During the second class, I showed the following two videos from "The Mechanical Universe and Beyond" series:

39. **Maxwell's Equations**

41. **The Michelson-Morley Experiment**

You can access these videos online by going to:

http://www.learner.org/resources/series42.html

and selecting the video you would like to see.

You can also access:

The Michelson-Morley Experiment
https://faculty.washington.edu/seattle/physics544/videos/41.pdf

General Relativity

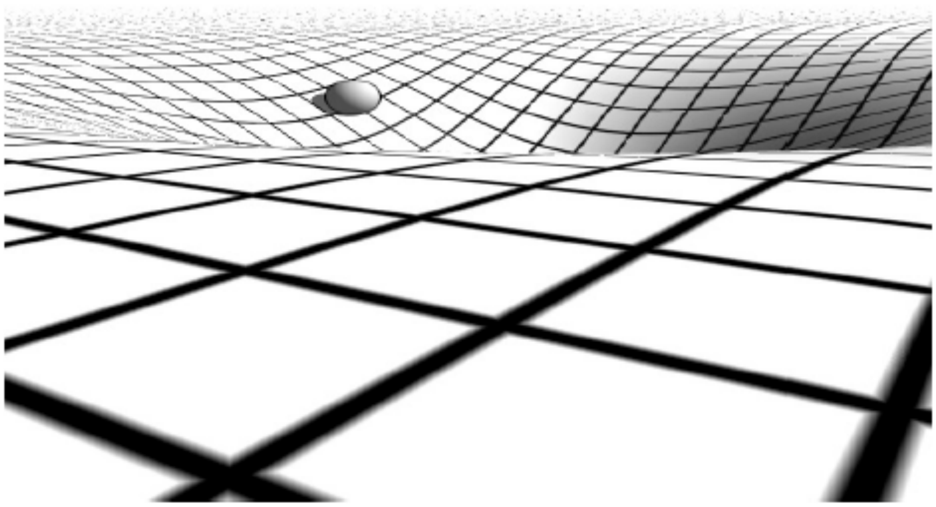
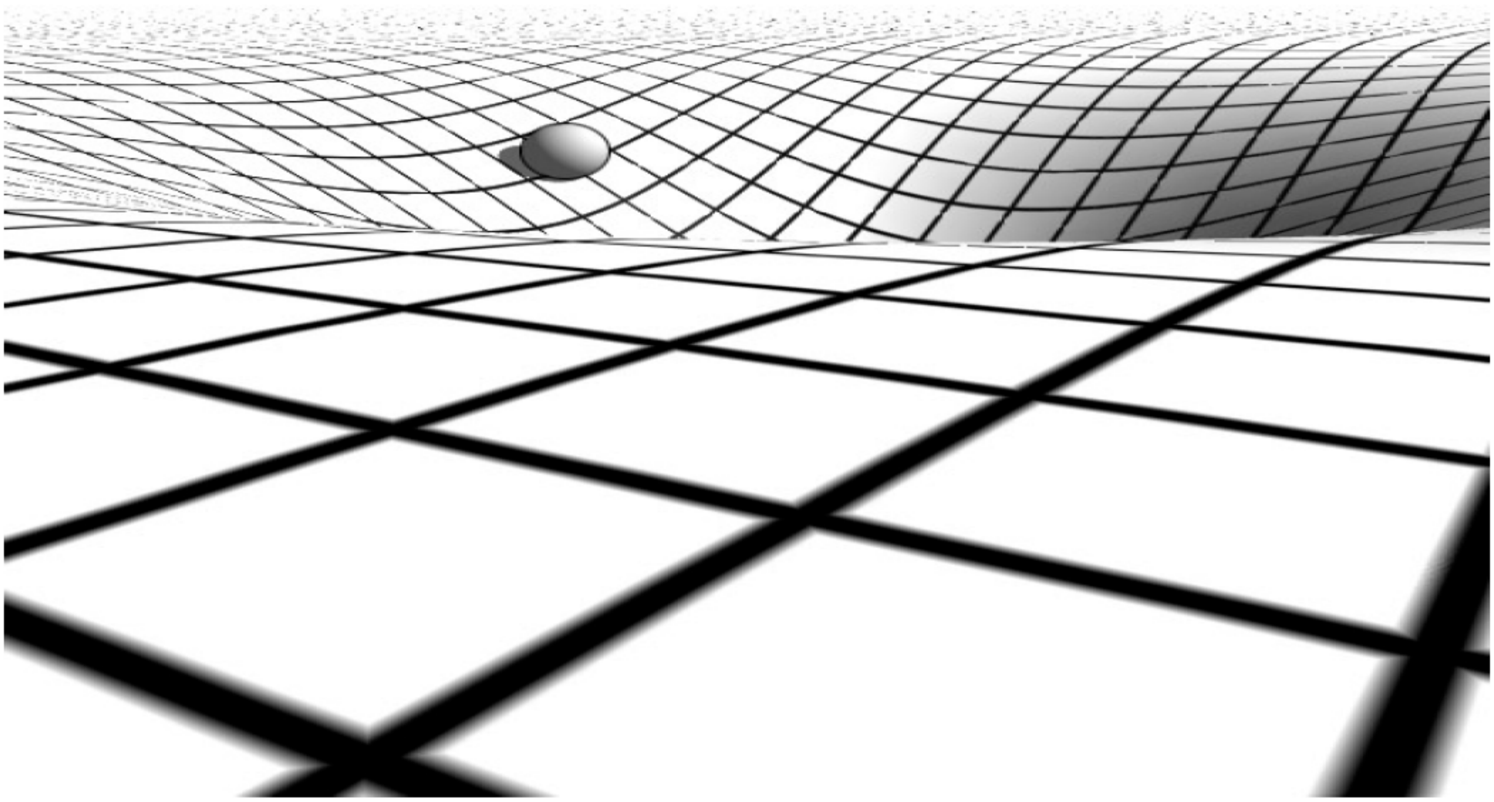
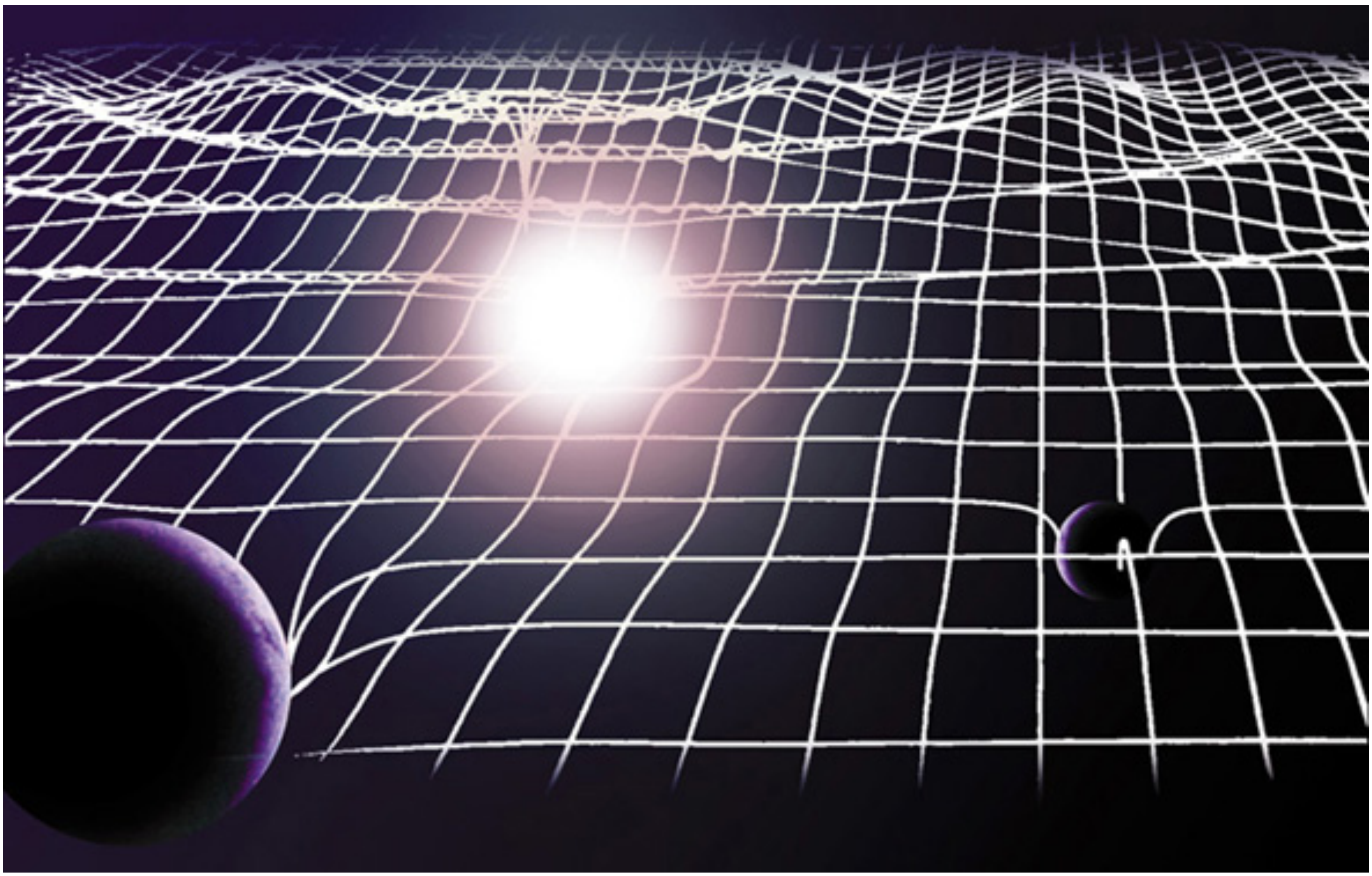
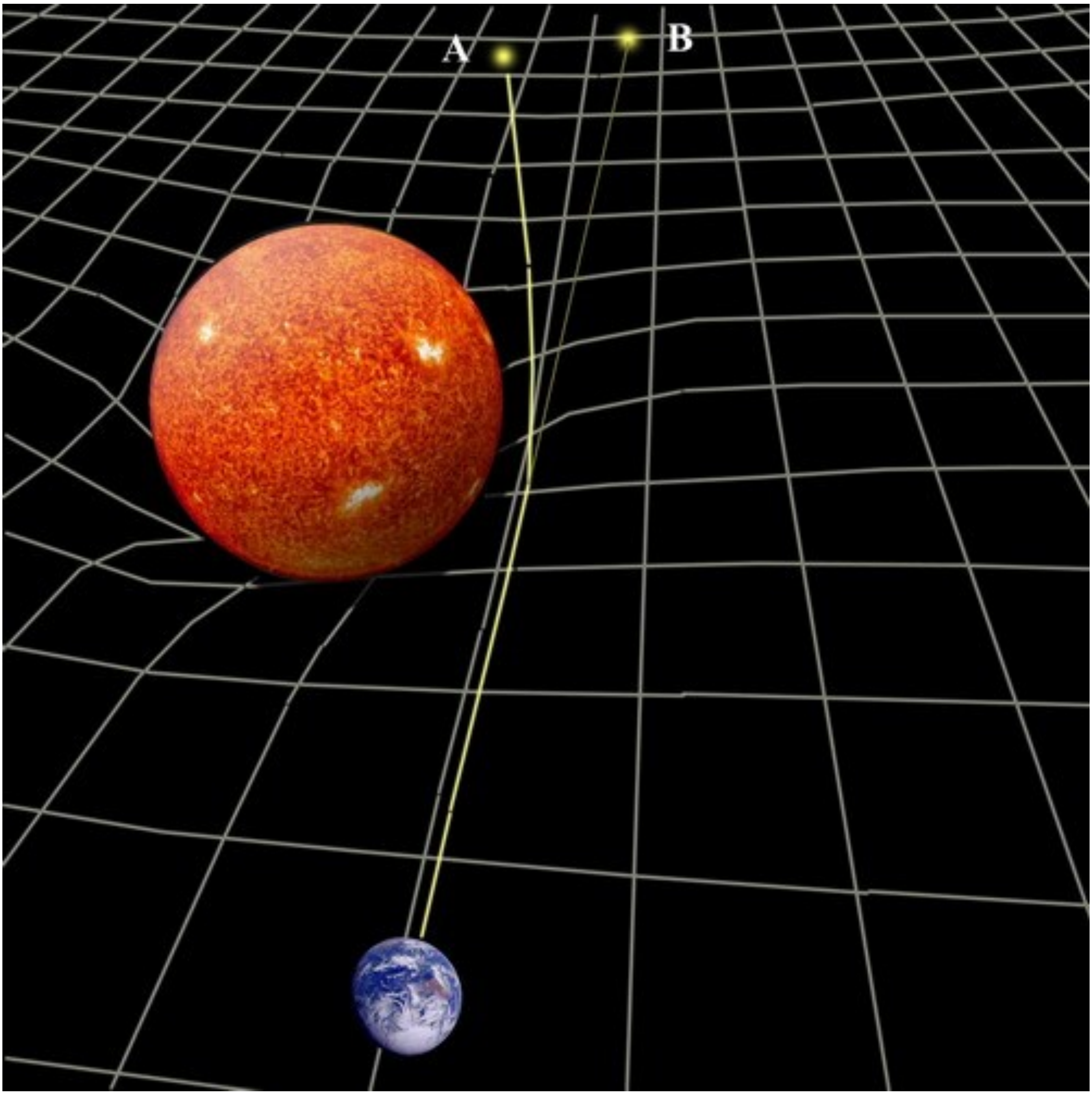


FIG. 1: An artist's depiction of planetary motion in general relativity. Heavy bodies such as our sun bend space-time. Planets go 'as straight as they can' in this curved geometry. In the flat space perspective of Newtonian physics, however, the same orbits appear to be elliptical, being eternally pulled to the sun by gravity. Thus the familiar gravitational force of Newtonian physics is just a 'poor man's way' of describing effects of space-time curvature using a flat space framework. Image: Boris Starosta, www. Starosta.com

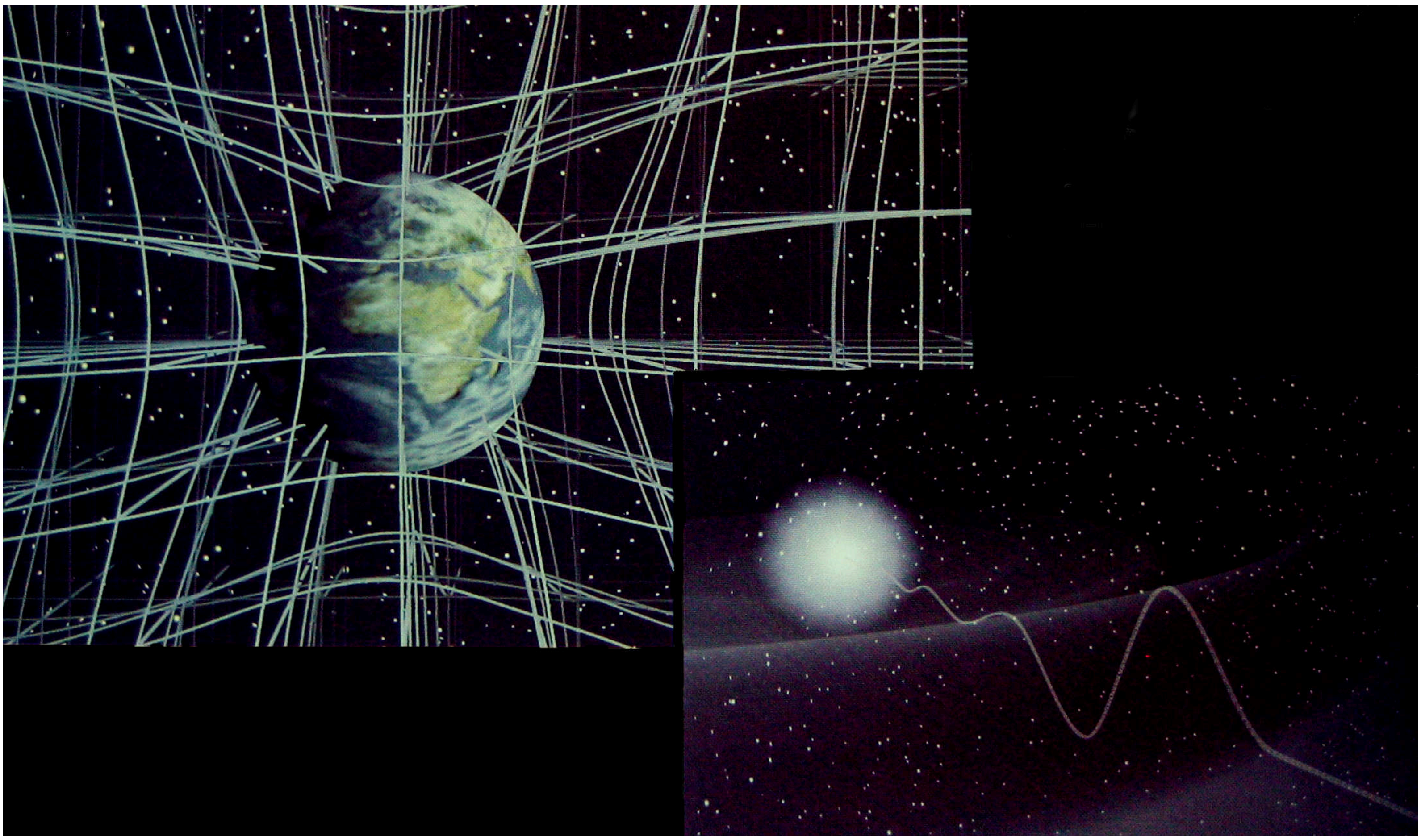
The magic of general relativity is that, through elegant mathematics, it transforms these conceptually simple ideas into concrete equations and uses them to make astonishing predictions about the nature of physical reality. It predicts that clocks should tick faster in Kathmandu than in Bombay. Galactic nuclei should act as giant gravitational lenses and provide spectacular, multiple images of distant quasars. Two neutron stars orbiting around each other must lose energy through ripples in the curvature of space-time caused by their motion and spiral inward in an ever tightening embrace. Over the last thirty years, astute measurements have been performed to test if these and other even more exotic predictions are correct. Each time, general relativity has triumphed [2]. The accuracy of some of these observations exceeds that of the legendary tests of quantum electrodynamics. This combination of conceptual depth, mathematical elegance and observational successes is unprecedented. This is why general relativity is widely regarded as the most sublime of all scientific creations [3].

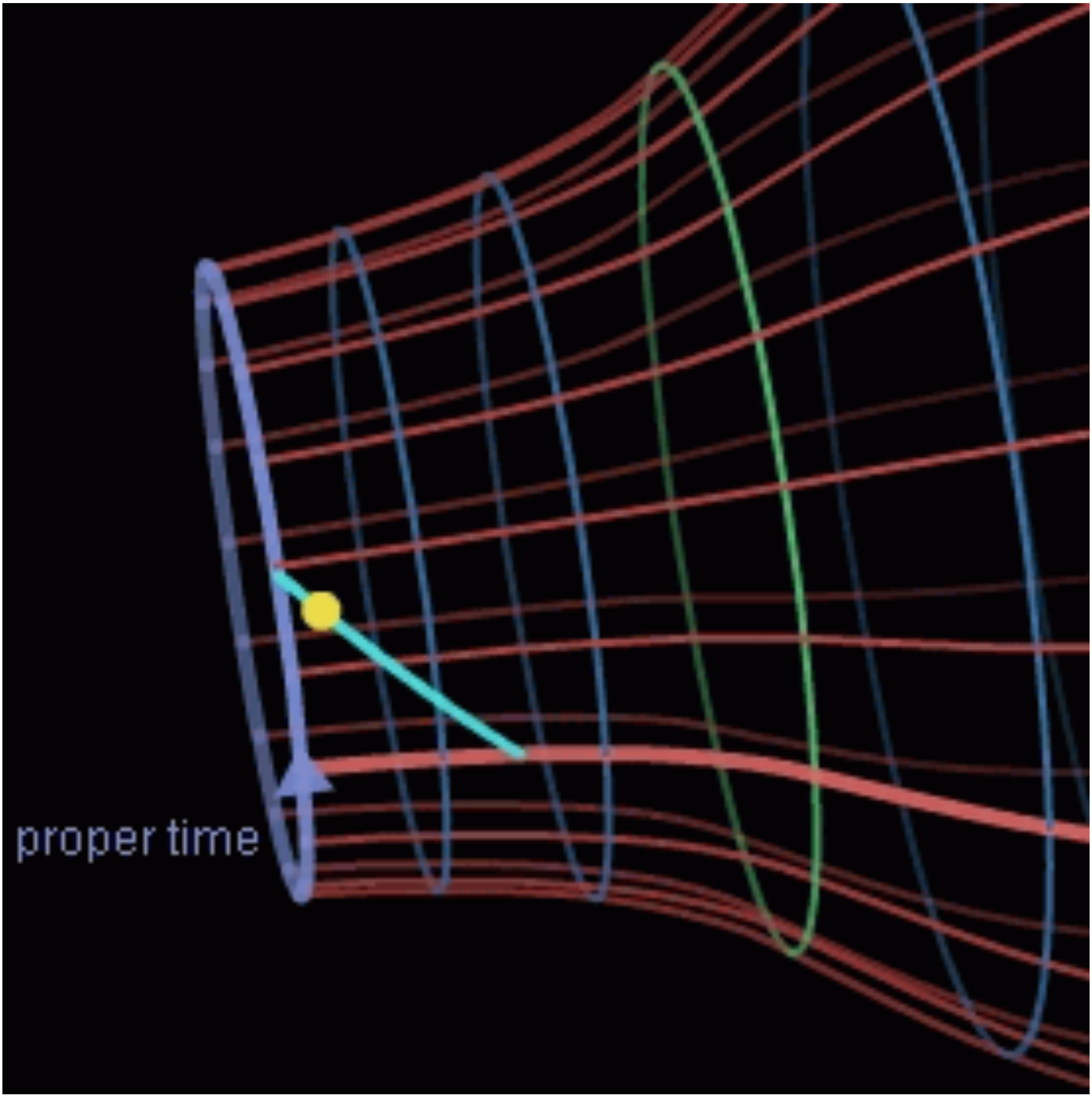






A
B




proper time

Electrodynamics

http://www.its.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html
http://webphysics.davidson.edu/applets/retard/Retard_FEL.html

Special Relativity

http://www.cco.caltech.edu/~phys1/java/phys1/Einstein/Einstein.html
http://www.univie.ac.at/future.media/moe/galerie/struct/struct.html
http://webphysics.davidson.edu/applets/Minkowski/Minkowski_FEL.html

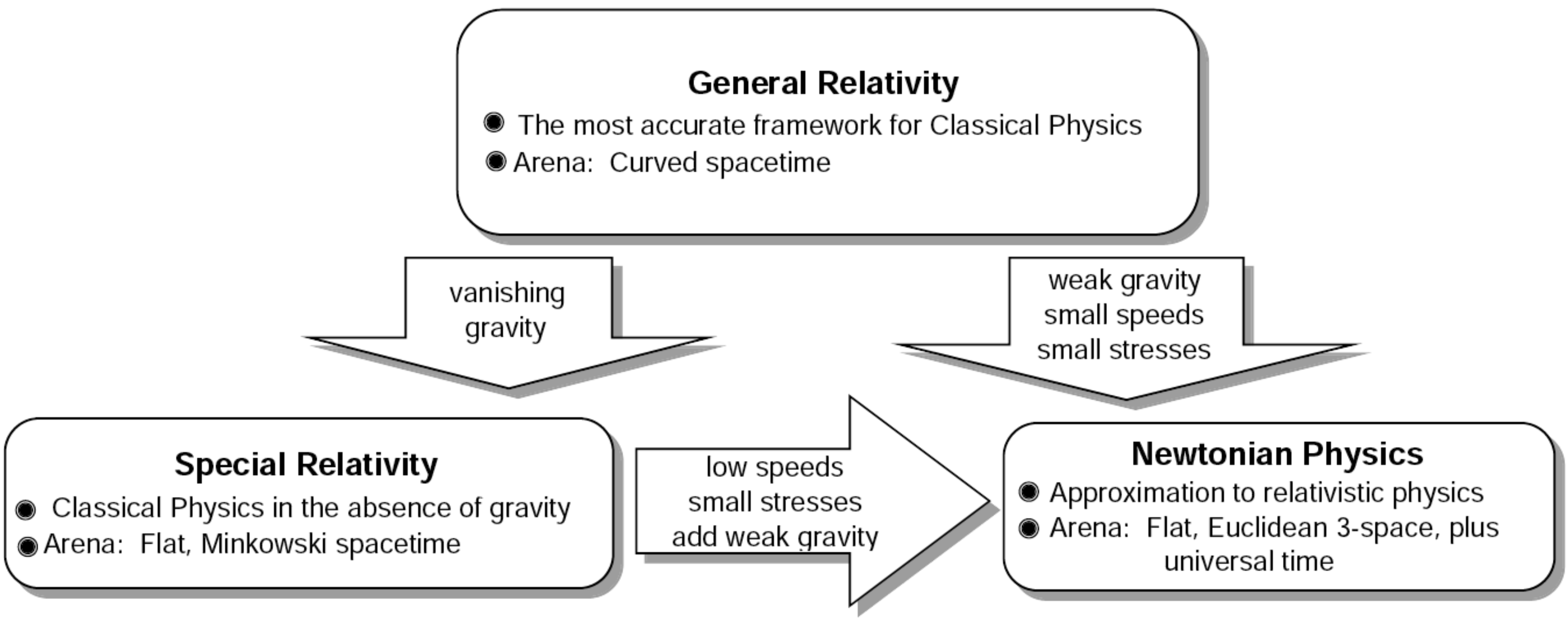
General Relativity

http://einstein.stanford.edu/Media/Newtons_Universe_Anima-Flash.html
http://einstein.stanford.edu/Media/Einsteins_Universe_Anima-Flash.html
http://einstein.stanford.edu/Media/Simple_Expt_Anima-Flash.html

http://www.youtube.com/watch?v=AAqSCuHA0j8 Gravity in terms of space-time
http://www.youtube.com/watch?v=DbhuRcmSkMg How gravity really works
http://www.youtube.com/watch?v=O-p8yZYxNGc Newton vs Einstein

http://faraday.physics.utoronto.ca/PVB/Harrison/GenRel/Flash/Precession.html GR vs CM Orbits
http://www.fourmilab.ch/gravitation/orbits/ GR Orbits
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/kepler6.htm CM Orbits
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/morekep.html
http://astro.unl.edu/naap/pos/animations/kepler.swf
http://burtleburtle.net/bob/physics/solar.html
http://www.youtube.com/watch?v=nuX1BKLPITU Gravity Well - Exploratorium
http://www.youtube.com/watch?v=HrVdb9027yQ Blue well for coins

http://archive.ncsa.illinois.edu/Cyberia/NumRel/mathmine1.html 2D GR 3 pages
http://test1.alan-dale.com/tapir/numrel2.html 3D GR 100 pages
http://grtensor.phy.queensu.ca/NewDemo/index.html 416 diagonal and 519 off-diagonal terms


General Relativity
The most accurate framework for Classical Physics
Arena: Curved spacetime
vanishing gravity
weak gravity
small speeds
small stresses
Special Relativity
Classical Physics in the absence of gravity
Arena: Flat, Minkowski spacetime
low speeds
small stresses
add weak gravity
Newtonian Physics
Approximation to relativistic physics
Arena: Flat, Euclidean 3-space, plus universal time

The irrelevance of quantum gravity....

- Gravity exists for everything, but only seems relevant for very large objects otherwise overwhelmed by other forces!

WHO CARES ABOUT QUANTUM GRAVITY?

Ignoring gravity

	Slow	Fast
Big	Classical Mechanics	Special relativity
Small	Quantum Mechanics	Quantum field theory

With gravity

	Slow	Fast
Big	Classical Mechanics	General relativity
Small	Quantum Mechanics	Quantum gravity

When is quantum gravity relevant?

We cannot be sure, but we can have a guess based on dimensional arguments.

We have three fundamental constants:

c: Gives the scale which special relativity becomes important

G: Gives the scale of gravity

h: Gives the scale of when quantum becomes important

Combinations of these three should give me the scale which quantum gravity becomes important. Note I have three constants: c, G and h. By combining them I can get a length, a mass and a time:

$$L_{Planck} = \sqrt{\frac{hG}{c^3}} = 1.6 \times 10^{-16}\, s$$

$$t_{Planck} = \sqrt{\frac{hG}{c^5}} = 5.4 \times 10^{-43}\, s$$

$$M_{Planck} = \sqrt{\frac{hc}{G}} = 2.7 \times 10^{-8}\, kg$$

QG relevant on times < t_p, length scales < l_p, masses > m_p.

Table of universal constants

Quantity v·d·e	Symbol	Value[5]	Relative Standard Uncertainty
speed of light in vacuum	c	$299\,792\,458\ \mathrm{m{\cdot}s^{-1}}$	defined
Newtonian constant of gravitation	G	$6.674\,28(67) \times 10^{-11}\ \mathrm{m^3{\cdot}kg^{-1}{\cdot}s^{-2}}$	1.0×10^{-4}
Planck constant	h	$6.626\,068\,96(33) \times 10^{-34}\ \mathrm{J{\cdot}s}$	5.0×10^{-8}
reduced Planck constant	$\hbar = h/(2\pi)$	$1.054\,571\,628(53) \times 10^{-34}\ \mathrm{J{\cdot}s}$	5.0×10^{-8}

Natural units

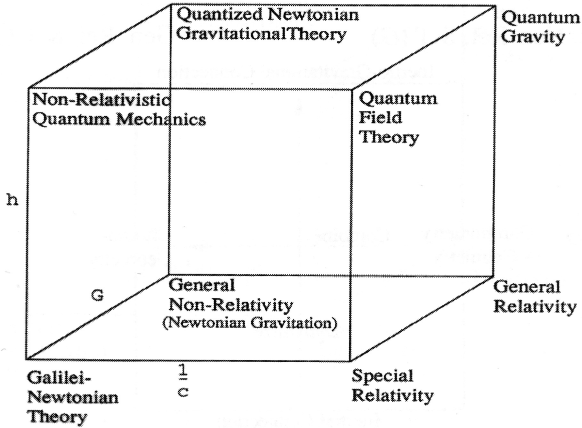
[edit]

Main article: Natural units

Using dimensional analysis, it is possible to combine fundamental physical constants to produce basic units of measurement. Depending on the choice and arrangement of constants used, the resulting natural units may have physical meaning. For example, Planck units, presented below, use $c, G, \hbar, \varepsilon_0$ and k to derive constants relevant to unified theories, including quantum gravity.

Name v·d·e	Dimension	Expression	Value[8] (SI units)
Planck length	Length (L)	$l_P = \sqrt{\frac{\hbar G}{c^3}}$	$1.616\,252(81) \times 10^{-35}$ m
Planck mass	Mass (M)	$m_P = \sqrt{\frac{\hbar c}{G}}$	$2.176\,44(11) \times 10^{-8}$ kg
Planck time	Time (T)	$t_P = \frac{l_P}{c} = \frac{\hbar}{m_P c^2} = \sqrt{\frac{\hbar G}{c^5}}$	$5.391\,24(27) \times 10^{-44}$ s
Planck charge	Electric charge (Q)	$q_P = \sqrt{4\pi\varepsilon_0 \hbar c}$	$1.875\,545\,870(47) \times 10^{-18}$ C
Planck temperature	Temperature (Θ)	$T_P = \frac{m_P c^2}{k_B} = \sqrt{\frac{\hbar c^5}{G k_B^2}}$	$1.416\,785(71) \times 10^{32}$ K

BRONSTEIN CUBE



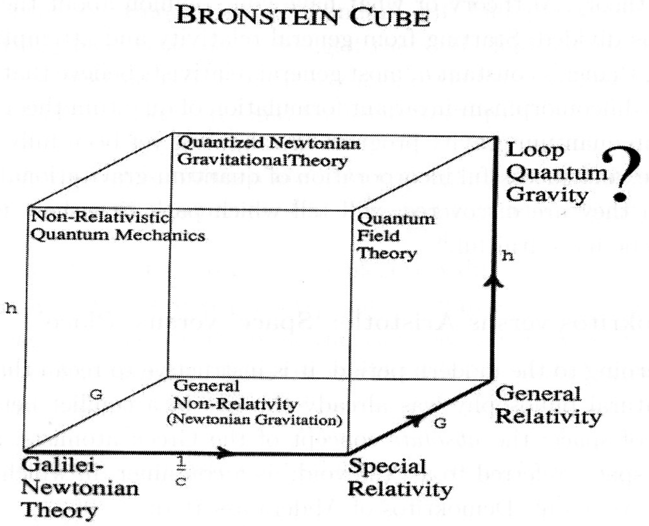


Fig. 3. General Relativists' Viewpoint.

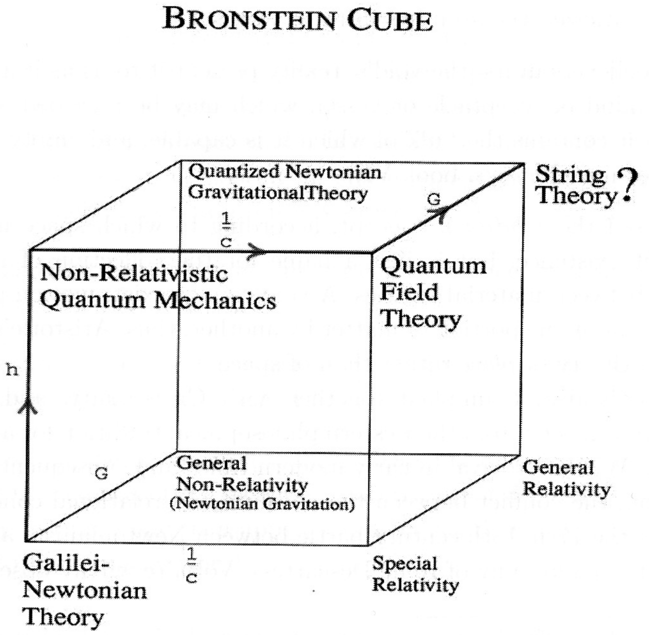
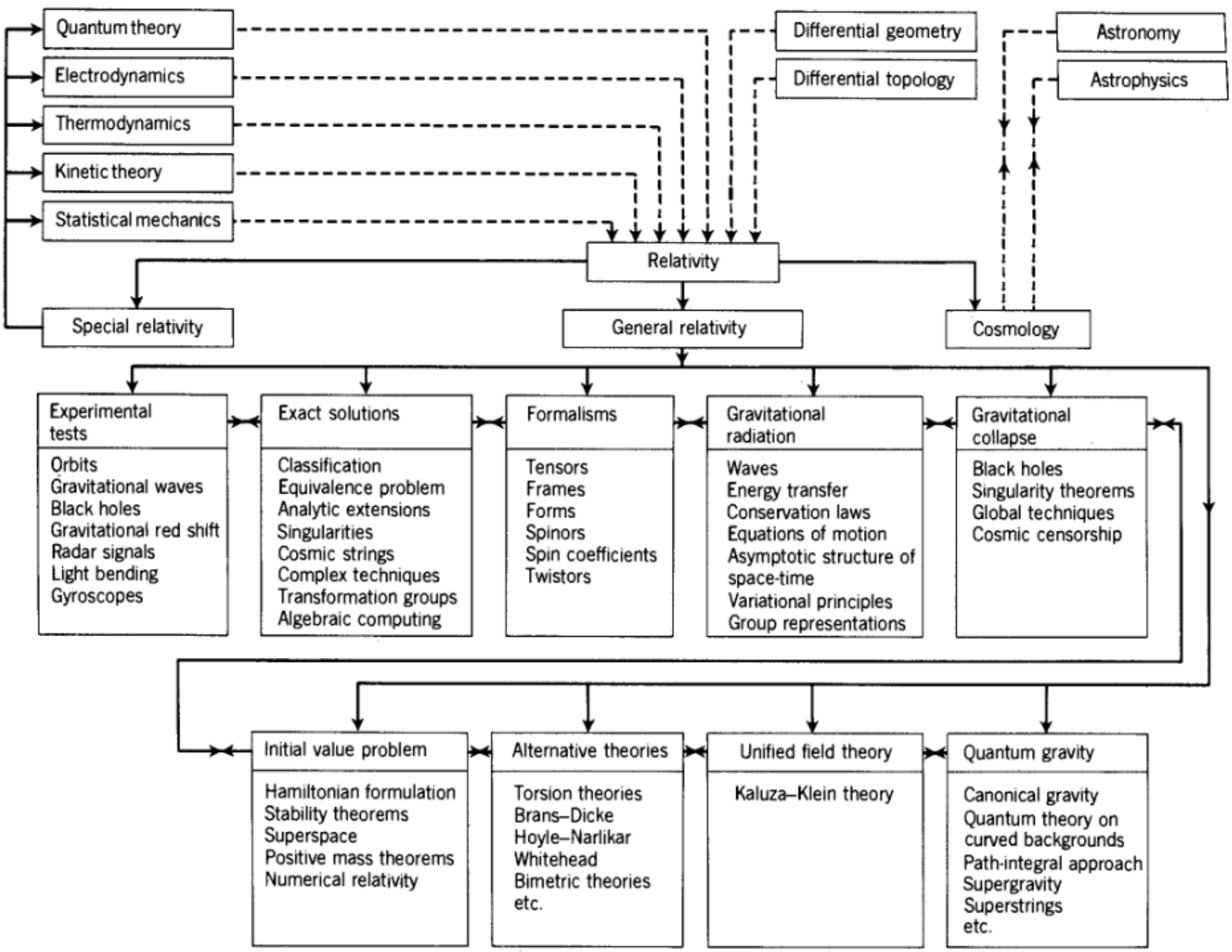


Fig. 4. Particle Physicists' Viewpoint.

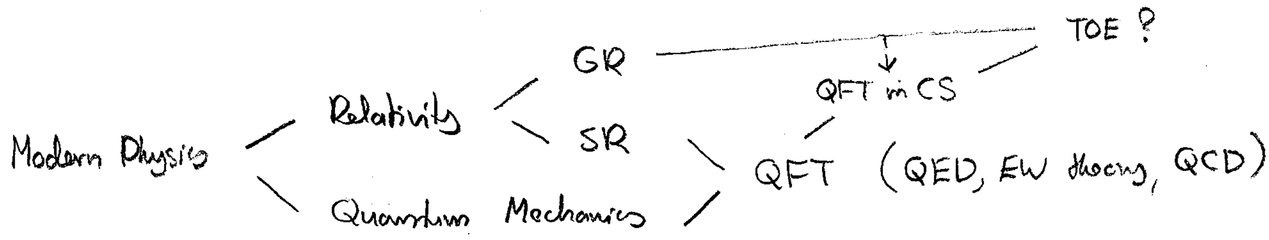
Table 3.1

Theory	Position	Velocity	Time	Acceleration
Newtonian	Relative	Relative	Absolute	Absolute
Special relativity	Relative	Relative	Relative	Absolute
General relativity	Relative	Relative	Relative	Relative


Quantum theory
Electrodynamics
Thermodynamics
Kinetic theory
Statistical mechanics
Differential geometry
Differential topology
Astronomy
Astrophysics
Relativity
Special relativity
General relativity
Cosmology
Experimental tests
Orbits
Gravitational waves
Black holes
Gravitational red shift
Radar signals
Light bending
Gyroscopes
Exact solutions
Classification
Equivalence problem
Analytic extensions
Singularities
Cosmic strings
Complex techniques
Transformation groups
Algebraic computing
Formalisms
Tensors
Frames
Forms
Spinors
Spin coefficients
Twistors
Gravitational radiation
Waves
Energy transfer
Conservation laws
Equations of motion
Asymptotic structure of space-time
Variational principles
Group representations
Gravitational collapse
Black holes
Singularity theorems
Global techniques
Cosmic censorship
Initial value problem
Hamiltonian formulation
Stability theorems
Superspace
Positive mass theorems
Numerical relativity
Alternative theories
Torsion theories
Brans–Dicke
Hoyle–Narlikar
Whitehead
Bimetric theories
etc.
Unified field theory
Kaluza–Klein theory
Quantum gravity
Canonical gravity
Quantum theory on curved backgrounds
Path-integral approach
Supergravity
Superstrings
etc.

SR and GR do not include quantum physics

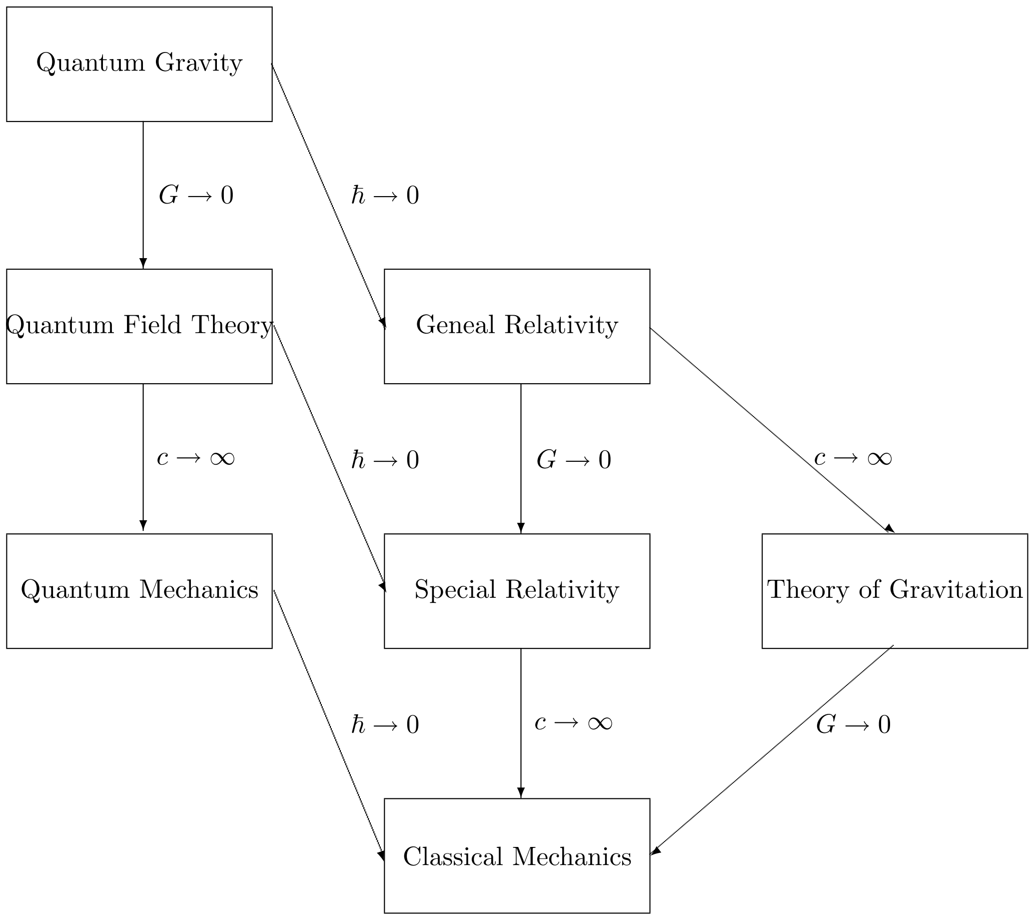
SR and quantum mechanics have been succesfully combined in Quantum Field Theory; but theorists are still looking for the right way to combine GR and quantum physics into a "Theory Of Everything" (TOE) (String Theory is a candidate).



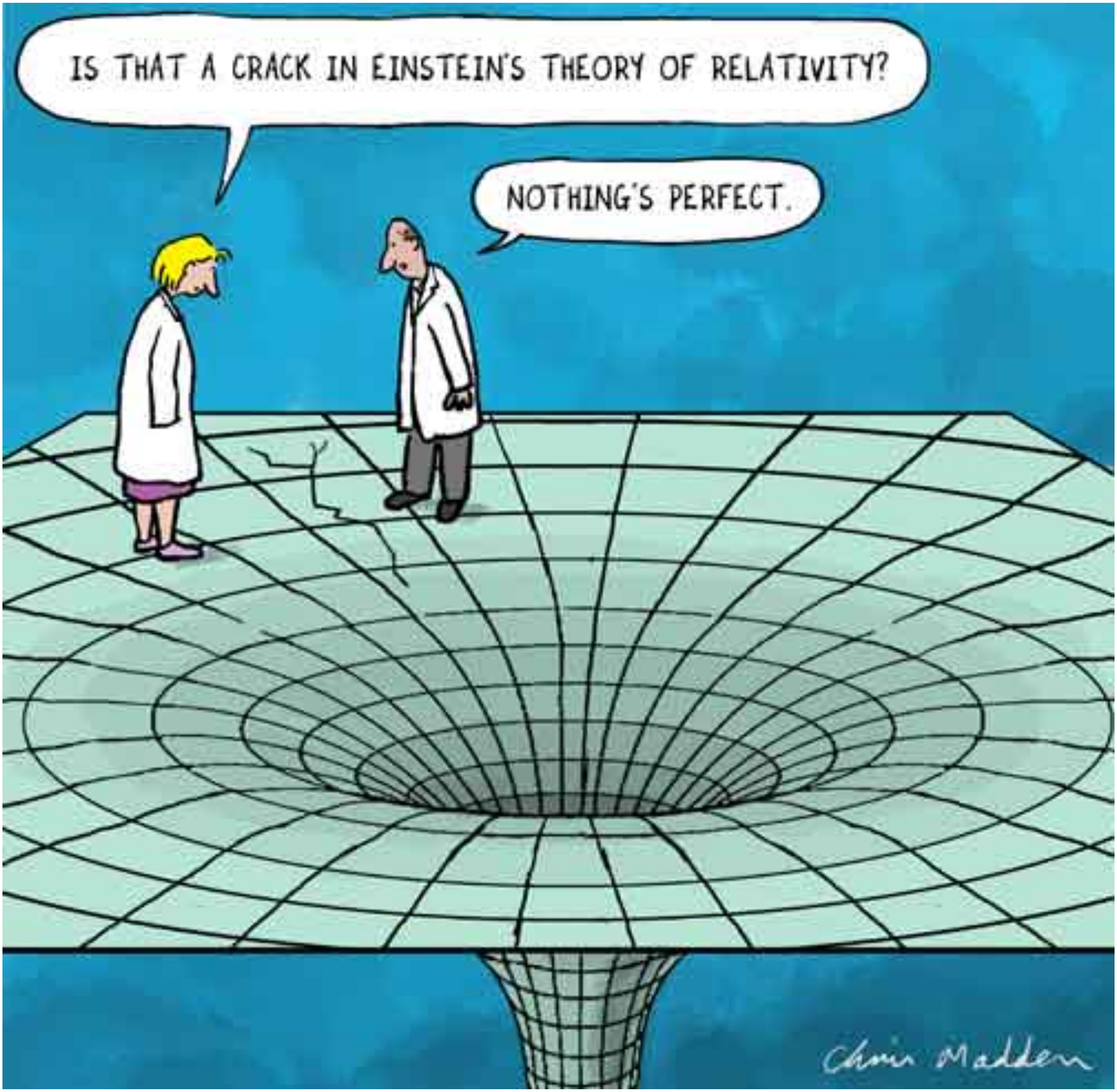
- QFT has been succesfully "half-combined" with GR as "Quantum Field Theory in Curved Spacetime", where other fields are quantized and evolve in a curved spacetime which is a solution of GR, but gravity itself remains classical (is not quantized). Important predictions of QFT in CS are 1) Hawking radiation from black holes, and 2) generation of primordial density perturbations from quantum fluctuations during inflation (cosmology).

- Linearized gravity: For weak gravitational fields, which can be considered as small perturbations around Minkowski space, one can make an approximation (first order in perturbation) to GR, where the equations of GR become linear (Chapter 7 of this course and Carroll's book). This linearized gravity can be succesfully quantized. Those gravitational field quanta are called gravitons.

- This course does NOT cover quantized linear gravity or QFT in curved spacetime. Chapter 9 of Carroll's book does give an introduction to the latter.



Therefore, the Quantum Field Theory and the Quantum Gravity can be viewed on as *deformations* of the classical theories corresponding to the fundamental constants c, $\hbar$, G. In the following we always put $\hbar = c = G = 1$, except for some explicit expressions where they are left for convenience.


IS THAT A CRACK IN EINSTEIN'S THEORY OF RELATIVITY?
NOTHING'S PERFECT.
Chris Madden