GRAVITY: THE INSIDE STORY

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VR Lecture, IAGRG Meeting

Kolkatta, 28 Jan 09

CONVENTIONAL VIEW

GRAVITY AS A FUNDAMENTAL INTERACTION

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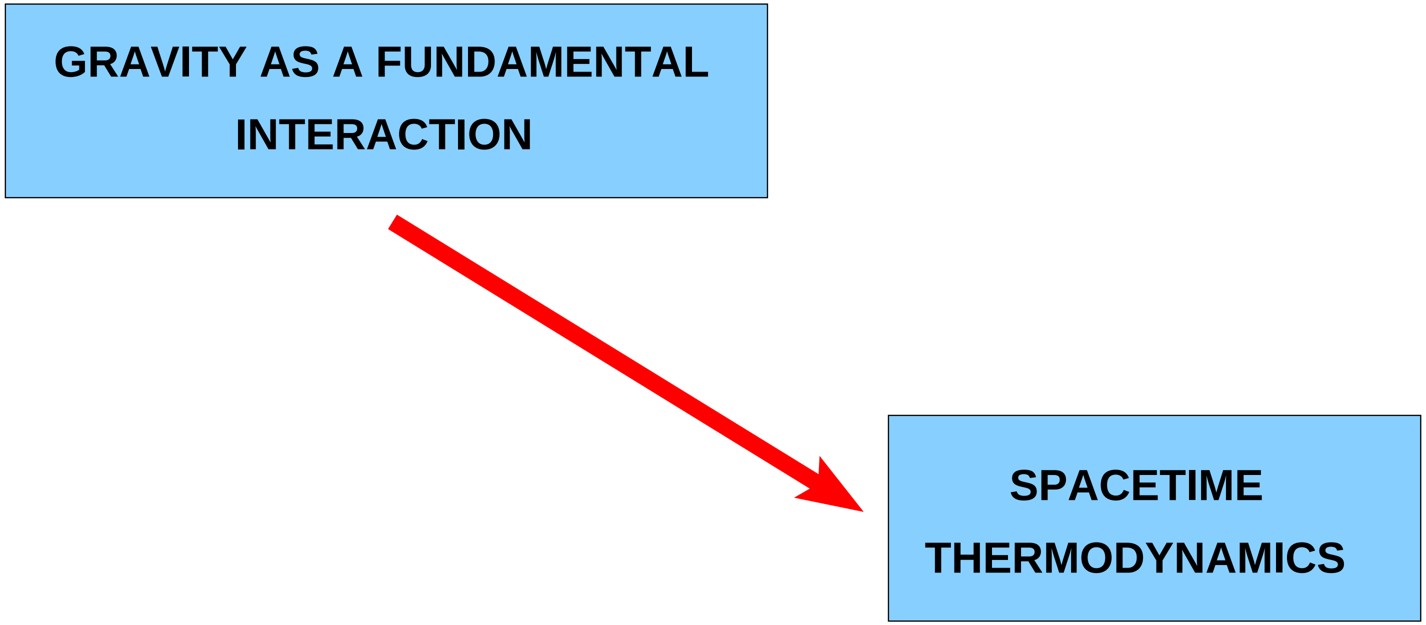
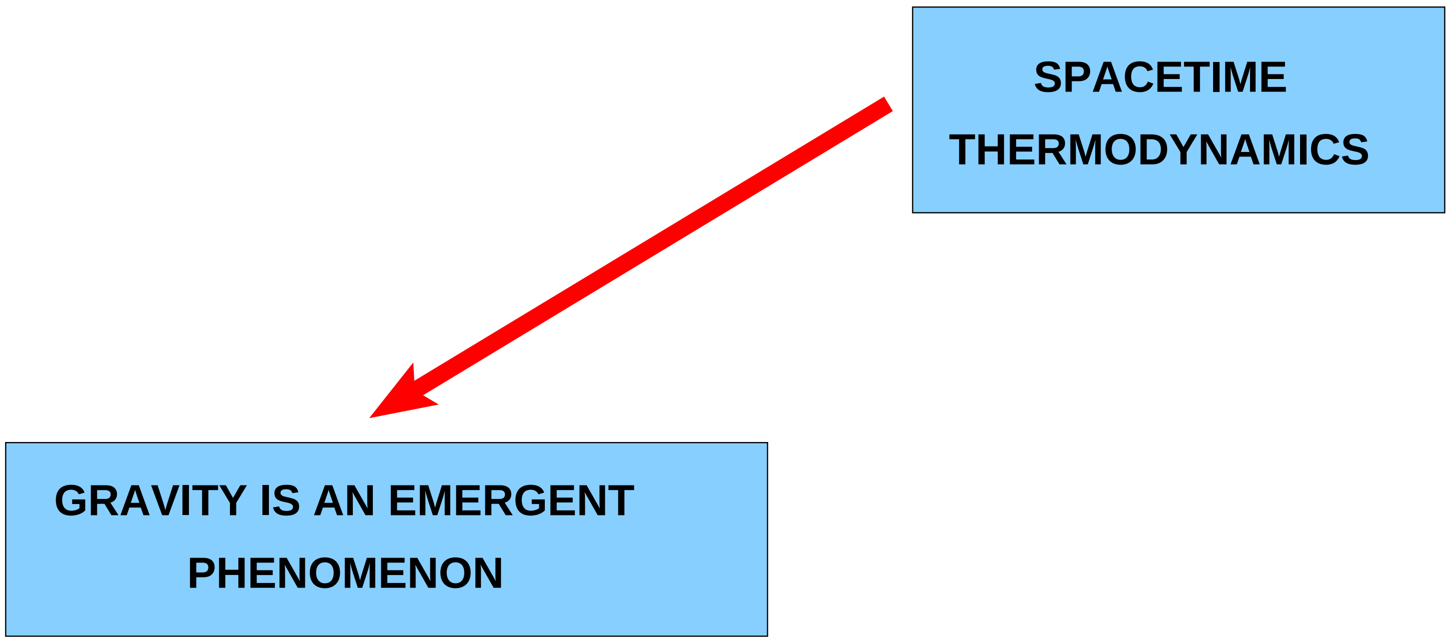


NEW PERSPECTIVE



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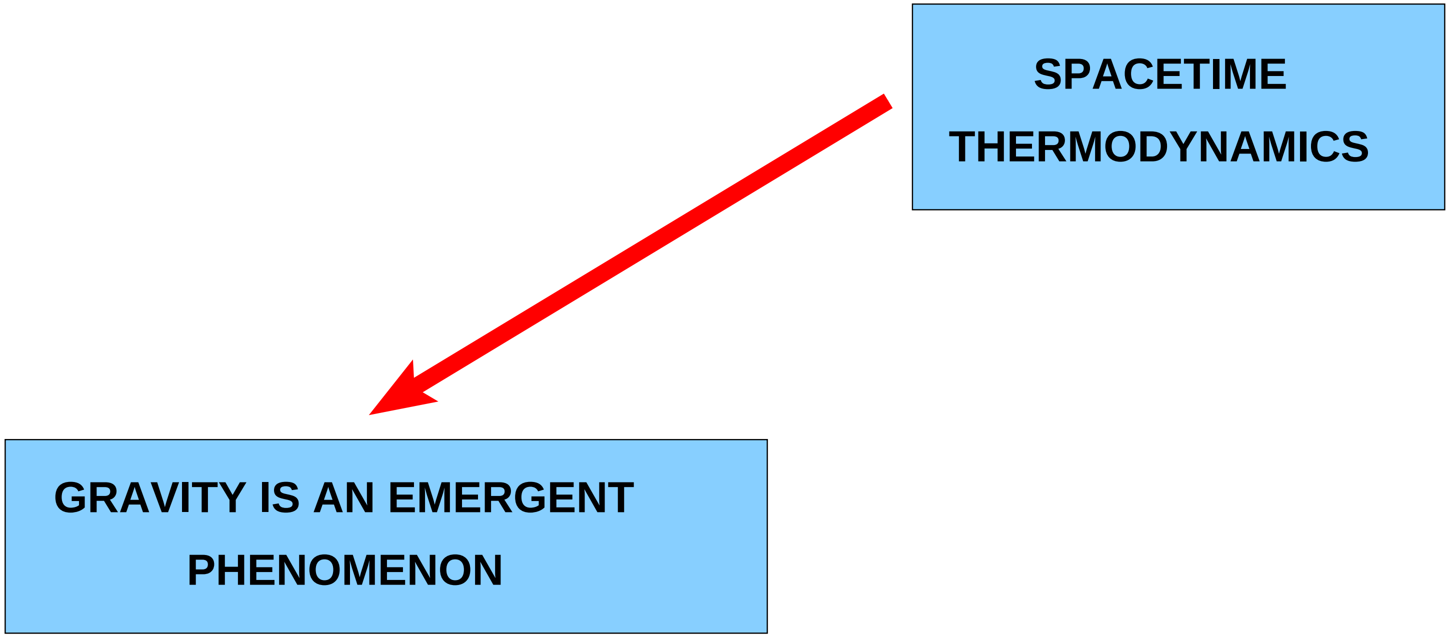

GRAVITY IS THE THERMODYNAMIC LIMIT OF THE STATISTICAL MECHANICS OF ‘ATOMS OF SPACETIME’

GRAVITY AS AN EMERGENT PHENOMENON

SAKHAROV PARADIGM

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- *You never took a course in 'quantum thermodynamics'*.

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- Rindler horizons have a temperature (1975-76)

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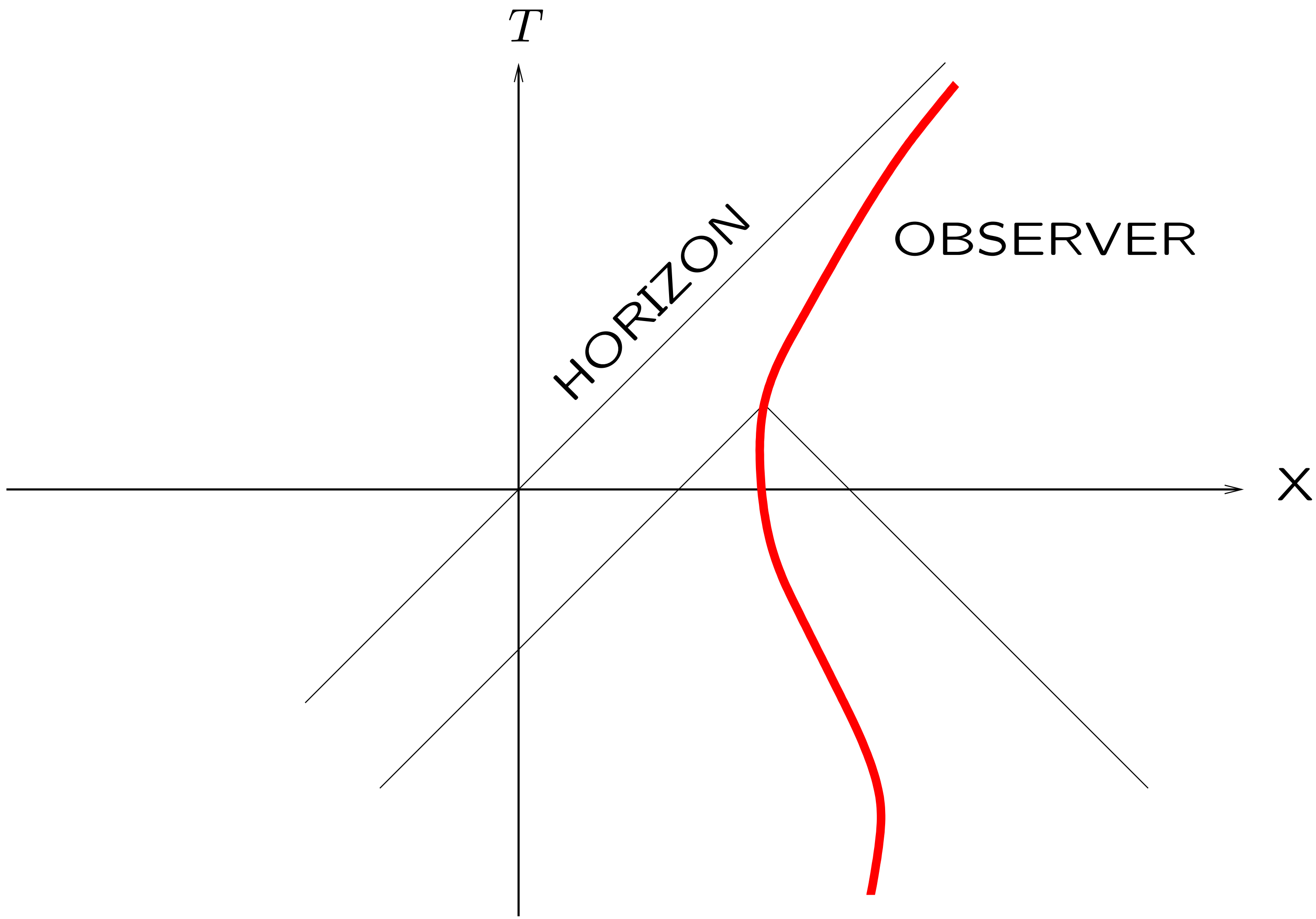

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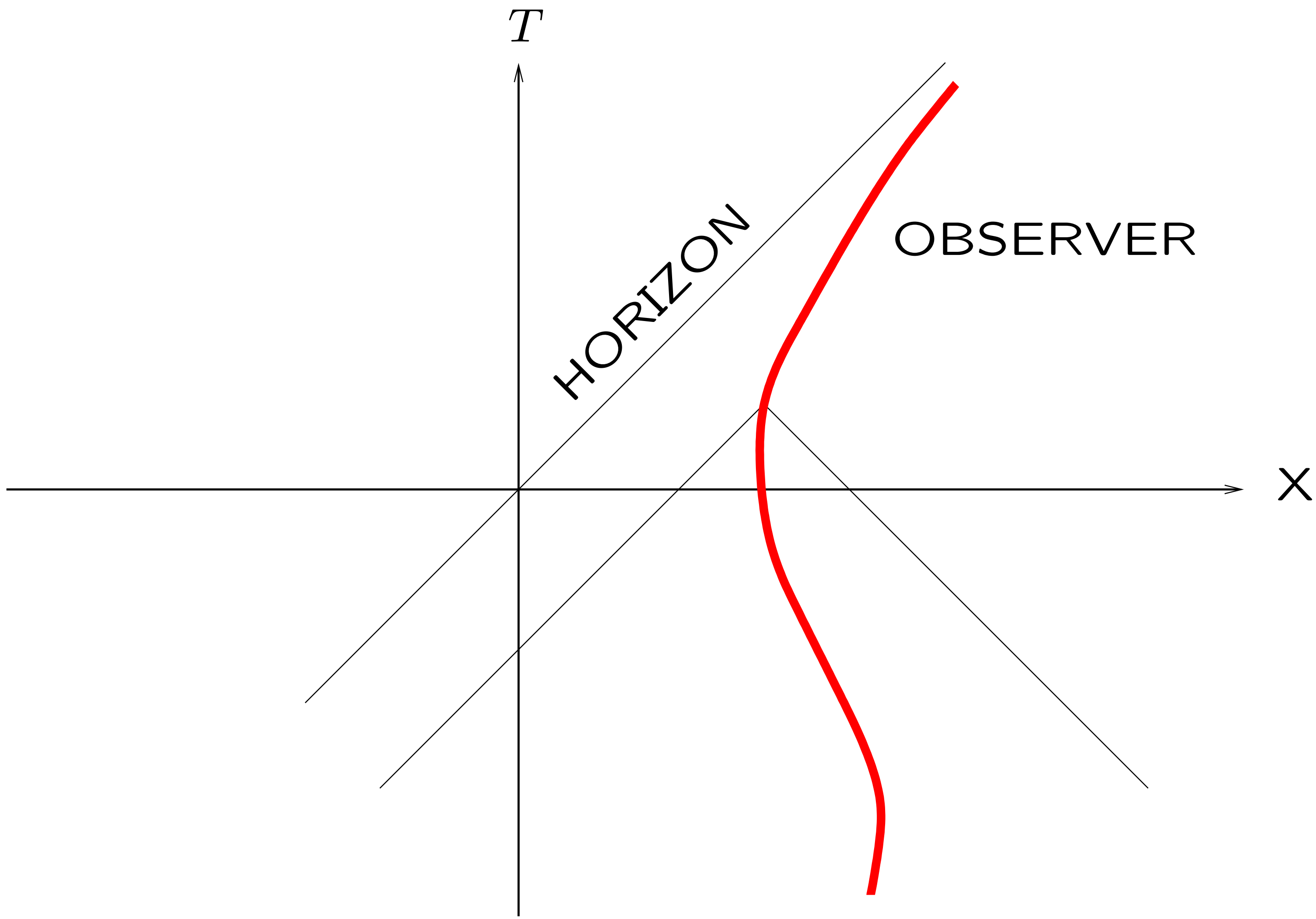

Works for Blackholes, deSitter, Rindler

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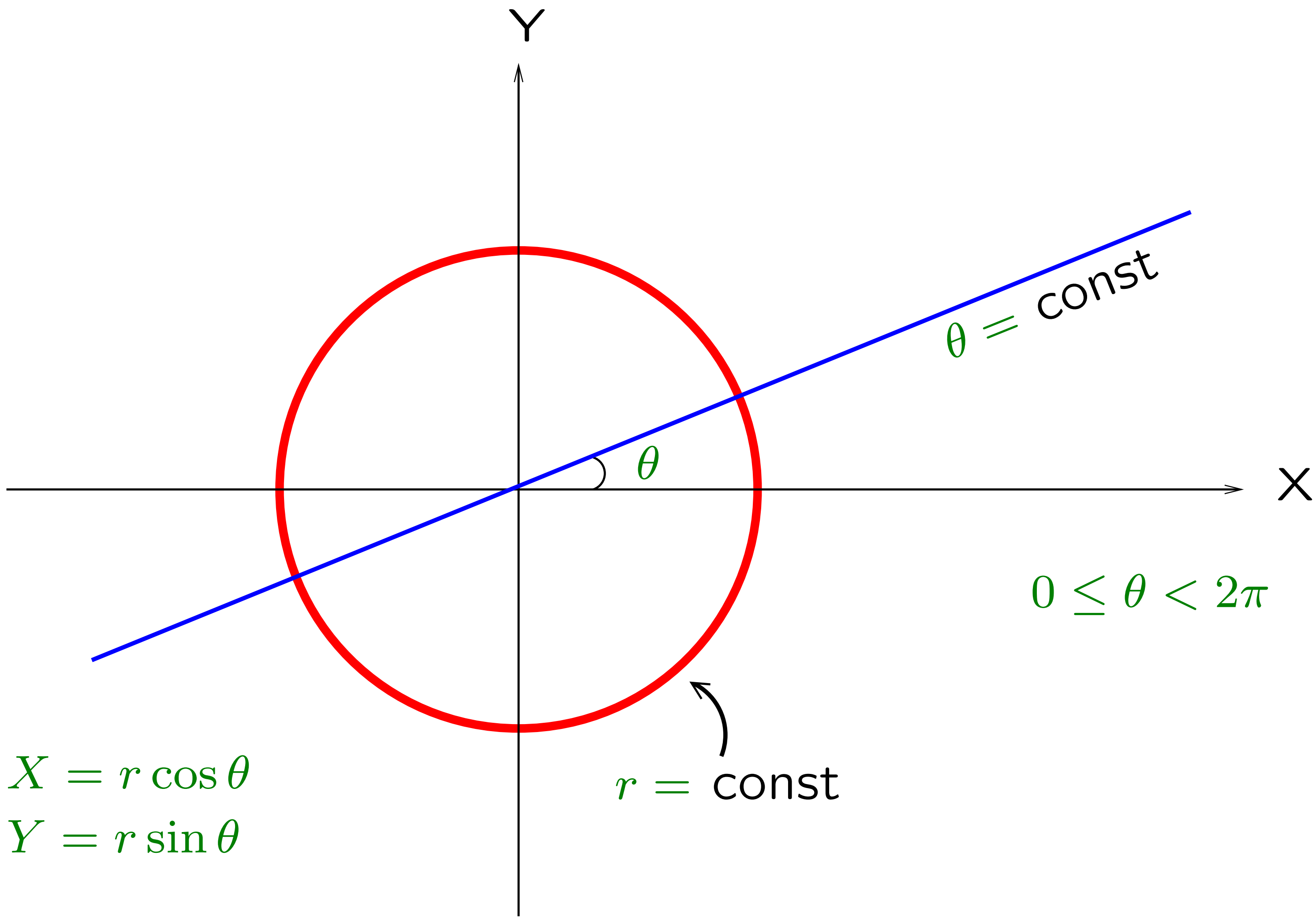

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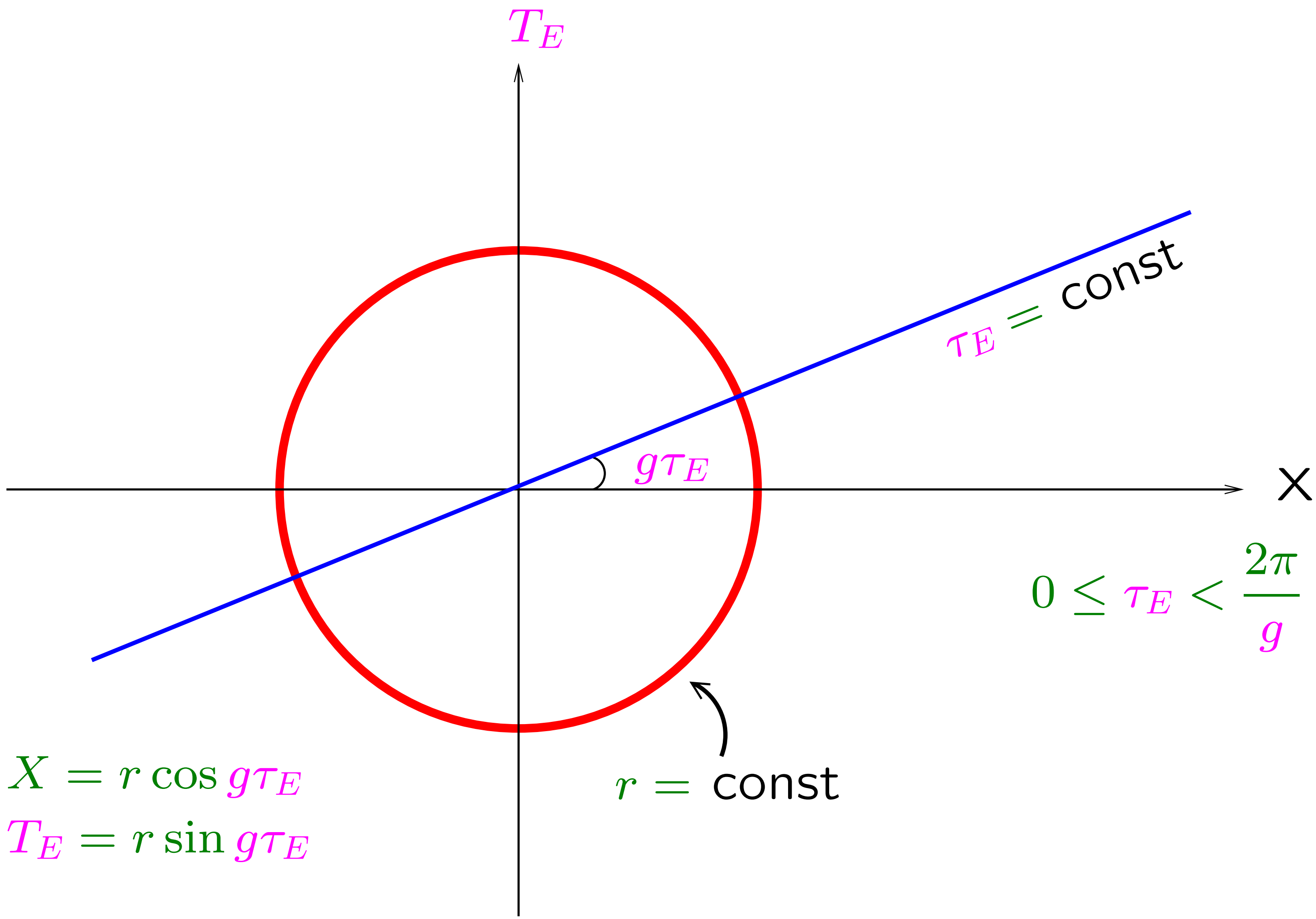

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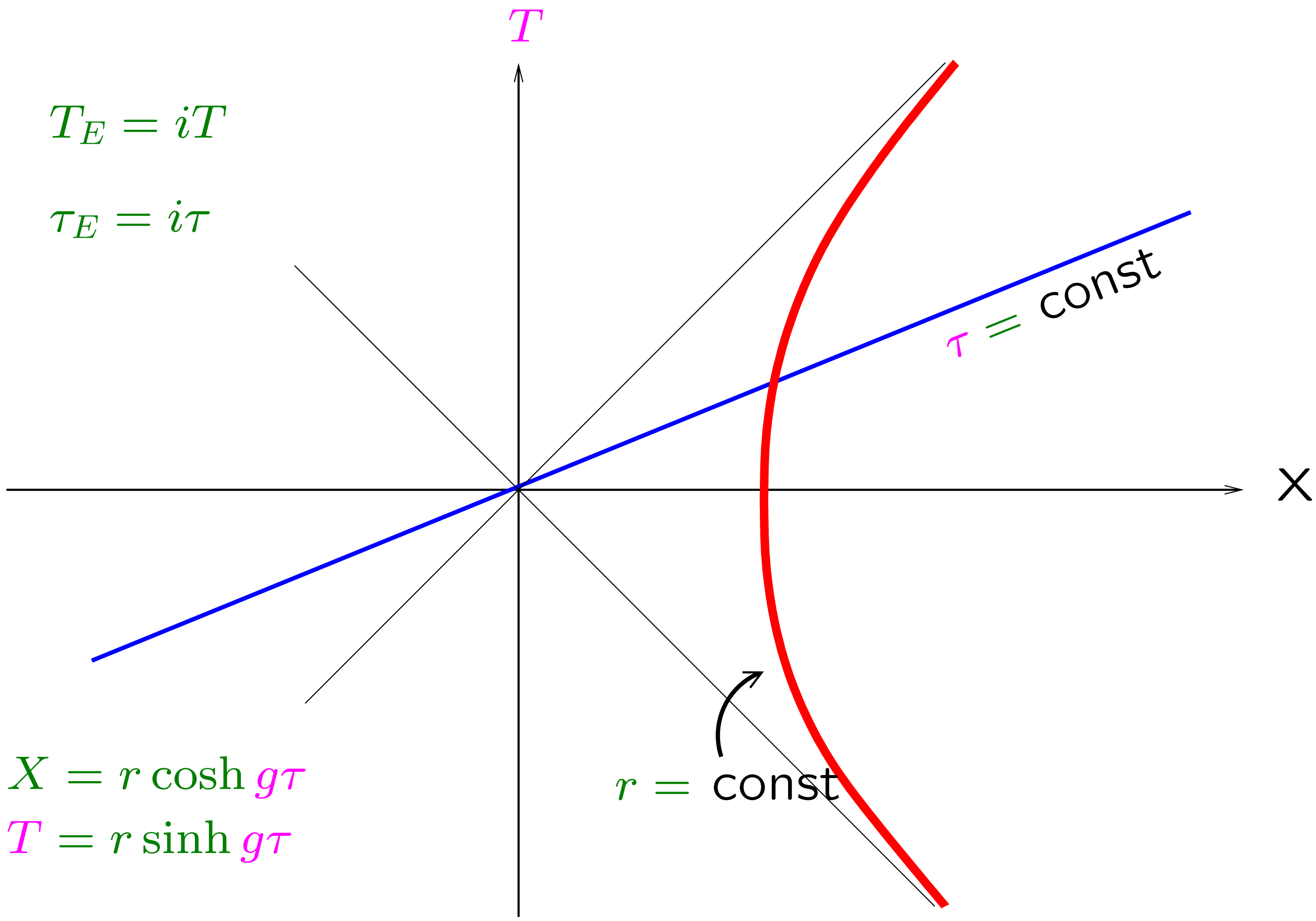

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PHYSICS PROGRESSES BY EXPLAINING FEATURES WHICH WE NEVER THOUGHT NEEDED ANY EXPLANATION !!

EXAMPLE: $m_{inertial} = m_{grav}$

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- Works for Kerr, FRW, ... [D. Kothawala et al., 06; Rong-Gen Cai, 06, 07]

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

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- In fact, one can develop a theory with $A_{total} = A_{sur} + A_{matter}$ using the virtual displacements of the horizon as key. [TP, 2005]

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- This leads to $n^a \partial_a (n^b P_b) = n^a n^b T_{ab}$ which leads to Einstein's equations!

[TP, 2005,08]

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- The Lanczos-Lovelock Lagrangian separates to a bulk and surface terms

$$\sqrt{-g} L = 2\partial_c \left[\sqrt{-g} Q_a{}^{bcd} \Gamma^a_{bd} \right] + 2\sqrt{-g} Q_a{}^{bcd} \Gamma^a_{dk} \Gamma^k_{bc} \equiv L_{\rm sur} + L_{\rm bulk}$$

and is 'holographic':

$$[(D/2) - m] L_{sur} = -\partial_i \left[g_{ab} \frac{\delta L_{bulk}}{\delta(\partial_i g_{ab})} + \partial_j g_{ab} \frac{\partial L_{bulk}}{\partial(\partial_i \partial_j g_{ab})} \right]$$

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- The D-dimensional Lanczos-Lovelock Lagrangian is a polynomial in the curvature tensor:

$$\mathcal{L}^{(D)} = Q_a{}^{bcd} R^a{}_{bcd} = \sum_{m=1}^{K} c_m \mathcal{L}_m^{(D)} \quad ; \quad \mathcal{L}_m^{(D)} = \frac{1}{16\pi} 2^{-m} \delta^{a_1 a_2 \ldots a_{2m}}_{b_1 b_2 \ldots b_{2m}} R^{b_1 b_2}_{a_1 a_2} \ldots . R^{b_{2m-1} b_{2m}}_{a_{2m-1} a_{2m}} \, ,$$

- The Lanczos-Lovelock Lagrangian separates to a bulk and surface terms

$$\sqrt{-g} L = 2\partial_c \left[\sqrt{-g} Q_a{}^{bcd} \Gamma^a_{bd} \right] + 2\sqrt{-g} Q_a{}^{bcd} \Gamma^a_{dk} \Gamma^k_{bc} \equiv L_{\rm sur} + L_{\rm bulk}$$

and is 'holographic':

$$[(D/2) - m] L_{sur} = -\partial_i \left[g_{ab} \frac{\delta L_{bulk}}{\delta(\partial_i g_{ab})} + \partial_j g_{ab} \frac{\partial L_{bulk}}{\partial(\partial_i \partial_j g_{ab})} \right]$$

- The surface term is closely related to horizon entropy in Lanczos-Lovelock theory.

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- Dynamics should now emerge from maximising $S_{matter} + S_{grav}$ for all Rindler observers!.
- Leads to gravity being an emergent phenomenon described by Einstein's equations at lowest order with calculable corrections.

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- Associate with virtual displacements of null surfaces an entropy/ action which is quadratic in deformation field: [T.P, 08; T.P., A.Paranjape, 07]

$$S[\xi] = S[\xi]_{grav} + S_{matt}[\xi]$$

with

$$S_{grav}[\xi] = \int_{\mathcal{V}} d^D x \sqrt{-g} 4P^{abcd} \nabla_c \xi_a \nabla_d \xi_b; \qquad S_{matt} = \int_{\mathcal{V}} d^D x \sqrt{-g} T^{ab} \xi_a \xi_b$$

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- Example: The lowest order term is:

$$S_1[\xi] = \int_{\mathcal{V}} \frac{d^D x}{8\pi} \left(\nabla_a \xi^b \nabla_b \xi^a - (\nabla_c \xi^c)^2 \right)$$

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- In a derivative coupling expansion, Lanczos-Lovelock terms are calculable corrections.

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- Comparison with quasi-normal modes approach shows that it is the gravitational entropy which is quantised in Lanczos-Lovelock theories.

[Kothawala, Sarkar,TP, 2008]

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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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- It also makes the variational principle for Lanczos-Lovelock theories well-defined.

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Resulting equation	Classical / Quantum	Einsteins theory with calculable corrections

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- The deep connection between gravity and thermodynamics *goes well beyond Einstein's theory.* Closely related to the holographic structure of Lanczos-Lovelock theories.

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- To go from thermodynamics to statistical mechanics, we have to postulate new degrees of freedom and an entropy functional.
- Local Rindler observers around any event attribute entropy to local patch of null surface. This is needed for consistency.
- Maximizing the entropy associated with *all* null surfaces gives Einstein's theory with Lanczos-Lovelock corrections [but not, e.g., $f(R)$ gravity].
- The deep connection between gravity and thermodynamics *goes well beyond Einstein's theory.* Closely related to the holographic structure of Lanczos-Lovelock theories.
- Connects with the radial displacements of horizons and $TdS = dE + PdV$ as the key to obtaining a thermodynamic interpretation of gravitational theories.

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- Connects with $A_{\rm sur}$ giving the horizon entropy; leads to quantisation of Wald entropy.

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