THE PHYSICS OF INTERSTELLAR - ADS/CFT AND THE TESSERACT

ERNEST YEUNG ERNESTYALUMNI@GMAIL.COM

Contents

Abstract.

Part 1.

Date: 25 juillet 2022.
Key words and phrases. AdS/CFT.

Part 2. Talk

1. Talk

Hi, my name is Ernest Yeung, and today I'm talking to you about the Physics of Interstellar.

Now, if you haven't seen the movie yet, I strongly encourage you to do so, because it has our most scientifically accurate depictions of a black hole.

And so they got a lot of physics right including the Gravitational lensing effect in General Relativity, where light from stars and galaxies behind the black hole come at us, gets bent coming around the black hole, and then focus into the camera to form the image we see.

So I strongly encourage you to watch it, it derives the images of the black hole from Einstein's field equations and the wormhole sequences.

But I want to talk to you about today is the part of the movie that bothers people, that raises the most questions, that people say no way, but I'm here to say there's a way.

And spoiler alert! It's after Cooper, played by Matthew McConaughey, falls into the black hole and enters the tesseract.

1.1. Einstein's Theory of General Relativity.

Now there are 2 cornerstones of modern physics I need to introduce to you. The first is Einstein's General Relativity.

This is Einstein's field equation, which tells us that mass-energy, on the right, curves spacetime, on the left, the curvature given by the Ricci Curvature Tensor and Ricci scalar.

The bottom equation is the Einstein-Hilbert action and physicists use it to calculate geodesics, paths of least distance, least time in curved spacetime, how stars, planets, rockets would travel freely in curved spacetime. It was also in the movie on the chalkboard of Professor Brand in the movie.

1.1.1. *Metric g.*

A concept out of our short visit into General Relativity is a metric; think of it like a ruler, measuring distances in space and time. Usually the ruler doesn't change in time and space, so we say spacetime is flat, its curvature is 0.

For a black hole, the metric depends on how close you are to the black hole, and so spacetime gets more curved as you approach the black hole. In this particular case, the curvature is positive since the black hole is spherically symmetric.

1.2. Quantum Field Theory.

The second cornerstone of modern physics I want to introduce to you is Quantum Field Theory. And I wanted to show you this huge equation, the Lagrangian, in Quantum Field Theory, because this tells us all of how all the fundamental forces in nature, except for gravity, works, the strong, the weak, and electromagnetic forces, tells us everything that comes out of the Large Hadronic Collider, of how stars, planets, atoms, matter, us are kept together.

One idea I want to introduce is that of symmetry. What does it mean to say something is symmetrical? If you take a vase and rotate it around, it doesn't change shape, because it's symmetrical. If I take my right hand and look at it in the mirror, it now looks like my left hand, so it's not symmetrical under a mirror. So we can abstract this and say if you do something to something and it doesn't change, then it's symmetrical under that transformation. And so physicists found that the huge Lagrangian I showed before, if you plug in these changes to the respective fields, terms add and cancel each other out such that the Lagrangian doesn't change! So we call them symmetries and it's what gives us the particles for the strong, weak, electromagnetic forces, that exchange forces.

1.3. Information, Entropy, and Black Holes.

One more ingredient I'll introduce is the relationship between information, entropy, and black holes.

So what's information? What's data, what makes a signal? We can define what's useful data against what's noise, and quantify how likely, the probability, of getting useful information that's not noise with what's called the Shannon entropy.

This Shannon entropy is formally equal to the entropy in classical and quantum physics, and to remind you entropy is a measure of disorder, your clean room has a lower entropy than a messy room that can be messy in many ways.

Now what about black holes?

Stephen Hawking and Jacob Bekenstein calculated that the entropy of a black hole is proportional to its surface area; its surface area and not its volume.

It's as if all the entropy or information about the black hole, its mass, electric charge, angular momentum, spin, was encoded on its 2 dim. surface, so that this 3-dim. black hole is a hologram of its surface!

1.4. AdS/CFT Correspondence via the Holographic Principle.

We can extend this idea to say that a "Description of a bulk of space is encoded onto the boundary of the bulk" the holographic principle. AdS/CFT is the technical term for this and what I use mostly.

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

The shape of the 5-dimensional bulk I want to present is called AdS or anti-de Sitter space. It's a solution to Einstein's field equations, and has negative curvature so it's inside out, and I think its surface is on the inside.

1.6. An Example of the AdS/CFT Correspondence.

So we have this holographic duality between quantum field theory, that huge equation I showed before, on the left side, living on the 4-dim. spacetime boundary surface of, on the right side, an anti-de Sitter space in 5 dimensions.

1.7. Hints in the movie "Interstellar".

So I'm watching this movie for the first time, and as Cooper and the team go through the wormhole the first time, a scientist tells Cooper they're passing through the bulk and I thought no way they're talking about the same bulk in AdS/CFT because physicists use it as a technical term.

And then after Cooper and Brand land on the first planet, they talk about communicating through the 5-dimensional bulk, and I thought no way were they talking about AdS_5 space and relating it to entropy and information theory.

But when I first saw the scene of Cooper in the tesseract I thought my God this is our best depiction of the AdS/CFT correspondence. Because the tesseract is 4-dimensional hypercube, in space, with 3-dimensional cubes in space as faces. And Cooper is inside those 3-dimensional spatial cubes, because he's a 3-dimensional being with his matter governed by the laws of quantum field theory.

1.8. Messaging from the Tesseract.

So there are 2 types of messaging from the tesseract: first, Cooper was able to hit on the bookshelves and exert a force and young Murph sees the falling books. Second type of messaging was the watch, where Cooper was able to push on the tesseract to move the second hand.

1.9. **How did Cooper Message Murph from the Tesseract.** For the first type, Cooper is exerting a gravitational force across the 5-dim. spacetime of the AdS_5 space. We know that the Einstein field equations allow for gravity waves to propagate and they're able to propagate at shorter distances because of the negative curvature of AdS_5 space. The only problem I have with it is force in a quantum theory has a particle associated to it, and that particle, a graviton, massless, spin-2 boson, would have to follow a null-like geodesic and might not be able to go back in time to Murph.

Restart, rebirth, reimagination, your reawakening

2. Drafts

I'm going to throw around a lot of technical terms because I am not going to pull any punches.

2.1. **Gravitational Lensing of Spinning (Kerr) Black Holes.** If you haven't seen the movie yet, I strongly encourage you to do so, because it has our most scientifically accurate depictions of a black hole, and why they are our most scientifically accurate depictions of a black hole is because Nobel Prize winning Professor Kip Thorne derived the geodesic equations directly from the Einstein field equations; and then the special effects team under Christoper Nolan and Paul Franklin coded those solutions to generate the bundle of light rays that propagate through the curved spacetime of a spinning or "Kerr" black hole and into an arbitrarily moving camera, forming the image we see.

And so the movie does a great job showing the effects of the Doppler and gravitational frequency shifts, the bending of light rays due to gravitational lensing from General Relativity, so that you can see stars and galaxies lying behind the black hole, and even camera lens flare.

2.2. **Einstein's General Relativity.**

2.3. **Quantum Field Theory.** An example of a quantum field theory is what's called the standard model of particle physics.

The second cornerstone of modern physics and another of our greatest intellectual achievements is quantum field theory. Now what is quantum? Quantum means a minimum amount, an indivisible unit, usually of energy.

And from Quantum Field Theory I want you to get 2 concepts. 1 of them being Quantum, because in quantum mechanics, atoms and molecules and electrons don't behave like particles or like bouncing billiard balls but both a particle and a wave, light itself is both a particle called the photon and an electromagnetic wave, electrons and protons aren't described by definitive positions and velocities but with probabilities; there's a chance that an electron could be inside a box and a chance that it might not be there; things are uncertain.

Concept number 2 is symmetry. How do we define symmetry? If you take a vase and you rotate it around, it still looks like a vase! If you take something and apply a transformation like that rotation and it doesn't change, then you say it has a symmetry, it's symmetrical under rotation or a transformation. Physicists say this equation, the Lagrangian for the Standard Model, has symmetry under what are called gauge transformations; you plug in these gauge transformations, these substitutions into these fields, and the covariant derivatives and terms add up, cancel each other, and this equation stays the same.

These gauge fields gives us all the particles associated with 3 of the 4 fundamental forces in our universe - the strong force, the weak force, and the electromagnetic force. And the Higgs boson from this Higgs term tells us how all the mass in the universe gets created, through something called symmetry breaking.

So quantum and symmetry are 2 concepts to take away from quantum field theory.

Last big concept to understand is information, entropy, and they're relationships together and with black holes.

To make the unknown, known.

I gave up a lot. I left my friends in the Czech Republic, and in Italy and Central Europe that I miss very much everyday. I missed out on a lot of wonderful relationships, analogous to how Cooper had missed out on much of Murph's life in the movie, and it's heartbreaking. But I was driven to be in space launch and chose to get into the space industry.

Cooper is exerting a force across the 5-dim. spacetime of the AdS_5 space, a gravitational force. We know that the Einstein field equations allow for gravity waves to propagate and it's able to propagate at shorter distances because of the negative curvature of AdS_5 space; the 4-dim. spacetime we live on the surface gets "sandwiched" in by the bulk interior of AdS_5. The only problem I have with it is force in a quantum theory has a particle associated to it, and that particle, a graviton, massless, spin-2 boson, would have to follow a null-like geodesic and might not be able to go back in time to Murph.

3. Talk Notes

We've always defined ourselves by the ability to overcome the impossible. And we count these moments, these moments when we dared to aim higher, to break barriers, to reach for the stars, to make the unknown, known. We count these moments to be our proudest achievements. But we lost all that, or perhaps we've just forgotten, that we're still pioneers, that we've barely begun, and our greatest accomplishments cannot be behind us, that our destiny lies above us.

Black holes Ch. 5, contain no matter but have surfaces called event horizons, circumference proportional to mass, I. Foundations 2 Our Universe in Brief. Thorne (2014) [1]

gravitational lensing, distortion, bending of light rays.

It seems likely from the quest to understand quantum gravity that our universe is a membrane (physicists call it a "brane") residing in a higher-dimensional "hyperspace" to which physicists give the name "bulk" (Ch. 4, 21), when physicists carry Einstein's relativistic laws int bulk, they discover the possibility of gravitational anomalies, anomalies triggered by physical fields that reside in the bulk.

Ch. 4, Warped Time and Space, and Tidal Gravity

"Einstein's law of time warps", 1959 Bob Pound, Glen Rebca, Mössbauer effect.

Einstein realized if time can be warped by massive bodies.

Robert Reasenberg and Irwin Shapiro of Harvard, 1976-77 radio transmission signals from Earth to spacecraft and back, if space were flat, roundtrip travel would've changed gradually and steadily. By constant c, distance from Earth to spacecraft had to be longer than expected passing near Sun.

Ch. 21 5th dim.

Tidal Gravity Einstein's laws dictate planets, stars, spacecraft move along straightest paths. (geodesic)

Riemann tensor, tendex lines.

Schwarzschild metric, warped spacetime around a nonspinning black hole, Kerr metric for spinning black hole.

Lynden-Bell, quasars, Lynden-Bell 1797.

Gannon's theory, any wormhole is traversable only if threaded by exotic matter.

VI. Extreme Physics 21 The Fourth and Fifth Dimensions, 1984, Green, Schwarz, our universe is a brane embedded in a bulk that has 1 time dim and 9 space dims, a bulk with 6 more space dims than our brane, superstring theory

"The nature of Bulk Beings, and Their Gravity"

Physicists: all particles, all forces and fields confined to our brane, except gravity, and warping of spacetime associated with gravity.

Ch 23: Confining Gravity - The Trouble with Gravity in 5 dims

If the bulk does exist, then its space must be warped.

String theory insists that gravity in the bulk is also described by force lines. Because bulk's extra dim., there are 3 transverse dims into which gravity can spread instead of just 2. Therefore, if bulk exists and is not warped, then density of force lines and thence gravity's strength should decrease as $1/r^2$ it must be warped in some manner that prevents gravity from spreading into 5th dim

The Anti-DeSitter Warp

1999 Randall, Sundrum, Anti-deSitter warping. 37

Confine AdS warping to a thin layer around our brane, a "sandwich". Place 2 confining branes.

Gregory, Rubakov, Sibiryakov AdS sandwich

Witten shown AdS sandwich is unstable.

A bulk field is a collection of force lines that resides in 5-dim. bulk.

cf. Bulk Fields Control the Strengh of Gravity. But if bulk does exist, then relativistic laws allow G to change.

Exotic matter that repels gravitationally, alternative, bulk fields may hold the wormhold open.

"Protecting Our Universe from Destruction"

for gravity in our universe to obey Newton's inverse square law to high accuracy, our brane must be sandwiched between 2 confining branes with AdS warping between them.

footnote 42 According to Einstein's relativistic laws, the dark energy that (presumably) makes the expansion of our universe accelerate has a 2nd. effect; it produces an enormous tension in our brane; Einstein's laws also dictate that, in order for spacetime outside AdS sandwich to be free of warping, each confining brane must have internal pressure that's half as big as our own brane's internal tension.

Einstein's relativistic laws applied to bulk and branes.

Bulk fields somehow exert a force on it, pushing back its proper, straight shape.

naked singularity - singularity not hidden beneath a black hole's event horizon, singularity outside a black hole.

Matthew Choptuik, imploding gravitational wave. naked singularity.

BKL Singularity inside a Black hole Einstein's laws taught us these singularities are unstable. Vladimir Belinsky, Isaac Khalatnikov, and Eugene Lifshitz in 1971 BKL singularity inside a Black Hole, Garfinkle at Oakland University confirmed guess. BKL singularities are allowed by Einstein's relativistic laws. A Black Hole's Infalling and Outflying Singularities. 1991 Eric Poisson and Werner Israel discovered second singularity, grows with time as the black hole ages.

lae 2021, 3rd singularity discovered by Donald Marolf, Amos Ori, it's outflying singularity that grows as black hole ages, produced by stuff (gas, dust, light, gravitational waves, etc) that fell into black hole *before you fell in, upscattered stuff gets compressed, by black hole's extreme slowing of time, into a thin layer rather like a sonic boom (a "shock front").*

1955 John Wheeler pointed out existence of quantum foam with wormhole sizes 10^{-35} meters, *Planck length.*

Andrew Abrahams and Chuck Evans at UNC repeated Choptuik's simulations using gravitational wave not scalar wave and got same result, a naked singularity.

28 Into Gargantua

2013 Falling into a black hole, 1985, we physicists thought core of all black holes were inhabited by chaotic, destructive BKL singularities. 2 additional singularities discovered, inside black holes, gentle singularities.

infalling singularity, produced by stuff that falls into Gargantua long after Cooper falls in (long after, measured by external universe's or Earth's time. If Cooper is hit by that singularity and survives, the universe's far future will e in his past.

Signals from aboe are Doppler shifted to red by Cooper's high speed, which compensates blue shift produced by hole's gravitational pull.

outflying singularity, from stuff that fell into Gargantua before the Ranger, not after it. Slingshot around a suitable intermediate-mass black hole soon after leaving Endurance. Cooper sees light from objects tat fell into Gargantua before him and still falling inward. He can see them in reflected light from the accretion disk above.

29 The Tesseract

From Point to Line to Square to Cube to Tesseract.

If we take a point, and move it in 1 dimension, we get a line. The line has 2 faces, they are points. If we take a line, and move it in a dimension perpendicular to the line, we get a square. It has 4 faces, the 4 sides. If we take a square and move it in the 3rd. dimension perpendicular to it, we get a cube. It has 6 faces, the 6 squares. If we take a cube and move it in the 4th. dimension, we get a tesseract. It has 8 faces, the 8 cubes.

Cooper made of atoms of E, nuclear fields, can exist only in 3 dims. He reside in 1 of tesseract's 3 space-dim. faces. Transports 3 dim. Cooper, lodeged in its 3-dim. face, through the bulk.

distance from Gargantua to Earth is about 10 billion light-years as measures in our brane (our universe), however as measured in bulk, that distance is only about 1 AU.

3 cm thick AdS layer that encases our brane to reach Murph's bedroom.

Back face of tesseract coincides with Murph's bedroom. everything in Murph's bedroom, including Murphs herself is also inside the tesseract's back face.

6 views of Murph's bedroom seen by Cooper

All 6 light rays have to pass through intermediate cubes (tesseract faces) before reaching Murphs' bedroom

3.0.1. *More Notes.* Riff.

3.1. **Riffs.** To make the unknown, known.

Aim to be rapidfire, shoot for time 10 mins. 5 mins.

References

[1] Kip Thorne. **The Science of Interstellar**. W.W. Norton and Company. 2014.