Title: The Genesis and Renaissance of General Relativity

Date: Jun 23, 2015 08:00 PM

URL: http://pirsa.org/15060009

Abstract: Albert Einstein developed the general theory of relativity 100 years ago as an answer to fundamental problems of contemporary physics. Yet the theory remained a marginal phenomenon of physics, especially in comparison to quantum theory, until the second half of the 20th century. That's when the renaissance in general relativity combined with the rise of relativistic astrophysics, turning general relativity into a key instrument in astrophysics. This talk will trace the genesis of general relativity, look at Einstein's research and the work of many other scientists who contributed to the theory, and show how general relativity eventually became not only a highly active field of research but one of the principal challenges to the conceptual unification of physics.

Perimeter Institute Convergence Meeting, Waterloo Canada,
June 23, 2015

The Genesis and Renaissance of General Relativity

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General Relativity as a challenge for the history of science

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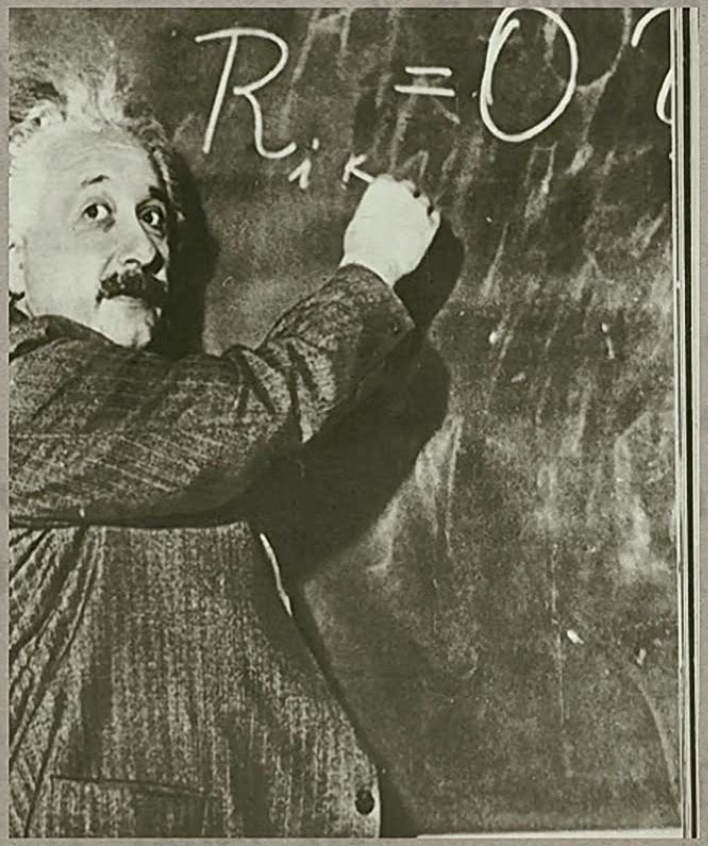
General Relativity as a challenge for the history of science

- **No empirically pressing problem:**
  - The perihelium motion of Mercury was minor problem for which there might have been other explanations;
  - Light bending, redshift, expanding universe, gravitational lensing, black holes all came later.

General Relativity as a challenge for the history of science

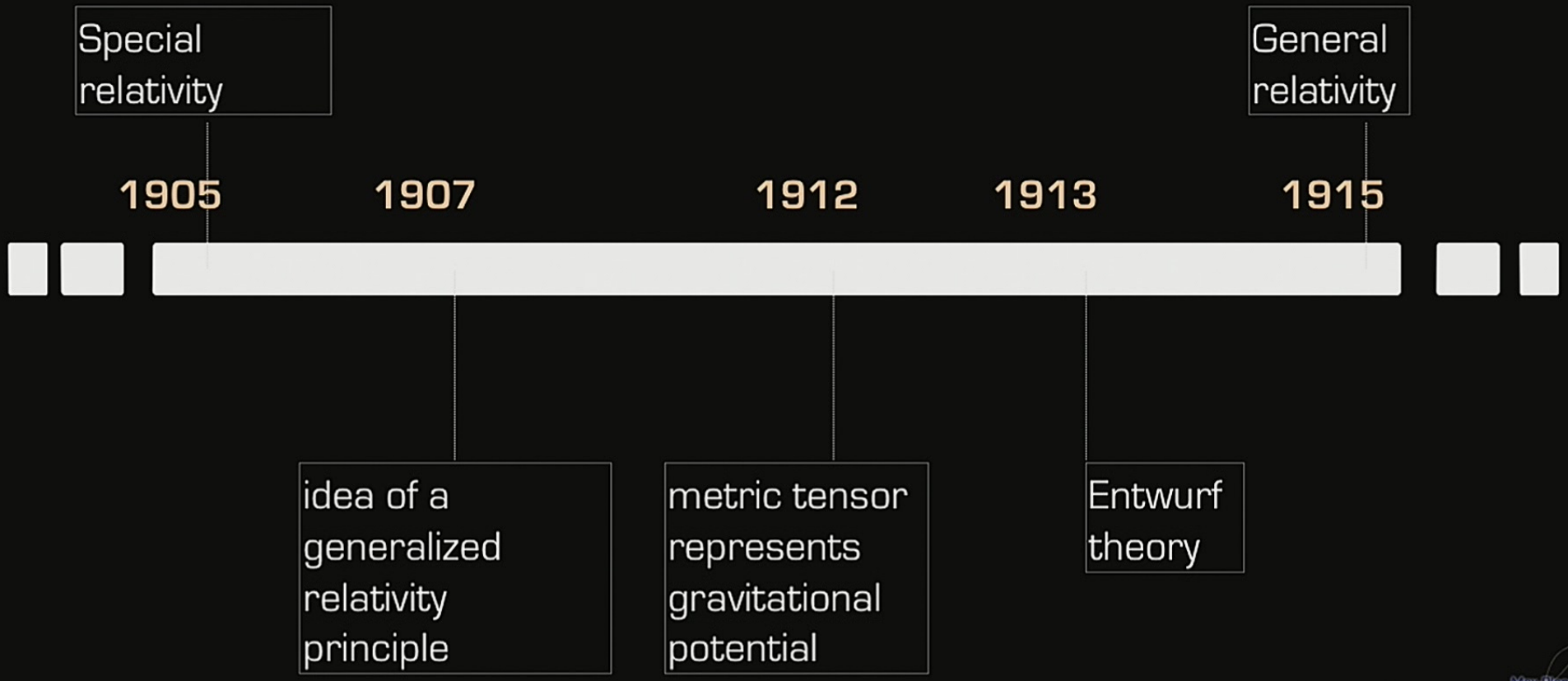
- **No empirically pressing problem:**
  - The perihelium motion of Mercury was minor problem for which there might have been other explanations;
  - Light bending, redshift, expanding universe, gravitational lensing, black holes all came later.
- **On what knowledge was GR built?**
  - Was it a revolutionary paradigm shift accomplished by a lonely genius?

Einsteins short CV



1879 born in Ulm
1880 - 1894 Munich period
1896 - 1900 studies physics at ETH Zurich
1904 - 1909 patent officer in Bern
1905 - annus mirabilis / PhD
1908 - Habilitation Univ. Bern
1909 - Assoc. Prof. Univ. Zurich
1911 - 1912 Ord. Prof. German Univ. Prague
1912 - 1914 Ord. Prof. ETH Zurich
1914 - 1933 Berlin
1915 - Final paper on General Relativity
1921 - Nobel Prize (photo effect)
1933 - 1955 Princeton

Important steps in the development of relativity



Jürgen Renn, 06/2015 Perimeter Institute Convergence Meeting, Waterloo

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A challenging problem for a relativistic theory of gravitation encountered in 1907:

A special relativistic theory of gravitation did not seem to do justice to Galileo's principle that all bodies fall with the same acceleration.

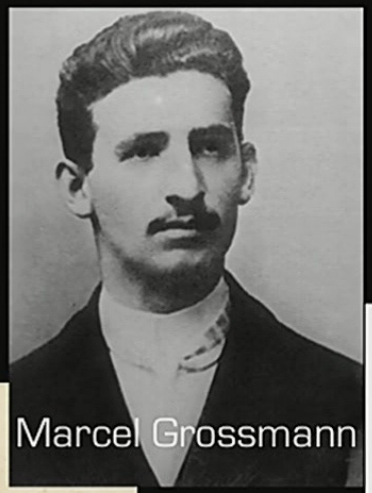
1907: the Equivalence Principle

By simulating gravity in terms of acceleration Einstein tried to preserve Galileo's insight that all bodies fall with the same acceleration:

A generalized principle of relativity?

The social roots of Einstein's original perspective:

Mileva Maric

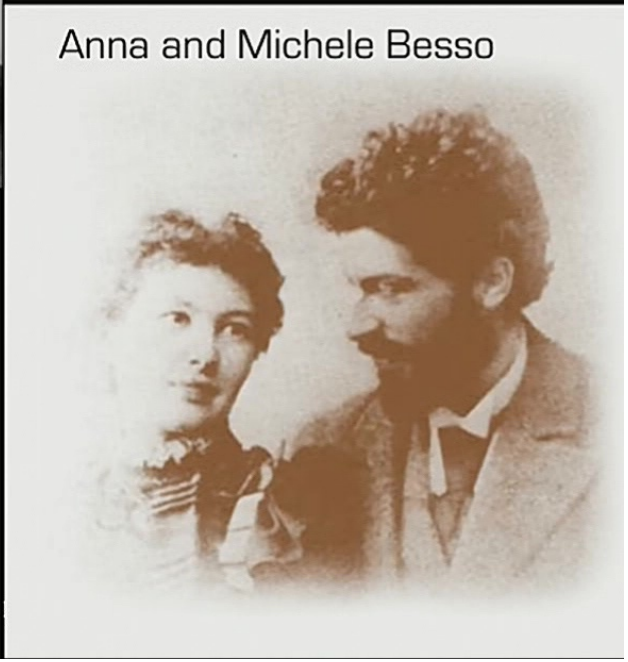


Marcel Grossmann

Akademie Olympia

2015 Perimeter

Anna and Michele Besso



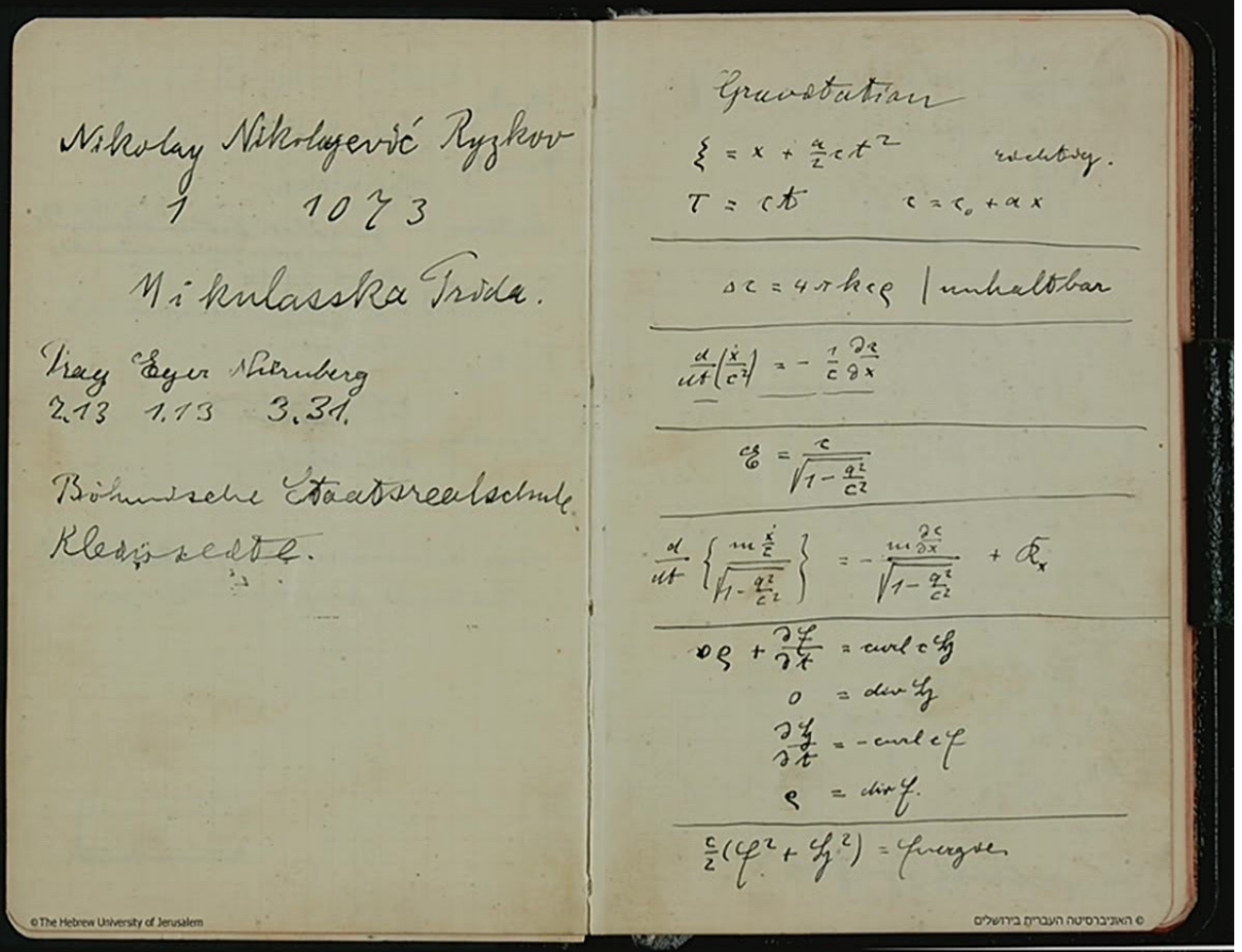
Prague Notebook 1912

Following the example of electromagnetic field theory:

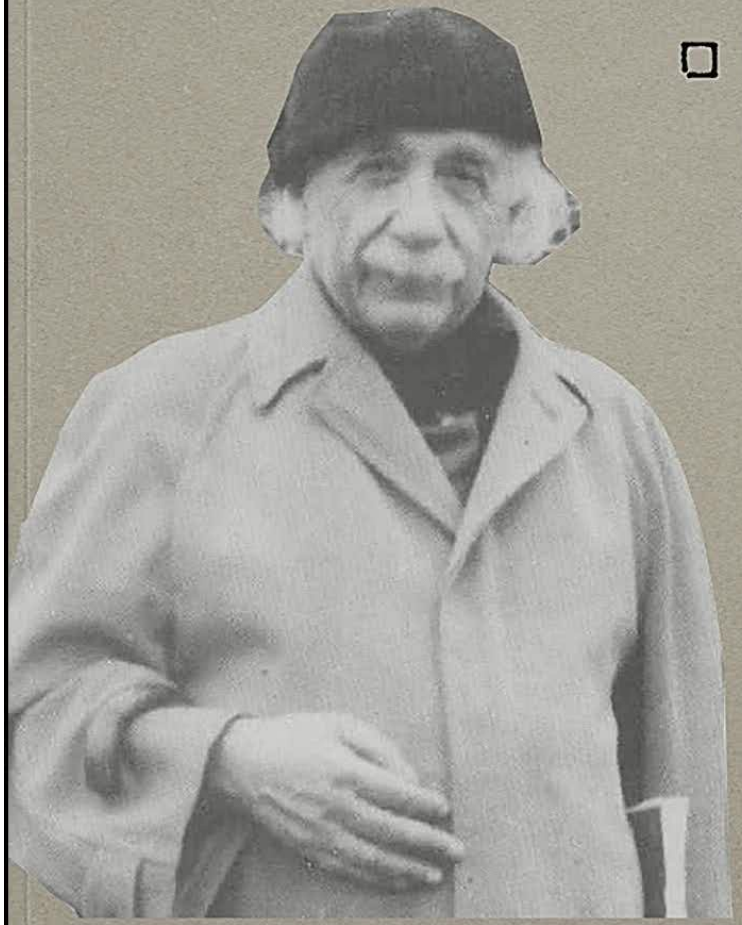
FIELD = - GRAD (POT)

DIV (FIELD) = SOURCE

ACCELERATION = FIELD



The old sage on how he built this arch

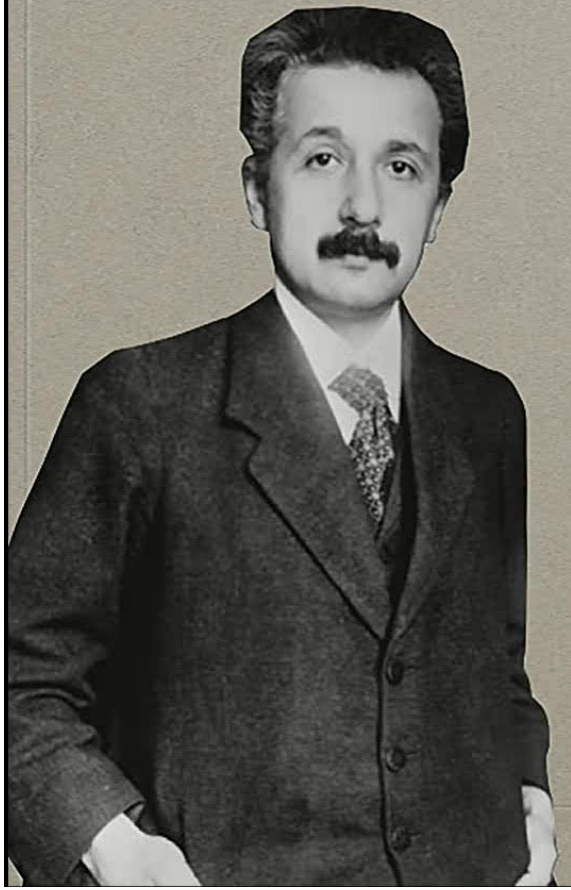


- Einstein's *Autobiographical Notes* ["my own obituary"] (1949):

  "I have learned something else from the theory of gravitation: no collection of empirical facts, no matter how comprehensive, can ever lead to the formulation of such complicated equations … [they] can only be found through the discovery of a logically simple mathematical condition that completely or almost completely determines the equations. Once one has those sufficiently strong formal conditions, one requires only little knowledge of facts to set up a theory."

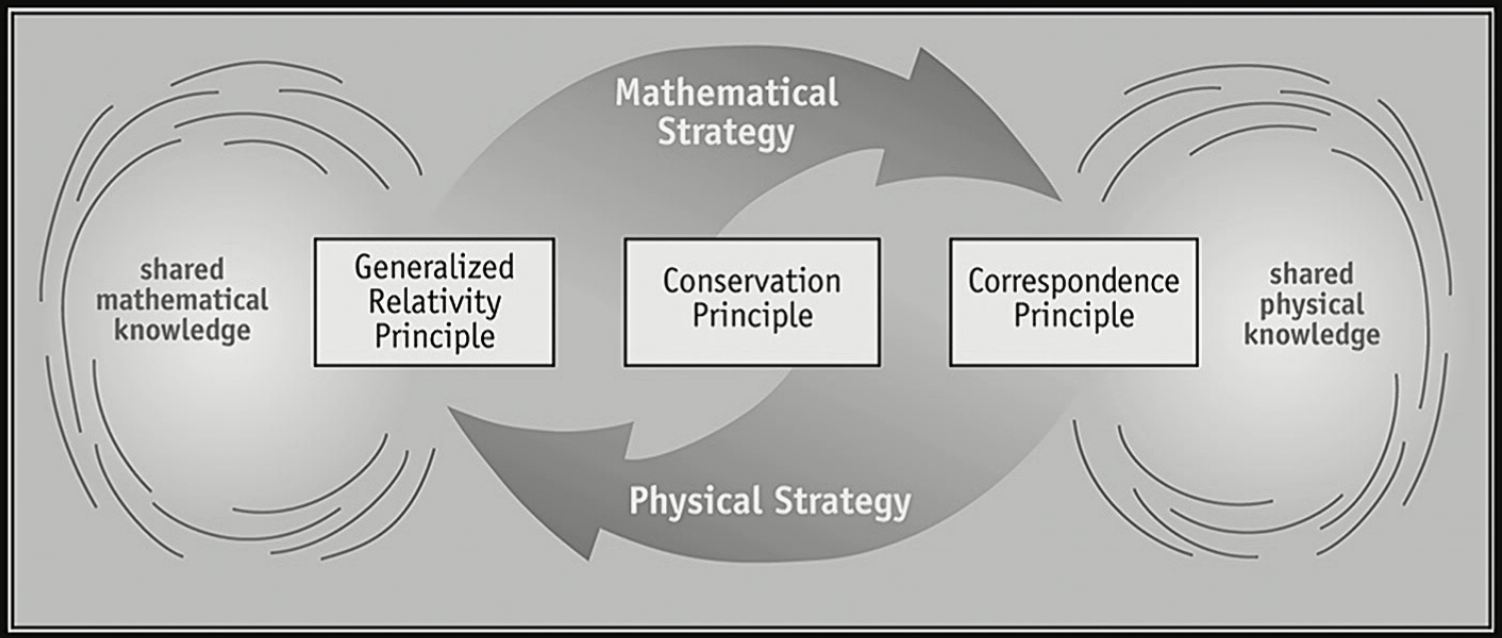
What Einstein said he did in 1949 seems to fit with what he said he did in 1915 ...

- In his first November 1915 communication to the Berlin Academy, Einstein suggested he had found his new field equations by picking the mathematically most natural candidate.



"I completely lost confidence in the field equations [of the *Entwurf* theory] … and looked for a way that would constrain the possibilities in a natural manner. I was thus led back to the demand of a more general covariance of the field equations, which I had abandoned with a heavy heart three years ago when I was collaborating with my friend Grossmann. In fact, back then we already came very close to the solution of the problem given below … Hardly anybody who has truly understood the theory will be able to avoid coming under its spell. It is a real triumph of the method of the general differential calculus developed by Gauss, Riemann, Christoffel, Ricci, and Levi-Civita … After what has been said so far, it is natural to posit field equations of the form $R_{\mu\nu} = -\kappa T_{\mu\nu}$."

Einstein double strategy

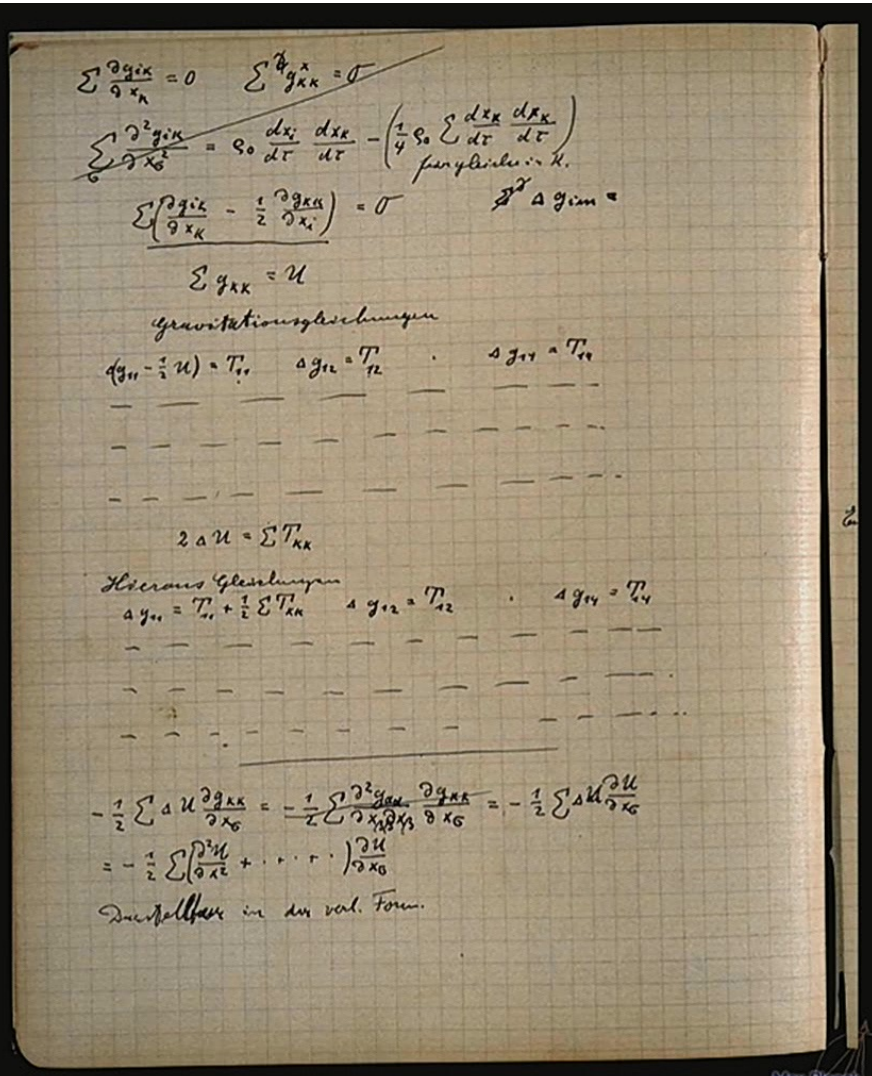


Einstein's double strategy arose from the different roles of the heuristic requirements of generalized relativity, conservation, and correspondence

Hitting on the final solution and not recognizing it!

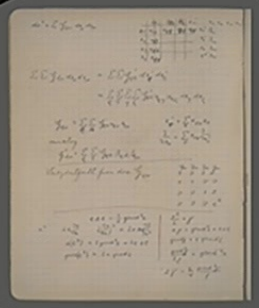
The linearized Einstein equations in the winter of 1912/13.

Einstein abandons the mathematical strategy and turns to the physical strategy.



Zurich Notebook, p. 20L

The tinkering phase



fall 1912

The systematic searching phase

late 1912
to early 1913

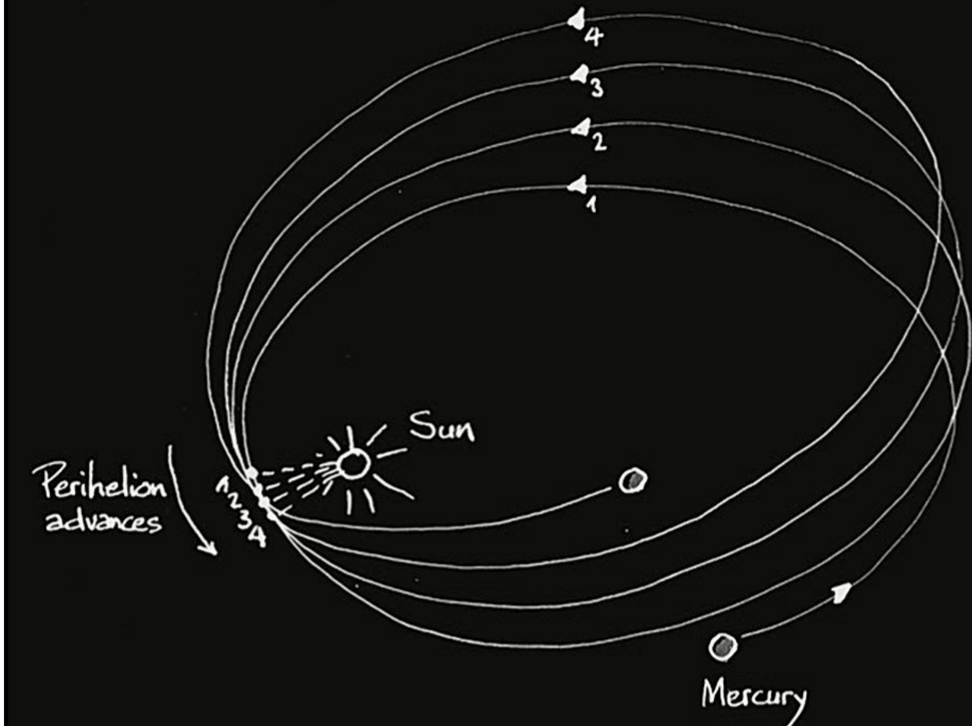
The consolidation phase

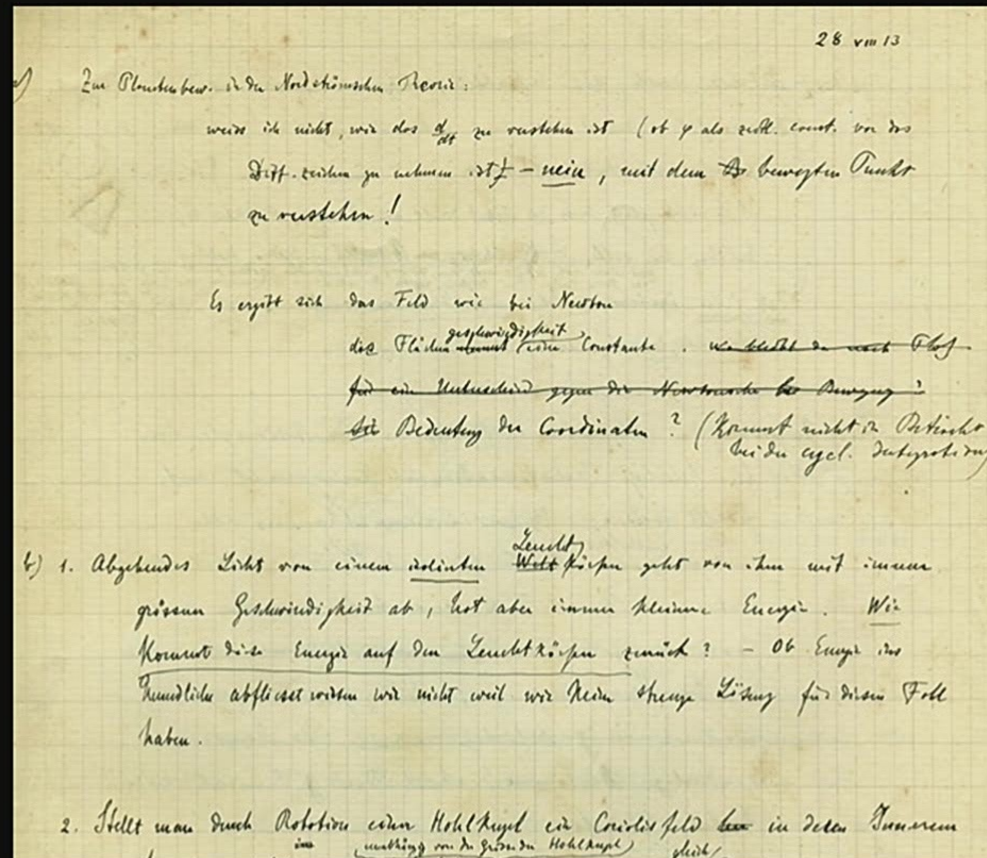
1913
to mid 1915

Advantages and Disadvantages of the Entwurf theory:

- The Entwurf theory contains Newton's equation for the gravitational potential as a limit case and satisfies energy-momentum conservation.

The Besso Memo





28 VIII 13

Zur Perihelbew. in der Nordströmschen Theorie:

weiss ich nicht, wie das $\frac{d}{dt}$ zu verstehen ist (ob φ als zeitl. const. von den Diff.-zeichen zu nehmen ist) – nein, mit dem bewegten Punkt zu verstehen!

Es ergibt sich das Feld wie bei Newton
die Flächengeschwindigkeit eine Constante. ~~[illegible]~~
~~[illegible]~~
Die Bedeutung der Coordinaten? (Kommt nicht in Betracht bei der angel. Integration)

b) 1. Abgehendes Licht von einem isolierten Leuchtkörper geht von ihm mit immer grösserer Geschwindigkeit ab, hat aber immer kleinere Energie. Wie kommt diese Energie auf den Leuchtkörper zurück? – Ob Energie ins Unendliche abfliessen werden wir nicht weil wir keine strenge Lösung für diesen Fall haben.

2. Stellt man durch Rotation einer Hohlkugel ein Coriolisfeld her in deren Innerem [illegible]

Notes by Michele Besso on discussions with Albert Einstein about the 'Entwurf' theory, August 1913

Jürgen Renn, 06/2015 Perimeter Institute Convergence Meeting, Waterloo

Max Planck Institute for the History of Science

Plenary lecture, "On the Present State of the Problem of Gravitation," on September 23, 1913, at the 85th Annual Meeting of the *GDNÄ*, the Society for German Natural Scientists and Physicians, September 21–28, 1913, Vienna.

VORTRÄGE UND DISKUSSIONEN VON DER 85. NATURFORSCHERVERSAMMLUNG ZU WIEN.

Aus der gemeinsamen Sitzung der Abteilungen für Physik, Mathematik und Astronomie:

A. Einstein (Zürich), Zum gegenwärtigen Stande des Gravitationsproblems.

§ 1. Allgemeines zur Problemstellung.

Das Erscheinungsgebiet der Physik, dessen theoretische Durchleuchtung zuerst gelang, war dasjenige der allgemeinen Massenanziehung. Die Gesetze der Schwere und der Bewegungen der Himmelskörper wurden von Newton auf ein einfaches Gesetz der Bewegung des Massen-

serer Kenntnisse von den elektromagnetischen Vorgängen in den letzten Jahrzehnten mit sich gebracht hat.

Vor Maxwell wurden die elektromagnetischen Vorgänge nämlich auf Elementargesetze zurückgeführt, die möglichst genau nach dem Muster des Newtonschen Kraftgesetzes gebaut waren. Nach diesen Gesetzen sollten elektrische Massen, magnetische Massen, Stromelemente usw. Fernwirkungen aufeinander ausüben, die zu ihrer Fortpflanzung durch den Raum keine Zeit brauchen. Da zeigte H. Hertz vor 25 Jahren

Newspaper reports on Einstein's Vienna lecture

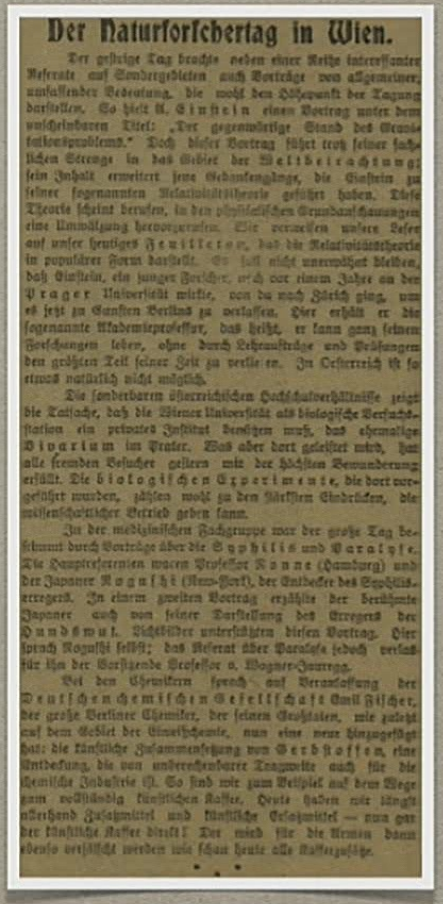
Morgenblatt.

Arbeiter-Zeitung

Zentralorgan der Deutschen Sozialdemokratie in Oesterreich.

Erscheint täglich um 6 Uhr morgens, Montag um 2 Uhr nachmittags.

Nr. 262. Wien, Mittwoch, 24. September 1913. XXV. Jahrgang.



Der Naturforschertag in Wien.

- "just a year ago, Einstein was working at the University of Prague, from there he moved to Zurich, and now he's leaving for Berlin. There he received a so-called Academy Professorship. This means that he can devote himself completely to his research, without losing most of his time to teaching and exams. In Austria, something like this, of course, is impossible."

Review article on the *Entwurf* theory (*Formale Grundlage*, October 1914)

- From "Outline [*Entwurf*] of a generalized relativity theory" to "Formal Foundation [*Formale Grundlage*] of the general relativity theory."

The creation of General Relativity was a team-effort:

Grossmann, Besso, Bernais, Fokker, Abraham, Nordström, Hilbert

"The fraternity of physicists behaves rather passively with respect to my gravitation paper. [...] Laue is not open to the fundamental considerations, and neither is Planck, while Sommerfeld is more likely to be so. A free, unprejudiced look is not at all characteristic of the (adult) Germans (blinders!)."

Einstein to Michele Besso, January 1914

Building metric field theory in analogy with electromagnetic field theory

- Relation between gravitational field $\Gamma^{\alpha}_{\mu\nu}$ and gravitational potential $g_{\mu\nu}$:
  - 1913 $\Gamma^{\alpha}_{\mu\nu} \equiv -\frac{1}{2} g^{\alpha\rho} g_{\rho\nu,\mu}$ (gradient of the metric)
  - 1915 $\Gamma^{\alpha}_{\mu\nu} \equiv -\left\{ {\alpha \atop \mu\nu} \right\} \equiv -\frac{1}{2} g^{\alpha\rho} \left(g_{\rho\nu,\mu} + g_{\rho\mu,\nu} - g_{\mu\nu,\rho} \right)$ (Christoffel symbols)

Reread the introduction of the first November 1915 paper

- "I completely lost confidence in the [*Entwurf*] field equations … I was thus led back to the demand of a more general covariance … Hardly anybody who has truly understood the theory will be able to avoid coming under its spell. It is a real triumph of the method of the general differential calculus developed by Gauss, Riemann, Christoffel, Ricci, and Levi-Civita … After what has been said so far, it is natural to posit field equations of the form $R_{\mu\nu} = -\kappa T_{\mu\nu}$."

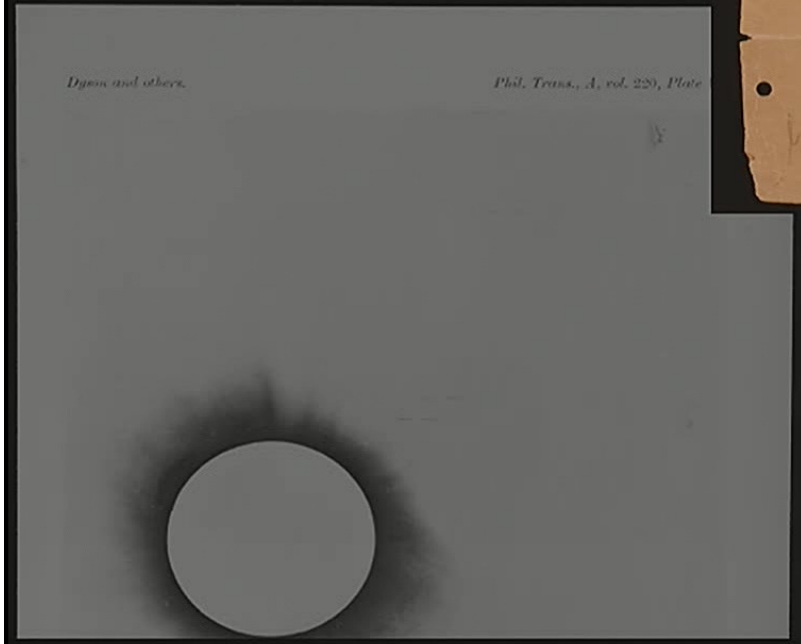
General Relativity as a transformation of classical physics

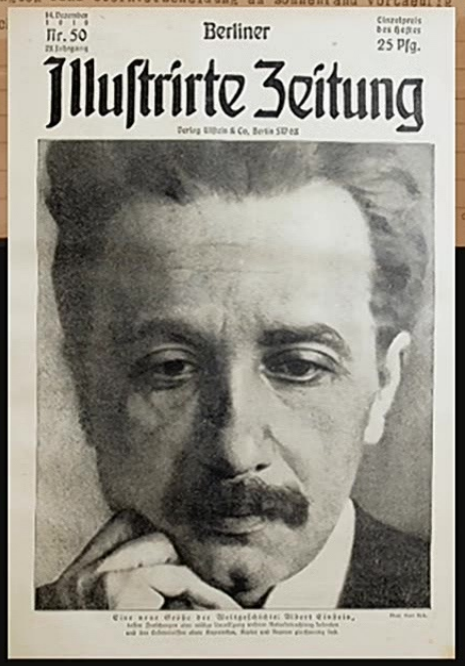
- **The Entwurf theory as a scaffold of General Relativity:**
  - It offered a formalism bringing together his conceptual insights;

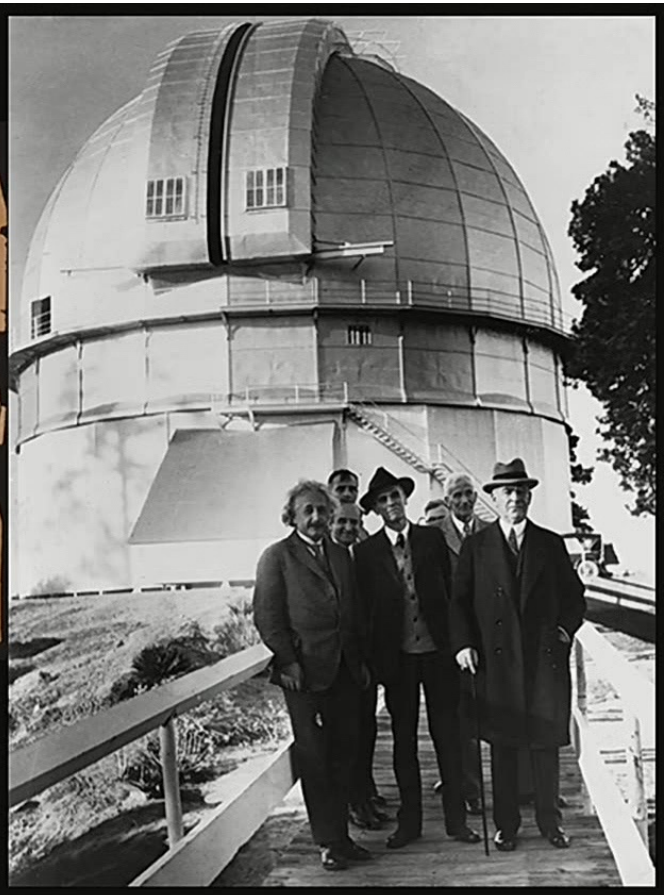
General Relativity as a transformation of classical physics

- **The Entwurf theory as a scaffold of General Relativity:**
  - It offered a formalism bringing together his conceptual insights;
  - He could adjust his conceptual insights to consequences of the formalism.
- **Which were the non anticipated conceptual insights?**
  - The Newtonian limit is attained differently from what Einstein expected.

Happy End?







Einstein with the director of the Mount Wilson Observatory (Walter S. Adams, in the middle), 1931

The Fragmentation of General Relativity (1920s-1940s)

John Lighton Synge:

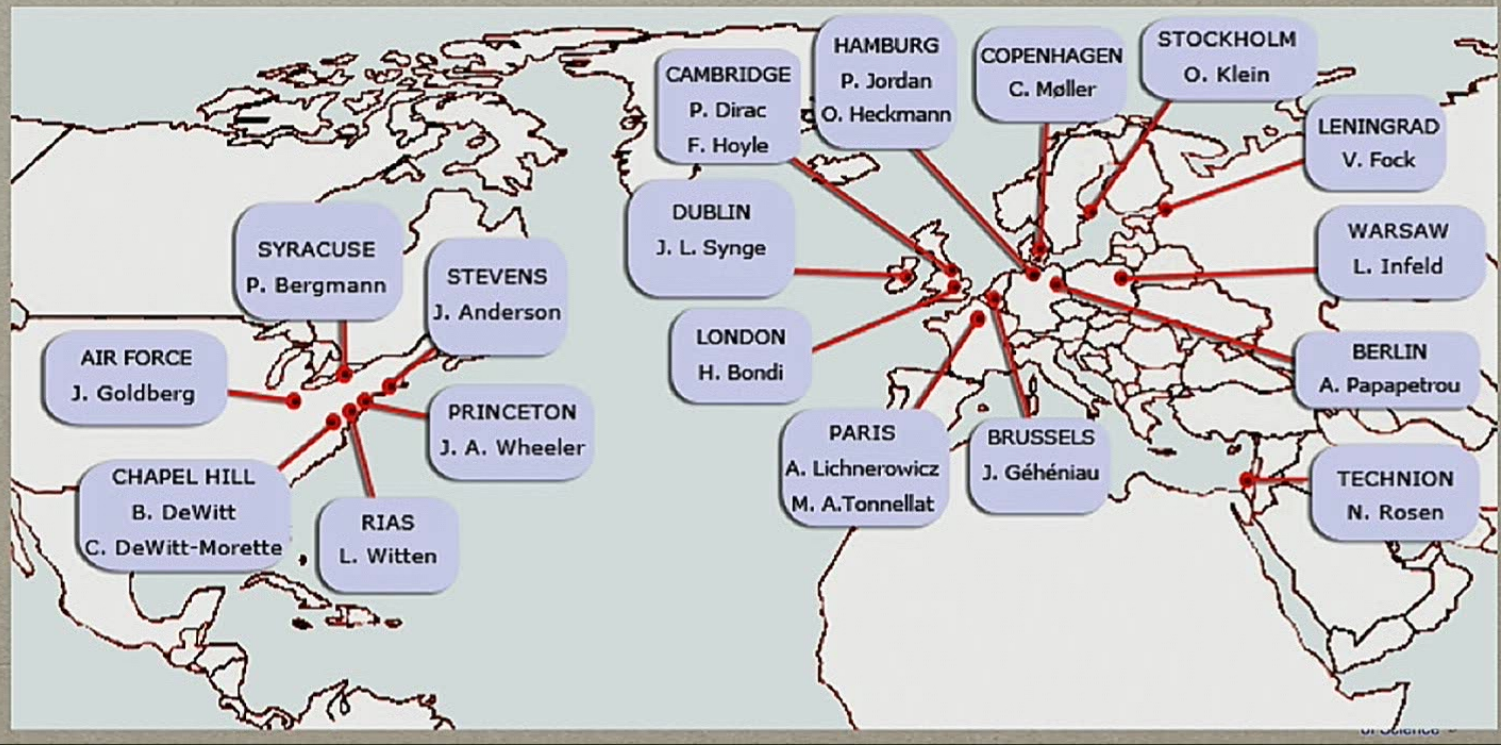
"...in those fifty years the progress that has been made is less than one might expect... Another reason is perhaps to be found in the scientific unrest of the twentieth century. Old theories have been broken up, and the infection of this destructive zeal has incited many to try to modify the new theories. Einstein himself devoted many years to the modification of his 1916 theory..."

(Les Houches, 1963)

Synge in Jablona 1962

The Growth of Physics after the War

- Population growth in number of PhDs in physics
- Postdoc cascade
- The establishment of research centers focused on themes related to GR (around 1955)
  - unified field theory
  - quantum theory
  - cosmology



A recent Nobel Prize Winner hopes for charity

Wolfgang Pauli to Pascual Jordan, 1955:

"In Spring 1955, we want to hold a congress on relativity theory and cosmology in Berne. Because of the 50th anniversary of Einstein's first work in Berne, there is actually a chance of getting money for this."

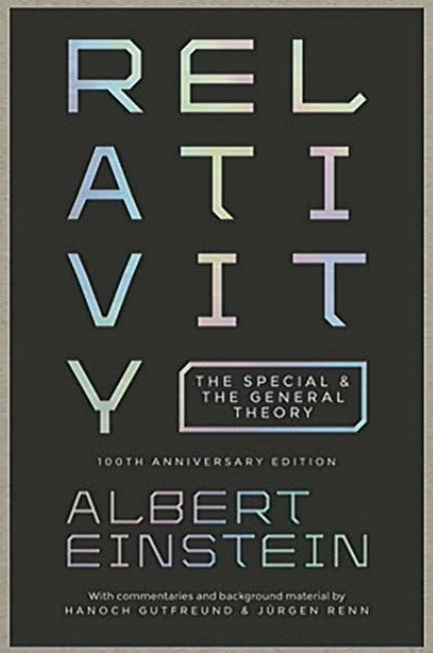
Pascual Jordan (1902–1980)

The new community of relativists

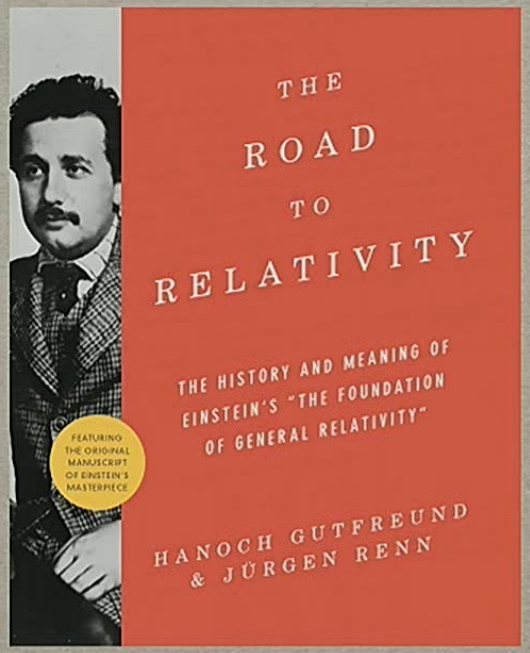
Before the renewal people followed Einstein's example,
after the renewal people followed Einstein's theory.

Thank you for your attention!

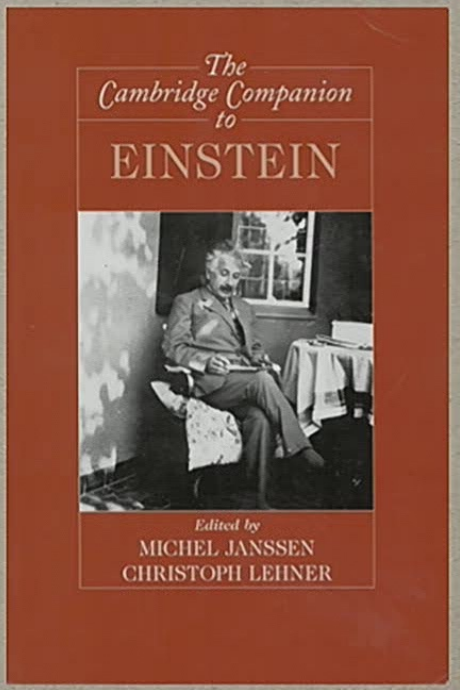
Einstein's Masterpieces



This new edition of Einstein's book features an English translation of the text along with an introduction and a reading companion that examines the evolution of Einstein's thinking and casts his ideas in a broader context.



A richly annotated facsimile edition of "The Foundation of General Relativity" introduces readers to the genesis of Albert Einstein's theory of gravitation.



State-of-the-art overview of Einstein scholarship edited at the Max Planck Institute.