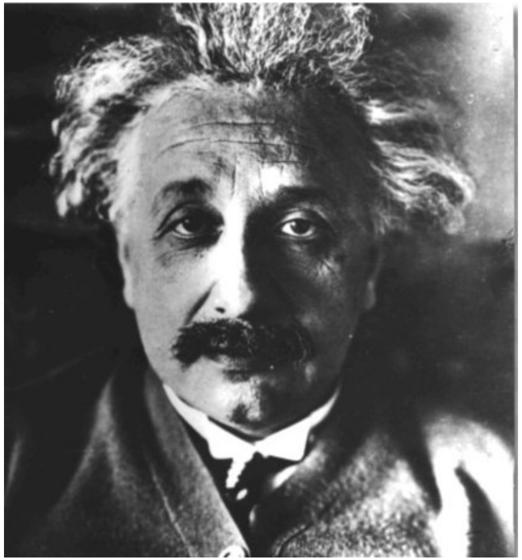
General Relativity *and* Quantum Gravity



Dr. W. F. Wall / Syzygy Asymptote
(Science Circle, 27 Feb 2021)

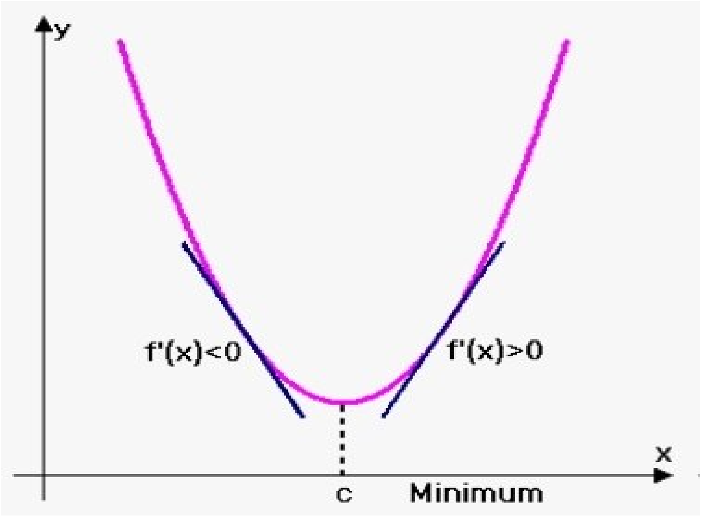
A *SHAMEFULLY* **BRIEF** LOOK AT *BOTH* General Relativity *and* The Theory of Everything!!

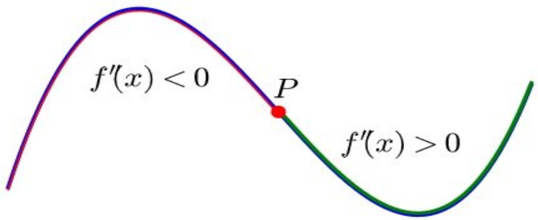
W. F. Wall / Syzygy Asymptote
(Science Circle, 27 Feb 2021)

Introduction provided by
Phil Youngblood and Matthew Burr.

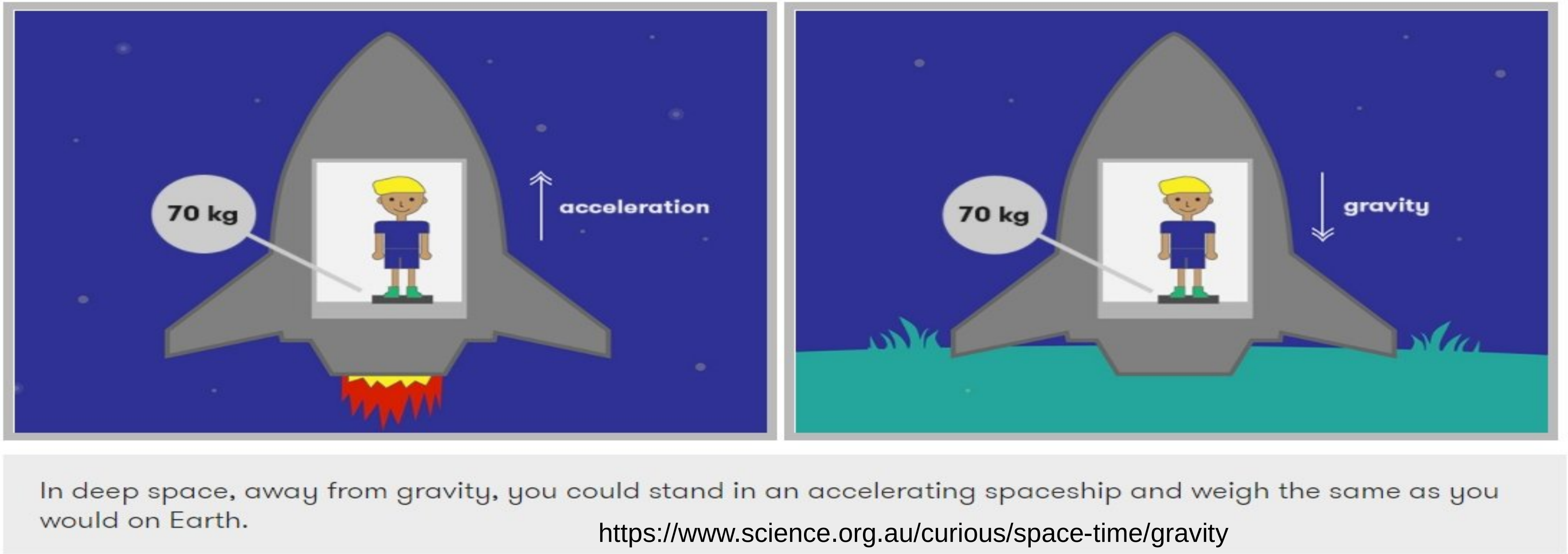
General Relativity (GR)

- It's useful to start with some *differential calculus*, specifically with the *first and second derivatives* of a function. Start with a curve that's represented by the function, *f*, of *x*: *f(x)*.
  - The first derivative of *f(x)*, called *f'(x)* or *df/dx*, is the rate at which *f* is changing with respect to *x*. Also called the slope of *f* at *x*.
  - The second derivative of *f(x)*, call *f''(x)* or d^2f/dx^2, is the rate at which *f'* is changing with respect to *x*. The rate of change of the slope. It's the curvature of *f(x)*.





General Relativity (GR)



https://www.science.org.au/curious/space-time/gravity

- Einstein recognized the equivalence of acceleration and gravity – Equivalence principle.
  - Demonstrates Einstein's genius. Einstein said that they seem to be the same because they are the same. (Genius is seeing something in its simplest possible terms and seeing its implications.)
  - [Two caveats: (1) Tidal effects exist on the surface of the Earth that don't occur in the accelerating rocket. (2) 70 kg is not weight, but mass. It would make more sense to list the weight instead: 686 N.]

General Relativity (GR)

https://www.science.org.au/curious/space-time/gravity

Distance travelled, *x*,
in time, *t,* is *x(t)*:

$$x(t)=\frac{1}{2}at^2$$

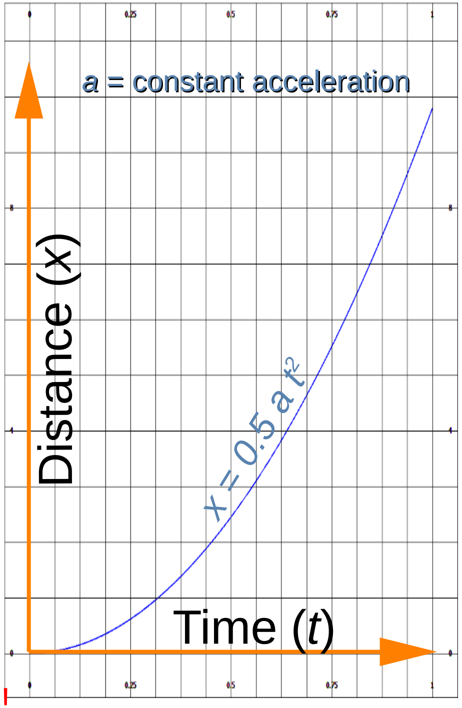
Velocity, *v*, at time, *t,* is *v(t)*:

$$v(t)=\frac{dx}{dt}=at$$

Acceleration, *a*:

$$a(t)=\frac{d^2x}{dt^2}=a(constant)$$

Non-zero second derivative means
curvature in that space-time graph!



Spacetime curvature due to mass of Earth.

(Relationship between such curvature and mass?)

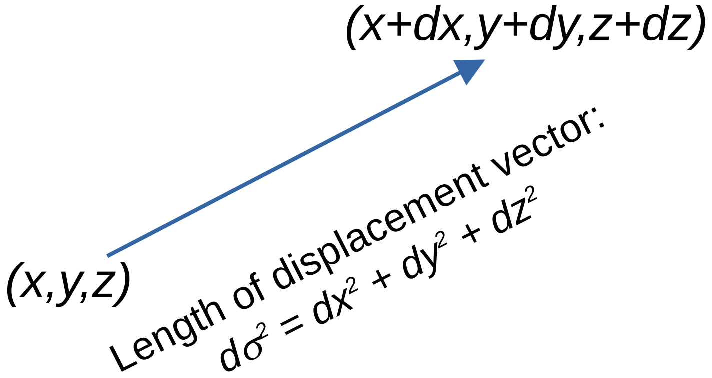
Spacetime curvature due to rocket engines.

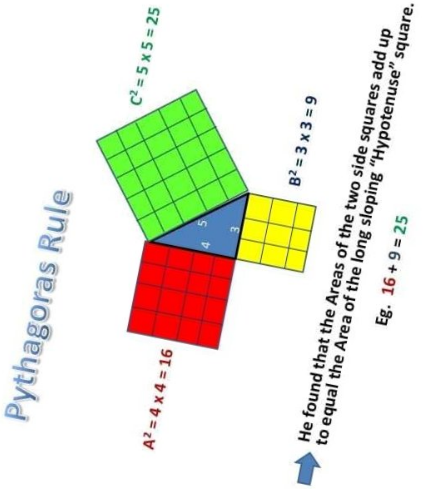
General Relativity (GR)

- Relationship between coordinates and distances.
  - Straight line in 3D Euclidean space.
    - Distances come from Pythagorean theorem.
    - Represents the shortest distance.

  - The equivalent in 4D space-time is the Minkowski, or ***flat***, space-time:

$$ds^2 = c^2dt^2 - (dx^2 + dy^2 + dz^2)$$





General Relativity (GR)

- Relationship between coordinates and distances.
  - Great circle in 2D spherical surface. It's apparent shape depends on the projection.
    - Distances are computed along great circles. The infinitesimal displacement along a great is given by

      $d\sigma^2 = r^2(d\theta^2 + \cos^2\theta\, d\Phi^2)$,

      where θ and Φ are latitude and longitude, respectively.
    - The great circle now represents shortest distance and, now, the relationship between coordinates and distance is different from that of flat space.
  - The equivalent in 4D space-time:

$$ds^2 = c^2 dt^2 - \left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

  - k is the curvature parameter and is positive for spherical curvature, θ is defined differently here.

General Relativity (GR)

- Relationship between coordinates and distances *(cont'd)*.
  - Mathematically speaking, spaces with coordinates may or may not have defined distances.
    - Spaces that do have defined distances have a *metric* that relates coordinate positional displacements to distances.
    - The paths of shortest distance are called *geodesics*. (Objects in motion tend to follow geodesics in whatever geometry of spacetime.)
      - Geodesic element of flat (Minkowski) spacetime:

$$ds^2 = 1c^2dt^2 - 1dx^2 - 1dy^2 - 1dz^2$$

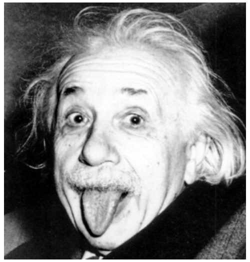
where the coefficients (+1, -1, -1, -1) are the components of the Minkowski metric.

      - For 4D spherical spacetime, those metric components are

$$(1, (1\text{-}kr)^{-1}, 1, 1)$$

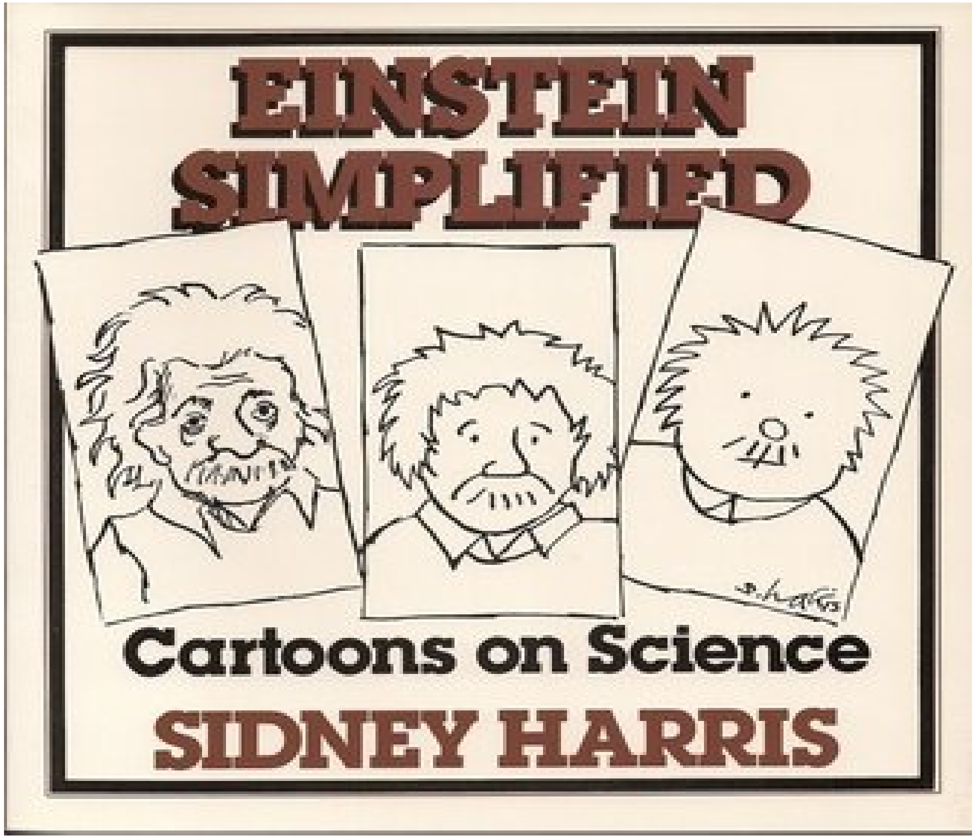
General Relativity (GR)

- Relationship between coordinates and distances *(cont’d)*.
    - The exact form of the coefficients of the metric depend on the choice of coordinate system but also on the geometry of the space(time).
    - ***Knowing that metric is essential for determining the geodesics, which are the paths followed by mass-energy in gravitational fields.***
  - Einstein had to learn a whole new branch of math (differential geometry) in order to calculate the metric for a given curved spacetime – curved because of the presence of mass-energy.



General Relativity (GR)

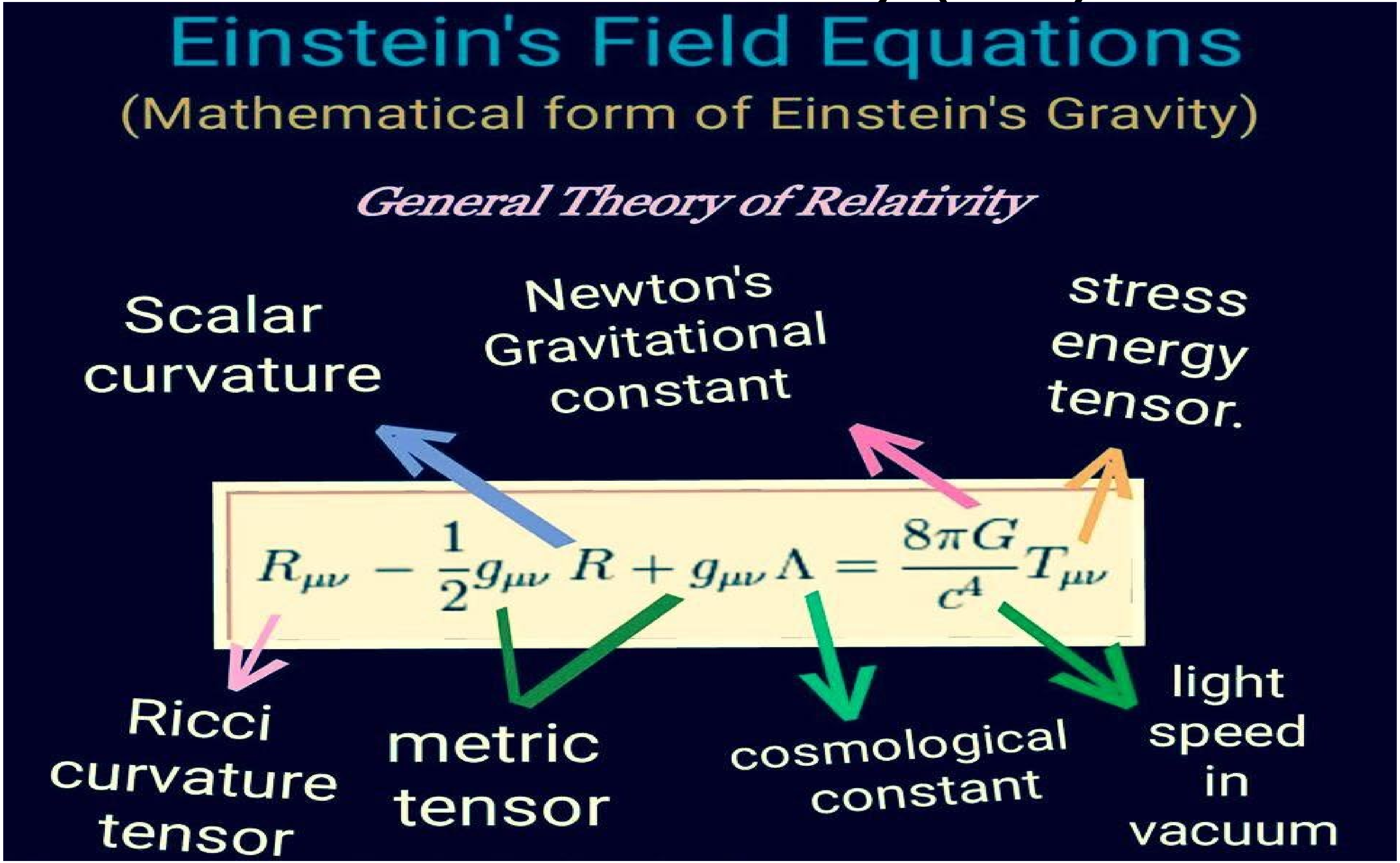
- Einstein Field Equations (EFE)!



General Relativity (GR)

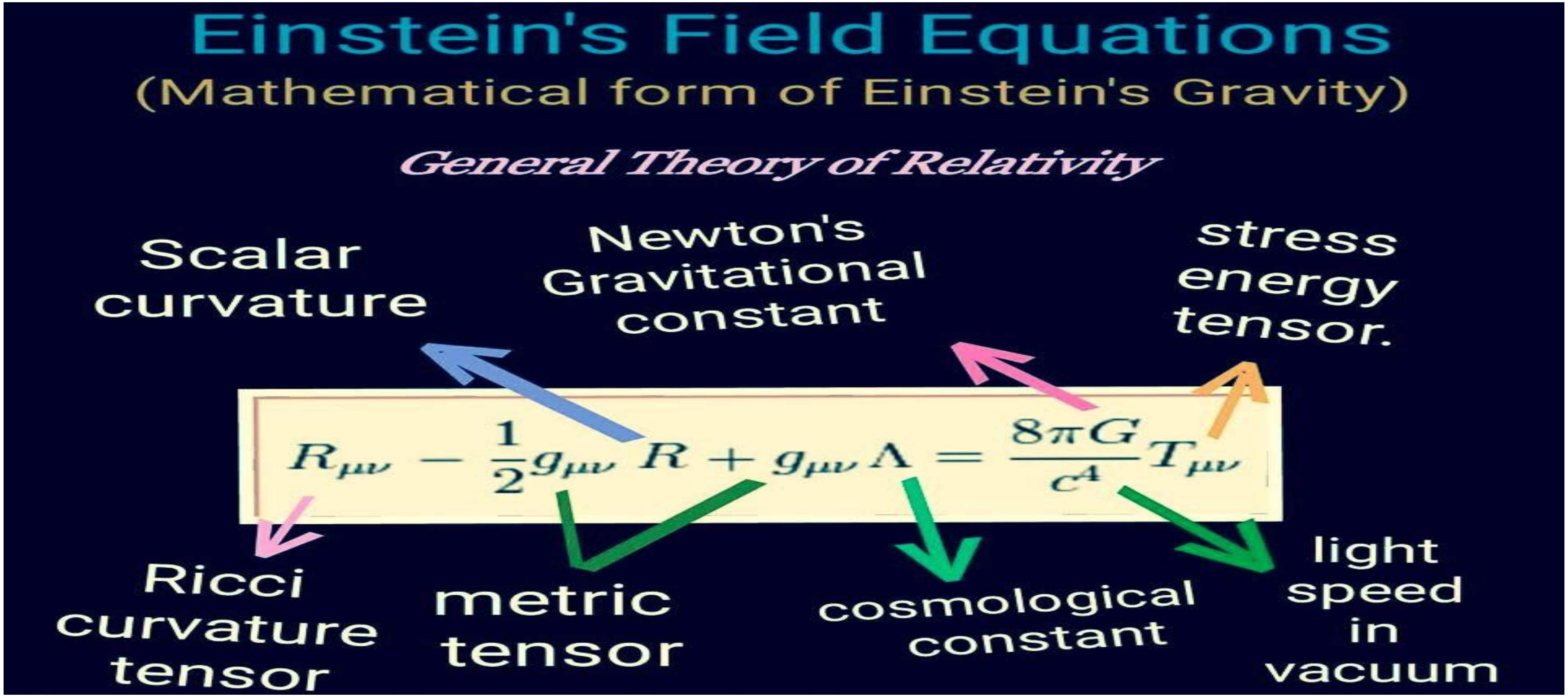
$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \Lambda \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

General Relativity (GR)



General Relativity (GR)

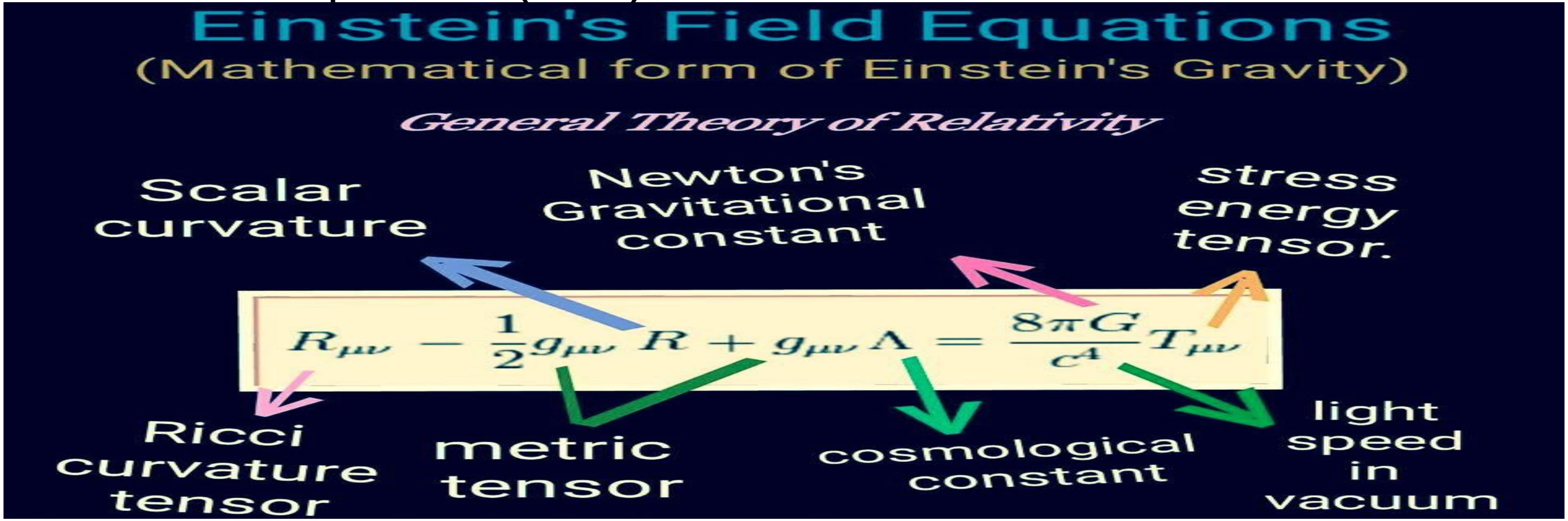
- Einstein Field Equations (EFE)!



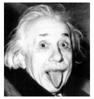
  - John Archibald Wheeler quote: *"Spacetime tells matter how to move; matter tells spacetime how to curve."*

General Relativity (GR)

- Einstein Field Equations (EFE)!



  - Written out fully, there are 10 coupled, non-linear, second-order partial differential equations, but are reducible to 6 independent such equations.
    - Extremely difficult to solve this system of equations because they are non-linear, they're differential equations, and a system of those equations.
    - You need to **guess** at what a possible solution looks like before you can determine a solution.

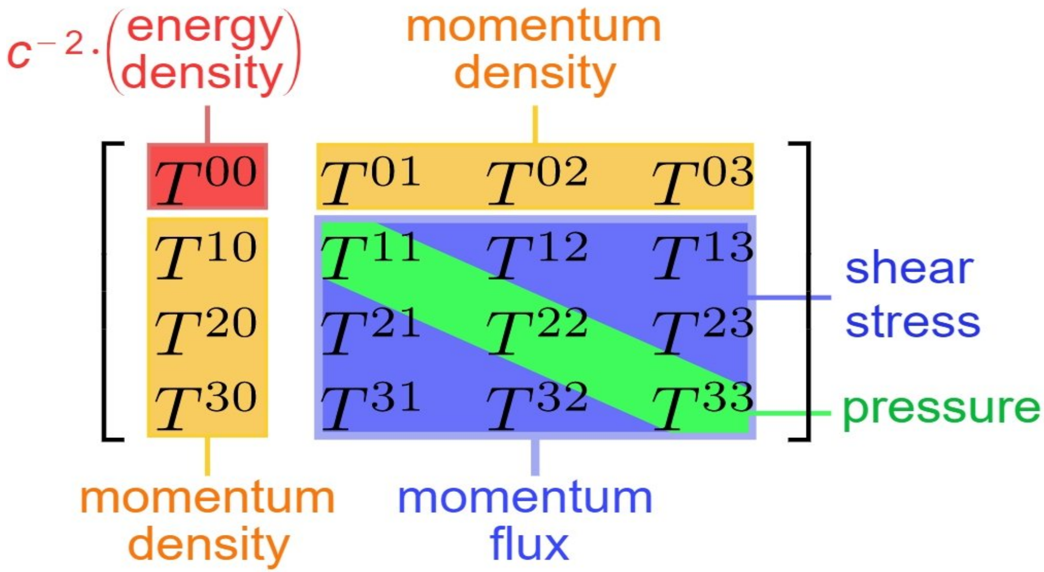


General Relativity (GR)

- Einstein Field Equations (EFE) *(cont'd)* !
  - The different parts of the displayed equation:
    - The Ricci curvature tensor is reduced form of the Riemannian curvature tensor. The Ricci tensor has 10 independent components. The curvature scalar is a reduced form of the Ricci tensor (the trace). They represent first and second derivatives of the metric with respect to spacetime coordinates.
    - That is, the curvature of that metric is necessary for determining the intrinsic curvature of spacetime! (The curvature of metric depends on the coordinate system in addition to the intrinsic spacetime curvature. Which is why it's necessary to determine the Ricci curvature tensor.)

General Relativity (GR)

- Einstein Field Equations (EFE) *(cont'd)* !
  - The different parts of the displayed equation *(cont'd)*:
    - The stress-energy-momentum tensor specifies the density and flux of energy and momentum in spacetime.



By Maschen, based on File:StressEnergyTensor.svg created by Bamse - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=24940142

General Relativity (GR)

- Einstein Field Equations (EFE) *(cont'd)* !
  - The different parts of the displayed equation *(cont'd)*:
    - Usually the stress-energy-momentum tensor is specified first, then the metric is solved for.
    - The solved-for metric then gives the geodesic that mass and energy naturally follow as they move. This can be tested observationally. And has been.

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

General Relativity (GR)

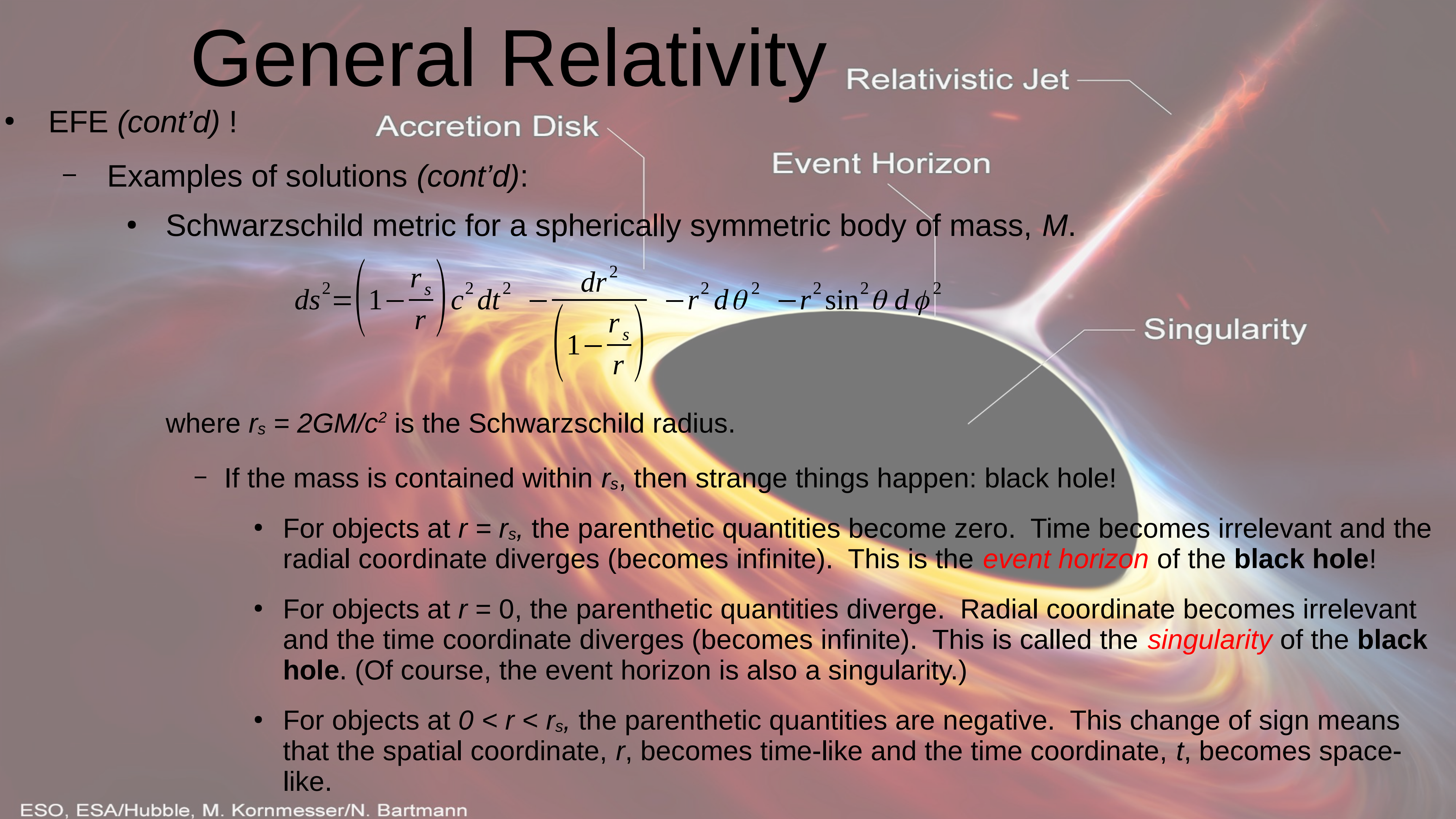
- Einstein Field Equations (EFE) *(cont'd)* !
  - Examples of solutions:
    - Schwarzschild metric for a spherically symmetric body of mass, *M*. (This is a vacuum solution for all space, except the central point with the mass.)

$$ds^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} - r^2 d\theta^2 - r^2 \sin^2\theta \, d\phi^2$$

where $r_s = 2GM/c^2$ is the Schwarzschild radius.

  - Behaves like a Newtonian orbit for $r >> r_s$.
  - Orbit is no longer closed. Correctly accounts for precession of perihelion of Mercury's orbit.

General Relativity



- EFE *(cont'd)* !
  - Examples of solutions *(cont'd)*:
    - Schwarzschild metric for a spherically symmetric body of mass, *M*.

$$ds^2=\left(1-\frac{r_s}{r}\right)c^2\,dt^2-\frac{dr^2}{\left(1-\frac{r_s}{r}\right)}-r^2\,d\theta^2-r^2\sin^2\theta\,d\phi^2$$

where $r_s = 2GM/c^2$ is the Schwarzschild radius.

  - If the mass is contained within r_s, then strange things happen: black hole!
    - For objects at $r = r_s$, the parenthetic quantities become zero. Time becomes irrelevant and the radial coordinate diverges (becomes infinite). This is the *event horizon* of the **black hole**!
    - For objects at $r = 0$, the parenthetic quantities diverge. Radial coordinate becomes irrelevant and the time coordinate diverges (becomes infinite). This is called the *singularity* of the **black hole**. (Of course, the event horizon is also a singularity.)
    - For objects at $0 < r < r_s$, the parenthetic quantities are negative. This change of sign means that the spatial coordinate, *r*, becomes time-like and the time coordinate, *t*, becomes space-like.

ESO, ESA/Hubble, M. Kornmesser/N. Bartmann

General Relativity (GR)

- EFE *(cont'd)* !
  - Examples of solutions:
    - Kerr metric for rotating bodies
      - Frame dragging (Lense-Thirring effect)
    - Alcubierre metric
      - Fundamentally different approach because the metric was specified and then the s-e-m tensor was solved for.
      - Warp drive!
      - But requires exotic matter (i.e., negative mass)
      - Invalidated by quantum effects?
      - Other problems (time travel).

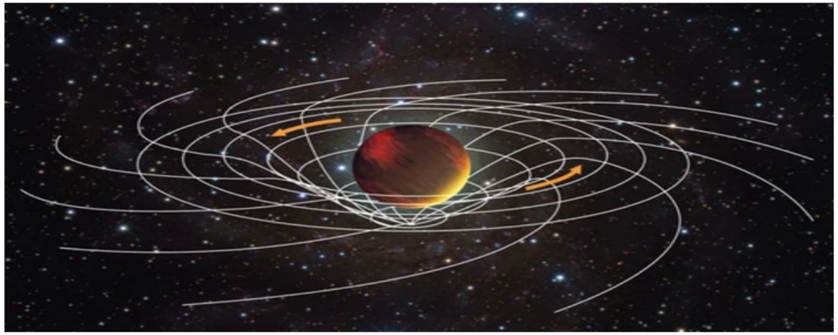
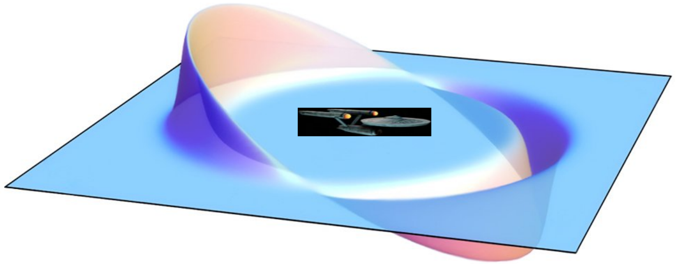


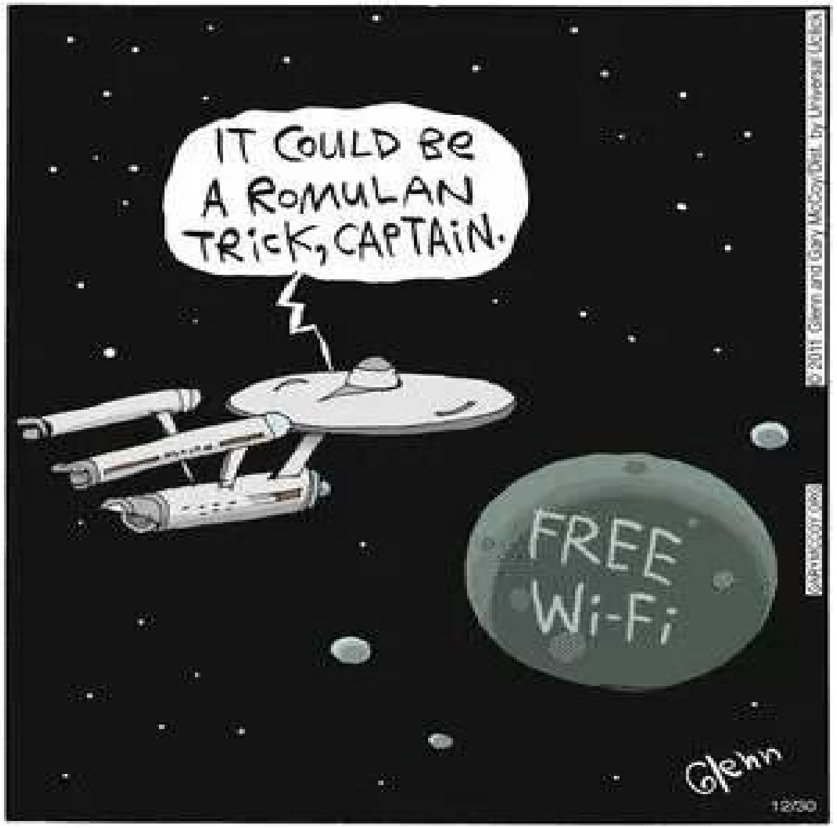
Illustration by Annie Rosen



Two-dimensional visualization of an Alcubierre drive, showing the opposing regions of expanding and contracting spacetime that displace the central region.

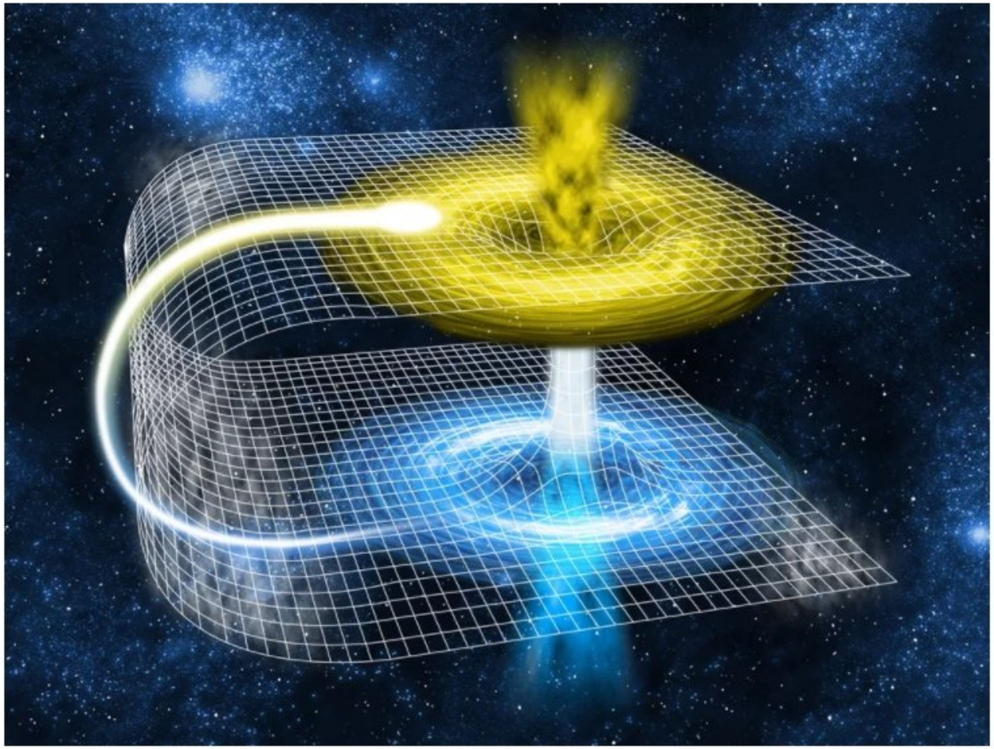
General Relativity (GR)

- Warped humour!



General Relativity (GR)

- EFE *(cont'd)* !
  - Examples of solutions *(cont'd)*:



Wormhole Theory: A model of 'folded' space-time illustrates how a wormhole bridge might form with at least two mouths that are connected to a single throat or tube. (Image credit: edobric | Shutterstock)

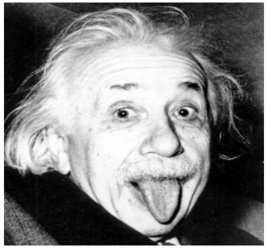
Wormholes:

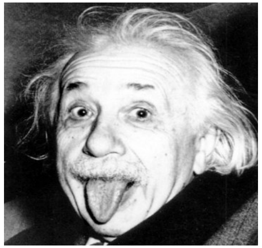
- Schwarzschild Wormhole or Einstein-Rosen Bridge
  - Eternal wormhole that will lengthen faster than c and pinch off in the middle and is, consequently, non-traversable.
- Ellis Drainhole
  - singularity free, free of event horizons, traversable.
  - Requires some hypothetical scalar field with negative coupling.
- Morris-Thorne Wormhole
  - This is stabilized by exotic matter – negative mass – and so is traversable.
- Quantum foam (Hawking, Thorne, Susskind)
  - Quantum field theory allows the vacuum energy to fluctuate and reach negative values momentarily, which might allow stabilization of wormholes.
  - Wormholes at Planck length (10^{-35} *m*) might appear and disappear spontaneously and be an intrinsic part of spacetime.
- Could allow time travel!

Quantum Gravity

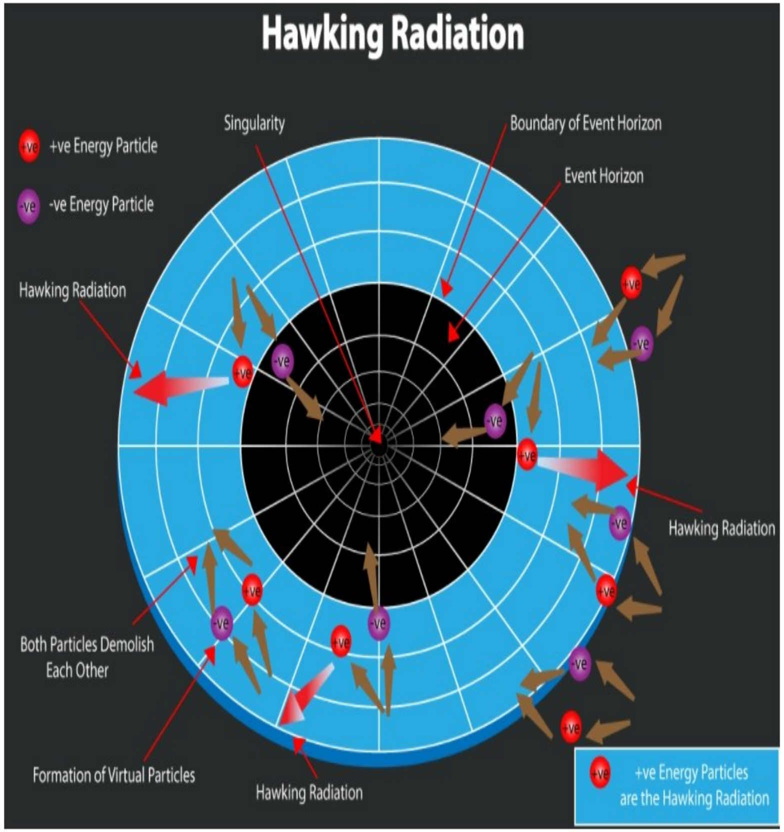
“Bill, despite your concerns that quantum gravity is too hypothetical, I think it is necessary to discuss because it illuminates the struggle of the last century to integrate gravity into the standard model…” - *M. Burr*

Irrefutable argument articulately expressed. I couldn’t refuse (nor refute).





Quantum Gravity



- Apply the principles of quantum mechanics (i.e., quantum field theory) to gravity where they cannot be ignored, such as near black holes or neutron stars (white dwarfs).
  - Hawking applied "QFT" to black holes to find that they emit radiation.
    - Performed a "brilliant hack" to get around curved-spacetime problem. (Interpolated between infinite time in past and that in the future without black hole and where spacetime is flat.)
    - Radiation is thermal and hotter for small black hole. (1 $M_\odot$ mass emits at 62 *nK*, 1 M_{Luna} emits at 2.7 *K*.) So, black holes eventually evaporate.
      - Leads to information paradox. If black holes evaporate, what happens to information inside them? Is it lost? Contradicts quantum mechanics. Probably encoded in Hawking radiation.
    - The area of classical black hole only increases with time like entropy. So, it was proposed that entropy of a black hole is proportional to its area (Hawking, Bekenstein) and *NOT* its volume!
      - That thoroughly weird idea prompted Gerard t' Hoof't and Leonard Susskind to propose the holographic principle: the content of the volume of the universe can be encoded in a surface surrounding it.

Quantum Gravity

- Three of the four fundamental forces have been unified in quantum field theory (QFT):
  - Electromagnetism (quantum electrodynamics or QED)
  - Nuclear strong force (quantum chromodynamics or QCD)
  - Nuclear weak force (electroweak theory or EWT)

- Is it really necessary to include gravity too? Is it even possible?
  - Given other 3 forces, then very likely gravity is necessary too.
  - Susskind argues that gravity provides hints that it is quantum too.

Quantum Gravity

- Gravity is more difficult to include in QFT framework:
  - QFT is framed in a given spacetime coordinate system and doesn't consider variable spacetime, which is what GR is all about.
  - QFT doesn't work in curved spacetime. (There is a QFT for curved spacetime [e.g., Howl et al. 2018], but it suffers shortcomings including the need for a fixed spacetime coordinate grid. The wavefunction of possible spacetimes should, instead, be a solution of quantum field theory.)

Quantum Gravity

- We've only discussed theory so far. What about experimental verification?
  - Gravitational quantum effects would occur at Planck scale [$(\hbar G/c^3)^{0.5}$] or 10^{-35} *m*, corresponding to energy 1.2×10^{28} *eV* or 10^{15} times higher than *Large Hadron Collider (LHC)* can attain.
    - Assuming magnets a million times better, an accelerator centred on the sun would extend out to the orbit of Neptune.
      - It would create Planck-scale black holes!

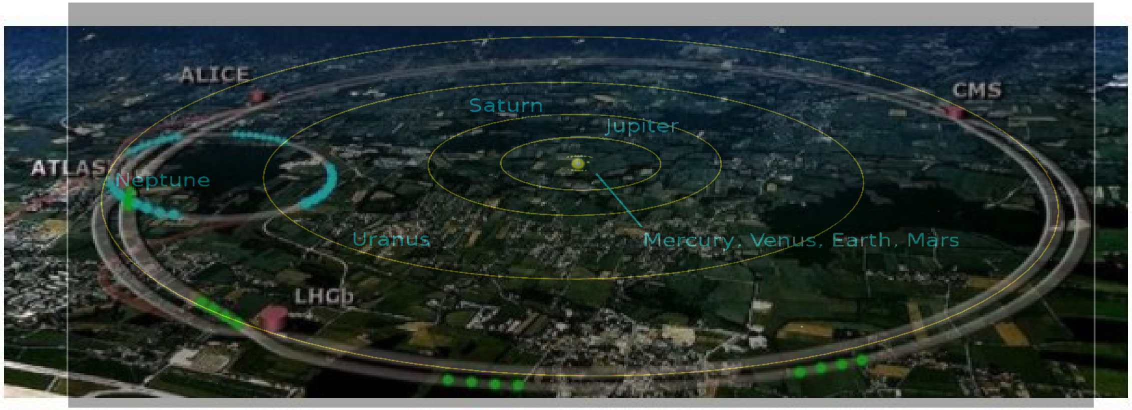
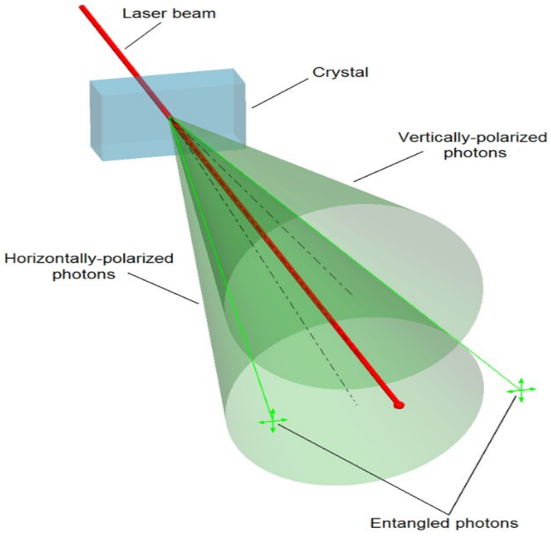


Image credit: CERN.

  - A radically different approach is necessary!

Quantum Gravity

- Quantum mechanics – exemplified by its weirdness.
  - So many quantum weirdness examples, but only time to examine one.
    - Quantum entanglement occurs when a pair (or group) of particles share a quantum state does not exist for them separately.
      - Usual example is entangled spins of pairs of particles. (Parametric down-conversion of laser photons into pairs of photons.)



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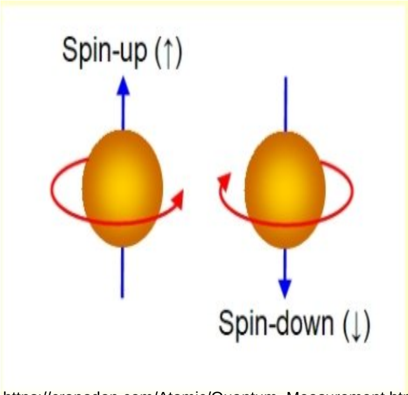
Quantum Gravity

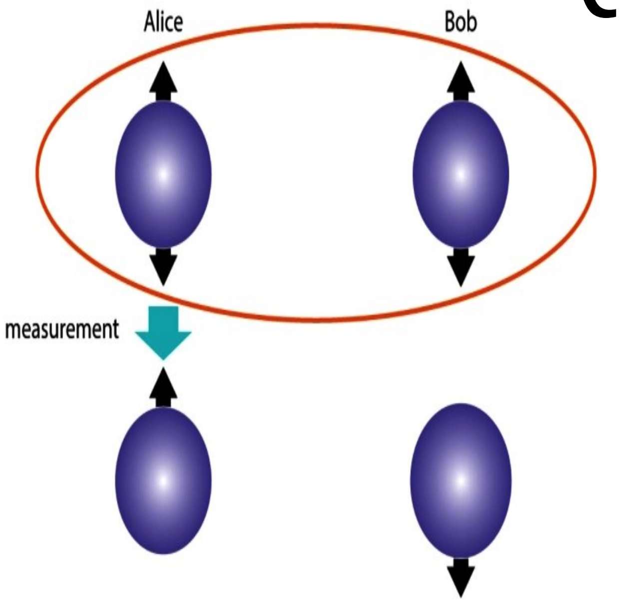
- Quantum mechanics – exemplified by its weirdness *(cont'd)*.
  - Spin is intrinsic angular momentum of particle, almost like it's a spinning top, except even fundamental particles (zero size) have spin.



https://cronodon.com/Atomic/Quantum_Measurement.html

  - One of the quirks of QM is the uncertainty principle which results in the inability to determine all 3 components of angular momentum vector simultaneously, only its magnitude and projection along one axis: spin up or spin down.
  - Another quirk of QM is that measuring any property of a particle with a given quantum state (or wave-function) changes that quantum state into one consistent with the measurement. For example, if the particle's spin is horizontal and you measure it vertically, it will suddenly be spin-up (50%) or spin-down (50%), not spin-sideways. Then it will be in that new state.

Quantum Gravity



When two electrons are entangled (top), a measurement on one instantly determines the state of the other (bottom), no matter how far away it is.

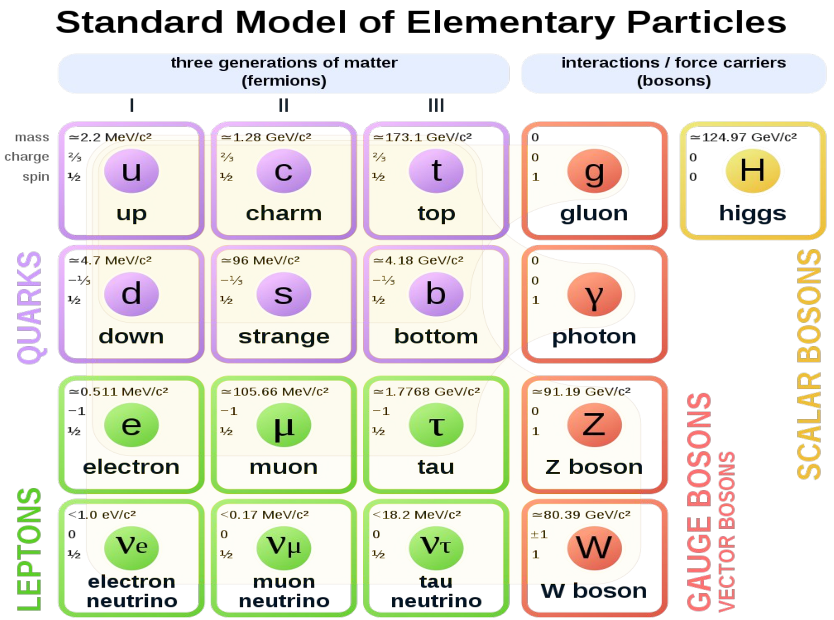
https://www.sciencemag.org/news/2015/08/more-evidence-support-quantum-theory-s-spooky-action-distance

- If a pair of particles has entangled spins, then as soon as you measure the spin of one them – whether it's up or down – the other will *instantaneously* be the opposite spin, *despite the distance between them!* *(*Measuring the spin makes the particle choose its spin; the quantum state collapses to one particular spin.)
  - *"Spooky action at a distance!" - Einstein*

- It is NOT the case that the two entangled particles start out with specific, and anti-parallel, spins from the moment of entanglement. There is no hidden, correlated information that they both start out with (contrary to Einstein, Podolsky, and Rosen 1935). John Bell (1964) proposed experiment that bore out QM and supported the spooky action at a distance.
  - In the simple example of predetermined anti-parallel spins and measuring at right angles to those spins, you'd find that the measured spins would "up" 50% of the time and "down" 50% of the time. And some of those times they'd both be "up" or both "down." That's not what happens. Along any axis that's chosen for both particles, one is always up and one is always down.

Quantum Gravity

- Quantum Field Theory (QFT) is a theoretical framework that combines classical field theory, special relativity, and quantum mechanics, but NOT GR! Traditionally, it's incompatible with curved spacetime.
  - Particles are excited states of the field. The field can be thought of as virtual particles popping in and out of existence. For gravity this would be the hypothetical *graviton*.
  - Predicted existence of anti-matter.
  - Standard Model of particles.
  - *Gravity is non-renormalizable*
  - *– infinities that cannot be removed.*
  -



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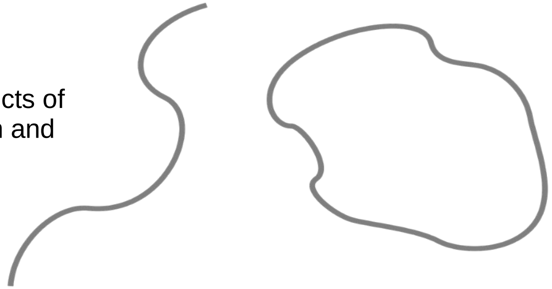
Quantum Gravity

- String theory – Point particles are replaced with open and closed strings are 1D objects vibrating in a multi-dimensional state. The vibrational state of the string determines its physical properties, such as mass, charge, etc.

The fundamental objects of string theory are open and closed strings.



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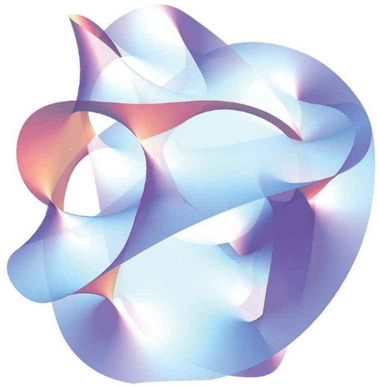
- One of the vibrational states is the graviton which appears very naturally!
- Requires multi-dimensional space like 11 dimensions or other numbers of dimensions. Implies that black holes would form easily.
- Predicts super-symmetric particles.
- *But assumes a background spacetime*

  coordinate grid.
- *Not confirmed by LHC experiments*

  – No mini-black holes and no supersymmetric particles.



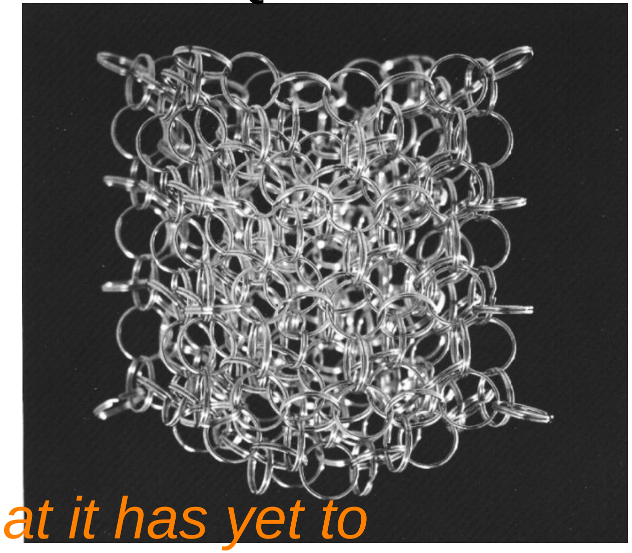
A cross section of a quintic Calabi–Yau manifold

By Jbourjai - Mathematica output, created by author, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5249718

Quantum Gravity

- Loop quantum gravity – Space and time are treated as quantized analogously to energy and momentum.   Space and time are granular and discrete because of quantization, just like photons in QED.

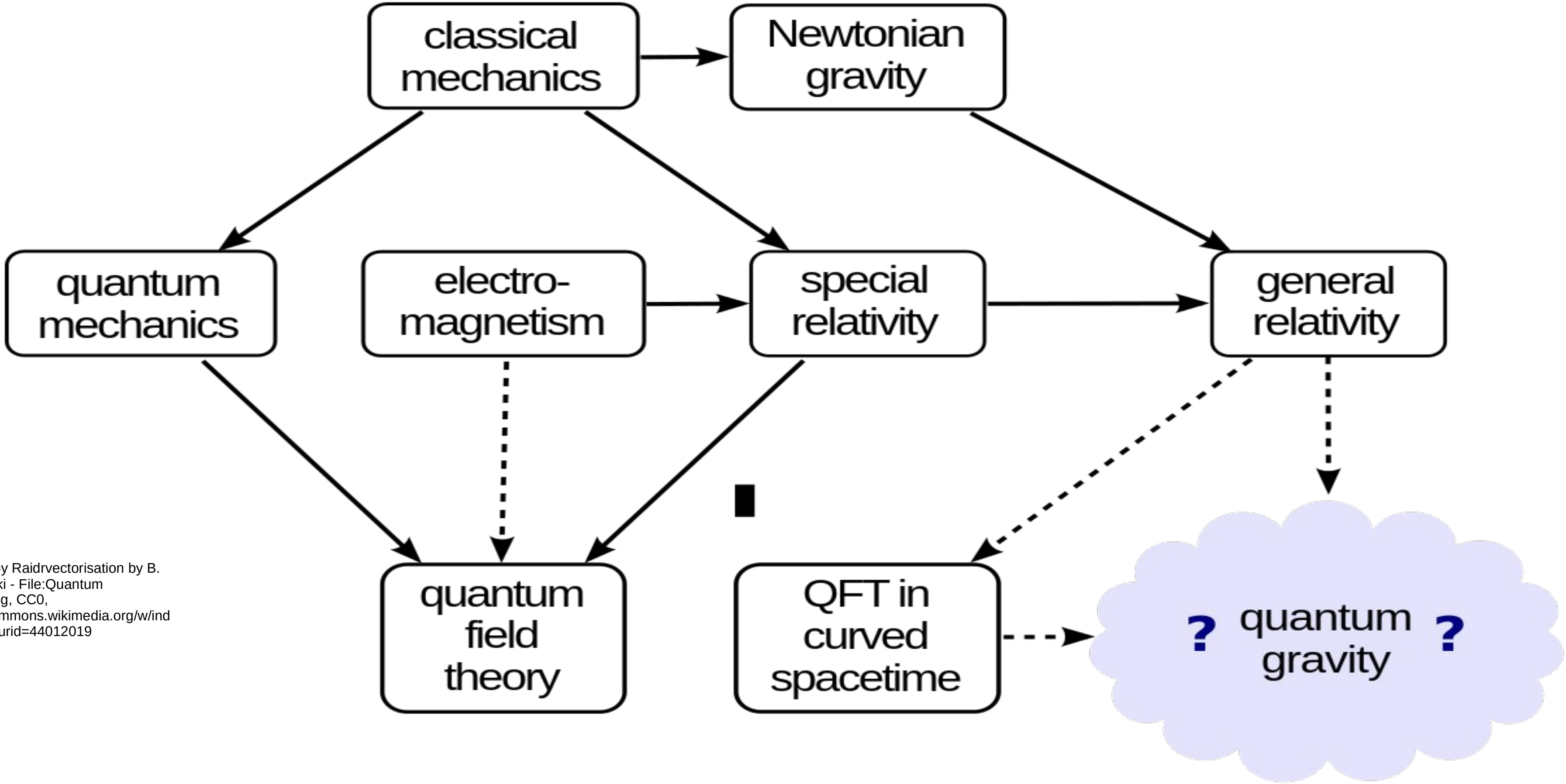
https://pediaa.com/difference-between-string-theory-and-loop-quantum-gravity/



- Independent of spacetime background.
- *Does not treat the other forces.*
- *The biggest flaw in loop quantum gravity is that it has yet to successfully show that you can take a quantized space and extract a smooth space-time out of it.*
- *Enough dimensions?.*

Quantum Gravity

– Quantum gravity in the grander scheme of things:



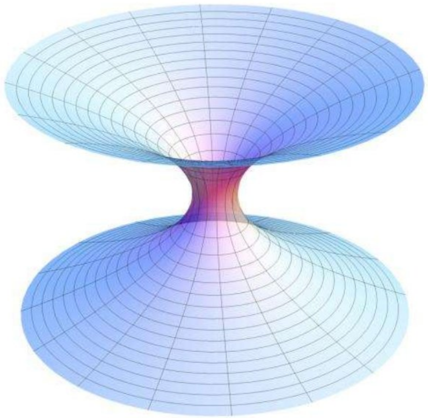
Quantum Gravity

- Wormholes to the rescue?! Or ER = EPR.
  - A conjecture that the Einstein-Rosen bridge, or wormhole, that connects two black holes is equivalent to quantum entanglement. It is possible to entangle two black holes. – Leonard Susskind & Juan Maldecena (2013).
  - Pairs of virtual particles in the vacuum are entangled and connected by wormholes. Wormholes are a fundamental part of spacetime.

DECEMBER 5, 2013

Creation of entanglement simultaneously gives rise to a wormhole

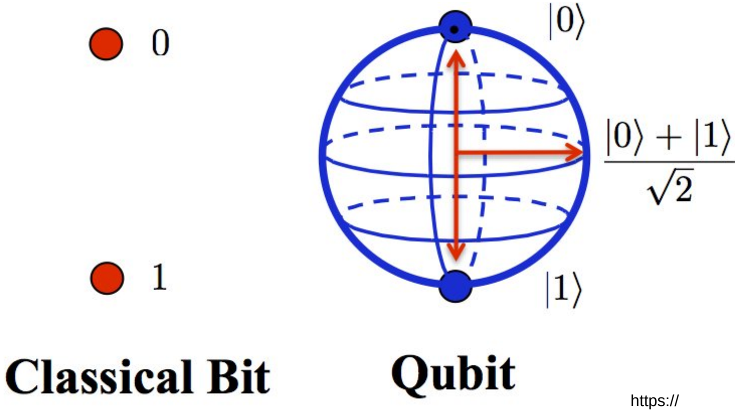
by Massachusetts Institute of Technology



https://phys.org/news/2013-12-creation-entanglement-simultaneously-wormhole.html

Quantum Gravity

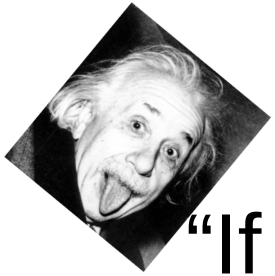
- Wormholes to the rescue?! Or ER = EPR.
  - So, entangled particles are like black holes connected by a wormhole. And entangled bits in a quantum computer are like proto-black holes, according to Susskind.
  - Quantum computers can supposedly directly simulate black holes and provide insights into quantum gravity.



https://www.astroblogs.nl/wp-content/uploads/2018/01/qubit.png

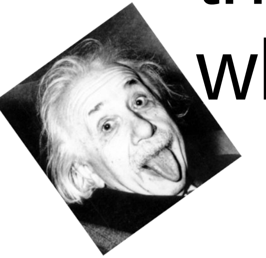
Quantum Laptop? Filled with nano black holes?

GR & QG



"If you think you understood any of that, then you weren't paying attention." – *not WFW*

"I know you think you understand what you thought I said but I'm not sure you realize that what you heard is not what I meant" — ALAN GREENSPAN



Recommended Reading / Viewing:

- https://www.cleanpng.com/png-theory-of-relativity-general-relativity-space-spec-4583160/
- https://royalsociety.org/people/stephen-hawking-11594/
- https://arc.aiaa.org/doi/10.2514/6.2019-4288
- https://www.sciencealert.com/scientists-are-starting-to-take-warp-drives-seriously-especially-this-one-concept
- https://www.bibliotecapleyades.net/ciencia/negativeenergy/negativeenergy.htm
- https://www.nasa.gov/centers/glenn/technology/warp/warp.html
- https://www.daviddarling.info/encyclopedia/A/Alcubdrive.html
- https://www.nytimes.com/2020/11/23/science/artificial-intelligence-ai-physics-theory.html
- https://en.wikipedia.org/wiki/Warp_drive#cite_note-AIAA-20190816-5
- https://en.wikipedia.org/wiki/AdS/CFT_correspondence
- https://en.wikipedia.org/wiki/Anti-de_Sitter_space
- https://en.wikipedia.org/wiki/Conformal_field_theory
- https://en.wikipedia.org/wiki/Firewall_(physics)
- https://en.wikipedia.org/wiki/Bose%E2%80%93Einstein_condensate
- https://en.wikipedia.org/wiki/Quantum_entanglement
- https://en.wikipedia.org/wiki/Einstein_field_equations
- https://en.wikipedia.org/wiki/Alcubierre_drive
- https://en.wikipedia.org/wiki/Wormhole
- https://en.wikipedia.org/wiki/White_hole

Recommended Reading / Viewing *(cont'd)*:

- https://en.wikipedia.org/wiki/Kruskal%E2%80%93Szekeres_coordinates
- https://www.livescience.com/most-important-surprising-quantum-physics-of-2019.html
- https://www.quantamagazine.org/john-preskill-quantum-computing-may-help-us-study-quantum-gravity-20200715/
- https://phys.org/news/2017-10-physicists-quantum-gravity-current-technology.html
- https://www.tandfonline.com/doi/full/10.1080/23746149.2017.1383184
- https://uwaterloo.ca/institute-for-quantum-computing/news/revealing-quantum-gravity-quantum-computer-simulation
- https://phys.org/news/2019-06-optimal-quantum-linked-gravity.html
- https://interestingengineering.com/physicists-to-build-a-quantum-teleporter-wormhole-modeled-on-black-holes#:~:text=Scientists%20are%20attempting%20to%20entangle,working%20wormhole%20using%20quantum%20computers.&text=A%20visionary%20group%20of%20physicists,black%20holes%2C%20reports%20Quanta%20Magazine.
- https://www.quantamagazine.org/wormholes-reveal-a-way-to-manipulate-black-hole-information-in-the-lab-20200227/
- https://www.insidequantumtechnology.com/news/physicists-using-quantum-computers-to-study-worm-holes/
- https://owlcation.com/stem/What-is-the-Firewall-Paradox
- Richard Howl, Lucia Hackermüller, David Edward Bruschi & Ivette Fuentes (2018) Gravity in the quantum lab, Advances in Physics: X, 3:1, 1383184, DOI:10.1080/23746149.2017.1383184
- (95) Mindscape 63 | Solo: Finding Gravity Within Quantum Mechanics - YouTube,
- (95) [Speaker 10] Leonard Susskind on Quantum Gravity in the Lab - YouTube,
- (95) Quantum Computation Linked to Gravity??? - YouTube,
- (95) Computing a theory of everything | Stephen Wolfram - YouTube,

Recommended Reading / Viewing *(cont'd)*:

- (95) Quantum Computing - YouTube,
- (95) Will Wormholes Allow Fast Interstellar Travel? - YouTube,
- (95) How Scientists Created A Wormhole In A Lab - YouTube,
- (95) Wormholes Explained – Breaking Spacetime - YouTube,
- (95) FTL04: Wormholes - YouTube,
- (95) Gravity and Entanglement - YouTube,
- (95) Can Quantum Entanglement Explain Gravity? - YouTube,
- (95) bluedot 2018 | Jim Al-Khalili: Entanglement and Wormholes - YouTube,
- (95) The Quantum Origins of Gravity by Leonard Susskind - YouTube,
- (95) FTL03: Alcubierre Warp Drives - YouTube,
- (95) Quantum Entanglement and the Great Bohr-Einstein Debate | Space Time | PBS Digital Studios - YouTube,
- (95) The incredible physics behind quantum computing | Brian Greene, Michio Kaku, & more | Big Think - YouTube,
- (95) Theory of Everything in Physics and Computation | Joe Rogan and Lex Fridman - YouTube,
- (95) String theory vs Loop quantum gravity: Wild hunt for Quantum Gravity: - YouTube,
- (95) The Quantum Origins of Gravity by Leonard Susskind - YouTube,
- (95) Wormholes Explained – Breaking Spacetime - YouTube,
- (95) The Quantum Origins of Gravity by Leonard Susskind - YouTube,
- (95) Wormholes Explained – Breaking Spacetime - YouTube,
- (95) The Quantum Origins of Gravity by Leonard Susskind - YouTube,
- (95) FTL03: Alcubierre Warp Drives - YouTube,
- (95) Is The Alcubierre Warp Drive Possible? | Space Time | PBS Digital Studios - YouTube,
- (95) The First Quantum Field Theory | Space Time - YouTube,

Recommended Reading / Viewing *(cont'd)*:

- (95) Quantum Field Theory - YouTube,
- (95) Hawking Radiation - YouTube,
- (95) Quantum Gravity - YouTube,
- (95) Quantum Gravity and the Hardest Problem in Physics | Space Time - YouTube,
- Jared Kaplan - Why Quantum Gravity Is Different (November 7, 2018) - YouTube,
- The Quantum Origins of Gravity by Leonard Susskind - YouTube,
- (78) FTL04: Wormholes - YouTube,
- (78) String theory vs Loop quantum gravity: Wild hunt for Quantum Gravity: - YouTube,
- Astrophysicist Explains Gravity in 5 Levels of Difficulty | WIRED - YouTube,
- https://socratic.org/questions/how-do-you-find-local-maximum-value-of-f-using-the-first-and-second-derivative-t-8
- http://www.math.iup.edu/~clamb/class/math115/2.2-second-derivative-info/
- https://www.science.org.au/curious/space-time/gravity
- https://i1.wp.com/sapulpatimes.com/wp-content/uploads/2018/10/pythagoras-theorem-explained-6-638.jpg?ssl=1
- https://gisgeography.com/great-circle-geodesic-line-shortest-flight-path/
- https://www.facebook.com/PhysicistPage/posts/terminology-of-einsteins-field-equations-general-relativity/1690198707720107/
- https://thespectrumofriemannium.files.wordpress.com/2015/06/einsteinfieldeq.jpg
- By Maschen, based on File:StressEnergyTensor.svg created by Bamse - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=24940142
- https://www.researchgate.net/topic/Schwarzschild-Metric
- https://chandra.harvard.edu/blog/node/737
- https://www.vice.com/en/article/8gmy4a/the-learning-corner-805-v18n5

Recommended Reading / Viewing *(cont'd)*:

- https://www.turbosquid.com/3d-models/starship-enterprise-star-trek-3d-model/850225
- https://www.space.com/20881-wormholes.html
- https://inventionsky.com/hawking-radiation/
- https://www.forbes.com/sites/startswithabang/2016/03/11/could-the-lhc-make-an-earth-killing-black-hole/?sh=3e428b7a2ed5
- https://moonblink.info/Eclipse/why/scales
- https://www.sciencemag.org/news/2015/08/more-evidence-support-quantum-theory-s-spooky-action-distance
- https://pediaa.com/difference-between-string-theory-and-loop-quantum-gravity/
- https://www.astroblogs.nl/wp-content/uploads/2018/01/qubit.png
- https://phys.org/news/2013-12-creation-entanglement-simultaneously-wormhole.html