

GRAVITY: A NEW PERSPECTIVE

T. Padmanabhan

(IUCAA, Pune)

**Indian Academy of Sciences Meeting
Bangalore, 2 July 2010**

THE ATTRACTION OF QUANTUM 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



COMBINING GRAVITY AND QUANTUM THEORY

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Possible road map for progress

T.P., 2002-2010

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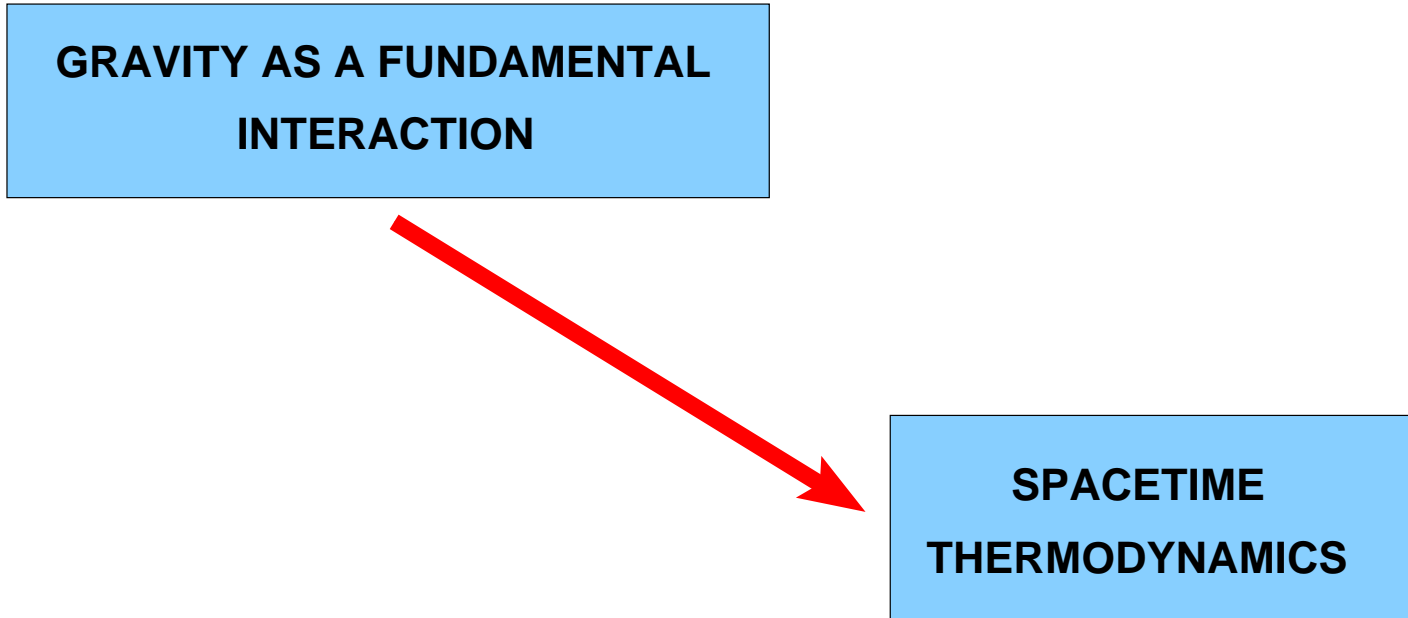
T.P., 2002-2010

- TREAT IT AS A CONCEPTUAL RATHER THAN TECHNICAL PROBLEM
- CONCENTRATE ON POINTS OF CONTACT AND CONFLICT: CONNECTION BETWEEN GRAVITY AND THERMODYNAMICS OF HORIZONS
- EXPLOIT THE 'INTERNAL EVIDENCE' TO MOTIVATE/DERIVE AN ALTERNATIVE PERSPECTIVE OF GRAVITY
- DEVELOP A 'TOP-DOWN' APPROACH

CONVENTIONAL VIEW

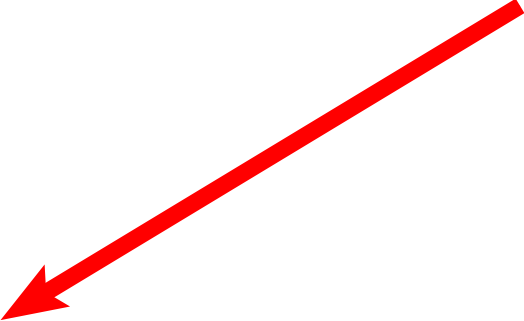
**GRAVITY AS A FUNDAMENTAL
INTERACTION**

CONVENTIONAL VIEW



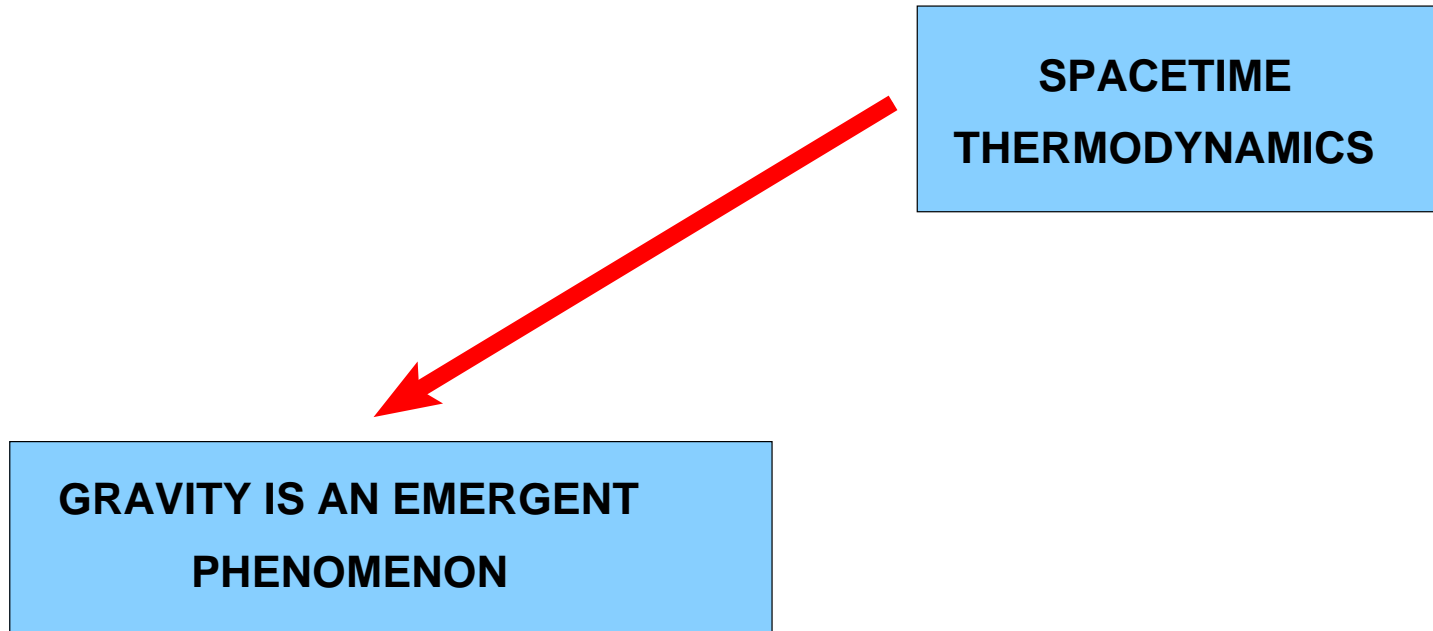
NEW PERSPECTIVE

**SPACETIME
THERMODYNAMICS**



**GRAVITY IS AN EMERGENT
PHENOMENON**

NEW PERSPECTIVE



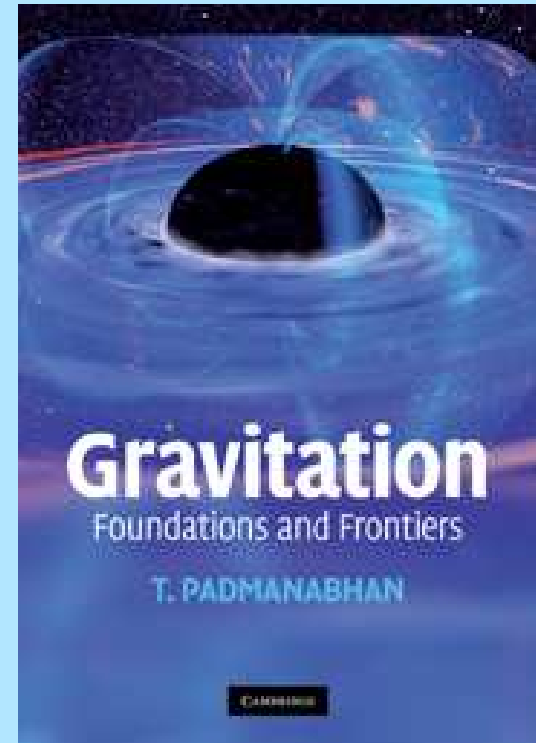
GRAVITY IS THE THERMODYNAMIC LIMIT OF THE
STATISTICAL MECHANICS OF 'ATOMS OF SPACETIME'

PLAN OF THIS TALK

- THE CONVENTIONAL APPROACH TO GRAVITY AND HORIZON THERMODYNAMICS
- 'INTERNAL EVIDENCE' FOR AN ALTERNATIVE PERSPECTIVE
- THE CONCEPT OF EMERGENT PHENOMENON
- DYNAMICS FROM ENTROPY DENSITY OF SPACETIME
- CONCLUSIONS, OPEN QUESTIONS

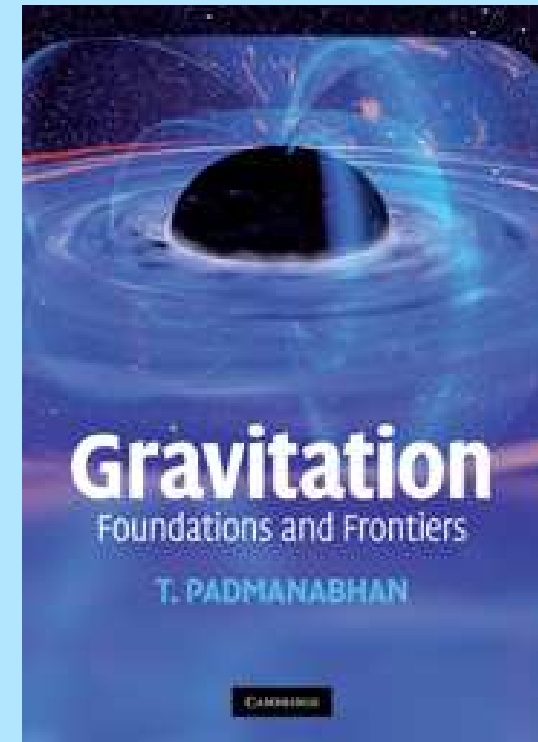
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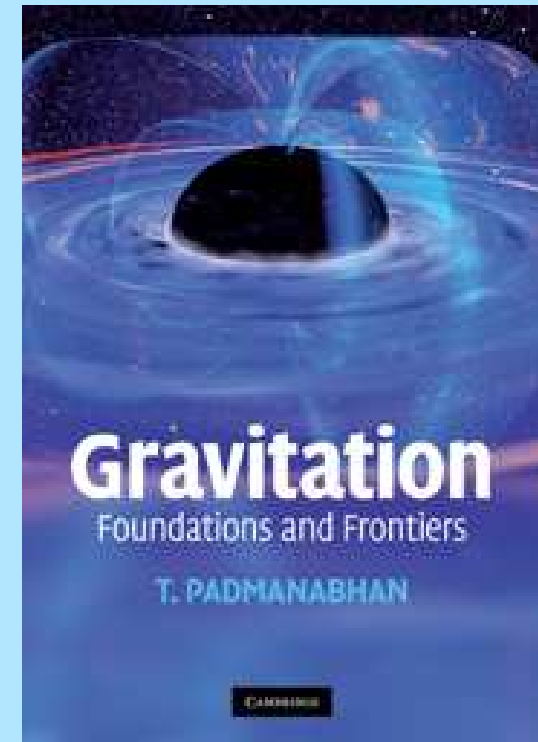
TEXT BOOK DESCRIPTION OF GRAVITY

- Principle of Equivalence



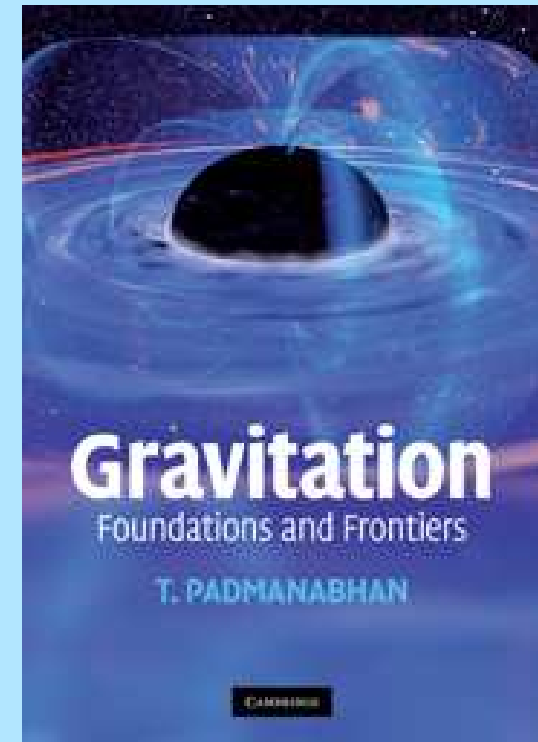
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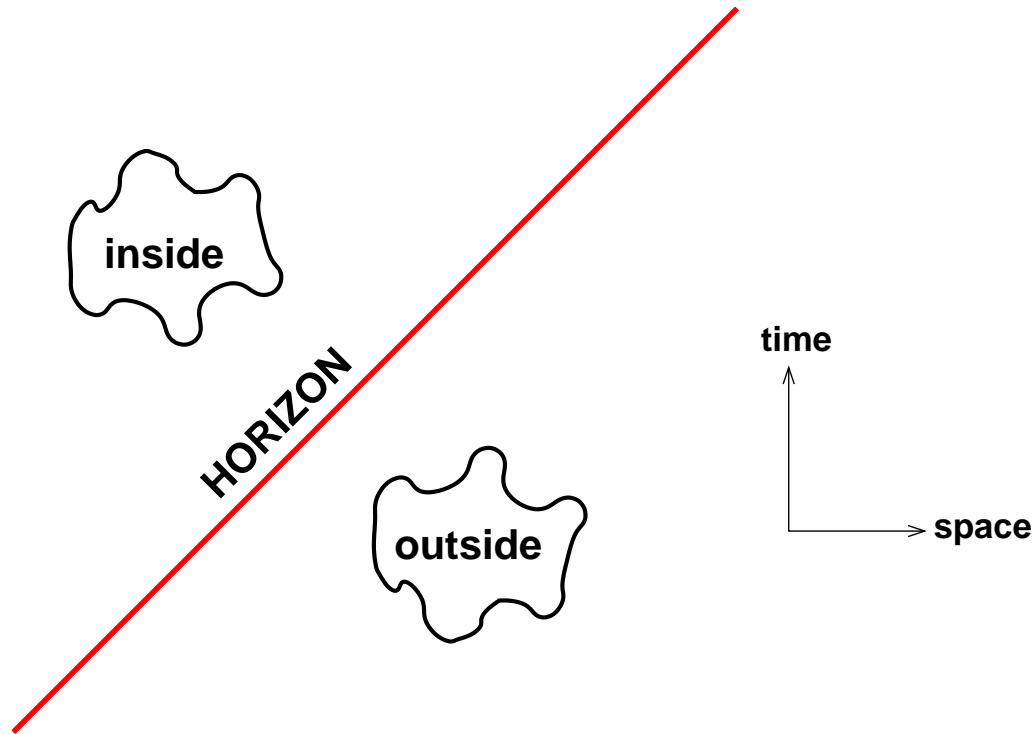
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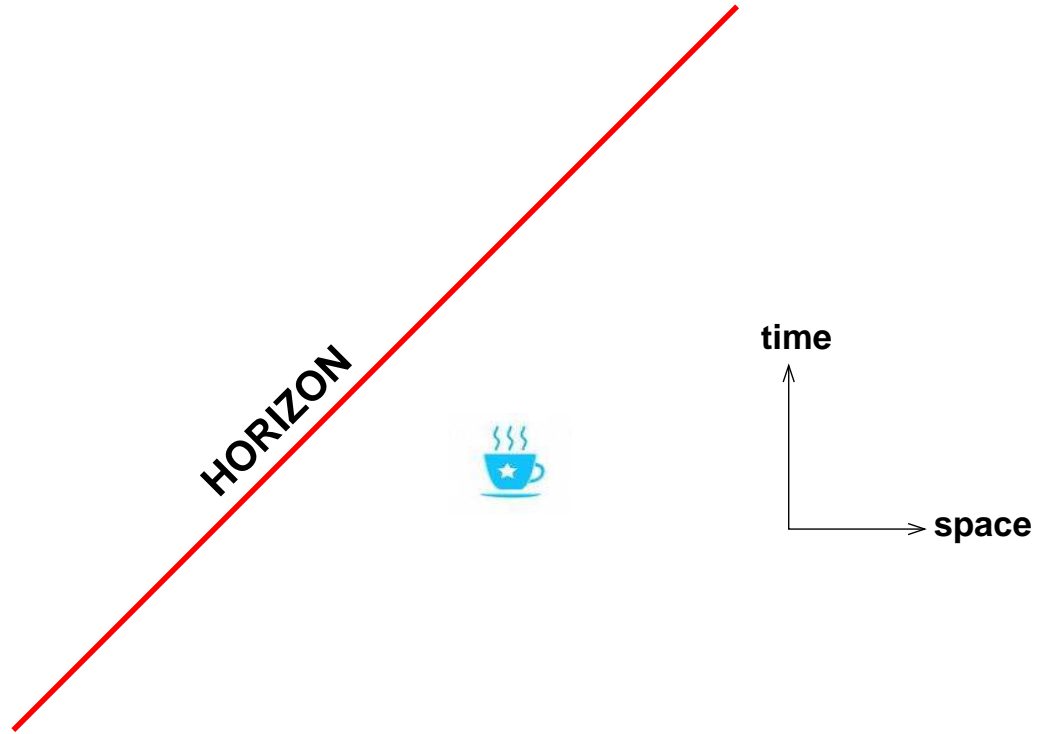
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- Gravitational theories are determined by the tensor P_{cd}^{ab} . A “nice” class of theories require $\nabla_a P^{abcd} = 0$, the simplest of which is Einstein’s theory.
- Horizons arise inevitably in the solutions to these field equations.

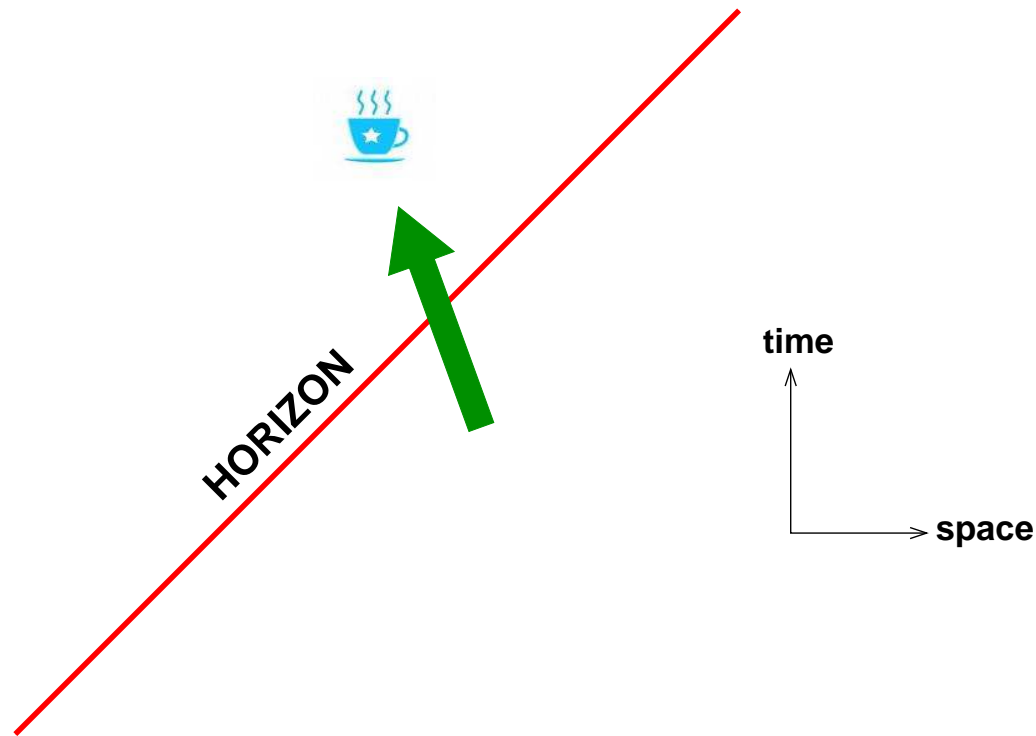
ENTROPY OF HORIZONS



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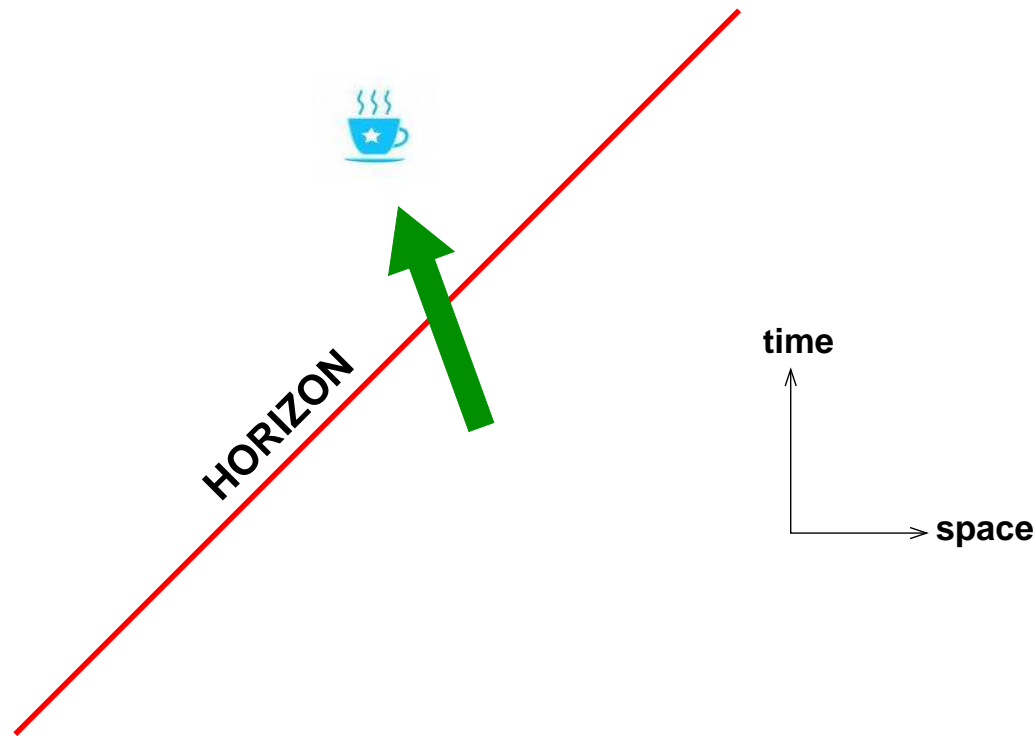


ENTROPY OF HORIZONS



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

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

INTUITIVE UNDERSTANDING OF $S \propto A$

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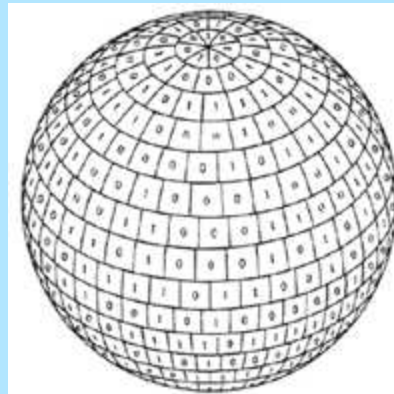
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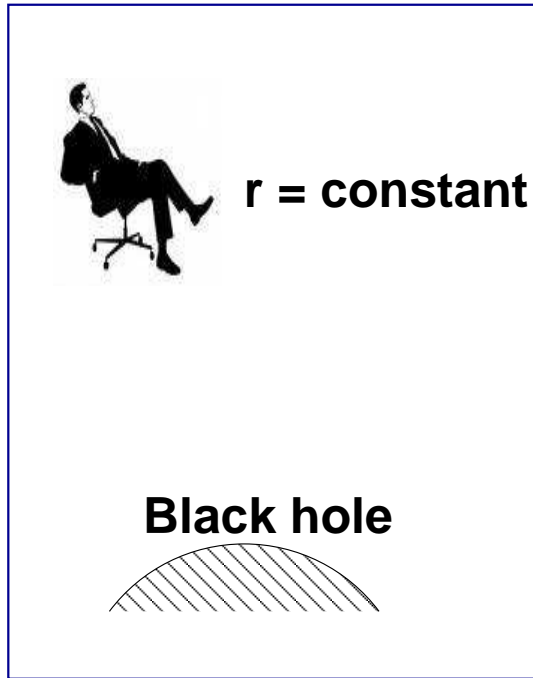
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- The Boltzmann entropy is:

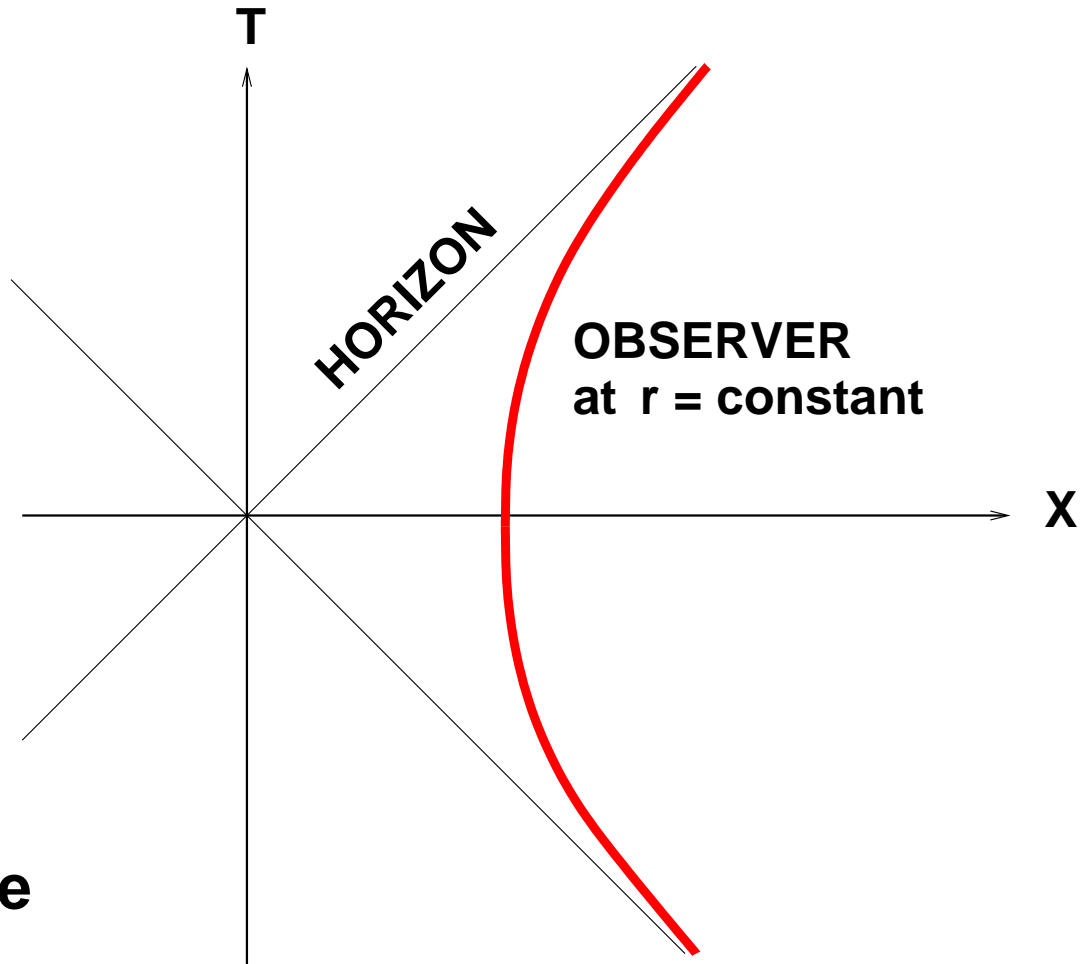
$$S = \ln \Omega \propto \frac{A}{A_{Planck}} \propto \frac{c^3 A}{G\hbar}$$

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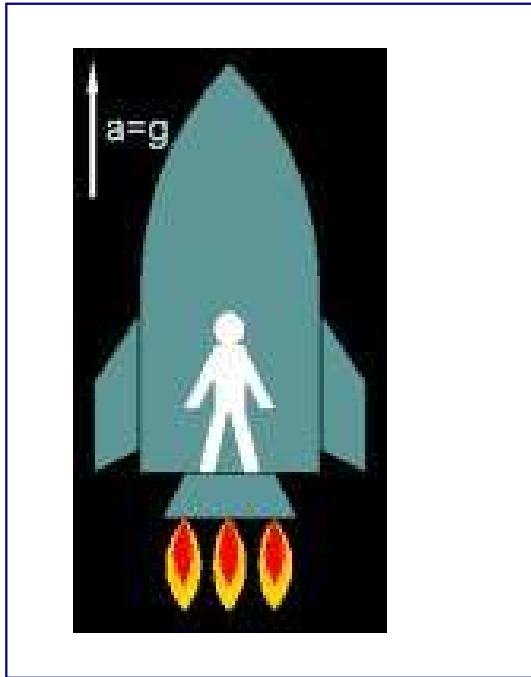
BLACK HOLE SPACETIME



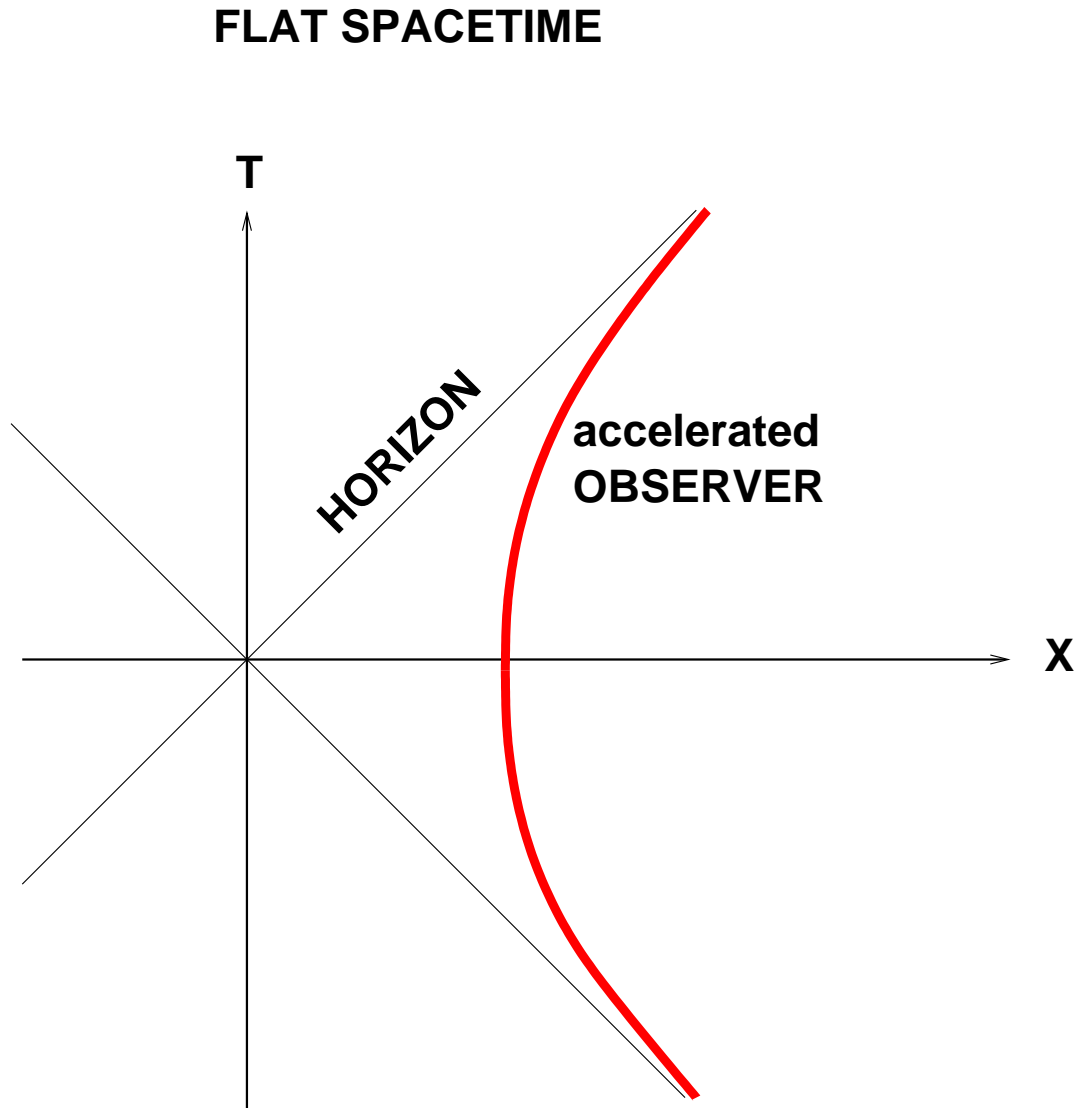
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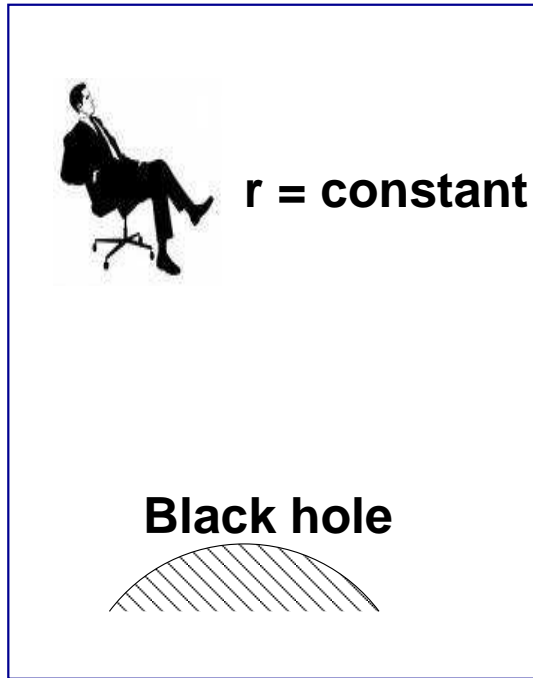
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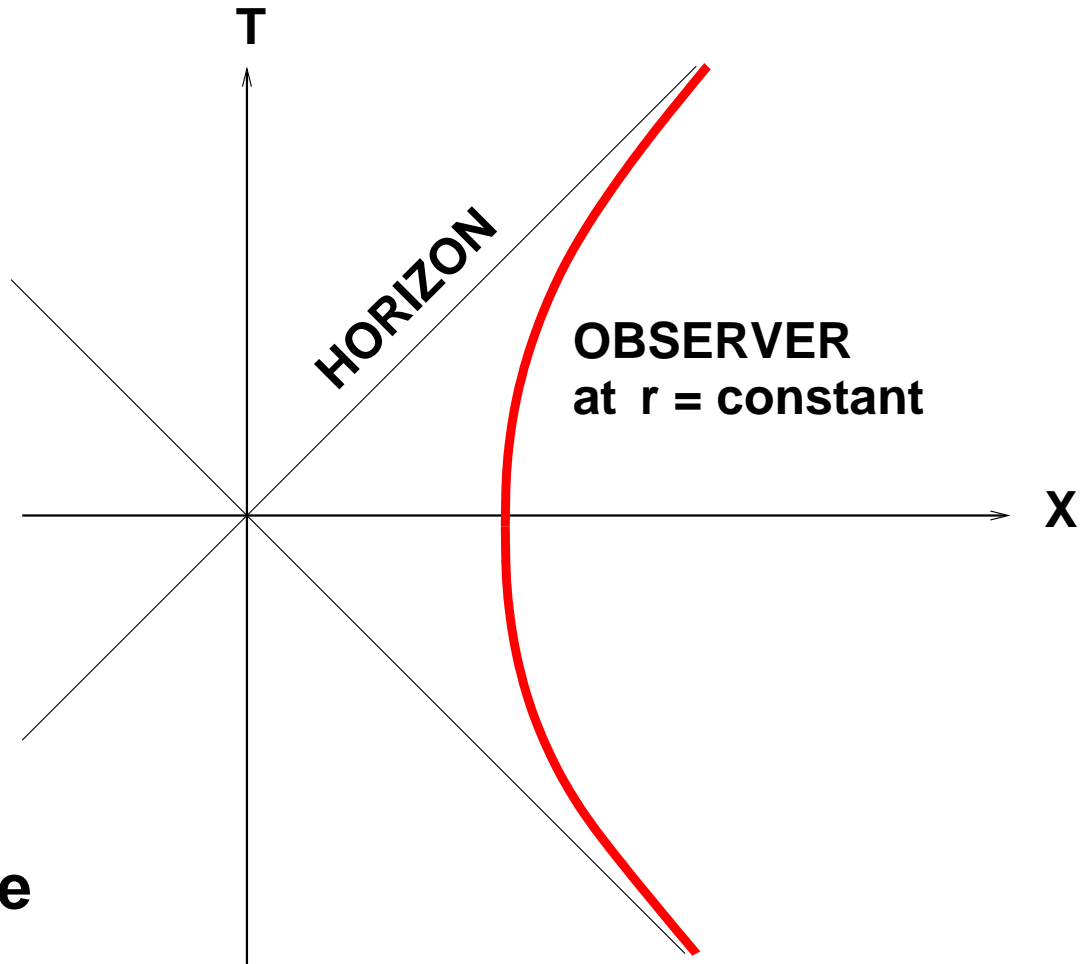


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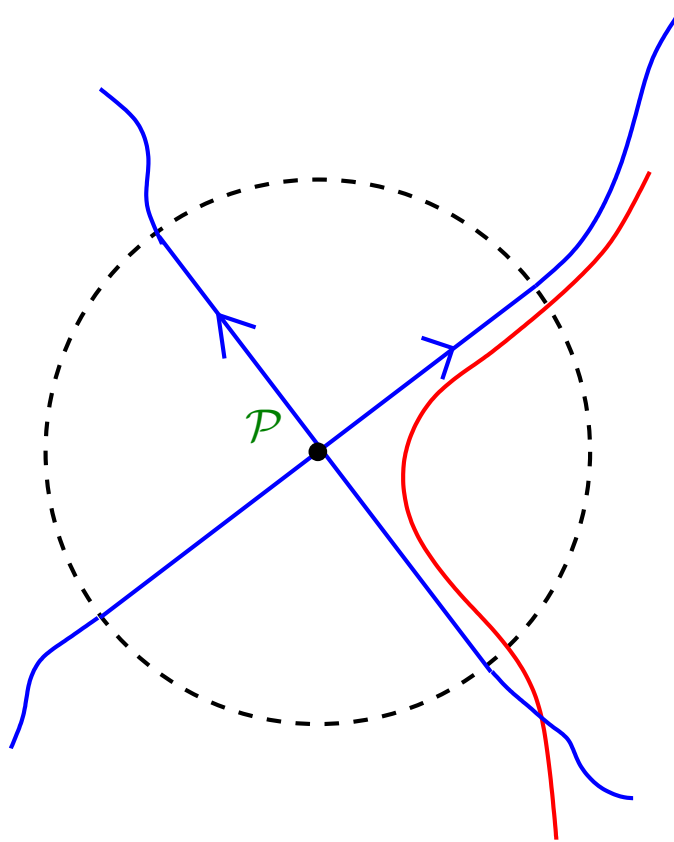
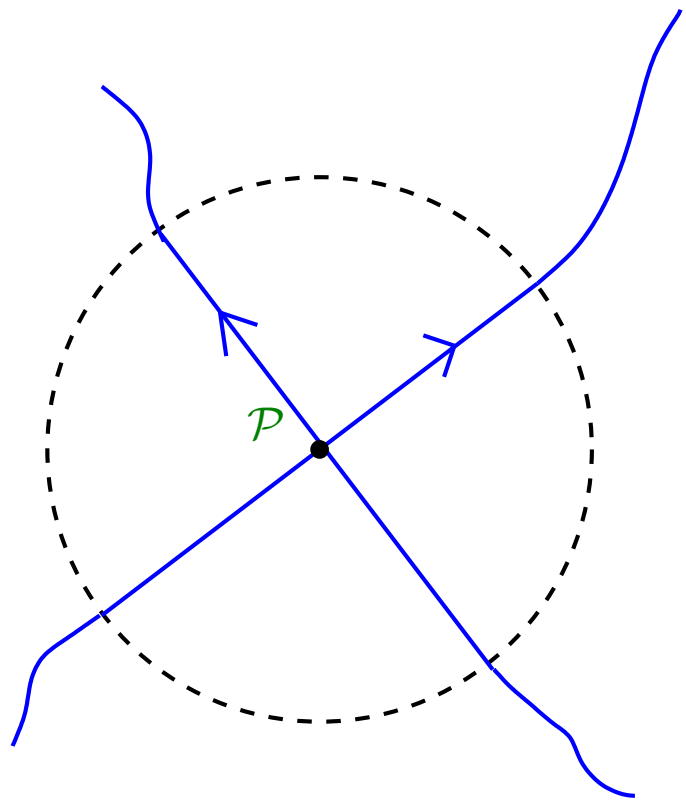
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OBSERVERS WHO PERCEIVE A HORIZON
ATTRIBUTE TO IT A TEMPERATURE

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



Vacuum state



Thermal state

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- This result is *independent* of the field equations of gravity.

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SPACETIMES WITH HORIZONS EXHIBIT PERIODICITY IN
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MOTIVATING THE ALTERNATIVE PERSPECTIVE

Why fix it when it works ?

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

FIELD EQUATIONS \Rightarrow THERMODYNAMIC IDENTITY

T.P, (2002) CQG **19**, 5387

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$$\frac{\hbar}{c} \left(\frac{g}{2\pi} \right) \frac{c^3}{G\hbar} d \left(\frac{1}{4} 4\pi a^2 \right) - \frac{1}{2} \frac{c^4 da}{G} = P d \left(\frac{4\pi}{3} a^3 \right)$$

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- So field equations become $TdS = dE + PdV$; with :

$$S = \frac{1}{4L_P^2} (4\pi a^2) = \frac{1}{4} \frac{A_H}{L_P^2}; \quad E = \frac{c^4}{2G} a = \frac{c^4}{G} \left(\frac{A_H}{16\pi} \right)^{1/2}; \quad L_P^2 \equiv G\hbar/c^3$$

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]
- Dynamical apparent horizons in Lanczos-Lovelock gravity, [arXiv:0810.2610]
- Generic, static horizon in Lanczos-Lovelock gravity [arXiv:0904.0215]
- Three dimensional BTZ black hole horizons [arXiv:0911.2556];[hep-th/0702029]
- FRW and other solutions in various gravity theories [hep-th/0501055]; [arXiv:0807.1232]; [hep-th/0609128]; [hep-th/0612144]; [hep-th/0701198]; [hep-th/0701261]; [arXiv:0712.2142]; [hep-th/0703253]; [hep-th/0602156]; [gr-qc/0612089]; [arXiv:0704.0793]; [arXiv:0710.5394]; [arXiv:0711.1209]; [arXiv:0801.2688]; [arXiv:0805.1162]; [arXiv:0808.0169]; [arXiv:0809.1554]; [gr-qc/0611071]
- Horava-Lifshitz gravity [arXiv:0910.2307] .

IN ALL THESE CASES FIELD EQUATIONS REDUCE

TO $TdS = dE + PdV$ ON THE HORIZON!

IF GRAVITATIONAL DYNAMICS PERMITS AN
ALTERNATIVE DESCRIPTION SHOULD NOT
GRAVITATIONAL ACTION FUNCTIONAL CONTAIN
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IT DOES !!

In static spacetimes with horizon, Euclidean action can be interpreted as free energy of spacetime:

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

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

THESE RESULTS ALSO HOLD FOR A MUCH WIDER CLASS
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- The surface term gives rise to entropy of horizons. On-shell action becomes the free energy in static spacetimes. [TP, 06, 09]
- Field equations can be interpreted as: [TP, 08, 09]

$$\left\{ \begin{array}{l} \text{Loss of matter entropy} \\ \text{due to flow of energy} \\ \text{across the hot horizon} \end{array} \right\} = \left\{ \begin{array}{l} \text{Gain of gravitational entropy} \\ \text{for infinitesimal virtual} \\ \text{displacements of the horizon} \end{array} \right\}$$

HOW COME GRAVITATIONAL DYNAMICS ALLOWS
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*GRAVITY IS AN EMERGENT PHENOMENON
INVOLVING THERMODYNAMIC DESCRIPTION OF
MICROSCOPIC SPACETIME DEGREES OF FREEDOM*

GRAVITY AS AN EMERGENT PHENOMENON
SAKHAROV PARADIGM

GRAVITY AS AN EMERGENT PHENOMENON
SAKHAROV PARADIGM

SOLIDS

Mechanics; Elasticity ($\rho, \mathbf{v} \dots$)

Statistical Mechanics

of atoms/molecules

SPACETIME

Einstein's Theory ($g_{ab} \dots$)

Statistical mechanics

of "atoms of spacetime"

GRAVITY AS AN EMERGENT PHENOMENON
SAKHAROV PARADIGM

SOLIDS

Mechanics; Elasticity ($\rho, \mathbf{v} \dots$)

Thermodynamics of solids

Statistical Mechanics

of atoms/molecules

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Einstein's Theory ($g_{ab} \dots$)

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You never took a course in 'quantum thermodynamics'!

YOU CAN HEAT UP GAS

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- Key new ingredient: Boltzmann postulate related thermodynamics to mechanics of microstructure.

The equipartition law

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

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

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- 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.**

THE ACID TEST OF THE IDEA:
THE AVOGADRO NUMBER OF SPACETIME

*IF SPACETIME HAS MICROSTRUCTURE AND IT
CAN BE HEATED UP, IS THERE AN EQUIPARTITION
LAW " $E = (1/2)nk_B T$ " FOR THE MICROSCOPIC
SPACETIME DEGREES OF FREEDOM ?*

IF SO, CAN WE DETERMINE n ?

EQUIPARTITION OF MICROSCOPIC DEGREES OF FREEDOM

TP (2004), *Class.Quan.Grav.*, **21**, 4485. [gr-qc/0308070]; T.P, arXiv: 0912.3165; T.P, arXiv:1003.5665

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- 'Gravity is holographic' !:

$$E \equiv \frac{1}{2}k_B \int_{\partial\mathcal{V}} dn T_{\text{loc}} \equiv \frac{1}{2}k_B \int_{\partial\mathcal{V}} dA \frac{dn}{dA} T_{\text{loc}}$$

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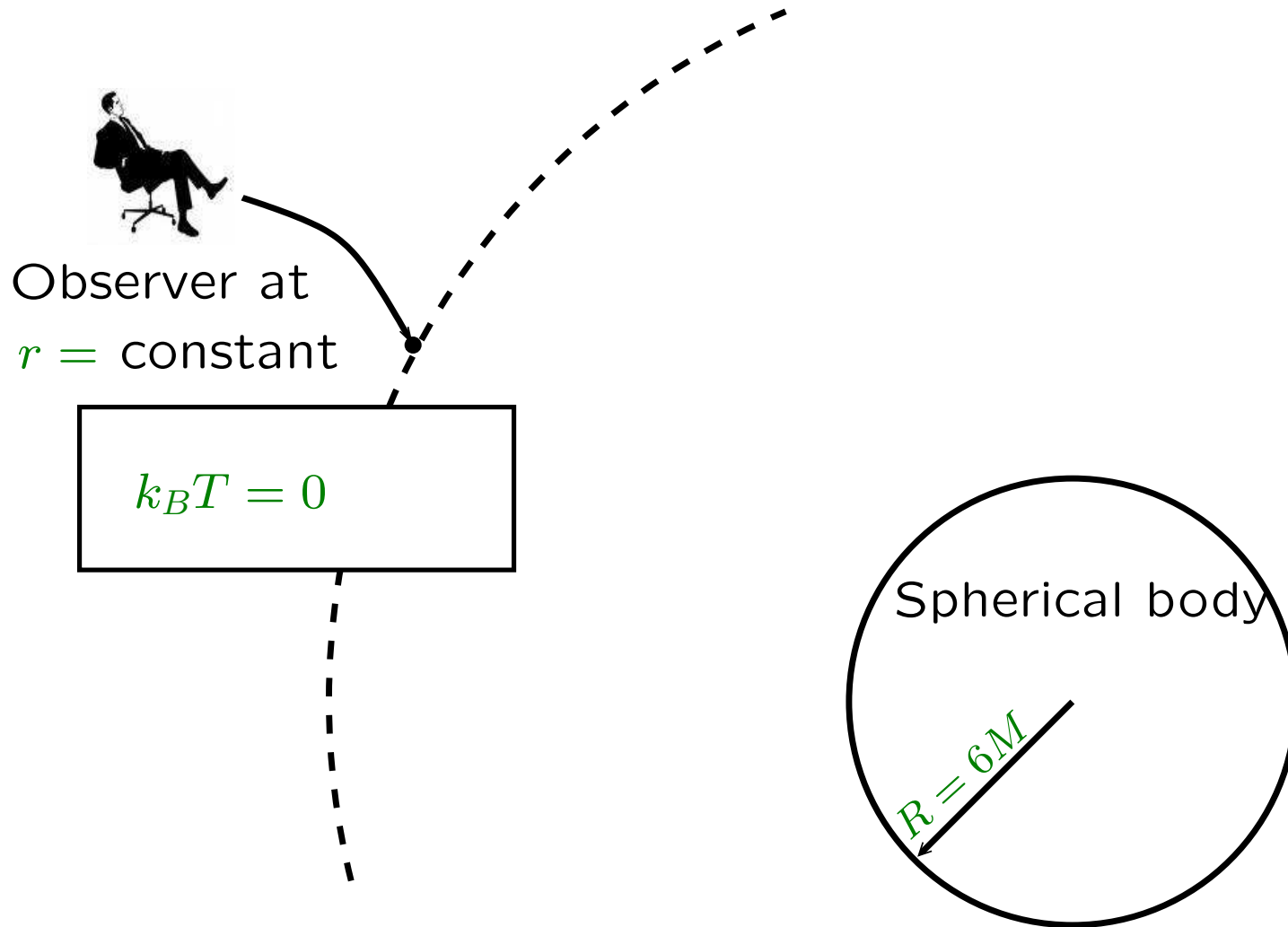
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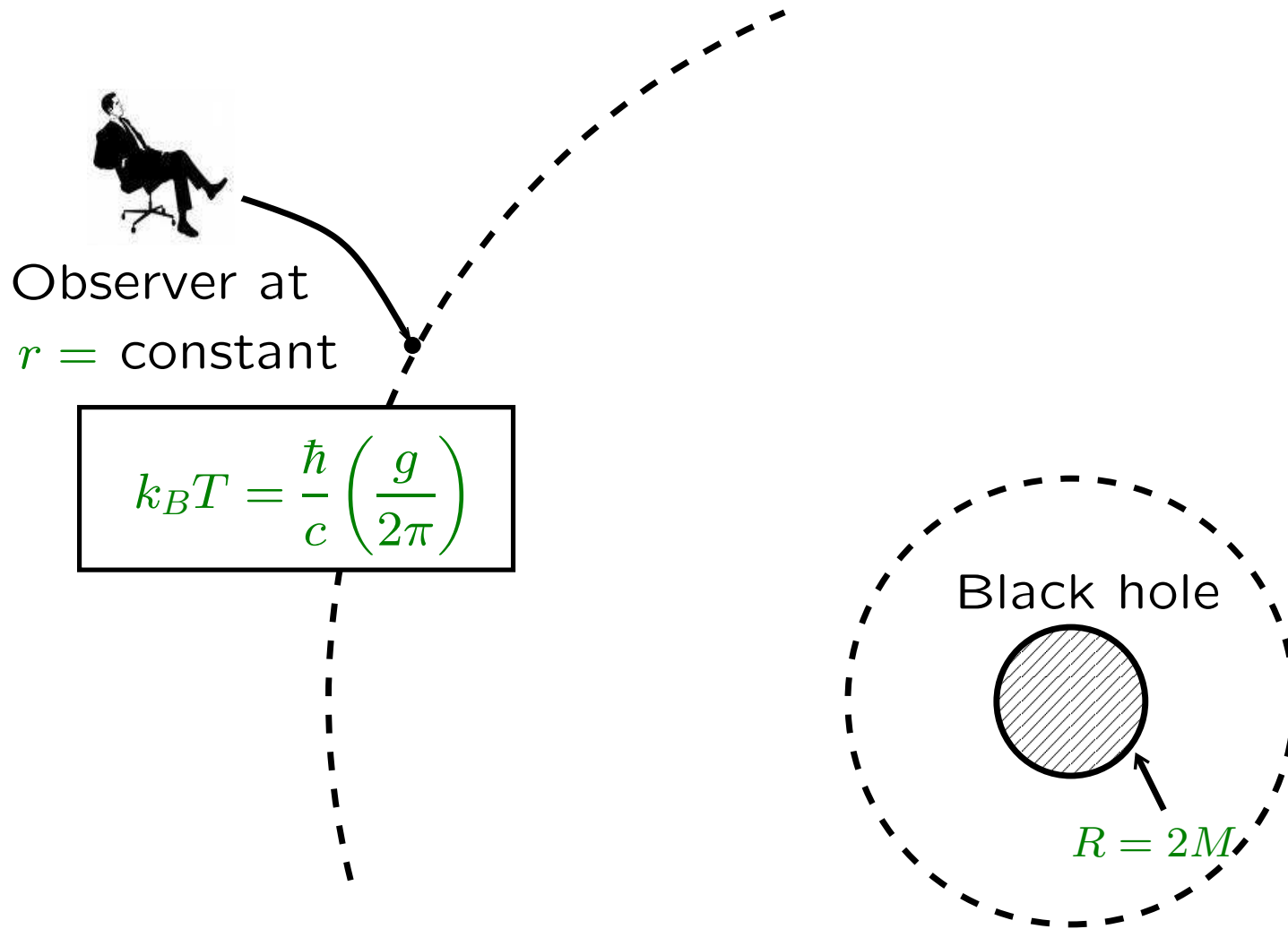
- Result generalizes to any Lanczos-Lovelock model:

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

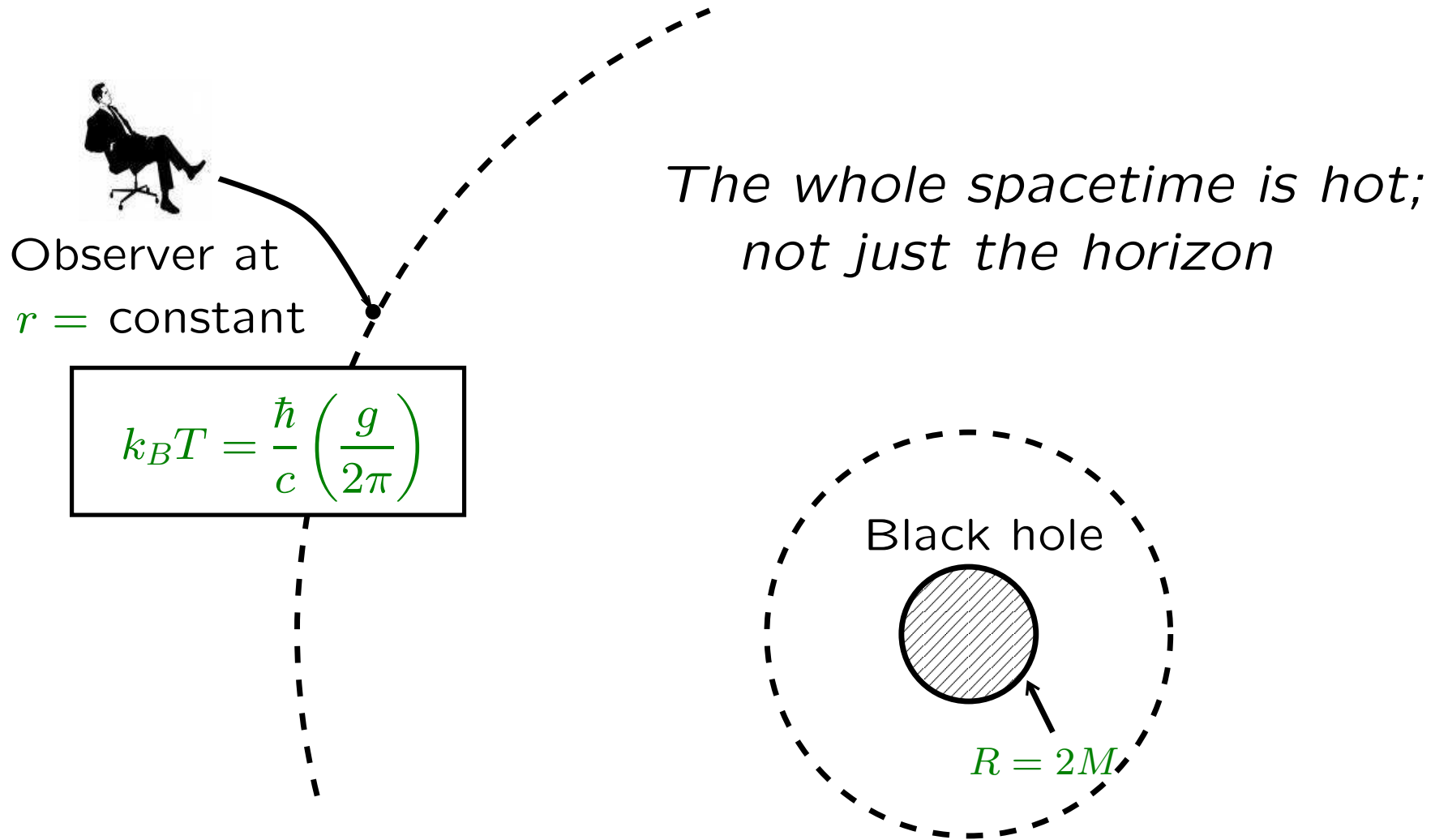
HEATING UP A SPACETIME



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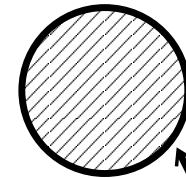


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Black hole



$$R = 2M$$

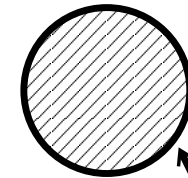
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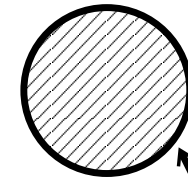
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$$\begin{aligned} \mathcal{E} &= \frac{1}{2} N(k_B T) = \frac{1}{2} \left(\frac{4\pi r^2 c^3}{G\hbar} \right) \left(\frac{\hbar}{c} \frac{GM}{2\pi r^2} \right) \\ &= M c^2 \end{aligned}$$

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- The nature of independent variables q_A and the form of entropy $S[q_A]$ depend on the class of observers and the model for gravity.
- We need a (phenomenological) entropy function for spacetime maximizing which for all class of observers should give the field equations.

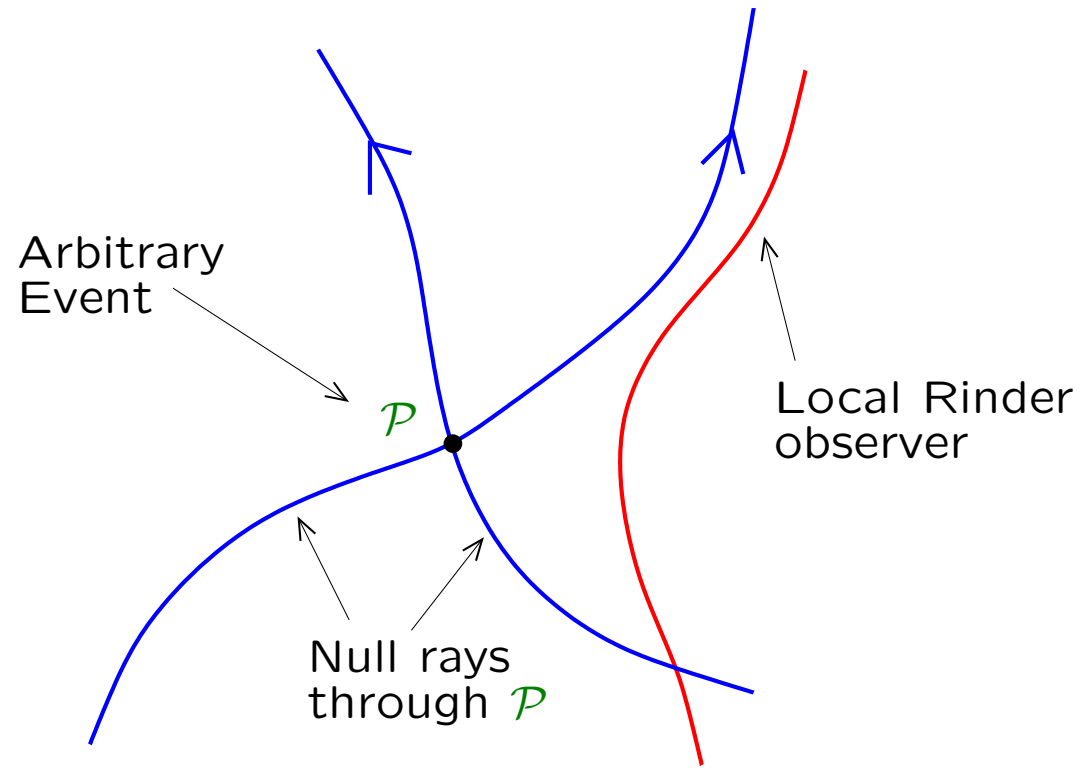
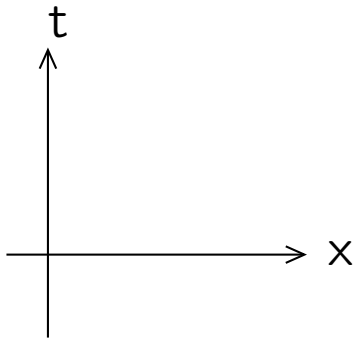
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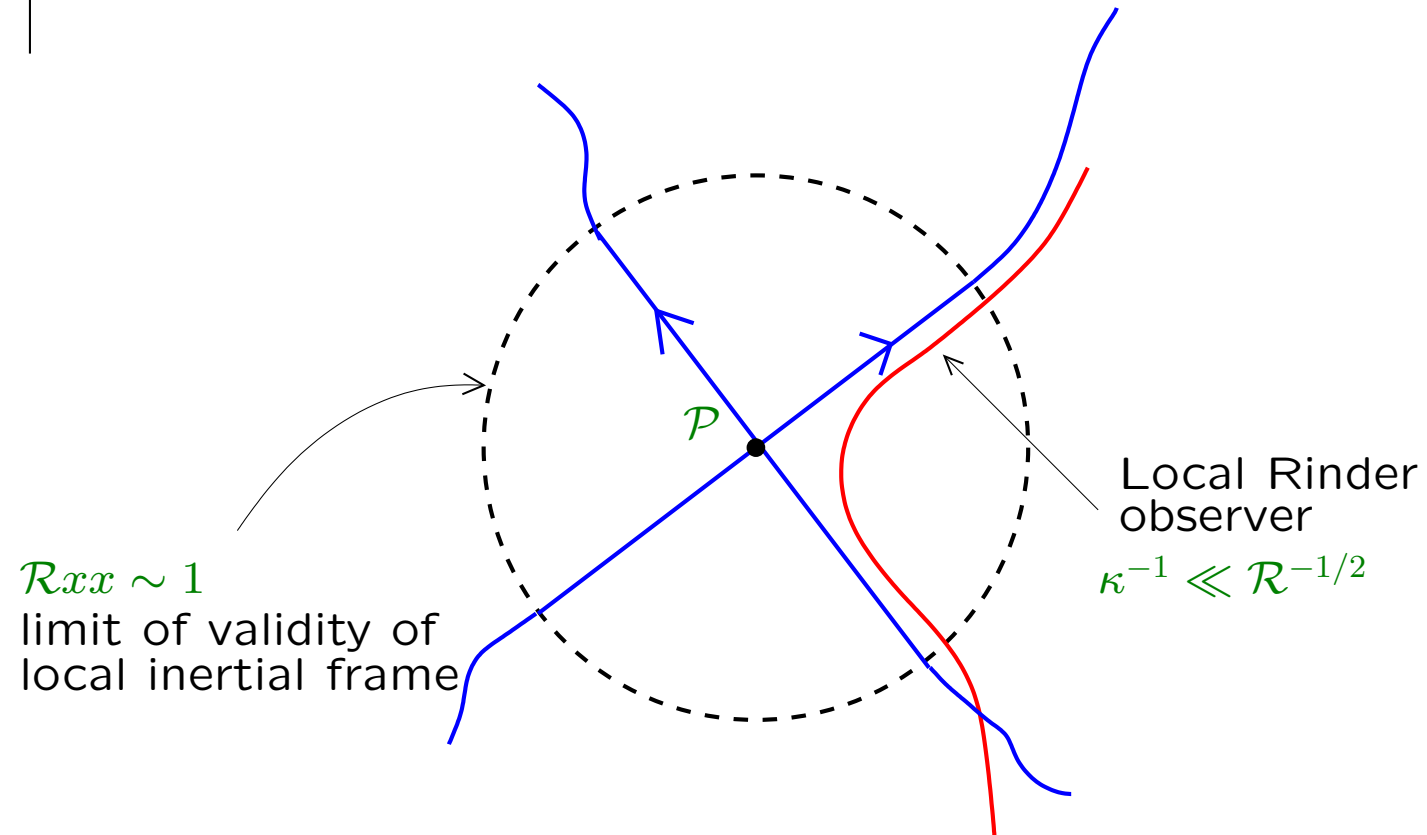
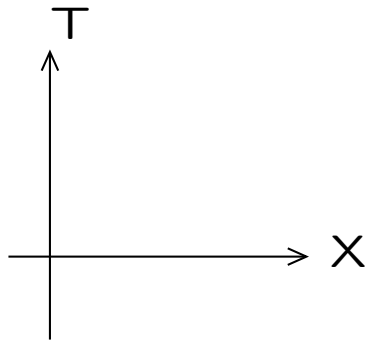
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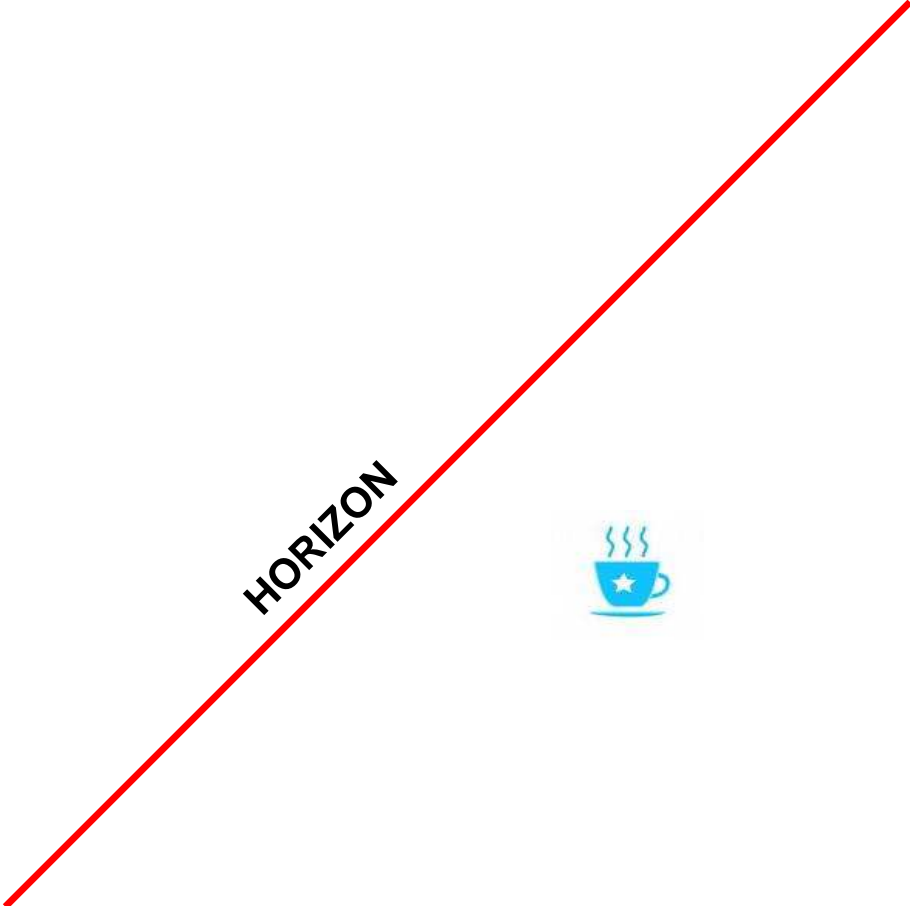


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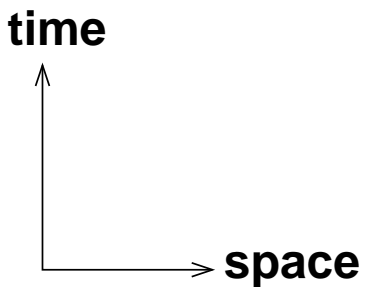
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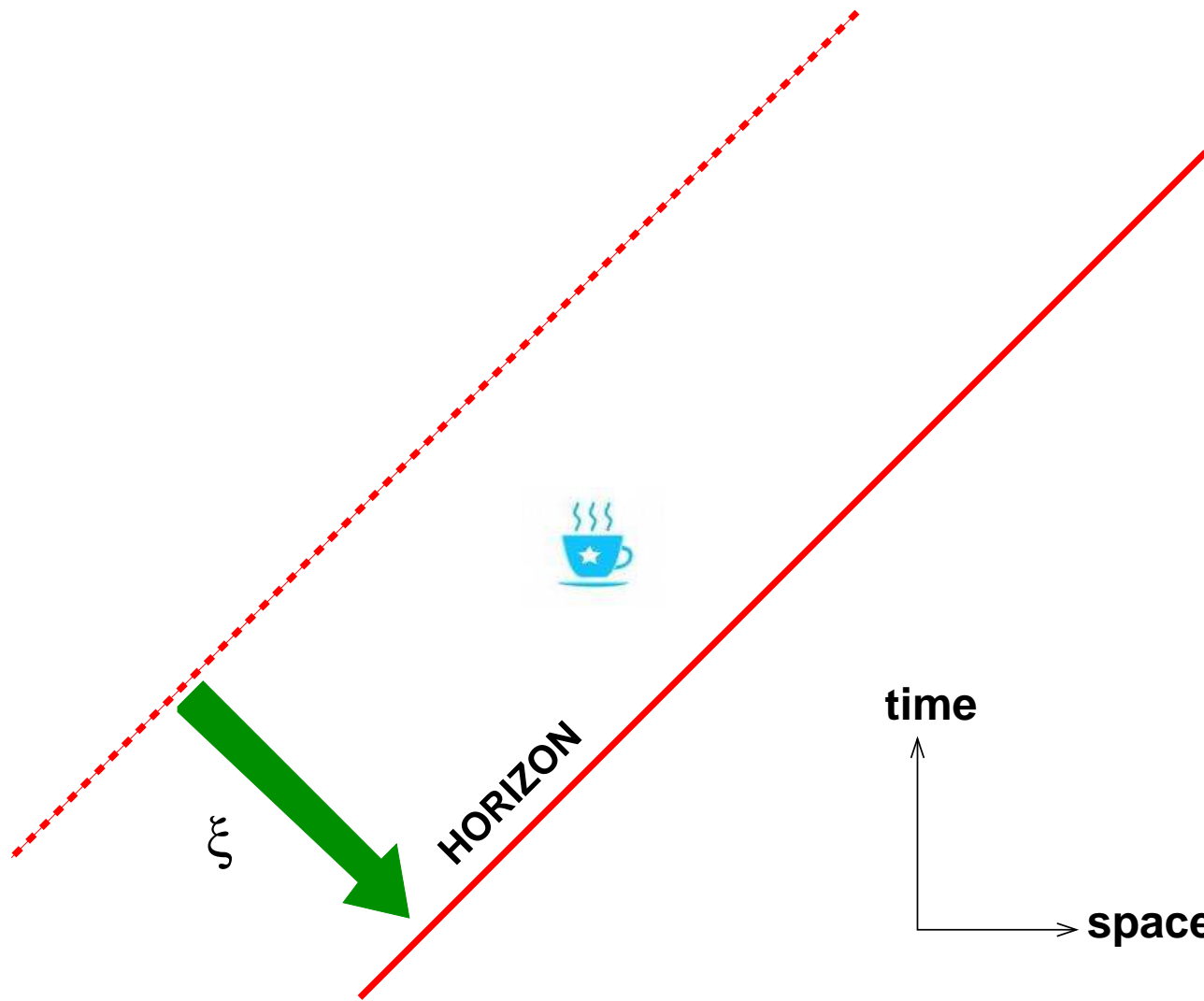
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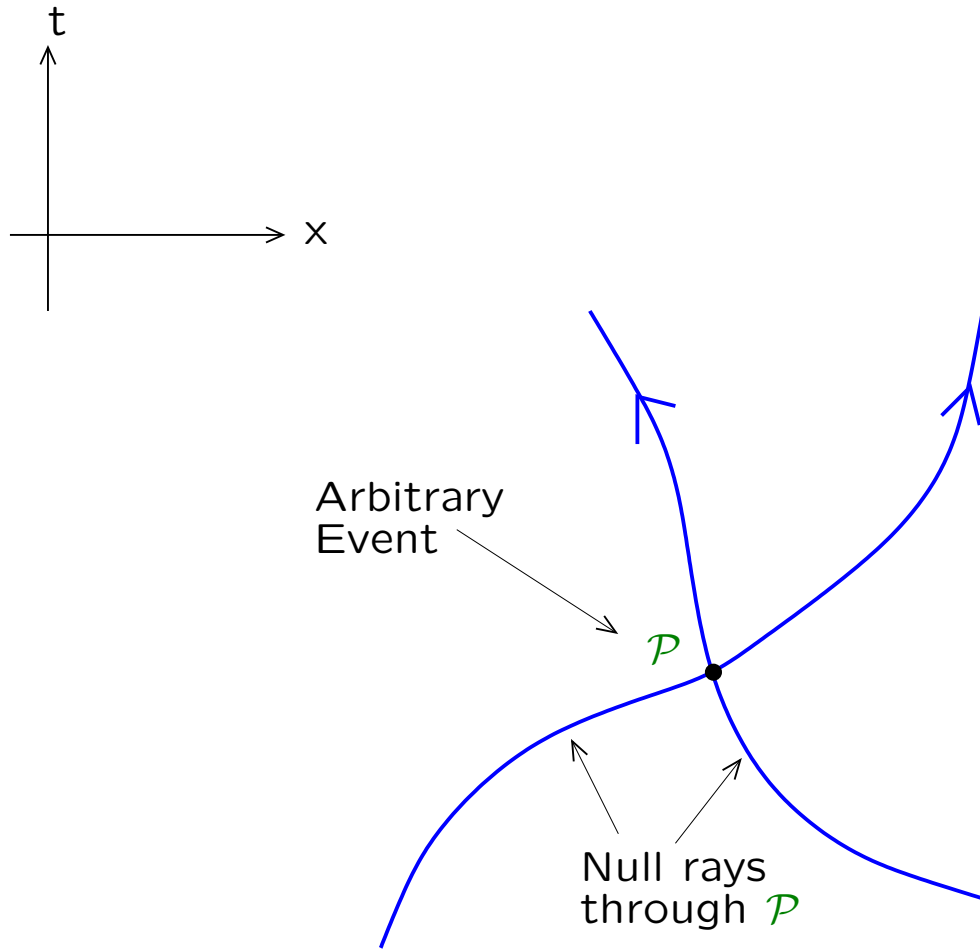
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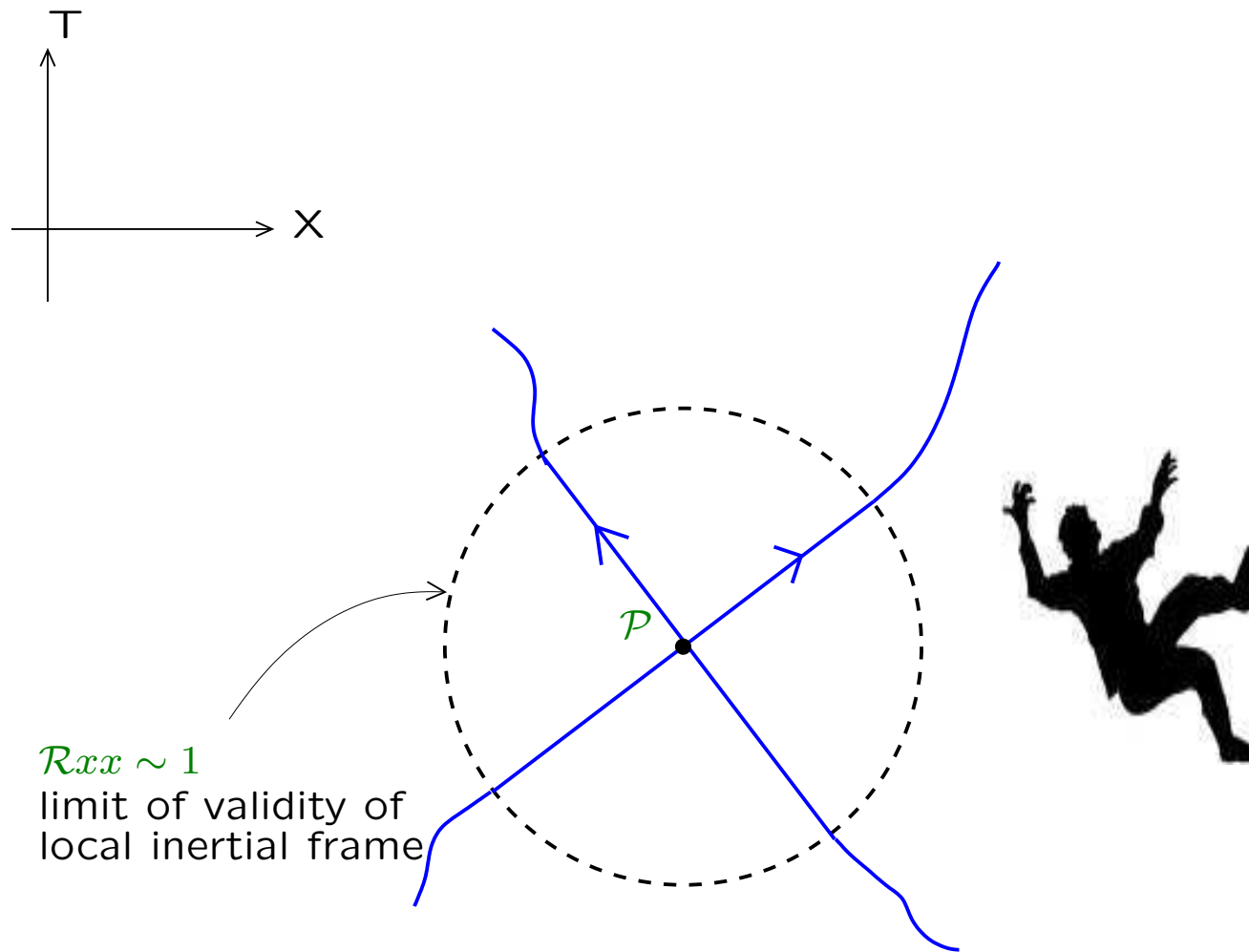
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- Structure:
 - Local Inertial frames \Rightarrow Kinematics of Gravity
 - Local Rindler frames \Rightarrow Dynamics of Gravity

SPACETIME IN ARBITRARY COORDINATES

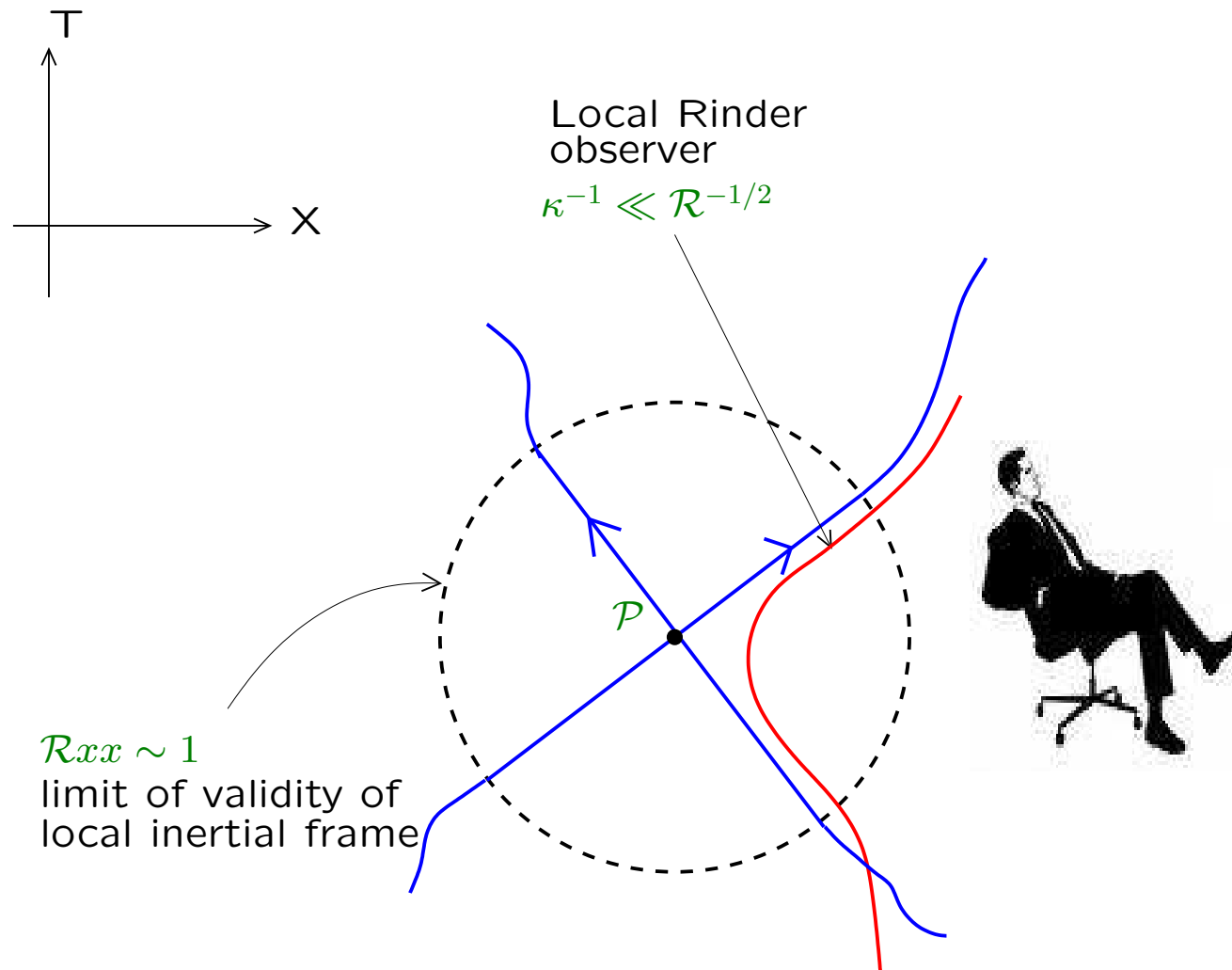


FREE – FALL OBSERVERS



Validity of laws of SR \Rightarrow kinematics of gravity

LOCAL RINDLER OBSERVERS



Validity of entropy extremisation \Rightarrow dynamics of gravity

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- Demand that the entropy is maximised for all local Rindler horizons and that the resulting equations are second order.
- This uniquely fixes the form of P^{abcd} and leads to Lanczos-Lovelock models in D -dimension. Gives Einstein's theory uniquely in $D = 4$.

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- If we allow for higher order field equations, a more general class of models are possible. (T.P., 09; S.F.Wu, 09)
- That is, given an $L(R_{cd}^{ab}, g_{ab})$ that leads to a field equation on varying g_{ab} , one can write down explicitly an $S[\xi^a]$ which gives the same field equations on varying ξ^a .

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Macroscopic body

Spacetime

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How does one close the loop on dynamics?	Use the entropy extremisation to obtain thermodynamical equations	Use the entropy extremisation to obtain gravitational field equations

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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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Kandaswamy Subramanian

Sudipta Sarkar

current student at IUCAA

past student at IUCAA or elsewhere

FOR THE MATHEMATICALLY INCLINED

- Action functional

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

leads to [with $P^{abcd} \equiv (\partial L / \partial R_{abcd})$] the field equation:

$$\begin{aligned} \mathcal{G}_{ab} &= P_a{}^{cde} R_{bcde} - \frac{1}{2} L g_{ab} - 2 \nabla^c \nabla^d P_{acdb} \\ &\equiv \mathcal{R}_{ab} - \frac{1}{2} L g_{ab} - 2 \nabla^c \nabla^d P_{acdb} = (1/2) T_{ab} \end{aligned}$$

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

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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)

$$S_{\text{grav}} = -4 \int_V d^D x \sqrt{-g} \left[P^{abcd} \nabla_c \xi_a \nabla_d \xi_b + (\nabla_d P^{abcd}) \xi_b \nabla_c \xi_a + (\nabla_c \nabla_d P^{abcd}) \xi_a \xi_b \right]$$

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

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- Note that

$$\begin{aligned}4P_{ab}{}^{cd}\nabla_c n^a \nabla_d n^b &= 4\nabla_c [P_{ab}{}^{cd} n^a \nabla_d n^b] - 4n^a P_{ab}{}^{cd} \nabla_c \nabla_d n^b \\ &= 4\nabla_c [P_{ab}{}^{cd} n^a \nabla_d n^b] - 2n^a P_{ab}{}^{cd} \nabla_{[c} \nabla_{d]} n^b \\ &= 4\nabla_c [P_{ab}{}^{cd} n^a \nabla_d n^b] - 2n^a P_{ab}{}^{cd} R^b{}_{icd} n^i \\ &= 4\nabla_c [P_{ab}{}^{cd} n^a \nabla_d n^b] + 2n^a E_{ai} n^i\end{aligned}$$

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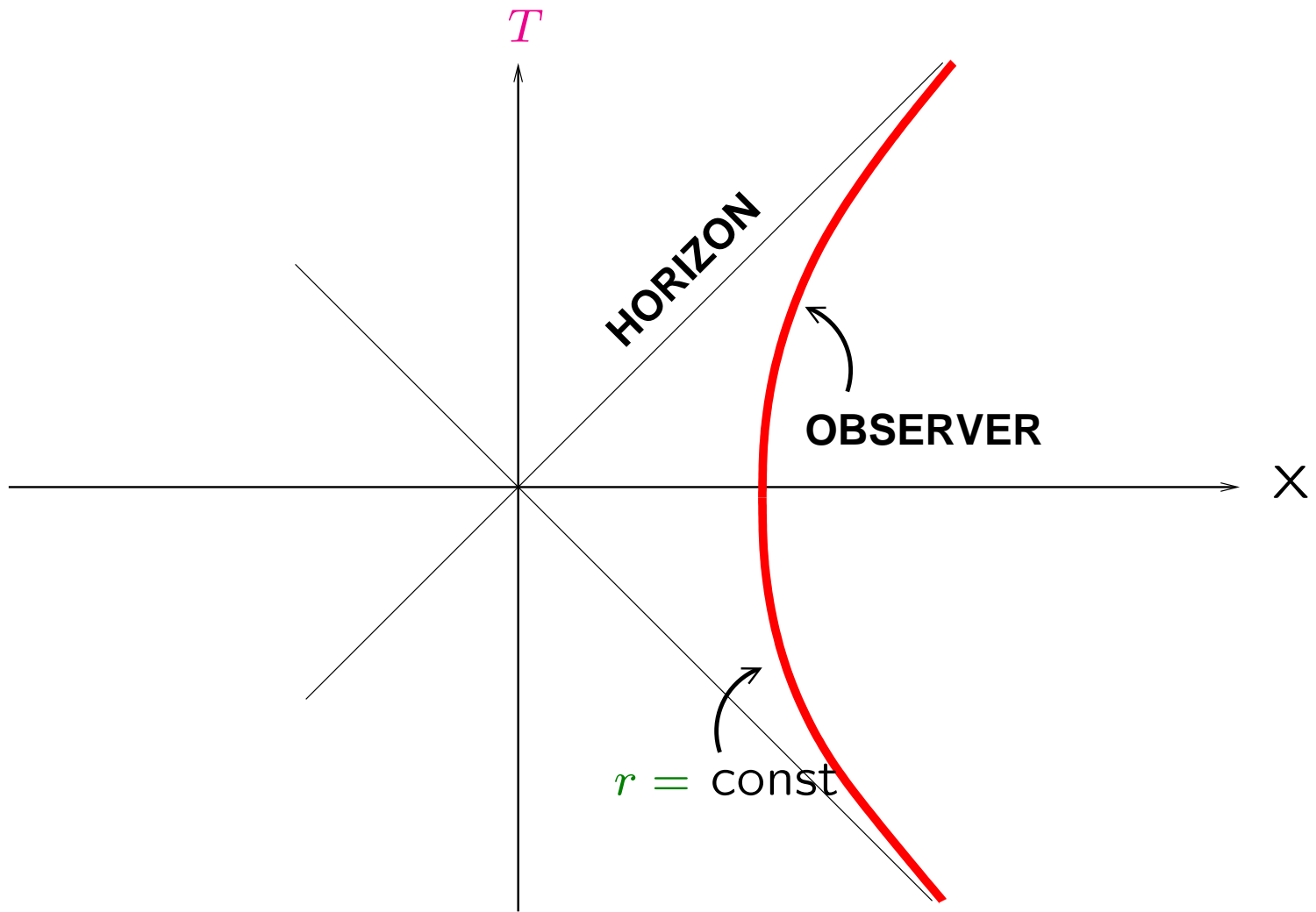
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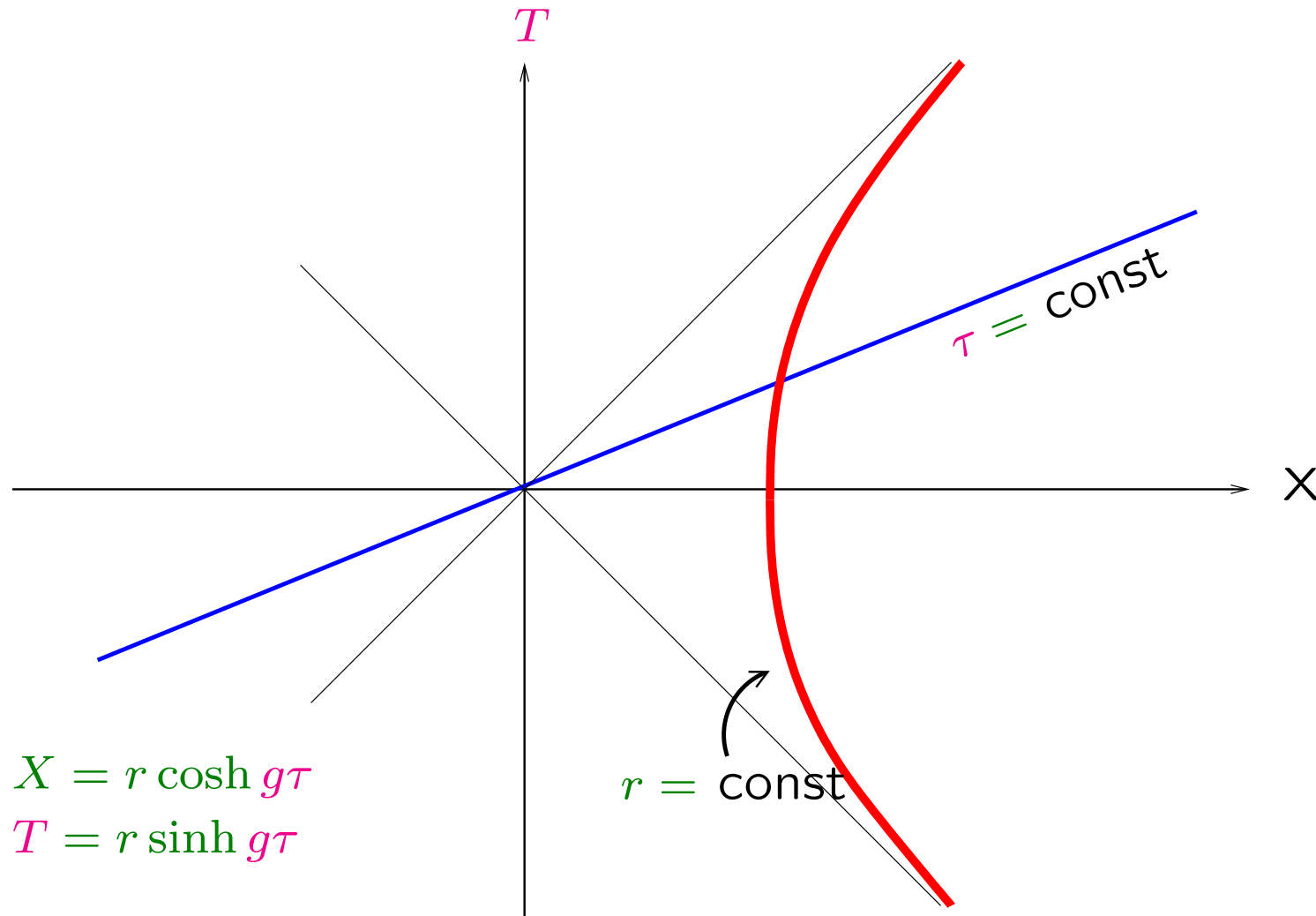
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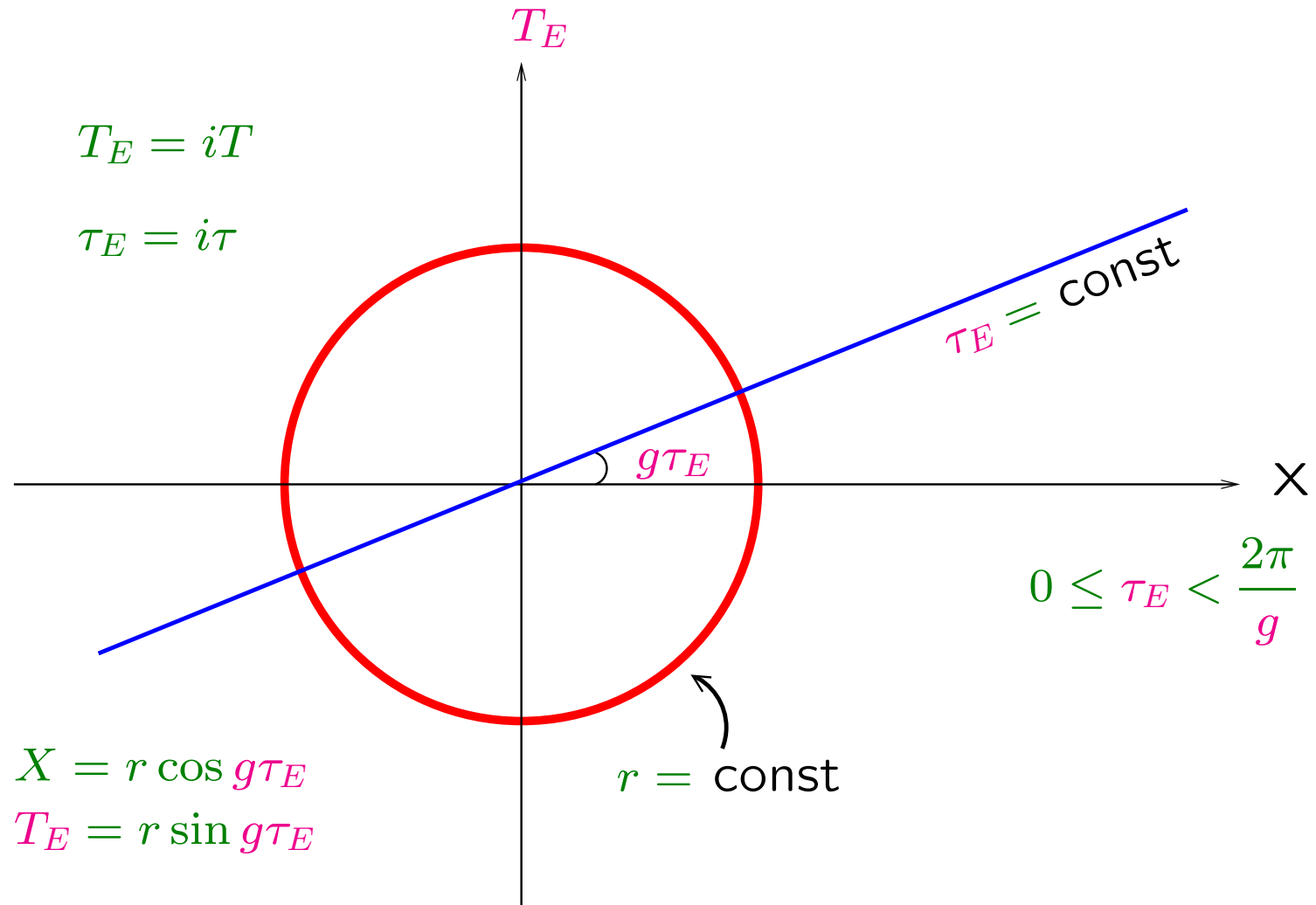
- The variation (ignoring the surface term) is same as varying $(2E_{ab} - T_{ab})n^a n^b$ with respect to n_a and demanding that it holds for all n_a . This is why we get $(2E_{ab} = T_{ab})$ except for a cosmological constant.



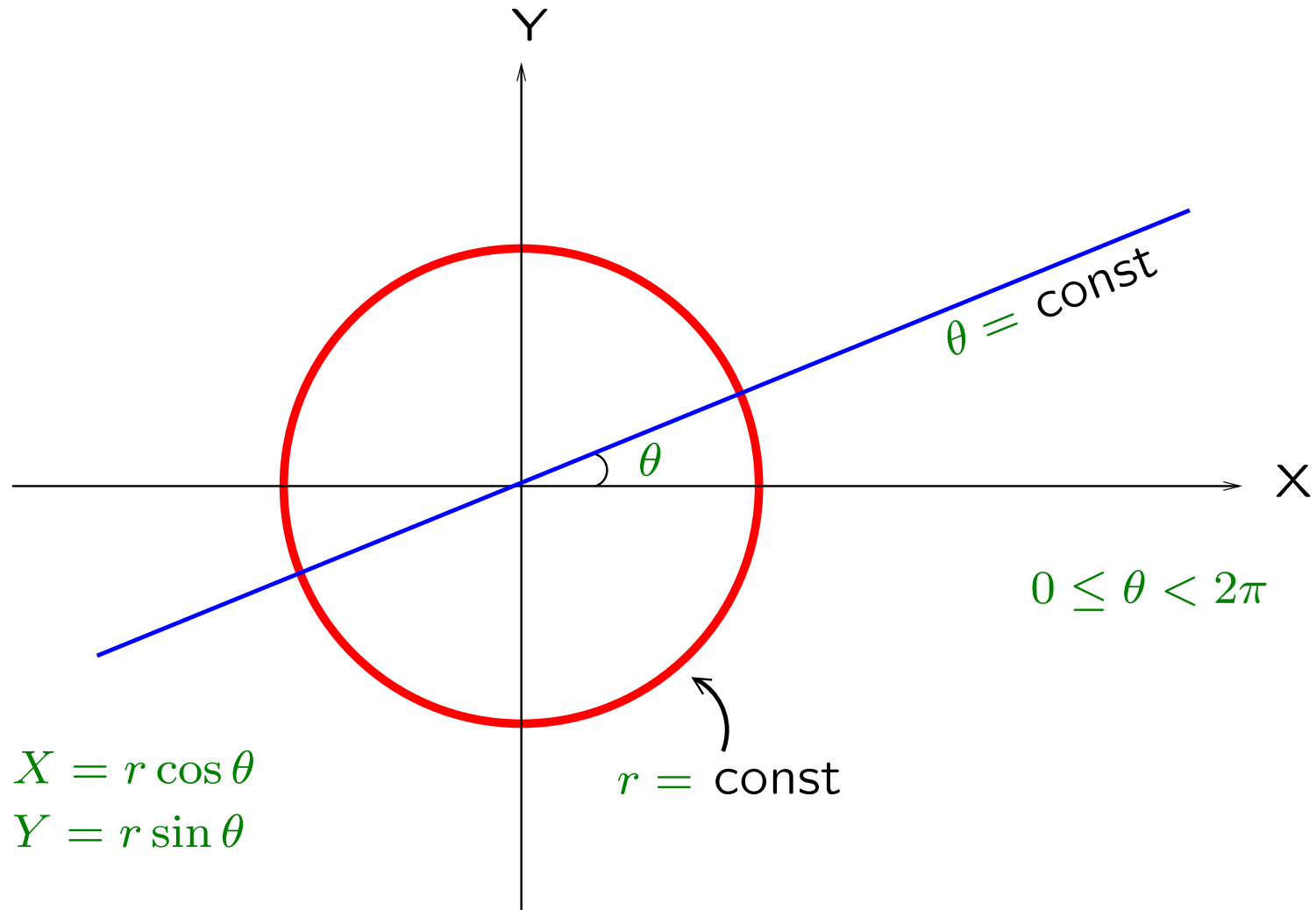
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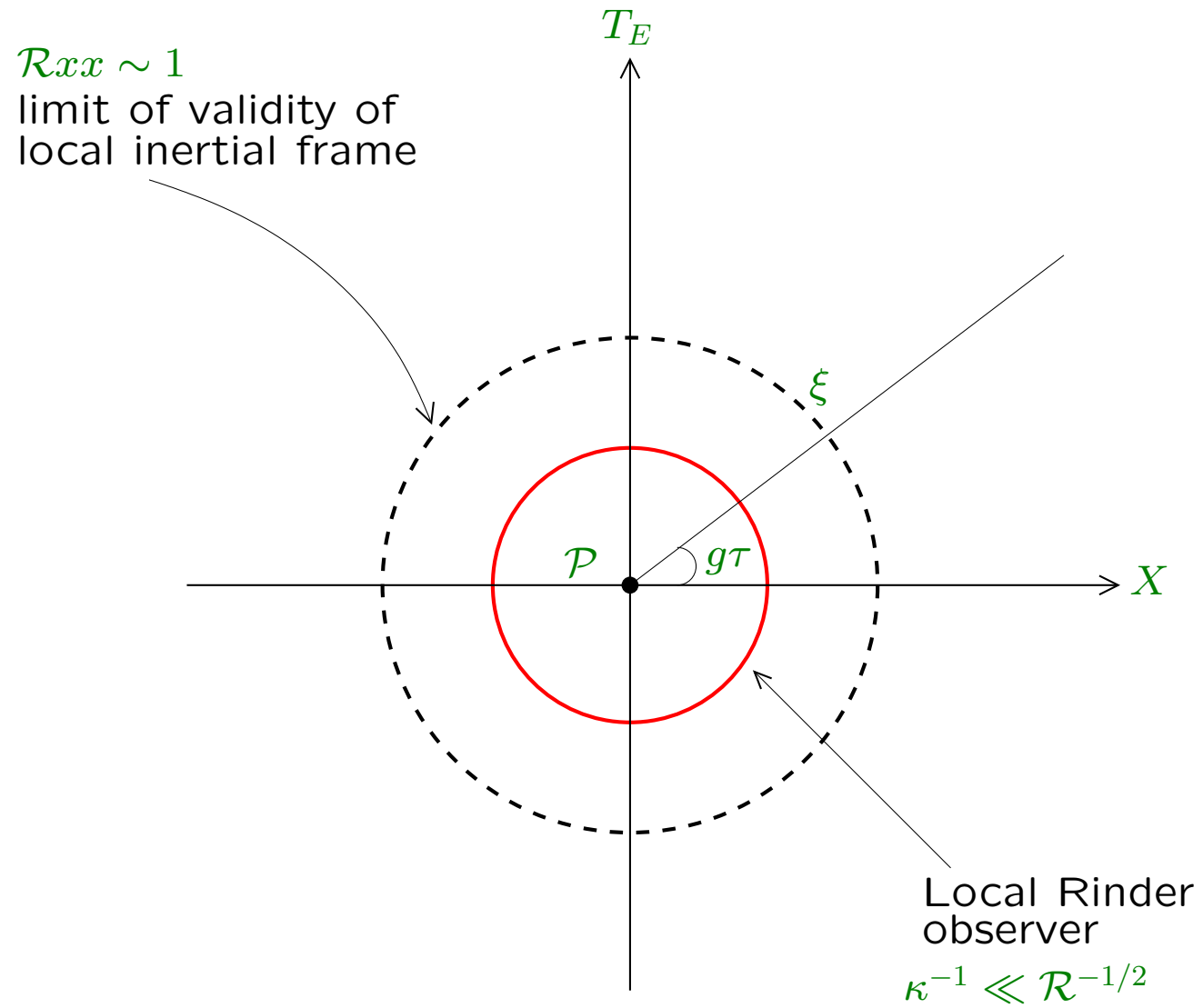


$$ds^2 = dT_E^2 + dX^2 = g^2 r^2 d\tau_E^2 + dr^2$$



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





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- The hierarchy:

$$\rho_{\text{vac}} = \left[\underbrace{\frac{1}{L_P^4}}_{\langle x \rangle}, \underbrace{\frac{1}{L_P^4} \left(\frac{L_P}{L_H} \right)^2}_{\langle x^2 \rangle^{1/2}}, \frac{1}{L_P^4} \left(\frac{L_P}{L_H} \right)^4, \dots \right]$$