Theoretical physics approaches to gravity: classical gravity, quantum gravity and string theory

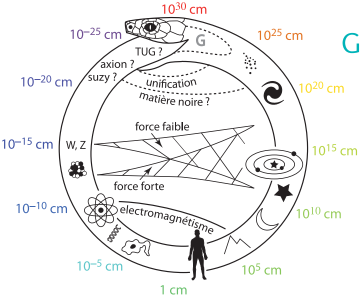
Pierre Vanhove

&

3rd French Government Fellow meeting,
Churchill College, Cambridge, England
July, 21rst, 2018

The importance of Gravity

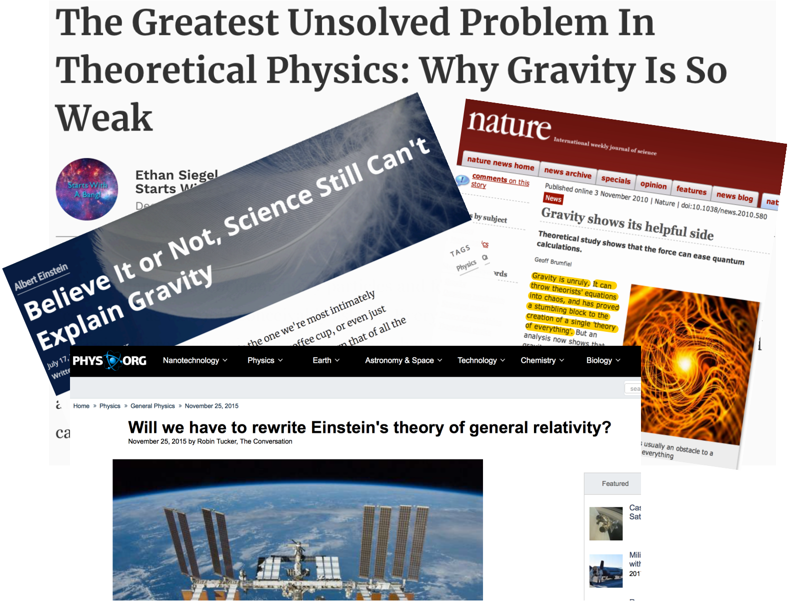
I've been noticing gravity since I was very young. (Cameron Diaz)



Gravity is the most universal force

- It couples to every type of matter and energy
- It is always attractive (we cannot switch off gravity)
- It is very weak

The least understood amongst the fundamental interactions


The Greatest Unsolved Problem In Theoretical Physics: Why Gravity Is So Weak
Ethan Siegel
Starts With A Bang!
Albert Einstein
Believe It or Not, Science Still Can't Explain Gravity
the one we're most intimately
offee cup, or even just
that of all the
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Published online 3 November 2010 | Nature | doi:10.1038/news.2010.580
News
Gravity shows its helpful side
Theoretical study shows that the force can ease quantum calculations.
Geoff Brumfiel
Gravity is unruly. It can throw theorists' equations into chaos, and has proved a stumbling block to the creation of a single 'theory of everything'. But an analysis now shows that
TAGS
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usually an obstacle to a
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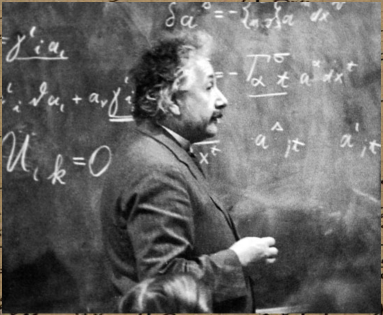
Home » Physics » General Physics » November 25, 2015
Will we have to rewrite Einstein's theory of general relativity?
November 25, 2015 by Robin Tucker, The Conversation
Featured

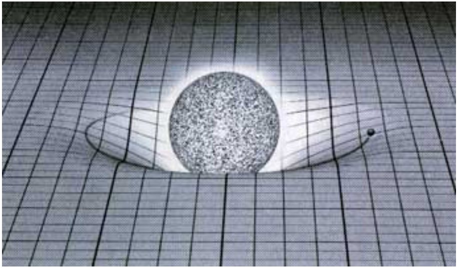
Nov. 25 1915, Albert Einstein publishes his theory of gravity



He changed the way we think about space, time and the Cosmos

Gravity as dynamics of space-time

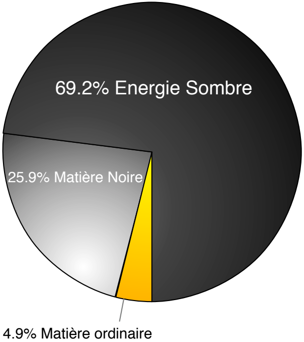
Gravity is the warping of space and time :



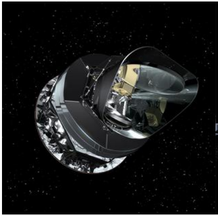
a body is not attracted by another body but moves freely in a curved space-time following a natural trajectory dictated by the shape of space-time

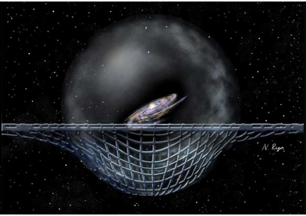
Space and time is dynamical whereas Newton's spacetime was rigid, real but non genuine

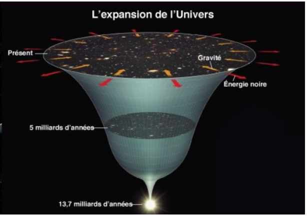
Gravity and our observed Universe



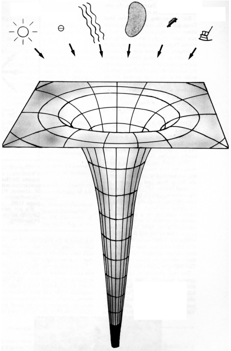
- Planck Legacy archive (July, 17, 2018)
- 4.9% ordinary matter (particles, ...)
- 25.9% dark matter (surrounding galaxies)
- 69.2% dark energy (driving the accelerated expansion)



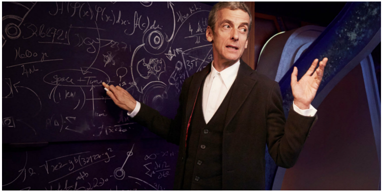




Black holes

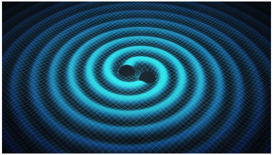


- *The most perfect macroscopic objects there are in the universe : the only elements in their construction are our concepts of space and time (S. Chandrasekhar)*
- Consequence of Einstein's theory of gravity
- Attract all matter and energy

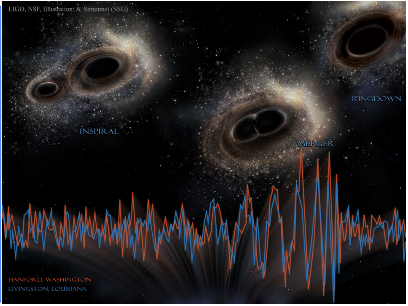


DOCTOR : Short version. Because of the black hole, time is moving faster at this end of the ship than the other. It's all about gravity. Gravity slows down time.
(World Enough And Time- Doctor Who, episode 275a)

Gravitational Waves



On September 14th 2015, LIGO has detected, for the first time, gravitational waves emitted by a black hole binary system



Einstein had doubts about

ON A STATIONARY SYSTEM WITH SPHERICAL SYMMETRY CONSISTING OF MANY GRAVITATING MASSES

BY ALBERT EINSTEIN

(Received May 10, 1939)

If one considers Schwarzschild's solution of the static gravitational field of spherical symmetry

$$ds^2 = -\left(1 + \frac{\mu}{2r}\right)^4 (dx_1^2 + dx_2^2 + dx_3^2) + \left(\frac{1 - \frac{\mu}{2r}}{1 + \frac{\mu}{2r}}\right)^2 dt^2 \quad (1)$$

sents the gravitating mass.)

There arises the question whether it is possible to build up a field containing such singularities with the help of actual gravitating masses, or whether such regions with vanishing g_{44} do not exist in cases which have physical reality. Schwarzschild himself investigated the gravitational field which is produced by an incompressible liquid. He found that in this case, too, there appears a region with vanishing g_{44} if only, with given density of the liquid, the radius of the field-producing sphere is chosen large enough.

This argument, however, is not convincing; the concept of an incompressible liquid is not compatible with relativity theory as elastic waves would have to travel with infinite velocity. It would be necessary, therefore, to introduce a compressible liquid whose equation of state excludes the possibility of sound

ON GRAVITATIONAL WAVES.

BY

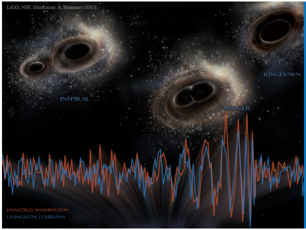
A. EINSTEIN and N. ROSEN.

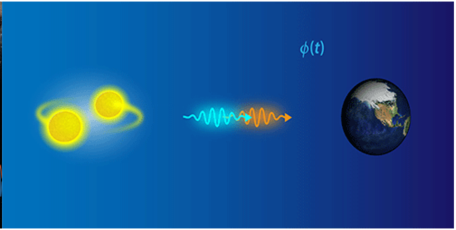
ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

- the reality of Black holes : is the black hole singularity real or fictitious ? How can matter collapse to form a black hole ?
- the reality of gravitational waves : are they physical waves or just mathematical unphysical solutions ?

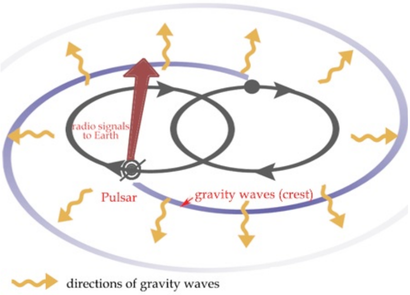
Why is this important? New observational window

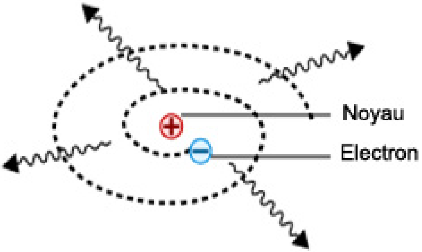




- First time detection of the dynamics of black holes
- New astronomical window on our Universe
  - neutron stars binary system : multi messenger signal (GW, X-rays, γ, ...)
- This puts strong constraints on theoretical models modifying gravity
- After 2018 between 1 and 50 gravitational-wave signals from binary neutron star mergers are expected per year

Gravity and quantum mechanics



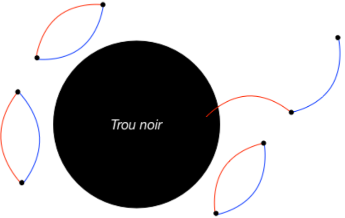


In 1916 Einstein writes

> *Because of the intra-atomic movement of electrons, the atom must radiate not only electromagnetic but also gravitational energy, if only in minute amounts.*
>
> *Since, in reality, this cannot be the case in nature, then it appears that the quantum theory must modify not only Maxwell's electrodynamics but also the new theory of gravitation*

Quantum Black hole : evaporation

Hawking explained that black hole emit a *quantum* radiation from quantum fluctuations near the horizon of the black hole



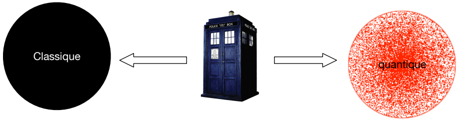
Black hole have a temperature

$$T_{BH} = \frac{\hbar c^3}{8\pi k_B G M}$$

Small black evaporate quickly

Can we observe Hawking radiation ?

Black hole entropy : irreversibility



Black holes have an entropy $dE = TdS$

$$dS_{Schw-BH} = \frac{d(Mc^2)}{T_{BH}} = d\left(\frac{k_B}{4\ell_P^2}\left(\frac{16\pi G^2 M^2}{c^4}\right)\right)$$

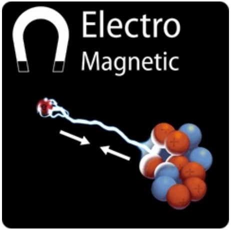
$$S_{BH} = \frac{k_B A}{4\ell_P^2}; \qquad \ell_P^2 = \frac{G\hbar}{c^3} = (1.6\times 10^{-35}\mathrm{m})^2$$

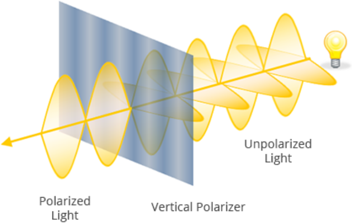
Irreversibility (second principle of thermodynamics) :

- Entropy increases $\Delta S \geq 0$
- Black hole area increases $\Delta A \geq 0$
  - From the observation of gravitational waves [LIGO/VIRGO]

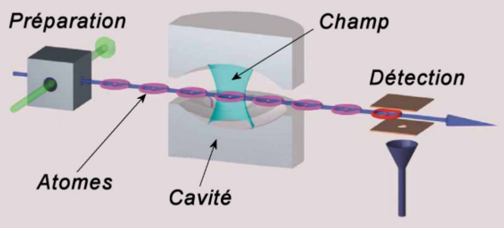
$$S_{BH}+S_{GW} \simeq S_{BH} \geq S_{BH_1}+S_{BH_2} \Longrightarrow \overset{=62^2}{A(BH)} \geq \overset{=36^2}{A(BH_1)} + \overset{=29^2}{A(BH_2)}$$

Quantum of light : photon



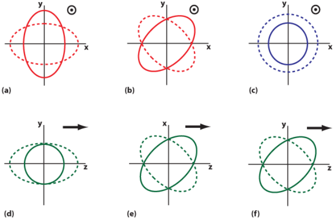


massless, spin 1, quantum of electromagnetic waves

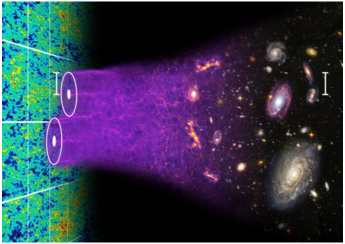


We detect and manipulate photons

Quantum of space-time : graviton



massless, spin 2, (hypothetical) quantum of space-time



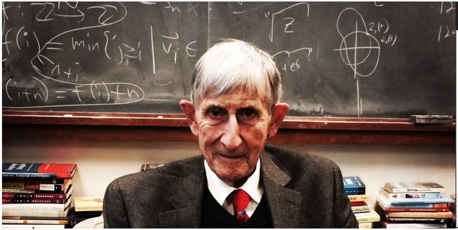
Still looking experimental signature

Das Lichtquant

Max Planck supported Eintein's election to the Prussian science academy (1913)

That he might sometimes have overshot the target in his speculations, as for example in his light quantum hypothesis, should not be counted against him too much., for it is not possible to introduce really new ideas even in the most exact sciences without sometimes taking a risk. (Max Planck, 1913)

Can we detect a graviton ?

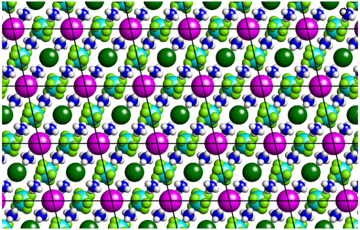


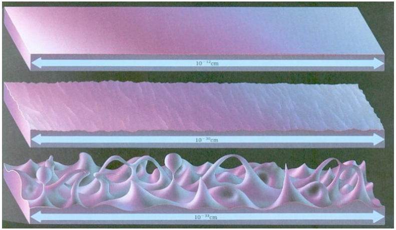
When he received the Poincaré prize Freeman Dyson argued against a possible detection of single graviton

Does it mean that the graviton does not exist ?

Can we imagine a theoretical framework, or experiments that would provide clues about the quantum nature of space-time ?

Fundamental or emerging symmetries

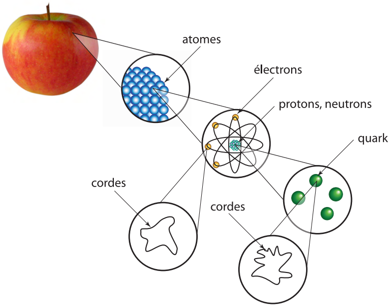


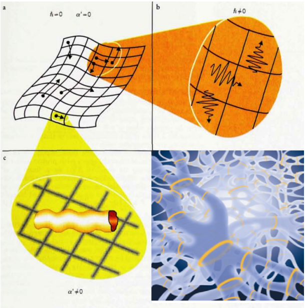


The gravitational wave confirm the validity of the symmetries of Einstein's gravity up to scale of 10% of the size of our observable Universe

What is their domain of validity ? What are the fundamental symmetries of space-time at very large or very small distances ?

String theory



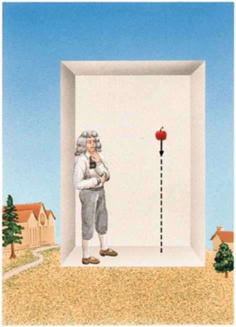
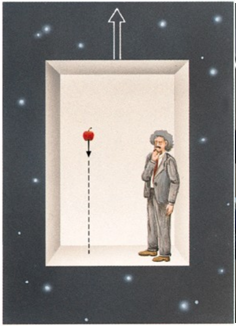


String theory unifies quantum mechanics and general relativity by modifying gravity following Einstein intuition

The typical size of the string is the Planck scale

Equivalence principle

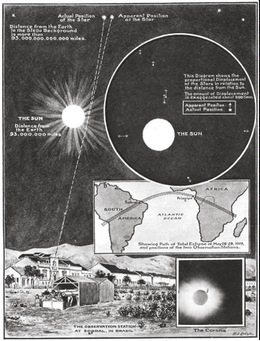
DOCTOR : Old Isaac ? Friend of mine on Earth. He discovered gravity. Well, I say he discovered gravity. I had to give him a bit of a prod. (The Pirate Planet – Episode 099)

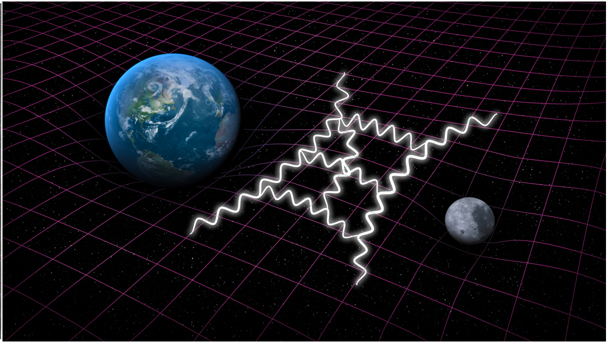




I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me : "If a person falls freely he will not feel his own weight." I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation. (Einstein 1907)

Violation of the equivalence principle

Emil Bjerrum-Bohr, John Donoghue, Barry Holstein, Ludovic Planté, Pierre Vanhove PRL **14** (2015)





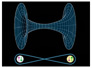
A spin dependent quantum correction

$$\theta_\gamma - \theta_\varphi = c_{\gamma,\varphi}\frac{8}{\pi}\frac{G^2\hbar M_\odot}{c^5 b^3}.$$

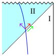
Very small corrections but shows that quantum gravity effect can arise at low-energy

String theory allows to compute the microscopic black hole entropy There are very active debate about the nature of Hawking's radiation

fundamental strings at the horizon of the black hole ?



Einstein-Rosen bridge = Einstein-Podolsky-Rosen entanglement ?



Observer dependent operators (subtle violation of the rules of quantum mechanics)

We remember Isaac Newton for answers, we remember Hawking for questions. (Kip Thorne)