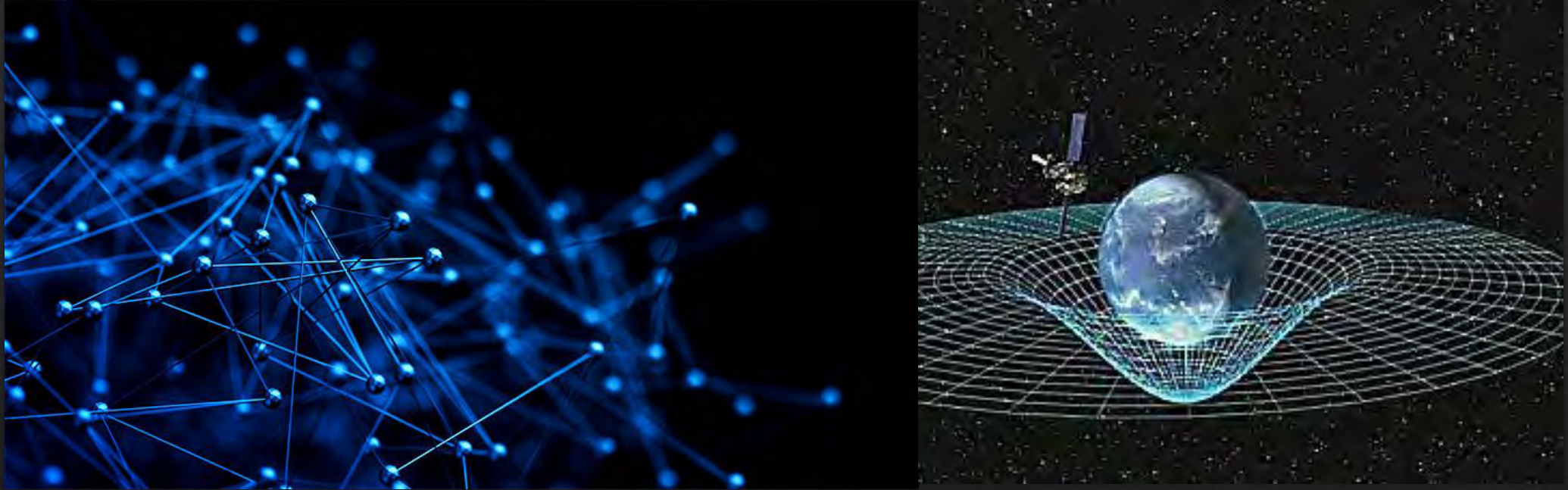
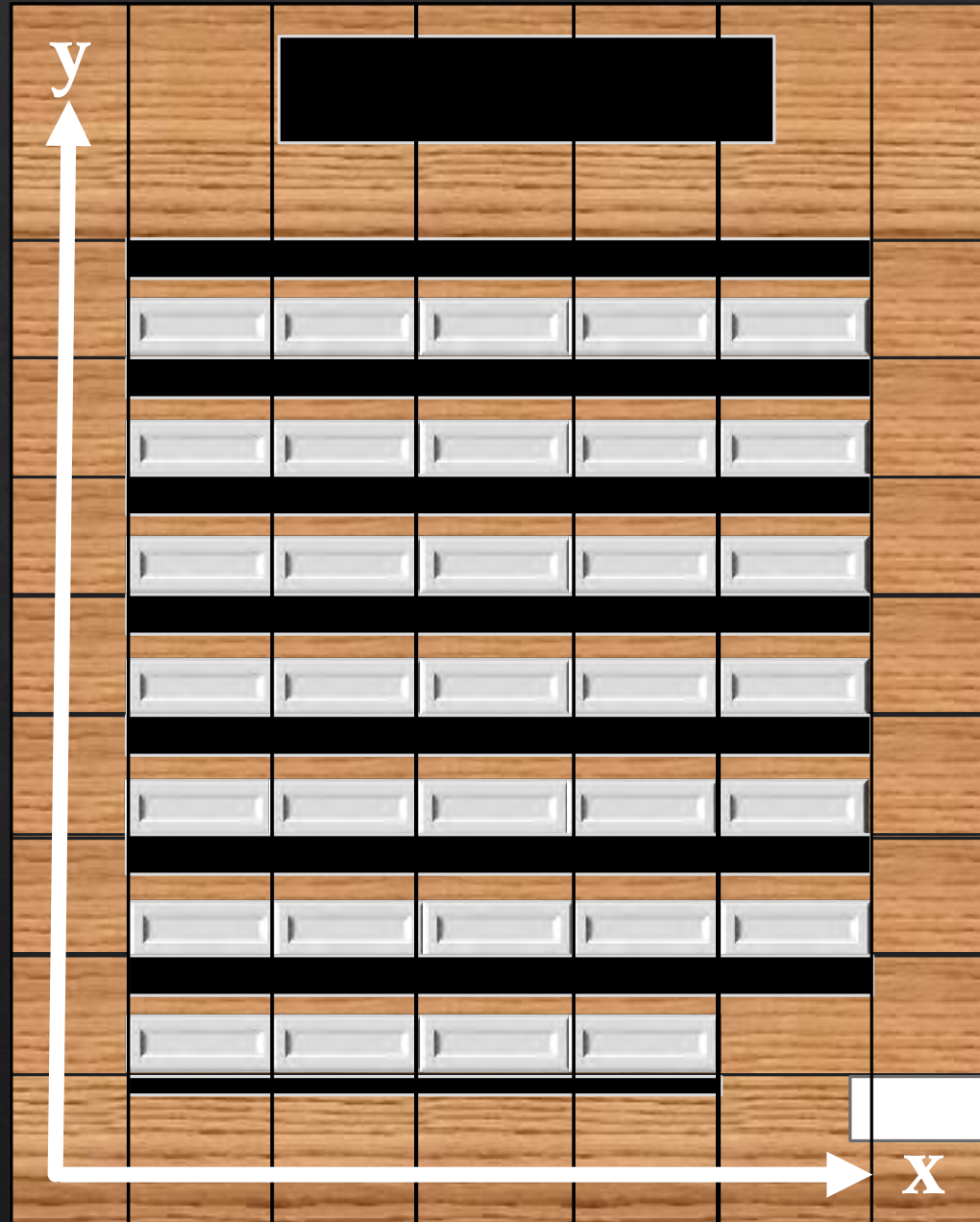


# The Quest for Quantum Gravity

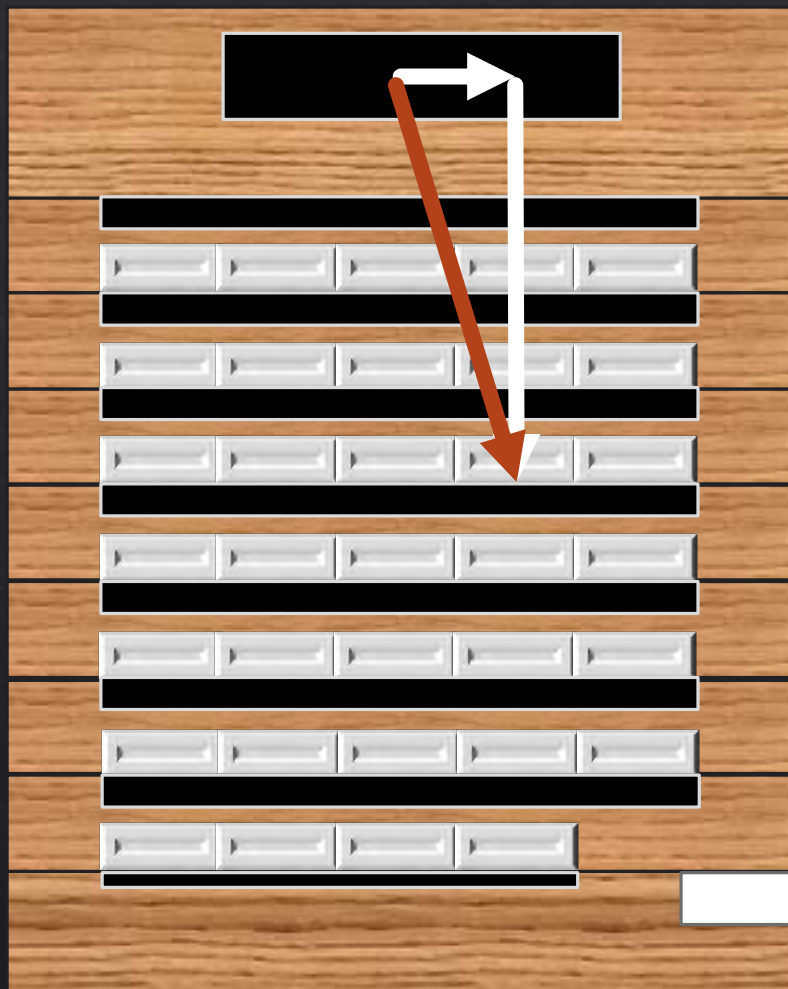
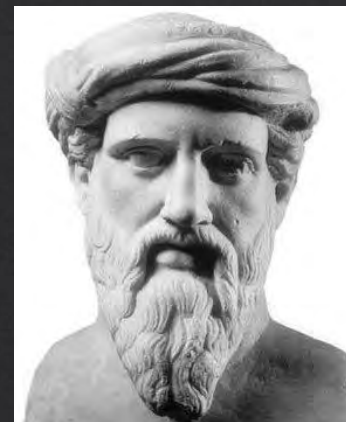
Think like a physicist:



Be specific!

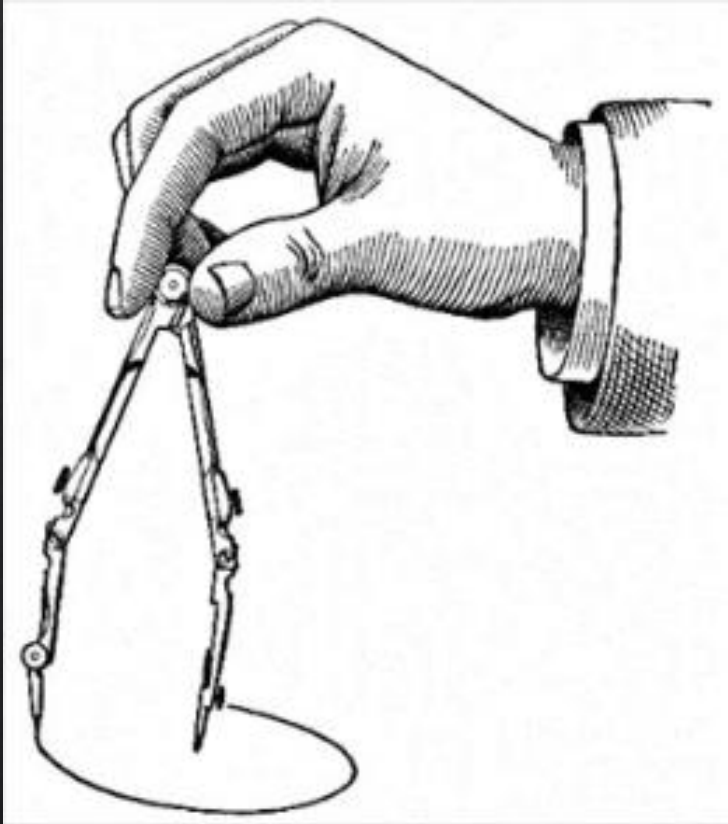


Use the Pythagorean Theorem!



$$x^2 + y^2 = d^2$$

# The World in a Sheet of Paper

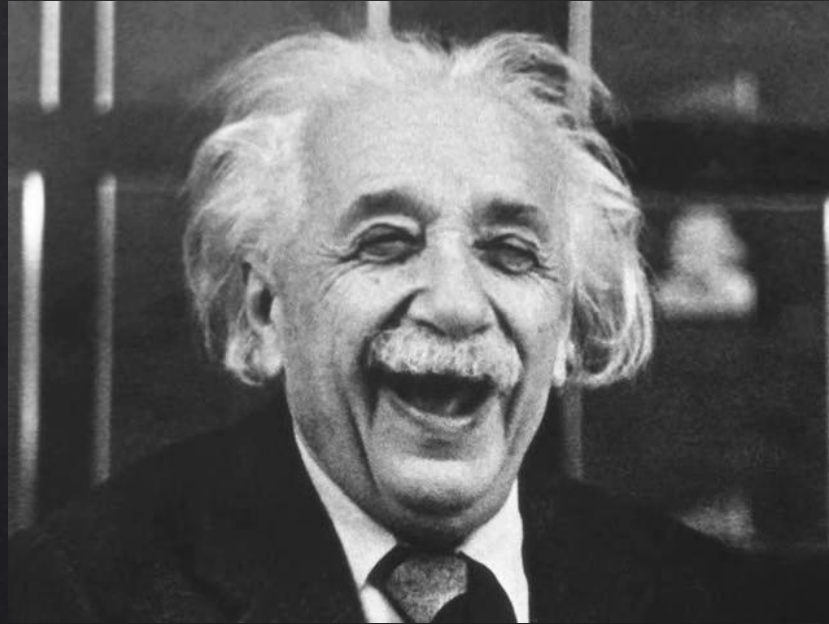


- ◇ This picture: a flat grid, positions, distances – ended up central to physics
- ◇ When Newton published his work on gravity, most arguments were geometrical proofs
- ◇ Only with Einstein did the “flat sheet of paper” world start breaking down

# Einstein

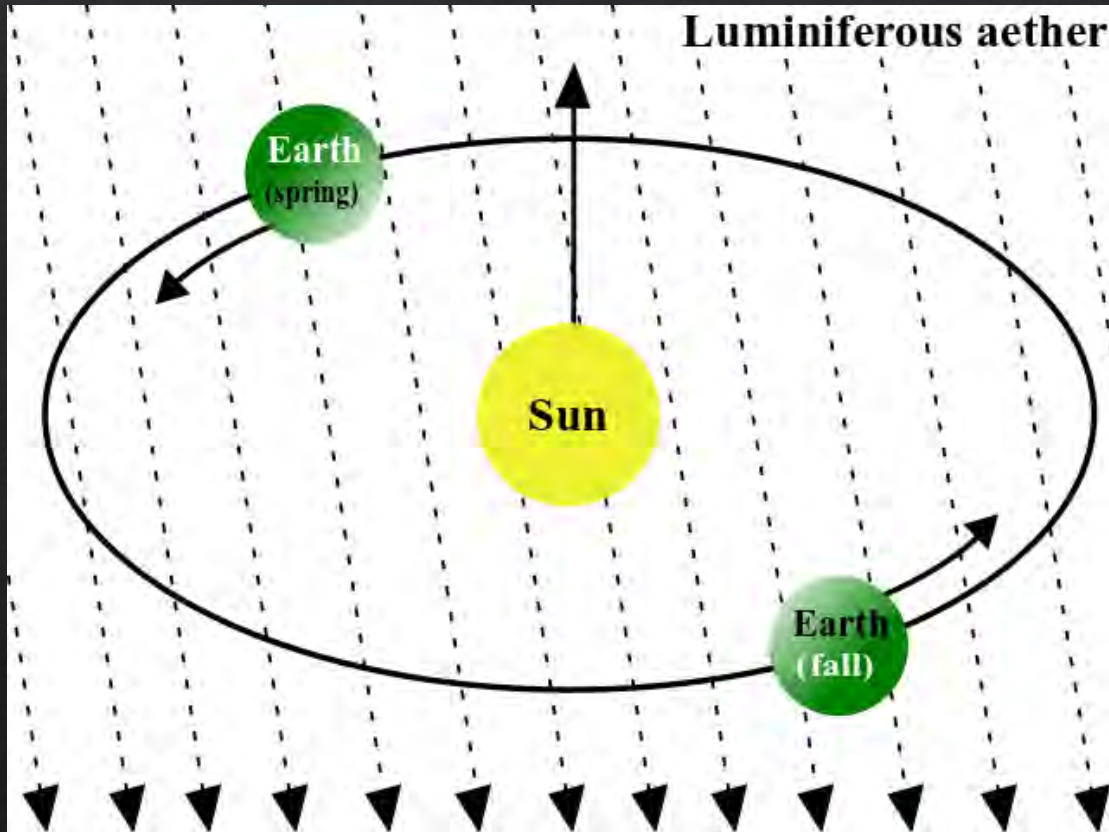
Special Relativity

General Relativity



The Photoelectric Effect

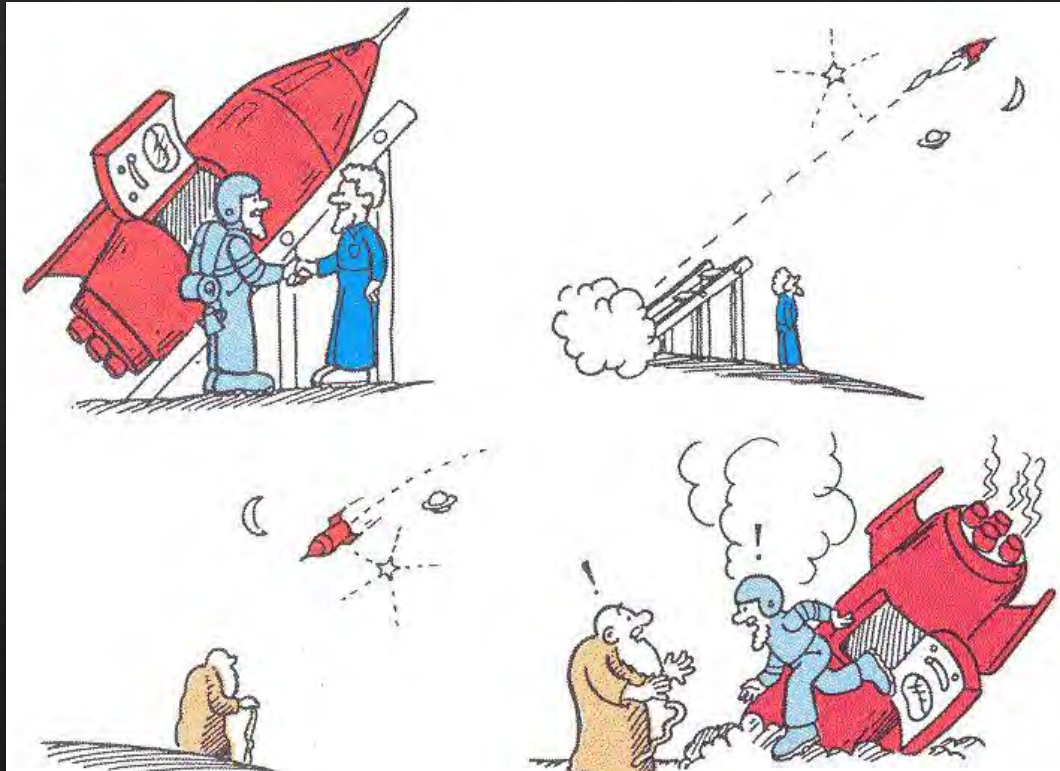
# Special Relativity: The Speed of Light



- ◇ Michelson-Morley experiment (1887) – measured the speed of light in different directions
- ◇ They expected “luminiferous aether”: fluid with light waves flowing past the Earth, so light goes faster or slower depending on direction
- ◇ Instead, light had a constant speed, no matter which way!

$$c = 299.792.458 \text{ m/s}$$

# Special Relativity: Einstein's Solution

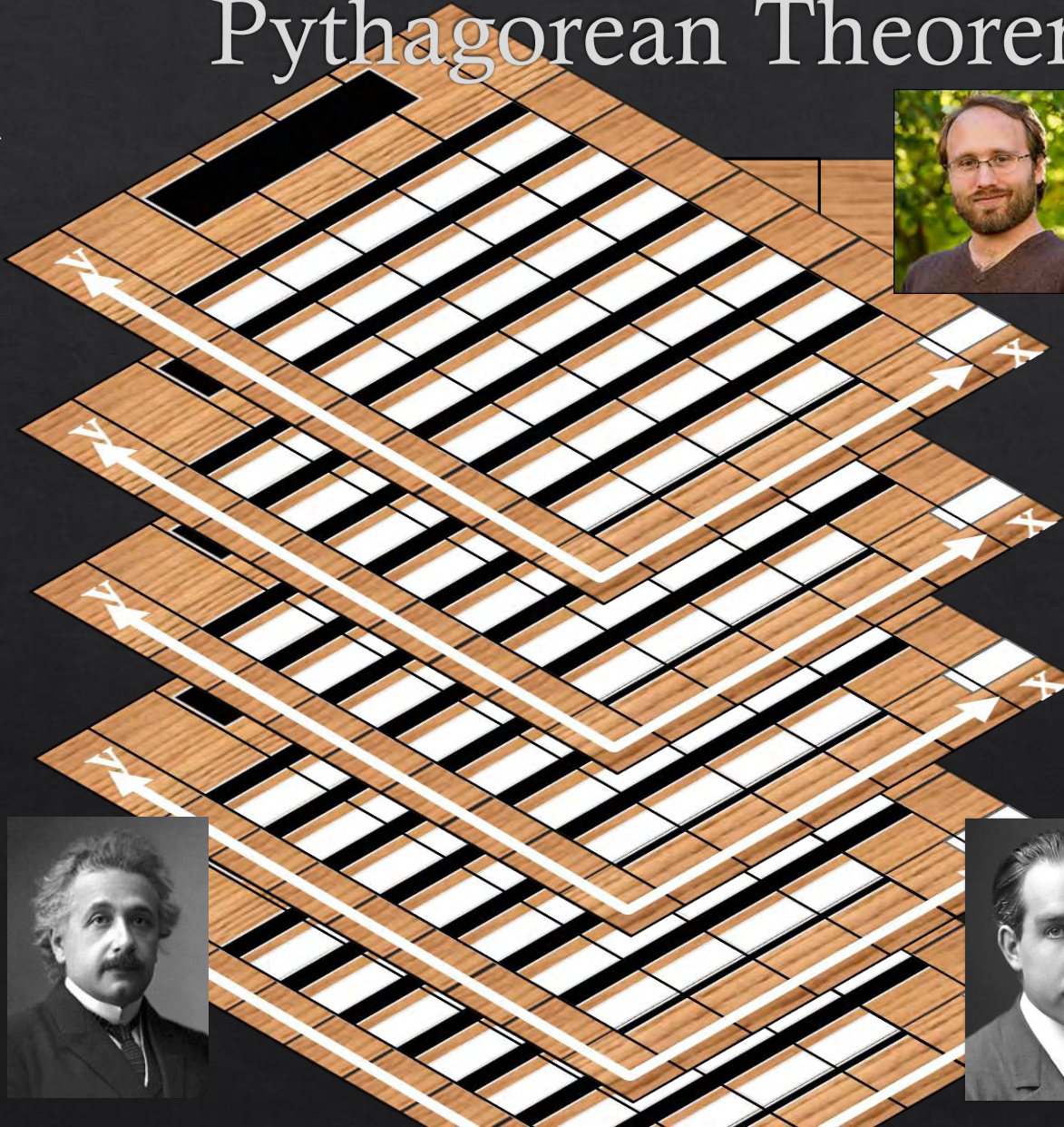


- ◇ In order to keep the speed of light fixed, Einstein had to do something radical: make distance and time relative: **Special Relativity (1905)**
- ◇ Strange consequences: length contraction, time dilation, mass-energy equivalence ( $E = mc^2$ )
- ◇ Twin thought experiment



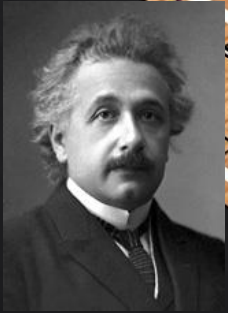
# Pythagorean Theorem in Space and Time

t

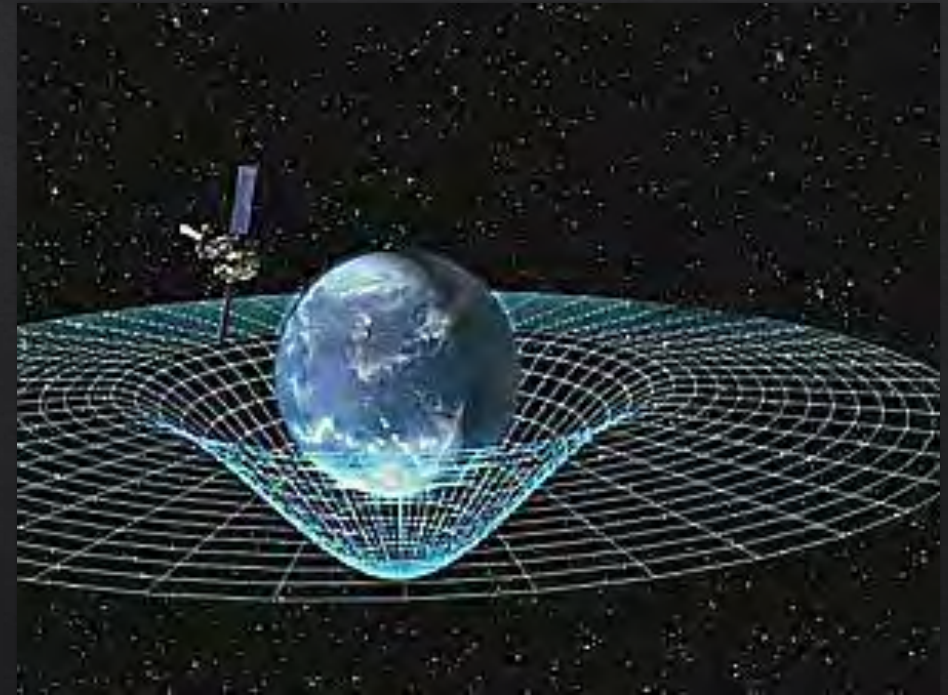
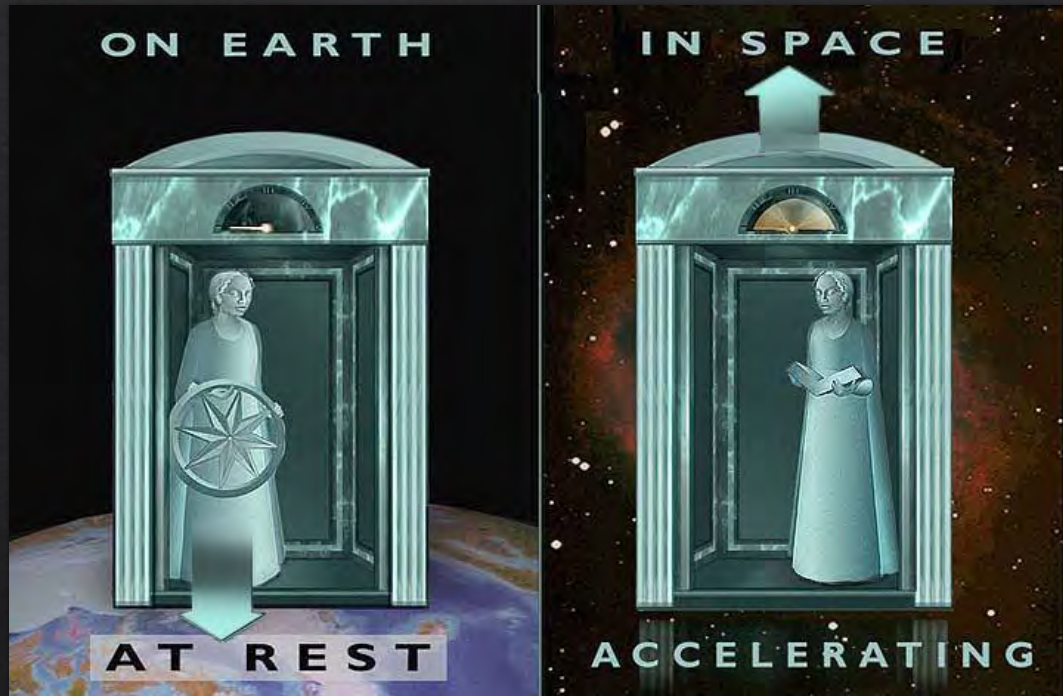


$$c^2t^2 - x^2 - y^2 = c^2T^2$$

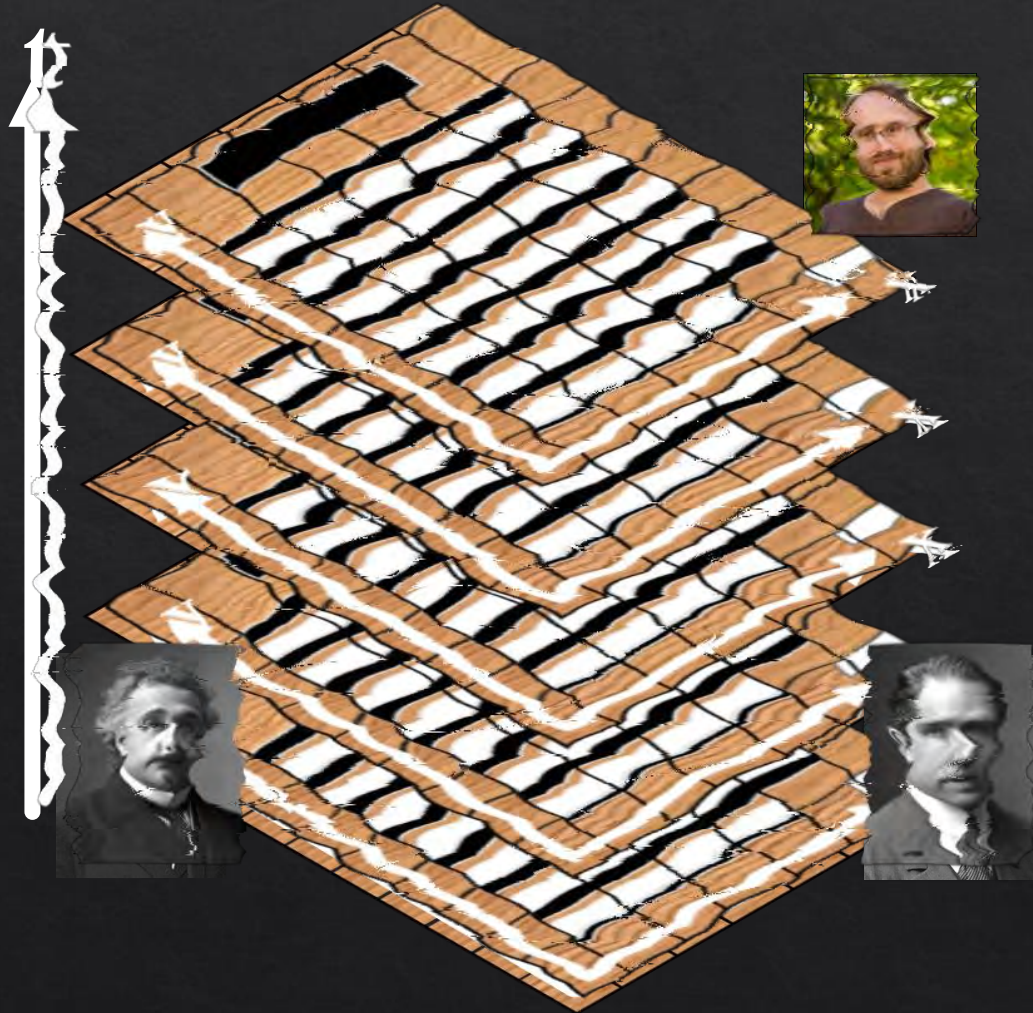
- ◇ The faster you go, the more distance you travel in less time, so the shorter your “Pythagorean time”
- ◇ For light, no time passes at all



# General Relativity: Gravity is Curved Space

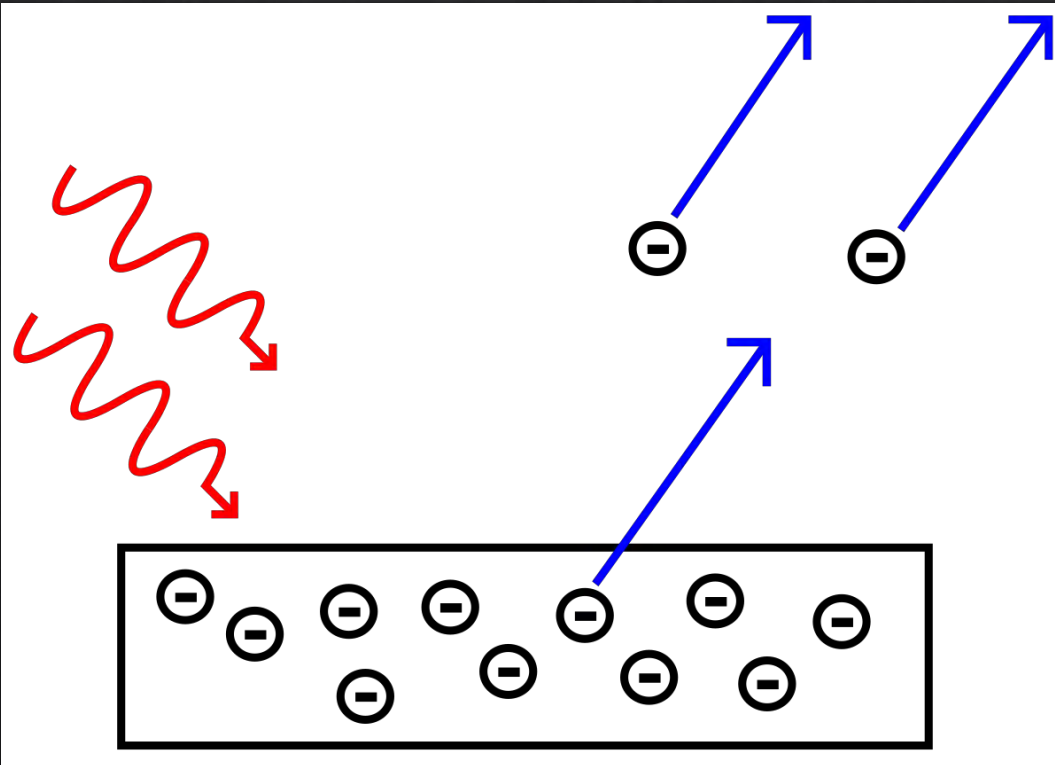


What does curved space mean?  
Change the Pythagorean theorem!



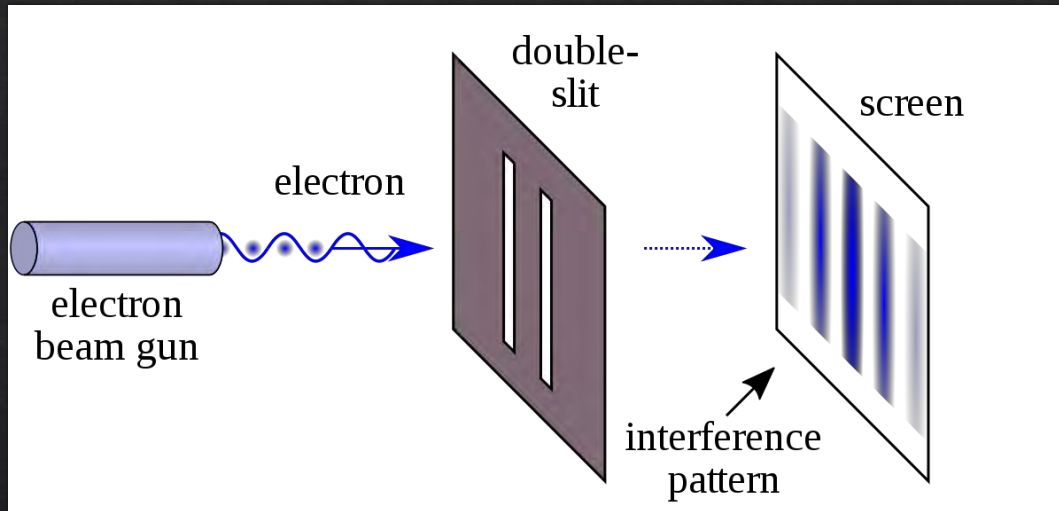
$$g_t c^2 t^2 - g_x x^2 - g_y y^2 = c^2 T^2$$

# The Photoelectric Effect: First Hints of Quantum



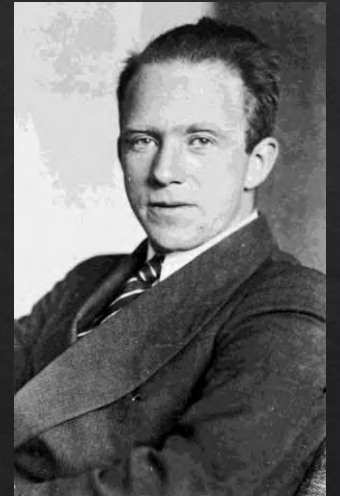
- ◇ Same year as Michelson-Morely: Heinrich Hertz notices he can make metal release sparks (emit electrons) with ultraviolet light
- ◇ Later, strange observations: energy of electrons determined by color of the light, not how much light
- ◇ Same year as Special Relativity: Einstein proposes that light comes in packets (now called photons) with energy related to their color

# Quantum Mechanics



## Heisenberg's Uncertainty Principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$
$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

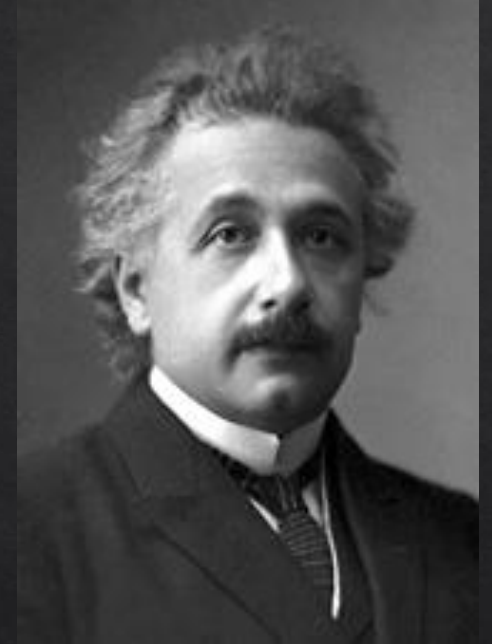


$$\hbar \approx 10^{-34} \text{ m}^2 \text{ kg/s}$$

# Bohr-Einstein Debates



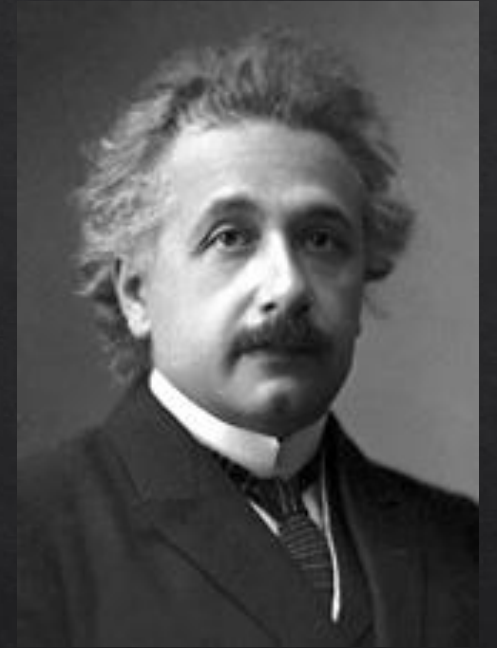
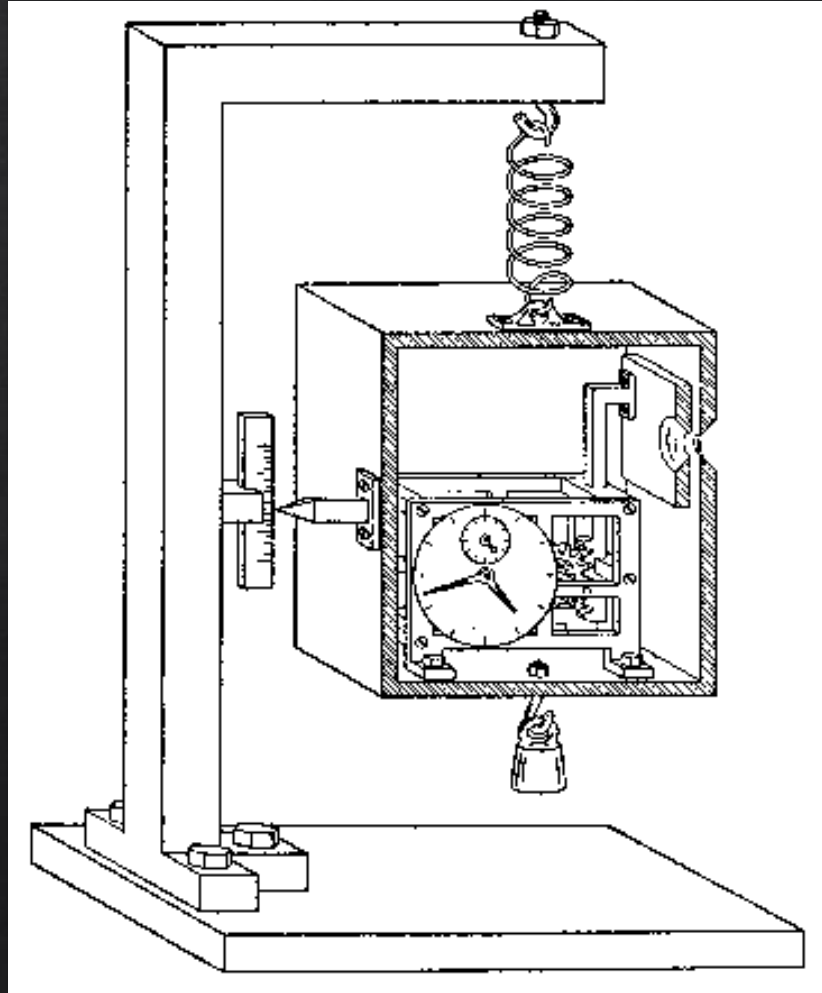
*“Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the “old one.” I, at any rate, am convinced that He does not throw dice.” –Albert Einstein*



1930

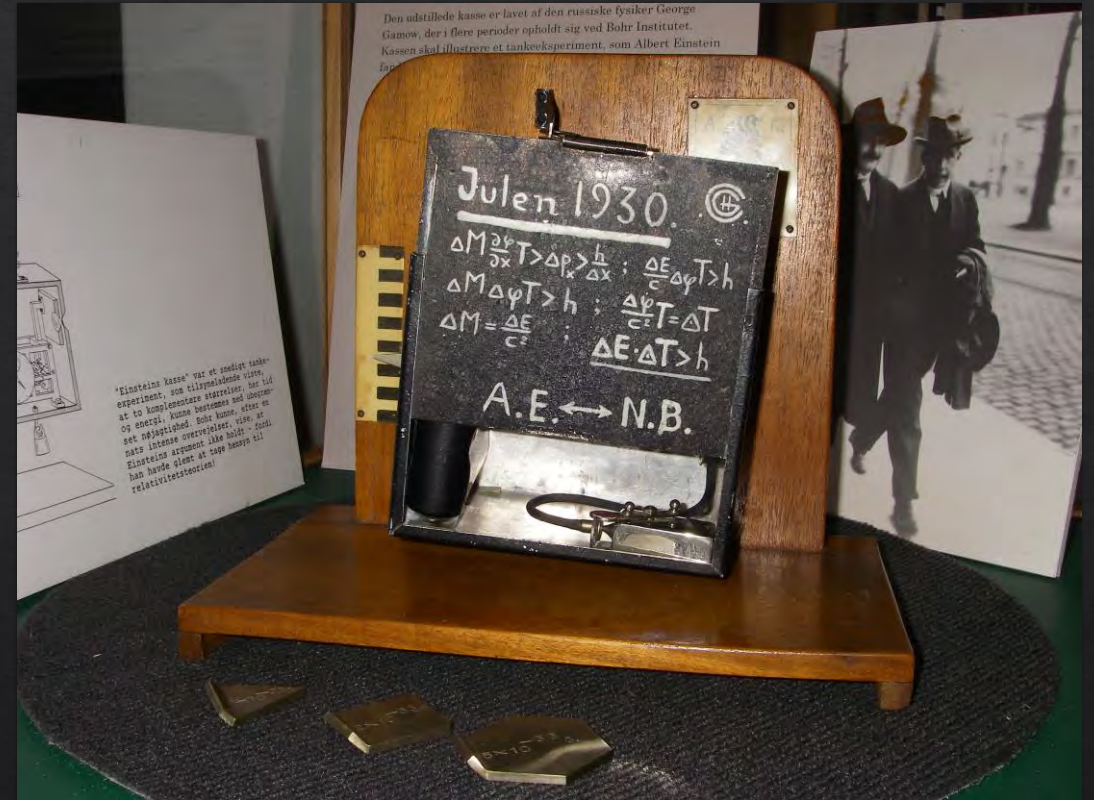
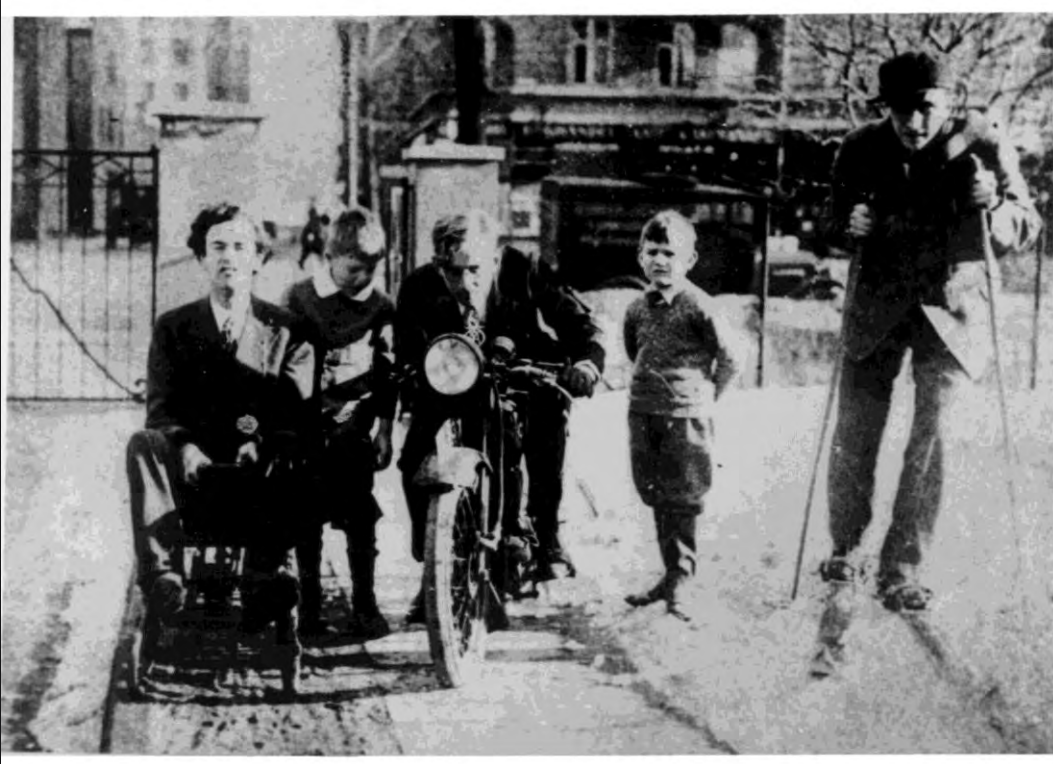


# Einstein's Objection





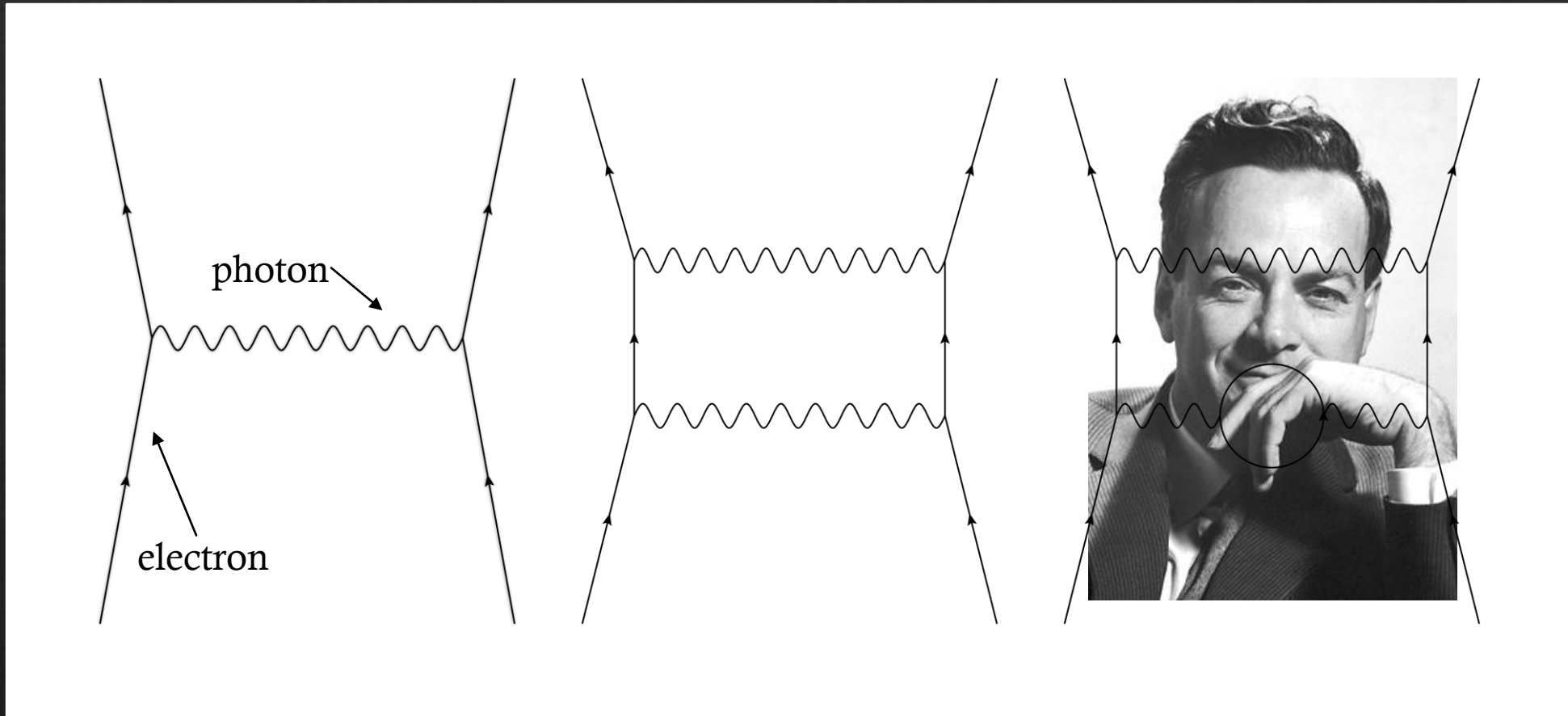
# “Thought Experiment Device”



# Break

Up next: Quantum Forces, and the Trouble with Quantum Gravity

# From Quantum Particles to Quantum Forces

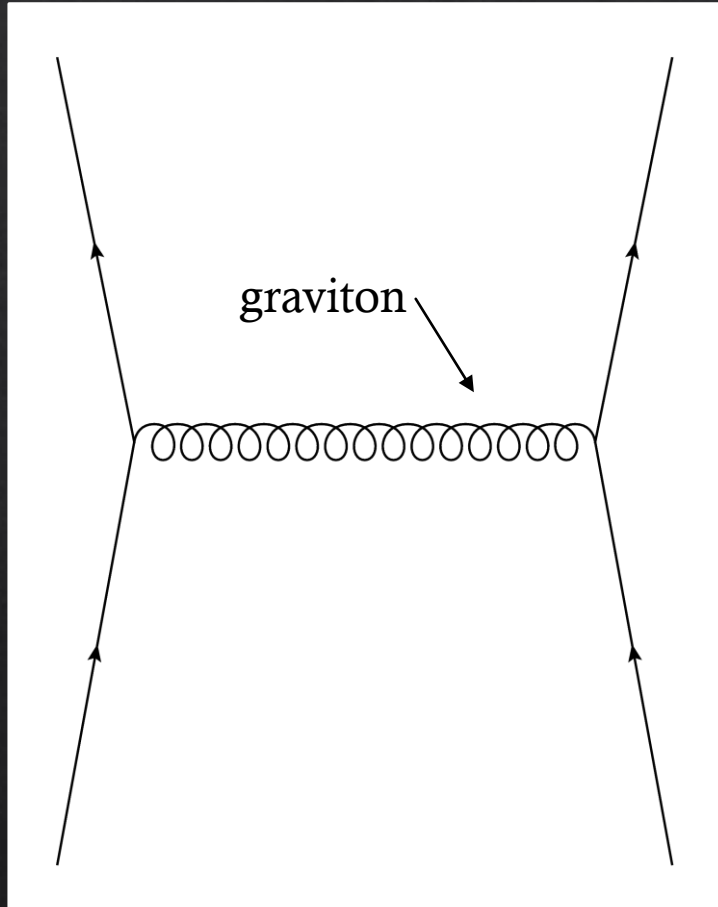


# Strengths of Quantum Forces

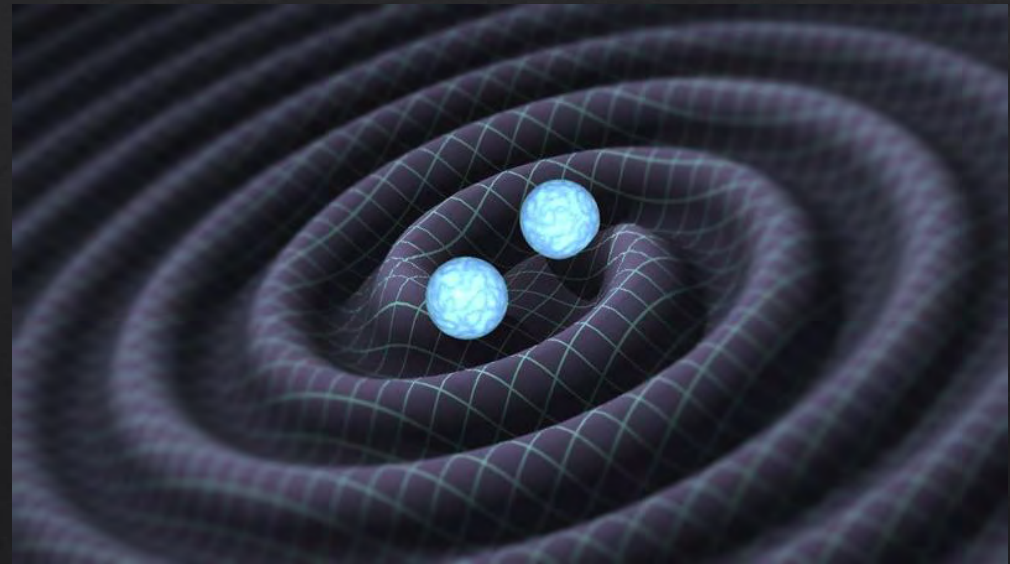
Fundamental Force	Coupling Constant
Strong Nuclear Force	$\sim 1$
Electromagnetism	$1/137$
Weak Nuclear Force	$\sim 10^{-6}$

- ◇ Feynman diagrams aren't just pictures, they're calculations!
- ◇ Each "loop" multiplies by a number related to the strength of the force, called the **coupling constant**

# For quantum gravity, just do the same thing!



- ◇ Photons carry electromagnetic force, hypothetical **gravitons** carry gravity
- ◇ Particle form of **gravitational waves**



# Two Interpretations

$$g_t c^2 t^2 - g_x x^2 - g_y y^2 = c^2 T^2$$

- ◆ Describes something traveling through curved space and time
- ◆ Describes a graviton interacting with something traveling through space and time

The same math!

# Strength of Quantum Gravity

Fundamental Force	Coupling Constant
Strong Nuclear Force	$\sim 1$
Electromagnetism	$\sim 1/137$
Weak Nuclear Force	$\sim 10^{-6}$
<b>Gravity</b>	<b><math>\sim 10^{-39}</math></b>

# Strength of Quantum Gravity





# Strength of Quantum Gravity

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BATAVIA, IL—In October, Fermilab scientists joined a growing number of physicists around the world in warning that the Very Large Earth Collider—a \$117 billion electromagnetic particle accelerator built to study astronomical phenomena by colliding Earth into various heavenly bodies—could potentially destroy Earth when it sends the planet careening headlong into Mars, Jupiter, or even the sun.

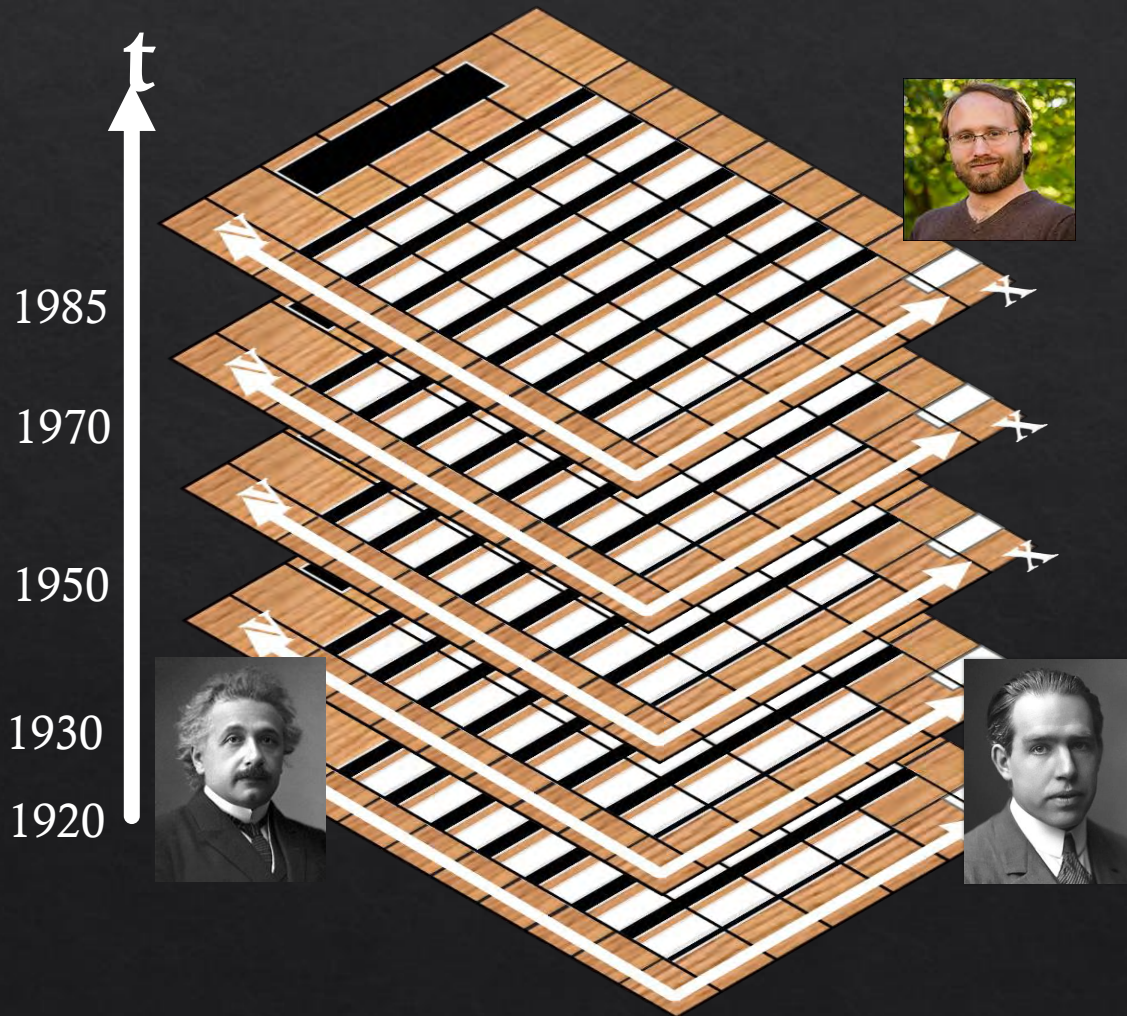


"The Large Earth Collider will surely gain us priceless scientific insight by offering a brief glimpse of the universe at the moment of its destruction," Fermilab director Gordon Jones said. "But because

Ok, we can't test it.

We still want to do the calculation!

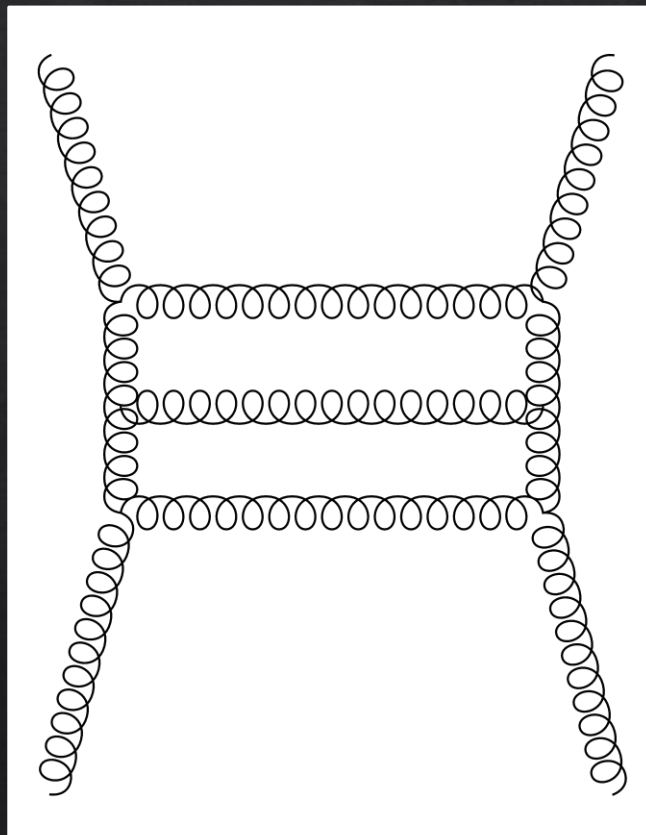
# The hard part: actually doing the calculation!



- ◇ Solvay Conference in 1930, basic ideas of quantum mechanics
- ◇ By 1950, QED, quantum theory of the electro-magnetic force using Feynman diagrams
- ◇ Around 1970, quantum theories for the nuclear forces
- ◇ 1985: Marc Goroff and Augusto Sagnotti calculate a “two loop” Feynman diagram for quantum gravity

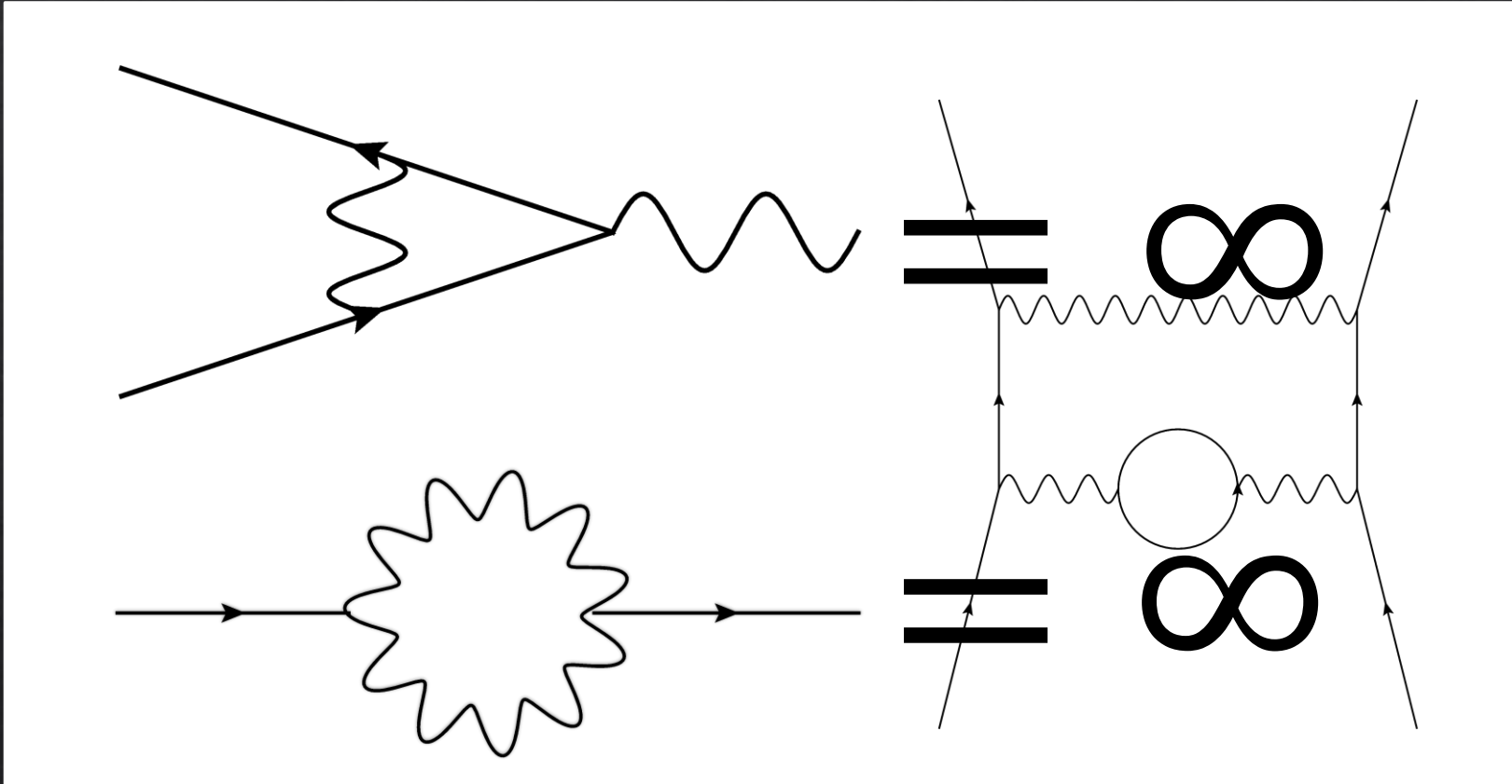


The Real Problem:



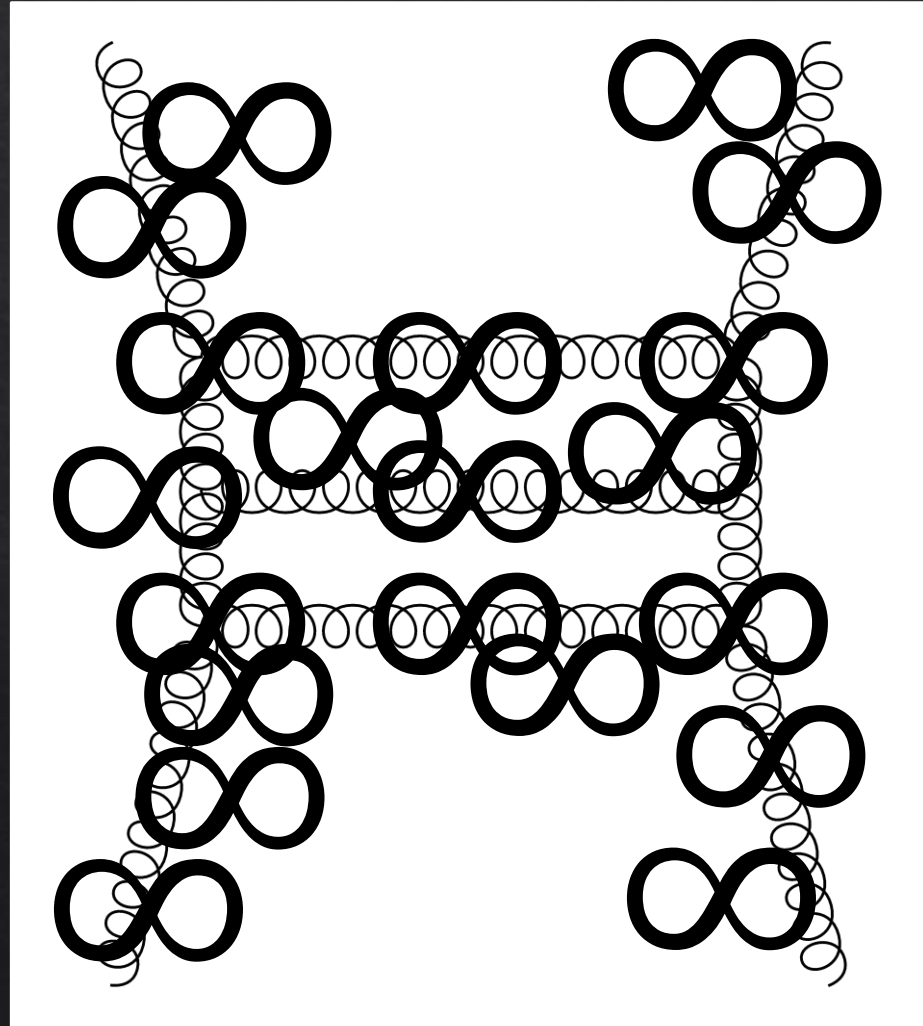
$$= \infty$$

# Hiding Infinity



Renormalization

# The Real Real Problem

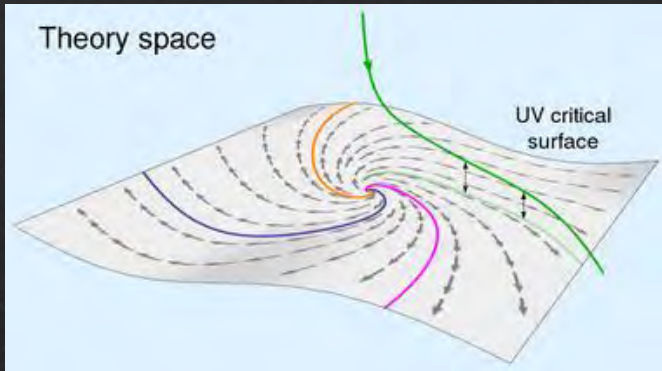


# The Real Real Problem

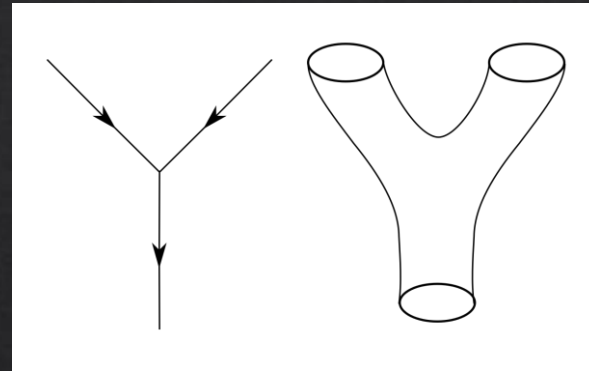


# Proposed Solutions

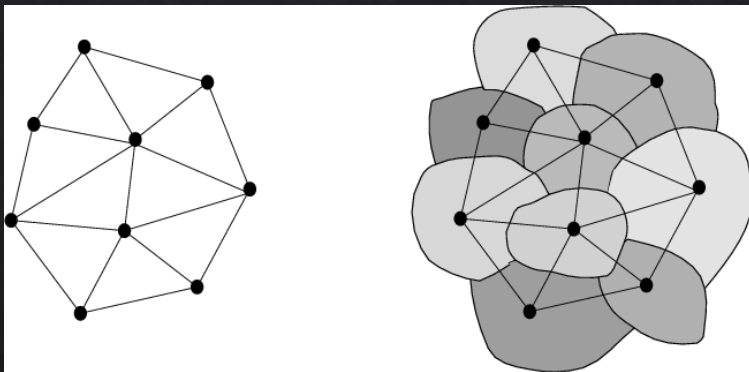
## Asymptotic Safety



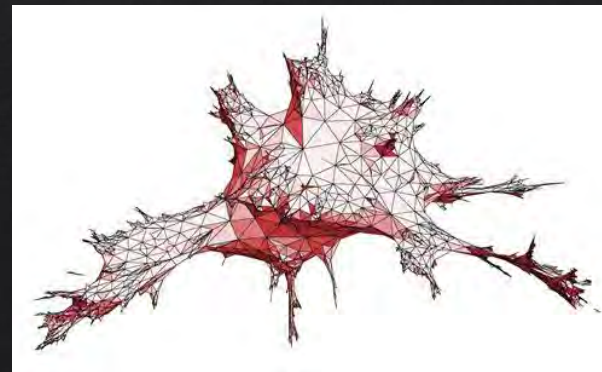
## String Theory



## Loop Quantum Gravity

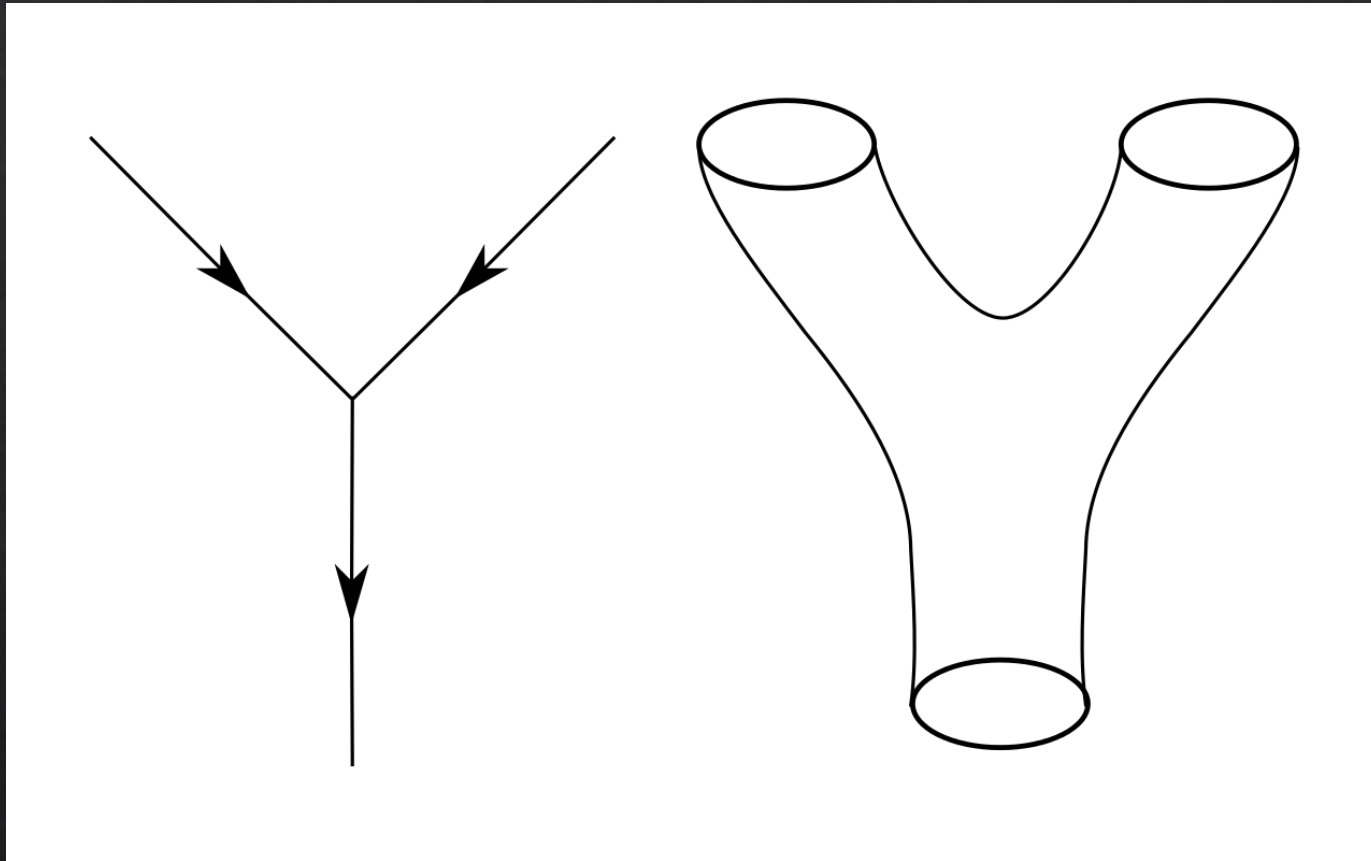


## Causal Dynamical Triangulations

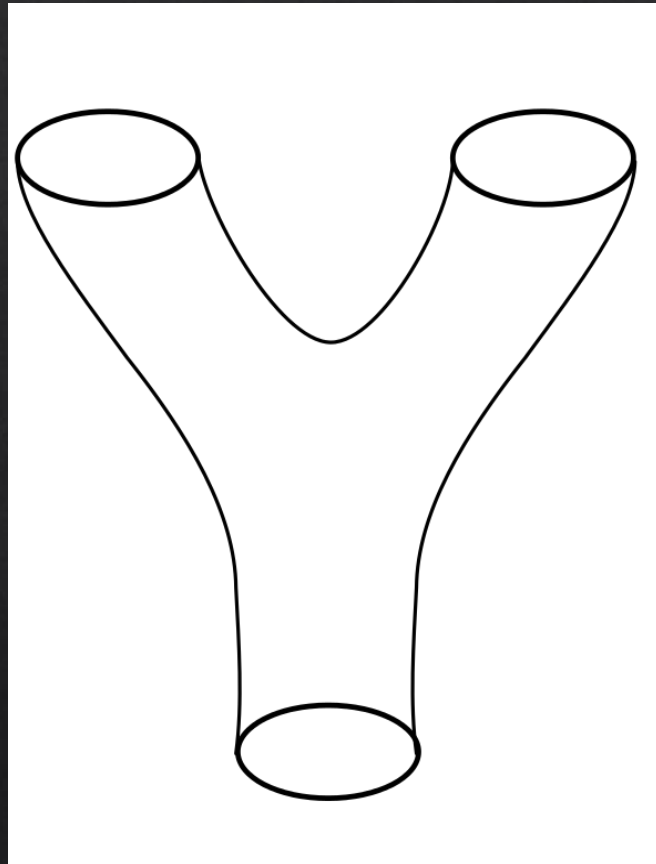




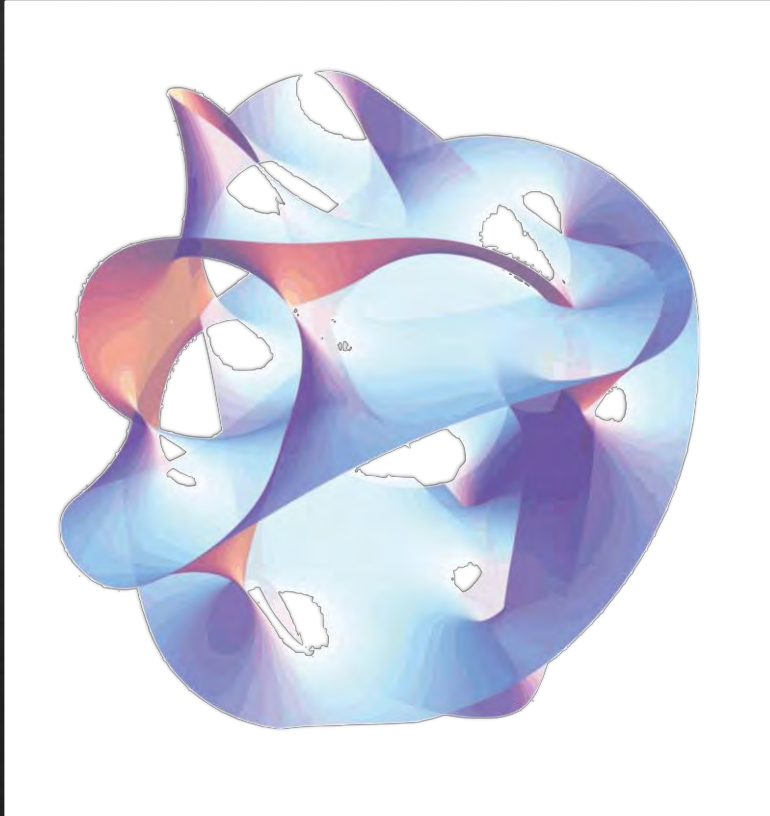
# String Theory



# String Theory

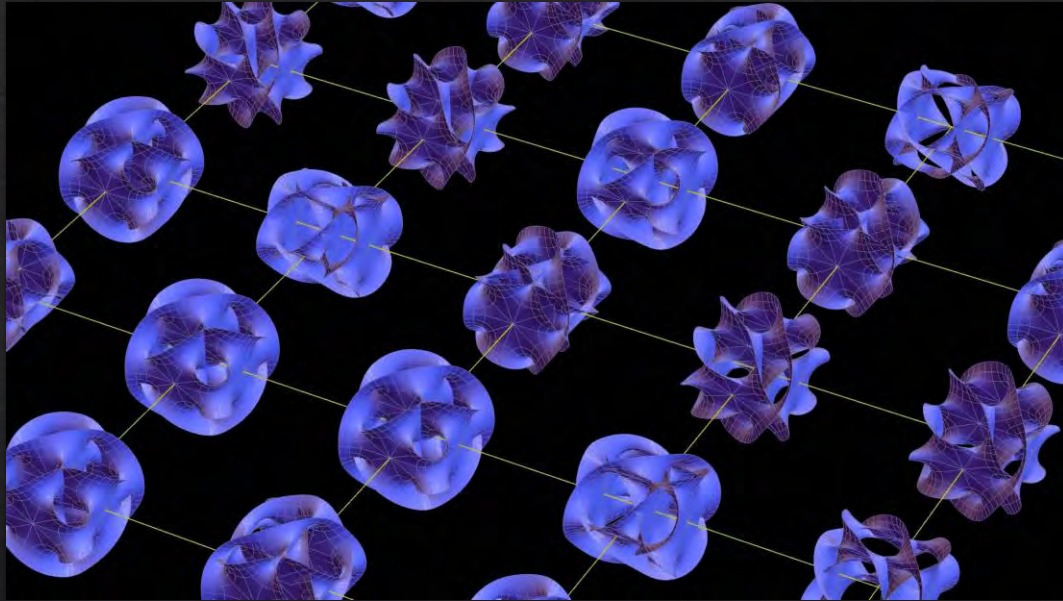


# Extra Dimensions



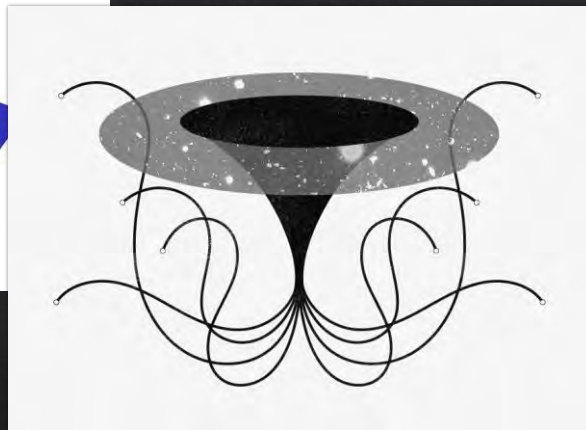
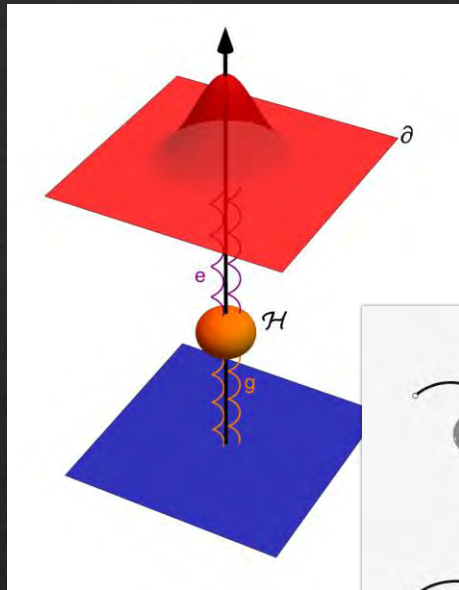
- ◇ Weird consequence: the math doesn't work out unless there are six or seven extra dimensions:  $t, x, y, z, a, b, c \dots$
- ◇ These dimensions curl up: travel a tiny distance and you're back where you started, so we don't notice
- ◇ Strings can curl around extra dimensions, making them look like different kinds of particles
- ◇ Can this let us predict new particles?

# Too many possibilities!

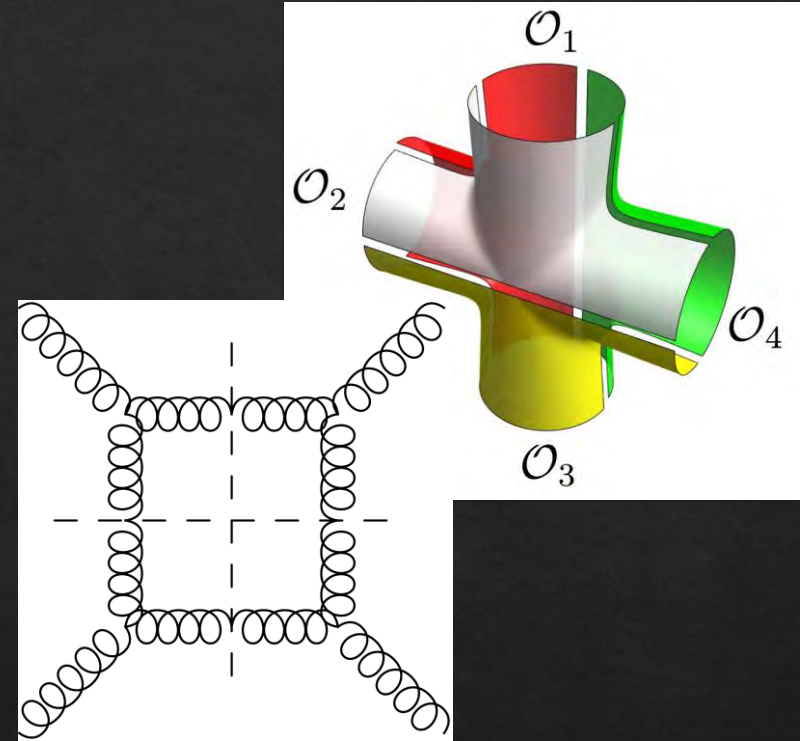


- ◇ Huge number of possible ways to twist extra dimensions around
- ◇ Currently, no way to find which is true in real world, if any

# What's next?



New Questions about  
Quantum Gravity



Using String Theory to  
find Mathematical Tricks

The Quest Continues...