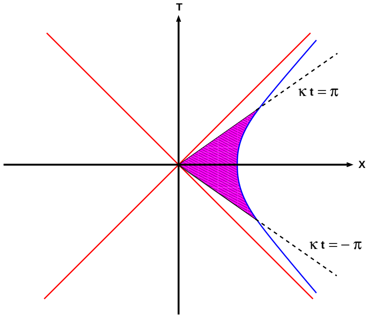

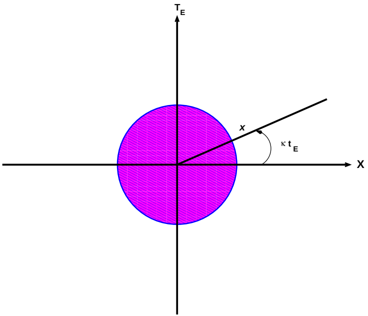

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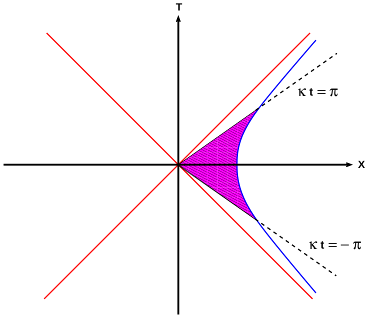

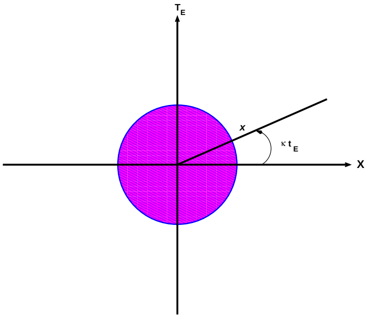

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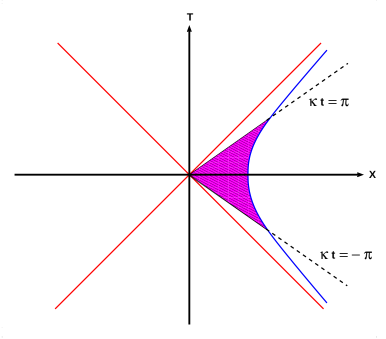

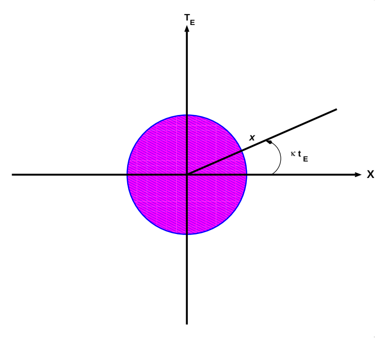

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- Complex plane "knows about " $X < 0$.

SPACETIMES, LIKE MATTER, CAN BE HOT

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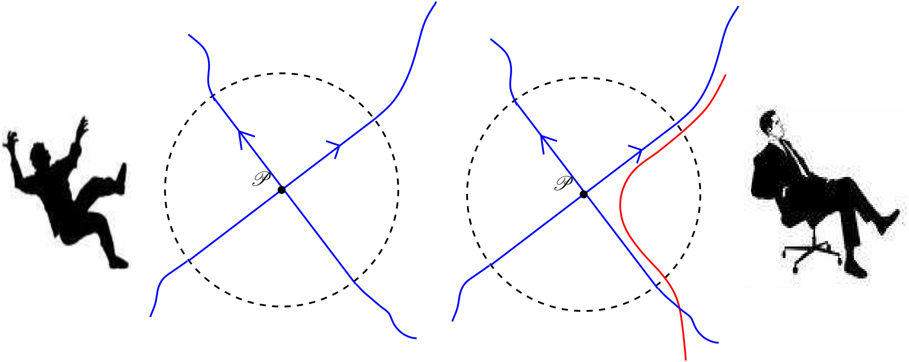
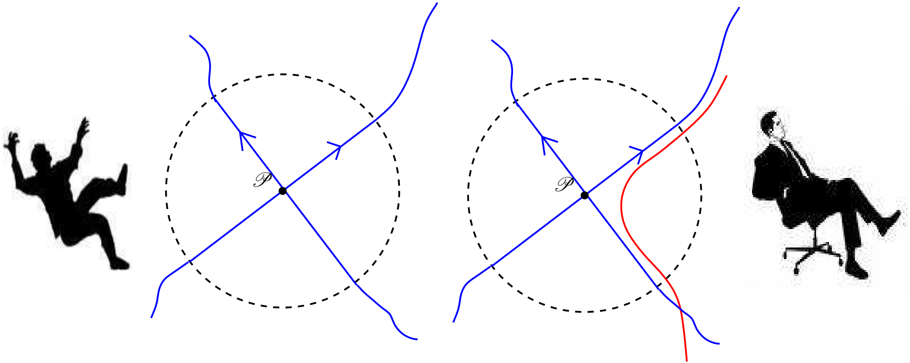


Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations



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A VERY NON-TRIVIAL EQUIVALENCE!

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- *Correct entropy depends on the dynamics.*

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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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- IN GR ACTION REDUCES TO A PURE SURFACE TERM IN LOCAL INERTIAL FRAME.

- Example: The standard action in from classical mechanics is:

$$A_q = \int dt \; L_q(q, \dot{q}); \quad \delta q = 0 \text{ at } t = (t_1, t_2)$$

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- Action for gravity has exactly this structure! [TP, 02, 05]

$$A_{grav} = \int d^4x \sqrt{-g}\, R = \int d^4x \sqrt{-g}\, [L_{\rm bulk} + L_{\rm sur}]$$

$$\sqrt{-g} L_{sur} = -\partial_a \left(g_{ij} \frac{\partial \sqrt{-g} L_{bulk}}{\partial(\partial_a g_{ij})}\right)$$

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- If $L_q = (1/2)\dot{q}^2 - V(q)$ then $L_p = -q\ddot{q} - (1/2)\dot{q}^2 - V(q)$. This is the structure of gravitational lagrangian!

ANOTHER ISSUE WITH DYNAMICS

A symmetry is ignored

- Action:

$$\begin{aligned} A_{\text{tot}} &= A_{\text{grav}}(g) + A_{\text{matter}}(g, \phi) \\ &= \int d^4x \sqrt{-g}\, \left[L_{\text{grav}}(g) + L_{\text{matter}}(g, \nabla_i \phi, \phi)\right] \end{aligned}$$

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- Equations of motion:

$\delta_\phi A_{\text{matter}} = 0$ ('spacetime tells matter to move')

$\delta_g A_{\text{tot}} = 0; \quad E_{ik} = T_{ik}$ ('matter tells spacetime to curve')

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$\delta_\phi A_{\rm matter} = 0$ ('spacetime tells matter to move')

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- But gravitational equations of motion are not:

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- *GRAVITY BREAKS A SYMMETRY PRESENT IN MATTER SECTOR.*

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- The only way out is to have a formalism for gravity which is invariant under $T_{ab} \to T_{ab} + \rho g_{ab}$.
- *All these have nothing to do with observations of accelerated universe! Cosmological constant problem existed earlier and will continue to exist even if all these observations go away!*

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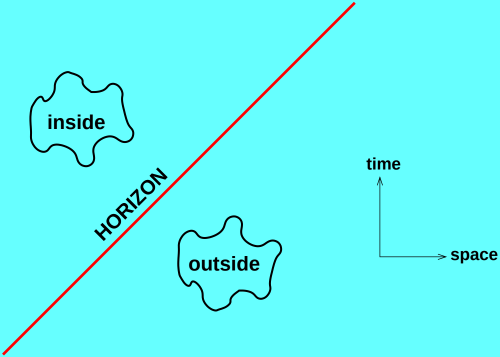
ENTROPY OF HORIZONS



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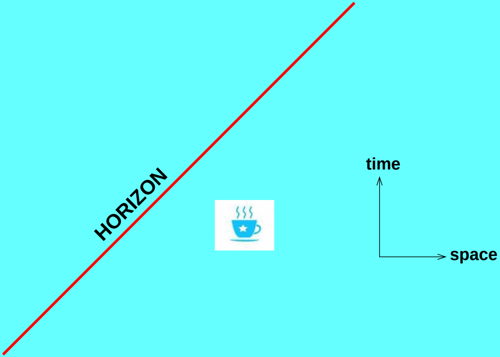

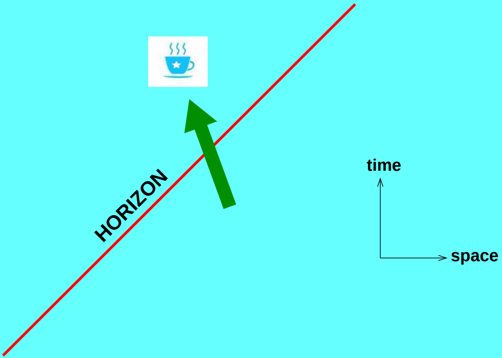

Wheeler ($\sim$ 1971): Can one violate second law of thermodynamics by hiding entropy behind a horizon ?

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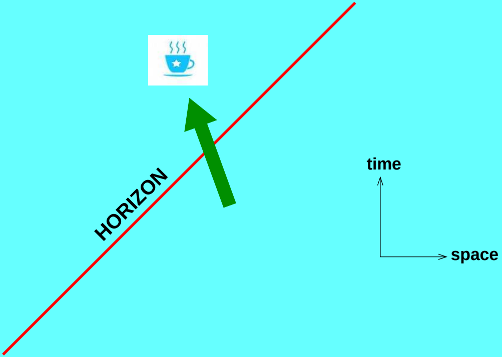

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Bekenstein (1972): No! Horizons have entropy $S \propto (Area)$ which goes up when you try this.

INTUITIVE UNDERSTANDING OF $S \propto A$

John Wheeler: 'It from Bit'

- Quantum gravity has a minimal 'quantum of area':
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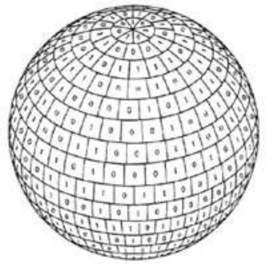

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- *Unfortunately $S \not\propto A_{hor}$ in general; this idea — and many others — fail when we go beyond GR.*

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

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

ENTROPY FROM SURFACE TERM IN ACTION

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

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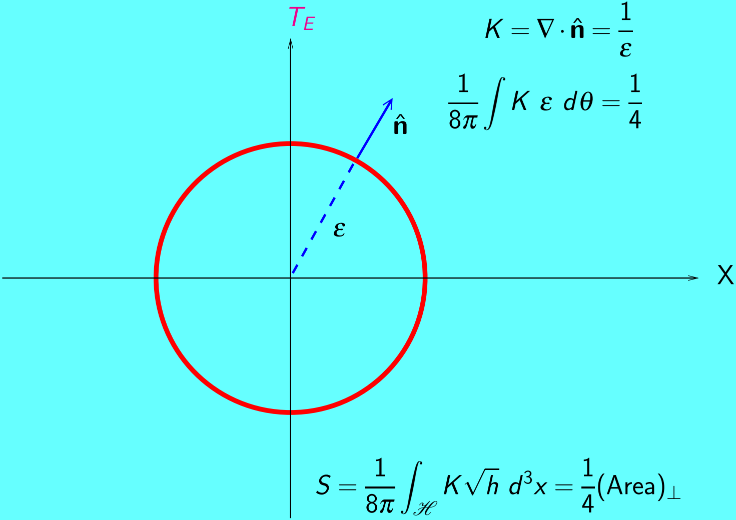
- Throw away (or cancel) surface term, vary the bulk term to get field equations. The discarded $A_{\rm sur}$, evaluated on any horizon gives its entropy !

SURFACE TERM IN ACTION



$$K = \nabla \cdot \hat{\mathbf{n}} = \frac{1}{\varepsilon}$$

$$\frac{1}{8\pi} \int K \; \varepsilon \; d\theta = \frac{1}{4}$$

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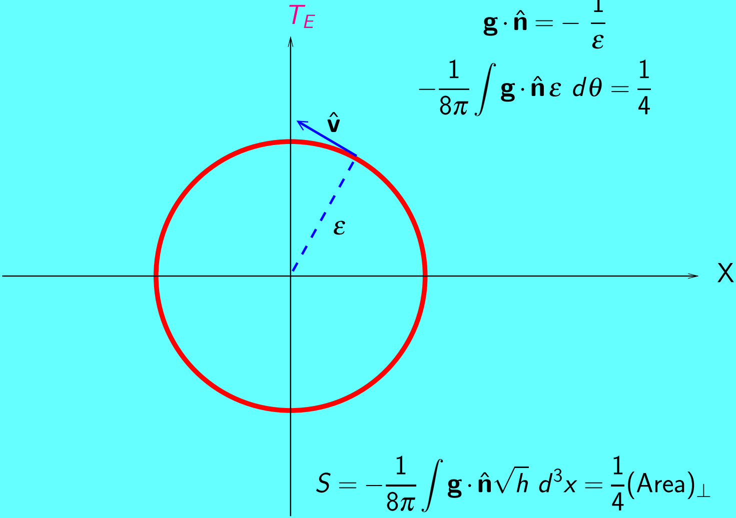

$$\mathbf{g}\cdot\hat{\mathbf{n}} = -\,\frac{1}{\varepsilon}$$

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$$\sqrt{-g}L_{\rm sur} = -\partial_a\left(g_{ij}\frac{\delta\sqrt{-g}L_{\rm bulk}}{\delta(\partial_a g_{ij})}\right)$$

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

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More Physics of the Surface Term

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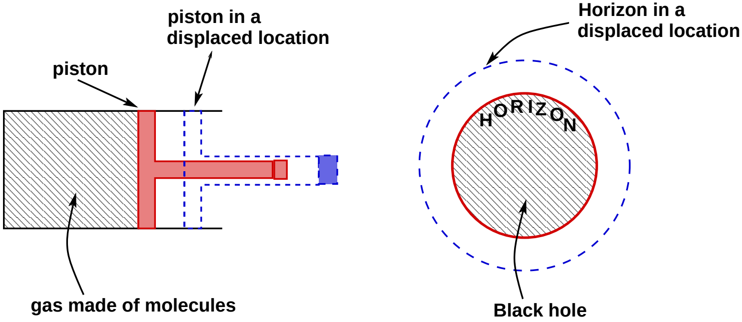
- One can obtain LL field equations from a suitable variation of the surface term [Sotiriou, Liberati, 06; TP, 06; 11]

FIELD EQUATIONS ON NULL SURFACES-I

TP, CQG, 19, 5387 (2002)[gr-qc/0204019]



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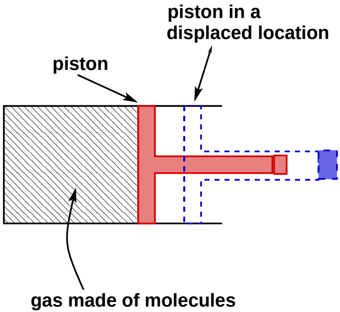

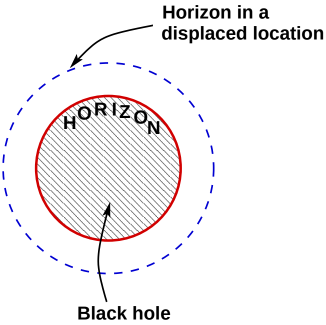

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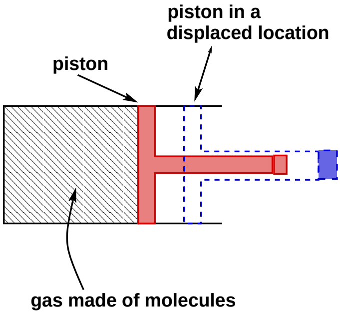

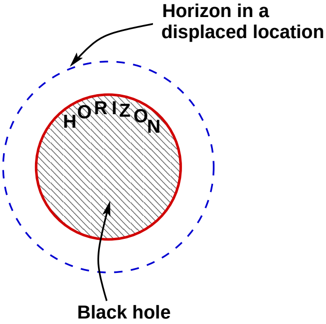

$$\frac{c^4}{G}\left[\frac{\kappa a}{c^2}-\frac{1}{2}\right]=4\pi P a^2 \quad \Rightarrow \quad \underbrace{\frac{\hbar}{c}\left(\frac{\kappa}{2\pi}\right)}_{k_B T}\underbrace{\frac{c^3}{G\hbar}d\left(\frac{1}{4}4\pi a^2\right)}_{k_B^{-1}dS}\underbrace{-\frac{1}{2}\frac{c^4 da}{G}}_{-dE}=\underbrace{Pd\left(\frac{4\pi}{3}a^3\right)}_{P\,dV}$$

HOLDS TRUE FOR A LARGE CLASS OF MODELS!

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- 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!*

FIELD EQUATIONS ON NULL SURFACES – II

The Navier-Stokes Einstein connection

[Damour, 1979; Price and Thorne, 1986; Eling, Liberati,2010;....., TP, 2010]

- A BH horizon can be thought of as a dissipative membrane with conductivity (σ), bulk viscosity (ζ), shear viscosity (η). In particular, (Damour, 1979)

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

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- Can we say anything about the microscopic d.o.f ?

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- 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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IF SO, CAN WE DETERMINE Δn*?*

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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- Extends to all Lanczos-Lovelock models:

$$E = \frac{1}{2} k_B \int_{\partial \mathcal{V}} dn T_{loc}; \qquad \frac{dn}{dA} = 32\pi P^{ab}_{cd} \epsilon_{ab} \epsilon^{cd}$$

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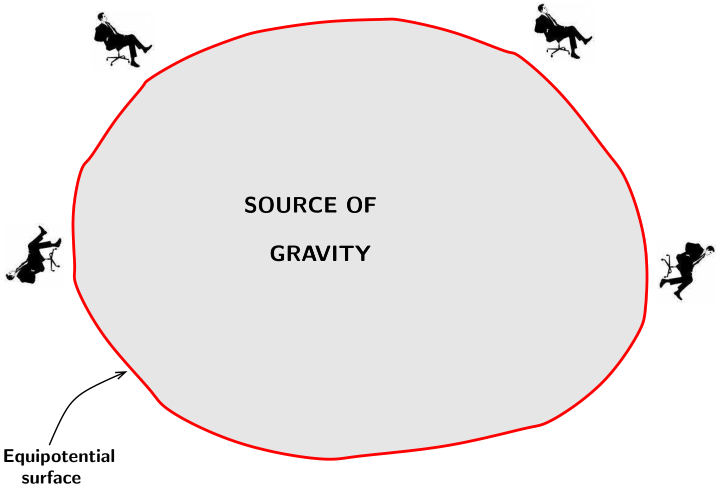

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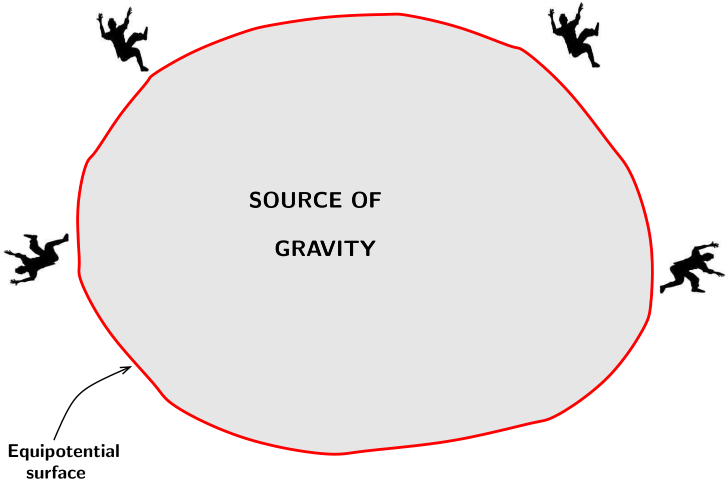

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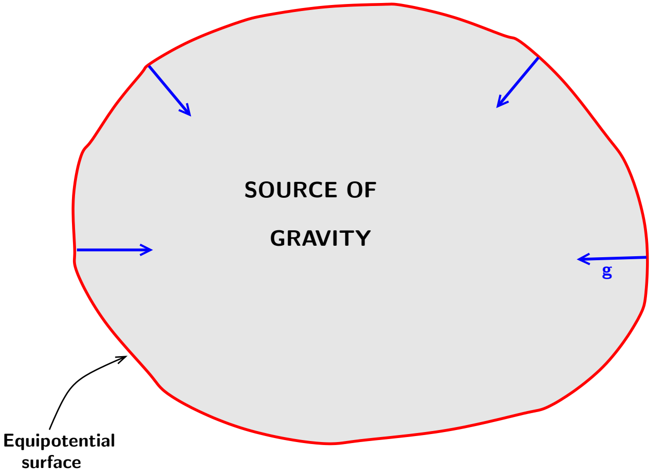

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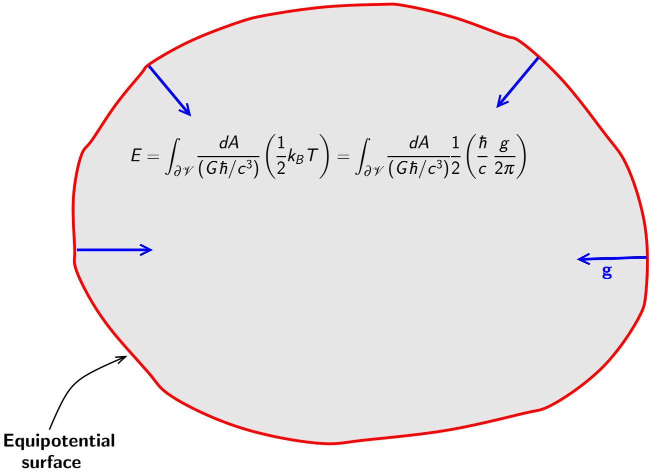

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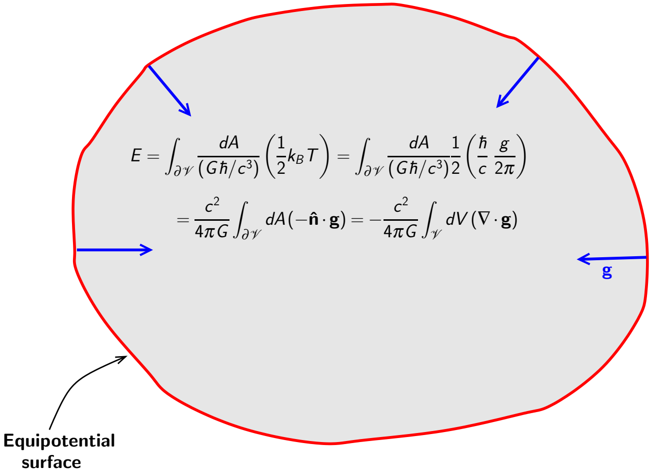

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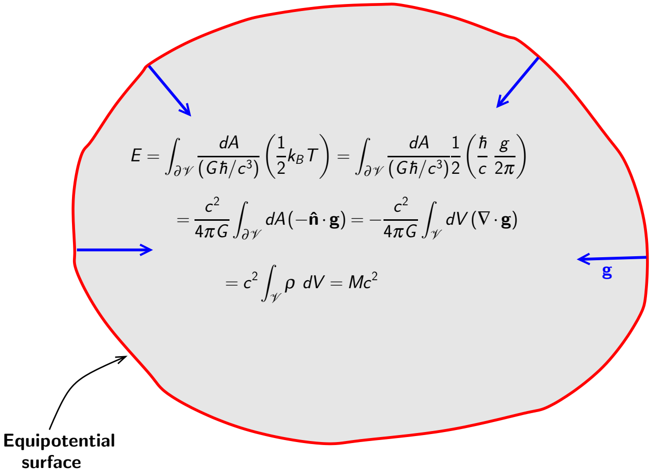

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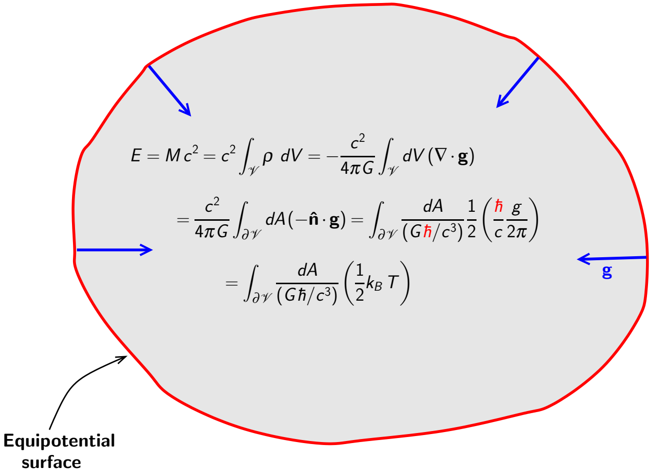

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- In static spacetimes GR gives an exact equation: [TP,1003.5665]

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

Holographic graviton noise ? [Hogan, 08]

COSMIC NUMEROLOGY!

- Emergent gravity-QCD connection? [Bjorken,astro-ph/0404233]

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- *Bottom Line:* Very imaginative (imaginary ?) ideas on DM-DE front but nothing which I will take seriously.

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 potentials like $\mathfrak{I} = (S[q_A], F[q_A], ...)$ connect the fundamental and emergent descriptions in terms of some suitable variables.

THERMODYNAMICS OF SPACETIME

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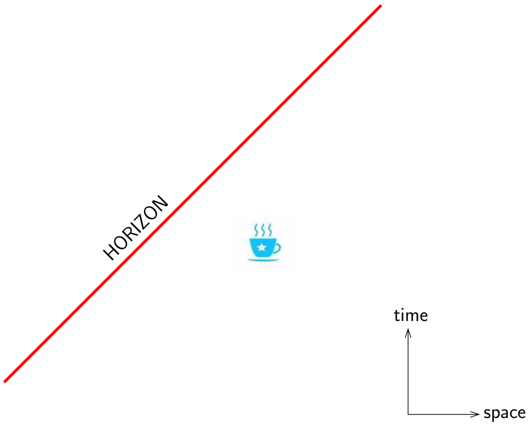
- We need a thermodynamical potential $\Im[q_A]$ for spacetime extremising which for all class of observers should give the field equations.

DEFORMATION OF NULL SURFACE



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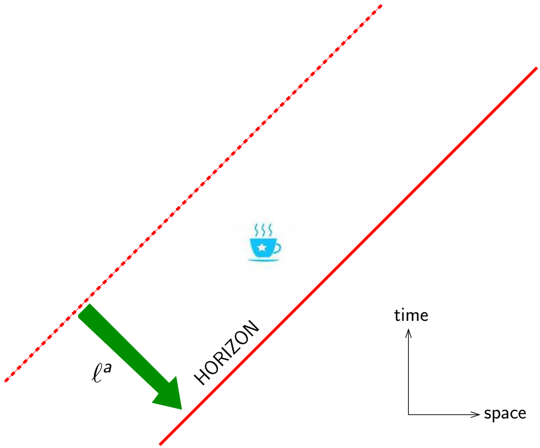

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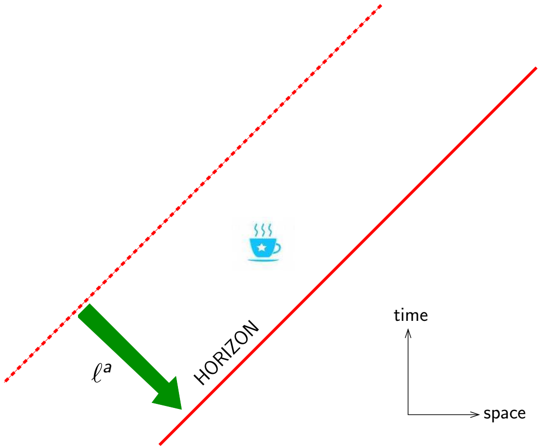
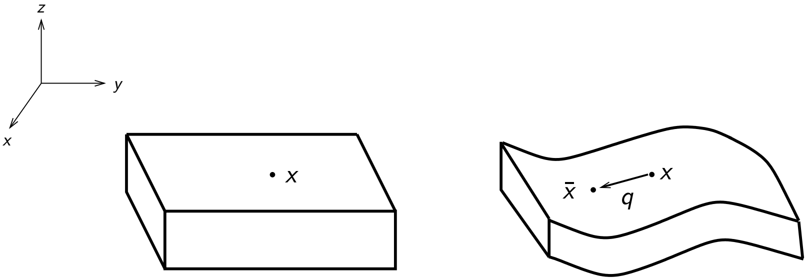


ASSOCIATE THERMODYNAMIC POTENTIALS
WITH NULL VECTORS

DEFORMING A SOLID



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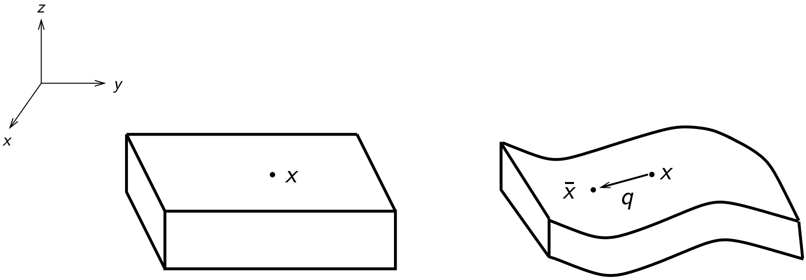

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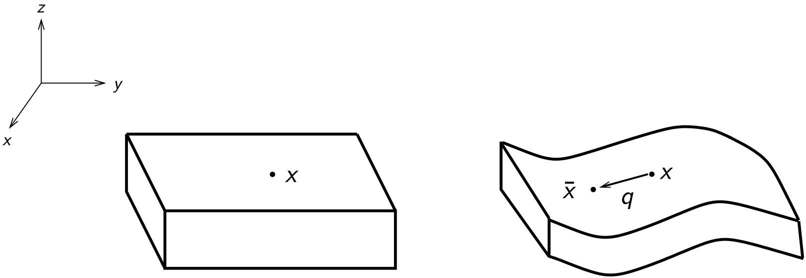

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$$\mathfrak{I} \sim A(\nabla q)^2 + Bq^2$$

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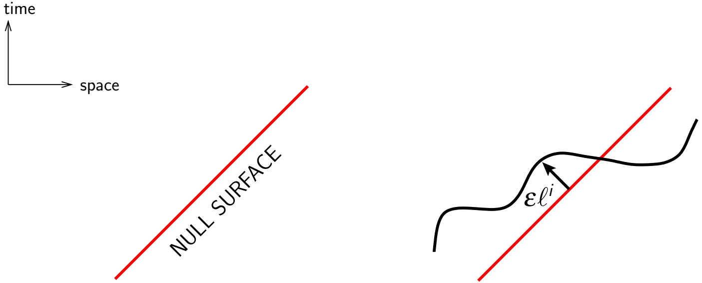

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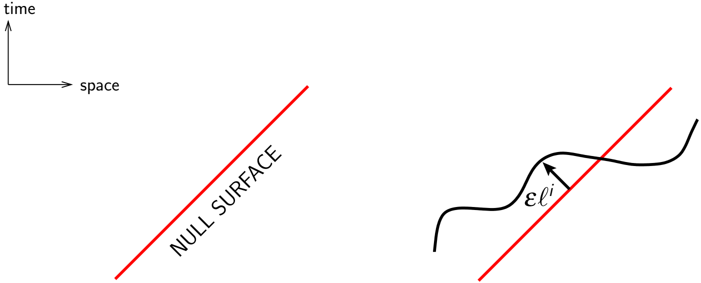

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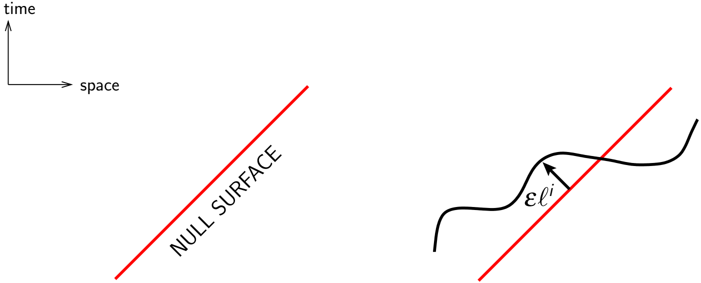

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A NEW VARIATIONAL PRINCIPLE

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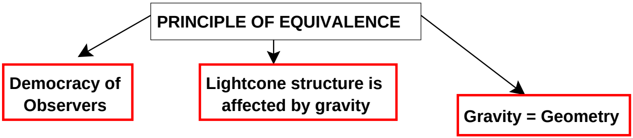
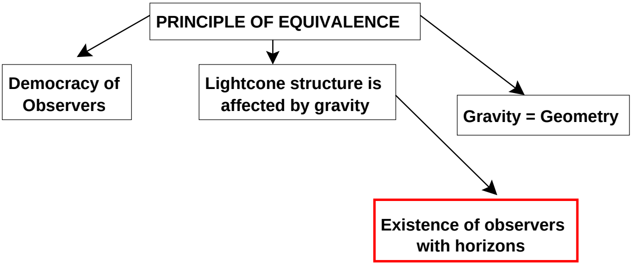
- A new symmetry: Action and field equations are invariant under $T_{ab}\to T_{ab}+\rho_0 g_{ab}$. Gravity does *not* couple to bulk vacuum energy.

PRINCIPLE OF EQUIVALENCE


PRINCIPLE OF EQUIVALENCE
Democracy of Observers
Lightcone structure is affected by gravity
Gravity = Geometry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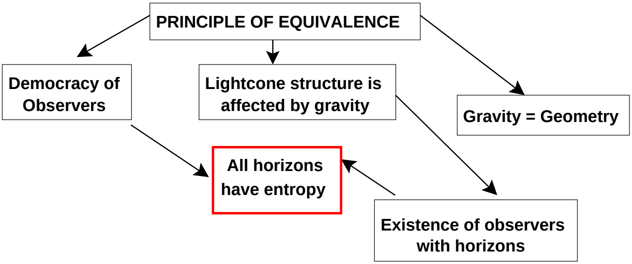
Democracy of Observers
Lightcone structure is affected by gravity
Gravity = Geometry
Existence of observers with horizons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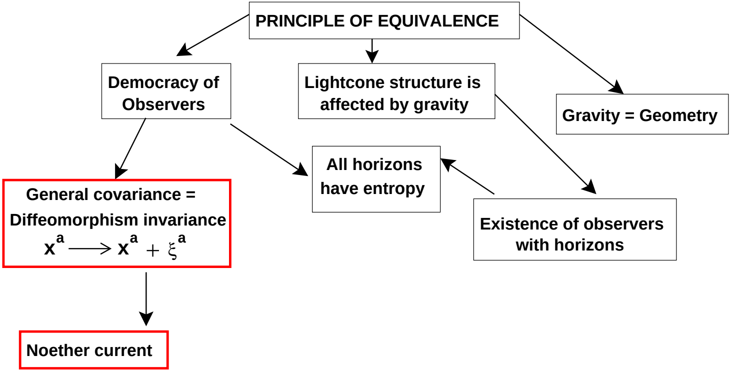
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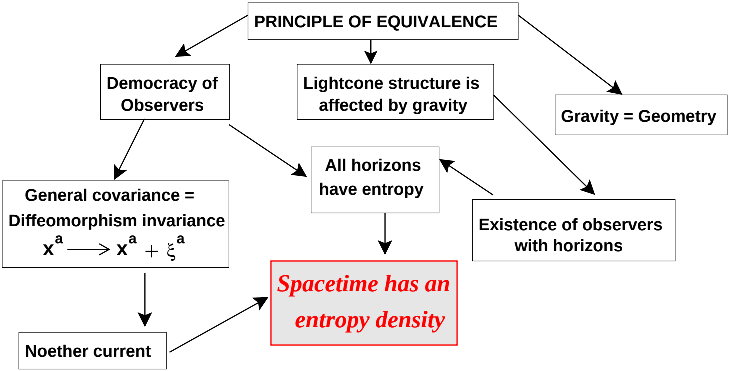
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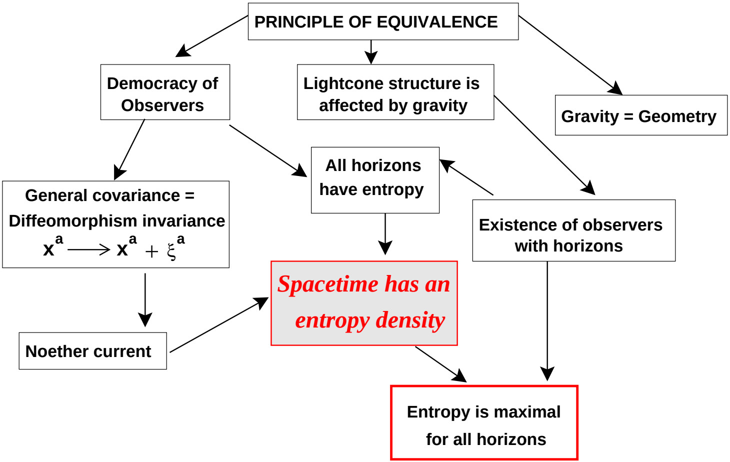
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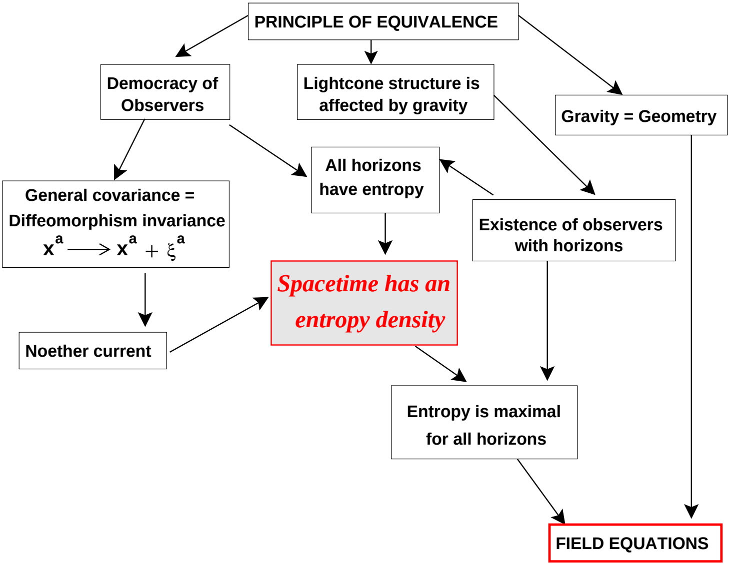
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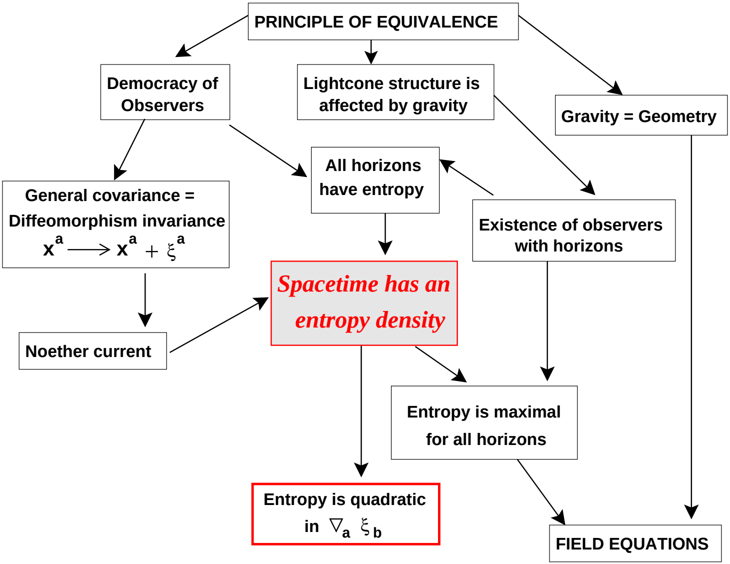
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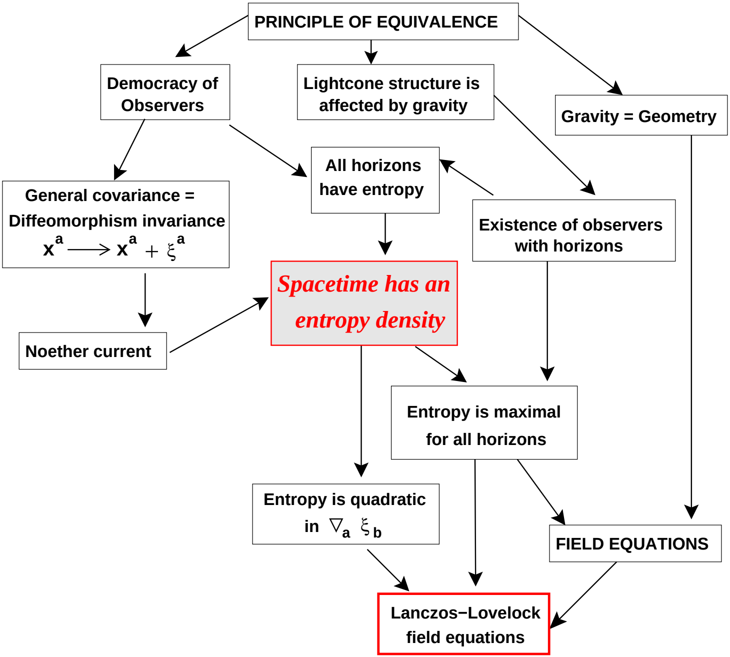
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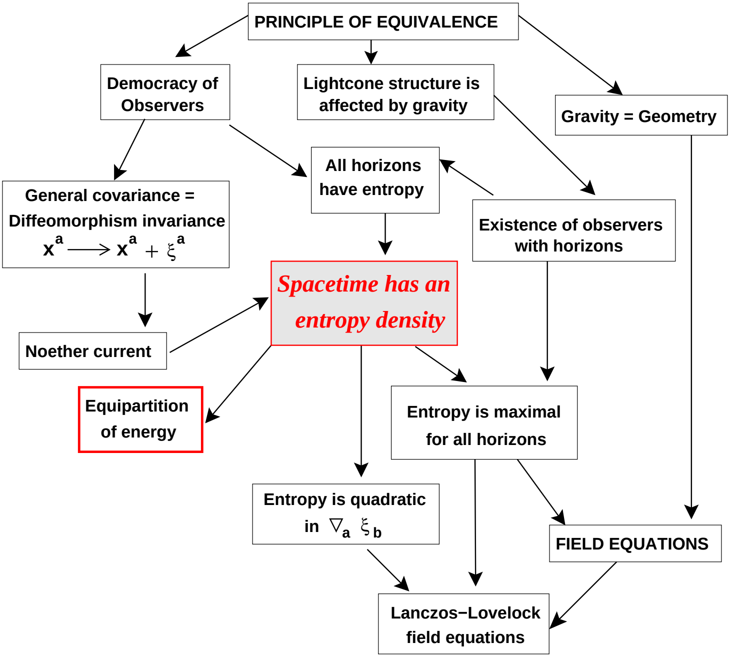
Lanczos−Lovelock field equations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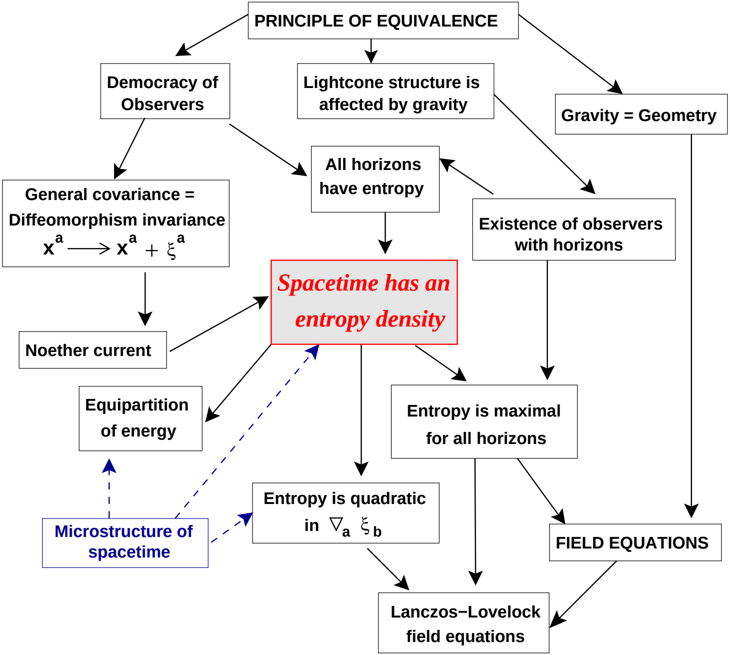
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- Null surfaces/vectors provides an effective, collective, description of microscopic physics at large scales.
- Gravity is 'holographic' in many ways.

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- Produce a falsifiable prediction. One would like to do better than usual QG candidate models!

REFERENCES

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ACKNOWLEDGEMENTS

Sunu Engineer	Suprit Singh	Ayan Mukhopadhyay
Dawood Kothawala	Krishna Parattu	Aseem Paranjape
Sudipta Sarkar	Bibhas Majhi	Donald Lynden-Bell
Sanved Kolekar		

THANK YOU FOR YOUR TIME!