



# THE PHYSICS OF INTERSTELLAR

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# GRAVITATIONAL LENSING OF SPINNING (KERR) BLACK HOLES



Spoiler alert!

”...BUT THEY CONSTRUCTED THIS 3-DIM.  
(DIMENSIONAL) SPACE INSIDE THEIR 5-DIM. REALITY  
TO ALLOW YOU TO UNDERSTAND IT...”



# EINSTEIN'S THEORY OF GENERAL RELATIVITY

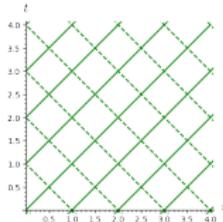
$$R_{ab} - \frac{1}{2}g_{ab}R = 8\pi G_N T_{ab}$$

$$S_{\text{Einstein-Hilbert}}[g] = \int_M \sqrt{-g}R$$

# METRIC $g$

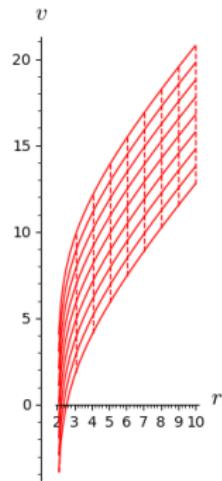
Minkowski metric (flat)

$$g = -dt^2 + dx^2 + dy^2 + dz^2$$



Schwarzschild (static, non-spinning black hole) metric

$$g = -d\tau^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2)$$



# QUANTUM FIELD THEORY (THE STANDARD MODEL)

## The Standard Model

$$\begin{aligned}\mathcal{L}_{fg} = & \frac{-1}{4} G_{\mu\nu}^\alpha G^{\alpha\mu\nu} - \frac{1}{4} W^{a\mu\nu} W_{\mu\nu}^a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{g_3^2 \Theta_3}{64\pi^2} \epsilon_{\mu\nu\lambda\rho} G^{\alpha\mu\nu} G^{\alpha\lambda\rho} \\ & - \frac{g_2^2 \Theta_2}{64\pi^2} \epsilon_{\mu\nu\lambda\rho} W^{a\mu\nu} W^{a\lambda\rho} - \frac{g_1^2 \Theta_1}{64\pi^2} \epsilon_{\mu\nu\lambda\rho} B^{\mu\nu} B^{\lambda\rho} - \frac{1}{2} \bar{L}_m \not{D} L_m \\ & - \frac{1}{2} \bar{E}_m \not{D} E_m - \frac{1}{2} \bar{Q}_m \not{D} Q_m - \frac{1}{2} \bar{U}_m \not{D} U_m - \frac{1}{2} \bar{D}_m \not{D} D_m\end{aligned}$$

in which gauge field-strengths given by

$$G_{\mu\nu}^\alpha = \partial_\mu G_\nu^\alpha - \partial_\nu G_\mu^\alpha + g_3 f_{\beta\gamma}^\alpha G_\mu^\beta G_\nu^\gamma$$

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_2 \epsilon_{abc} W_\mu^b W_\nu^c$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$+ \mathcal{L}_{\text{Higgs}}$$

# QUANTUM FIELD THEORY (SYMMETRY)

Invariance of Lagrangian under symmetries

$$\delta L_m = \left[ \left( \frac{-i}{2} \omega_1(x) + \frac{i}{2} \omega_2^a(x) \tau_a \right) P_L + \left( \frac{i}{2} \omega_1(x) - \frac{i}{2} \omega_2^a(x) \tau_a^* \right) P_R \right] L_m$$

$$\delta E_m = [i\omega_1(x)P_L - i\omega_1(x)P_R]E_m$$

$$\begin{aligned} \delta Q_m = & \left[ \left( \frac{i}{6} \omega_1(x) + \frac{i}{2} \omega_2^a(x) \tau_a + \frac{i}{2} \omega_3^\alpha(x) \lambda_\alpha \right) P_L + \right. \\ & \left. + \left( -\frac{i}{6} \omega_1(x) - \frac{i}{2} \omega_2^a(x) \tau_a^* - \frac{i}{2} \omega_3^\alpha(x) \lambda_\alpha^* \right) P_R \right] Q_m \end{aligned}$$

$$\delta U_m = \left[ \left( \frac{-2i}{3} \omega_1(x) - \frac{i}{2} \omega_3^\alpha(x) \lambda_\alpha^* \right) P_L + \left( \frac{2i}{3} \omega_1(x) \frac{i}{2} \omega_3^\alpha(x) \lambda_\alpha \right) P_R \right] U_m$$

$$\delta D_m = \left[ \left( \frac{i}{3} \omega_1(x) - \frac{i}{2} \omega_3^\alpha(x) \lambda_\alpha^* \right) P_L + \left( -\frac{i}{3} \omega_1(x) + \frac{i}{2} \omega_3^\alpha(x) \lambda_\alpha \right) P_R \right] D_m$$

$$\delta G_\mu^\alpha = \partial_\mu \omega_3^\alpha(x) - f_{\beta\gamma}^\alpha \omega_3^\beta(x) G_\mu^\gamma$$

$$\delta W_\mu^a = \partial_\mu \omega_2^a(x) - \epsilon^{abc} \omega_2^b(x) W_\mu^c$$

$$\delta B_\mu = \partial_\mu \omega_1(x)$$

Symmetry groups

$$\begin{array}{ccccccc} SU_c(3) \times & SU_L(2) \times & U_Y(1) & & & U_{\text{em}} & \\ \downarrow & \downarrow & \downarrow & & & \downarrow & \\ 8G_\mu^\alpha & 3W_\mu^a & B_\mu & & & \gamma & \\ \alpha = 1, \dots, 8 & a = 1, 2, 3 & & & & & \end{array}$$

# INFORMATION, ENTROPY, AND BLACK HOLES

Entropy

(Information Theory)

$$H(X) := - \sum_{x \in X} p(x) \log_2 p(x)$$

(Classical)

(Quantum)

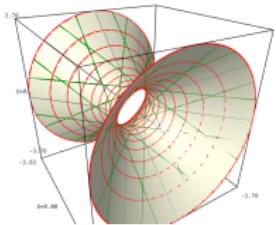
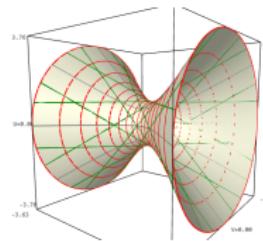
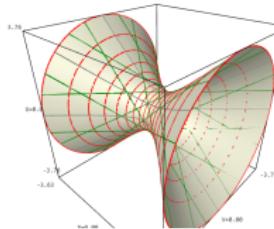
$$S = - \sum p_i \ln p_i \quad S = -\text{Tr}(\rho \ln \rho)$$

Black hole entropy

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

# ADS/CFT CORRESPONDENCE VIA HOLOGRAPHIC PRINCIPLE

# ANTI-DE SITTER (AdS) SPACE; "THE BULK"



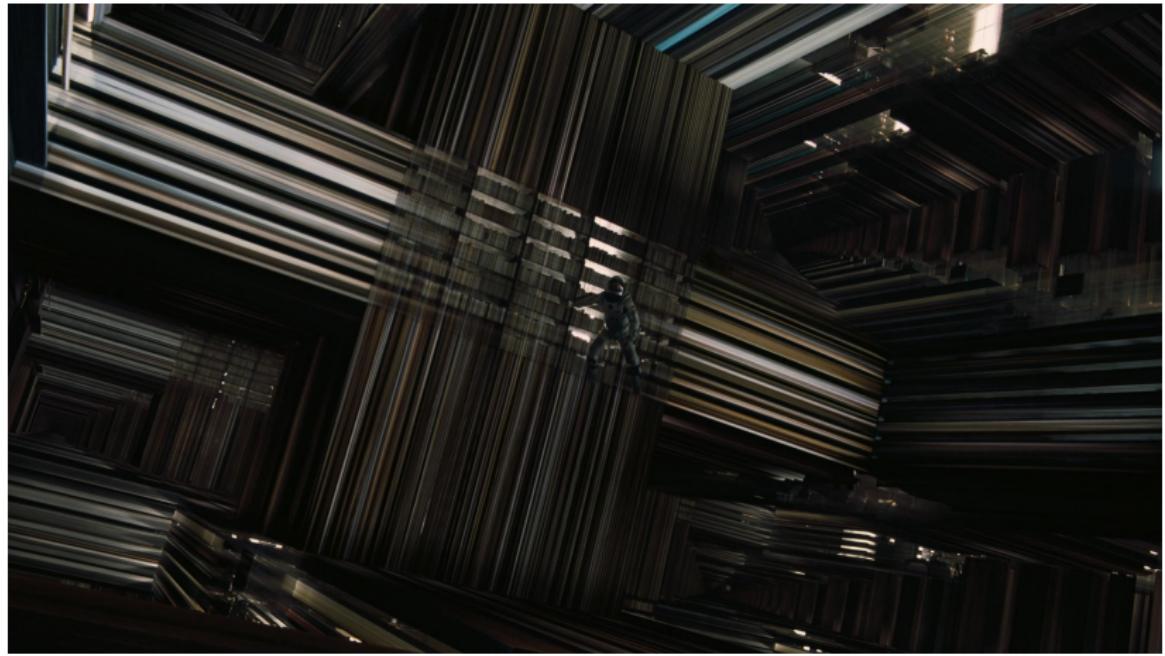
$$g = -dt^2 + \sum_{i=1}^4 dx_i^2$$

A coordinate patch for half-space:

$$ds^2 = \frac{1}{y^2} \left( -dt^2 + dy^2 + \sum_i dx_i^2 \right)$$

# CFT (CONFORMAL FIELD THEORY)

TESSERACT  $\subset$   $AdS_5$



# HOW DID COOPER MESSAGE MURPH FROM THE TESSERACT

1. Graviton
2. EPR (Einstein-Podolsky) pair

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# NEW DIRECTIONS FOR QUANTIZATION

1. Brane Quantization
2. BV QQuantization