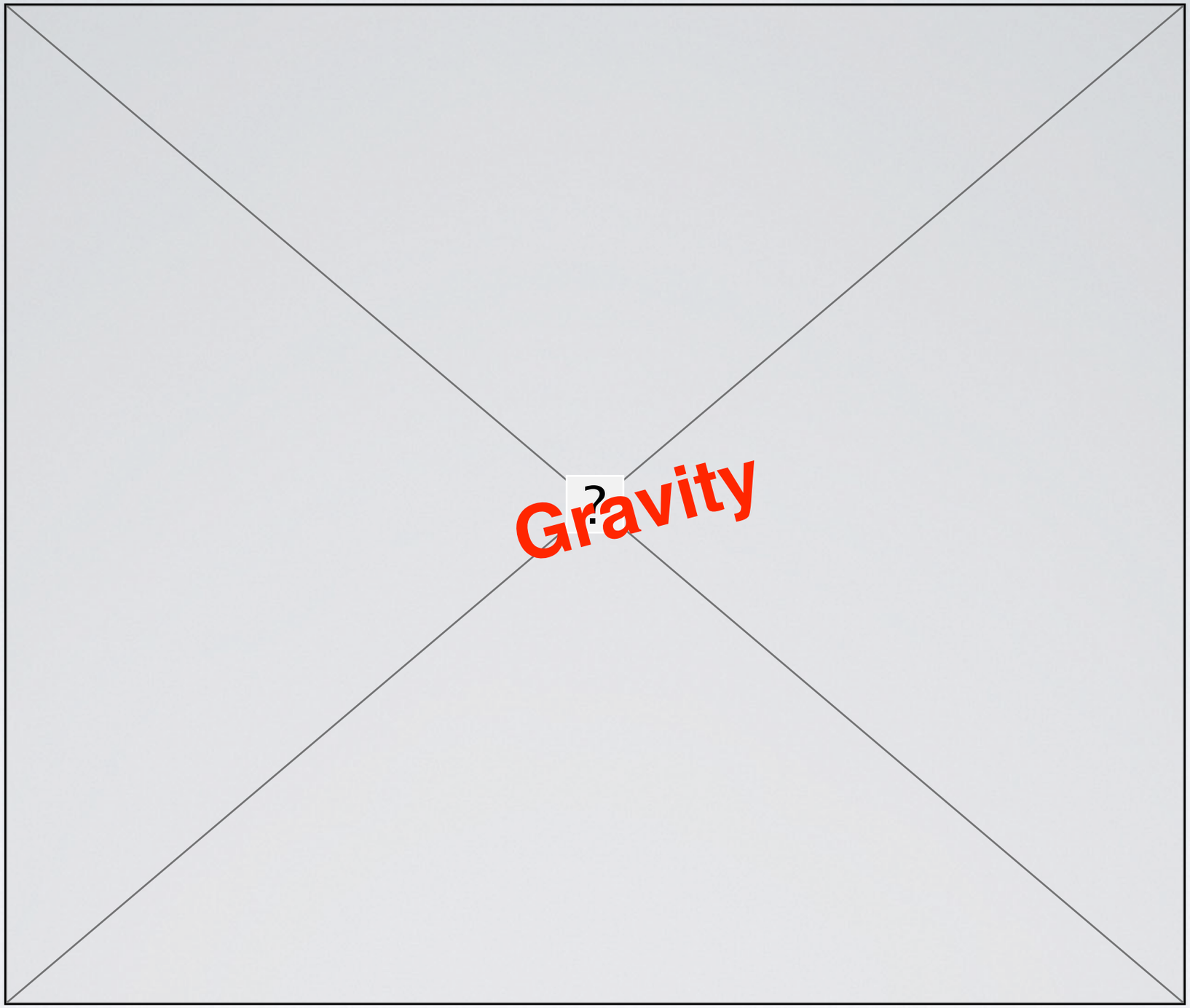
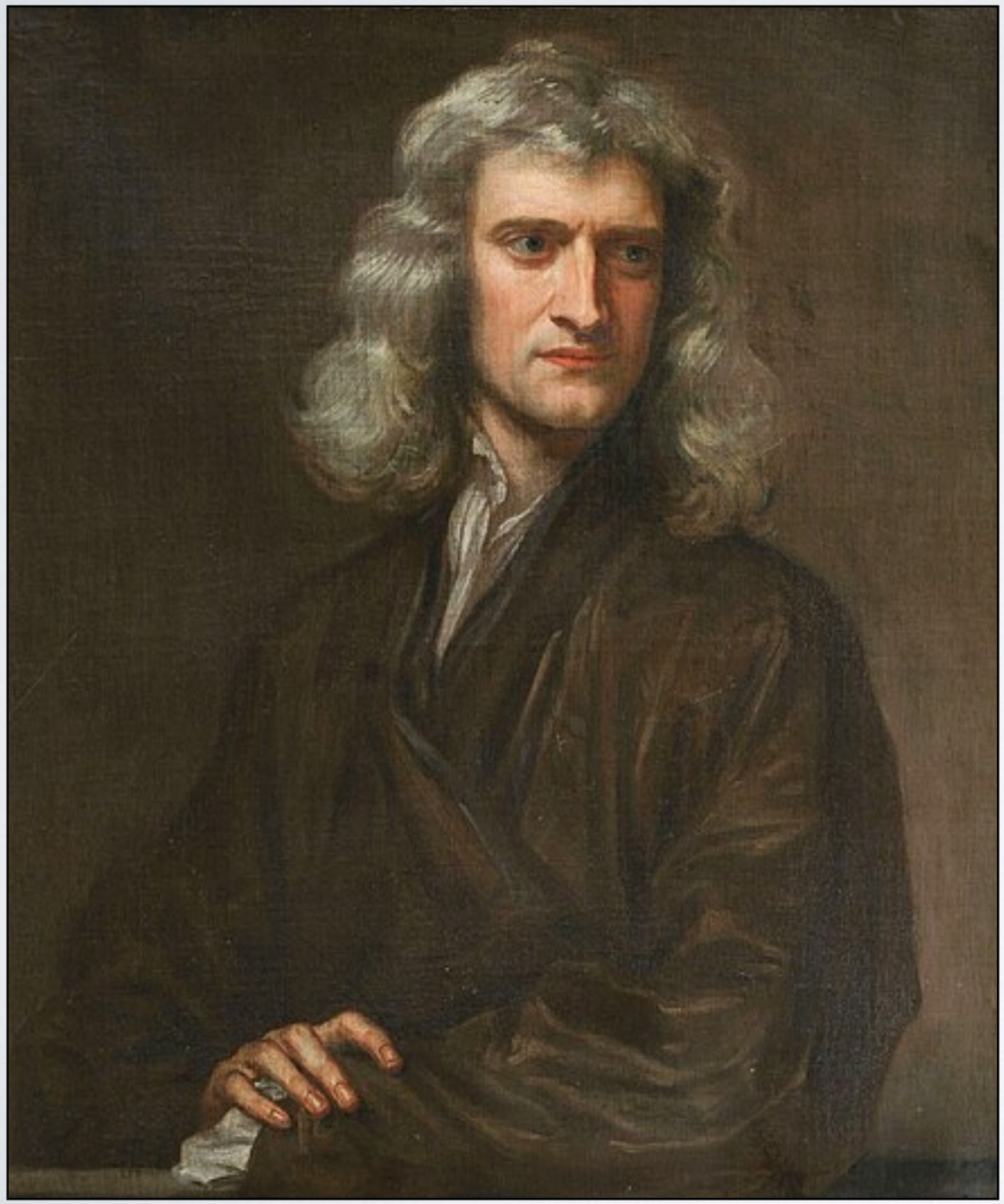


What is Gravity?

Maulik Parikh — Arizona State University

Zakopane 2024

Gravity as a Force

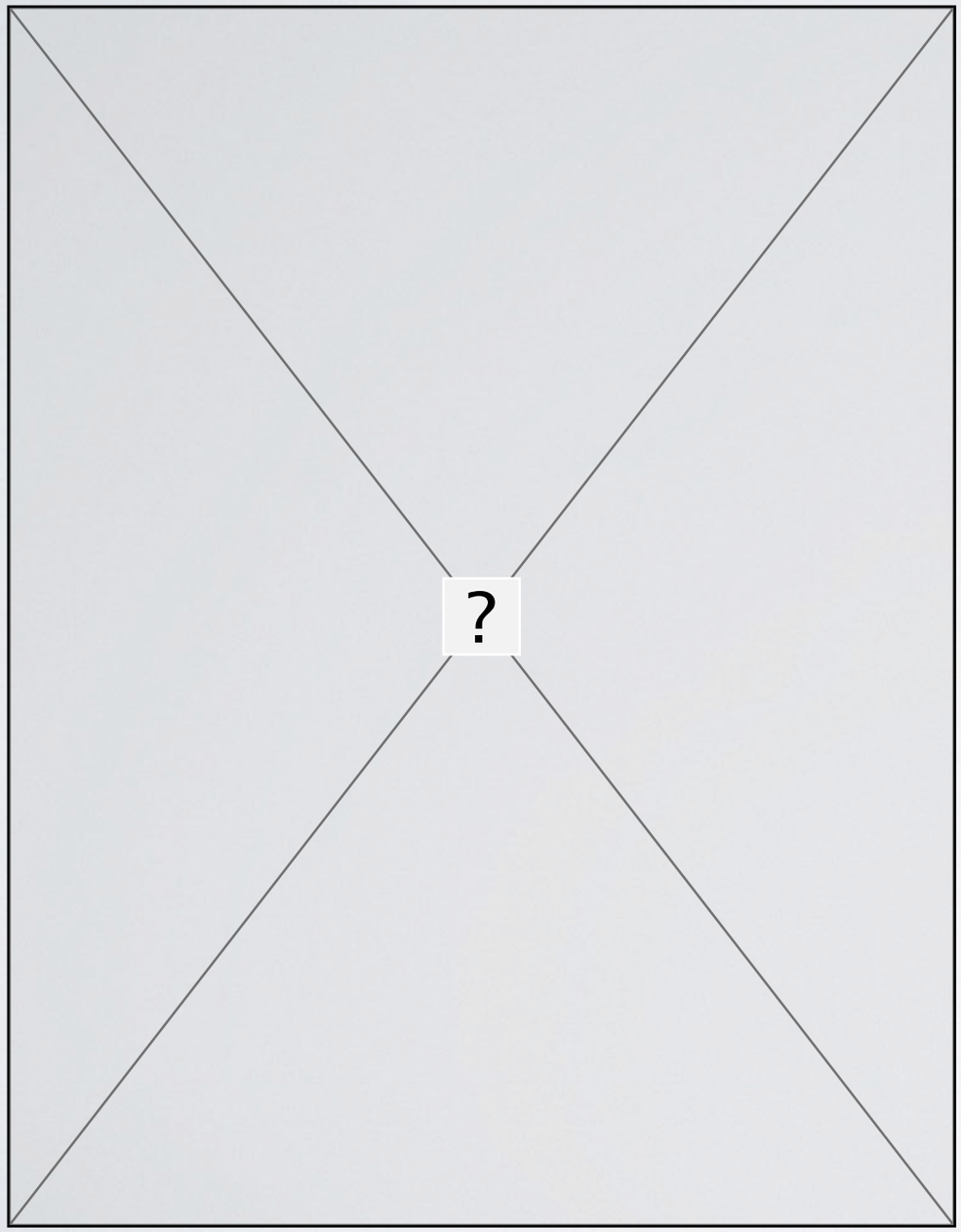


Newton, 1666

$$\vec{F} = -\frac{G_N m_1 m_2}{r^2}\hat{r}$$

Universal force
Non-relativistic
No effect on light
Non-dynamical space

Gravity as the Curvature of Spacetime



Einstein, 1915

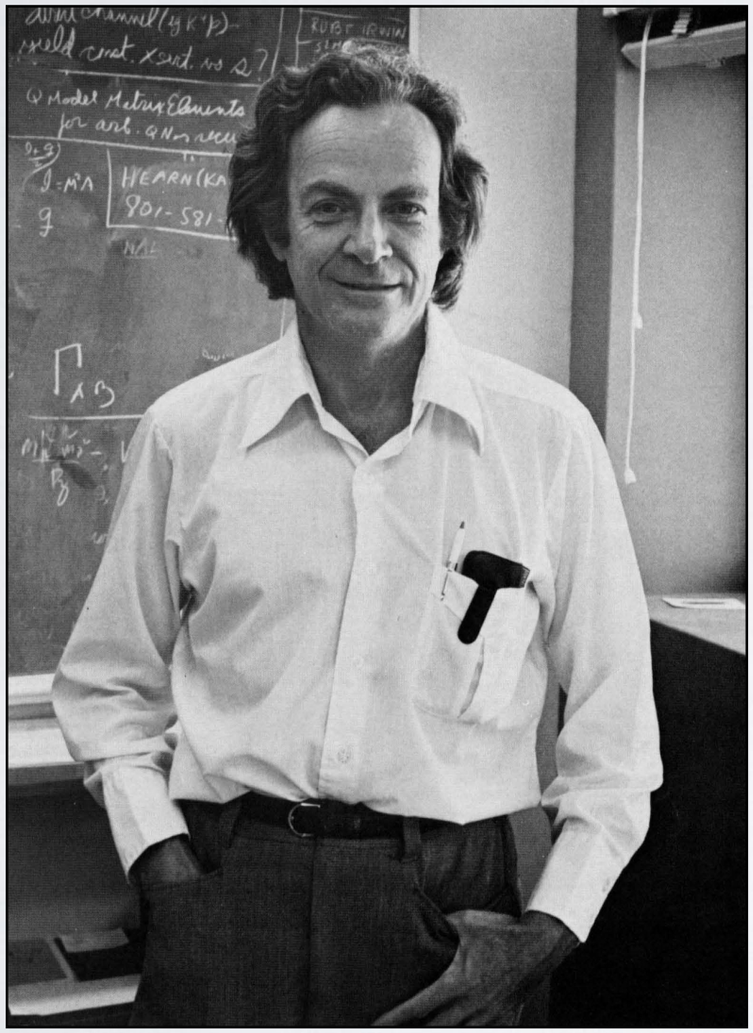
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

$$u^\alpha \nabla_\alpha u^\mu = 0$$

Principle of equivalence
Black holes
Cosmology
Gravitational waves
No comment on global topology
Classical theory
Many unphysical solutions
Theory of spacetime: distinct from other branches of physics

Gravity from Self-Interactions of a Massless Helicity-2 Particle

Feynman, 1957

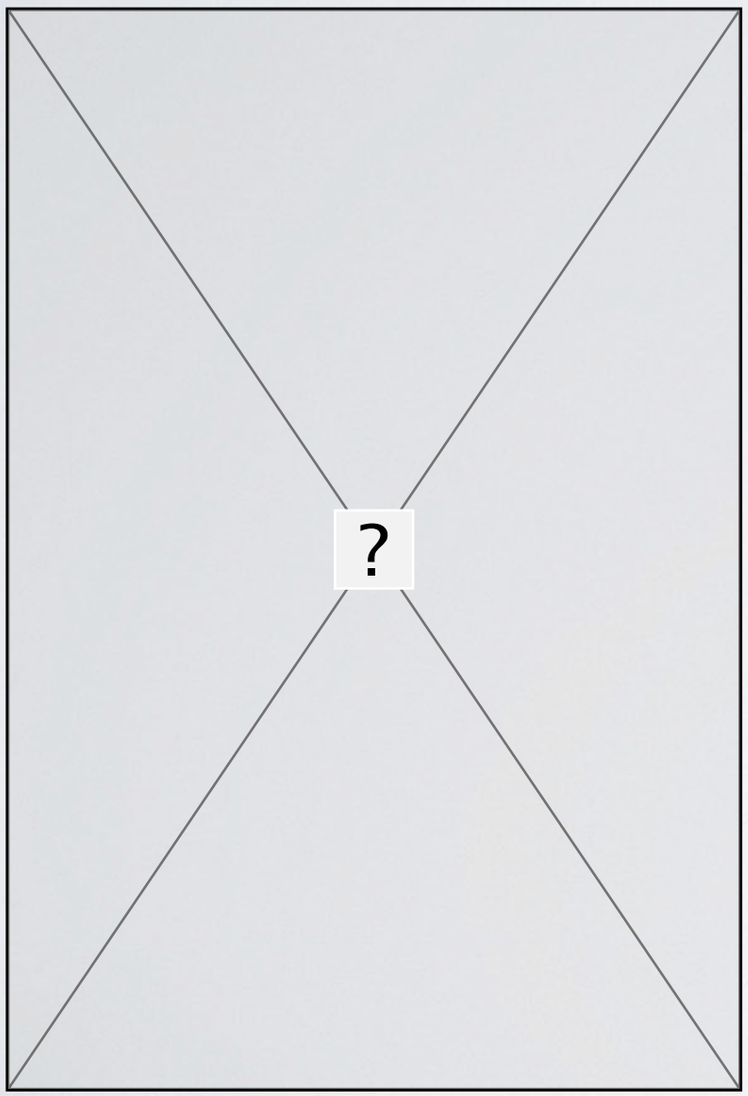


Start with a linear theory of a free massless helicity-2 particle in flat space that couples to the energy-momentum tensor

Demand that the total energy-momentum tensor be conserved, which requires adding an infinite number of extra interaction terms that sum up to the Einstein-Hilbert action

Non-geometric approach
Gravity similar to other field theories, especially non-Abelian theories
Pathway to perturbative quantization

Induced Gravity



Sakharov, 1968

Consider matter fields in a non-dynamical but curved background

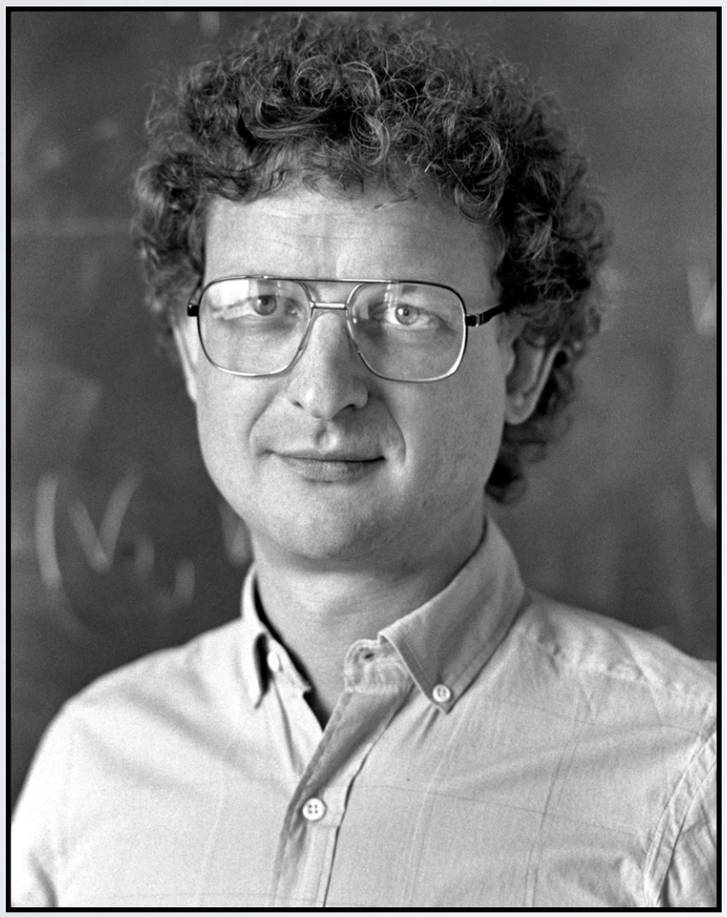
$$\Gamma_{1-\text{loop}} = \int d^4x\sqrt{-g}\left(c_0 + c_1 R(g) + c_2 R^2 + c_3 C_{abcd}C^{abcd}\right)$$

One-loop effective action of matter fields induces Lambda, R, and R^2 terms in the action, thereby making the background dynamical

Gravity is induced from the quantum theory of matter but is not itself quantized
Coefficents depend on matter content

Gravity from 2D Conformal Invariance of Strings

Friedan, 1980



Consider the world-sheet theory of a string propagating in a curved background

$$S = \frac{1}{4\pi\alpha'} \int d^2\sigma \sqrt{h} \left(g_{\mu\nu}(X) \partial_\alpha X^\mu \partial_\beta X^\nu h^{\alpha\beta} + \alpha' \Phi(X) R^{(2)} \right)$$

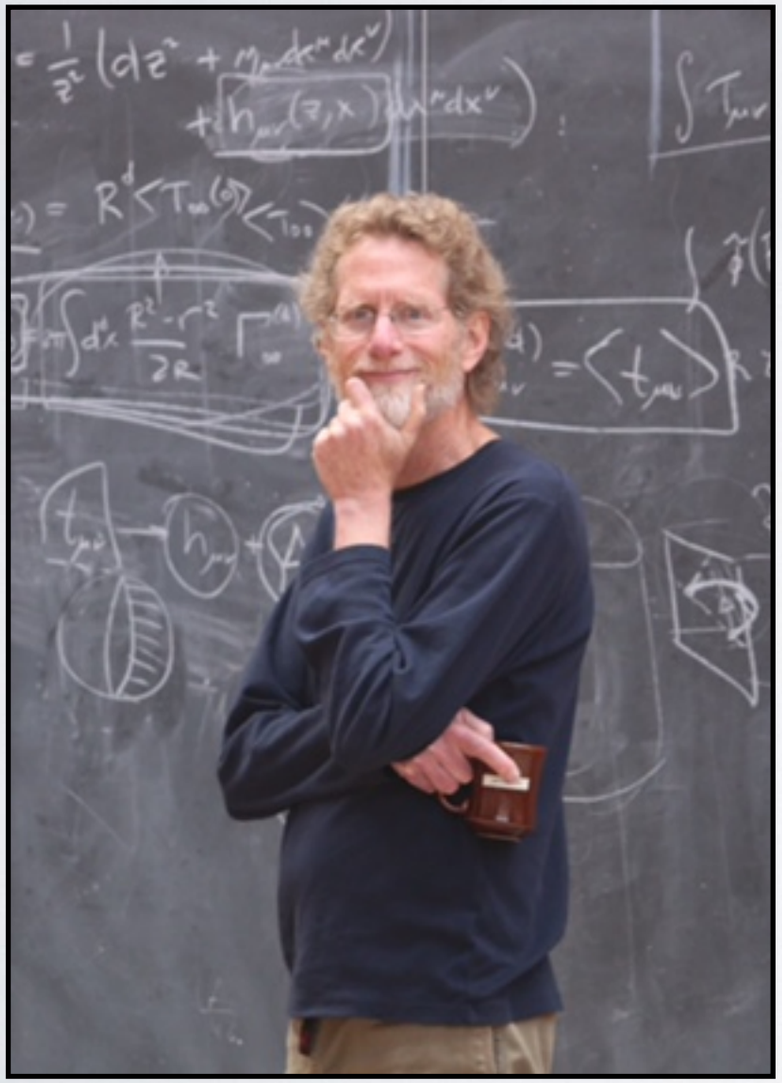
This is an interacting theory in which the spacetime metric appears as a series of interaction couplings

Conformal invariance requires vanishing of the beta-function for these couplings:

$$0 = \beta(g_{\mu\nu}) = \alpha'(R_{\mu\nu} + 2\nabla_\mu \nabla_\nu \Phi)$$

This is Einstein's equation in string (Jordan) frame

Gravity from Thermodynamics of Spacetime



Jacobson, 1995

Associate Bekenstein-Hawking entropy to the area of local null hypersurfaces:

$$S = \frac{A}{4G_N}$$

Use Raychaudhuri's equation:

$$\dot{\theta} = -R_{ab}k^a k^b \Rightarrow \theta = -R_{ab}k^a k^b \lambda$$

$$\Delta A = \int \theta d\lambda dA = -\int R_{ab}k^a k^b \lambda d\lambda dA$$

Clausius theorem:

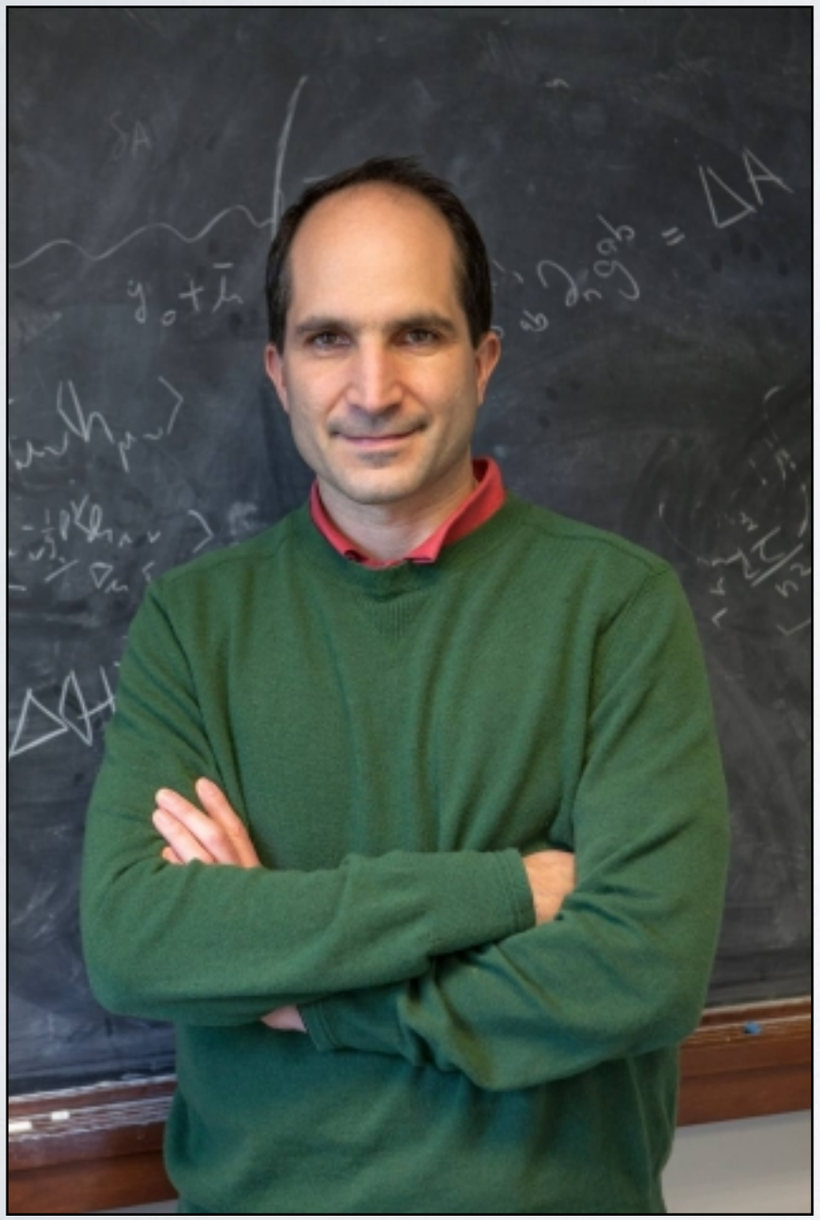
$$T\Delta S = Q \Rightarrow \frac{1}{2\pi}\frac{1}{4G_N}\int(-R_{ab}k^a k^b)\lambda d\lambda dA = -\int T_{ab}\xi^a d\Sigma^b = -\int T_{ab}k^a k^b \lambda d\lambda dA$$

$$R_{ab}k^a k^b = 8\pi G_N T_{ab}k^a k^b \Rightarrow R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = 8\pi G_N T_{ab}$$

By using Wald entropy, can also derive higher-curvature gravitational equations from local thermodynamics

Gauge-Gravity Duality

Maldacena, 1997



The AdS/CFT correspondence originated from open-closed string duality in the presence of D-branes

Both gravity and an extra dimension are emergent from the point of view of the CFT

The extra dimension has the interpretation of energy scale in the CFT

RG flow in the CFT thus maps to Hamiltonian flow in the bulk

Bulk gravity equations in Hamiltonian form arise as the RG equation of the CFT

Entropic Gravity

Verlinde, 2010

Entropic force: $F\Delta x = T\Delta S$

Unruh temperature: $T = \dfrac{\hbar a}{2\pi k_B c}$

Postulate for entropy change: $\Delta S = 2\pi k_B \dfrac{\Delta x}{\left(\frac{\hbar}{mc}\right)}$

Then $F = T\left(\dfrac{\Delta S}{\Delta x}\right) = ma$

Somewhat different postulates give
Newton's law as an entropic force
Partly just dimensional analysis
Main idea is to reverse thought
experiments that led Bekenstein to entropy

Other Points of View

Fluid-gravity duality

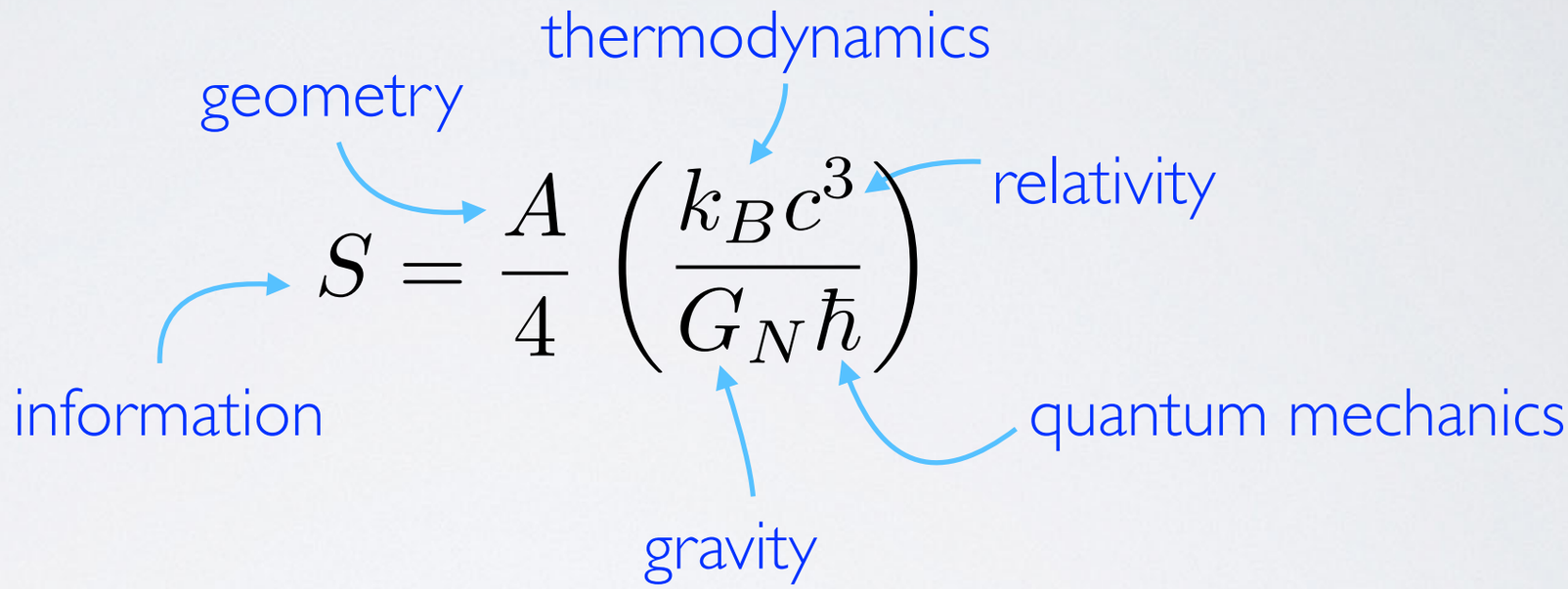
Gravity from holographic entanglement entropy

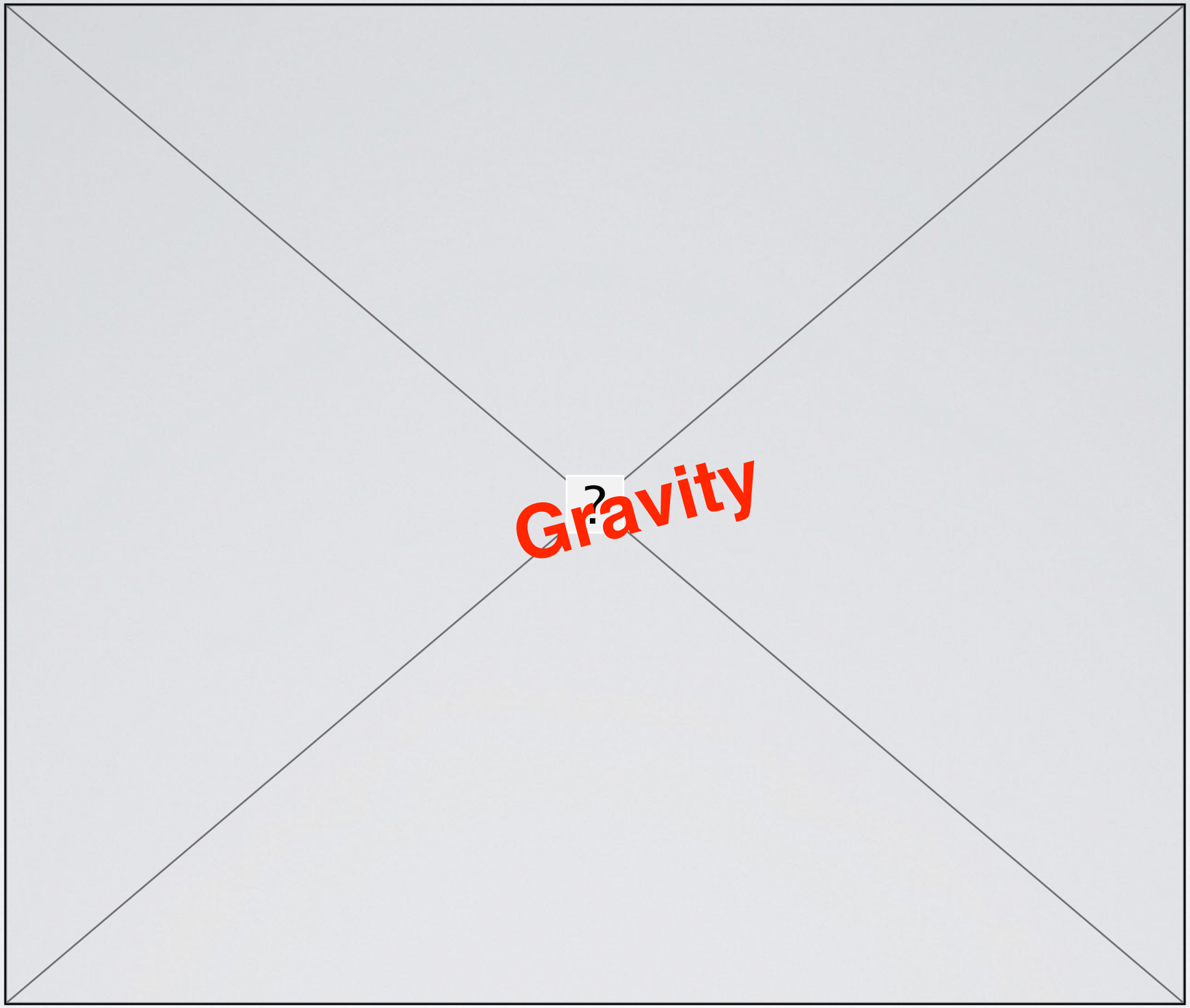
Gravity from matrix models

Gravity as a gauge theory

Gravity as a double copy of Yang-Mills theory

Why So Many Derivations?





What is Gravity?

It's an induced holographic thermodynamic renormalization group universal force curving spacetime entropically via a massless helicity-2 particle.

Obviously.