Gravity under the microscope

Leonardo Castellani

Università del Piemonte Orientale

Belgrade, June 23-d, 2015

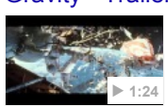
Google gravity Accedi

Web Video Immagini Notizie Shopping Altro Strumenti di ricerca

Circa 193.000.000 risultati (0,53 secondi)

GRAVITY - Now playing
gravitymovie.warnerbros.com/ Traduci questa pagina
From acclaimed filmmaker Alfonso Cuaron comes "**Gravity**", starring Sandra Bullock and George Clooney. View the trailer and explore the exclusive 3D ...

Gravity (film) - Wikipedia
https://it.wikipedia.org/wiki/**Gravity**_(film)
Gravity è un film del 2013 diretto, co-scritto, co-montato e co-prodotto da Alfonso Cuarón, che ha per protagonisti Sandra Bullock e George Clooney. Il film ha ...
Alfonso Cuarón - Plausibilità scientifica di Gravity - Sospensione dell'incredulità

Gravity - Trailer Ufficiale in Italiano | HD - YouTube


www.youtube.com/watch?v=aMUOOC5uNUM
29 mag 2013 - Caricato da Warner Bros. Italia
Segui **Gravity** su: https://www.facebook.com/GravityIT **Gravity** è disponibile in digital download su ...

Gravity - MYmovies
www.mymovies.it › film › 2013
Valutazione: 3,5 - 189 recensioni
Acquista su Ibs.it Soundtrack **Gravity** Dvd **Gravity** Blu-Ray **Gravity**. Un film di Alfonso Cuarón. Con Sandra Bullock, George Clooney, Ed Harris, Orto Ignatiussen, ...

Gravity (2013) - IMDb
www.imdb.com/title/tt1454468/ Traduci questa pagina
Valutazione: 7,9/10 - 504.459 voti
Videos. **Gravity** -- Winner of 7 Academy Awards, including Best Director! Astronauts Ryan Stone · **Gravity** -- Clip: Detached ...

"Gravity", che bello far finta di crederci - La Stampa
www.lastampa.it/2013/10/03/societa/**gravity**-che-bello.../pagina.html
03 ott 2013 - La lunghissima sequenza di apertura di «**Gravity**» è fantastica. I critici che se ne intendono la paragonano al miglior Antonioni. Non so, per me ...

Nelle notizie

Passengers, Jennifer Lawrence e Chris Pratt protagonisti della versione romantica di Gravity
www.Mauxa.com - 1 ora fa
Jennifer Lawrence e Chris Pratt: lauto cachet per interpretare i protagonisti di Passengers, ...

Zero Gravity: musica elettronica fra vintage e elettro wave
mentelocale.it - 2 giorni fa

Altre notizie su gravity

Gravity - Film (2013) - Comingsoon.it
www.comingsoon.it › film › 2013
Valutazione: 3,8 - 758 voti
Gravity, scheda del film di Alfonso Cuaron con George Clooney e Sandra Bullock, leggi la trama e la recensione, guarda il trailer, trova la programmazione al ...

Gravity (2013) - Rotten Tomatoes
www.rottentomatoes.com/m/**gravity**_2013/ Traduci questa pagina
Valutazione: 97% - 306 voti
Critics Consensus: Alfonso Cuarón's **Gravity** is an eerie, tense sci-fi thriller that's masterfully directed and visually stunning.

Gravity Reviews - Metacritic
www.metacritic.com/movie/**gravity** Traduci questa pagina
Valutazione: 96% - 49 recensioni

Altre immagini

Gravity
Film (2013)

3,5/5 · MYmovies.it
7,9/10 · IMDb
3,8/5 · Comingsoon.it
97% · Rotten Tomatoes

Gravity è un film del 2013 diretto, co-scritto, co-montato e co-prodotto da Alfonso Cuarón, che ha per protagonisti Sandra Bullock e George Clooney.
Wikipedia

Data di uscita: 3 ottobre 2013 (Italia)
Regista: Alfonso Cuarón
Durata: 1h 31m
Premi: Oscar al miglior regista, Oscar ai migliori effetti speciali, altri
Sceneggiatura: Alfonso Cuarón, George Clooney, Jonás Cuarón

Cast
Visualizza oltre 2 elementi


Sandra Bullock
Dottoressa Ryan Stone


George Clooney
Matt Kowalsky


Ed Harris

Ricerche correlate
Visualizza oltre 15 elementi

Interstellar
2014

Apollo 18
2011


Abbando… nello spa...
1969

Feedback

2015

100-th anniversary of Einstein's equations

$$R_{ij} + \frac{1}{2} g_{ij} R = \frac{8\pi G}{c^4} T_{ij}$$


1915 XLIV

SITZUNGSBERICHTE

DER

KÖNIGLICH PREUSSISCHEN

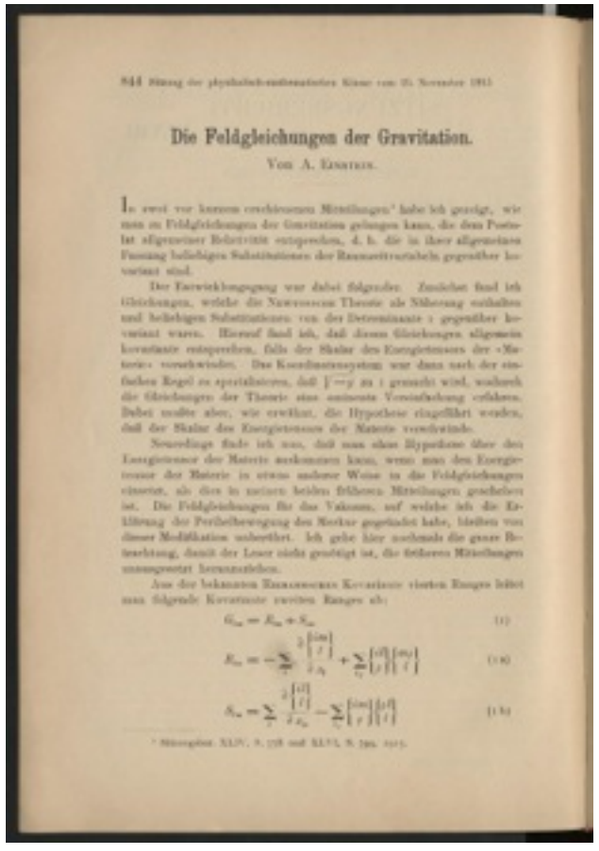
AKADEMIE DER WISSENSCHAFTEN

Gesamtsitzung am 4. November. (S. 777)

Einstein: Die Feldgleichungen der Gravitation. (S. 778)

BERLIN 1915

VERLAG DER KÖNIGLICHEN AKADEMIE DER WISSENSCHAFTEN


844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas andere Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gehe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen auszugsweise heranzuziehen.

Aus der bekannten Riemannschen Krümmungstensor vierten Ranges läßt man folgende Kovariante zweiten Ranges ab:

$$G_{\mu\nu} = R_{\mu\nu} + S_{\mu\nu} \qquad (1)$$

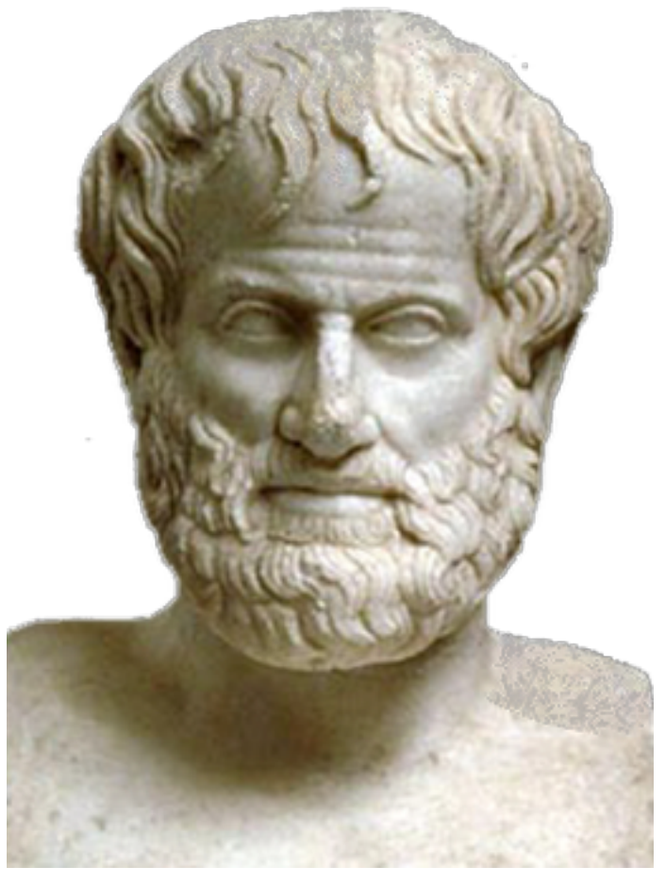
$$R_{\mu\nu} = -\sum_{\alpha\beta} \frac{\partial \left\{ \begin{matrix} \alpha\mu \\ \beta \end{matrix} \right\}}{\partial x_\alpha} + \sum_{\alpha\beta} \left\{ \begin{matrix} \alpha\beta \\ \beta \end{matrix} \right\} \left\{ \begin{matrix} \mu\nu \\ \alpha \end{matrix} \right\} \qquad (1a)$$

$$S_{\mu\nu} = \sum_{\alpha\beta} \frac{\partial \left\{ \begin{matrix} \alpha\beta \\ \beta \end{matrix} \right\}}{\partial x_\mu} - \sum_{\alpha\beta} \left\{ \begin{matrix} \alpha\mu \\ \beta \end{matrix} \right\} \left\{ \begin{matrix} \beta\nu \\ \alpha \end{matrix} \right\} \qquad (1b)$$

[1] Sitzungsber. XLIV, S. 778 und XLVI, S. 799, 1915.

Aristotle (385-322 BC)

Aristotle. Metaphysica, Physica, and De Meteoris



- falling bodies: velocity proportional to weight

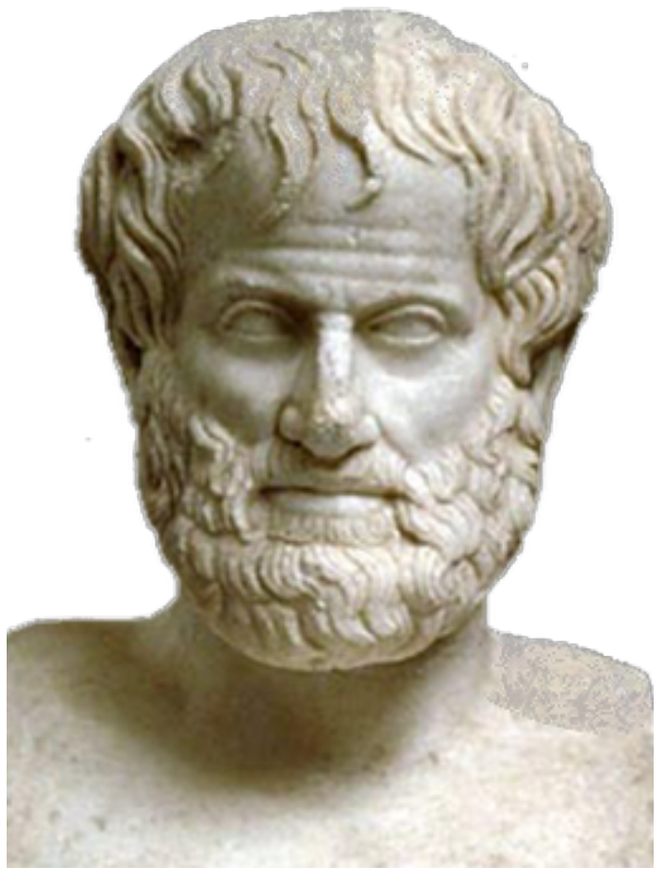
  Note: not so wrong, since bodies are falling in a *medium*,
  and terminal velocity depends on weight

- knows that velocity increases

- no quantitative law

Aristotle (385-322 BC)

Aristotle. Metaphysica, Physica, and De Meteoris



The works of Aristotle that have survived from antiquity through medieval manuscript transmission are collected in the Corpus Aristotelicum.

Physics: a treatise which divides into two main parts, the first an inquiry into nature (books 1–4) and the second a treatment of motion (books 5–8)

- falling bodies: velocity proportional to weight

  Note: not so wrong, since bodies are falling in a *medium*,
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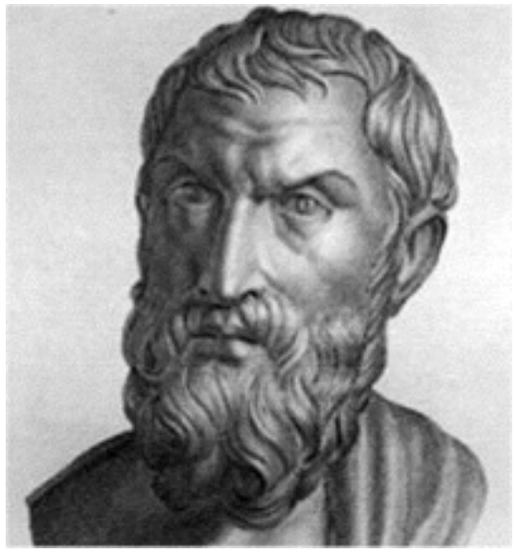
Lucretius (c. 99 BC – c. 55 BC)

De rerum natura The poem consists of six books, in dactylic hexameters.



(1)

T. LUCRETII CARI
DE
RERUM NATURA
Liber Primus.

AENEADUM genetrix, hominum divumque voluptas,
Alma Venus, cœli subter labentia signa
Quæ mare navigerum, quæ terras frugiferentis
Concelebras: per te quoniam genus omne animantum
Concipitur, visitque exortum lumina solis:
Te, Dea, te fugiunt venti, te nubila cœli,
Adventumque tuum: tibi suavis dædala tellus
Summittit flores, tibi rident æquora ponti,
Placatumque nitet diffuso lumine cœlum.
Nam simul ac species patefacta 'st verna diei,
Et reserata viget genitabilis aura Favoni:
Aeriæ primum volucres te, diva, tuumque
Significant initum perculsæ corda tua vi.
Inde feræ pecudes persultant pabula læta,
Et rapidos tranant amnis: ita capta lepore
Illecebrisque tuis omnis natura animantum

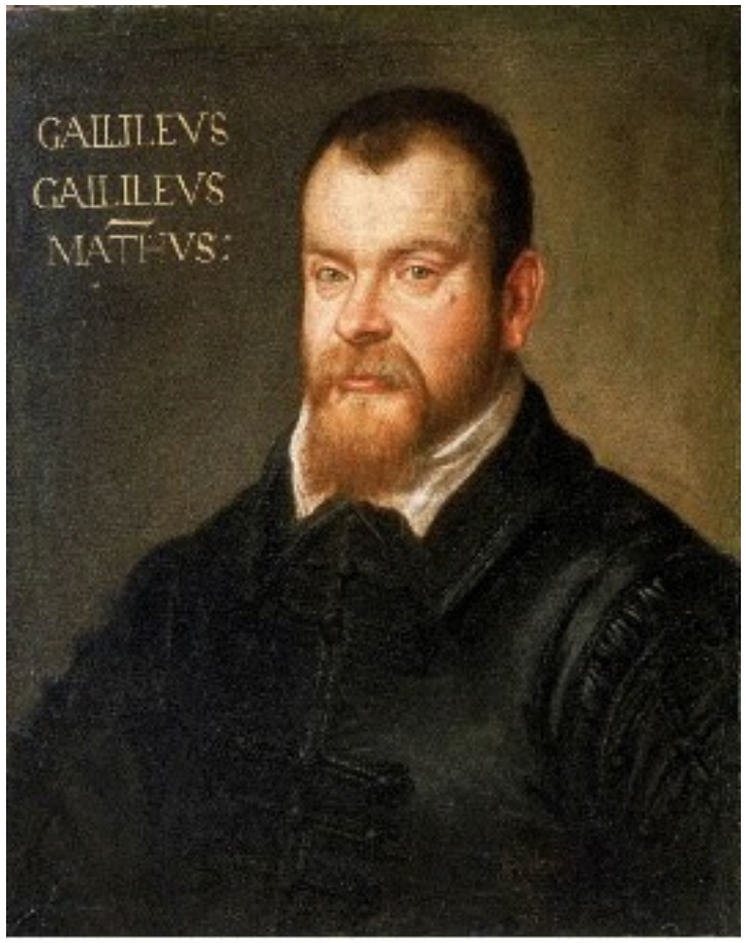
B Te

omnia quapropter debent per inane quietum
aeque ponderibus non aequis concita ferri.

II, 238-239

"…wherefore all things carry on through the calm void moving at equal rate with unequal weights."

Galileo (1564 – 1642)



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR. DVCA DI TOSCANA.

Doue ne i congressi di quattro giornate si discorre sopra i due

MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;

Proponendo indeterminatamente le ragioni Filosofiche, e Naturali tanto per l'una, quanto per l'altra parte.

CON PRI VILEGI.

IN FIORENZA, Per Gio: Batista Landini MDCXXXII.

CON LICENZA DE' SVPERIORI.

- all bodies on Earth fall with same acceleration **g** (if air neglected)

two spheres
unequal densities

Apollo 15

Launched: 26 July 1971 UT 13:34:00 (09:34:00 a.m. EDT)
Landed on Moon: 30 July 1971 UT 22:16:29 (06:16:29 p.m. EDT)
Landing Site: Hadley Rille/Apennines (26.13 N, 3.63 E)
Returned to Earth: 7 August 1971 UT 20:45:53 (04:45:53 p.m. EDT)

David R. Scott, commander
Alfred M. Worden, command module pilot
James B. Irwin, lunar module pilot

"The feather and the hammer"

Let’s try a little experiment here on Earth…

- PRINCIPLE OF INERTIA

  A body moving on a level surface will continue in the same direction at constant speed unless disturbed

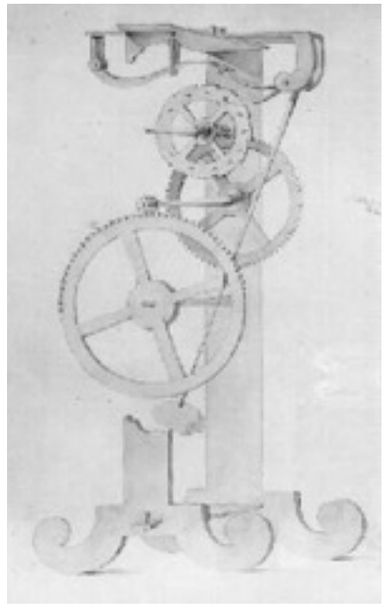
- PRINCIPLE OF RELATIVITY

  the laws of physics are the same in any system that is moving at a constant speed in a straight line

* *Esperienza opposta alle prodotte contra al moto della terra.*

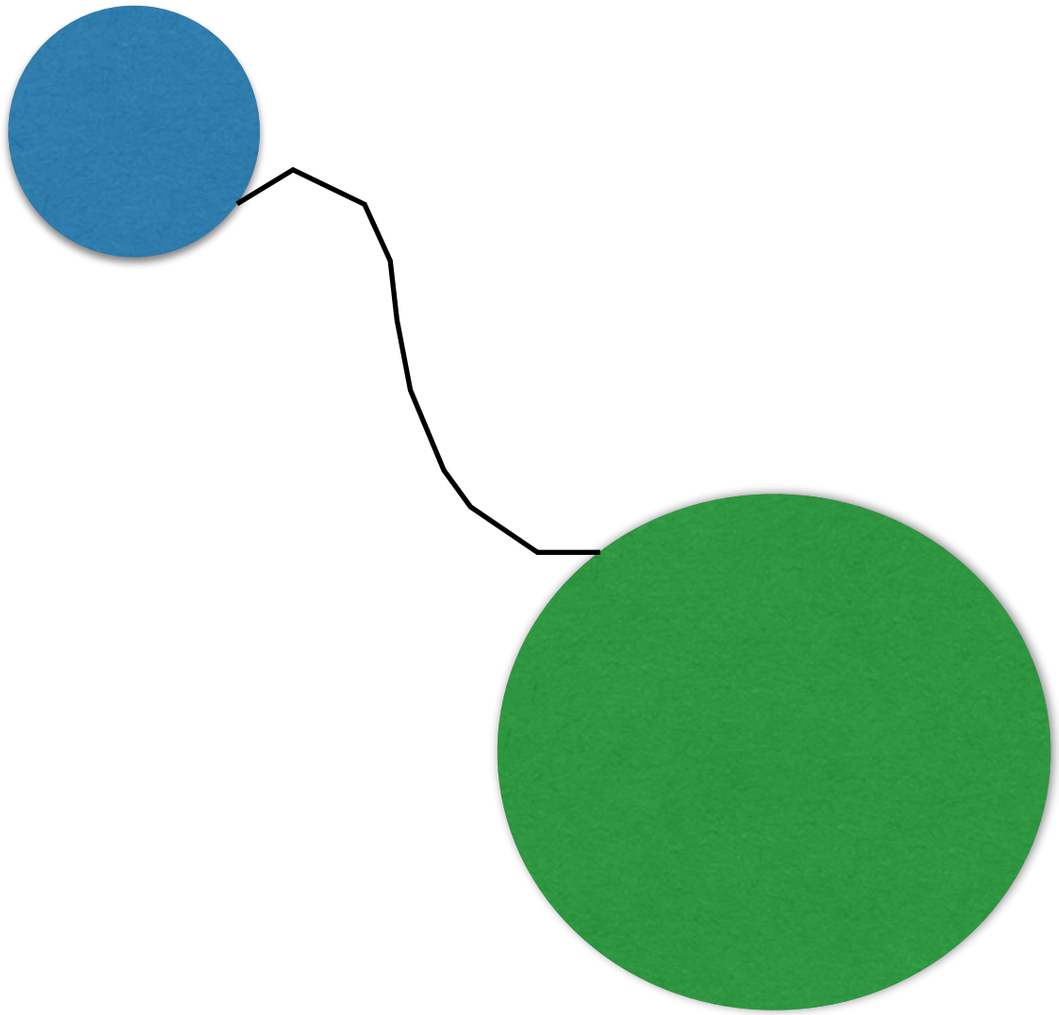
della nullità di tutte le esperienze addotte, mi par tempo, e luogo di mostrar'il 181
modo di sperimentarle tutte facilissimamente. Riserratevi con qualche amico nella maggiore stanza, che sia sotto coverta di alcun gran navilio, e quivi fate d'aver mosche, farfalle, e simili animaletti volanti: siavi anco un gran vaso d'acqua, e dentrovi de' pescetti; sospendasi anco in alto qualche secchiello, che a goccia a goccia vadi versando dell'acqua in un'altro vaso di angusta bocca, che sia posto a basso; e stando ferma la nave, osservate diligentemente, come quelli animaletti volanti, con pari velocità, vanno verso tutte le parti della stanza; i pesci si vedranno andar notando indifferentemente per tutti i versi, le stille cadenti entreranno tutte nel vaso sottoposto; e voi gettando all'amico alcuna cosa, non più gagliardamente la dovrete gettare verso quella parte, che verso questa, quando le lontananze sieno eguali; e saltando voi, come si dice, a piè giunti, eguali spazii passerete verso tutte le parti. Osservate che averete diligentemente tutte queste cose; benchè niun dubbio ci sia, che mentre il vassello sta fermo non debbano succeder così; fate muover la nave con quanta si voglia velocità: che (pur che il moto sia uniforme, e non fluttuante in qua, e in là) voi non riconoscerete una minima mutazione in tutti li nominati effetti; nè da alcuno di quelli potrete comprender se la nave cammina, o pure sta ferma. Voi saltando passerete nel tavolato i medesimi spazii, che prima; nè perchè la nave si muove velocissimamente, farete maggior salti verso la poppa, che verso la prora, benchè nel tempo, che voi state in aria, il tavolato sottoposto vi scorra verso la parte contraria al vostro salto; e gettando alcuna cosa al compagno, non con più forza bisognerà tirarla per arrivarlo, se egli sarà verso la prora, e voi verso poppa, che se voi fuste situati per l'opposito: le gocciole cadranno, come prima, nel vaso inferiore, senza caderne pur una verso poppa, benchè, mentre la gocciola è per aria, la nave scorra molti palmi; i pesci nella lor'acqua non con più fatica noteranno verso la precedente, che verso la susseguente parte del vaso; ma con pari agevolezza verranno al cibo posto su qualsivoglia luogo dell'orlo del vaso; e finalmente le farfalle, e le mosche continueranno i lor voli indifferentemente verso tutte le parti; nè mai accà-

- quantitative study of motion of falling bodies
- use of balls rolling on inclined planes
- use of water-clocks
- real and mental experiments

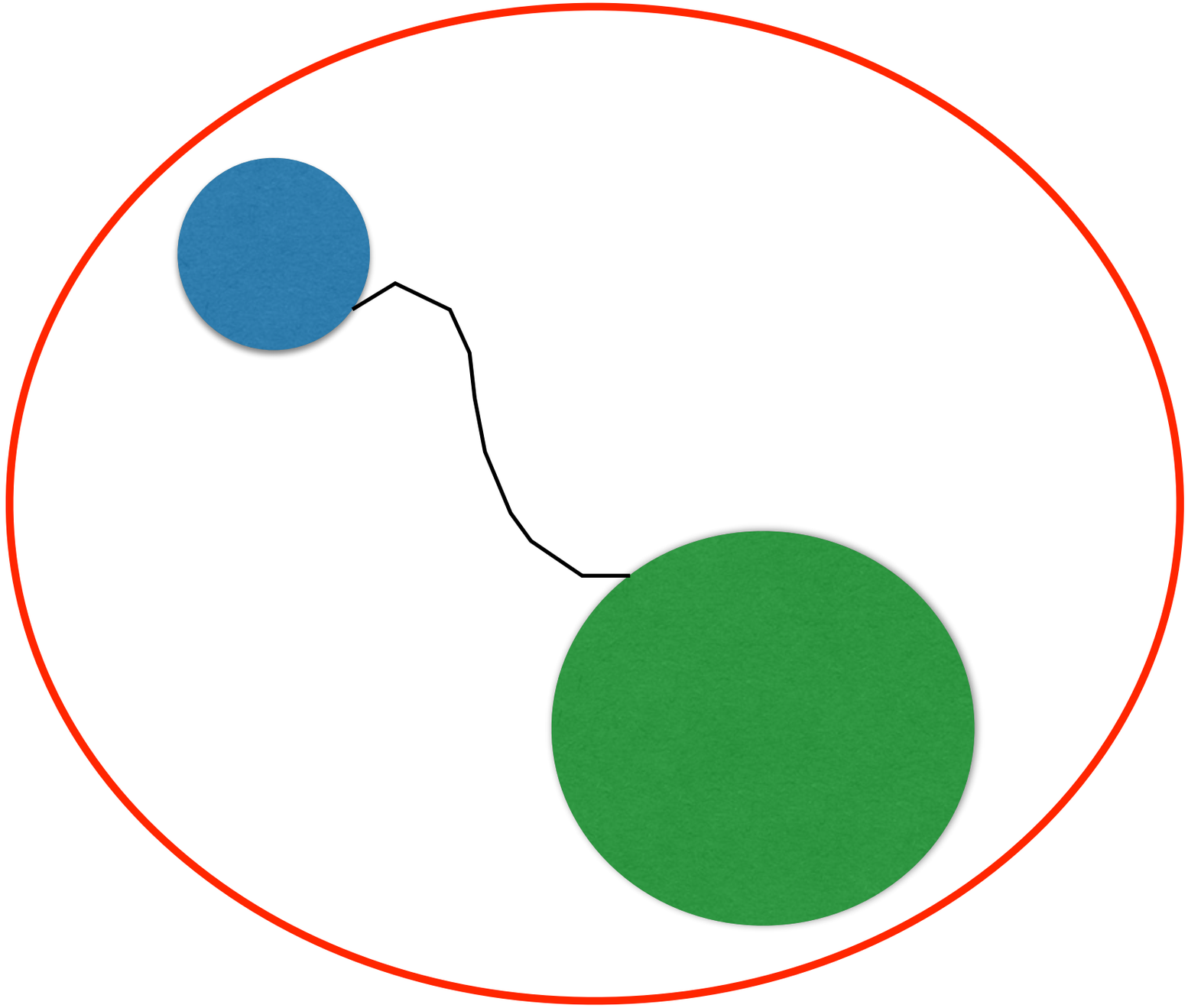


Mental experiment

ASSUME that heavier bodies fall faster

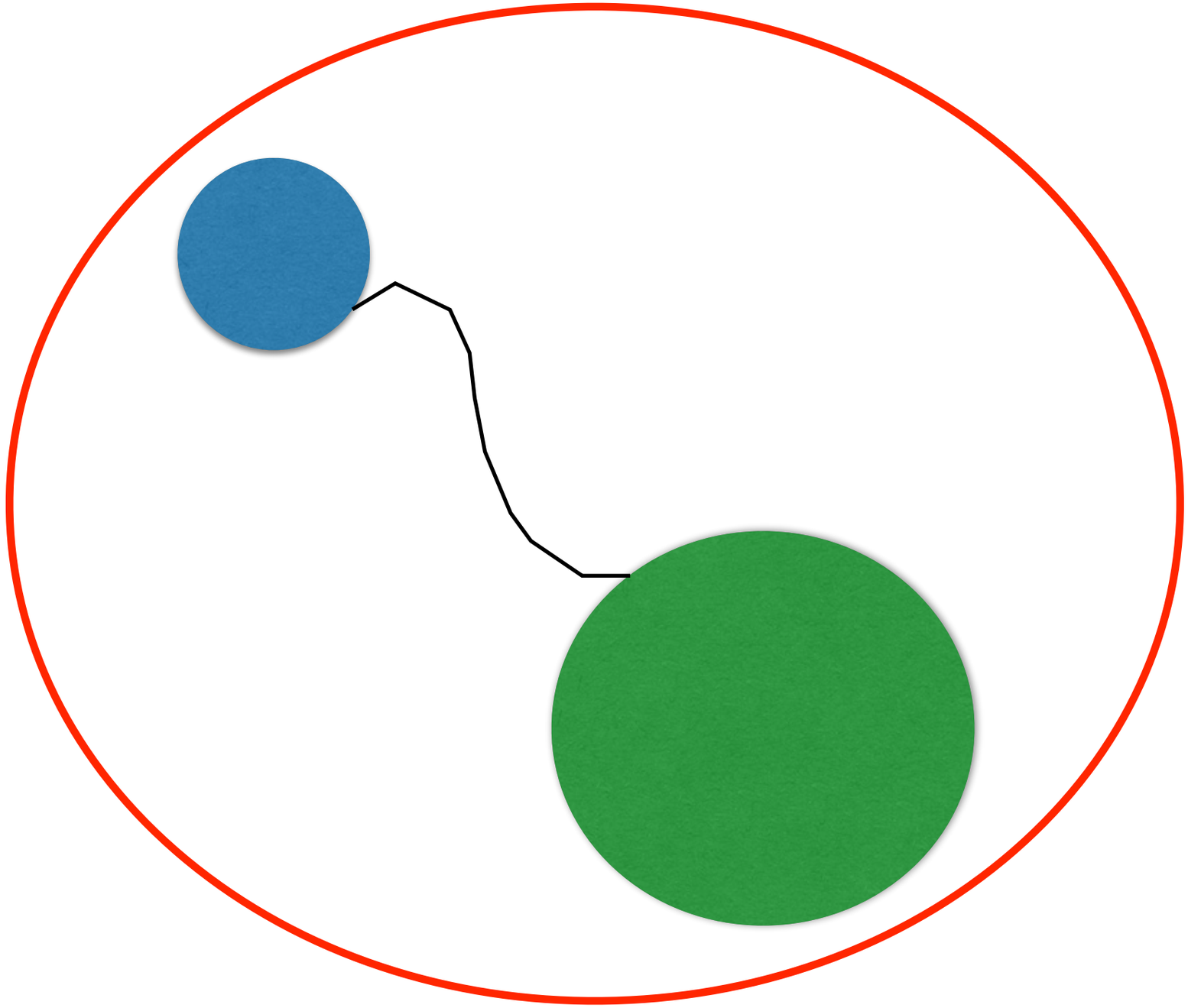


Then the lighter object retards the fall of the heavier object.



Then the lighter object retards the fall of the heavier object.

Whole system falls SLOWER



But whole system is heavier then the heavy object.

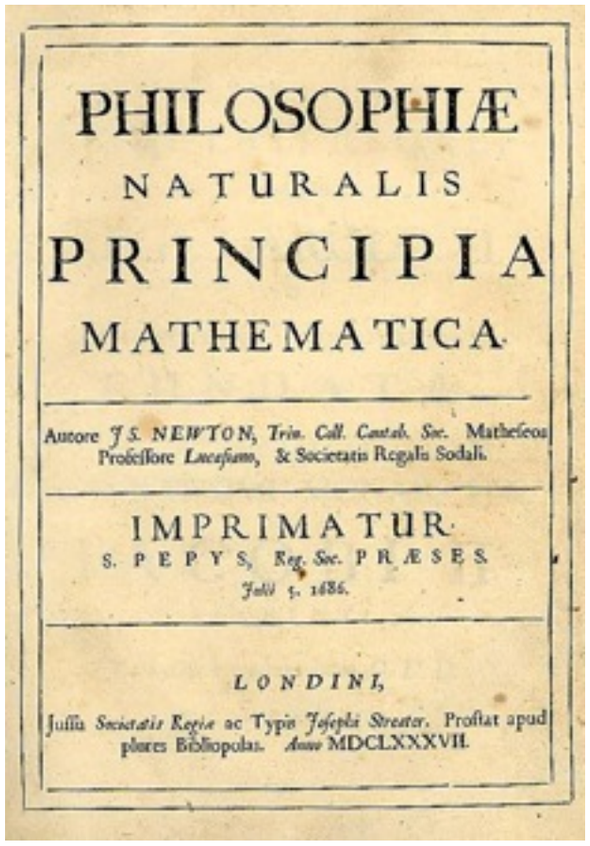
Then according to the assumption it should fall FASTER

CONTRADICTION:

then assumption that heavier bodies fall faster must be FALSE

Newton (1643 – 1727)

1687 Principia



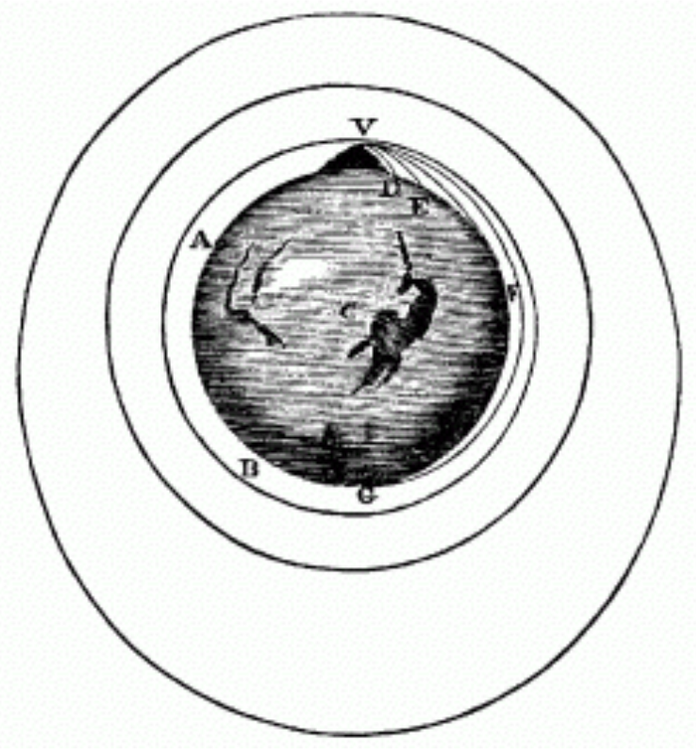
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

Autore *J. S. NEWTON, Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Justu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

mental experiment:



$$\vec{F} = m_{inertial}\ \vec{a}$$

II-nd law of dynamics

$$F_{grav} = G\ \frac{m_{grav}\ M_{grav}}{r^2}$$

Law of gravitation

$$\vec{F} = m_{inertial}\ \vec{a}$$

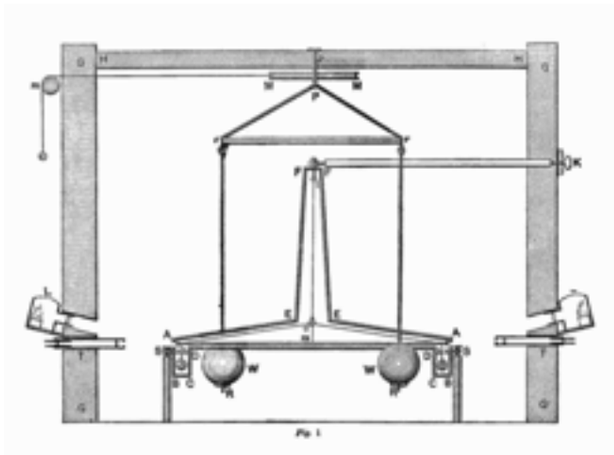
II-nd law of dynamics

$$F_{grav} = G\ \frac{m_{grav}\ M_{grav}}{r^2}$$

Law of gravitation

Newton's constant
measured by H. Cavendish in 1798:

$$G \approx 6.674 \times 10^{-11}\ \mathrm{N}\ (\mathrm{m/kg})^2.$$



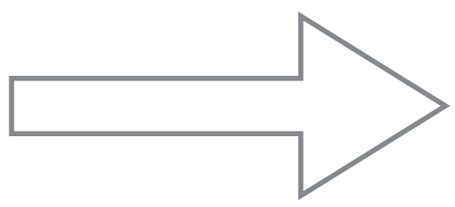
$$\vec{F} = m_{inertial}\ \vec{a}$$

II-nd law of dynamics

$$F_{grav} = G\ \frac{m_{grav}\ M_{grav}}{r^2}$$

Law of gravitation

same g for all falling bodies

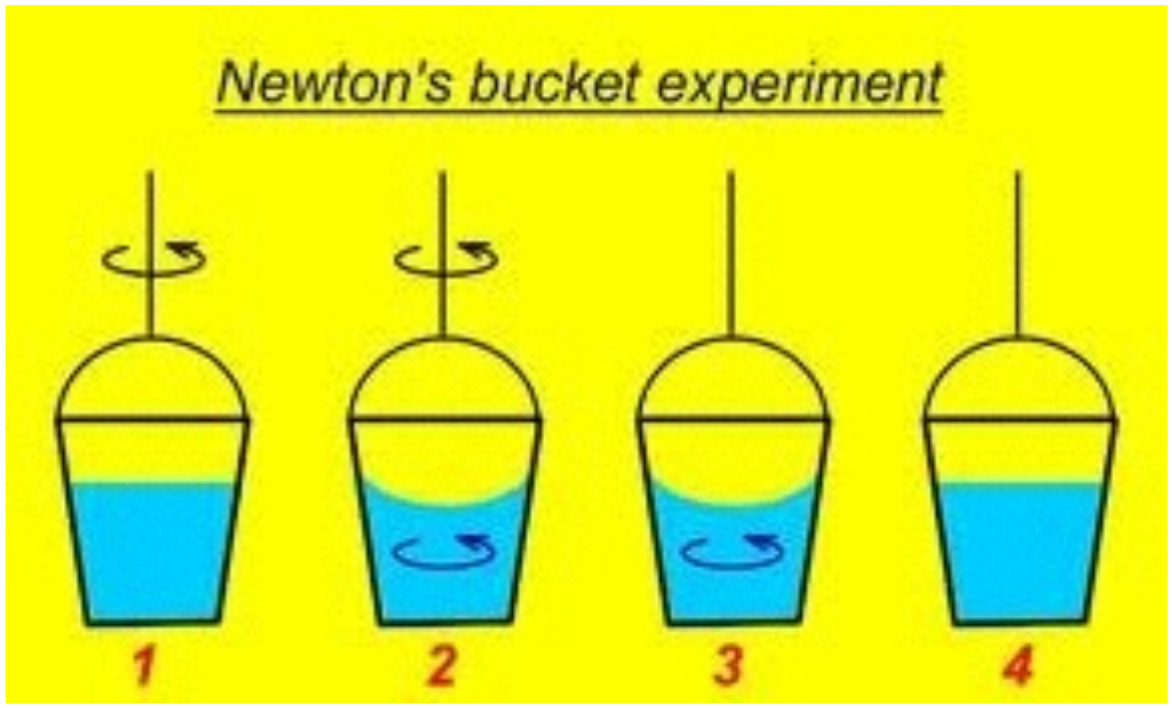


$$m_{grav} \sim m_{inertial}$$

This is why we can measure mass by weighing it

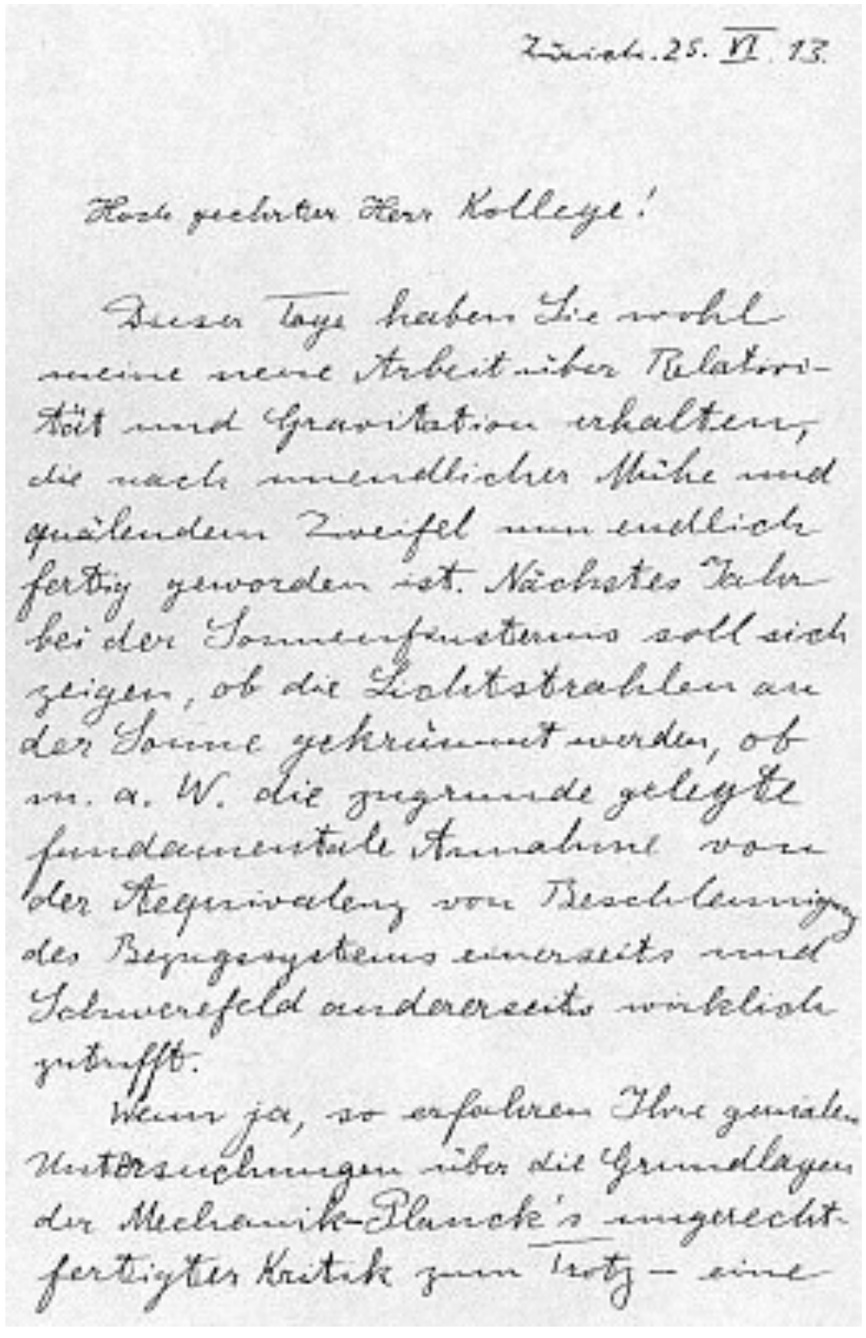
Newton's space and time

- absolute inertial reference frame (fixed stars)
- absolute universal time



Mach's criticism: reference frame of rotating bucket can be considered INERTIAL as well, but with centrifugal force produced by rotation of the earth and other celestial bodies.

Letter of Einstein to Mach (1913)

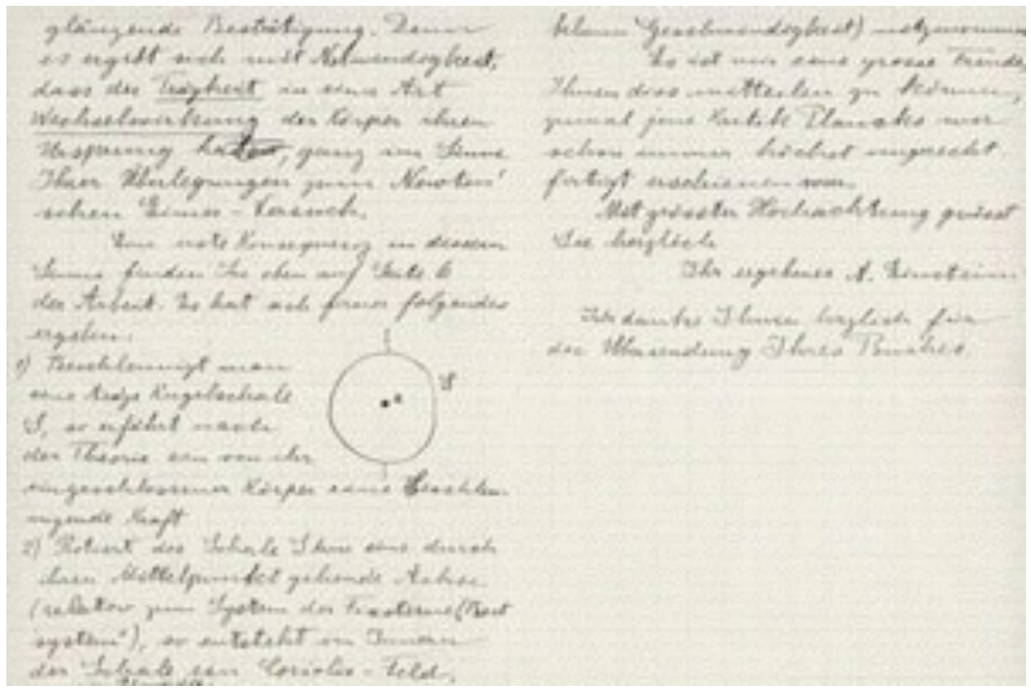


Zürich. 25. VI. 13.

Hoch geehrter Herr Kollege!

Dieser Tage haben Sie wohl meine neue Arbeit über Relativität und Gravitation erhalten, die nach unendlicher Mühe und quälendem Zweifel nun endlich fertig geworden ist. Nächstes Jahr bei der Sonnenfinsternis soll sich zeigen, ob die Lichtstrahlen an der Sonne gekrümmt werden, ob m. a. W. die zugrunde gelegte fundamentale Annahme von der Aequivalenz von Beschleunigung des Bezugsystems einerseits und Schwerefeld andererseits wirklich zutrifft.

Wenn ja, so erfahren Ihre genialen Untersuchungen über die Grundlagen der Mechanik-Planck's ungerechtfertigter Kritik zum Trotz — eine



glänzende Bestätigung. Denn es ergibt sich mit Notwendigkeit, daß der Trägheit zu eine Art Wechselwirkung der Körper ihren Ursprung hat, ganz im Sinne Ihrer Ausführungen zum Newton'schen Eimer-Versuch.

Eine nette Bestätigung zu diesem Sinne finden Sie eben auf Seite 6 der Arbeit. Es hat sich [illegible] ergeben:

1) Beschleunigt man eine Masse Kugelschale S, so entsteht nach der Theorie [illegible] eine beschleunigende Kraft

2) Rotiert die Schale S um eine durch den Mittelpunkt gehende Achse (relativ zum System der Fixsternsphäre), so entsteht im Innern der Schale ein Coriolis-Feld,

[illegible] Gastfreundschaft) entgegennahm.

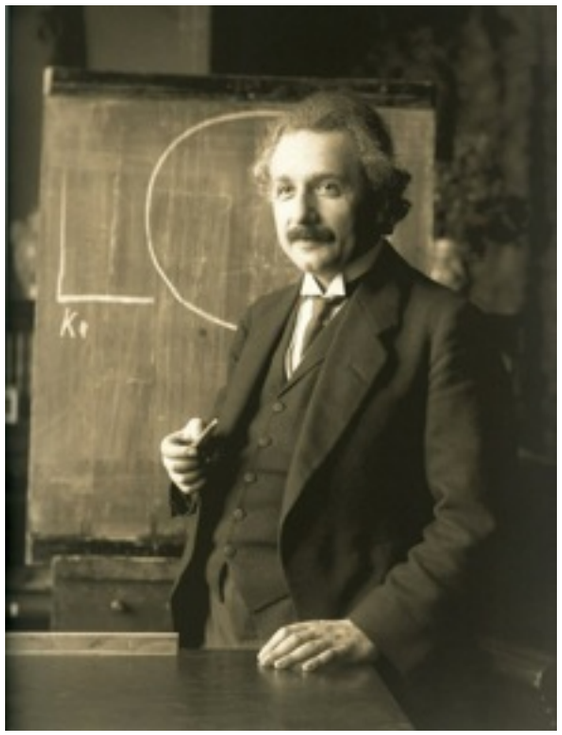
Es ist nun eine große Freude, Ihnen dies mitteilen zu können, zumal jene Kritik Plancks unrichtig [illegible] fertigt erscheinen muß.

Mit größter Hochachtung grüßt Sie herzlich

Ihr ergebener A. Einstein

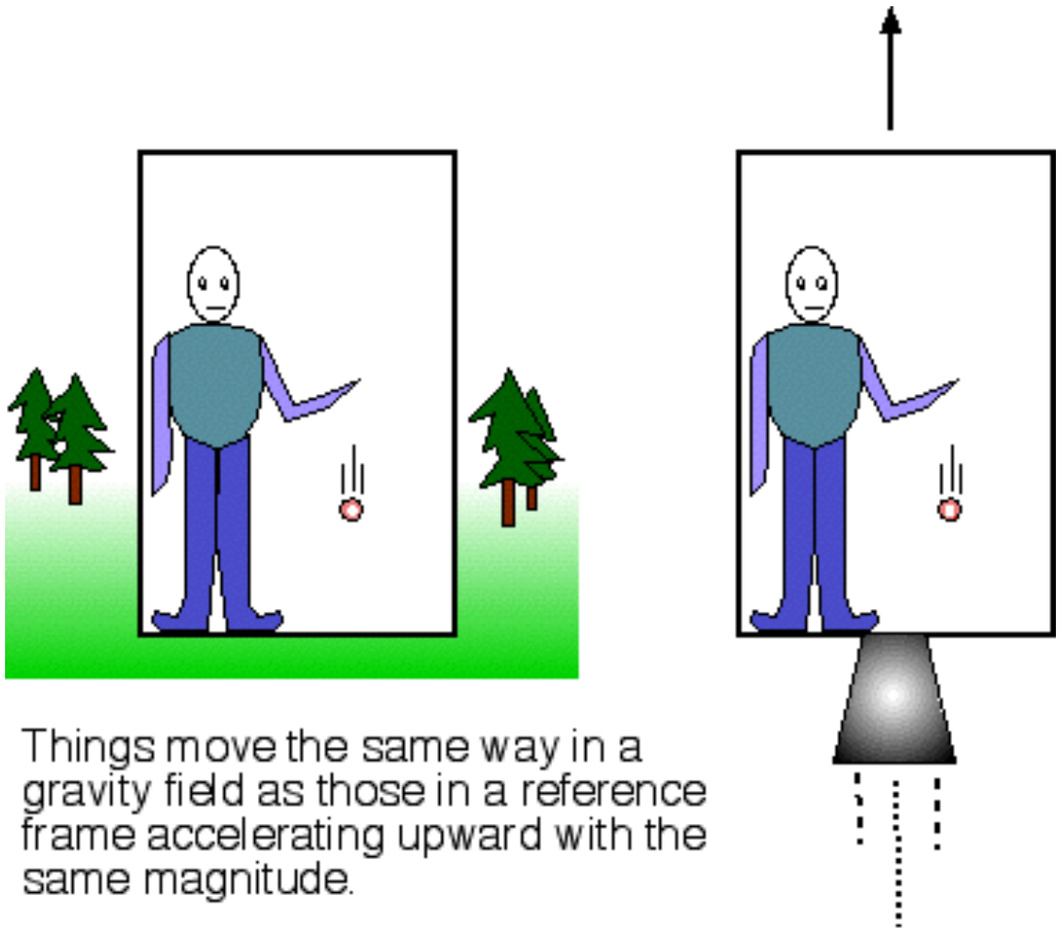
Ich danke Ihnen herzlich für die Übersendung Ihres Buches.

Einstein (1879 – 1955)



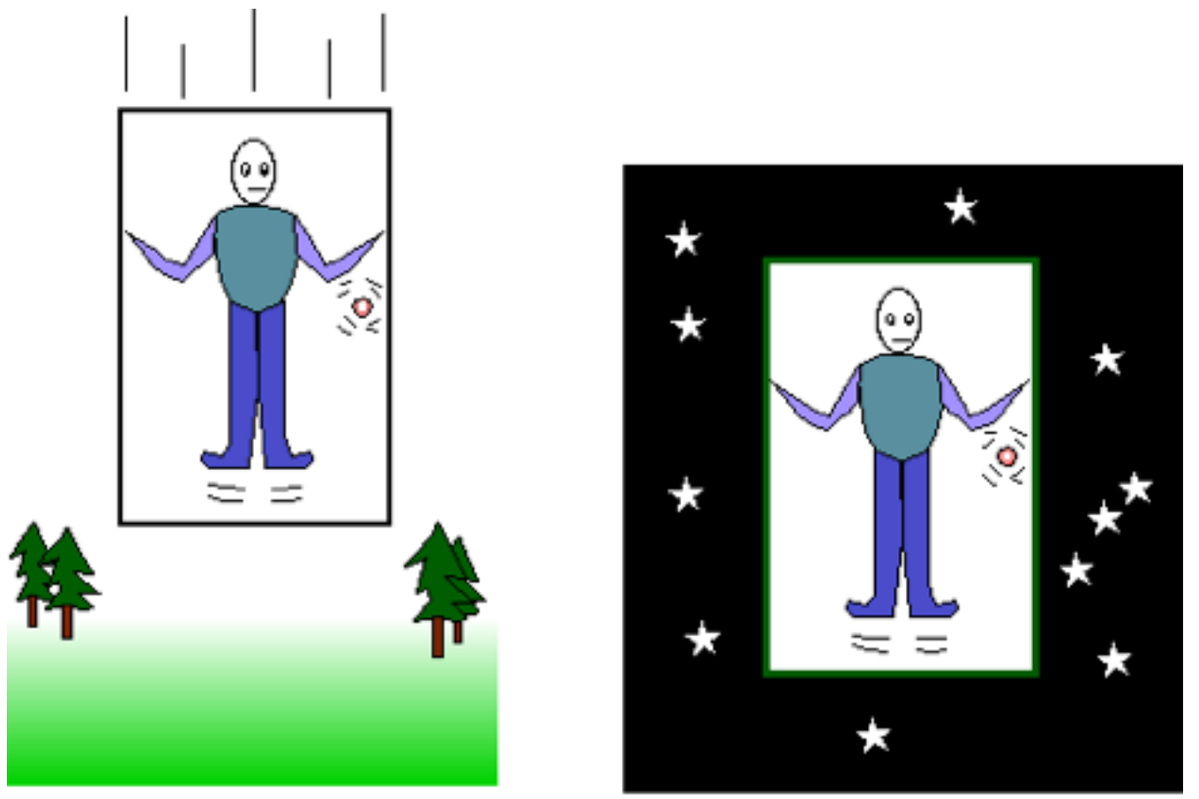
"The happiest thought of my life"

realizes that an observer in free fall experiences
no gravitational field



Things move the same way in a gravity field as those in a reference frame accelerating upward with the same magnitude.

because all objects fall with same acceleration



Things falling freely in a gravity field all accelerate by the same amount, so they move the same way as if they were in a region of zero gravity — ``weightlessness''!

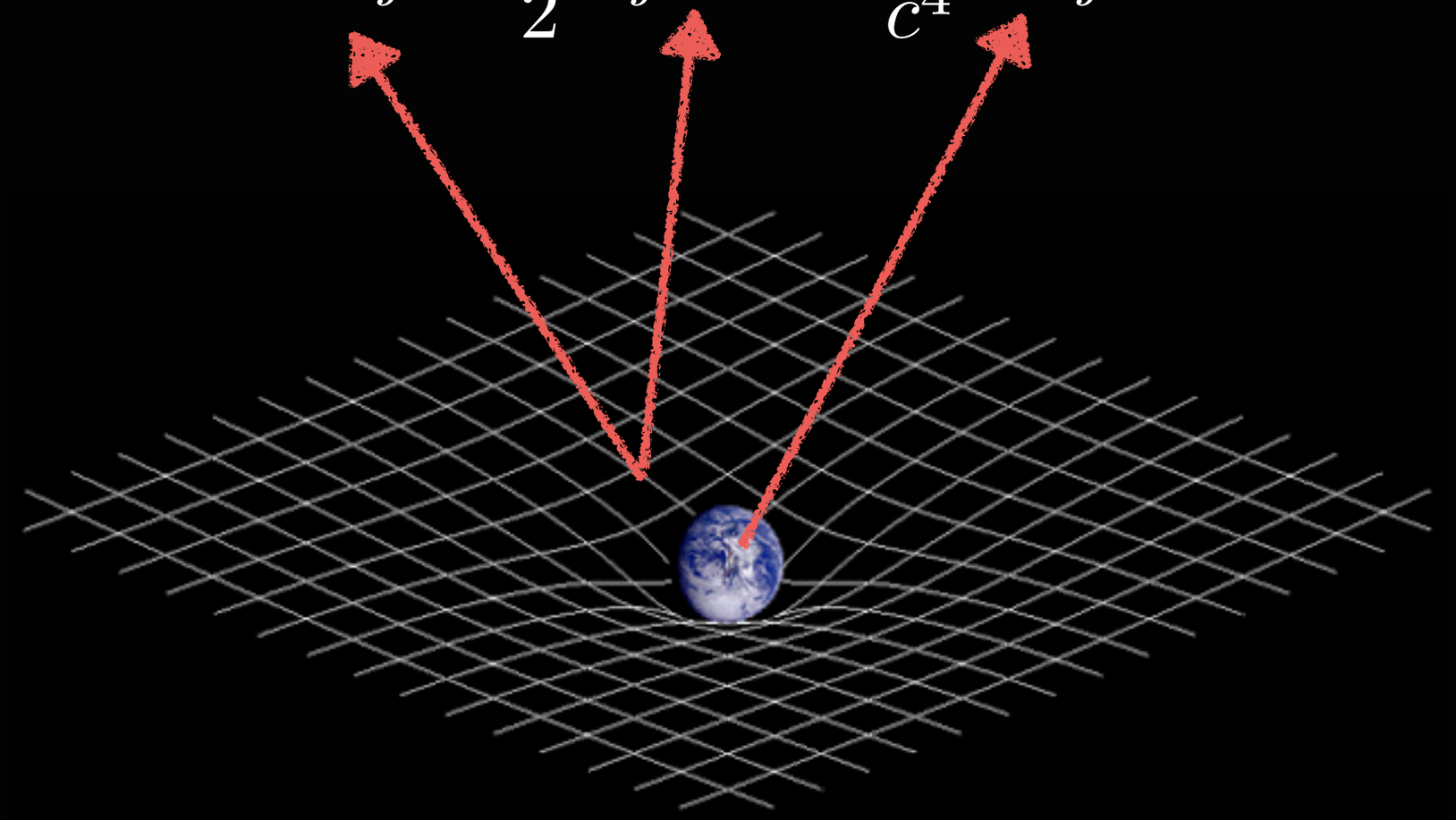
gravity field ≃ accelerated frame

These images are courtesy of Nick Strobel at www.astronomynotes.com

Gravity is a geometric effect

curvature mass ~ energy

$$R_{ij} + \frac{1}{2} g_{ij} R = \frac{8\pi G}{c^4} T_{ij}$$



$$R_{ij} + \frac{1}{2} g_{ij} R = \frac{8\pi G}{c^4} T_{ij}$$

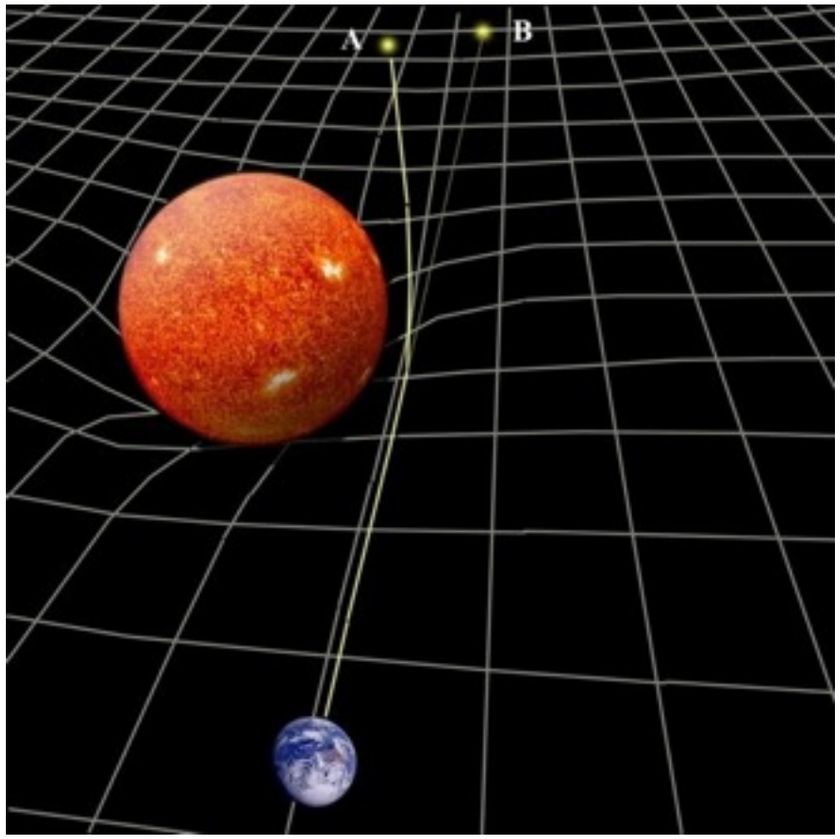
10 nonlinear diff. eq.s

Solutions:

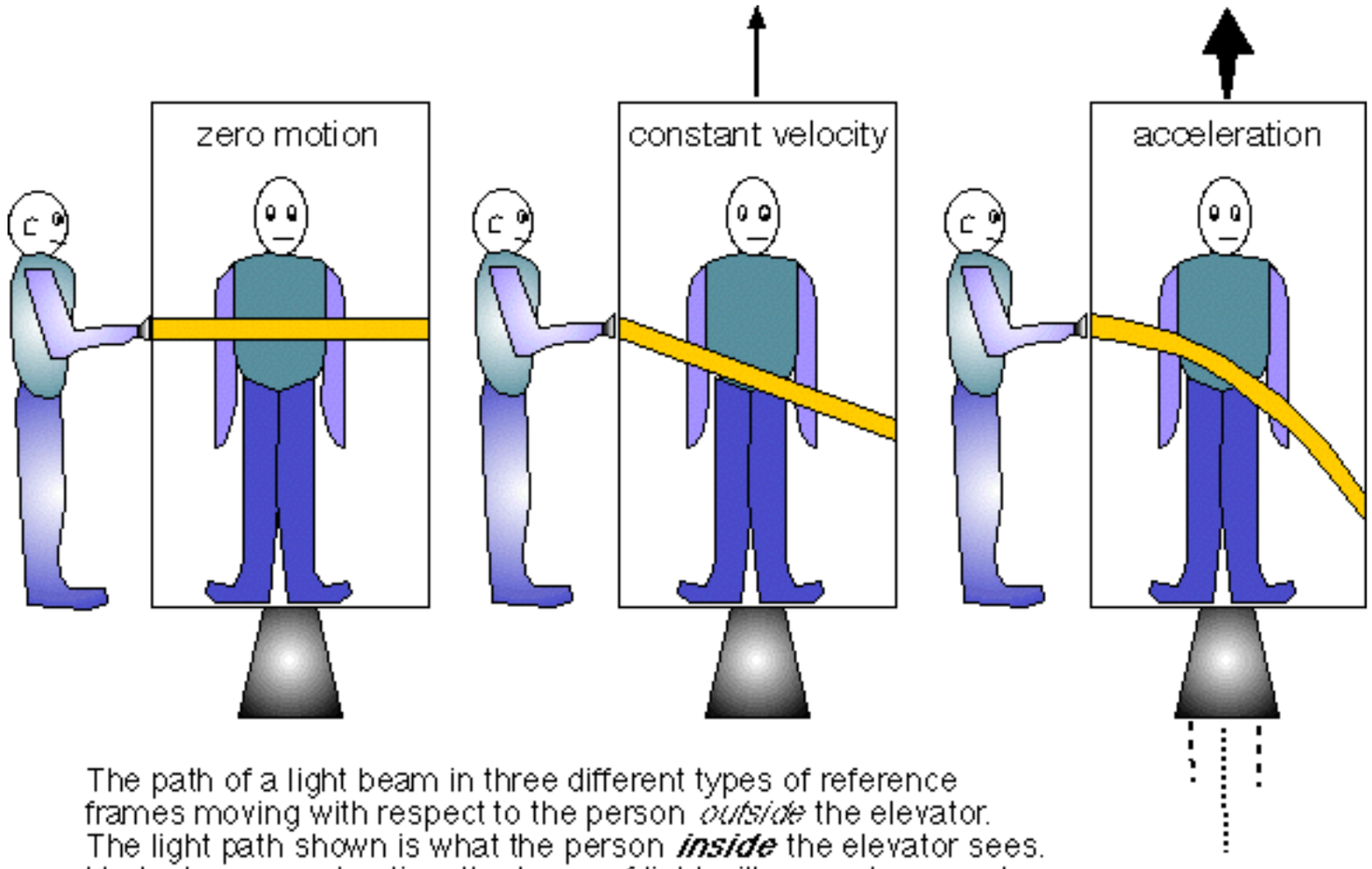
- Schwarzschild : spherically symmetric, non rotating, uncharged massive object. If density is high enough —> **Black hole** with central singularity
- Reissner-Nordström: charged
- Kerr: rotating
- Friedmann-Lemaître-Robertson-Walker: cosmological, describes expansion of universe —> standard cosmological model

Predictions

- anomalous perihelion precession of Mercury
- time runs slower at lower gravitational potential (used in GPS)
- deflection of light, first confirmed by Eddington in 1919. Gravitational lensing
- gravitational radiation, indirectly confirmed by study of binary pulsars
- expansion of universe, observed by Hubble in 1929



Deflection of light



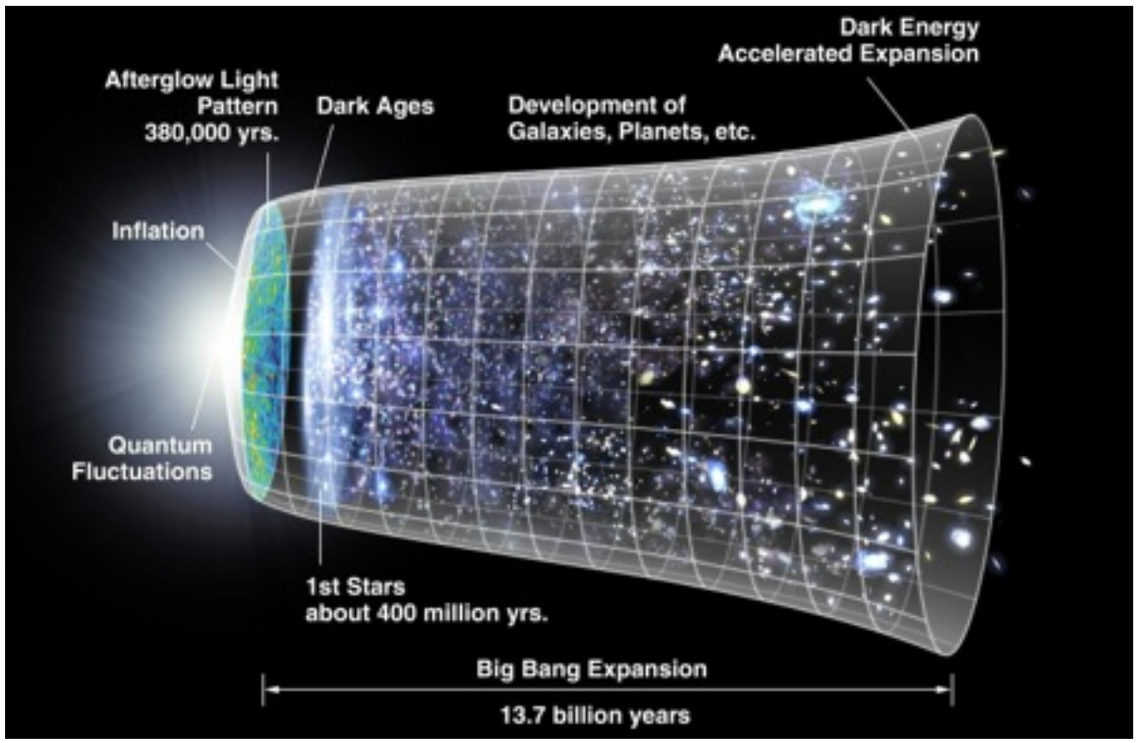
The path of a light beam in three different types of reference frames moving with respect to the person *outside* the elevator. The light path shown is what the person ***inside*** the elevator sees. Under large acceleration, the beam of light will curve downward. It should also do that in a region of strong gravity.

gravitational lensing

This image is courtesy of Nick Strobel at www.astronomynotes.com

Virgo

history of the universe



Gravity is by far the weakest of the four fundamental forces in nature. On molecular or atomic scale it is negligible with respect to nuclear or e.m. forces

However, on macroscopic scales gravity becomes dominant, determining our weight, the shape and structure of the Solar system, of the galaxies, and of the universe

from cosmic scales down to 0.1 mm gravitational phenomena are very well described by GR, which reduces to classical Newton's theory for velocities << c

- GR is a field theory, as electromagnetism.

- Quantum electrodynamics, developed in the last century, marries quantum mechanics to Maxwell's theory, and describes with extreme precision the interactions of quantum matter (for ex. electrons) with quantum light (photons).

- Its generalization, that includes nuclear and weak forces, is the Standard Model of particle physics, precision-tested at LHC and other laboratories.

STANDARD MODEL

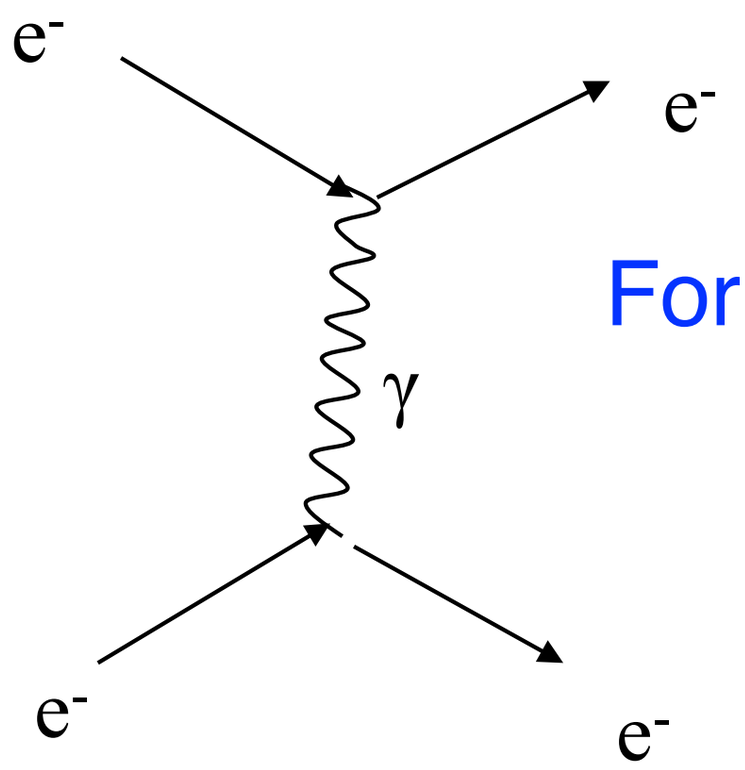
MATTER

quarks leptons

INTERACTIONS

- Electromagnetic: *photons* γ
- Strong : *gluons*
- Weak: Z^0 , W^+, W^-

+ Higgs



For ex: electromagnetic interaction is mediated by photons

Interaction regions are point-like

STANDARD MODEL

MATTER

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INTERACTIONS

- Electromagnetic: *photons* γ
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STANDARD MODEL

MATTER

quarks leptons

INTERACTIONS

- Electromagnetic: *photons* γ
- Strong : *gluons*
- Weak: Z^0 , W^+, W^-
- Gravitational: *gravitons*

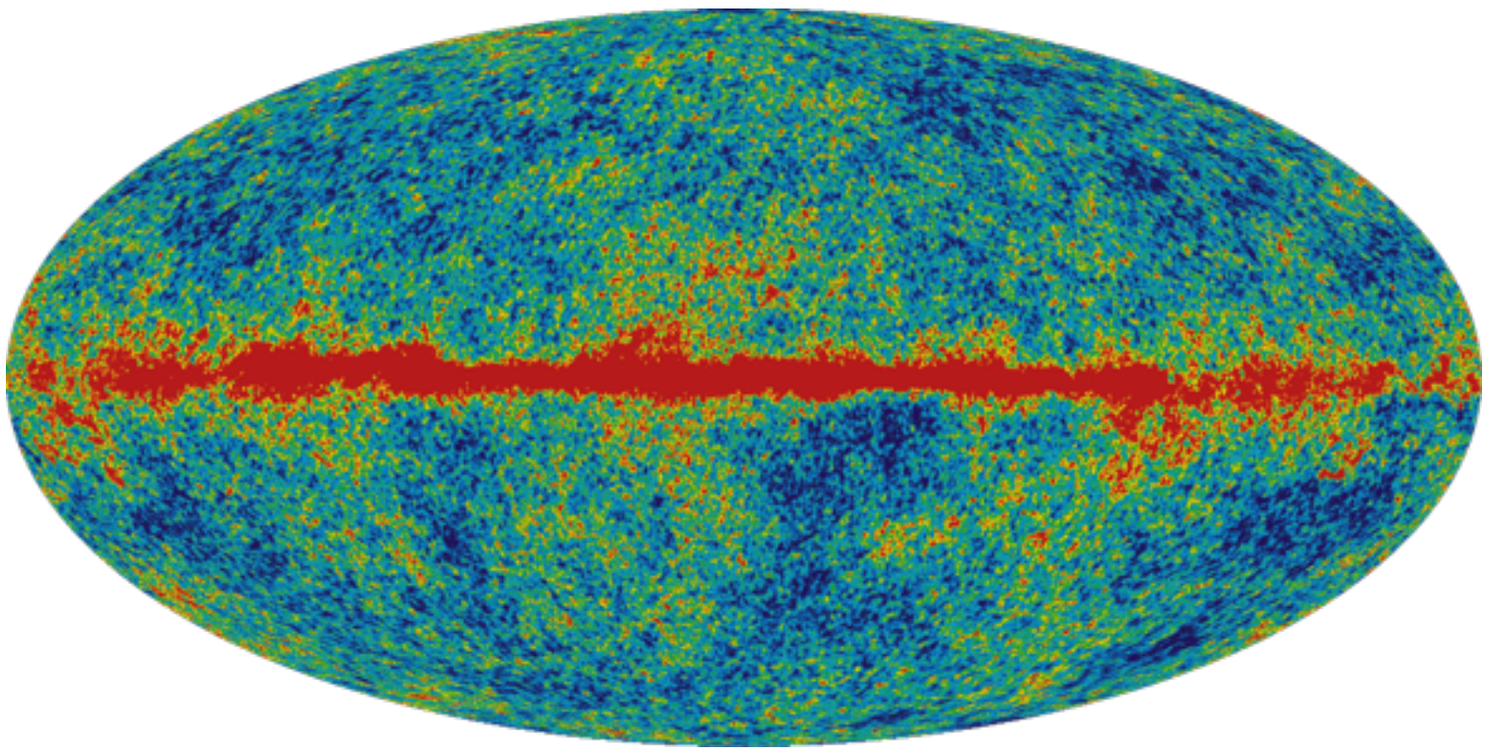
+ Higgs

What is the status of quantum general relativity ?

And why should we need it ?

From GR solutions :

—> Universe is microscopic immediately after the Big Bang , c.a 13.5 billions of years ago. Then quantum gravity must affect **early evolution**. Amplification (via inflation) of quantum fluctuations visible in the anisotropies of the Cosmic Background Radiation (2.725 K)

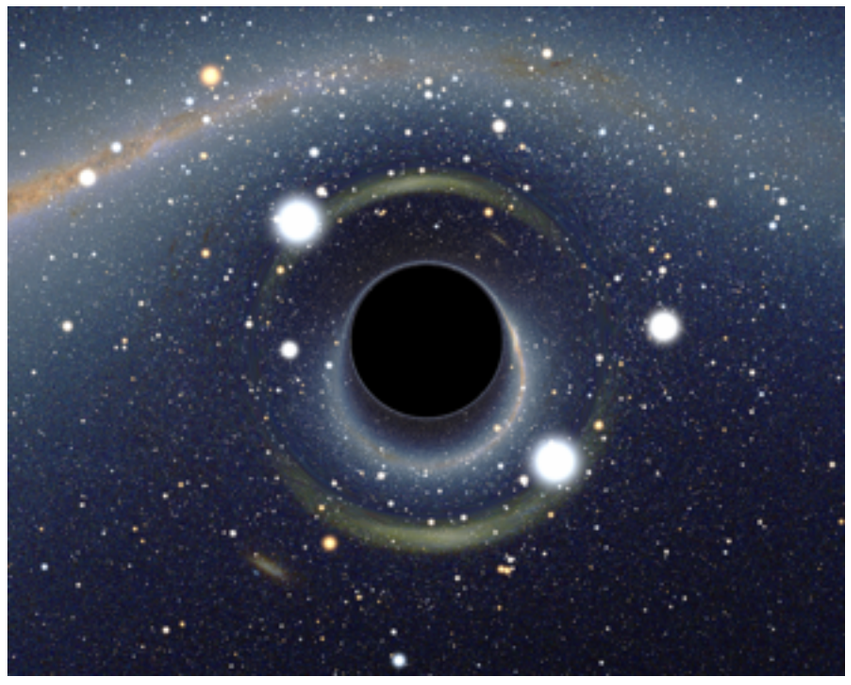


WMAP

From GR solutions :

Inside black holes: strong gravitational fields on arbitrarily short distance scales.
—> Need quantum gravity to describe collapsing matter.

Singularity: breakdown of classical theory.
—> Quantum theory to “cure” it ?



Simulated view of a black hole in front of the Large Magellanic Cloud.

S. Hawking experiencing absence of gravity

But: applying to gravity the same procedure ("quantization") used in electrodynamics leads to inconsistencies, due to the point-like interaction between the elementary particles.

The problem can be cured in the standard model ("renormalization"), but not for gravity.

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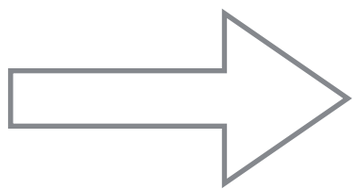
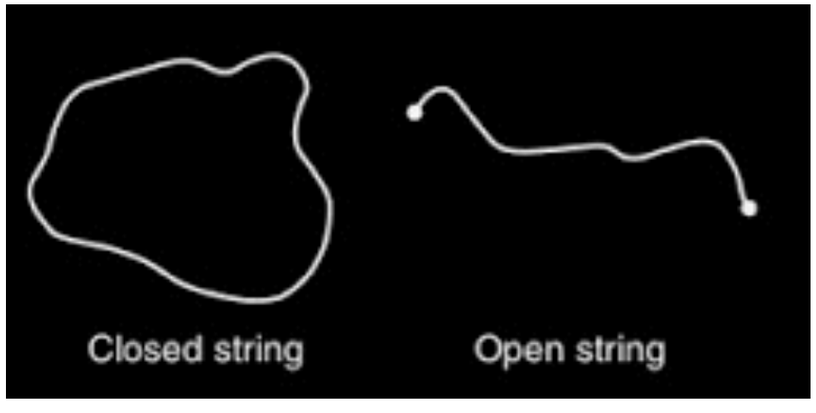
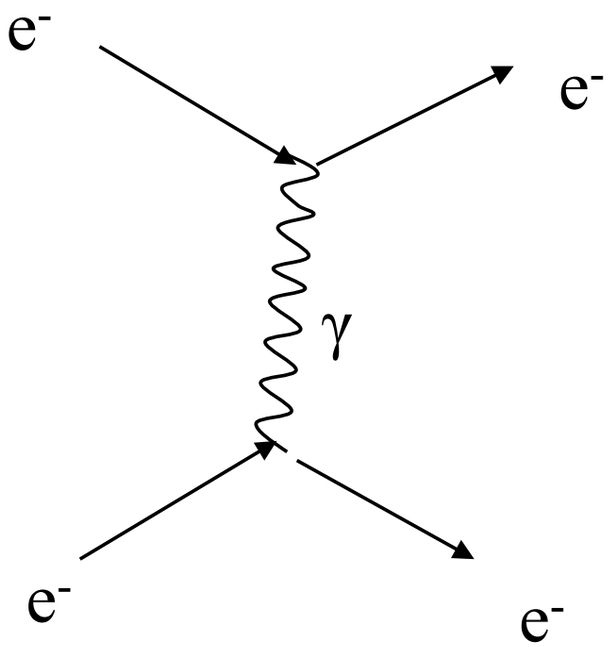
The problem can be cured in the standard model ("renormalization"), but not for gravity.

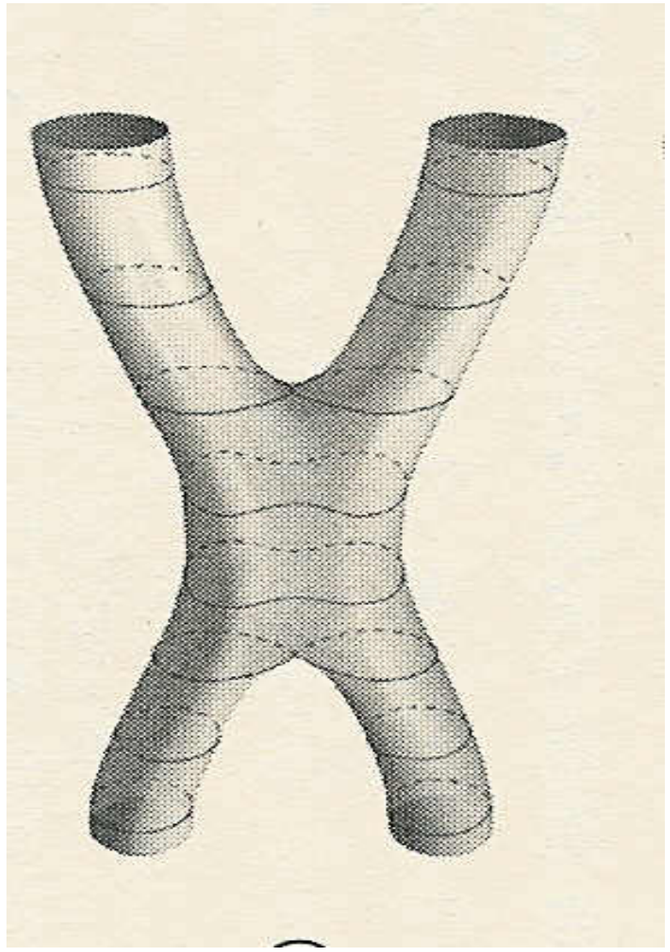


String theory: a relativistic quantum theory where the fundamental objects are not point-like, but string-like (and even membrane-like)

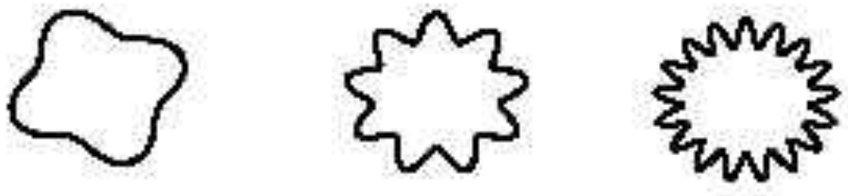




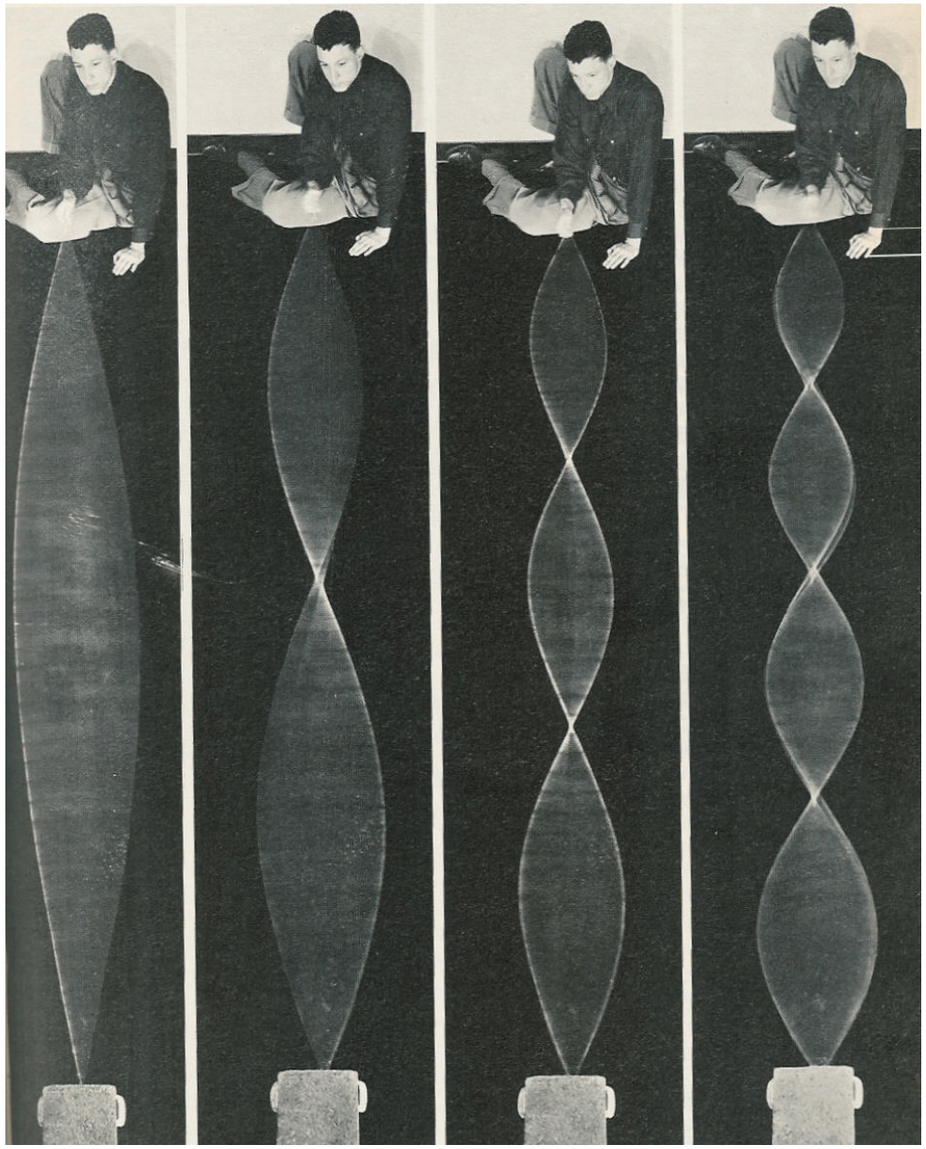
STRINGS

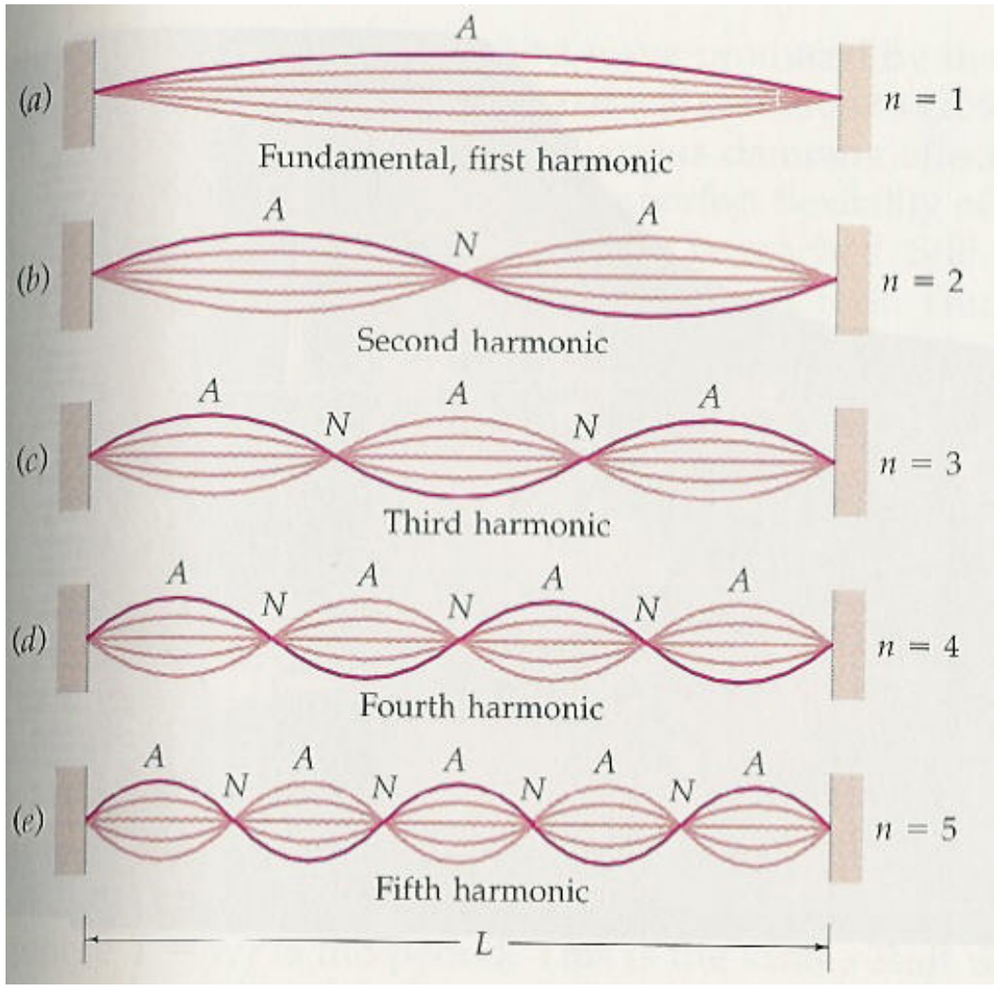


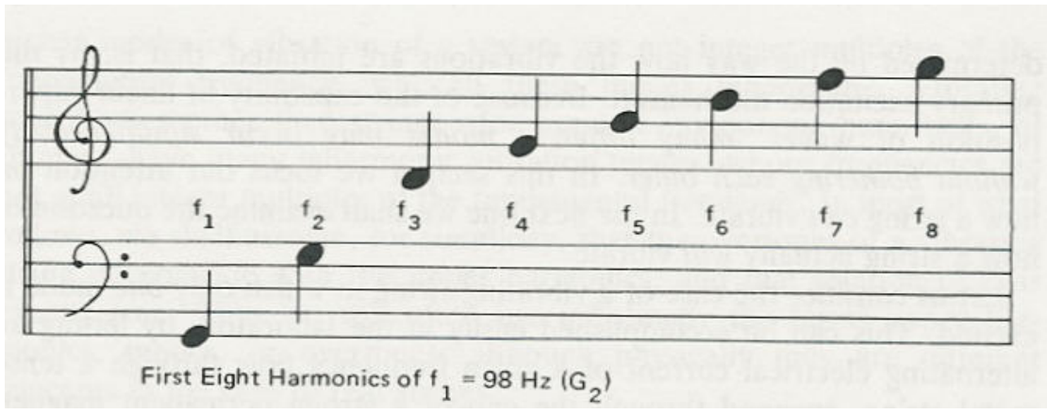
Interaction regions are extended



strings can vibrate, as the strings of a violin.




A
(a)
n = 1
Fundamental, first harmonic
A
N
A
(b)
n = 2
Second harmonic
A
N
A
N
A
(c)
n = 3
Third harmonic
A
N
A
N
A
N
A
(d)
n = 4
Fourth harmonic
A
N
A
N
A
N
A
N
A
(e)
n = 5
Fifth harmonic
L

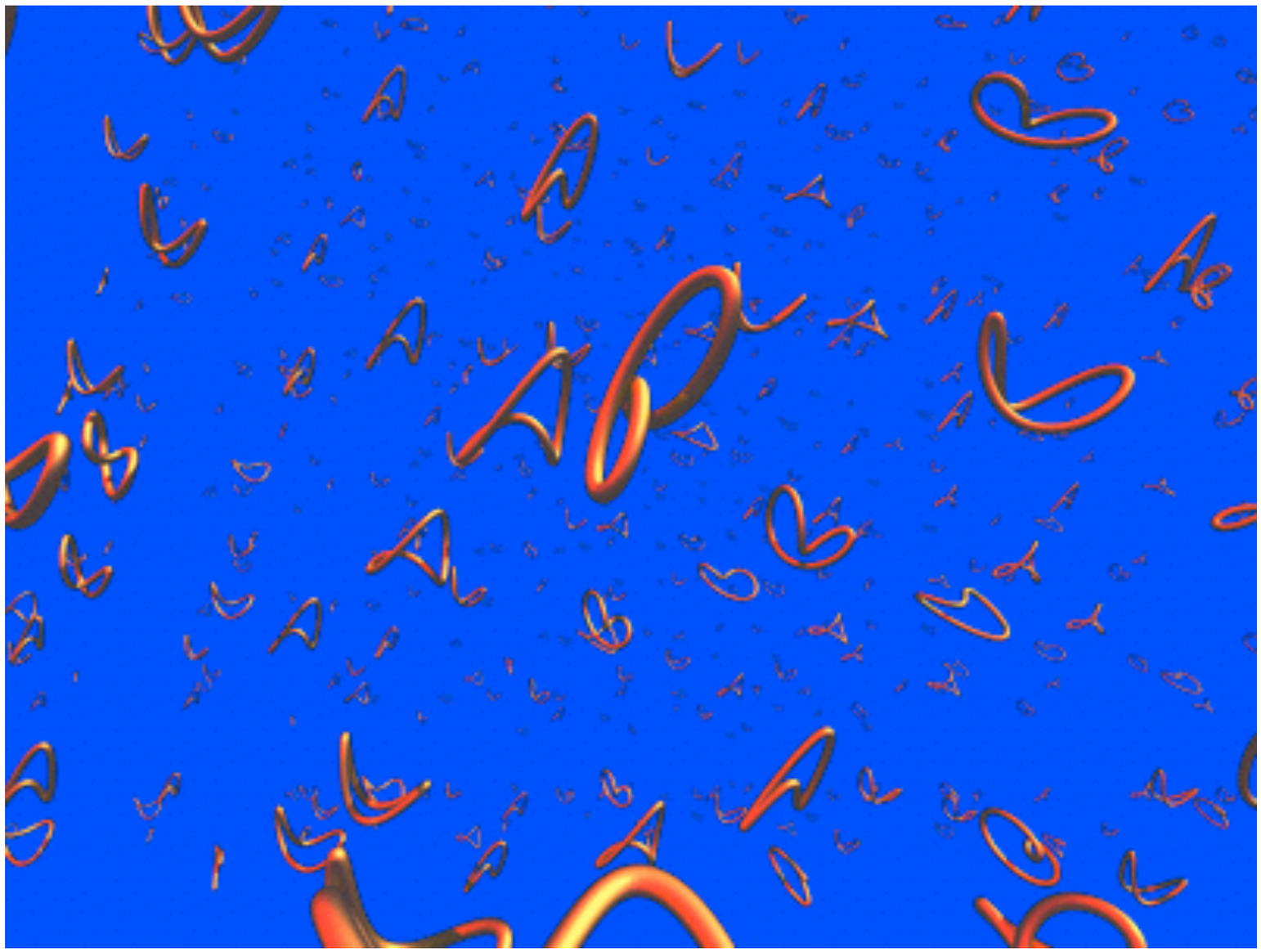

f1
f2
f3
f4
f5
f6
f7
f8
First Eight Harmonics of f1 = 98 Hz (G2)

Every note corresponds to a type of elementary particle:
electron, neutrino, photon, quark…

…and GRAVITON.

—> unification of gravitation with the other fundamental interactions in a quantum theory

One fundamental object, many vibration modes



R. Dijkgraaf

strings have a very small extension: ~10^{-33} cm

—> **appear point-like** even to the most powerful microscopes (particle accelerators)

At the scales available at LHC, does string theory reproduce the particle content and the interactions of the standard model ?

Equations of the theory difficult to solve, and this is a problem also in the SM: approximation methods (perturbation theory) yield many approximate solutions, some of them containing particles and interactions close to SM.

But no reason is known at present why string theory should “prefer” these solutions.

Nonetheless, some predictions are there: features common to all solutions

- Supersymmetry. Strings are consistent only if "supersymmetric" : each bosonic particle has a fermionic partner —> **superstrings**
  Supersymmetry may be broken in particular solutions

- Hidden dimensions: quantum theory of superstrings is consistent in 10 space-time dimensions —> 6 hidden extra compact dimensions, observable only at very high energies

- Modifications to Newton's law, if our space-time is a 4-dim membrane fluctuating in a 10-dim space, and in the 6 extra dimensions only gravity can propagate. Numerous experiments on deviations in the submillimeter regime

- Noncommutative spacetime:

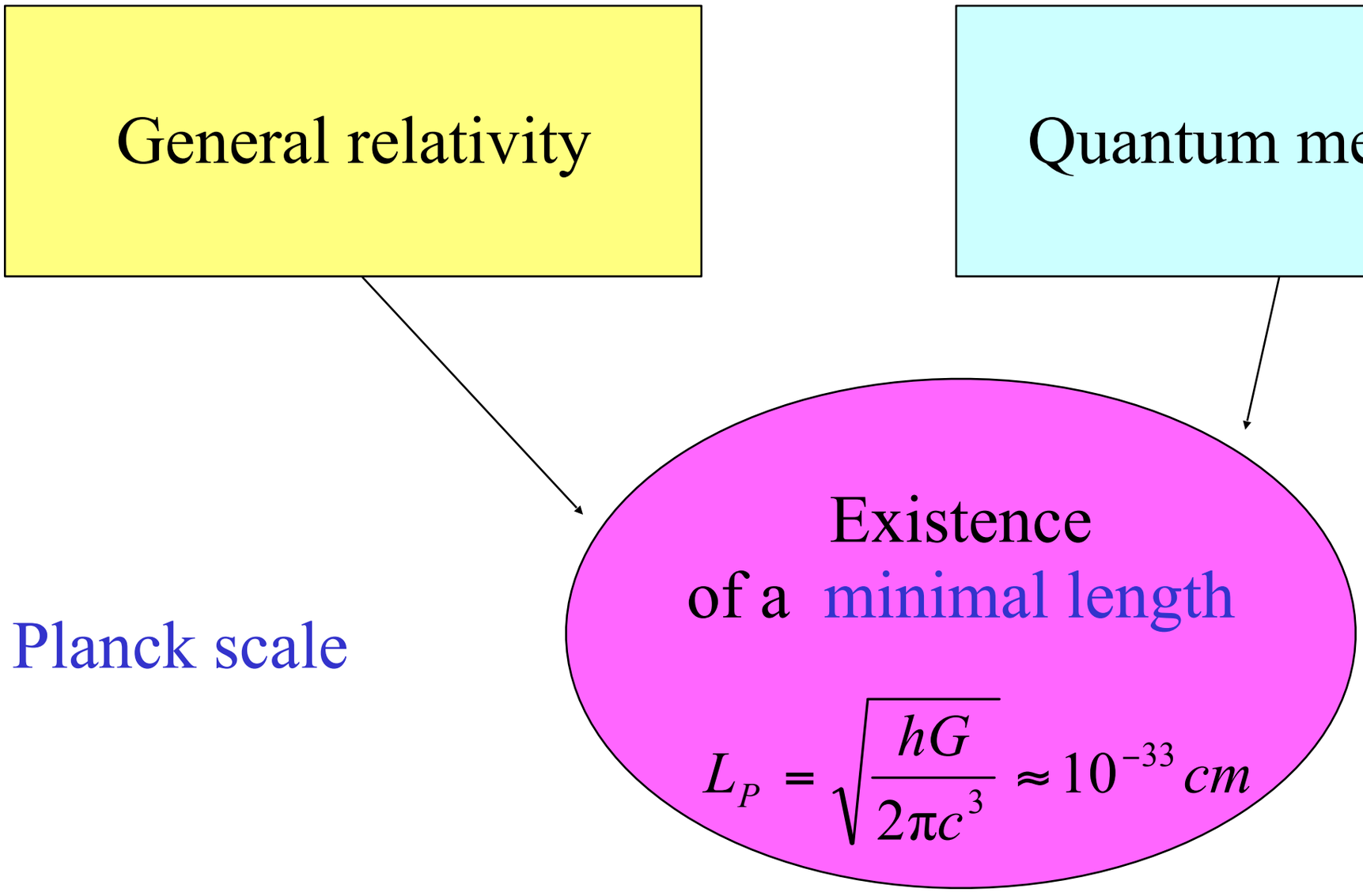
  - At very small distances not necessarily $x\,y = y\,x$

  - Spacetime is then described by
    NON COMMUTATIVE GEOMETRY

  - x, y, … become OPERATORS

- Why noncommutative geometry at small scales ?

- Euristically:



L_P: Planck scale

- To “measure” geodetics in a gravitational field:
  use freely falling particles.

- How precisely can we measure geometry?

- Need particles with very short wavelength λ —> very high energy

- To decrease λ, increase energy → then also the curvature of spacetime increases until …

$$\text{curvature radius} \approx \lambda$$

This happens when $\lambda \approx L_P$

It is therefore impossible to observe phenomena (or spacetime structure) under the Planck scale L_P

- This indetermination emerges automatically if the coordinates are noncommutative.

—> Field theories (gravity, gauge) directly formulated on noncommutative spacetime.

Emergent gravity

- Gravity induced by quantum effects (Sakharov, 1967)

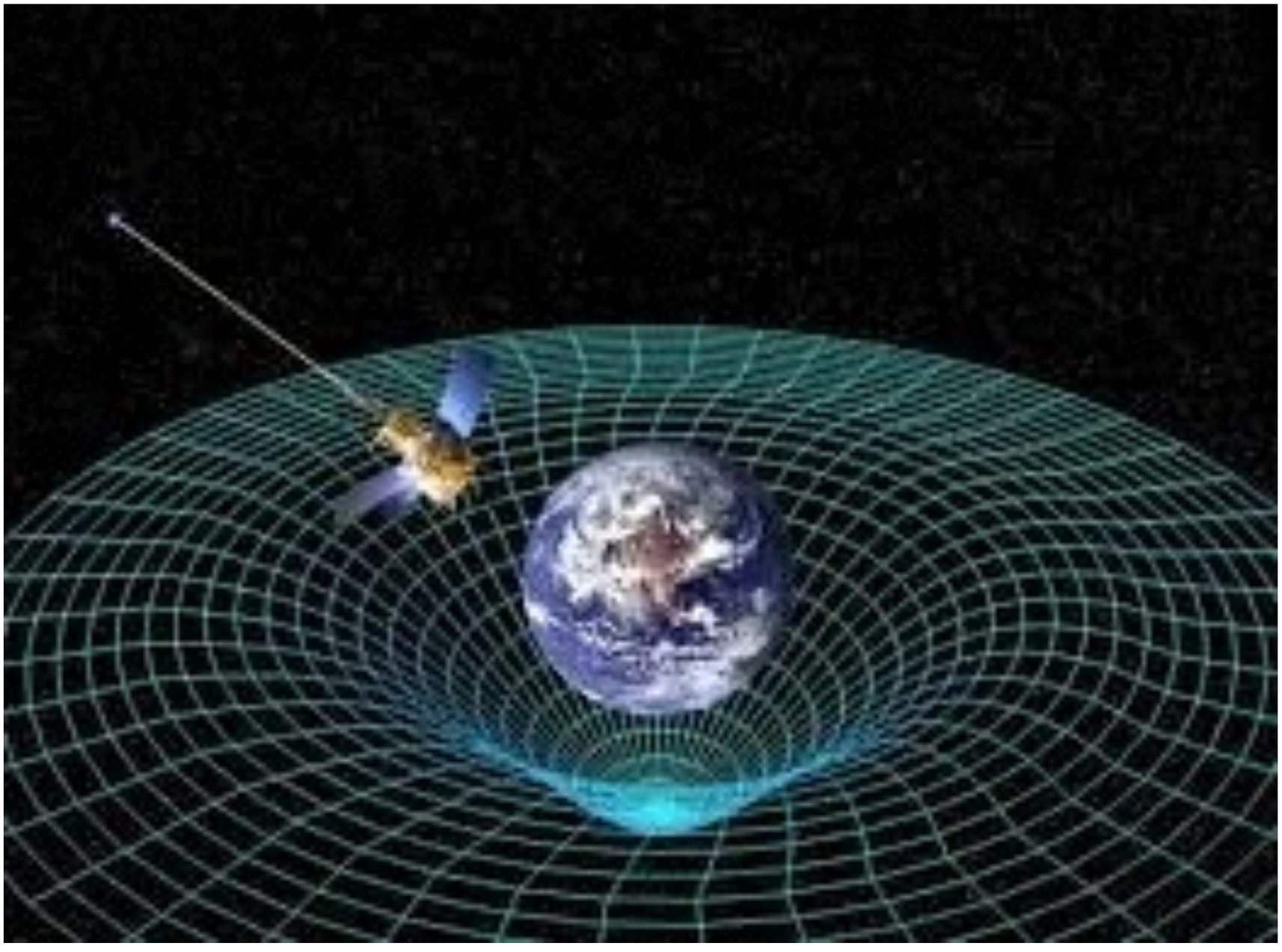
  Introduce quantum fields in arbitrary background Riemannian manifold.
  Effective action at one-loop contains Einstein-Hilbert term.

- AdS/CFT, and more generally gauge/gravity correspondence (Maldacena 1997)

  Gravity theory in the interior of AdS space-time dual to gauge theory on its boundary. Realization of holographic principle.

- Entropic gravity (Verlinde 2009)

  Gravity as entropic force, not a fundamental interaction. Probabilistic consequence of entropy increase. Inspired by black hole thermodynamics.



Thank you !