What does classical gravity tell us about quantum structure of spacetime?

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CHANDRAYANA

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06 Jan 2011

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I will describe on the work by me and my collaborators.

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So for the ‘top-down’ view to work we need a strong guiding principle like the principle of equivalence.

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- LOOK FOR "INTERNAL EVIDENCE" IN CLASSICAL GRAVITY.

PLAN OF THE TALK

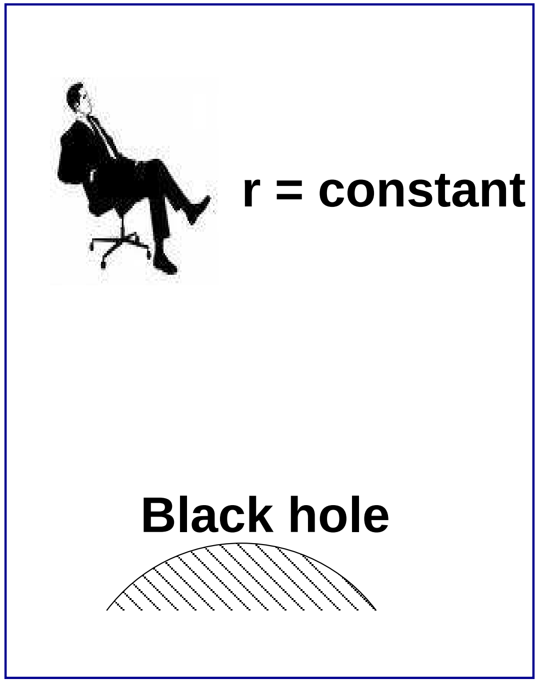
- THE CONVENTIONAL APPROACH TO GRAVITY AND HORIZON THERMODYNAMICS
- ‘INTERNAL EVIDENCE’ FOR AN ALTERNATIVE PERSPECTIVE
- THE AVOGADRO NUMBER OF SPACETIME
- GRAVITATIONAL DYNAMICS FROM A THERMODYNAMICAL EXTREMUM PRINCIPLE
- CONCLUSIONS, OPEN QUESTIONS ....

SPACETIMES, LIKE MATTER, CAN BE HOT

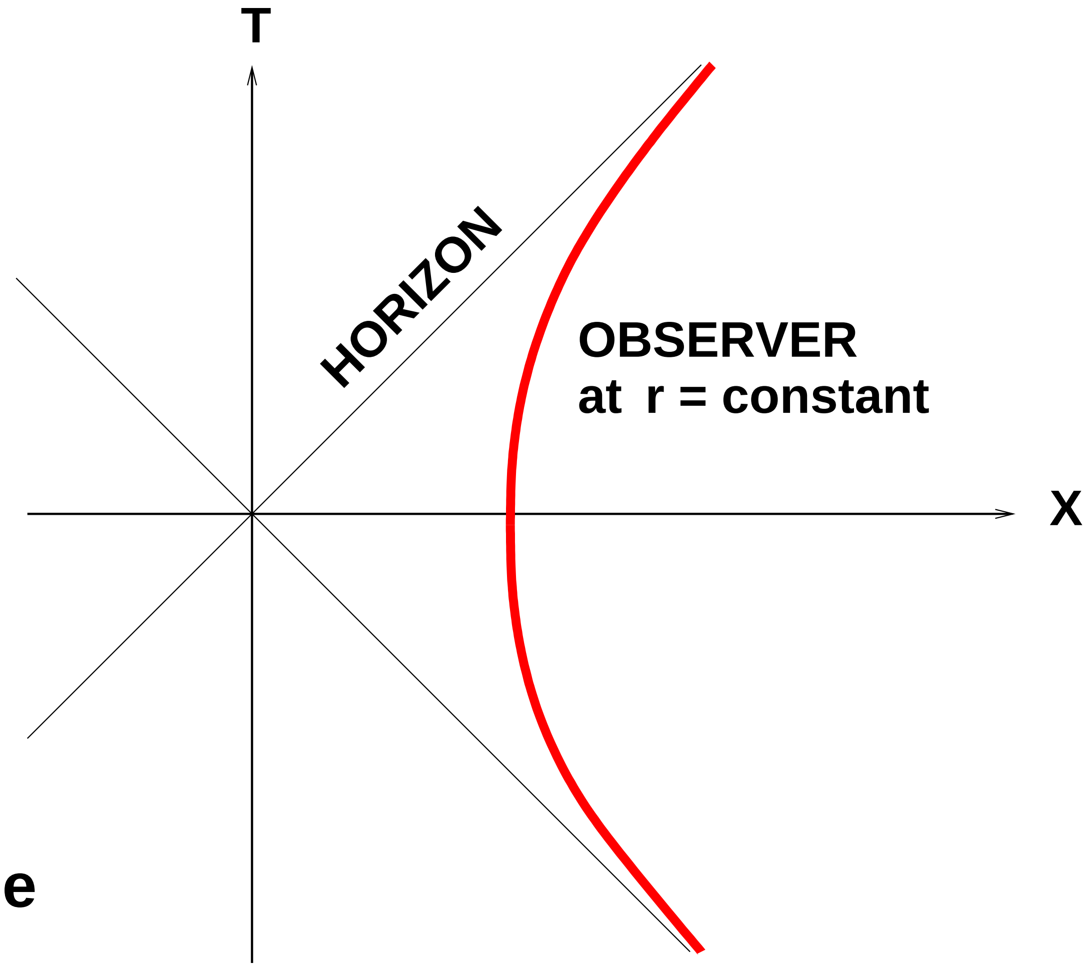
- *The connection between horizons and temperature is quite generic.*

OBSERVERS WHO PERCEIVE A HORIZON ATTRIBUTE TO IT A TEMPERATURE

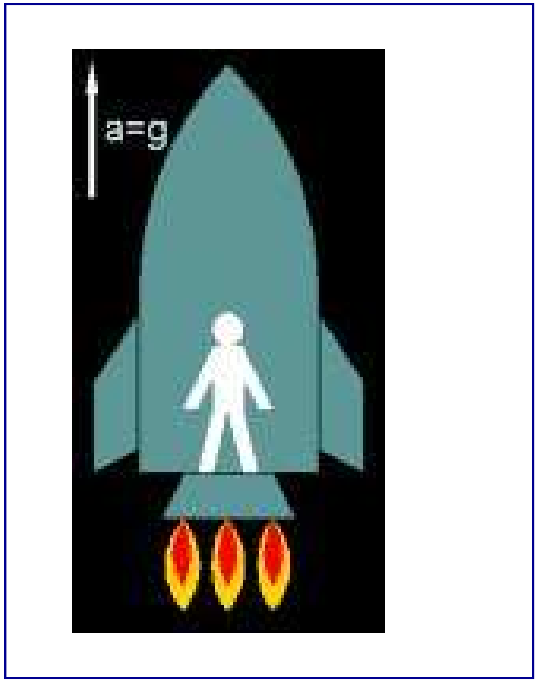
$$k_B T = \frac{\hbar}{c}\left(\frac{\kappa}{2\pi}\right)$$



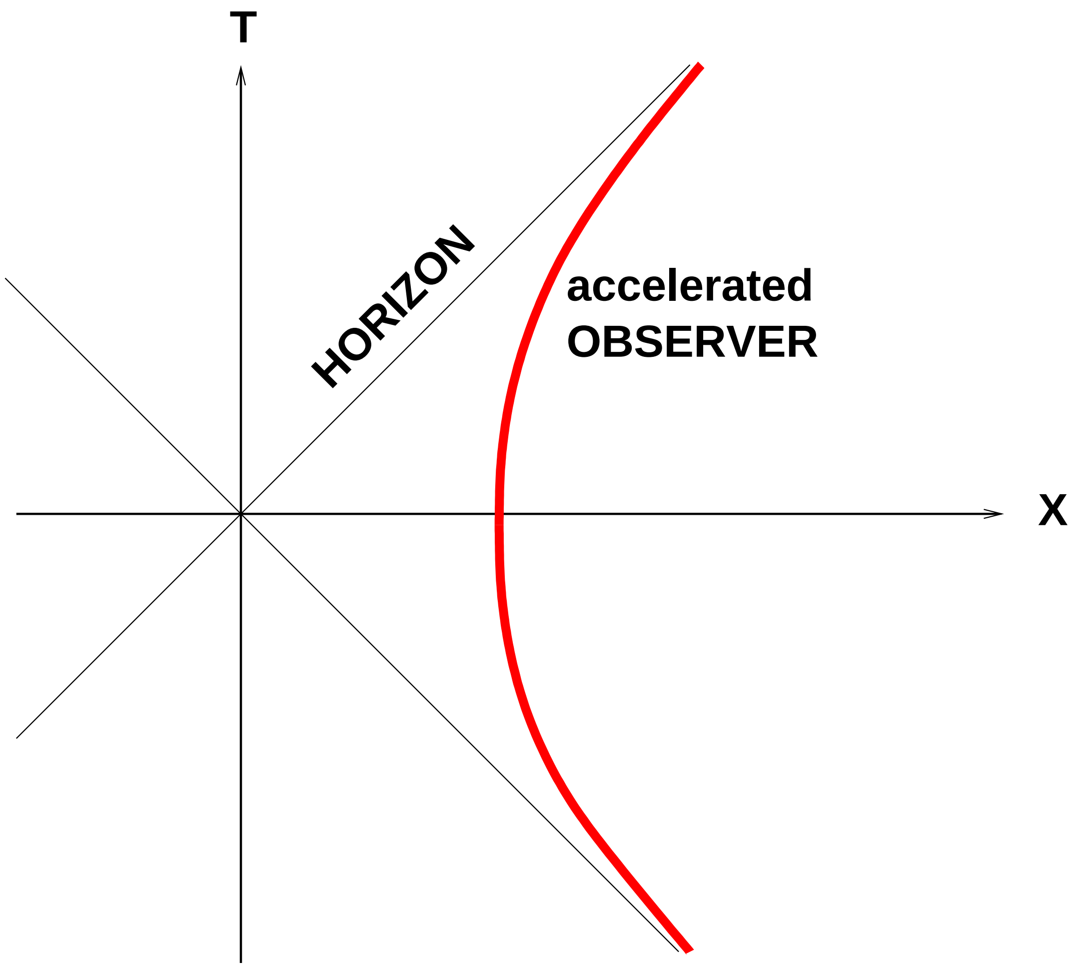
BLACK HOLE SPACETIME



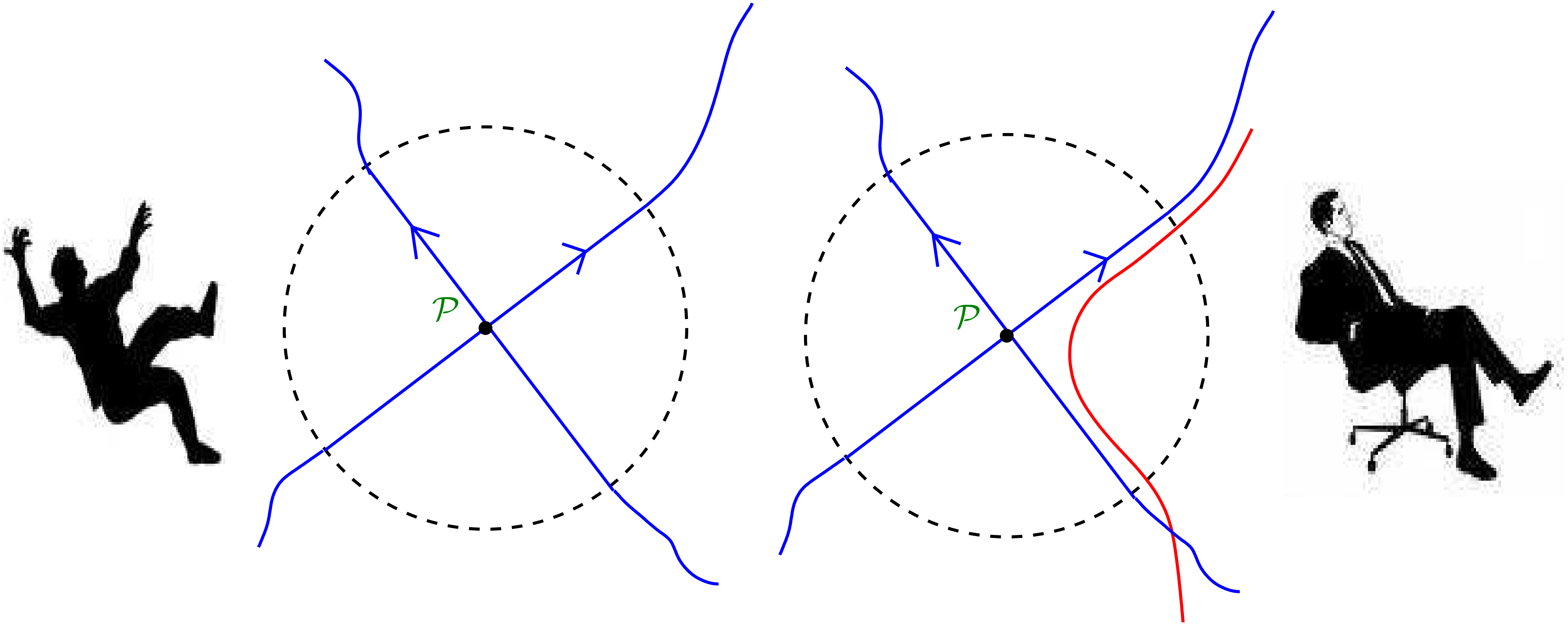
Temperature
$\propto$ acceleration
of the black hole



FLAT SPACETIME



Temperature
$\propto$ acceleration
of the observer



Vacuum state $\Longrightarrow$ Thermal state

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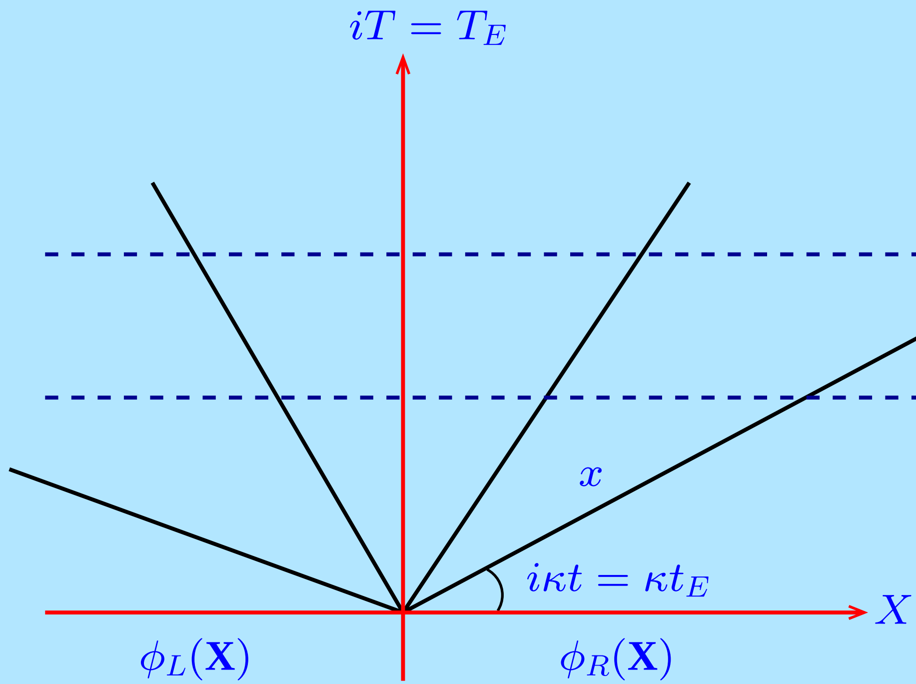

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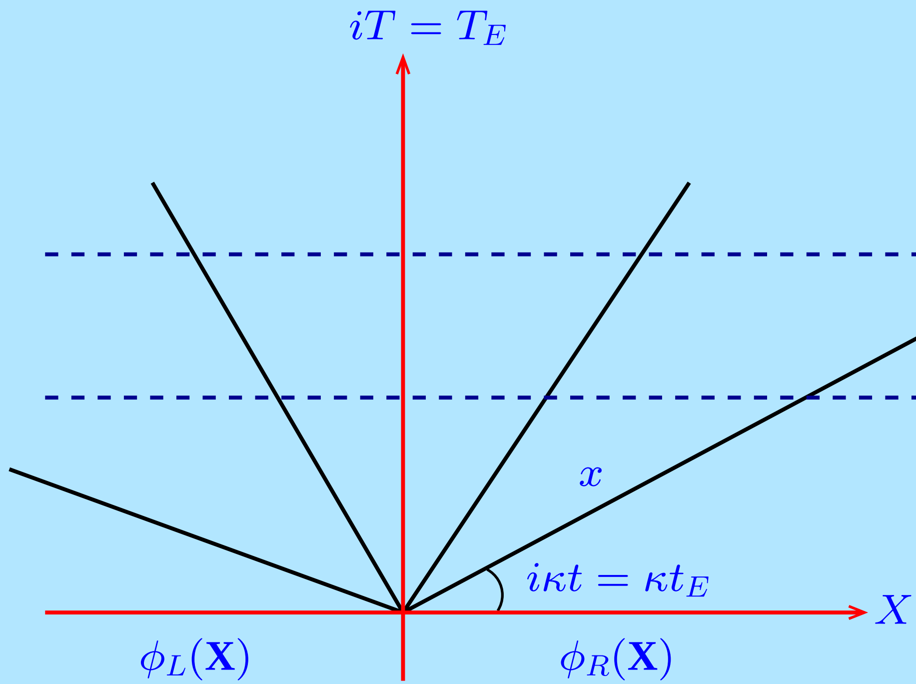

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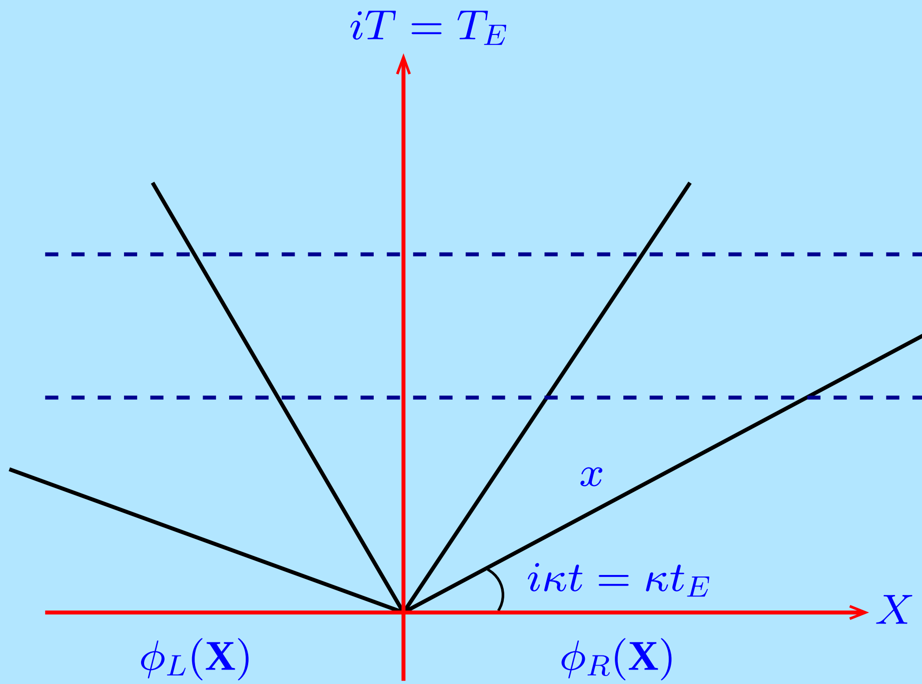

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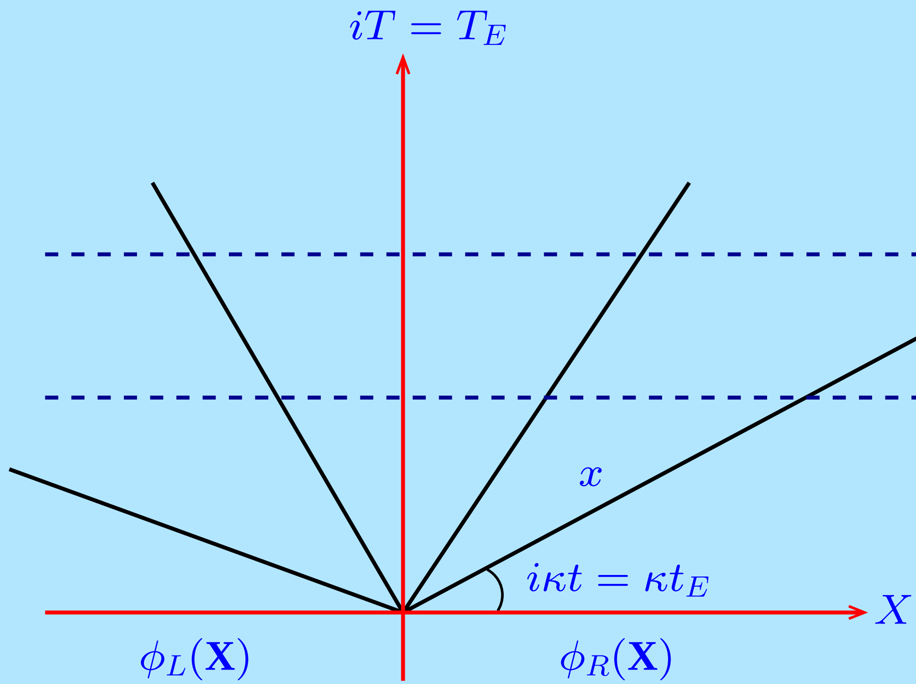

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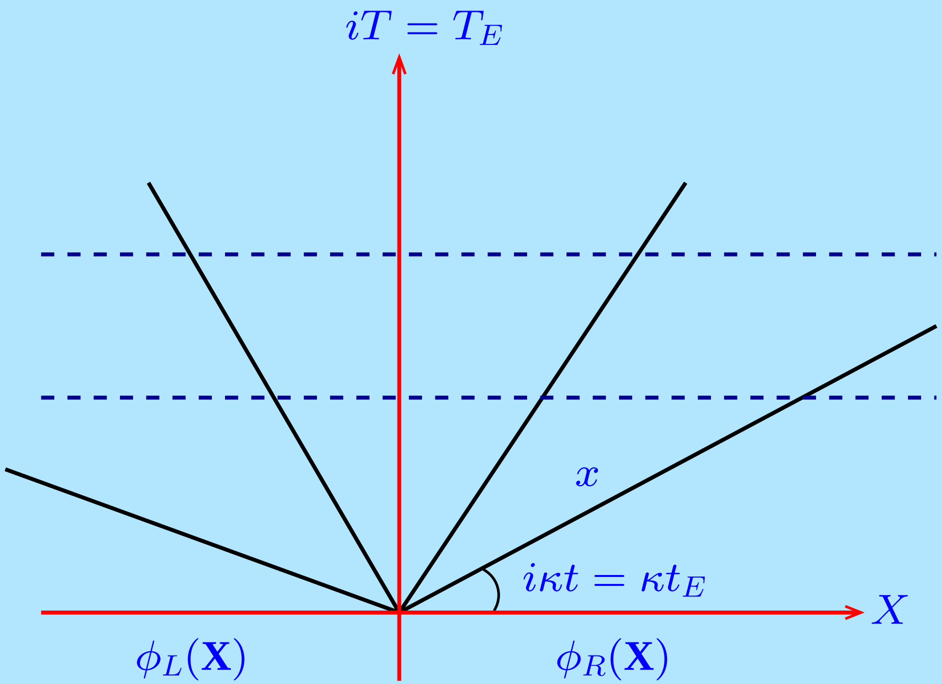

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- Tracing out ϕ_L gives a density matrix: (Lee, 1986)

$$\rho(\phi'_R,\phi_R) = \int \mathcal{D}\phi_L \langle \mathrm{vac}|\phi_L,\phi'_R\rangle\langle \mathrm{vac}|\phi_L,\phi_R\rangle \propto \langle \phi'_R|e^{-(2\pi/\kappa)H_R}|\phi_R\rangle$$

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- Shows spacetimes — like matter — can be hot in an observer dependent way.
- The entropy $S = -\mathrm{Tr}\ \rho \ln \rho$ is divergent and meaningless. QFT in CST can give temperature but not entropy!

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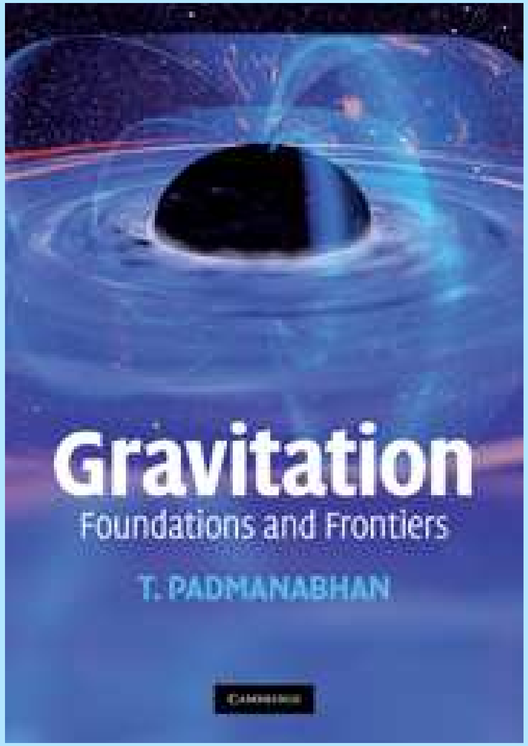

TEXT BOOK DESCRIPTION OF GRAVITY

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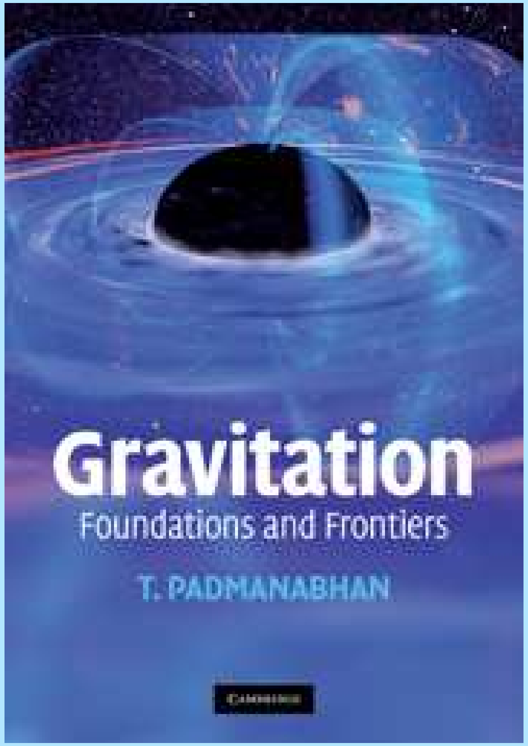

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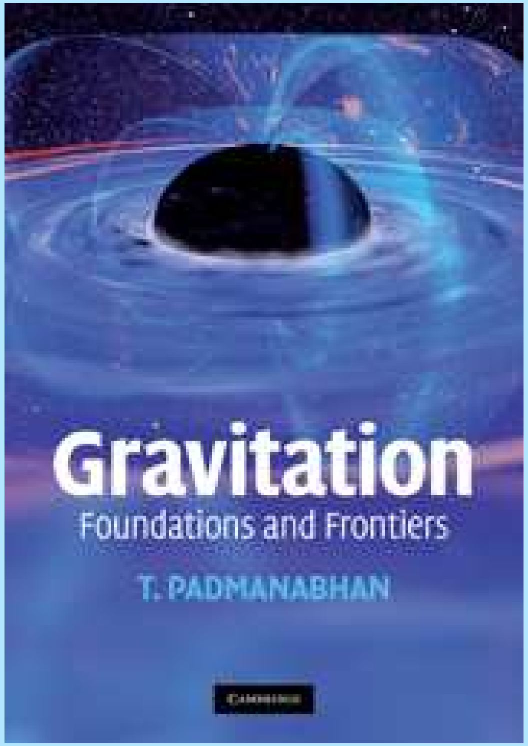

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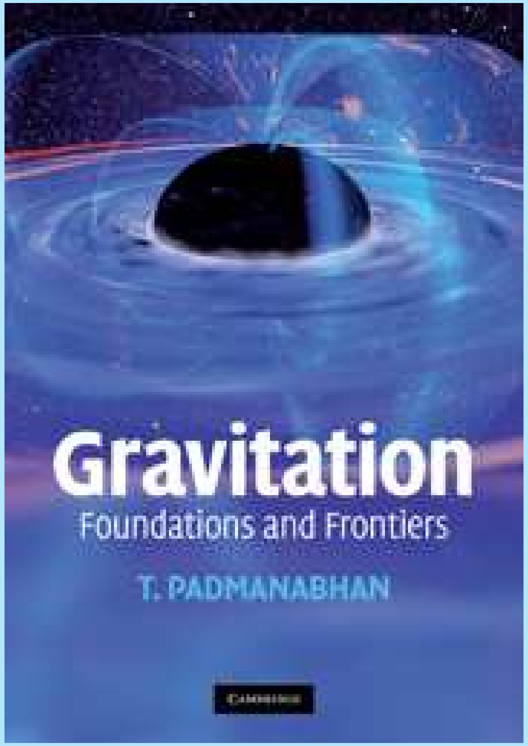
- Principle of Equivalence
- General Covariance
- Action functional (?)



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$$A = \int d^D x \sqrt{-g} \left[L(R^{ab}_{cd}, g^{ab}) + L_{matt}(g^{ab}, q_A) \right]$$

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- A "nice" class of theories: $\nabla_a P^{abcd} = 0$ for which

$$\mathcal{R}_{ab} - \frac{1}{2} L g_{ab} = (1/2) T_{ab}$$

- Horizons arise inevitably in the solutions to these field equations.

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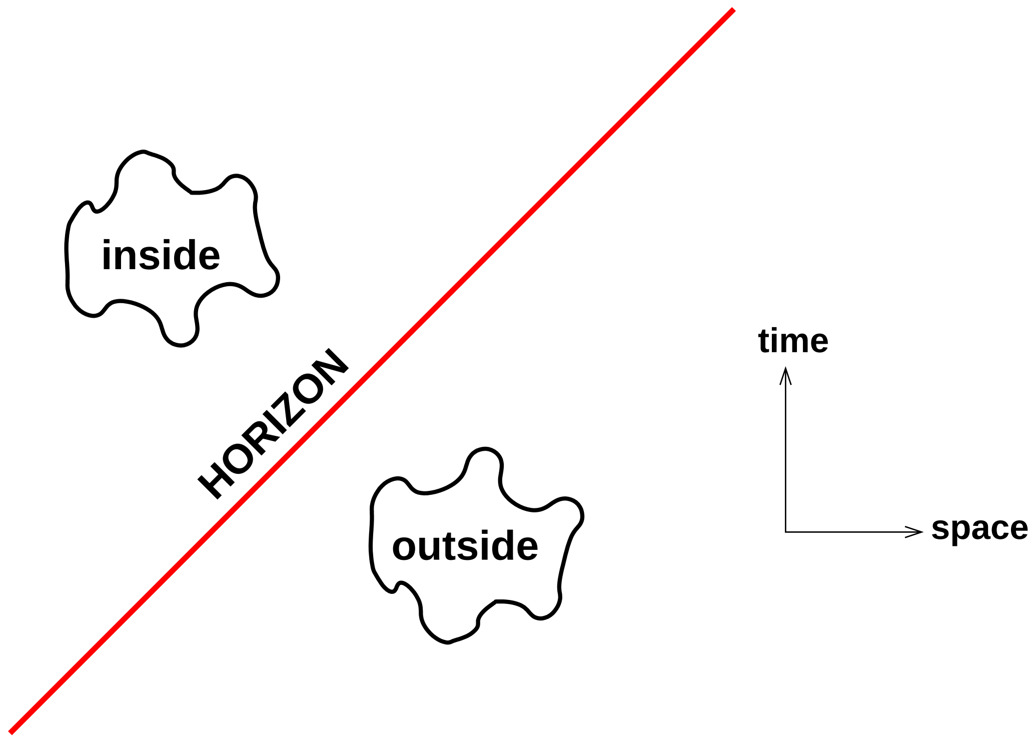

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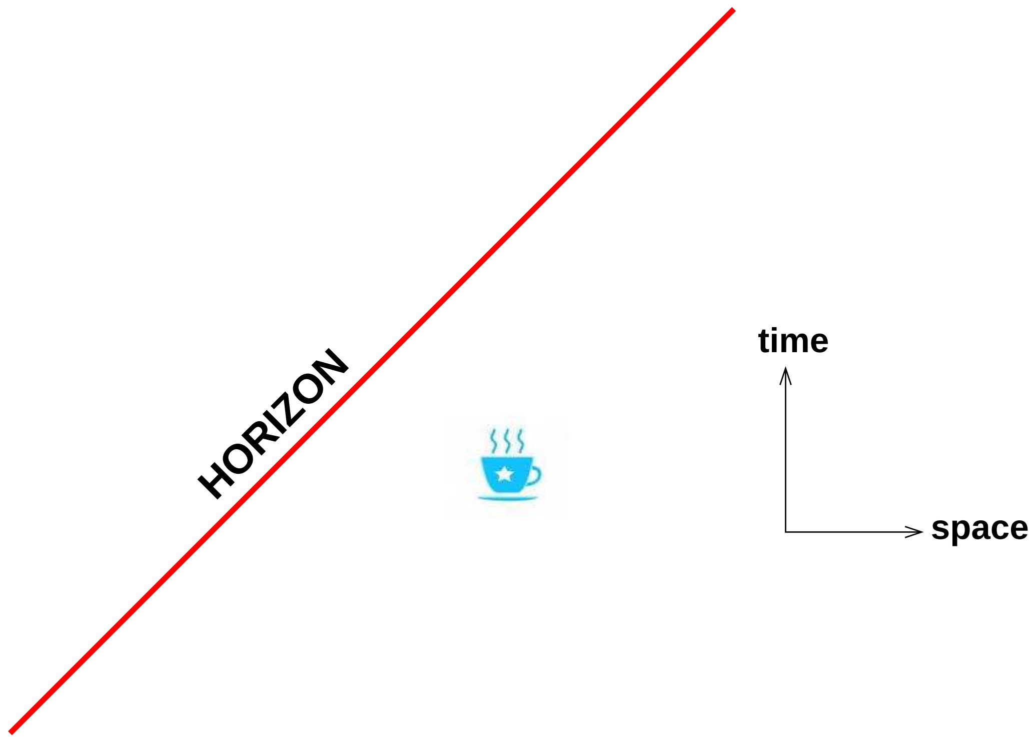

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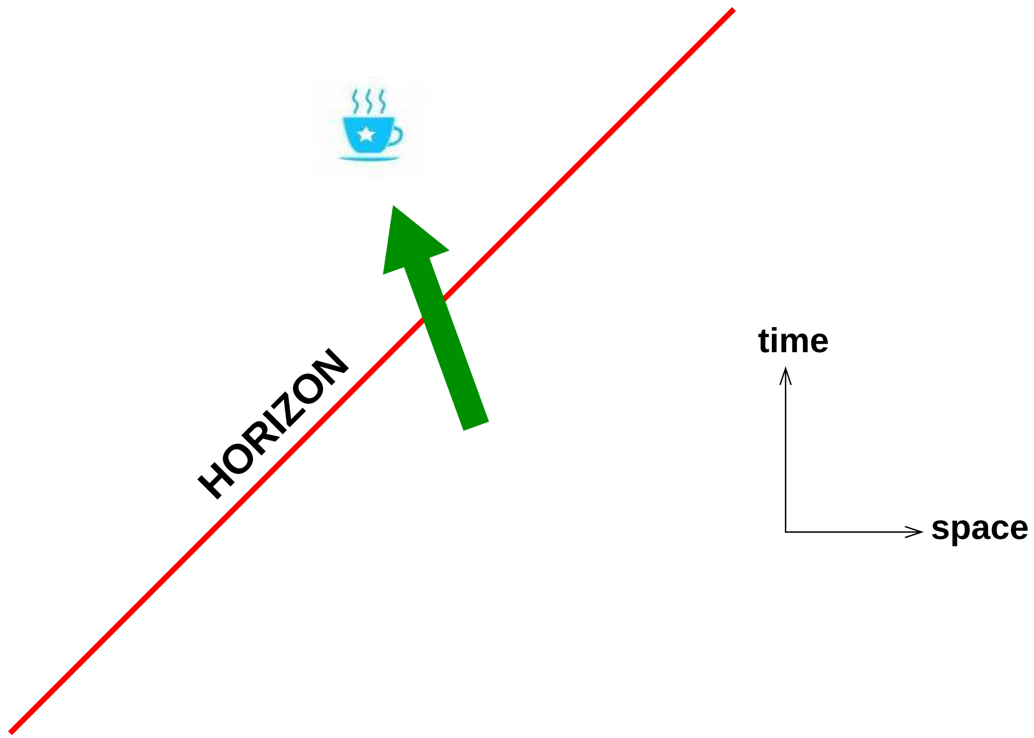

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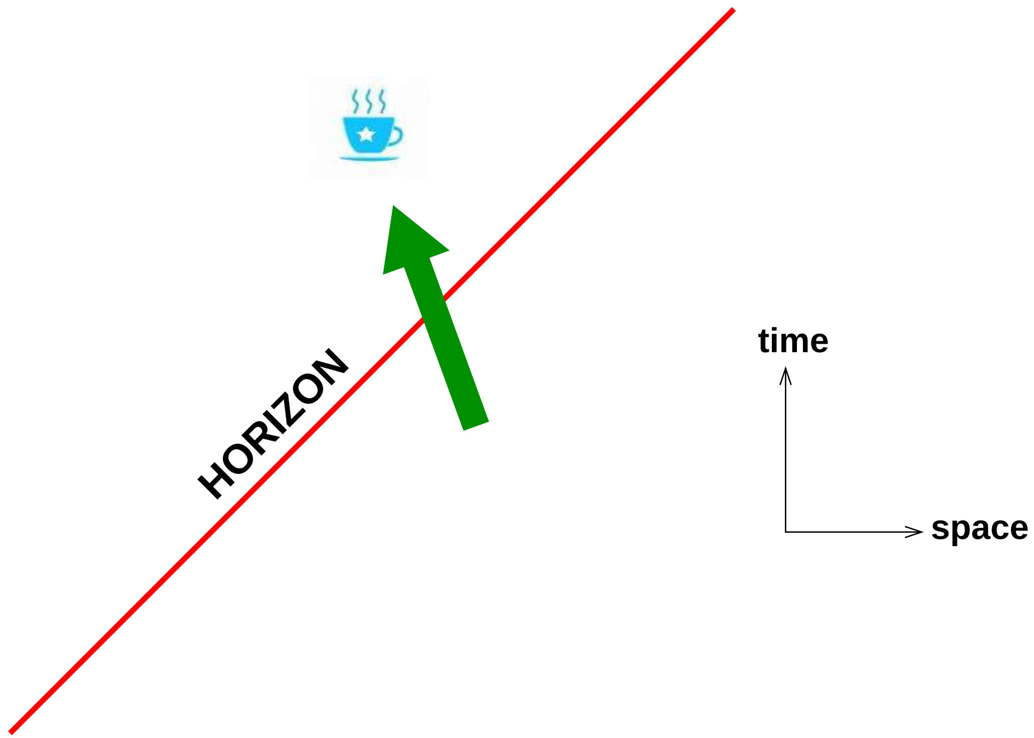

Wheeler ($\sim$ 1971): Can one violate second law of thermodynamics by hiding entropy behind a horizon ?

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

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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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Example: $m_{inertial} = m_{grav}$ is 'internal evidence' for geometrical nature of gravity.

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- Field equations become $TdS = dE + PdV$; with : (TP,02)

$$S = \frac{1}{4L_P^2}(4\pi a^2) = \frac{1}{4}\frac{A_H}{L_P^2}; \qquad E = \frac{c^4}{2G}a = \frac{c^4}{G}\left(\frac{A_H}{16\pi}\right)^{1/2}$$

HOLDS TRUE FOR A LARGE CLASS OF MODELS!

- Stationary axisymmetric horizons and evolving spherically symmetric horizons in Einstein gravity, [gr-qc/0701002]
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IN ALL THESE CASES FIELD EQUATIONS REDUCE TO $TdS = dE + PdV$ WITH CORRECT S!

IF GRAVITATIONAL DYNAMICS PERMITS AN ALTERNATIVE DESCRIPTION SHOULD NOT GRAVITATIONAL ACTION FUNCTIONAL CONTAIN A HINT OF THIS ?

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

- Example of ‘holography in action’: The classical mechanics action is:

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- Information is duplicated in $L_{\rm bulk}$ and $L_{\rm sur}$!

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

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- If J^{ab} is the Noether potential for $q^a = (1, \mathbf{0})$ in a static spacetime, then

$$\sqrt{-g}L = -\underbrace{2\sqrt{-g}\mathcal{G}^0_0}_{\text{bulk term}} + \underbrace{\partial_\alpha \left(\sqrt{-g}\, J^{0\alpha}\right)}_{\text{surface term}}$$

HOW COME GRAVITATIONAL DYNAMICS ALLOWS A THERMODYNAMIC INTERPRETATION ?

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GRAVITY IS AN EMERGENT PHENOMENON INVOLVING THERMODYNAMIC DESCRIPTION OF MICROSCOPIC SPACETIME DEGREES OF FREEDOM

YOU CAN HEAT UP GAS

Boltzmann Postulate: If you can heat it, it has microstructure!

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- Boltzmann postulated microscopic degrees of freedom and connected the thermodynamical variables to mechanical variables of these d.o.f.
- Key new ingredient: Boltzmann postulate related thermodynamics to mechanics of microstructure.

The equipartition law

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

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

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- Elastic constants, gas density, pressure etc are useful variables in the thermodynamic limit. Metric, curvature etc. have a similar status in the description of spacetime.
- Entropy of a gas is related to the degrees of freedom which are ignored. Entropy of spacetime is related to unobservable degrees of freedom for a given observer.

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IF SO, CAN WE DETERMINE n?

EQUIPARTITION OF MICROSCOPIC DEGREES OF FREEDOM

TP, *Class.Quan.Grav.*, **21**, 4485 (2004); TP, 0912.3165; Phys.Rev., **D 81**, 124040 (2010)

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$$E = \frac{1}{2}k_B \int_{\partial\mathcal{V}} \underbrace{\frac{\sqrt{\sigma}\, d^2x}{L_P^2}}_{\text{Area `bits'}} \underbrace{\left\{\frac{N a^\mu n_\mu}{2\pi}\right\}}_{\substack{\text{acceleration}\\ \text{temperature}}} \equiv \frac{1}{2}k_B \int_{\partial\mathcal{V}} dn\, T_{\rm loc}$$

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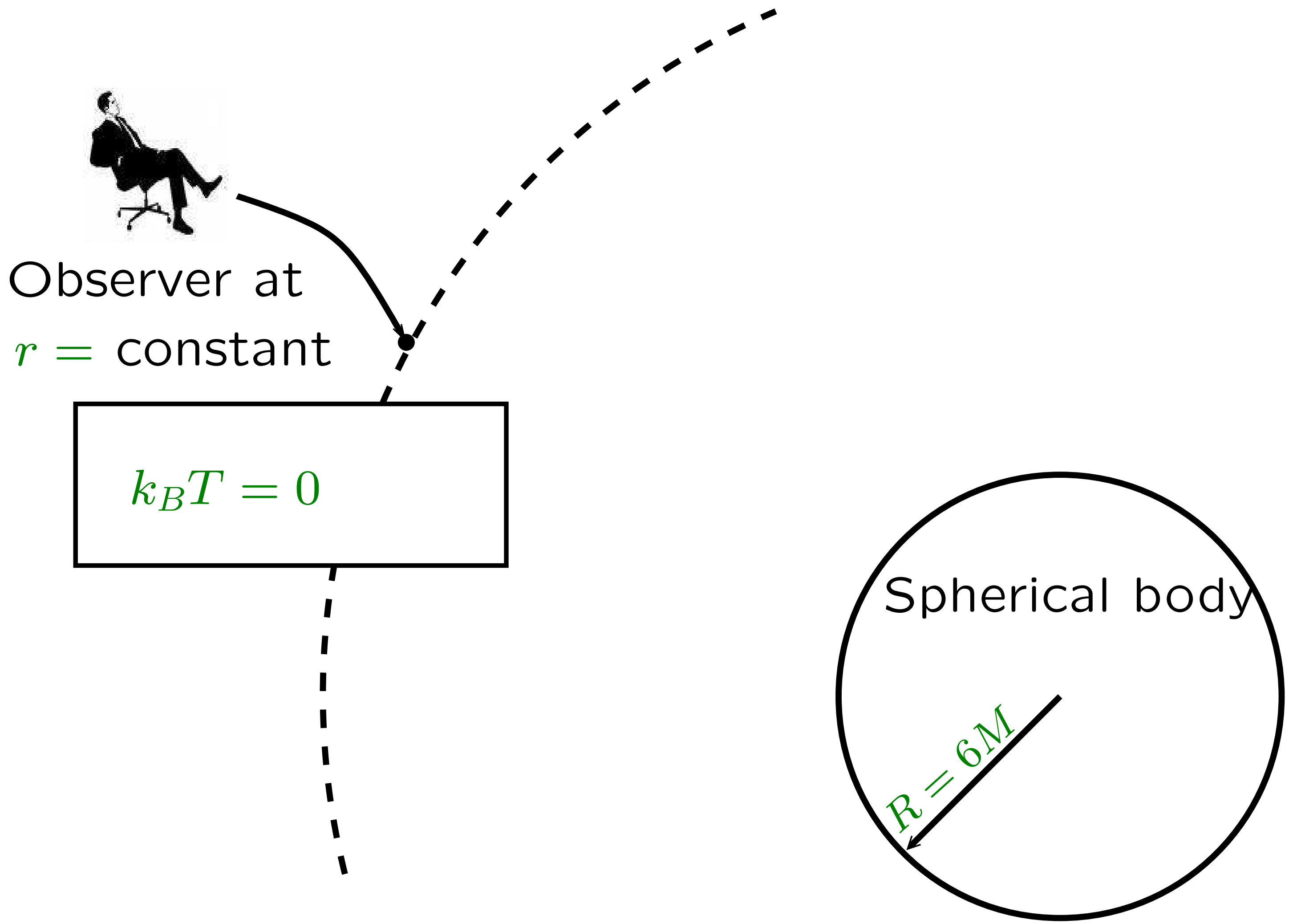
- Result generalizes to any Lanczos-Lovelock model:

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

HEATING UP A SPACETIME



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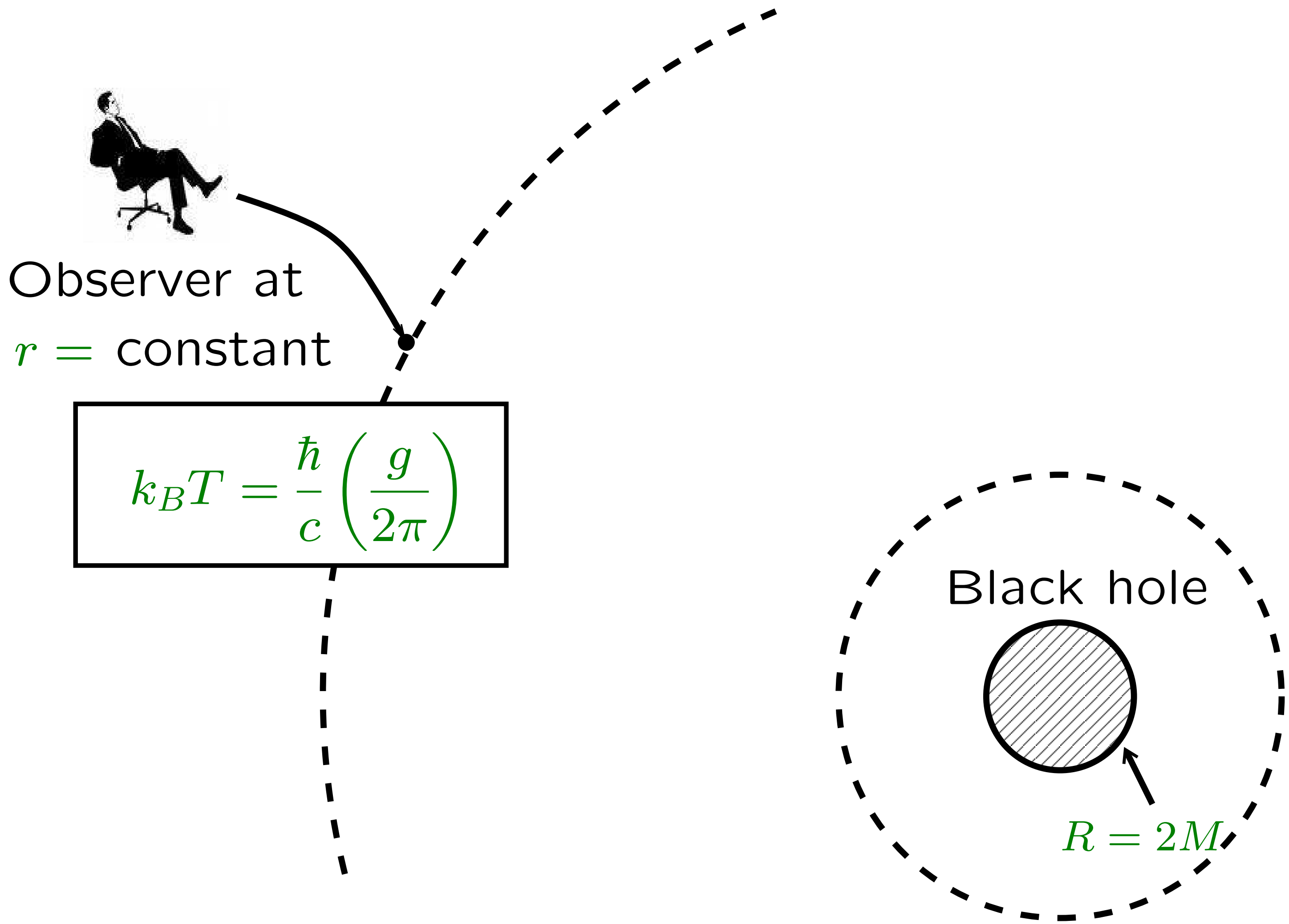

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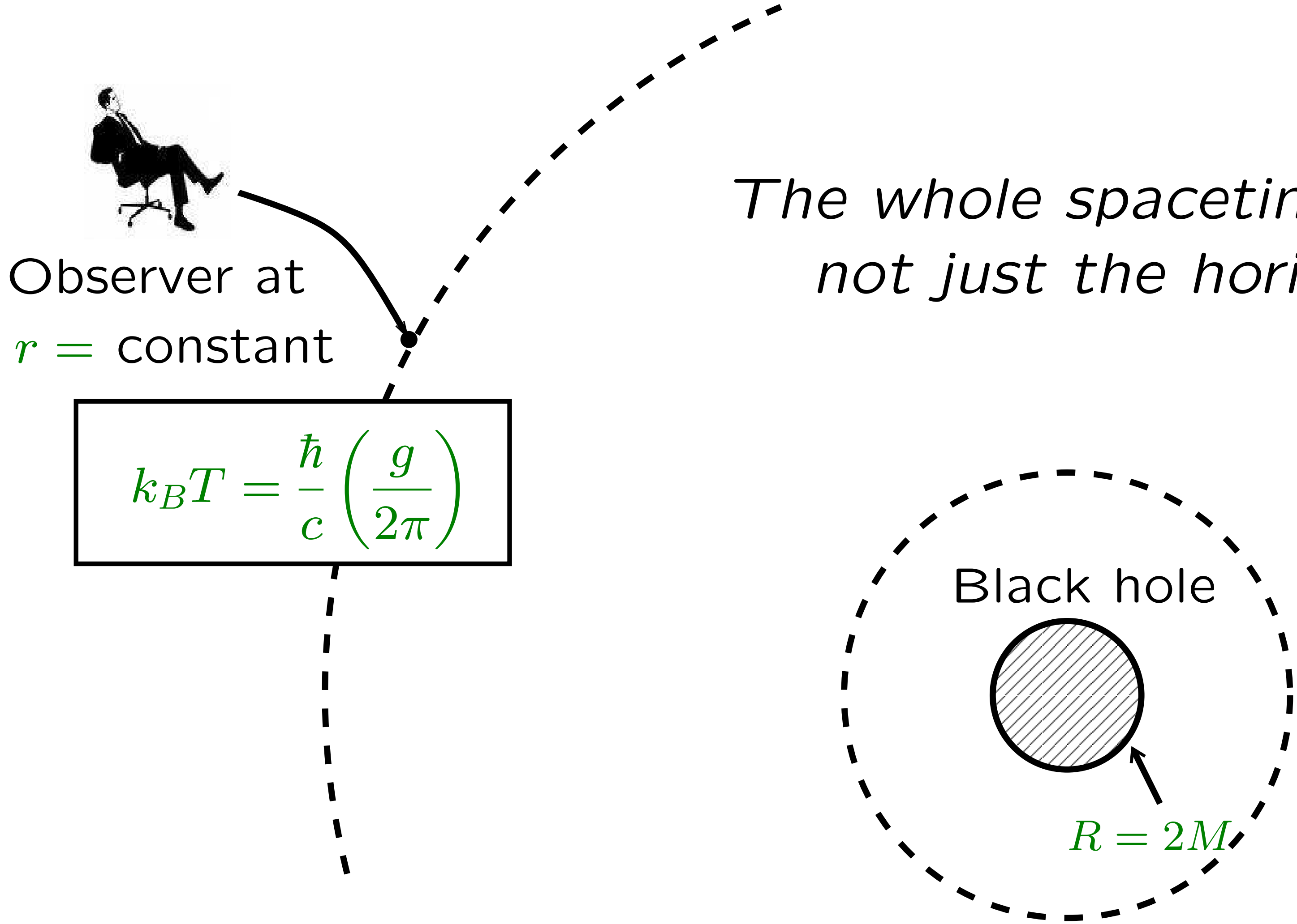

The whole spacetime is hot;
not just the horizon

EQUIPARTITION OF “AREA BITS”: $S = (1/2)\beta E$

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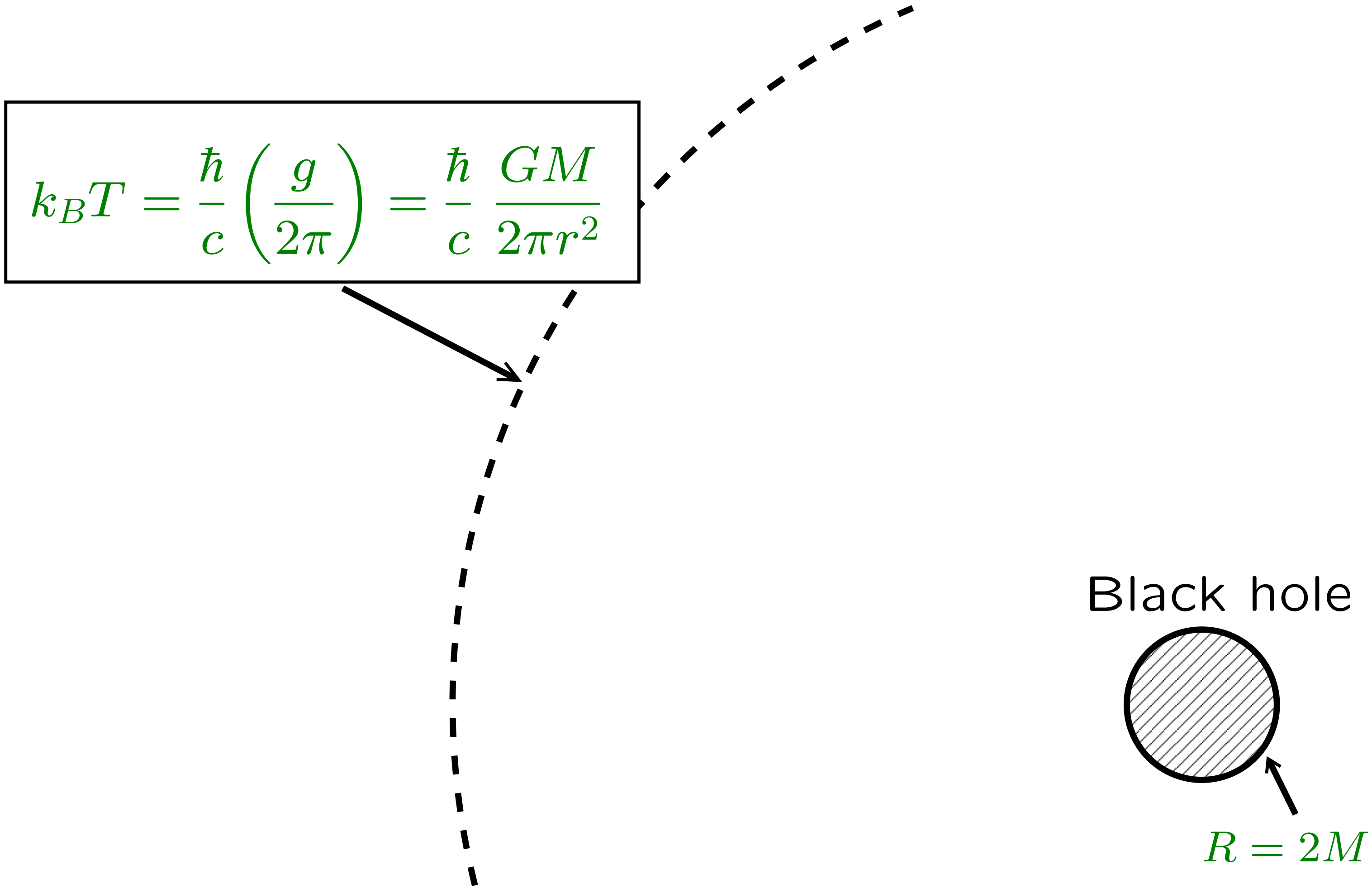

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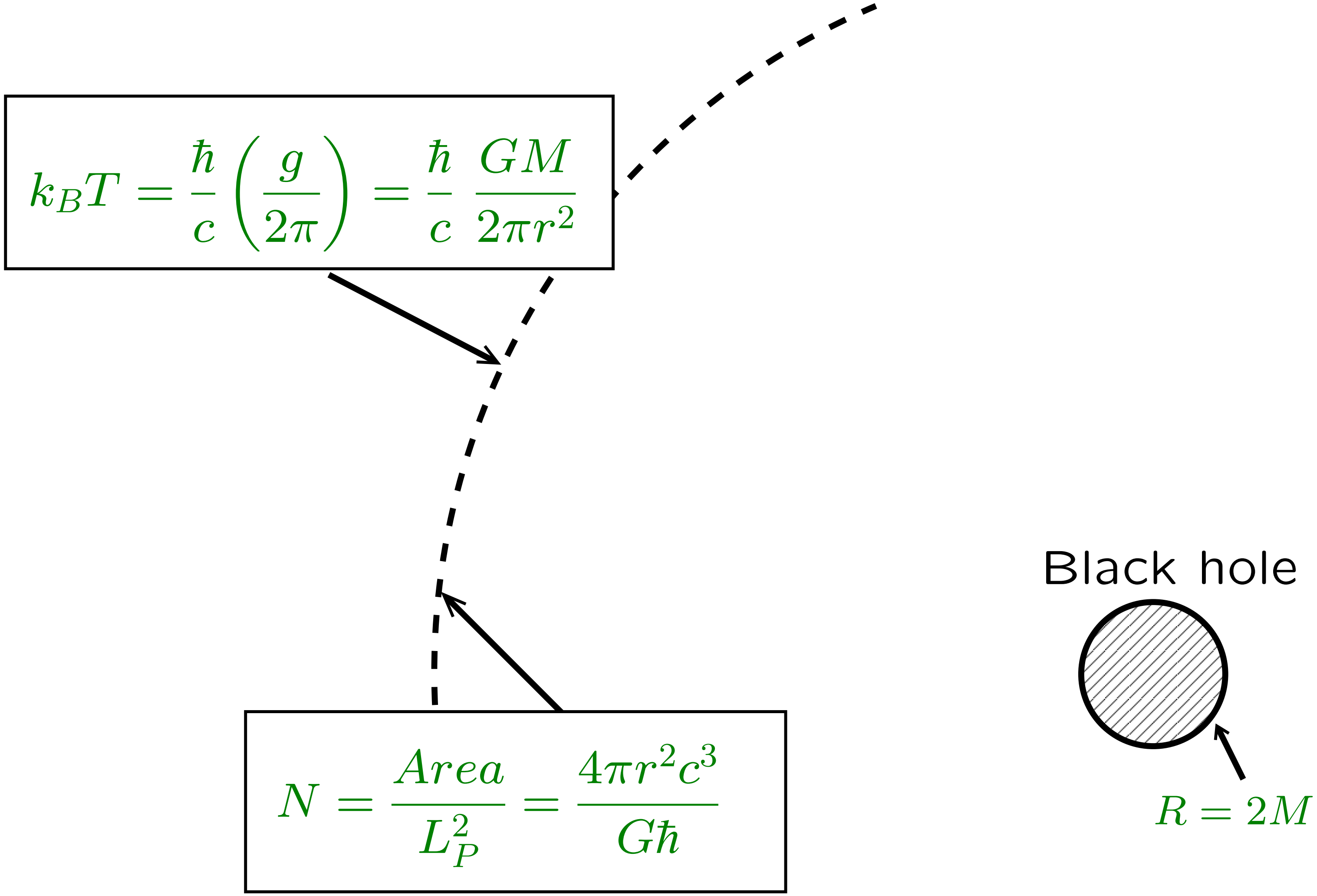

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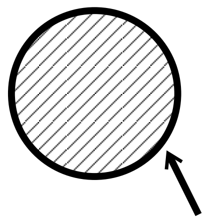
$$k_B T = \frac{\hbar}{c}\left(\frac{g}{2\pi}\right) = \frac{\hbar}{c}\,\frac{GM}{2\pi r^2}$$

$$N = \frac{Area}{L_P^2} = \frac{4\pi r^2 c^3}{G\hbar}$$

$$\mathcal{E} = \frac{1}{2}N(k_B T) = \frac{1}{2}\left(\frac{4\pi r^2 c^3}{G\hbar}\right)\left(\frac{\hbar}{c}\,\frac{GM}{2\pi r^2}\right)$$
$$= Mc^2$$

Black hole



$R = 2M$

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Can the system be hot?	Yes	Yes

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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 $(S, F, ...)$

THERMODYNAMICS OF SPACETIME

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- The nature of independent variables q_A and the form of $\Im[q_A]$ depend on the class of observers and the model for gravity. New level of observer dependence.
- We need a thermodynamical potential $\Im[q_A]$ for spacetime extremising which for all class of observers should give the field equations.

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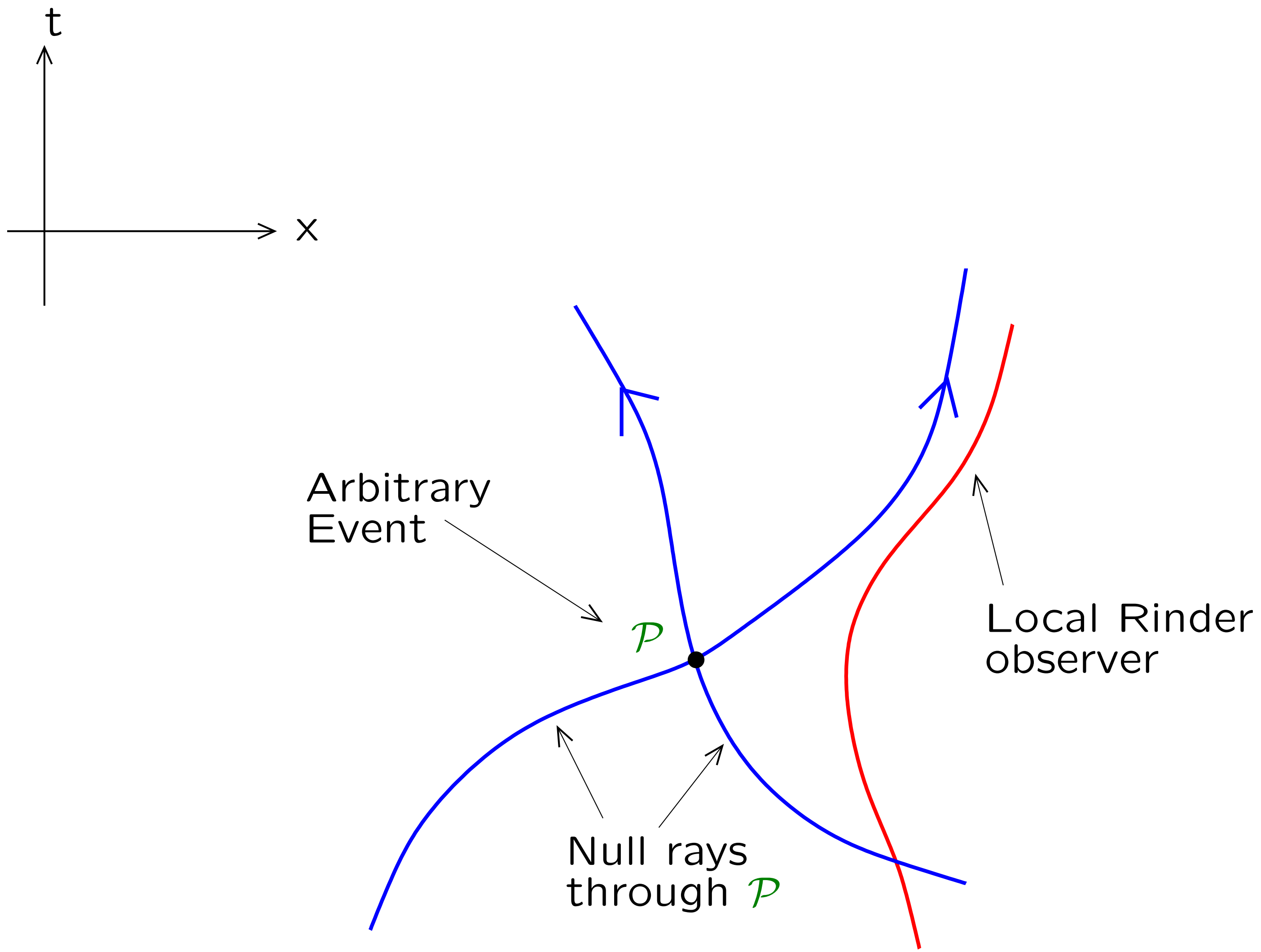
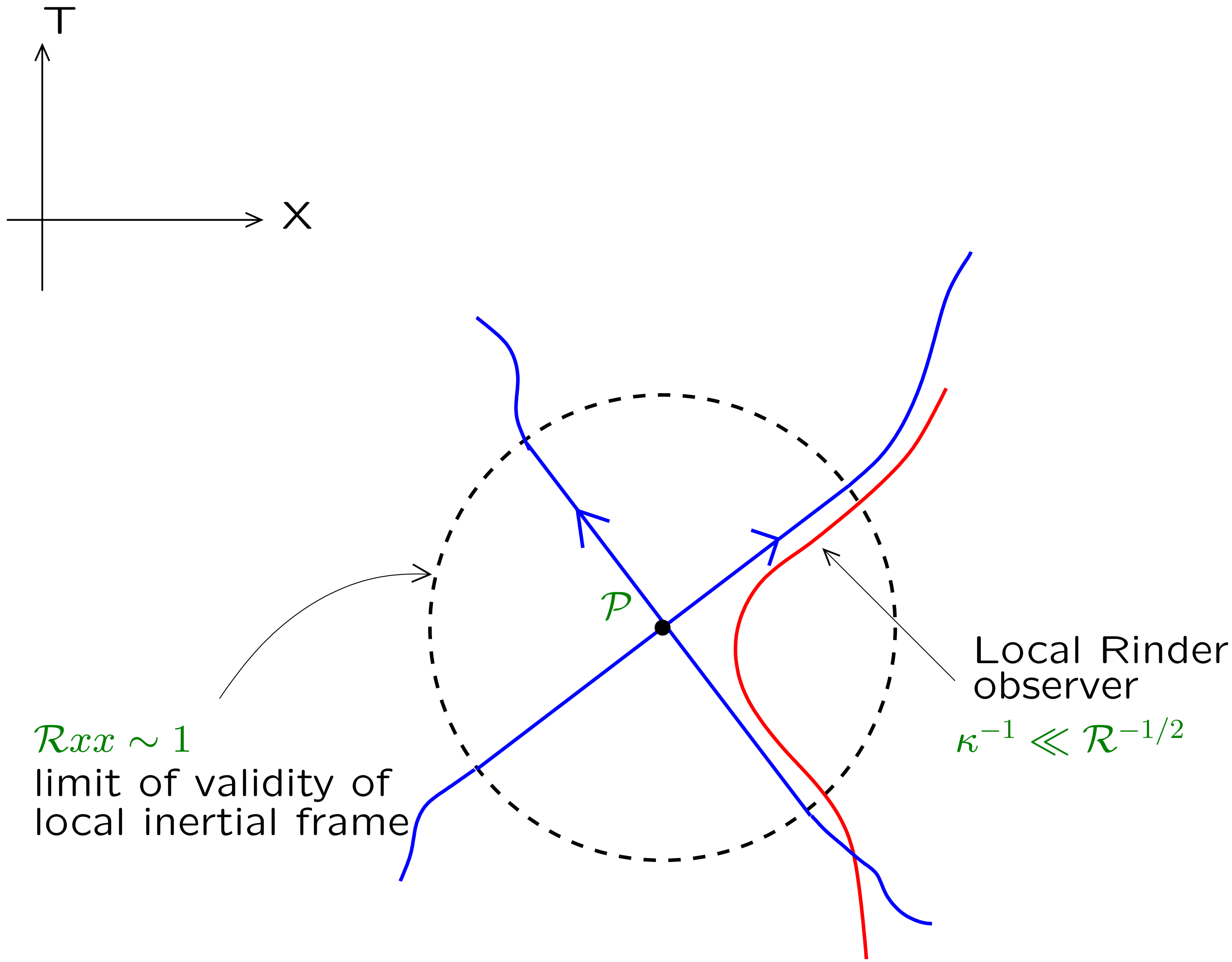


t
x
Arbitrary
Event
$\mathcal{P}$
Local Rinder
observer
Null rays
through $\mathcal{P}$



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$\kappa^{-1} \ll \mathcal{R}^{-1/2}$
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limit of validity of
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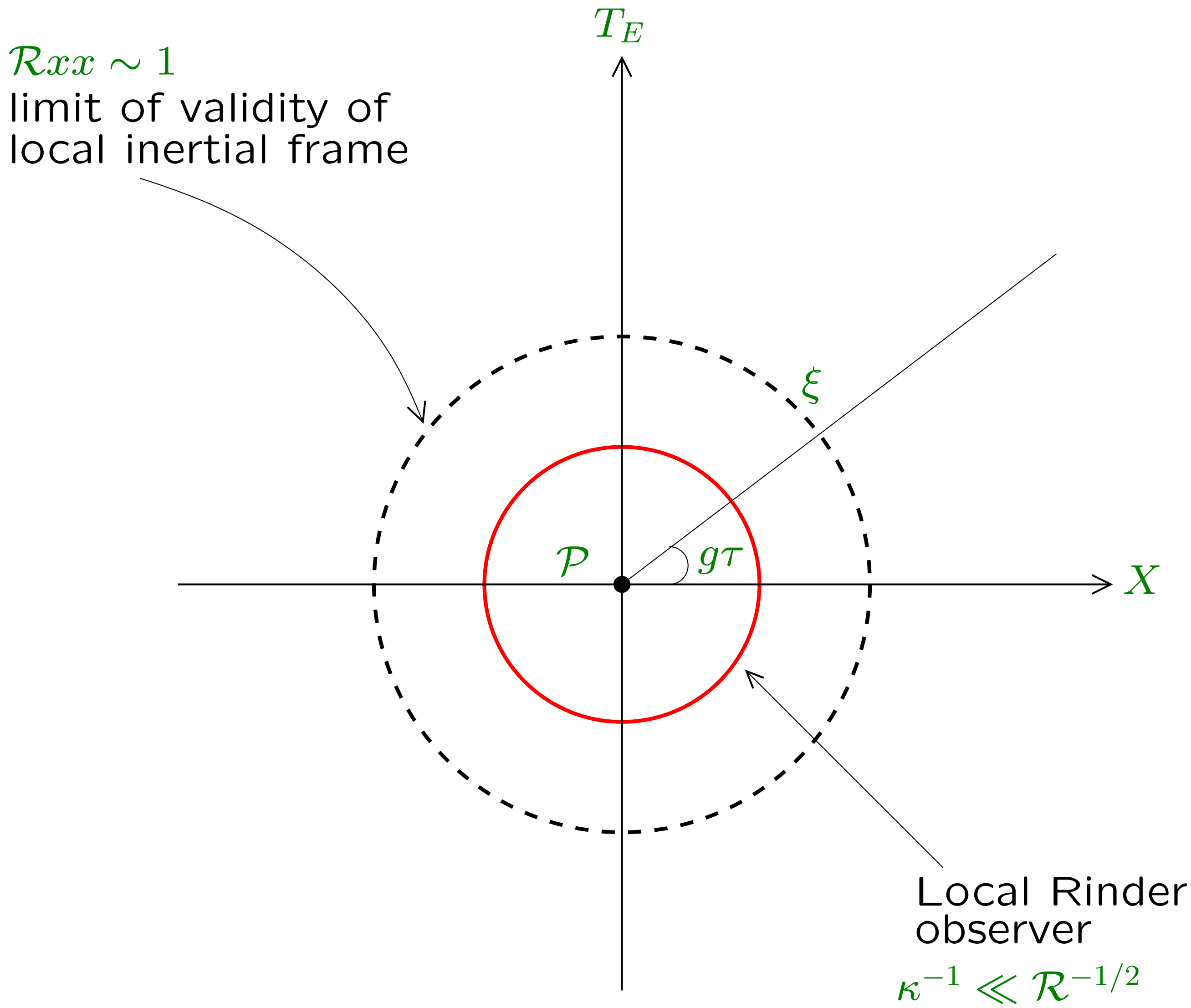
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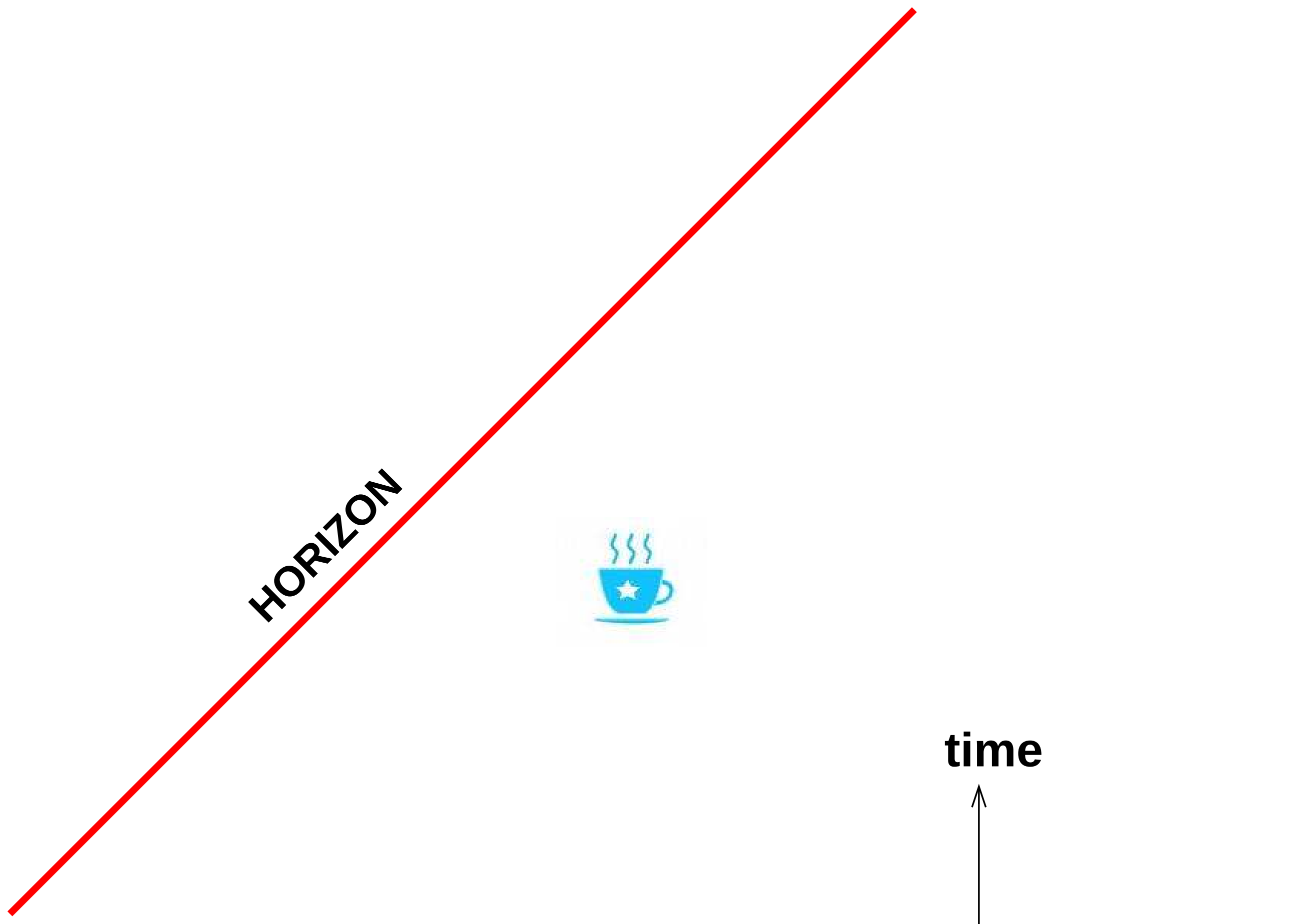
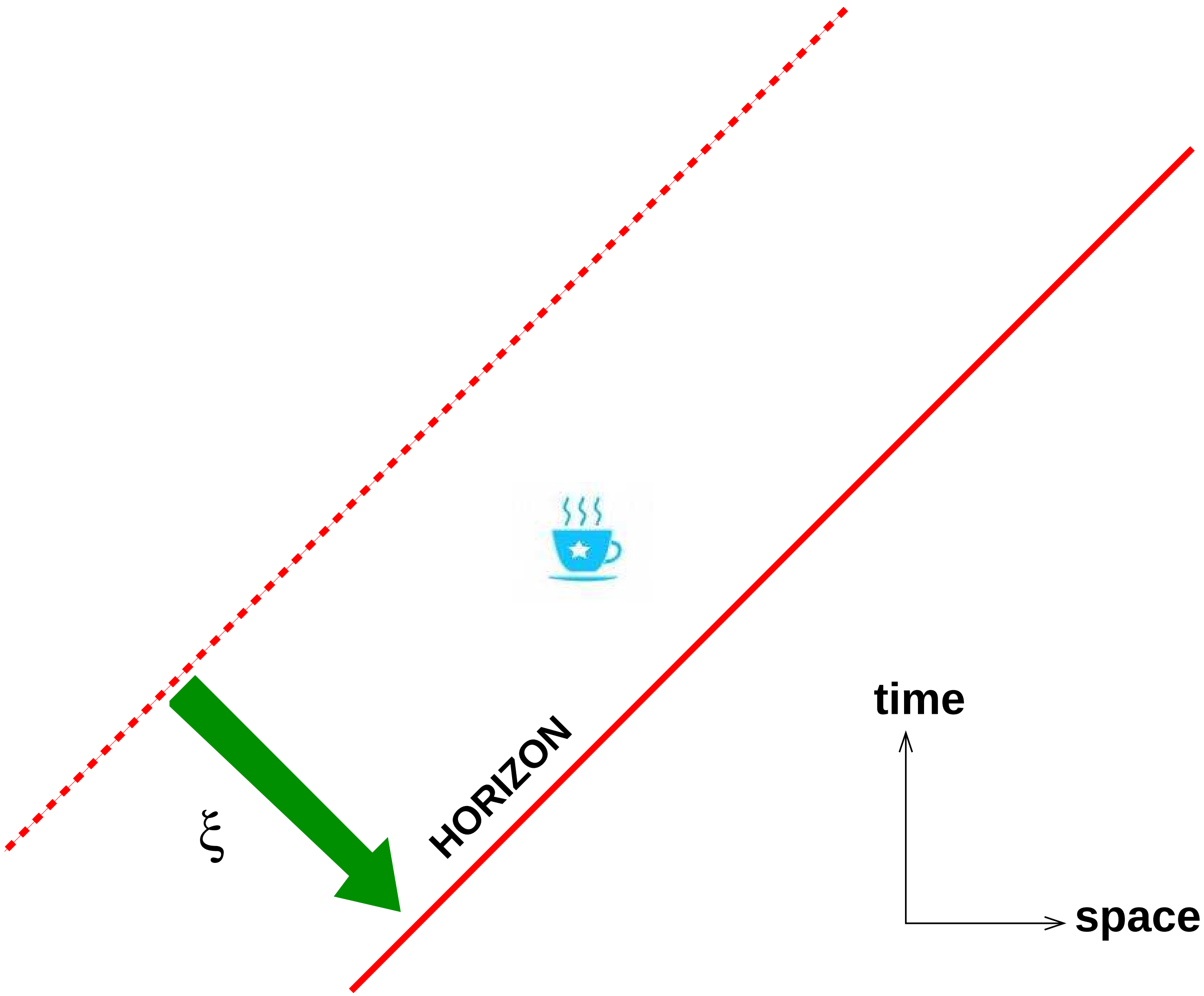

HORIZON
time
space



time
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GRAVITY – THE 'RIGHT WAY UP'

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- Structure:

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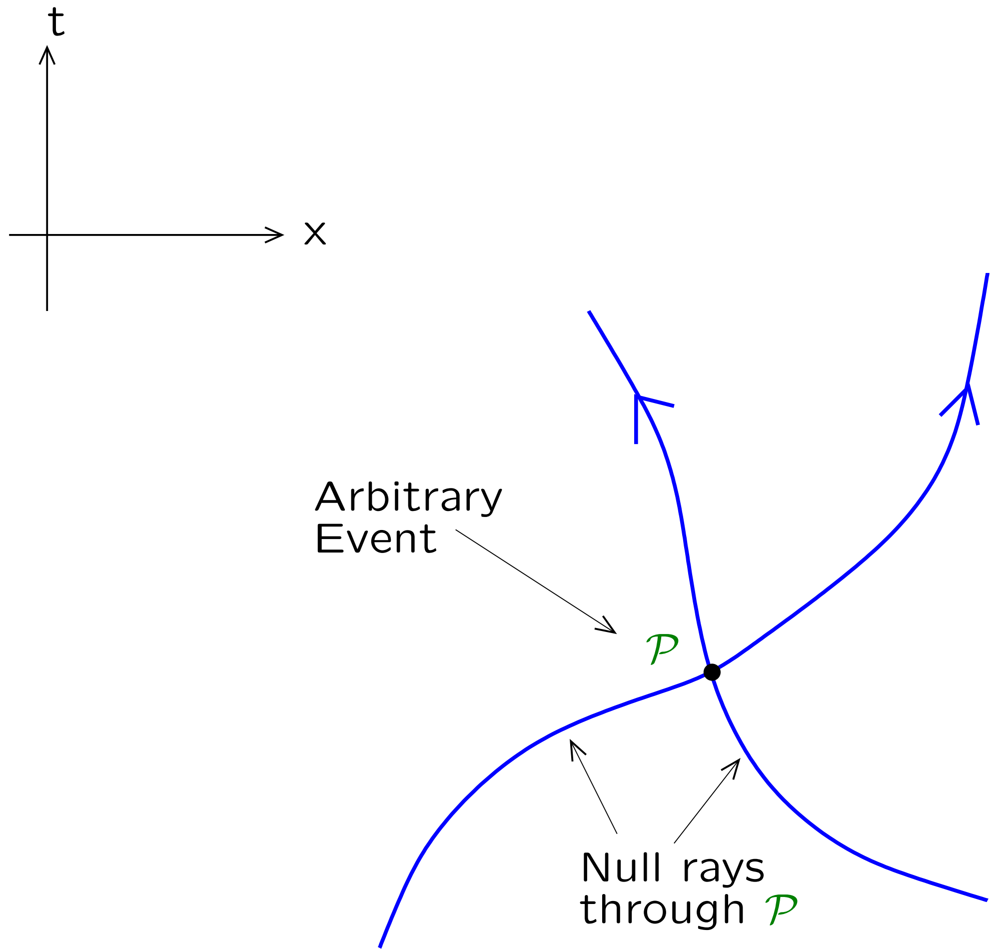
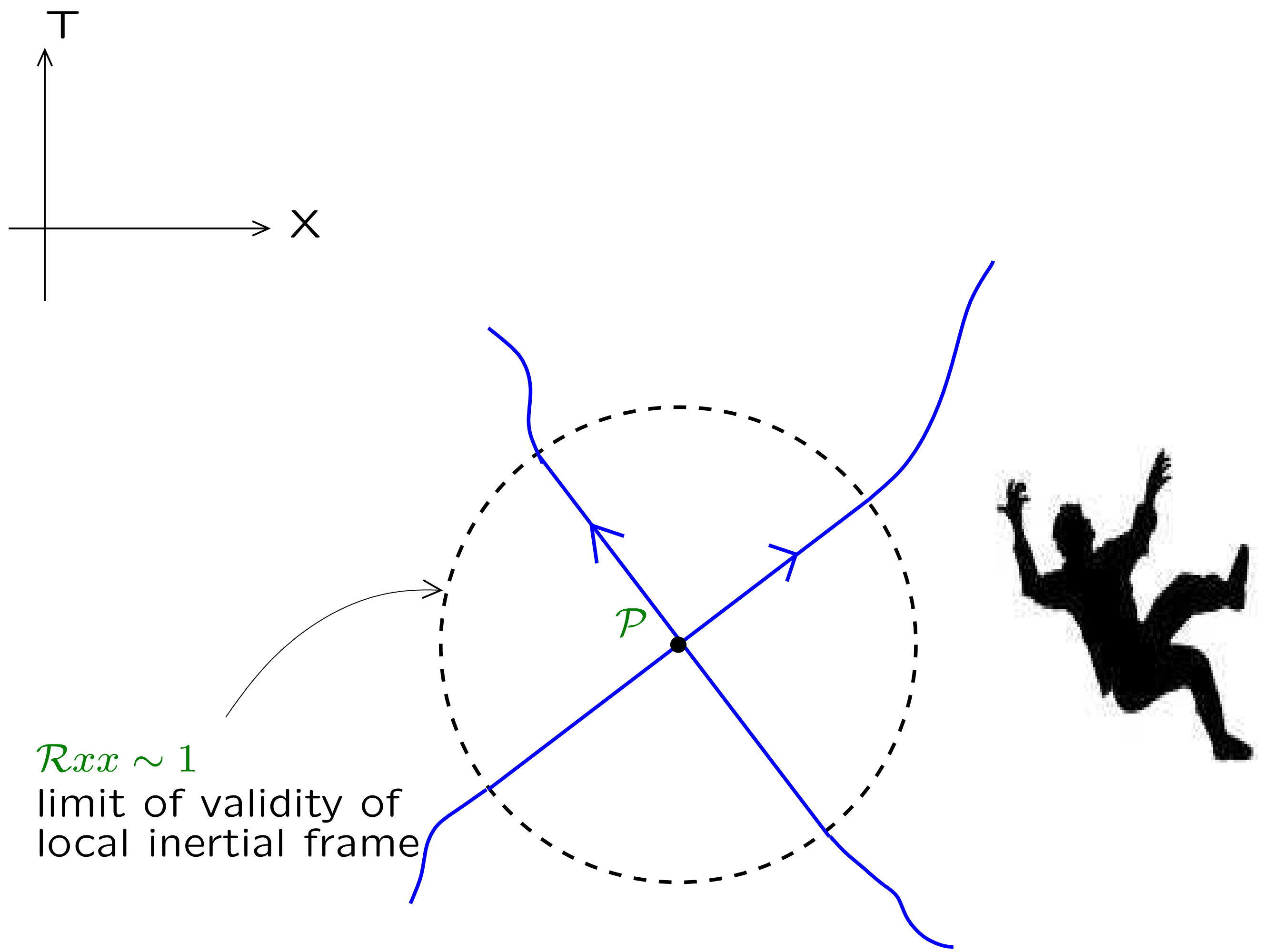
$$\text{Local Rindler frames} \Rightarrow \text{Dynamics of Gravity}$$

SPACETIME IN ARBITRARY COORDINATES

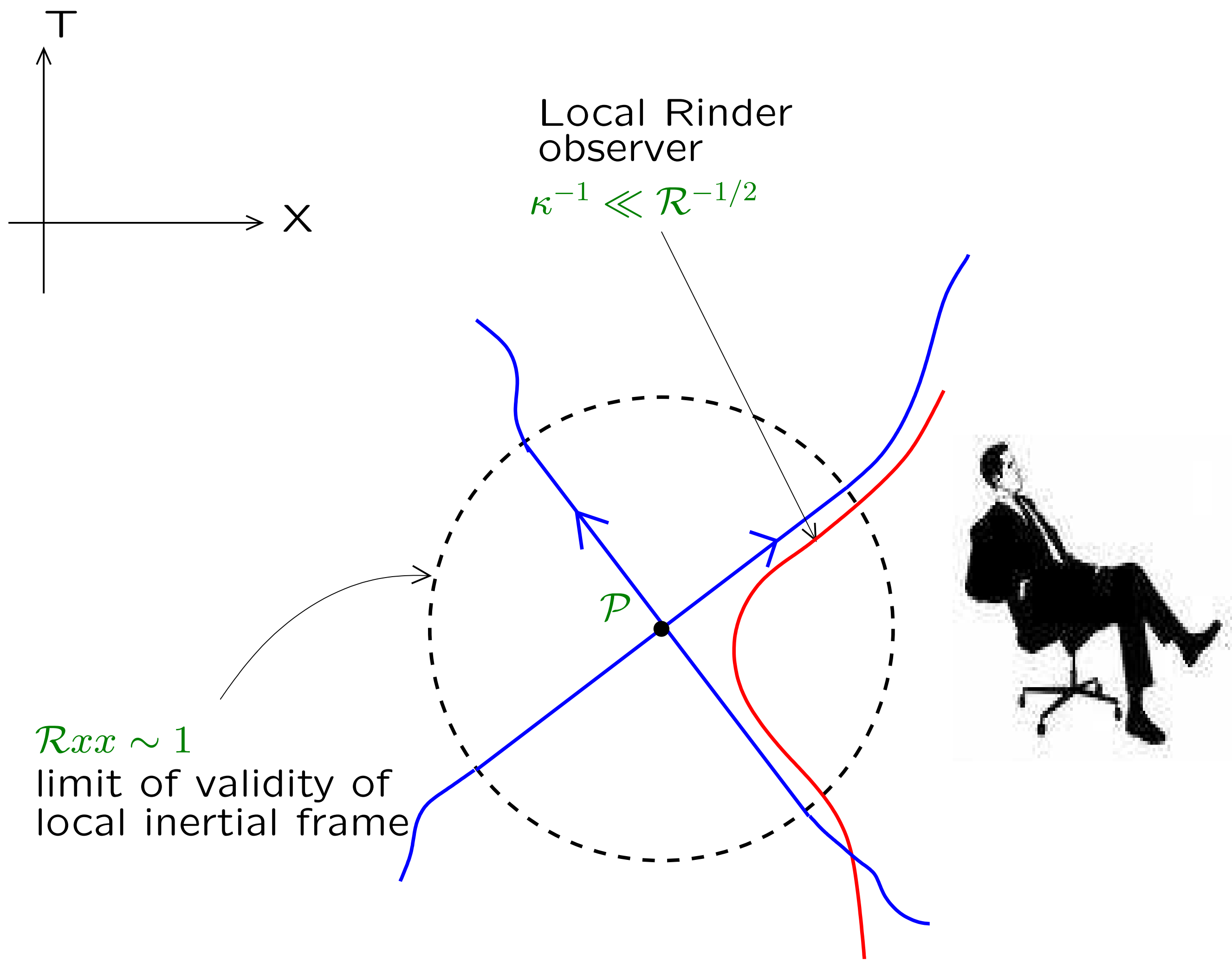


FREE – FALL OBSERVERS



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

LOCAL RINDLER OBSERVERS



Validity of entropy extremisation $\Rightarrow$ dynamics of gravity

A NEW VARIATIONAL PRINCIPLE

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

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- Uniquely fixes the form of P^{abcd} as

$$P^{abcd} = \left(\frac{\partial F[R^{ab}_{cd}, g_{ij}]}{\partial R_{abcd}}\right); \quad \nabla_a P^{abcd} = 0$$

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- The key point is:

$$\nabla_c\left[\frac{\partial\Im}{\partial(\nabla_c\xi_a)}\right] \propto \nabla_c(P^{abcd}\nabla_d\xi_b) \propto P^{abcd}R^j{}_{bcd}\xi_j$$

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- The field equations now have a new symmetry. The action and field equations are invariant under $T_{ab} \to T_{ab} + \rho_0 g_{ab}$. Gravity does *not* couple to bulk vacuum energy (cosmological constant).

ASIDE: MORE GENERAL CLASS OF MODELS

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- If we allow for higher order field equations, a more general class of models are possible with (T.P., 09; S.F.Wu, 09)

$$\Im_{\mathrm{grav}} = -4\left[P^{abcd}\nabla_c\xi_a\,\nabla_d\xi_b + (\nabla_d P^{abcd})\xi_b\nabla_c\xi_a + (\nabla_c\nabla_d P^{abcd})\xi_a\xi_b\right]$$

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- That is, given an $L(R^{ab}_{cd}, g_{ab})$ that leads to a field equation on varying g_{ab}, one can write down explicitly an $\Im[\xi^a]$ which gives the same field equations on varying ξ^a.

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- Connects with the equipartition idea.

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- The deep connection between gravity and thermodynamics *goes well beyond Einstein's theory.* Closely related to the holographic structure action functional.

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- Can one do better than a host of other ‘QG candidate models’ ? e.g., cosmological constant problem, singularity problem ...

...IN CASE YOU GO FOR A SECOND OPINION...

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Questions you need to answer!

- 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 ?
- 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?

REFERENCES

T.P, *Lessons from Classical Gravity about the Quantum Structure of Spacetime*, [arXiv:1012.4476]

T.P, *Thermodynamical Aspects of gravity: New Insights*, [arXiv:0911.5004], Rep.Prog.Physics, **73**, 046901 (2010),

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THANK YOU FOR YOUR TIME!

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- The variation (ignoring the surface term) is same as varying $(2E_{ab} - T_{ab})n^a n^b$ with respect to n_a and demanding that it holds for all n_a. This is why we get $(2E_{ab} = T_{ab})$ except for a cosmological constant.