The Physics of Interstellar

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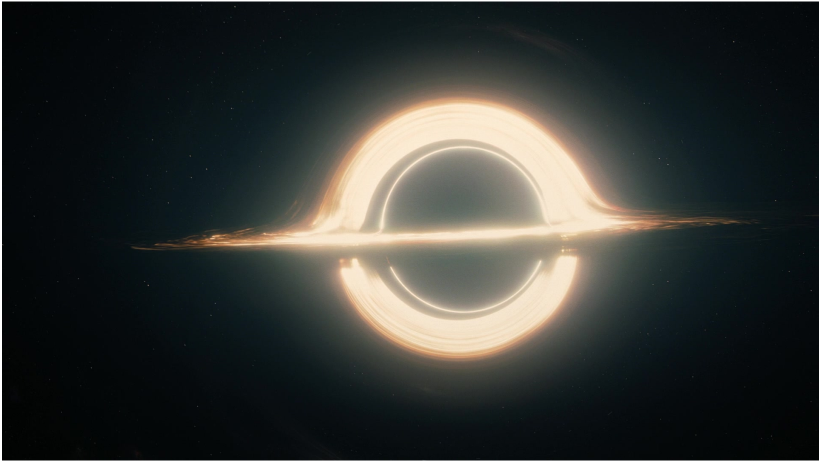
Gravitational lensing of spinning (Kerr) black holes



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

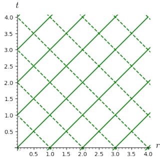
$$R_{ab} - \frac{1}{2} g_{ab} R = 8\pi G_N T_{ab}$$

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

Metric g

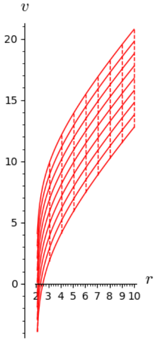
Minkowski metric (flat)

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



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

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

in which gauge field-strengths given by

$$
\begin{aligned}
G^{\alpha}_{\mu\nu} &= \partial_\mu G^{\alpha}_{\nu} - \partial_\nu G^{\alpha}_{\mu} + g_3 f^{\alpha}_{\beta\gamma} G^{\beta}_{\mu} G^{\gamma}_{\nu} \\
W^{a}_{\mu\nu} &= \partial_\mu W^{a}_{\nu} - \partial_\nu W^{a}_{\mu} + g_2 \epsilon_{abc} W^{b}_{\mu} W^{c}_{\nu} \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu
\end{aligned}
$$

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

Quantum Field Theory (Symmetry)

Invariance of Lagrangian under symmetries

$$
\begin{aligned}
\delta L_m &= \left[\left(\frac{-i}{2}\omega_1(x) + \frac{i}{2}\omega_2^a(x)\tau_a\right)P_L + \left(\frac{i}{2}\omega_1(x) - \frac{i}{2}\omega_2^a(x)\tau_a^*\right)P_R\right]L_m \\
\delta E_m &= [i\omega_1(x)P_L - i\omega_1(x)P_R]E_m \\
\delta Q_m &= \left[\left(\frac{i}{6}\omega_1(x) + \frac{i}{2}\omega_2^a(x)\tau_a + \frac{i}{2}\omega_3^\alpha(x)\lambda_\alpha\right)P_L + \right. \\
&\quad \left. + \left(-\frac{i}{6}\omega_1(x) - \frac{i}{2}\omega_2^a(x)\tau_a^* - \frac{i}{2}\omega_3^\alpha(x)\lambda_\alpha^*\right)P_R\right]Q_m \\
\delta U_m &= \left[\left(\frac{-2i}{3}\omega_1(x) - \frac{i}{2}\omega_3^\alpha(x)\lambda_\alpha^*\right)P_L + \left(\frac{2i}{3}\omega_1(x)\,{}_{\frac{i}{2}}\,\omega_3^\alpha(x)\lambda_\alpha\right)P_R\right]U_m \\
\delta D_m &= \left[\left(\frac{i}{3}\omega_1(x) - \frac{i}{2}\omega_3^\alpha(x)\lambda_\alpha^*\right)P_L + \left(-\frac{i}{3}\omega_1(x) + \frac{i}{2}\omega_3^\alpha(x)\lambda_\alpha\right)P_R\right]D_m \\
\delta G_\mu^\alpha &= \partial_\mu\omega_3^\alpha(x) - f^\alpha_{\beta\gamma}\omega_3^\beta(x)G_\mu^\gamma \\
\delta W_\mu^a &= \partial_\mu\omega_2^a(x) - \epsilon^{abc}\omega_2^b(x)W_\mu^c \\
\delta B_\mu &= \partial_\mu\omega_1(x)
\end{aligned}
$$

Symmetry groups

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

Information, Entropy, and Black Holes

Entropy

(Information Theory)

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

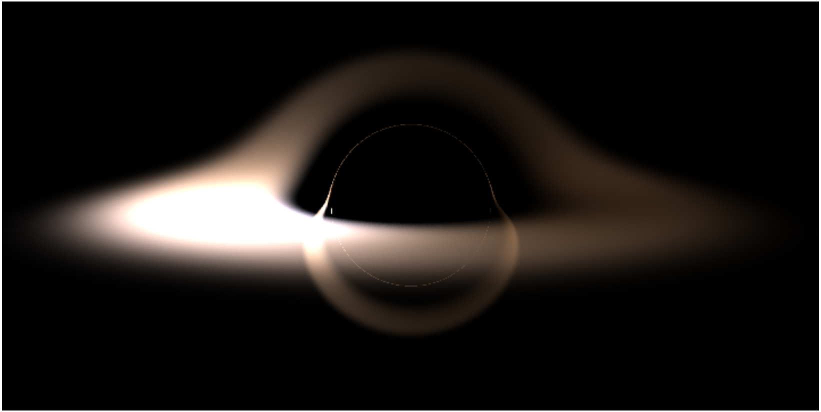
(Classical) (Quantum)

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

Black hole entropy

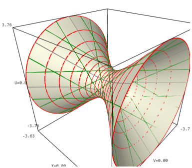
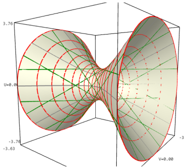
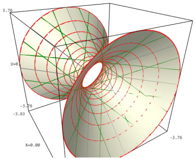
$$S = \frac{A}{4G}$$

AdS/CFT correspondence via The Holographic principle



"Description of a bulk of space is encoded on boundary to bulk"

Anti-de Sitter (AdS) space; "The Bulk"

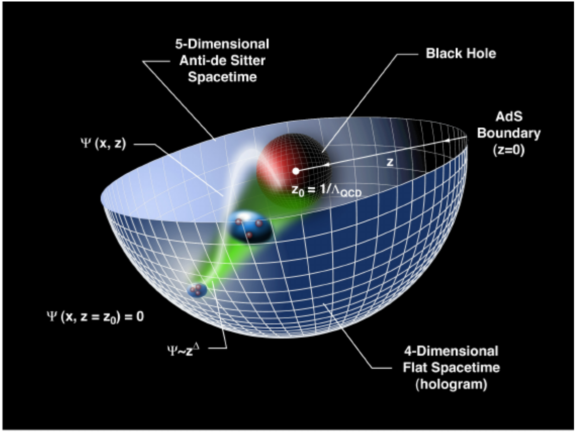
$$g = -dt^2 + \sum_{i=1}^{4} dx_i^2$$

A coordinate patch for half-space:

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

An example of the AdS/CFT correspondence

Quantum Field Theory in d dimensions	AdS/CFT duality $\Longleftrightarrow$ Holographic duality	String theory in $(d+1)$-dim. Anti-de Sitter space
$\mathcal{N}=4$ Super Yang-Mills with gauge group in $SU(N)$		Type IIB String theory on $AdS_5 \times S_5$



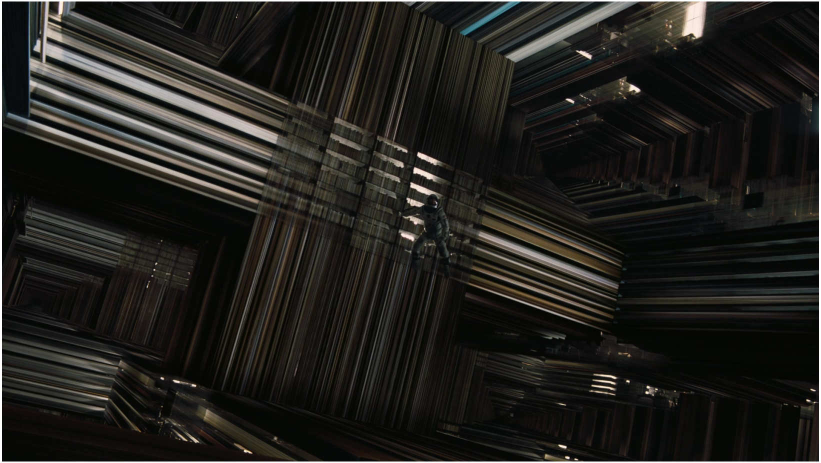
Hints in the movie "Interstellar"

Controls won't work here. We're passing through the **bulk** - space beyond our 3 dims. All we can do is record and observe.

Hints in the movie "Interstellar"

Cooper: The beings who led us here. They communicate through gravity, right? ... *Brand*: They are beings of 5 dimensions - to them time might be another physical dimension.

Tesseract $\subset AdS_5$



Messaging from the Tesseract $\subset$ bulk, 1

TARS: You've seen that time is represented here as a physical dimension - you've worked out that you can exert a force across spacetime.

Messaging from the Tesseract $\subset$ bulk, 2

Cooper: The watch. That's it. We encode the data into the movement of the second hand. TARS, Translate the data into Morse and feed it to me.

How did Cooper message Murph from the tesseract

1. on AdS_5 metric
   - gravity field
   - Graviton (massless, spin-2 boson)
2. EPR (Einstein-Podolsky) pair
   - EPR = ER

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New directions for quantization

1. Brane Quantization
2. BV QQuantization