100 years of general relativity in Portugal

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Outline

1. Einstein and general relativity

- Einstein played a major role in several fields in physics: statistical physics, solid state physics, quantum mechanics, electrodynamics, special relativity, general relativity, unification theories, foundations of quantum mechanics, and philosophic principles of physics.

- The pinnacle is without a doubt the general theory of relativity.

- Born (1955) wrote: "The foundation of general relativity appeared to me then, and it still does, the greatest feat of human thinking about Nature, the most amazing combination of philosophical penetration, physical intuition, and mathematical skill."

- Dirac (1968) stated: "General relativity is probably the greatest scientific discovery that was ever made."

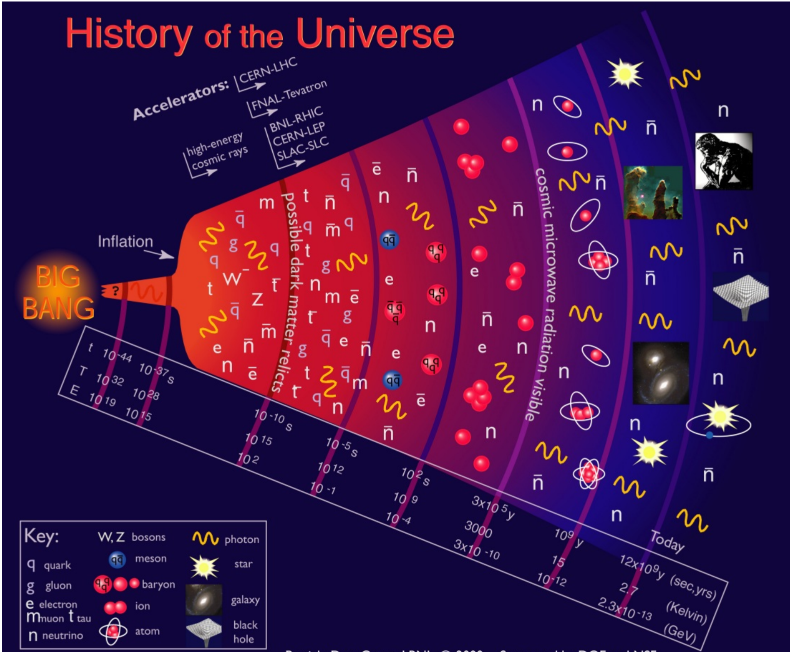
1. Einstein and general relativity

- After an effort that started in 1907, Einstein presented to the Prussian Academy of Sciences, on November 4th, 1915, the first of four seminars on a new, relativistic, tensorial and covariant theory of gravitation. In the fourth seminar, on November 25th, 1915, 100 years today, he gave the final version of a theory which he called the General Theory of Relativity, or General Relativity, for short.
- Einstein equation (1915): $$G_{ab} = \frac{8\pi G}{c^4} T_{ab} \,.$$
- Confirms notion of spacetime initiated by Minkowski, and states physics is geometry, spacetime is curved, free particles follow geodesics. The metric is the gravitational potential, the connection is the gravitational force, and the curvature is the tidal force. The connection can be put to zero locally (principle of equivalence), but the curvature no, maintaining the universality of the gravitational field.
- General relativity is the most intriguing among the fundamental interactions in the universe. In its 100-year-long history, GR has passed many stringent tests, and is now accepted as the standard theory of gravitation and one of mankind's greatest achievements.

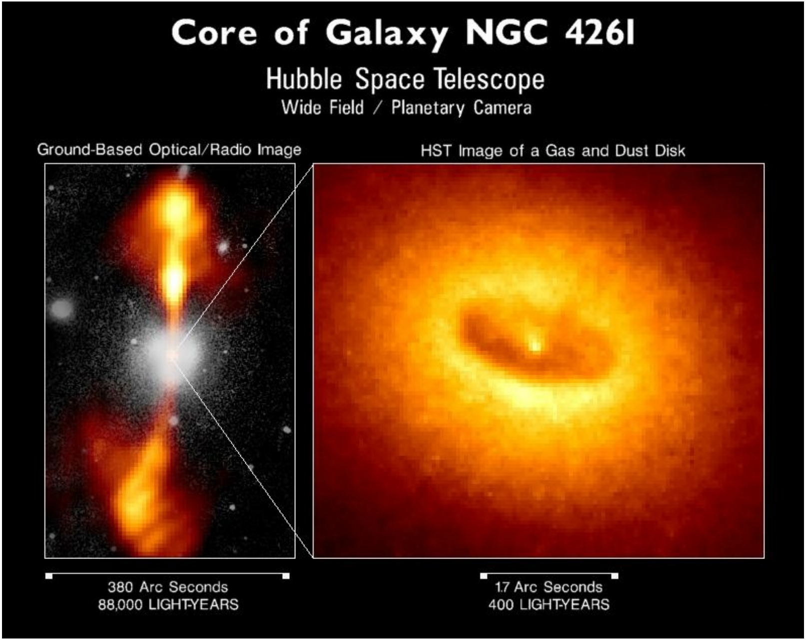
1. Einstein and general relativity

- **Classical tests: Mercury perihelion precession, light deflection in the gravitational field of the Sun (gravitational lensing), gravitational Doppler effect, and delay in the radar echo from a planet.**
- **Technological applications: GPS. It would not function without general relativistic corrections.**
- **Gravitational waves: spacetime ripples predicted by Einstein in 1916. Detected by Hulse e Taylor (Nobel 1993). To be detected by LIGO 2016 and eLISA.**
- **Cosmology: dynamical study of the universe. Started by Einstein in 1917 with the static universe solution. Then expanding universe of Lemaitre and Hubble up to the amazing developments of today.**
- **Black holes: the geometrical object of general relativity par excellence. Einstein never understood it. Nicknamed by Wheeler in 1968.**
- **Fundamental theories: Unification of gravitation and electromagnetism started by Weyl in 1918 and Eddington in 1921, and picked up by Einstein in 1922 onwards. Now are called theories of everything and try to unify all four fields in a quantum geometrical scheme, perhaps.**

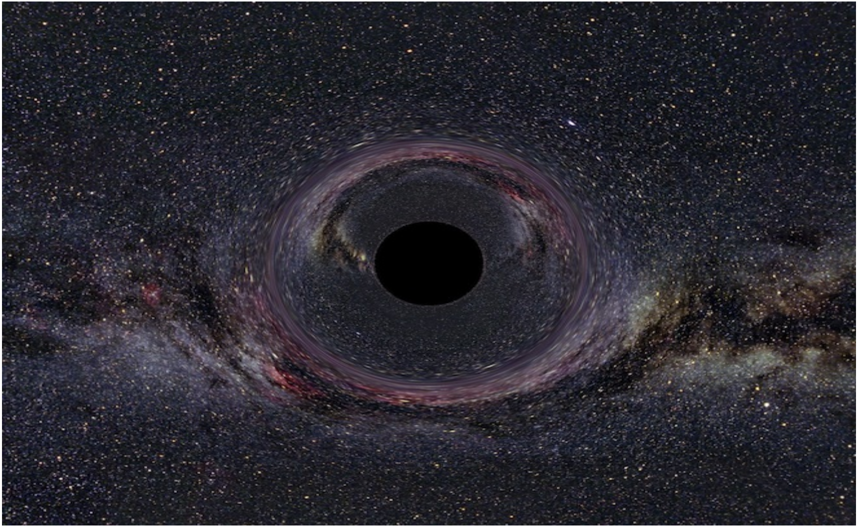
1. Einstein and general relativity



1. Einstein and general relativity



1. Einstein and general relativity



2. Einstein in Lisbon

- **In March 11th, 1925, in transit to Buenos Aires, Montevideu, and Rio, the cruise ship Nord Cap of the shipliner Hamburg-Rio, in which Einstein traveled, docked in Lisbon for two days. He visited the Castle and the Monastery of Jerónimos.**
- **He is not recognized, nobody notices his passage, in spite of being already very famous (Nobel in 1921).**
- **In his log he writes that he liked the Varinas (fisher women in downtown Lisbon).**
- **He annotates: "A fisher woman selling fish, photographed with a fish basket, proud gesture, naughty".**
- **Then later in Rio in the Copacabana Palace he said to Gago Coutinho (famous Portuguese Admiral for being the first to traverse by plane the South Atlantic, making the trip Lisbon-Rio in 1922): "Sellers of fish of great elegance; I stopped several times to admire them. In the group where I was we photographed them often and put the portraits in our dining table on board."**

2. Einstein in Lisbon

Varina in a beach.

2. Einstein in Lisbon

Lisbon varinas at river Tejo.

2. Einstein in Lisbon

- **In March 17h, 1932, under the presidency of Egas Moniz (Nobel of Medicine in 1945) and following a suggestion of the great Portuguese mathematician Mira Fernandes, Einstein and Levi-Civita, are nominated foreigner correspondents of the Lisbon Academy of Sciences. It certainly was a welcome event for the country.**

- **Interesting to note that in the following day, amid hundreds of many other news, the newspaper Pittsburgh Press announces this ceremony (Pittsburgh Press, Friday, March 18, 1932, p. 35):**

Lisbon Honors Einstein

Lisbon, March 18 - Prof. Albert Einstein has been named an associate at the Academy of Sciences in Lisbon.

3. General relativity in Portugal

- A major event worldwide was the 1919 eclipse and the confirmation of general relativity through the light deflection prediction.

- The May 29, 1919, eclipse was special because the Hyades were on the background.

- Frank Dyson, astronomer royal, presided a committee of the Royal Society of London and the Royal Astronomical Society. It approved two expeditions to minimize the risk of failure by bad weather.

- Eddington went to Príncipe, a Portuguese island at the time, belonging to the archipelago of São Tomé and Príncipe.

- Crommelin went to Sobral in Ceará state, North of Brazil.

- They arrived six weeks before.

3. General relativity in Portugal

São Tomé e Príncipe

3. General relativity in Portugal

Come and visit São Tomé e Príncipe.

3. General relativity in Portugal

Príncipe and the village Santo António.

3. General relativity in Portugal

Santo António bay. Eddington stayed here.

3. General relativity in Portugal

Brazil

3. General relativity in Portugal

State of Ceará and Sobral region.

3. General relativity in Portugal

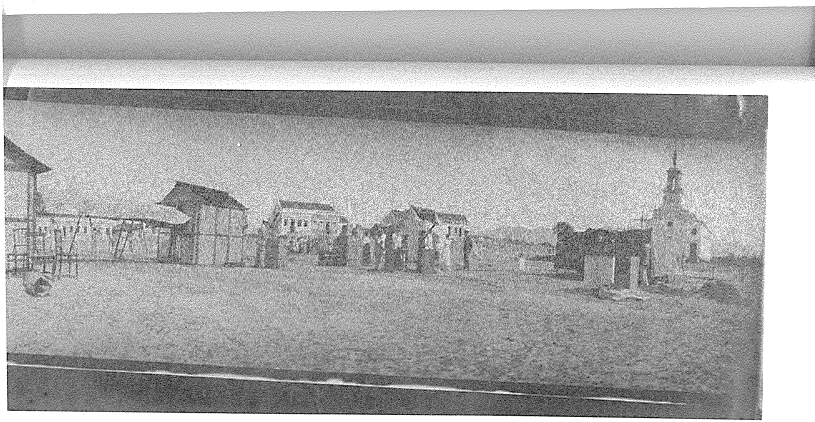


Fig. 22 – Vista panorâmica do observatório em Sobral

Panoramic view of the observatory camp in Sobral in 1919, with the church.

3. General relativity in Portugal

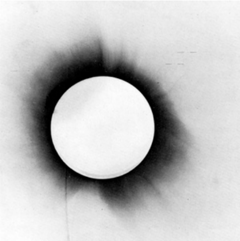
Museum of the eclipse in Sobral, panoramic view with the church.

3. General relativity in Portugal

- In Príncipe the weather was unfavorable, but it cleared up when totality began. In Sobral the weather was fine.

- The data pointed to 1.6”±0.3 in Príncipe and 1.98”±0.12 in Sobral, compatible with the 1.75” deflection predicted by general relativity.

- Einstein is acclaimed.



3. General relativity in Portugal

- The Royal Society established contacts with the Astronomical Observatory of Lisbon.
- Correspondence between Eddington and the director and vice-director Campos Rodrigues and Frederico Oom to finalize the logistics. The trip had a stop in Funchal, Madeira Island.
- The newspaper O Século (Lisbon), informs in November 15, of the Royal Society and the Royal Astronomical Society meeting, in 6 November, when the results were publicized. The Times (London) announced it in November 7, the New York Times in November 10, and O Jornal (Rio de Janeiro) in November 12.
- The astronomer Manuel Peres Júnior of Observatório of Mozambique wanted to be present, but bureaucratic problems prevented him to join. In Rio de Janeiro Henrique Morize and Brazilian astronomers were present in Sobral.
- Peres Júnior wrote about general relativity in the 1920s. The astronomers Ramos da Costa and Melo Simas also took interest.

3. General relativity in Portugal

- The Portuguese mathematical community also took part in the interest and development of general relativity in Portugal.
- The 1st Mathematical Portuguese-Spanish Congress for the Advancement of Science, in Porto in 1921, gave a boost to general relativity.
- Plans y Freire gave a lecture that strongly inspired Portuguese Mathematicians.
- Santos Lucas of Faculdade de Ciências, spurred by it delivered a course during the year 1922-1923 in general relativity, the first regular course in general relativity in the world.
- Others: Manuel dos Reis (Coimbra), Ruy Luis Gomes (Porto), António Geão (Lisbon). The personality that stands above all is Mira Fernandes (IST).
- From the 1950s until today great developments in the Portuguese Universities.
- Almost every Physics Department has a theoretical group working in gravitation, general relativity and related areas.

3. General relativity in Portugal

- Mira Fernandes was a mathematician, Professor at IST from 1911 (inaugural year of IST) to 1954 (retirement).
- He got his Doctorate in Coimbra under Sidónio Pais (later, President of the Republic).
- From the very beginning he showed interest in differential geometry and general relativity. In 1930 he published several interesting papers in Rendiconti della Accademia dei Lincei in unification theories of gravitation and electromagnetism.
- He corresponded with Levi-Civita and E. Cartan. Here in Portugal he standed alone.

4. General relativity and unitary theories: Scientific context in the epoch of Mira Fernandes

A. Generalities and general relativity

· **The idea of unification is old.**
Mie 1912 wanted to unify fields and sources. Followers Born and Infeld (1934). Nordström 1913 tried unification of (scalar) gravitation and electromagnetism in five spacetime dimensions.

· **General relativity (1915) changed the picture.**
Unified gravitation and special relativity.
Left electromagnetism out, though $G_{ab} = 8\pi T^{\rm em}_{ab}$ **and** ${F_a}^b{}_{;b} = j_a$.

· **Rationale: If electricity and magnetism were unified in electromagnetism in a special relativity framework, then gravity and electromagnetism should be unified in a unitary theory in a special world background framework.**

· **Is general relativity a field theory or an arena (as special relativity)?**

· **From 1916 onwards unification schemes have been always forefront problems.**

4. General relativity and unitary theories: Scientific context in the epoch of Mira Fernandes

B. Weyl theory of gravitation and electromagnetism (1918)

- **The theory attempts to introduce electromagnetic potentials as geometrical quantities which determine the transport law of a length scale.**
- **In Weyl transport is** $d\xi^a = \Gamma^a{}_{bc} dx^b \xi^c$**, where** $\Gamma^a{}_{bc}$ **is the connection.**
- **Weyl length** $l^2 = g_{ab}\xi^a\xi^b$ **can change:** $dl = \phi_b dx^b l$, ϕ_b **a new field.**
- **Deduce:** $\Gamma^a{}_{bc} = \left\{ {a \atop bc} \right\} + g^{da}\left(g_{db}\phi_c + g_{dc}\phi_b - g_{bc}\phi_d\right)$**, and** $g_{bc;a} = \phi_a g_{bc}$
- **Find** $R^a{}_{bcd} = K^a{}_{bcd} + T^a{}_{bcd}$**, where** $K^a{}_{bcd}$ **is the Riemann-Christoffel curvature and** $T^a{}_{bcd}$ **is the curvature due to** ϕ_a**.**
- **Get Weyl's equations:** $G_{ab} = 8\pi T_{ab}(\phi)$ **and** $F^{ab}{}_{;b} = j^a$**.**
- **Problems: Properties depend on history (Einstein 1918). Devastating.**
- **Anyway, the door to unification was open. Brazilian saying: Where one ox passes a herd of oxen passes.**
- **Moreover: London (1927) applied to atomic physics and gave rise to gauge transformations in quantum mechanics Weyl (1929).**

4. General relativity and unitary theories: Scientific context in the epoch of Mira Fernandes

C. Eddington theory (1921)

· **Einstein (1923-1925) tried field equations for the theory.**

D. The spectrum of unitary theories

· **Afterwards differential geometry and tensor calculus enter a high tide.**

· **Previous mathematical ideas: Hessenberg (1917), Levi-Civita (1917), Schouten (1917), and then Cartan (1923) with his torsion (distorsion).**

· **General connections and their properties explored (Schouten, *Der Ricci-Kalkül* (1923)).**

· **Assume two connections: Γ for contravariant tensors and Γ' for covariant tensors. So two parallel transports.**

· **Get: Riemann-Christoffel curvature, torsion curvature, homothetic curvature for Γ, and other similar quantities for Γ'.**

· **Get: a C-field, $C^c{}_{ab} = \Gamma^c{}_{ab} + \Gamma'^c{}_{ab} = \delta^c_{b;a}$, where δ^c_b is the identity tensor.**

4. General relativity and unitary theories: Scientific context in the epoch of Mira Fernandes

E. Table of theories:

- **Theories with Riemann-Christoffel and homothetic curvature (without torsion): Weyl (1918), Eddington (1921), Einstein (1923), Γ symmetric.**
- **Theories with Riemann-Christoffel and torsion curvature (without homothetic curvature): Cartan (1924), Weitzenböck (1925), Einstein (1925), Infeld (1928) Γ asymmetric, i.e., $\Gamma = \Gamma_{\text{symmetric}} + \Gamma_{\text{antisymmetric}}$.**
- **Theories with all three curvatures: Schouten (1924), Eyraud (1926), Infeld (1928), Straneo (1931).**
- **Theories with the C-field: Mira Fernandes (1927-1933).**
- **Other theories: Einstein (1942), Schrödinger (1943), Γ asymmetric and g asymmetric.**
- **Other ways: Riemannian geometry in higher dimensions $d > 4$: Kaluza (1921), Klein (1926), Einstein-Mayer (1931), Einstein-Bargmann-Bergmann (1941), Jordan and Thiry (1945), Podolansky (1950), supergravity and superstring theories (nowadays).**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

A. The book (1927) *Foundations of the differential geometry of linear spaces* **(in Portuguese)**

- **Follows Schouten's** *Ricci Kalkül*, **acknowledges Blashcke, Struik, Weyl, Eddington.**
- **Linear transport of a contravariant vector** v^a**:** $D\mathrm{v}^a = d\mathrm{v}^a + \Gamma^a{}_{cb}\mathrm{v}^c dx^b$.
- **Linear transport of a covariant vector** u_a**:** $Du_a = du_a + \Gamma'^c{}_{ab}u_c dx^b$.
- **The identity tensor** δ_a^b **has covariant derivative:** $\delta_{a;c}^b = \delta_{a,c}^b + \Gamma^b{}_{dc}\delta_a^d + \Gamma'^d{}_{ac}\delta_d^b = \Gamma^b{}_{ac} + \Gamma'^b{}_{ac} \equiv C_{ca}{}^b$, **the** C**-field.**
- **Now, in general,** $(u_a\mathrm{v}^a)_{;b} = u_{a;b}\mathrm{v}^a + u_a\mathrm{v}^a{}_{;b} - C_{ba}{}^c(u_c\mathrm{v}^a)$. **When** $C_{ba}{}^c = 0$ **(the case we are used to), transport is said invariant by contraction.**
- **Simplify** $C_{ba}{}^c = C_b\delta_a^c$ **(Schouten 1923). Then** $(u_a\mathrm{v}^a)_{;b} = u_{a;b}\mathrm{v}^a + u_a\mathrm{v}^a{}_{;b} - C_b(u_a\mathrm{v}^a)$.
  When $u_a\mathrm{v}^a = 0$**, i.e.,** v^a **belongs to the** $(n-1)$**-direction of** u_a **(they are incident vectors) the Leibniz rule for the differentiation of the product is verified - transport is invariant by incidence.**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

- **Another important quantity** $S^c{}_{ab} = \frac{1}{2}\left(\Gamma^c{}_{ab} - \Gamma^c{}_{ba}\right)$**, the torsion of the connection. Transport of a vector in a closed path of the manifold corresponds to a transport in a nonclosed path in the tangent space.**
- $Q'_{abc} = g_{bc;a}$ **and** $Q_a{}^{bc} = g^{bc}{}_{;a}$**. The non-metricities.**
  When $Q'_{abc} = Q'_a g_{bc}$ **transport is contravariant conform, or Weyl.**
- **Now,** Γ **and** Γ' **can be expressed in the fields** C, g, S, S', Q, Q'**:**
  $\Gamma^d{}_{ac} = \quad \left\{ {d \atop ac} \right\} + T^d{}_{ac}$, $\Gamma'^d{}_{ac} = -\left\{ {d \atop ac} \right\} + T'^d{}_{ac}$, **where** $T^d{}_{ac} = C^d{}_{ac} - T'^d{}_{ac}$
  and $T'^d{}_{ac} = \frac{1}{2}\left(Q'_{cab} + Q'_{acb} - Q'_{bac}\right) g^{bd} - S'^e{}_{bc} g_{ae} g^{bd} - S'^e{}_{ba} g_{ce} g^{bd} + S'^d{}_{ac}$**.**
- **Curvature** $R^a{}_{cbd} = \Gamma^a{}_{dc,b} - \Gamma^a{}_{db,c} + \Gamma^a{}_{eb}\Gamma^e{}_{dc} - \Gamma^a{}_{ec}\Gamma^e{}_{db}$
  as Riemann tensor formally. Equivalently for $R'^a{}_{cbd}$**.**
- **Particular cases:**
  Riemann transport: $C = 0 \quad S = 0 \quad Q = 0$.
  Weyl transport: $C = 0 \quad S = 0 \quad Q_{cab} = Q_c g_{ab}$.
  Affine transport: $C = 0 \quad S = 0 \quad Q$ any.
- **Most theories have** $C = 0$**, a relief. Not for Mira!**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

B. Rendiconti 1931 "Properties of some linear connections" (in Italian)

· **Shows 7 properties not in Schouten's book, not in Mira's book.**

· **Typical one: Shows that with the connector tensor $C^c{}_{ab} = C_a \delta^c_b$ (invariantce by incidence) he can recover some of Eddington formulas.**

C. Rendiconti 1932 "Sulla teoria unitaria dello spazio fisico" I (in Italian)

· **Ventures into unitary theories.**

· **Analyzes Paolo Straneo's papers in Rendiconti 1931-1932 and in Nuovo Cimento 1931.**

· **Recovers Straneo's result if we put $C_a = -2\psi_a$, the electromagnetic potential of the unitary theory.**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

D. Rendiconti 1933 "Sulla teoria unitaria dello spazio fisico" II (in Italian)

- **From his book displays the relation between R' and R, and R and K,**
  $R'^{d}{}_{abc} = R^{d}{}_{abc} + 2S'^{e}{}_{ab}C^{d}{}_{ec} + C^{d}{}_{bc,a} - C^{d}{}_{ac,b}$
  $R^{d}{}_{abc} = K^{d}{}_{abc} + T^{d}{}_{ca;b} - T^{d}{}_{cb;a} + T^{d}{}_{ea}T^{e}{}_{cb} - T^{d}{}_{eb}T^{e}{}_{ca}$**.**
- **From symmetries of $R^{d}{}_{abc}$ follows if $R^{d}{}_{abc} = 0$ then**
  $K^{d}{}_{abc} - T^{d}{}_{ab;c} + T^{d}{}_{ec}T^{e}{}_{ab} = 0$ **(Straneo 1932).**
- **Recovers distant parallelism of Einstein, Cartan, Weitzenbök (1929s).**
- **Mira: "translates a remarkable structure of physical space characterizing a chronotope of contravariant curvature zero."**
- **For Straneo $C^{a}{}_{bc} = 0$ and so $R'^{d}{}_{abc} = 0$. Mira shows that for $C^{a}{}_{bc} \neq 0$ then $R'^{d}{}_{abc} \neq 0$ and so no distant parallelism for covariant vectors.**
- **Mira's final remark: "E non sarà privo d'interesse, per future utilizzazioni della teoria unitaria l'aver constatato che la equazzioni del prof. Straneo sono compatibili con connessioni lineari in cui il tensore $C^{a}{}_{bc}$ non è nullo; ciò que non sono invariante per contrazione."**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

(iii) What else

Papers:

- **Rendiconti 1934 "The unitary theory of physical space and the relativistic equations of atomic mechanics". A paper on the Dirac equation, tries to unify GR, electromagnetism and wave mechanics.**
- **Portugaliae Mathematica 1945 "Connessioni finite".**
- **Revista da Faculdade de Ciências 1950 "Transporti finite". Both on bivectors and an Einstein idea.**
- **Revista da Faculdade de Ciências 1950 "Le geodetiche degli spazi unitari". On complex manifolds, quoted in Schouten 1954** *Ricci Calculus* **and Mme. Tonnelat 1955** *La théorie du camp unifié d'Einstein et quelques-uns de ses développements*.

Reviews:

- **Técnica 1933 "Modernas concepções da mecânica", two masterful lectures in the Instituto de Altos Estudos in Lisbon, the first on relativity and unitary theories, the second on quantum mechanics.**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

- **J. Vicente Gonçalves, his friend and mathematician (Coimbra and FCUL), in 1971 in an essay "Aureliano de Mira Fernandes: investigador e ensaísta" writes:**
- **"Merecem também especial citação as três notas sobre a teoria unitária do espaço físico (1932-34), onde Mira Fernandes concebe e estuda diversas conexões lineares compatíveis com a síntese geométrica gravitação-electromagnetismo que P. Straneo andava então elaborando. Uma dessas conexões (invariante por incidência, contravariante simétrica e covariante métrica) mostrou-se igualmente compatível com as novas equações relativistas da mecânica ondulatória propostas por Levi-Civita. A despeito de suas possibilidades, a teoria unitária que Mira Fernandes então concebeu (e por vezes recordou) não fugiu ao destino das múltiplas tentativas congéneres que ao tempo se fizeram; mas é de assinalar a virtuosidade analítica do autor na sua investigação."**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

My sources:

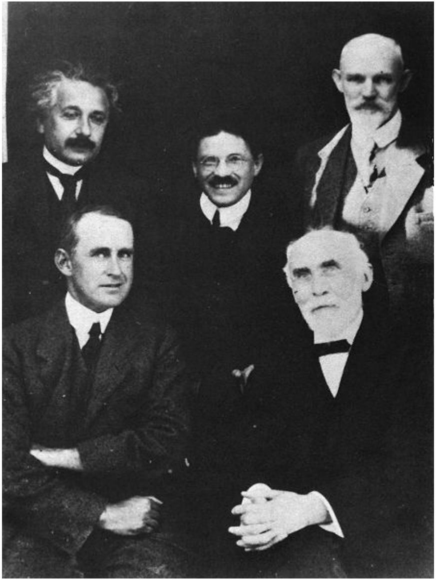
- **Schouten 1923 "Ricci-Kalkül".**
- **Tonnelat 1965 "Les théories unitaires de l'électromagetism et de la gravitation".**
- **Adler, Bazin, Schiffer 1965 "Introduction to GR".**
- **Pais 1982 "Subtle is the Lord".**
- **Goenner 2004, 2014 "On the history of unified theories".**
- **Straneo's papers 1931-1932.**
- **Mira Fernandes' book and papers 1927-1933.**

5. The works of Mira Fernandes on unitary theories of gravitation and electromagnetism

References:

- **J. P. S. Lemos, 2010, "Unitary theories in the work of Mira Fernandes (beyond general relativity and differential geometry)", Boletim da Sociedade Portuguesa de Matemática, (Número Especial - Aureliano Mira Fernandes), eds. L. Saraiva e J. T. Pinto, (SPM, Lisboa, 2010), p. 147; arXiv:1012.5093 [physics.hist-ph].**
- **J. P. S. Lemos, 2011, "Differential geometry, general relativity, and unitary theories in the work of Mira Fernandes", Proceedings of the 12th Marcel Grossmann Meeting, Paris, July 2009, eds. R. Jantzen et al, (World Scientific, Singapore, 2012), p. 1745; arXiv:1011.6269 [phys].**
- **J. P. S. Lemos, 2011, "A introdução da relatividade em Portugal e Aureliano de Mira Fernandes", Gazeta de Física 34, 27 (2011).**
- **J. P. S. Lemos, 2013, "Mira Fernandes e a Física-Matemática na fundação e consolidação da revista Técnica", Técnica 01 (nova contagem), 6 (2013).**

4. Conclusions and acknowledgements



Einstein, Ehrenfest, de Sitter, Lorentz, and Eddington. Leiden, 1920.

4. Conclusions and acknowledgements

Einstein in Haberlandstrasse. Berlin, 1930.