The Birth of Cosmology as a Science

(with some remarks about the de Sitter Universe)

XIIth School of Cosmology

September 15 - 20, 2014 — IESC, Cargèse

Ugo Moschella

Università dell'Insubria – Como

ugomoschella@gmail.com

History of ideas

- A. Einstein, *Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.* Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften, VI. Berlin, *1917.*
- W. de Sitter, *On the relativity of inertia. Remarks concerning Einstein's latest hypothesis*. Proc. Royal Acad. Amsterdam **19**, 1217-25 (1917).
- W. de Sitter, *Further Remarks on the Solutions of the Field-Equations of Einstein's Theory of Gravitation*. Proc. Royal Acad. Amsterdam 20 II, 1309-12 (1918).
- W. de Sitter, *On the curvature of space*. Proc. Royal Acad. Amsterdam , 20 I, 229-243 (1918)
- A. Friedmann *Über die Krümmung des Raumes*. Zeitschrift für Physik 10 (1): 377–386. (1922)
- A. Friedmann, *Über die Möglichkeit einer Welt mit konstanter negativer Krümmung des Raumes*. Zeitschrift für Physik 21 (1): 326–332. (1924)
- Abbé G. Lemaître, *Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques*. Annales de la Societe Scientifique de Bruxelles, A47, p. 49-59 (1927) (and its english translation)

References

- Remi Brague

La Sagesse du monde, Histoire de l'experience humaine de l'univers.
Fayard (1999).

- Christian Smeenk

Einstein's Role in the Creation of Relativistic Cosmology.
In: *The Cambridge Companion to Einstein*. M. Janssen and C. Lehner (Eds.) Cambridge University Press (2004)

- Michel Janssen

The Einstein-De Sitter Debate and Its Aftermath.
Ibidem

First premise

THE NAME IS THE THING

A missing wor(l)d

- The first condition for a *cosmology*, i.e. a reflexive relationship with the « world », is that the idea of « world » has become a theme.
- The sign of such a thematization is the existence of a word to designate the « world ». The presence of a word does not mean the presence of concept but its absence means at that least that the concept has not become a theme.
- History conventionally begins with the invention of writing, around 3200 B.C. A (series of) word(s) capable of designating all of reality in a unified way appeared only around the year 500 B.C.
- Humanity was able to do without the idea of « world » for half of its history (not to mention the immensity of prehistory).

A missing wor(l)d II

- A word for « world » requires that the idea it expresses has reached human consciousness.
- And this implies a synthesis between the first two categories of quantity: plurality and unity.
- It is necessary that the parts that make the whole are dealt with exhaustively without anything being excluded and that such totality be considered unified.

The fluvial civilizations

- The great river valley civilizations had a name for the earth, not of course as a planet, but as *oikumené*, a common dwelling place for men and animals as opposed to the inaccessible dwelling place of the gods.

- But these civilizations did not have a word to designate the world in its entirety, uniting the two components.

The whole as a list

- In the case where it was necessary to consider the totality as a whole the first solution was listing the components it contained (the list could be more or less exhaustive)
- Or else applying alternating opposition following horizontal and vertical axes (terra firma/sea, sky/underground…)
- In the long run the parts of the world were brought into a basic binary opposition.
- Thus when the Bible names the result of the creative work it names «the heaven and the earth».
- This formula is very old and is perhaps the first used to designate the world. It appears in Egyptian texts of the XXth century BCE

An adjective is not a world

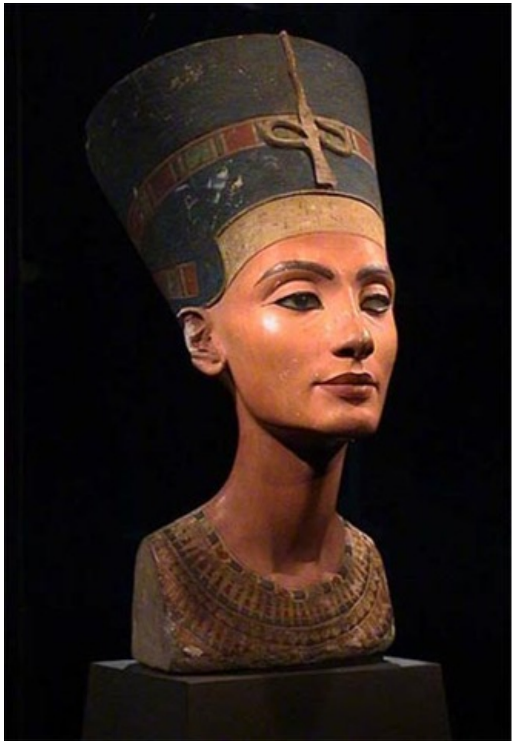
- The fluvial civilizations use also words to designate the idea of totality: *tm, tamm, tamam, panta*
- Egyptian cosmogony : self-genesis of the god Atum. What he creates is everything: *tm*
- This totality, listed or substantivized into an adjective, is not yet a world.
- What it lacks to be one is, paradoxically, that there is too many.
- The world is constituted as a totality because it unfolds before a subject, before which reality is firmly established, as if independent of it. It is necessary, for the world to appear, that the organic unity that linked it to one of its inhabitants, the man, be broken.

Anti-anthropic principle

- What prevented the rise of the idea of world is not the incomplete nature of the list. The ancient civilizations extended that order too widely, encompassing the action of the gods or men.
- The very division of all of reality into heaven and earth prepares the emergence of the concept of world, at the same time prevents it from coming fully into being.
- The implicit criterion behind is human: earth and heaven are contrasted as things that man can, at least in principle, grasp and that which completely escapes him.
- The world cannot appear as such until that criterion is placed in parentheses.
- This was only to be the case in Greece. It was there, and there alone, that that distanced position would appear,that Archimedes point from which man would be able, conscious of being a subject, submit nature to objective research.
- **So that the idea of a physical universe which is specified only by factors that relate to nature is in no way primitive.**

The proper noun: *κόσμος*

- All: *tm, tamam, panta* → Everything: *ta panta* (Hesiod, Heraclitus) →The All: *to pan* (Empedocles)
- The Greeks gave the world a name in its own: *kosmos* (order), *kata kosmon* (in good order).
- Original sense: “woman’s ornament“



The proper noun: κόσμος

- The Original sense of “woman’s ornament“ is metaphorically turned into order and beauty. More precisely, the beauty resulting from order (cosmetics). The usage was for a long time perceived as a metaphor.
- The cosmological meaning of the Latin word *mundus* (italian: *monile* - necklace) comes by imitation of the Greek (*What the Greek call kosmos we call mundus due to its perfect and faultless elegance* – Pliny the Elder)
- Universe – Ad unum vertere. *Acre fluit frigus , non primam quamque solemus Particulam venti sentire, et frigoris ejus, Sed magis* ***unvorsum*** *: fierique perinde videmus, Corpore tum plagas in nostro, tamquam aliquae res.* Lucrezio De rerum natura

Emergency of the idea of cosmos: Heraclitus decision.

- *«Pythagoras was the first to call kosmos the encompassing of all things, because of the order that reigns in it»* Aetius, Placita (1st century A.C.).
- Heraclitus -Fragment 30: *Kosmon ton auton hapanton oute tis theonoute anthropon epoiesen, all'en aei kai estin kai estai.* (This world, the same for all, it is neither a god nor a man who has made it, but always was, it is, it will be.)
- Kosmos = idea of a self-sustaining ordered totality, not requiring the intervention of any external influence (i.e. *Kosmos* is already a cosmology)

Is it safe studying physics?

- At the time of Socrates's revolution the word *kosmos* started to be understood in the exclusive sense of a cosmic order.
- Here is a revealing text by Xenophon. He wishes to defend Socrates from the accusation of supreme impiety and that was: having been interested in physics!
- «Socrates did not discuss the nature of all things (*he ton panton phusis*) by examining how what the specialists (*sophistai*) call order (*kosmos*) exists and through which necessity each celestial thing occurs».
- Not only did Socrates abstained from practicing physics, he ridiculed those who participated in the study of physics and he called them fouls.
- Note the identification between <u>the nature of all things</u> and the <u>kosmos</u>
- Here the accent is on our inability to influence something that we can only observe. Before studying nature the the mankind should better consider human things.

The world as a choice

- It was with Plato the word kosmos took definitively the meaning of world. Timaeus: the first description of reality as forming an ordered whole, both good and beautiful.

- *«This world (hode ho kosmos) has thus become a visible living creature, embracing all that are visible and an image of the intelligible, a perceptible god, supreme in greatness and excellence, in beauty and perfection, this Heaven single in its kind and one».* Plato, conclusion of Timaeus.

- *Kosmos* has never designated a simple description of reality but always translated a judgment of value, either positive or negative
- Greek science was not aware only of the kosmos. The use of the term had constructed the *kosmos* as such, as a *kosmos*.

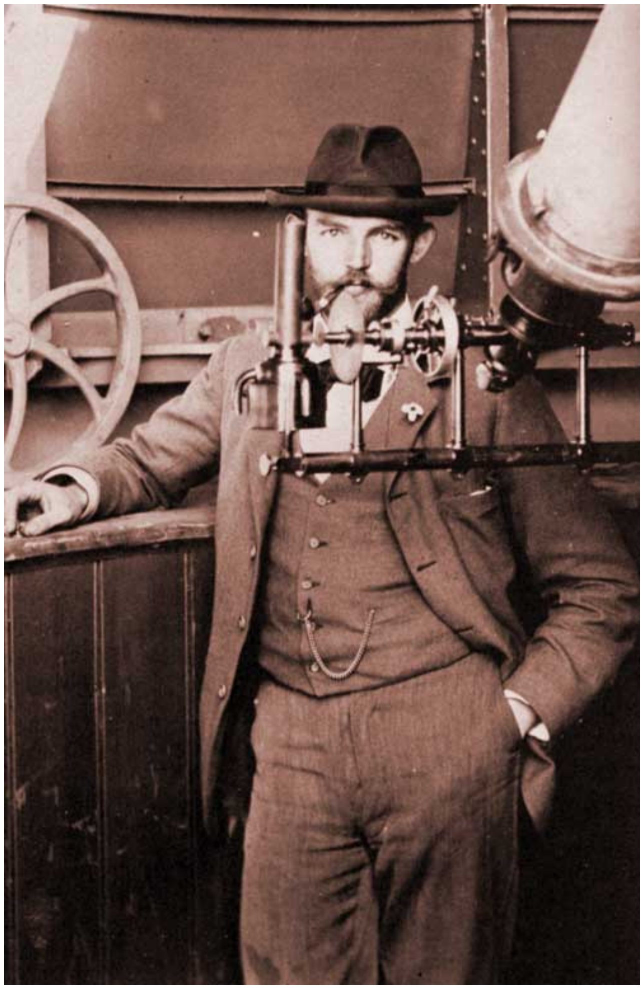
Theoretical Physics vs Astronomy

The task of the contemplation of nature (*theoria phusikè*) is to examine the substance of the sky and the stars, the power and the quality of generation and corruption, and, by Zeus! , it is capable of leading demonstrations on the subject of the size the form and the order of things.

As for astronomy (*astrologia*) it does not undertake to speak of anything like that, but it demonstrates the order (*taxis*) of celestial things, having declared that the sky (*ouranos*) is truly a cosmos; it speakes of forms, sizes, distances from the Terre to the Sun and the Moon, eclipses, conjunctions of stars, on the quality and quantity that are shown in their revolutions.

Posidonios, 2nd Century B.C.

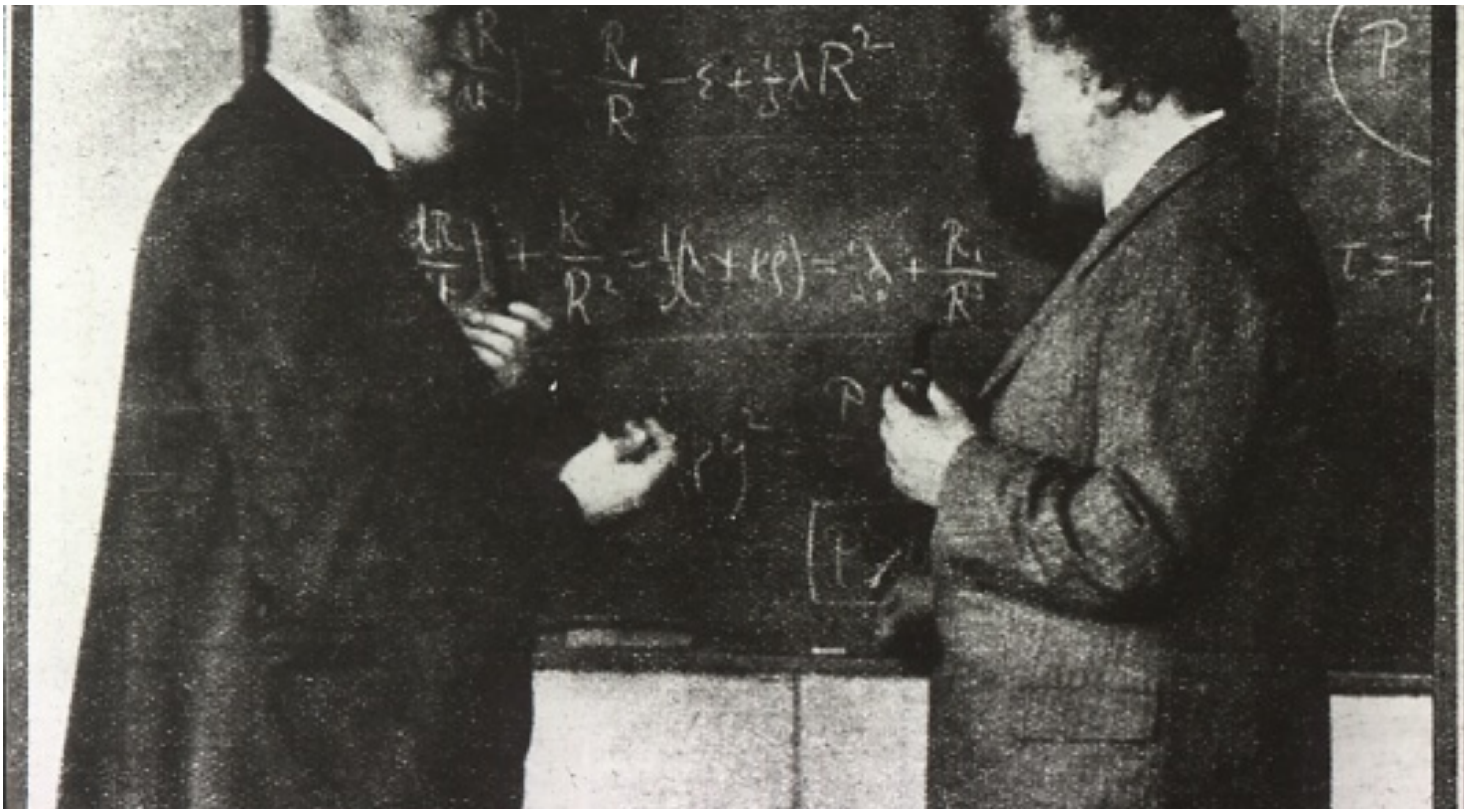
«Makers of Universes (G. B. Shaw) »



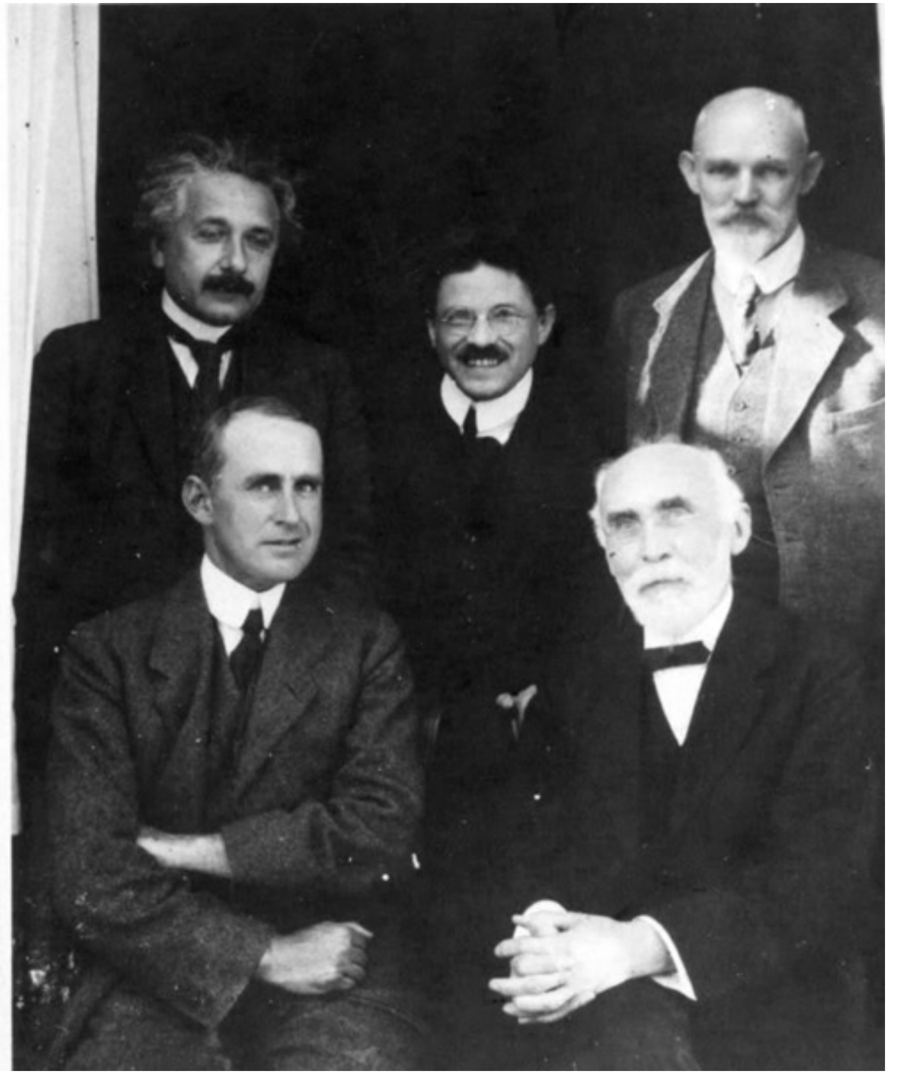
Astronomer

Theoretician

«Makers of Universes»

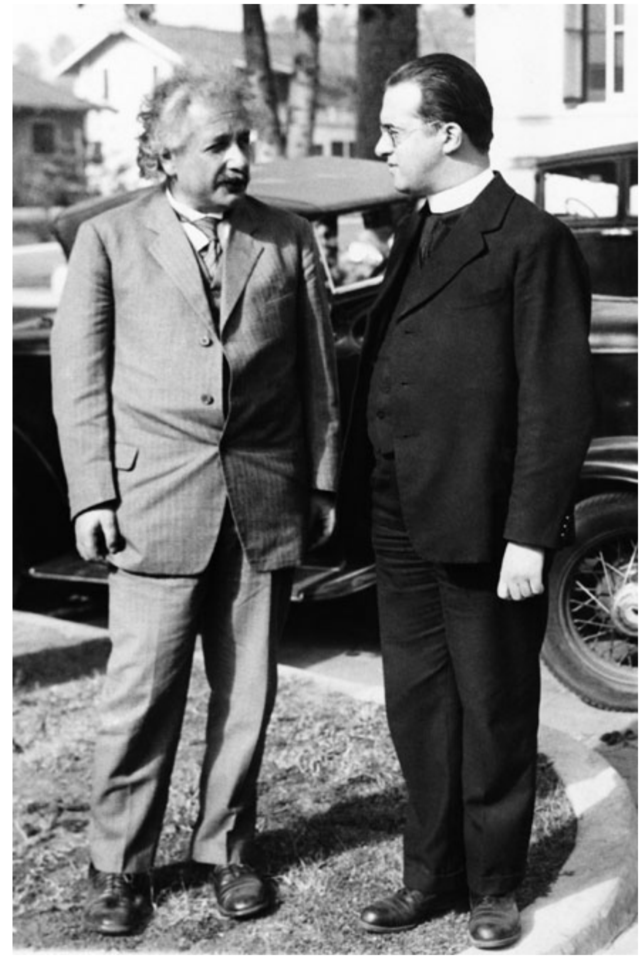


«Makers of Universes»



Leiden, 1923

«Makers of Universes»



Theoreticians

«Makers of Universes»

Astronomers

A valuable article

CHRISTIE'S

EINSTEIN, Albert.
Kosmologische Betrachtungen
zur allgemeinen Relativitätstheorie.
[Offprint from:]
Sitzungsberichte der Königlich
preussischen Akademie der Wissenschaften,
VI. Berlin, 1917.

Lot 52 / Sale 1677 / 14 June 2006
New York, Rockefeller Plaza
Estimate $1,000 - $1,500
Price Realized at the Auction $5,040

Christie's lot Description


SITZUNGSBERICHTE

1917.
VI.

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN.

Sitzung der physikalisch-mathematischen Klasse vom 8. Februar.

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Sonderabdruck.

FIRST EDITION, OFFPRINT ISSUE.

It is in this paper that Einstein introduces an entire field, general relativistic cosmology, and introduces a constant - termed the Cosmological Constant - to describe a universe that is ever expanding.
Einstein will later reject this concept as the worst mistake of his life. Nevertheless, discoveries since the year 2000 suggest that we live in a universe that will always expand, and at an ever-increasing rate.

Leopold Infeld’s Tribute

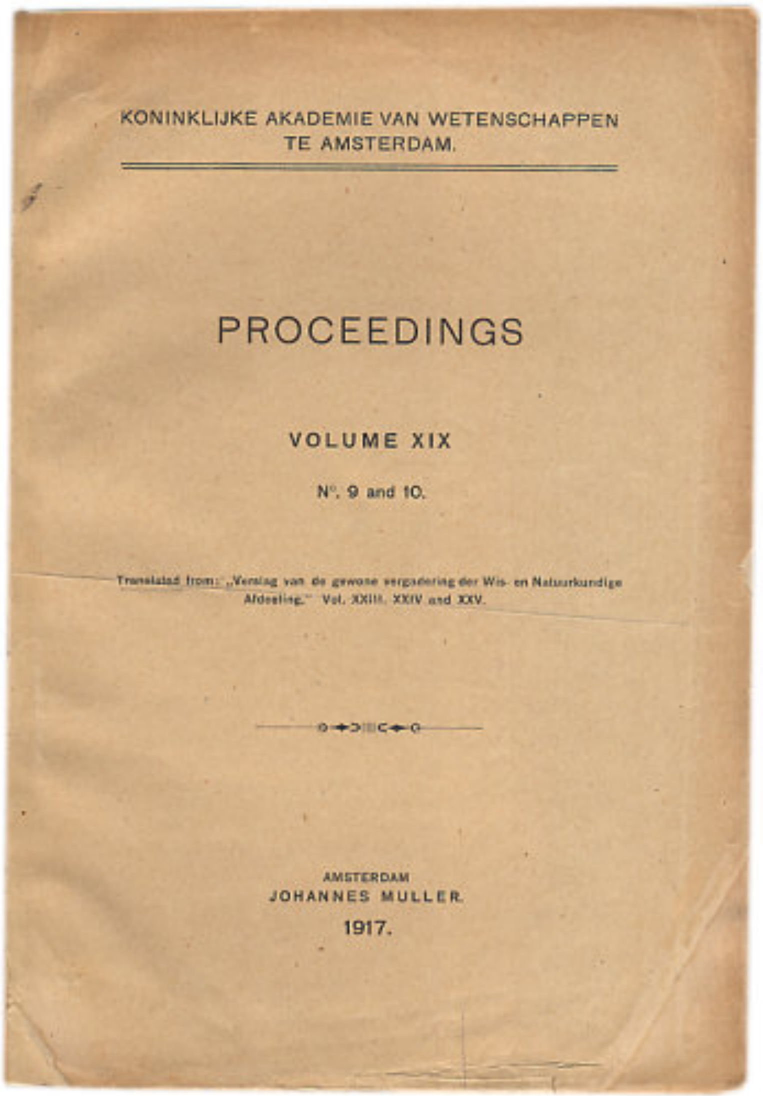
Speculations about the universe in which men live are as old as human thought and as art; as old as the view of shining star on a clear night. Yet it was general relativity which, only thirty years ago, shifted cosmological problems from poetry or speculative philosophy into physics. We can even fix the year in which modern cosmology was born. It was in 1917, when Einstein’s paper appeared in the Prussian Academy of Science under the title «Cosmological Considerations in General Relativity Theory».

Although is difficult to exaggerate the importance of this paper, and although it created a flood of other papers, Einstein's original ideas, as viewed from the perspective of our present day are antiquate if not even wrong. I believe Einstein would be the first to admit this.

Yet the appearence of this paper is of great importance in the story of theoretical physics. Indeed it is one more instance showing how a wrong solution of a fundamental problem may be incomparably more important than a correct solution of a trivial, uninteresting problem.

L. Infeld, in Einstein Philosopher-Scientist (1949)

Another valuable article



The Manahattan Rare Book Company
1050 Second Ave, Gallery 50E
New York, NY 10022

DE SITTER, Willem.

On the relativity of inertia.

Remarks concerning Einstein's latest hypothesis. In Proceedings Koninklijke Akademie Van Wetenschappen Te Amsterdampp, vol 19, no. 9 and 10, pp. 1217-1225.

First editions in English (translated from the German-language issue of the same journal) of two of cosmology's most important papers: Willem de Sitter's solution to Einstein's field equations, later to become known as the "De Sitter universe", providing a mathematical basis for an expanding universe.

Two complete issues. Octavo, original wrappers neatly rebacked.

$4500.

Lot Description

After studying Einstein's landmark 1916 paper on general relativity, De Sitter began a lengthy correspondence with Einstein concerning the solution to Einstein's provocative gravitational field equations.

De Sitter then published the results of his findings and correspondence first in the Dutch journal *Proceedings Koninklijke Akademie Van Wetenschappen Te Amsterdam*.

De Sitter "showed that in addition to the solution given by Einstein himself for the Einstein field equation... a second model was possible with systematic motions--particularly the 'expanding universe'--provided the density of matter could be considered negligible" .

Hubble's dramatic discovery in 1929 of the velocity-distance relationship for galaxies confirmed the De Sitter model.

Einstein had included a controversial "cosmological constant" in his field equations to prevent the seemingly absurd conclusion of an expanding universe; Hubble's discoveries later prompted Einstein to famously declare that the cosmological constant was the greatest error of his life.

Second premise

PHYSICS, METAPHYSICS (AND COSMOLOGY): EINSTEIN'S WAY

Akademie Olympia

Critical thinking

- Nowadays the philosophy of science plays almost no role in the training of physicists or in physics research
- Careful reflection on philosophical ideas is rare. Even rarer is systematical instruction
- Worse still, publically indulging an interest is often treated as a social blunder
- Things were not always so.
- Einstein was typical in his generation of physicists in the seriousness and the extent of his early and lasting engagement with philosophy
- Einstein's philosophical *forma mentis* had to play a fundamental role in his physical thinking and particularly in the invention of cosmology as a science (and ironically also led him to big mistakes)

Source: Albert Einstein as a Philosopher of Science.

D. Howard. Physics Today (2005)

"So many people today—and even professional scientists—seem to me like someone who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is —in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth".

Albert Einstein. Letter to R. Thornton, 1944

“The reciprocal relationship of epistemology and science is of noteworthy kind. They are dependent upon each other. Epistemology without contact with science becomes an empty scheme. Science without epistemology is—insofar as it is thinkable at all— primitive and muddled.”

Albert Einstein 1949.

In Albert Einstein – Philosopher, Scientist

A. Einstein. Obituary for E. Mach, Phys. Zeitschrift, 17, 101–104, 1917

How does it happen that a properly endowed natural scientist comes to concern himself with epistemology? Is there not some more valuable work to be done in his specialty? That's what I hear many of my colleagues ask, and I sense it from many more. But I cannot share this sentiment.

When I think about the ablest students whom I have encountered in my teaching — that is, those who distinguish themselves by their independence of judgment and not just their quick-wittedness — I can affirm that they had a vigorous interest in epistemology. They happily began discussions about the goals and methods of science, and they showed unequivocally, through tenacious defense of their views, that the subject seemed important to them.

Concepts that have proven useful in ordering things easily achieve such authority over us that we forget their earthly origins and accept them as unalterable givens. Thus they might come to be stamped as "necessities of thought," "a priori givens," etc. The path of scientific progress is often made impassable for a long time by such errors. Therefore it is by no means an idle game if we become practiced in analyzing long-held commonplace concepts and showing the circumstances on which their justification and usefulness depend, and how they have grown up, individually, out of the givens of experience. Thus their excessive authority will be broken. They will be removed if they cannot be properly legitimated, corrected if their correlation with given things be far too superfluous, or replaced if a new system can be established that we prefer for whatever reason.

A. Einstein

Meta-principles of relativity

- They are not laws of nature but principles that the laws of physics must satisfy
- The epistemological concern leading to General Relativity is explicitly declared at the opening of the founding article:
- *In classical mechanics and no less in the special theory of relativity there is an inherent epistemological defect which was, perhaps for the first time, clearly elucidated by Ernst Mach….Of course an answer may be satisfactory from the point of view of epistemology and yet unsound physically…*

Mach’s principle

“In a consistent theory of relativity there can be no inertia relatively to ‘space,’ but only an inertia of masses relatively to one another”

A. Einstein, Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie (1917) .

SITZUNGSBERICHTE 1917. VI.
DER
KÖNIGLICH PREUSSISCHEN
AKADEMIE DER WISSENSCHAFTEN.

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Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Sonderabdruck.

Verlag der Königlichen Akademie der Wissenschaften.
In Kommission bei Georg Reimer.

THE ROUGH AND WINDING ROAD TO COSMOLOGY

Einstein's cosmological work was not motivated by the problems of the observational cosmology contemporary to him.

Einstein walks on his *rough and winding road* towards cosmology following the trail that led him to RG. Relativistic cosmology is the final attempt to guarantee the agreement of his new theory of gravitation with Mach's ideas

The crucial question

- *It iswell known that Poisson's Equation*

$$\nabla^2\Phi = 4\pi G\rho$$

  in combination with the equations of motion of a material point is not a perfect substitute for Newton's action at a distance
- *There is still to be taken into account the condition that at spatial infinity for the potential tends towards a fixed limiting value*

The crucial question II

- *There is an analogous state of things in the theory of gravitation in general relativity.Here too we must supplement the differential equations by limiting conditions at spatial infinity if we conceive the universe as being of infinite spatial extent*

- *In my treatment of the planetary problem I choose the following assumption: it is possible to select a system of reference so at spatial infinity all the gravitational potential* $g_{\mu\nu}$ *become constant*

- *But it is by no means evident* a priori *that we may lay down the same limiting conditions when we wish to take larger portion of the physical universe under consideration*

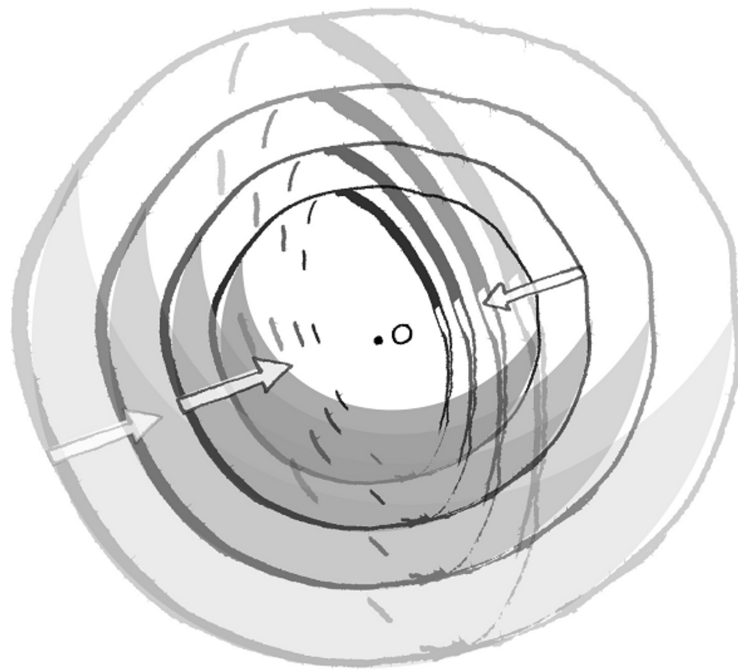
Difficulties of Newton's cosmology

- An embarassing dilemma of Newton's cosmology:
- Gauss law: for a constant mass density the force per unit surface diverges

$$F = -\frac{16\pi^2 G\rho R}{3} \xrightarrow[R\to\infty]{} \infty$$

- Impossible!

Difficulties with Newton's cosmology



Think of a Newtonian universe uniformly filled with matter.
The total force on the point mass O is given by the sum of forces due to each hemispherical shell. Each half-shell contributes a force of equal magnitude, $F = G\pi\rho d$, and the sum does not converge (Courtesy: Smeenk, op. cit.).

Newton's Island Univers

$$\nabla^2\Phi = 4\pi G\rho, \quad \Phi = G\int\frac{\rho(r)}{r}dV$$

$$\rho(r)r^2 \rightarrow 0$$

An island universe would not be stable. The island would evaporate as long as individual stars acquire enough kinetic energy to escape the gravitational attraction of the other stars.

The crucial question

- What to do?
- Modify Poisson's equation (not to be taken to seriously, *Einstein souligne*)

$$\nabla^2\Phi - \lambda\Phi = 4\pi G\rho$$
$$\Phi = -4\pi G\rho/\lambda$$

- *This solution would correspond to the case in which the matter of the fixed stars was distributed uniformly through space, if the density is the actual mean density of matter in the universe…*
- *A universe so constituted would have with respect to its gravitational field, no centre*

Mach’s principle reloaded

The opinion which I entertained until recently as to the condition to be laid at spatial infinity took its stand from the following considerations. In a consistent theory of relativity there can be no inertia relatively to ‘space,’ but only an inertia of masses relatively to one another”. If therefore I have a mass at a sufficient distance from all other masses in the universe, its inertia must fall to zero.

Cosmological principle

- *In the particularly perspicuous case of the possibility of choosing the system of coordinates so that the gravitational field is at every point spatially isotropic we have more simply*
  $$ds^2 = Bdx_0^2 - A(dx_1^2 + dx_2^2 + dx_3^2), \quad g = \sqrt{A^3 B} = 1$$

- $mA/\sqrt{B}$ *plays the role of the inertial mass. It can vanish only if* $A \to 0, \quad B \to \infty$

Einstein and de Sitter debate

- Einstein: the existence of distant masses would provide such degeneracy at infinity and also Minkowskian values at large but finite distances (necessary for explaining planetary motion).
- De Sitter: Einstein's distant masses have to be outside the observable universe. Such explanation is not more satisfactory and is maybe worse than Newton's absolute space.
- *«It proved that for the system of the fixed stars no boundary condition of the kind can come into question at all, as was also emphasized by the astronomer de Sitter recently»*

Three possibilities (a)

We may require as in the problem of the planets that the metric in spatial infinity approximate the values

$$g_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

This is unsatisfactory in more respects than one

a) A definite choice of a SR contrary to spirit of the relativity priciple

b) Inertia would be influenced but not conditioned by matter present in finite space

Three possibilities (b)

We may refrain entirely from laying down boundary condition at infinity claiming general validity. This holds out no hope of solving the problem and amounts to giving it up. This is an incontestable position which is taken at present time by de Sitter. But I must confess that such a complete resignation in this fundamental question is for me a difficult thing. I should not make up my mind to it until every effort to make headway toward a satisfactory view had proved to be vain.

Three possibilities (c)

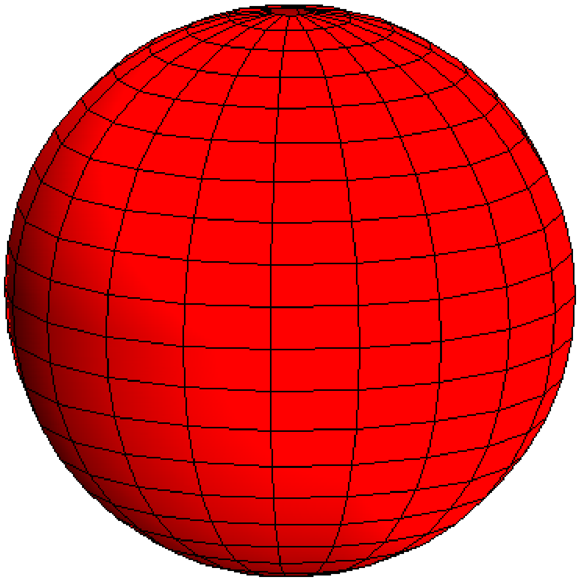
I have completely abandoned my views, rightfully contested by you, on the degeneration of the metric. I am curious to hear what you will have to say about the somewhat crazy idea I am considering now.

Letter to W. De Sitter of February 2, 1917

I have again perpetrated something relating to the theory of gravitation that might endanger me of being committed to a madhouse

Letter to P. Ehrenfest, February 4, 1917

A spherical universe!



$$x_1^2 + x_2^2 + x_3^2 + x_4^2 = R^2$$

$$dl^2 = dx_1^2 + dx_2^2 + dx_3^2 + dx_4^2 \Big|_{\mathbf{S}^3}$$

$$= \sum_{i,j=1}^{3} \left(\delta_{ij} + \frac{x_i x_j}{R^2 - x_1^2 - x_2^2 - x_3^2} \right) \; dx^i dx^j$$

Cosmological Principle

The curvature is defined at every point by the matter at that point and the state of matter. On account of the lack of uniformity the metrical structure must be extremely complicated. But if we are concerned with the structure only on a large scale, we may represent matter as being uniformly distributed over enormous space so that the density varies extremely slowly. Our procedure resemble that of a geodesist who by means of an ellipsoid approximates the shape of the Earth which on small scale is extremely complicated

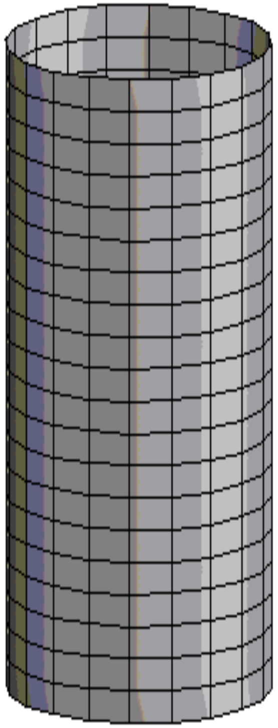
The cosmological constant
(The name is the thing)

$$\nabla^2\Phi - \lambda\Phi = 4\pi G\rho$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu} \qquad (1915-1916)$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \qquad (1917)$$

Einstein's static world



$$\frac{1}{R_0^2} = \Lambda = 4\pi G\rho$$

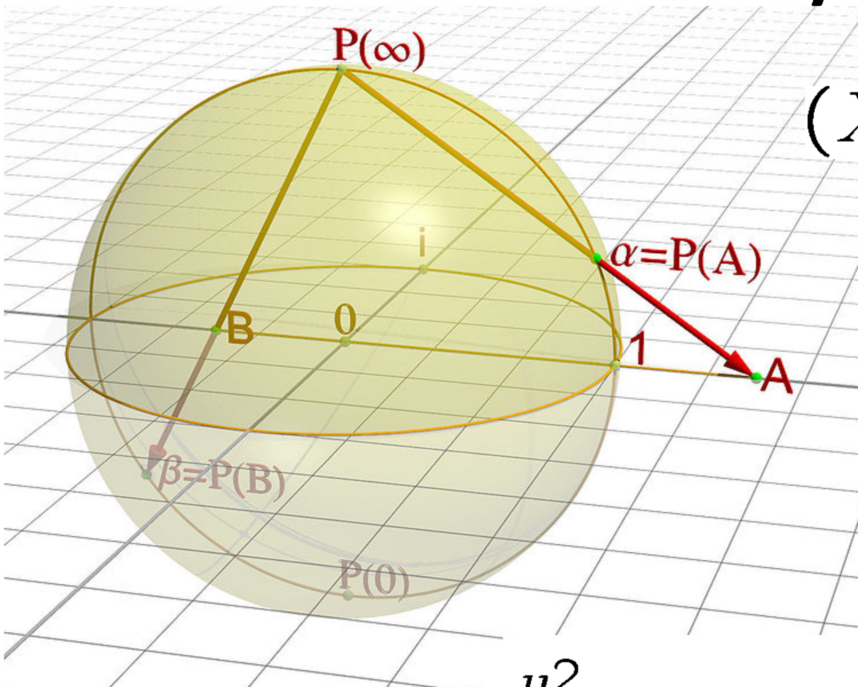
$$M = 2\pi^2 R_0^3 \rho = \frac{\pi R_0}{2G}$$

In order to arrive at this view we had to introduce an extension of the field equation that is not justified by our actual knowledge of gravitation. It is to be emphasized that a positive curvature of space is given by our results even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi static distribution of matter as required by the small velocity of the stars

A spacious castle in the air

- de Sitter admired Einstein conception of the cosmos as a contradiction-free chain of reasoning. However he preferred the original GR without the cosmological constant which is "just philosophically and not physically desirable". Furthermore he criticized the staticity assumption:
- We cannot and must not conclude from the fact that we do not see any large changes on this photograph [our observational snapshot of stellar distributions] that everything will always remain as at that instant when the picture was taken de Sitter to Einstein 1916
- I have erected but a lofty castle in the air... I compare space to a cloth floating (at rest) in the air, a certain part of which we can observe. This part is slightly curved similarly to a small section of a sphere's surface. ... So let us be satisfied and not expect an answer, and rather see each other again as soon as possible in acceptable health in Leyden.
  Einstein to de Sitter, 1916
- How the metric tensor is outside our neighborhood we do not know, and any assumption regarding its values is an extrapolation, whose uncertainty increases with the distance (in space, in time, or in both) from the origin. de Sitter 1917

Still a boundary condition remains!



$$(X_1, X_2, X_3, X_4) \to (x_1, x_2, x_3)$$

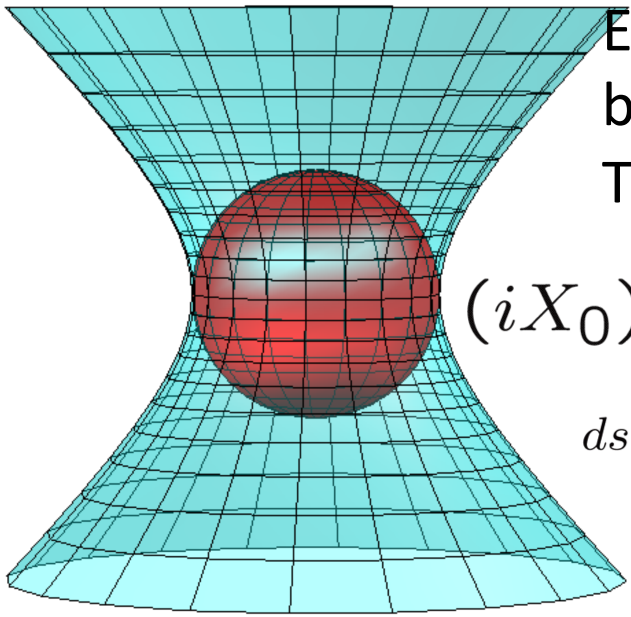
$$X_i = \frac{2x_i}{1 + x_1^2 + x_2^2 + x_3^2}$$

$$X_4 = \frac{-1 + x_1^2 + x_2^2 + x_3^2}{1 + x_1^2 + x_2^2 + x_3^2}$$

$$dl^2 = \frac{4}{(1 + x_1^2 + x_2^2 + x_3^2)^2}(dx_1^2 + dx_2^2 + dx_3^2)$$

$$g_{\mu\nu} \xrightarrow[x_i \to \infty]{} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Ehrenfest-de Sitter's analogy



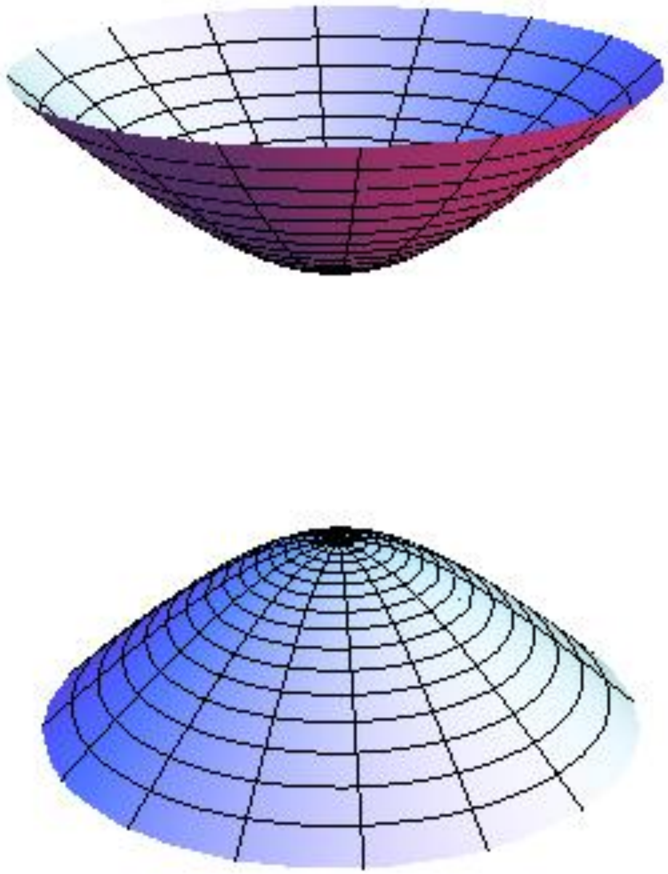
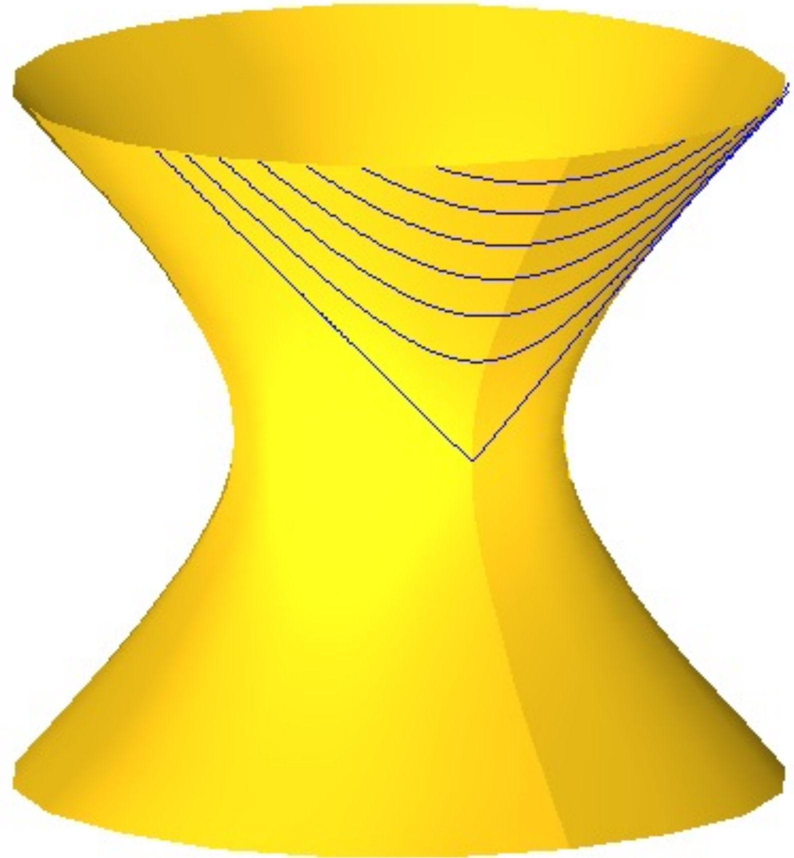
Einstein's static model does not solve the boundary condition problem in an invariant way. There is a sort of 'absolute space' remaining in it.

$$(iX_0)^2 + X_1^2 + X_2^2 + X_3^2 + X_4^2 = R^2 = \frac{3}{\Lambda^2}$$

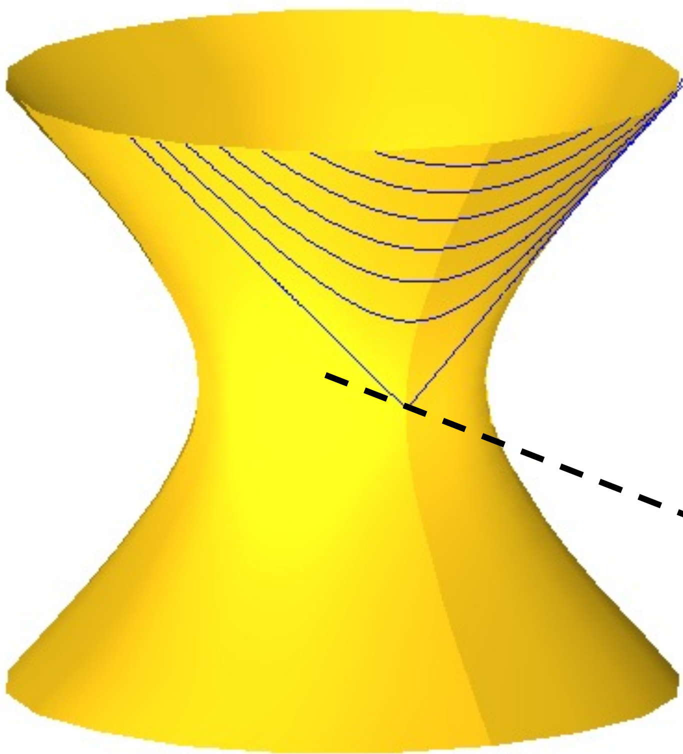
$$ds^2 = \sum_{\mu,\nu=0}^{3} \left(\eta_{\mu\nu} - \frac{X_\mu X_\nu}{R^2 - X_1^2 - X_2^2 - X_3^2 + X_0^2} \right) dX^\mu dX^\nu$$

This discontinuity is however only apparent. The four dimensional world, which we have for the sake of symmetry represented as spherical, is in reality hyperbolical, and consists of two sheets, which are only connected with each other at infinity.

de Sitter 1917

Open FRW model (de Sitter 1917)



$$\begin{cases} X_0 = R \sinh \frac{t}{R} \cosh \chi \\ X_1 = R \sinh \frac{t}{R} \sinh \chi \sin \theta \sin \phi \\ X_2 = R \sinh \frac{t}{R} \sinh \chi \sin \theta \cos \phi \\ X_3 = R \sinh \frac{t}{R} \sinh \chi \cos \theta \\ X_4 = R \cosh \frac{t}{R} \end{cases}$$

$$ds^2 = dX_0^2 - dX_1^2 - \ldots dX_4^2 \Big|_{dS} =$$

$$= dt^2 - R^2 \sinh^2 \frac{t}{R} \left(d\chi^2 + \sinh^2 \chi (d\theta^2 + \sin^2 \theta d\phi^2) \right)$$

A matter of taste

- *Which of the three systems is to be preferred? From the purely physical point of view, for the description of phenomena in our neighborhood, this question has no importance. The question thus really is: how are we to extrapolate outside our neighborhood?*
- *The choice can thus not be decided by physical arguments, but must depend on metaphysical or philosophical considerations, in which of course personal judgment or predilections will have some influence.*
- *To the question: If all matter is supposed not to exist, with the exception of one material point which is to be used as a test-body has then this test-body inertia or not? The school of Mach requires the answer NO. Our experience however very decidedly gives the answer YES.*

Einstein frankly unhappy

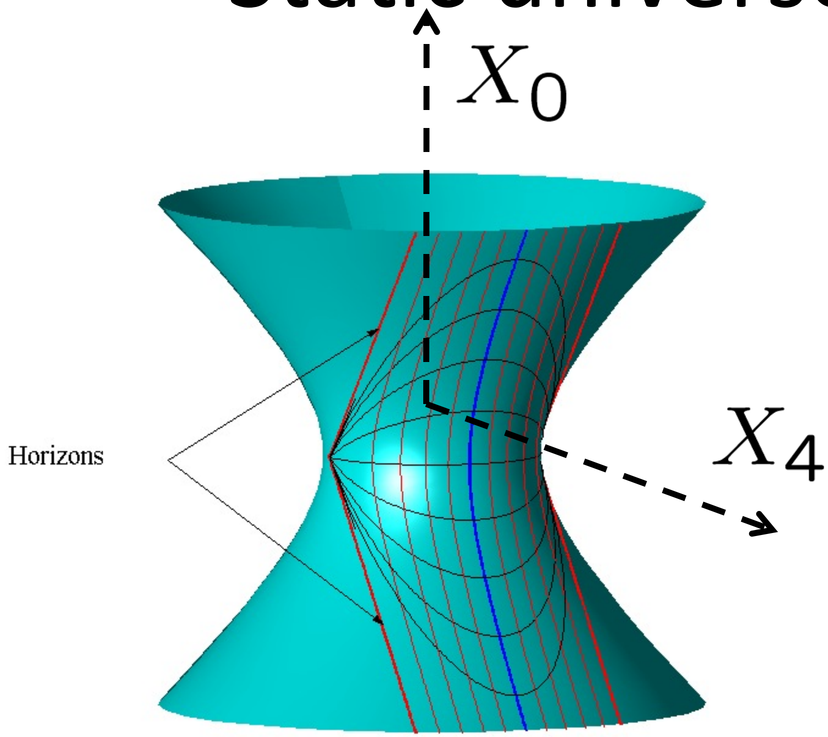
- *It would be unsatisfactory, in my opinion, if a world without matter were possible. Rather, the metric field should be fully determined by matter and not be able to exist without the latter.*

- *This circumstance irritates me.*

- *To admit such possibilities seems senseless.*

Querelle de"rest"

Static universe (de Sitter 1917



$$\begin{cases} X_0 = \sqrt{R^2 - r^2}\,\sinh(t/R) \\ X_1 = r\sin\theta\sin\phi \\ X_2 = r\sin\theta\cos\phi \\ X_3 = r\cos\theta \\ X_4 = \sqrt{R^2 - \vec{r}^2}\,\cosh(t/R) \end{cases}$$

$$ds^2 = dX_0^2 - dX_1^2 - dX_2^2 - dX_3^2 - dX_4^2\Big|_{dS_4} =$$

$$= (1 - \frac{r^2}{R^2})dt^2 - \frac{1}{1-\frac{r^2}{R^2}}dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

Querelle de“rest”

Static universe (de Sitter 1917)

$$ds^2 = (1 - \frac{r^2}{R^2})dt^2 - \frac{1}{1 - \frac{r^2}{R^2}}dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

- Einstein liked the new metric
- But g_{tt} =0 et g_{rr} = infinity on the equator (mass horizon *d’apres* Einstein). Such behaviour seemed inacceptable; maybe there was matter on the equator
- Einstein convinced himself that the singularity of the metric occurred at a finite proper distance from an arbitrarily chosen point of the space-time and that it was not just an artifact of the coordinates used
- The threat that De Sitter’s solution posed to Mach’s principle thus finally seemed to be removed

Then…

- Hermann Weyl pieced together a complete solution out of the static de Sitter solution and the solution for an incompressible fluid. The resulting solution has a zone of matter around the equator and the resulting surface layer of matter has a finite mass
- This result (1919) seemed to vindicate Einstein's hunch that the de Sitter solution describes a universe very much like his own cylindrical universe, the difference being that all mass is concentrated on the equator.
- In his last letter to de Sitter (of April 15, 1918) Einstein had already announced that Weyl had found a proof for this conjecture.

And then..

- On May 19, 1918, Weyl wrote to Einstein that the result of the calculation mentioned above “might meet with your approval.”
- Einstein wrote back on May 31 that he was happy that Weyl had finally resolved the “zone issue,” and added: “Now the result of your calculation is just what one had to expect.”

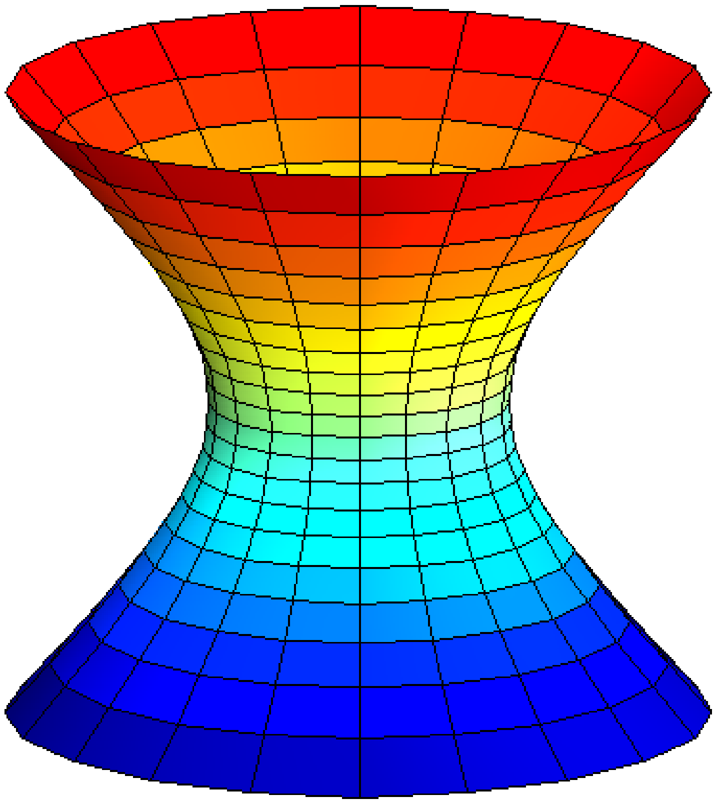
End of the *querelle*: de Sitter world

- In two letters to Einstein (of April 25 and June 16, 1918) Klein solves all the paradoxes by writing the transformation from the pseudo-Cartesian coordinates of the de Sitter hyperboloid in 4+1-dimensional Minkowski space-time to the coordinates used to write the solution in static form.

End of the querelle: de Sitter world

- Klein explicitly points out that the singularity at the equator is an artifact of the static coordinates.

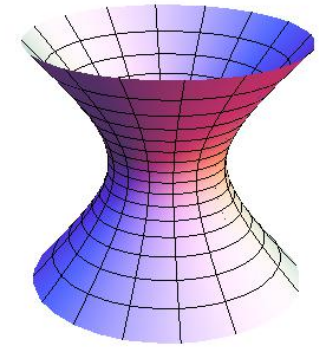
- Einstein's criticisms were all essentially wrong. But in the end he dismssises the de Sitter universe as unphysical because of its non static character



$$X_0^2 - X_1^2 - \dots X_d^2 = -R^2$$

$M^{(d+1)}$: $\eta_{\mu\nu}$ = diag(**1,-1,……,-1**)

First moral to the story



- Einstein admitted that the de Sitter solution is a counterexample to Mach's principle.
- However he rejected as a physically unreasonable model because non-static. A criterion used opportunistically just to rule out De Sitter's anti-Machian solution.
- A weakly motivated simplifying assumption in deriving his own model had turned into a substantive constraint that Einstein did not critically examine for the next decade.
- If Einstein had stuck to his original field equations of November 1915, he would have predicted that the only way in which his theory allows a spatially closed geometry is through a model in which space-time is expanding. Hubble's discovery would then have been another triumph for Einstein.
- Purely on the strength of his epistemological conviction (Mach's principle) he would have made the revolutionary prediction that the universe is expanding.

Interlude

DE SITTER COORDINATES AND GEOMETRY

«Makers of Universes»

Cosmological Equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$ds^2 = dt^2 - a(t)^2\left(\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

In comoving coordinates:

$$T_{\mu\nu} = \begin{bmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{bmatrix}$$

Raychaudhuri Eq.

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G(\rho + 3p)$$

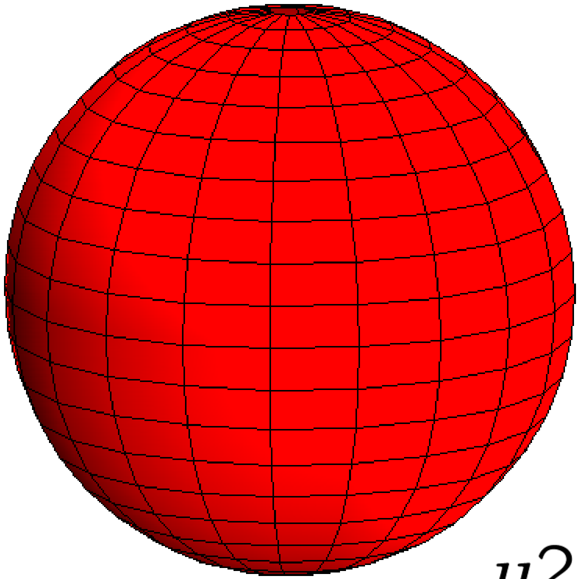
Friedmann Eq.

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8}{3}\pi G\rho - \frac{K}{a^2}$$

Together imply (for each component):

$$\dot{\rho}_i = -3\frac{\dot{a}}{a}(\rho_i + p_i)$$

Spherical Universe



$$x_1^2 + x_2^2 + x_3^2 + x_4^2 = 1$$

$$\begin{cases} x_1 = \sin\chi \sin\theta \sin\phi \\ x_2 = \sin\chi \sin\theta \cos\phi \\ x_3 = \sin\chi \cos\theta \\ x_4 = \cos\chi \end{cases}$$

$$0 < \chi < \pi$$
$$0 < \theta < \pi$$
$$0 < \phi < 2\pi$$

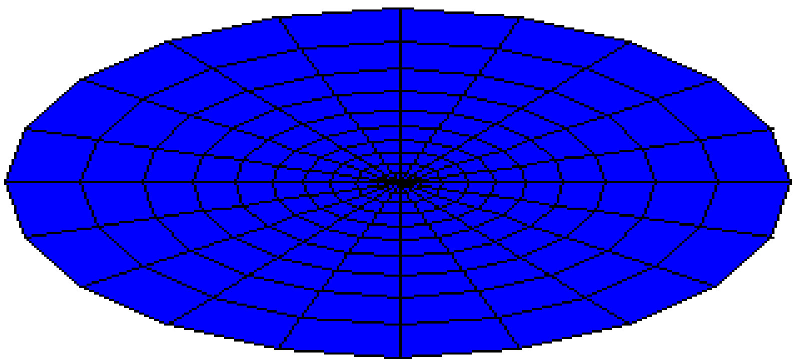
$$dl^2 = dx_1^2 + dx_2^2 + dx_3^2 + dx_4^2\Big|_{\mathbf{S}^3}$$

$$= \frac{1}{K}\left(d\chi^2 + \sin^2\chi(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

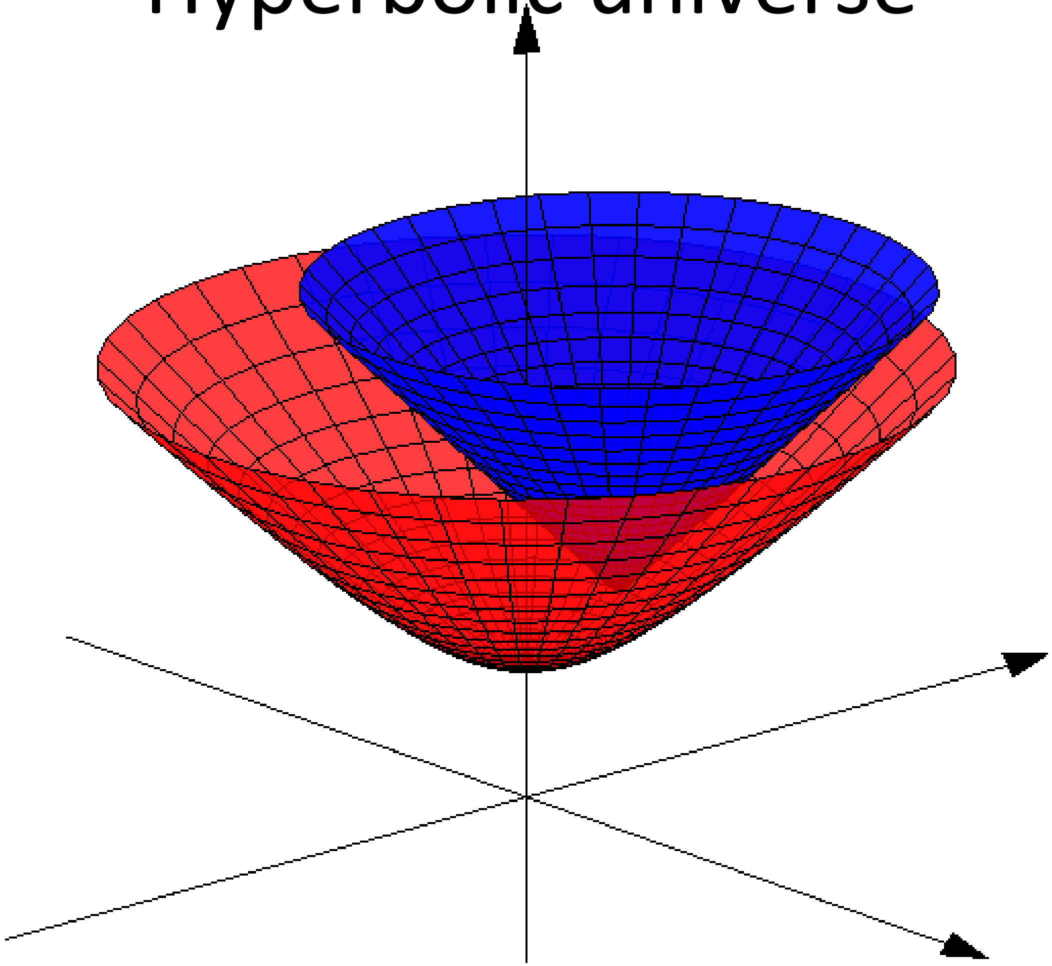
$$= \frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

Flat universe

$$dl^2 = dr^2 + r^2(d\theta^2 + \sin^2\theta \ d\phi^2)$$

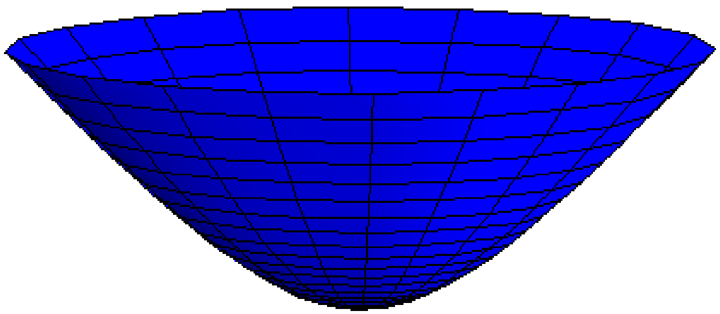


Hyperbolic universe



$$x_0^2 - x_1^2 - x_2^2 - x_3^2 = 1$$

Hyperbolic Universe (negative curvature)

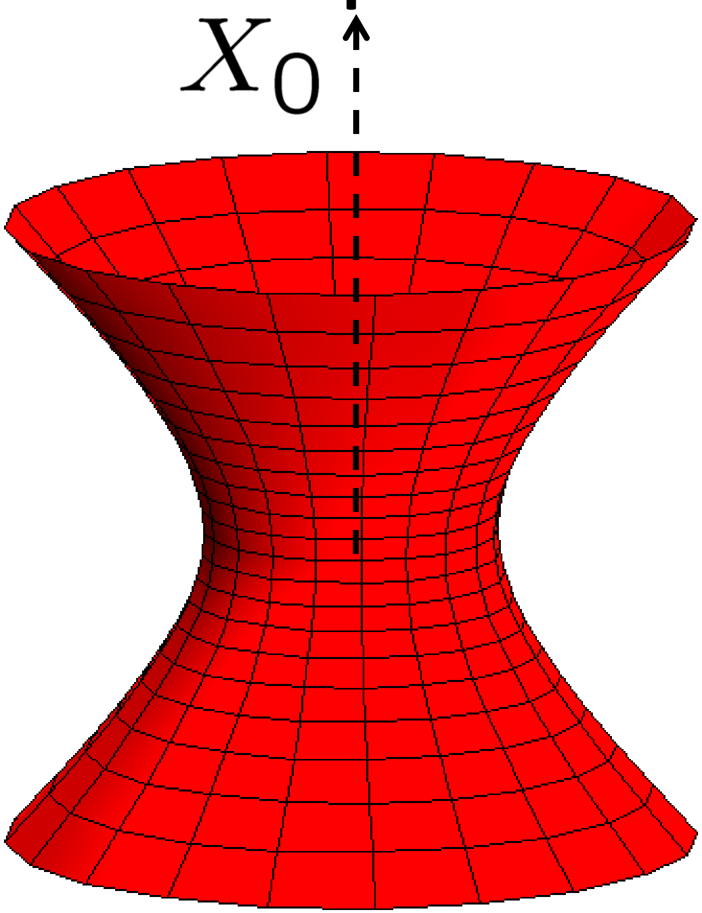


$$x_0^2 - x_1^2 - x_2^2 - x_3^2 = 1$$

$$\begin{cases} x_0 &= \cosh\chi \\ x_1 &= \sinh\chi \sin\theta \sin\phi \\ x_2 &= \sinh\chi \sin\theta \cos\phi \\ x_3 &= \sinh\chi \cos\theta \end{cases}$$

$$\begin{aligned} dl^2 &= dx_0^2 - dx_1^2 - dx_2^2 - dx_3^2 \Big|_{\mathbf{H}^3} \\ &= \frac{1}{|K|}\left(d\chi^2 + \sinh^2\chi(d\theta^2 + \sin^2\theta d\phi^2)\right) \\ &= \frac{dr^2}{1+|K|r^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \end{aligned}$$

Spherical model (Lanczos)



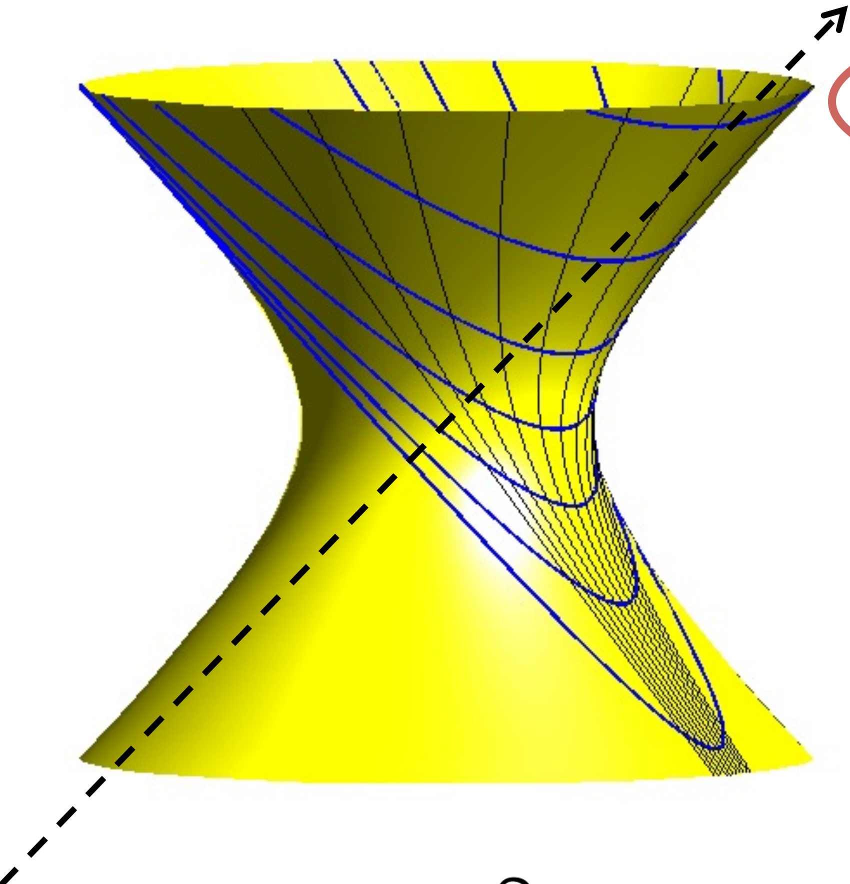
$$\begin{cases} X_0 = R\sinh(t/R) \\ X_1 = R\cosh(t/R)\sin\theta\sin\chi\sin\phi \\ X_2 = R\cosh(t/R)\sin\theta\sin\chi\cos\phi \\ X_3 = R\cosh(t/R)\sin\theta\cos\chi \\ X_4 = R\cosh(t/R)\cos\theta \end{cases}$$

$$R = \sqrt{\frac{3}{\Lambda}}$$

$$ds^2 = dX_0^2 - dX_1^2 - \ldots dX_4^2\Big|_{dS} =$$

$$= dt^2 - R^2\cosh^2\frac{t}{R}\left(d\theta^2 + \sin^2\theta(d\chi^2 + \sin^2\chi d\phi^2)\right)$$

Flat model (Lemaître, 1924)



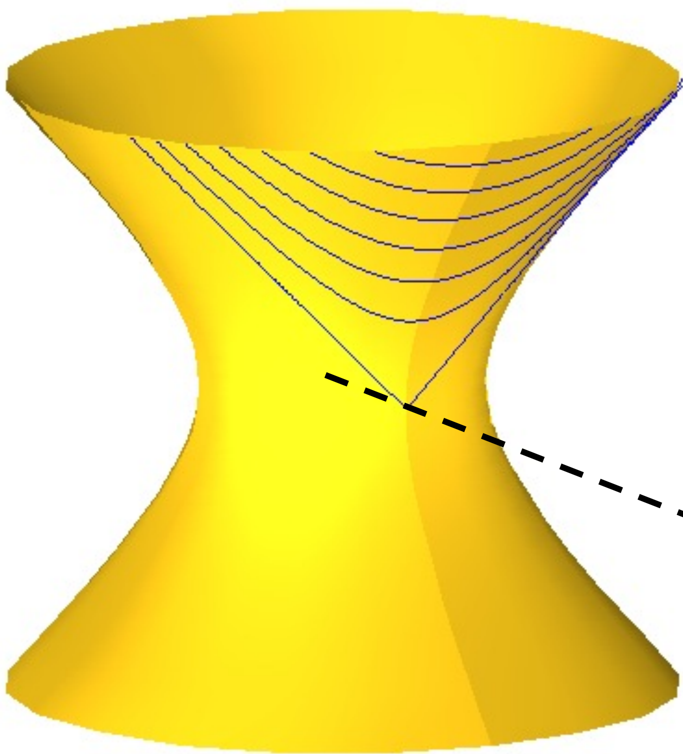
$$X_0 + X_4 = R \exp \frac{t}{R}$$

$$\begin{cases} X_0 &= R \sinh \frac{t}{R} + \frac{1}{2R} e^{\frac{t}{R}} |\vec{x}|^2 \\ X_1 &= \exp\left(\frac{t}{R}\right) x_1 \\ X_2 &= \exp\left(\frac{t}{R}\right) x_2 \\ X_3 &= \exp\left(\frac{t}{R}\right) x_3 \\ X_4 &= R \cosh \frac{t}{R} - \frac{1}{2R} e^{\frac{t}{R}} |\vec{x}|^2 \end{cases}$$

$$ds^2 = dX_0^2 - dX_1^2 - \ldots dX_4^2 \Big|_{dS} =$$

$$= dt^2 - \exp \frac{2t}{R} \left(dx_1^2 + dx_2^2 + dx_3^2 \right)$$

Hyperbolic model (de Sitter 1917)



$$\begin{cases} X_0 &= R \sinh \frac{t}{R} \cosh \chi \\ X_1 &= R \sinh \frac{t}{R} \sinh \chi \sin \theta \sin \phi \\ X_2 &= R \sinh \frac{t}{R} \sinh \chi \sin \theta \cos \phi \\ X_3 &= R \sinh \frac{t}{R} \sinh \chi \cos \theta \\ X_4 &= R \cosh \frac{t}{R} \end{cases}$$

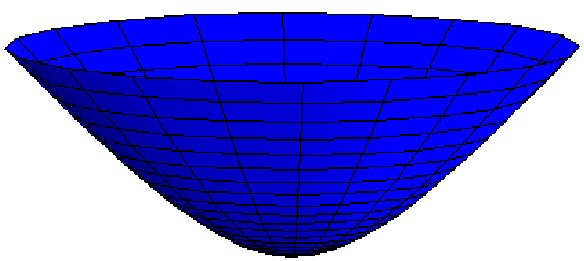
$$ds^2 = dX_0^2 - dX_1^2 - \dots dX_4^2 \Big|_{dS} =$$

$$= dt^2 - R^2 \sinh^2 \frac{t}{R} \left(d\chi^2 + \sinh^2 \chi (d\theta^2 + \sin^2 \theta d\phi^2) \right)$$

Λ=0

$$\ddot{a} = 0 \qquad \dot{a}^2 = -K$$

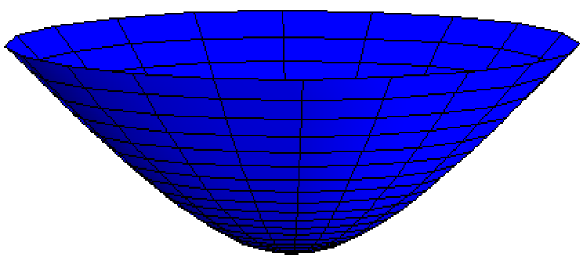
$K = 0$  $a(t) = 1$



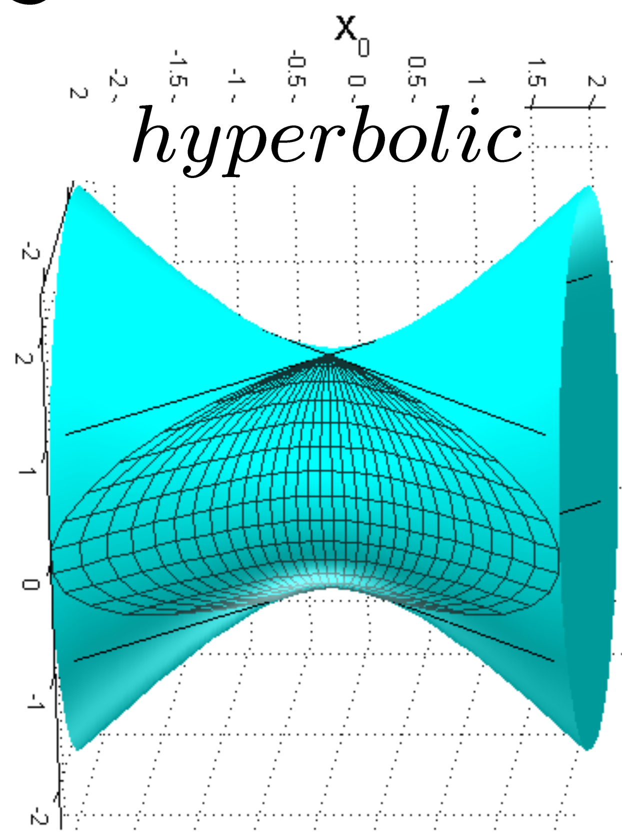
$K = -1$ $a(t) = t$

Λ<0

$$\ddot{a} = -\frac{1}{3}|\Lambda|\, a \qquad \dot{a}^2 = -\frac{1}{3}|\Lambda|\, a^2 - K$$



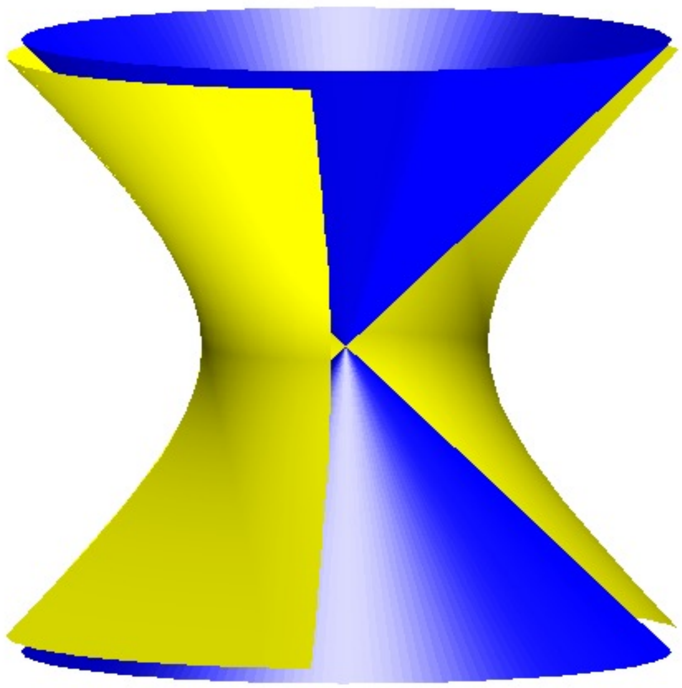
$$K = -1$$



$$a(t) = \sqrt{\frac{3}{|\Lambda|}} \sin \sqrt{\frac{|\Lambda|}{3}}\, t$$

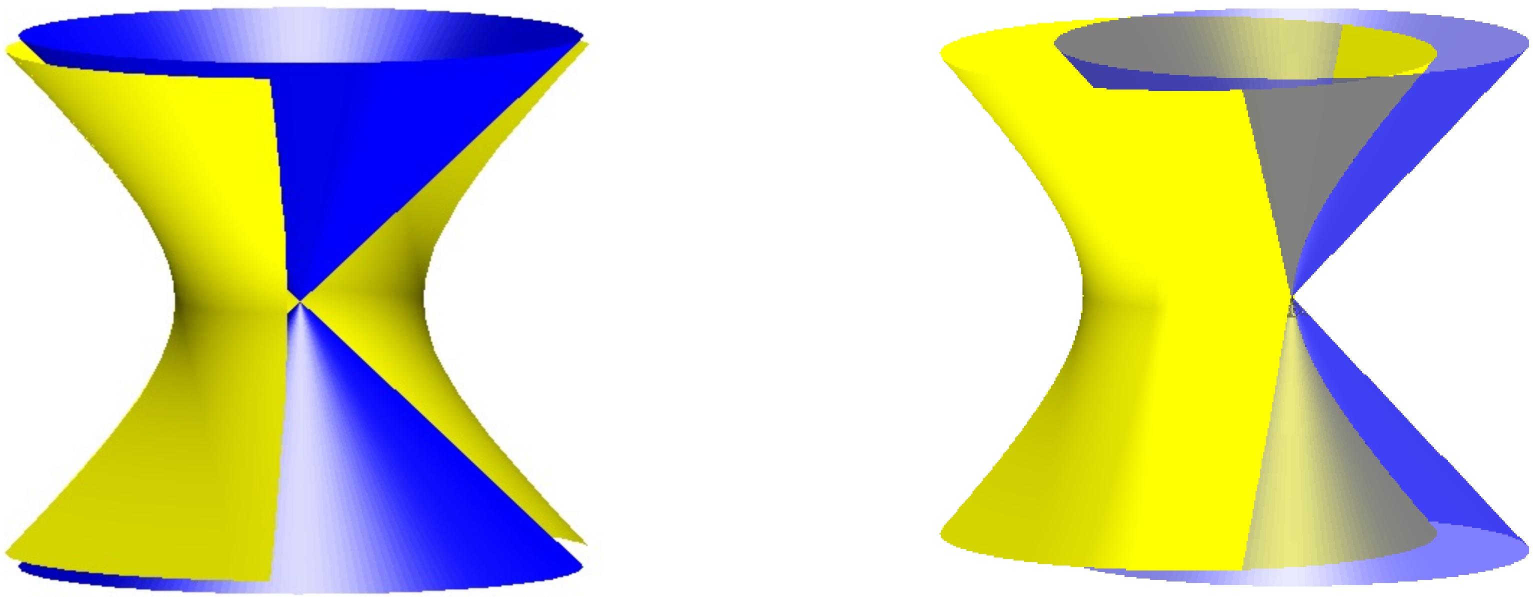
Asymtototic cone

$$\{\xi_0^2 - \xi_1^2 - \ldots - \xi_d^2 = 0\}$$



$M^{(d+1)}$: $\eta_{\mu\nu}$ = diag(**1**,**-1**,……,**-1**)

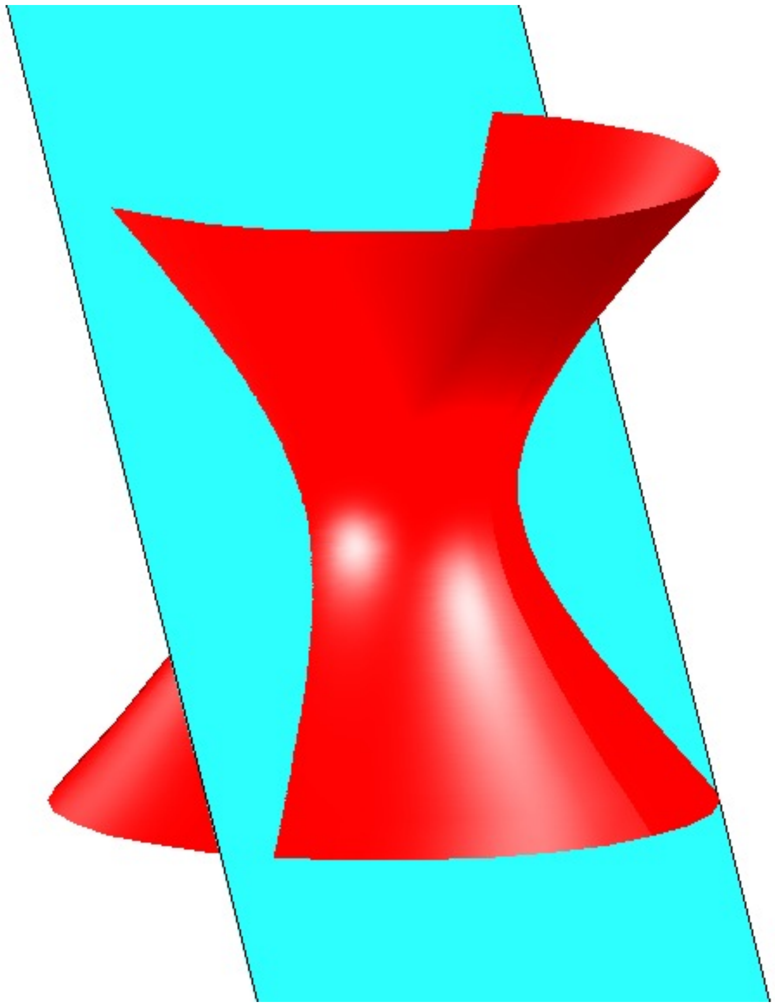
Causal structure



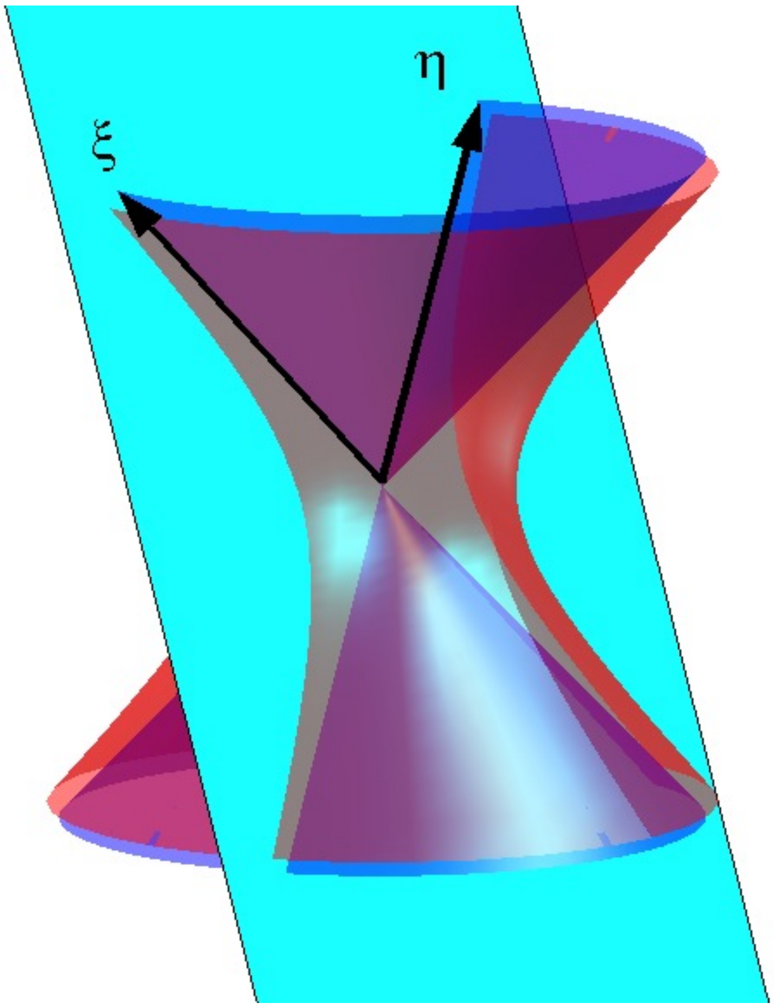
X, Y are spacelike separated iff $(X-Y)^2 < 0$ ($X - Y$ is outside the cone)

$$(X-Y)^2 = X^2 + Y^2 - 2X \cdot Y = -2R^2 - 2X \cdot Y$$

Geodesiques



Geodesics



Geodesics: de Sitter

$$X_\mu(\tau) = \frac{R}{\sqrt{2\xi\cdot\eta}}\left(\xi_\mu e^{\frac{c\tau}{R}} - \eta_\mu e^{-\frac{c\tau}{R}}\right)$$

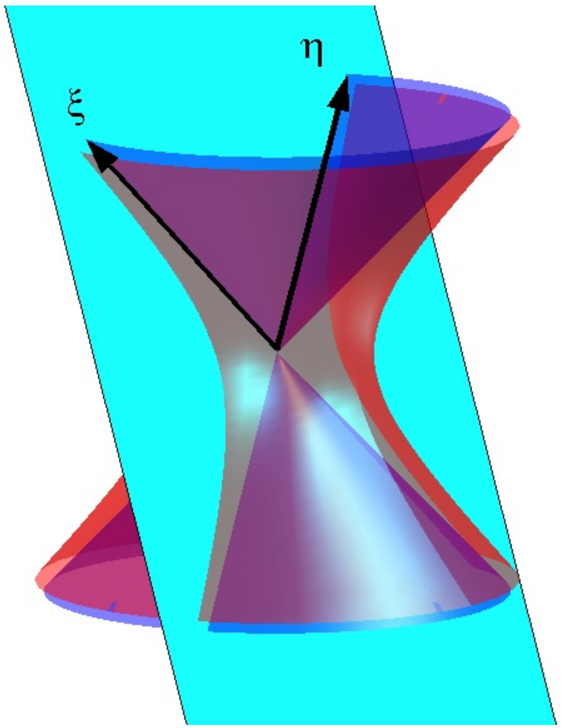
Minkowski

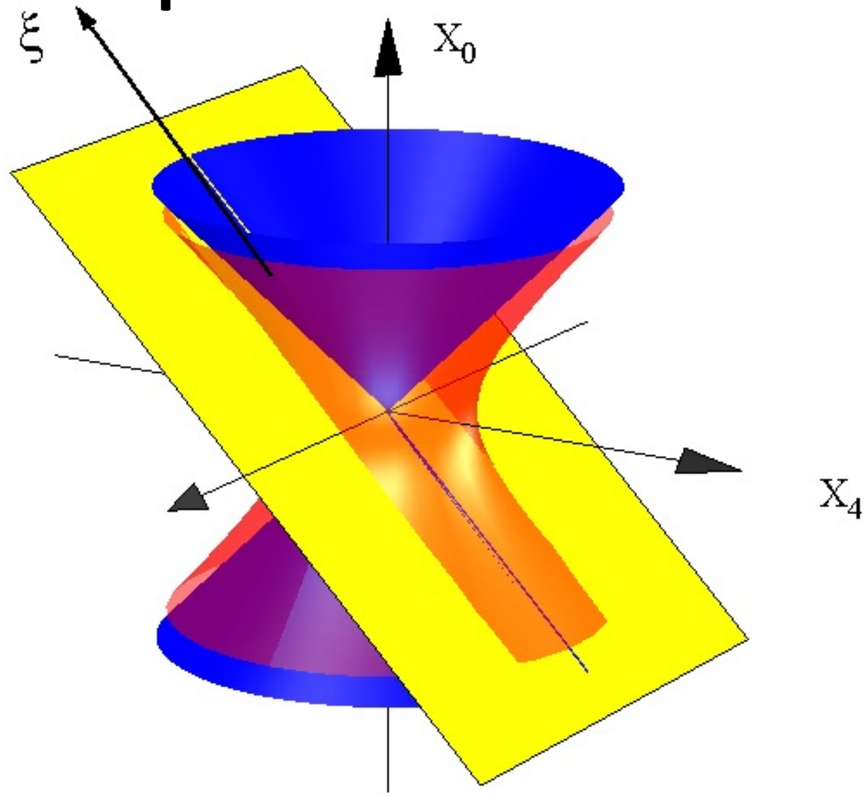
$$x_\mu(\tau) = x_\mu(0) + \frac{p_\mu \tau}{mc}$$

$$X_\mu(0) = \frac{R}{\sqrt{2\xi\cdot\eta}}(\xi_\mu - \eta_\mu)$$

$$X(\tau) = X(0)e^{-\frac{c\tau}{R}} + \frac{kR\xi}{m}\sinh\frac{c\tau}{R}.$$

Geodesiques





$$X_\mu(\lambda) = x_0 + \xi_\mu \lambda, \qquad \text{with } \xi \cdot x_0 = 0$$

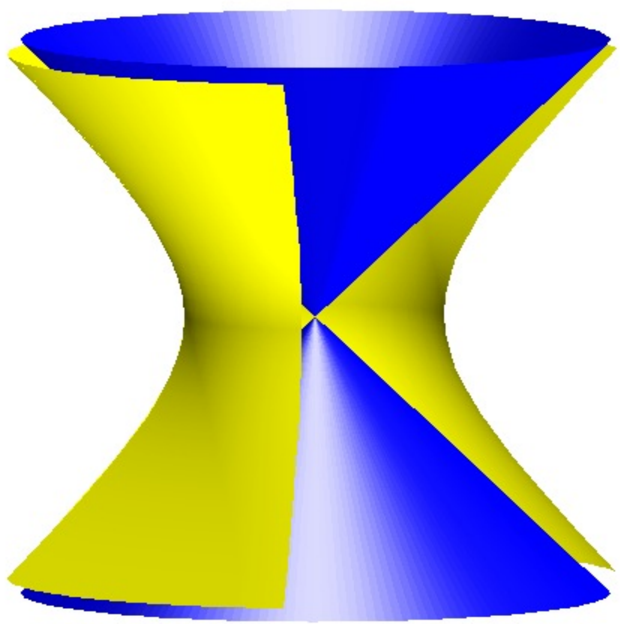
to be compared with

$$x_\mu(\lambda) = x_\mu(0) + k_\mu \lambda$$

The asymptotic cone

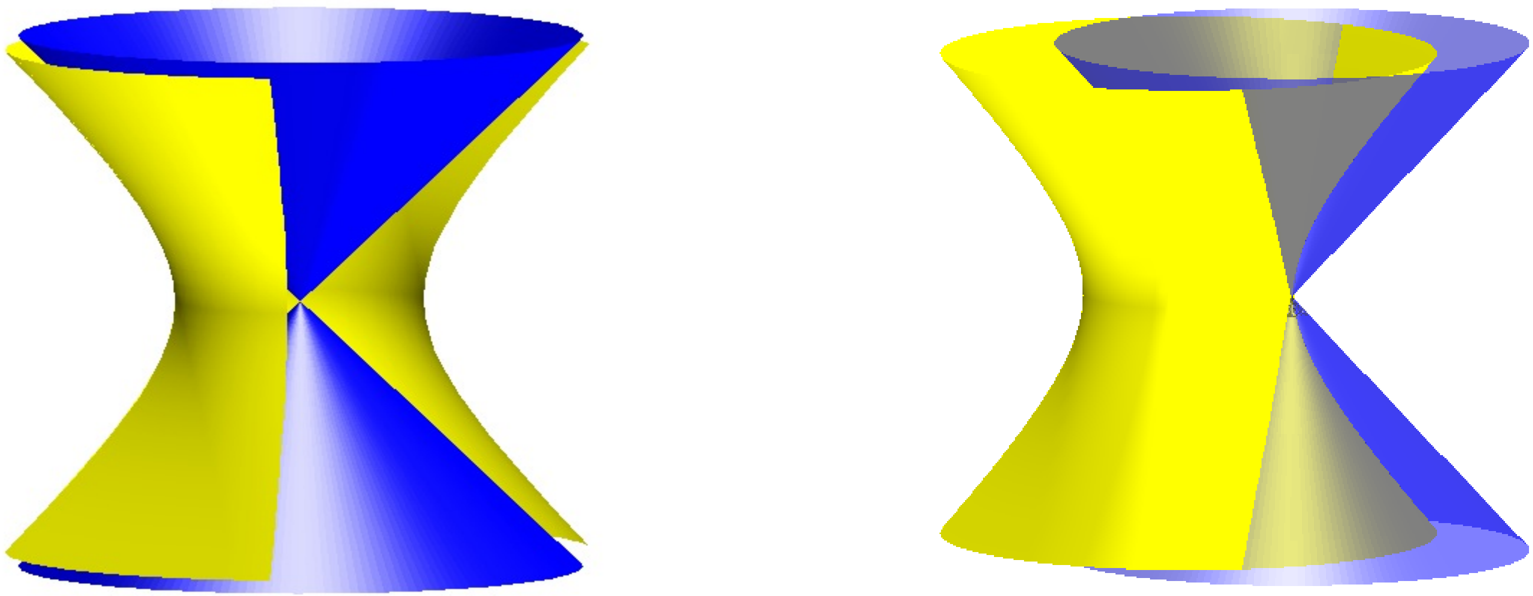
$$X_0^2 - X_1^2 - \ldots X_4^2 = -R^2$$

$$\{\xi_0^2 - \xi_1^2 - \ldots - \xi_4^2 = 0\}$$



$M^{(5)}$: $\eta_{\mu\nu}$ = diag(**1**,**-1,……,-1**)

Causal structure



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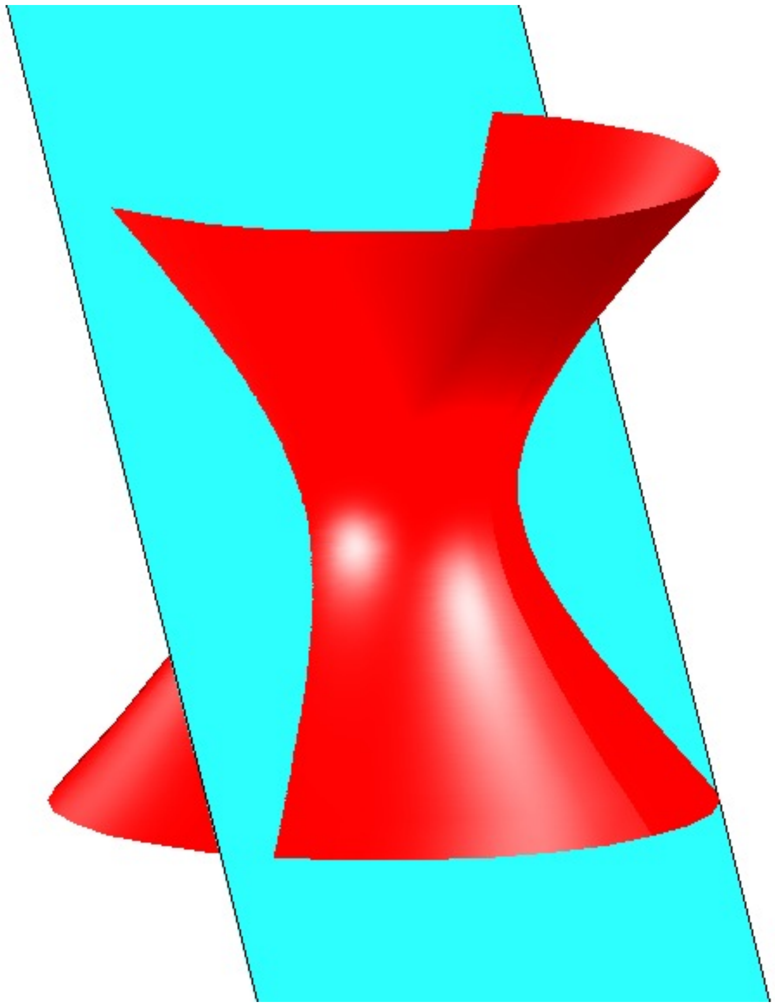
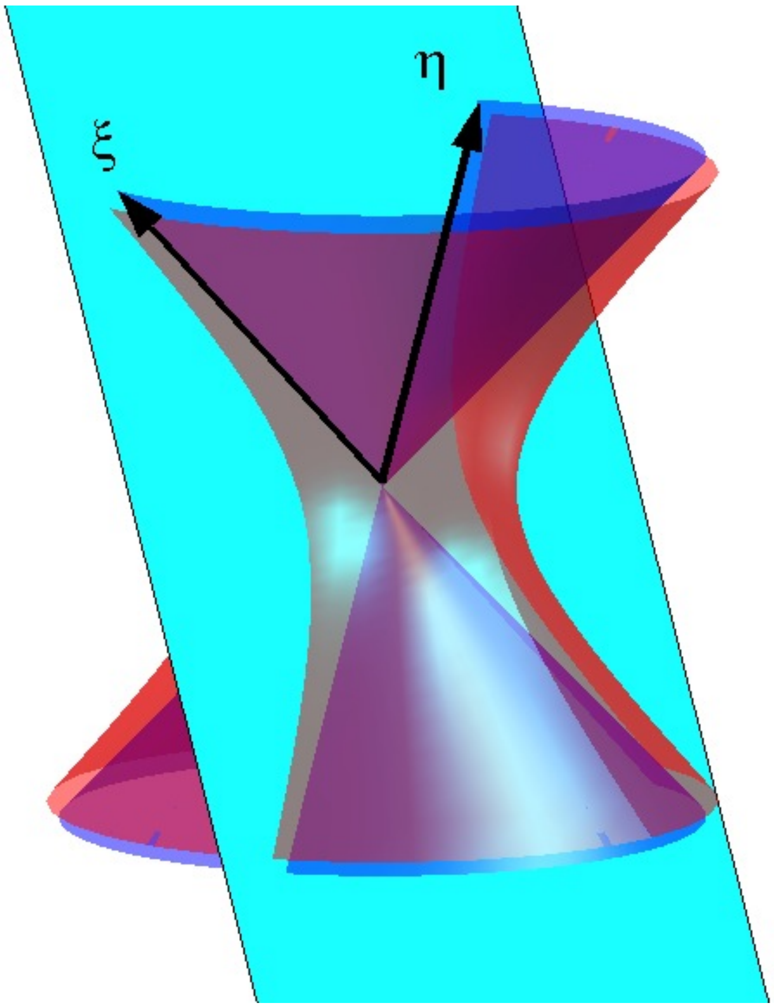
Geodesics



Geodesics



Geodesics: de Sitter

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Minkowski

$$x_\mu(\tau) = x_\mu(0) + \frac{p_\mu \tau}{mc}$$

$$X_\mu(0) = \frac{R}{\sqrt{2\xi \cdot \eta}} (\xi_\mu - \eta_\mu)$$

$$X(\tau) = X(0) e^{-\frac{c\tau}{R}} + \frac{kR\xi}{m} \sinh \frac{c\tau}{R}.$$

Stringy coordinate systems

(M. Gaudin & UM 2013)

$$t, s \to Y(t, s) \in dS(AdS)$$

String equations

$$\partial_t^2 Y_i - \partial_s^2 Y_i + [(\partial_t Y)^2 - (\partial_s Y)^2] Y_i = 0$$

Conformal gauge constraints:

$$(\partial_t Y \pm \partial_s Y)^2 = 0.$$

Constraints on the cone

dS string in homogeneous coordinates

$$t, s \to Y_i(t,s) = \frac{\xi_i(t,s)}{\xi_{d+1}(t,s)}, \quad i = 0, 1, \ldots, d; \tag{1}$$

$t, s \to \xi_\mu(t,s)$, $\mu = 0, 1, \ldots, d+1$, is a two-surface in $C_{2,d}$.

$$\xi^2 = 0 \quad \longrightarrow \quad \partial_z Y^i \partial_w Y_i = \frac{1}{\xi_{d+1}^2} \partial_z \xi^\mu \partial_w \xi_\mu, \tag{2}$$

z, w can be either t or s.

If Y_i satisfy the constraints in dS_d, the functions ξ_μ also do in $C(2,d)$ and viceversa. .

Doubly elliptic strings on the cone

A fundamental quadratic identity between theta functions:

$$\vartheta_1(\hat{t})^2\,\vartheta_1(\hat{s})^2 - \vartheta_2(\hat{t})^2\,\vartheta_2(\hat{s})^2 + \vartheta_3(\hat{t})^2\,\vartheta_3(\hat{s})^2 - \vartheta_4(\hat{t})^2\,\vartheta_4(\hat{s})^2 = 0$$

$$(t,s) \to \xi(t,s) = \begin{cases} \xi_0 = \vartheta_1(\hat{t})\,\vartheta_1(\hat{s}), & \xi_1 = \vartheta_3(\hat{t})\,\vartheta_3(\hat{s}), \\ \xi_2 = \vartheta_2(\hat{t})\,\vartheta_2(\hat{s}), & \xi_3 = \vartheta_4(\hat{t})\,\vartheta_4(\hat{s}). \end{cases}$$

$$\xi^2 \;= \xi_0^2 + \xi_1^2 - \xi_2^2 - \xi_3^2 = 0$$

$$(t,s) \to \xi(t,s) \in C_{2,2}$$

Constraints

Amounts to another (possibly unknown) identity among theta functions and their derivatives

$$\partial_t\xi\cdot\partial_t\xi+\partial_s\xi\cdot\partial_s\xi=-\theta_3^{-2}\sum_{i=1}^{4}(-1)^\alpha(\vartheta'_\alpha(\hat{t})^2\,\vartheta_\alpha(\hat{s})^2+\vartheta_\alpha(\hat{t})^2\,\vartheta'_\alpha(\hat{s})^2)=0.$$

Proof: apply the Laplace operator to the defining identity

$$\begin{aligned}
0&=\frac{1}{2}(\partial_x^2+\partial_y^2)\sum_{\alpha=1}^{4}(-1)^\alpha(\vartheta_\alpha(x)^2\vartheta_\alpha(y)^2)=\\
&=\sum_{\alpha=1}^{4}(-1)^\alpha(\vartheta'_\alpha(x)^2\vartheta_\alpha(y)^2+\vartheta_\alpha(x)^2\vartheta'_\alpha(y)^2+\vartheta_\alpha(x)\vartheta''_\alpha(x)\vartheta_\alpha(y)^2+\vartheta_\alpha(x)^2\vartheta_\alpha(y)\vartheta''_\alpha(y))=\\
&=\sum_{\alpha=1}^{4}(-1)^\alpha(\vartheta'_\alpha(x)^2\vartheta_\alpha(y)^2+\vartheta_\alpha(x)^2\vartheta'_\alpha(y)^2)+\frac{2i}{\pi}\frac{\partial}{\partial\tau}\sum(-1)^\alpha(\vartheta_\alpha(x)^2\vartheta_\alpha(y)^2)=\\
&=\sum_{\alpha=1}^{4}(-1)^\alpha(\vartheta'_\alpha(x)^2\vartheta_\alpha(y)^2+\vartheta_\alpha(x)^2\vartheta'_\alpha(y)^2)=0.
\end{aligned}$$

Finite open strings

Project back to AdS/dS

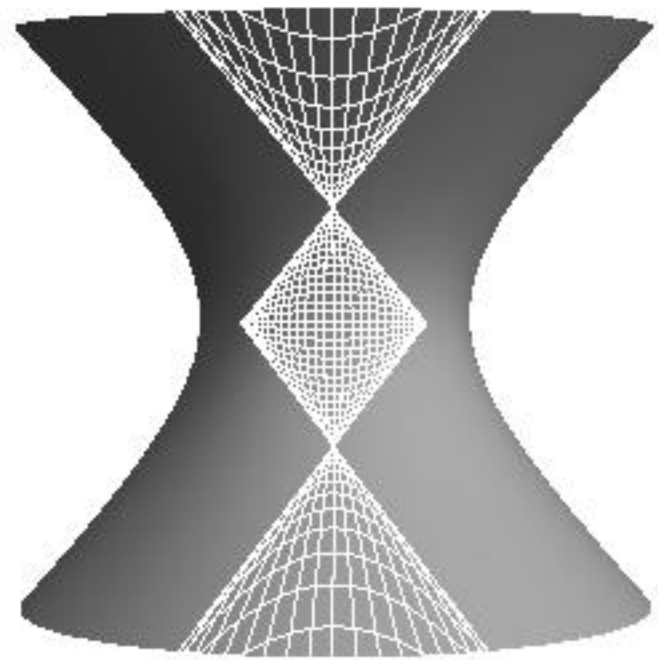
$$(t,s) \to \xi(t,s) = \begin{cases} \xi_0 = \vartheta_1(\hat{t})\,\vartheta_1(\hat{s}), & \xi_1 = \vartheta_3(\hat{t})\,\vartheta_3(\hat{s}), \\ \xi_2 = \vartheta_2(\hat{t})\,\vartheta_2(\hat{s}), & \xi_3 = \vartheta_4(\hat{t})\,\vartheta_4(\hat{s}). \end{cases}$$

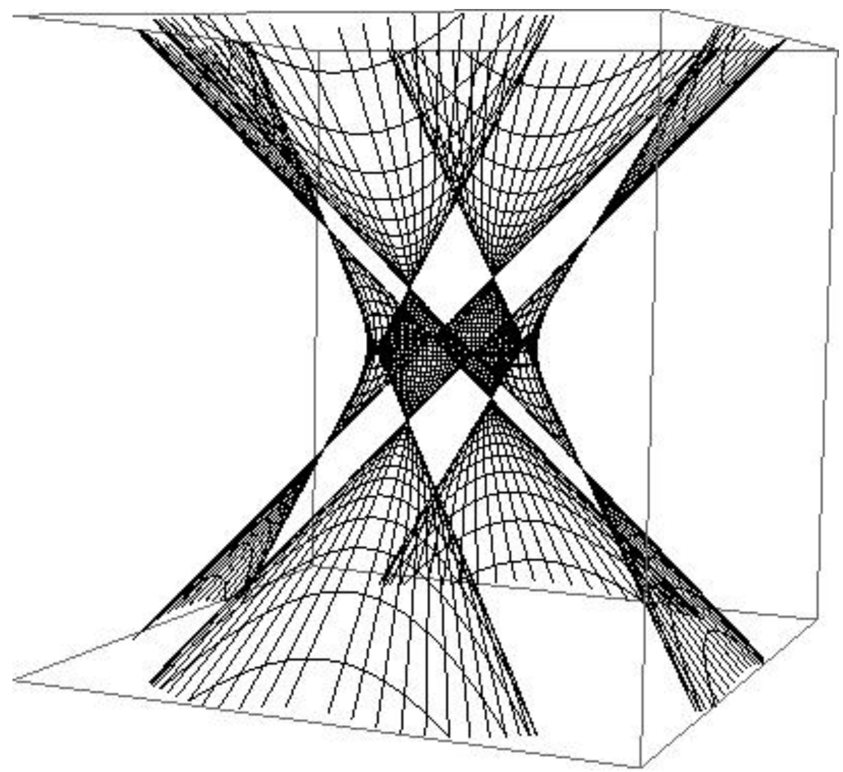
$$(t,s) \to Y^{(1)} = \begin{cases} Y_0(t,s) = \frac{\xi_0}{\xi_3} = \frac{\vartheta_1(\hat{t})\vartheta_1(\hat{s})}{\vartheta_4(\hat{t})\vartheta_4(\hat{s})} = k\ \mathrm{sn}(t,k)\,\mathrm{sn}(s,k), \\ Y_1(t,s) = \frac{\xi_1}{\xi_3} = \frac{\vartheta_3(\hat{t})\vartheta_3(\hat{s})}{\vartheta_4(\hat{t})\vartheta_4(\hat{s})} = \frac{1}{k'}\,\mathrm{dn}(t,k)\,\mathrm{dn}(s,k), \\ Y_2(t,s) = \frac{\xi_2}{\xi_3} = \frac{\vartheta_2(\hat{t})\vartheta_2(\hat{s})}{\vartheta_4(\hat{t})\vartheta_4(\hat{s})} = \frac{k}{k'}\,\mathrm{cn}(t,k)\,\mathrm{cn}(s,k), \end{cases}$$

Constraints are satisfied.

String equations also (I leave this as an exercise!)

Finite open strings





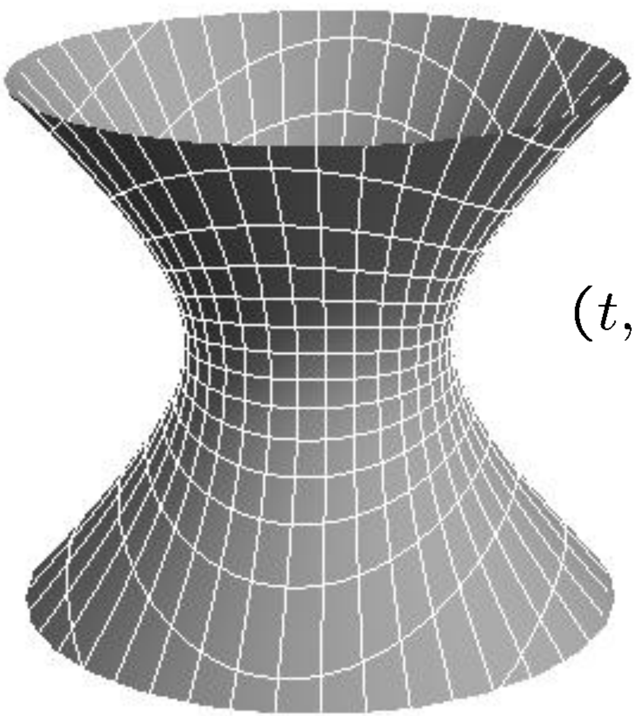
$$(t,s) \to Y^{(1)} = \begin{cases} Y_0(t,s) &= k\, \mathrm{sn}(t,k)\, \mathrm{sn}(s,k), \\ Y_1(t,s) &= \frac{1}{k'}\, \mathrm{dn}(t,k)\, \mathrm{dn}(s,k), \\ Y_2(t,s) &= \frac{k}{k'}\, \mathrm{cn}(t,k)\, \mathrm{cn}(s,k), \end{cases}$$

Closed (dS) strings

A second well-known relation between theta functions

$$\xi^2 = \vartheta_1(\hat{t})^2\,\vartheta_3(\hat{s})^2 + \vartheta_2(\hat{t})^2\,\vartheta_4(\hat{s})^2 - \vartheta_3(\hat{t})^2\,\vartheta_1(\hat{s})^2 - \vartheta_4(\hat{t})^2\,\vartheta_2(\hat{s})^2 = 0.$$

$$(t,s) \to \xi(t,s) = \begin{cases} \xi_0 = \vartheta_1(\hat{t})\,\vartheta_3(\hat{s}), & \xi_1 = \vartheta_2(\hat{t})\,\vartheta_4(\hat{s}), \\ \xi_2 = \vartheta_3(\hat{t})\,\vartheta_1(\hat{s}), & \xi_3 = \vartheta_4(\hat{t})\,\vartheta_2(\hat{s}). \end{cases}$$

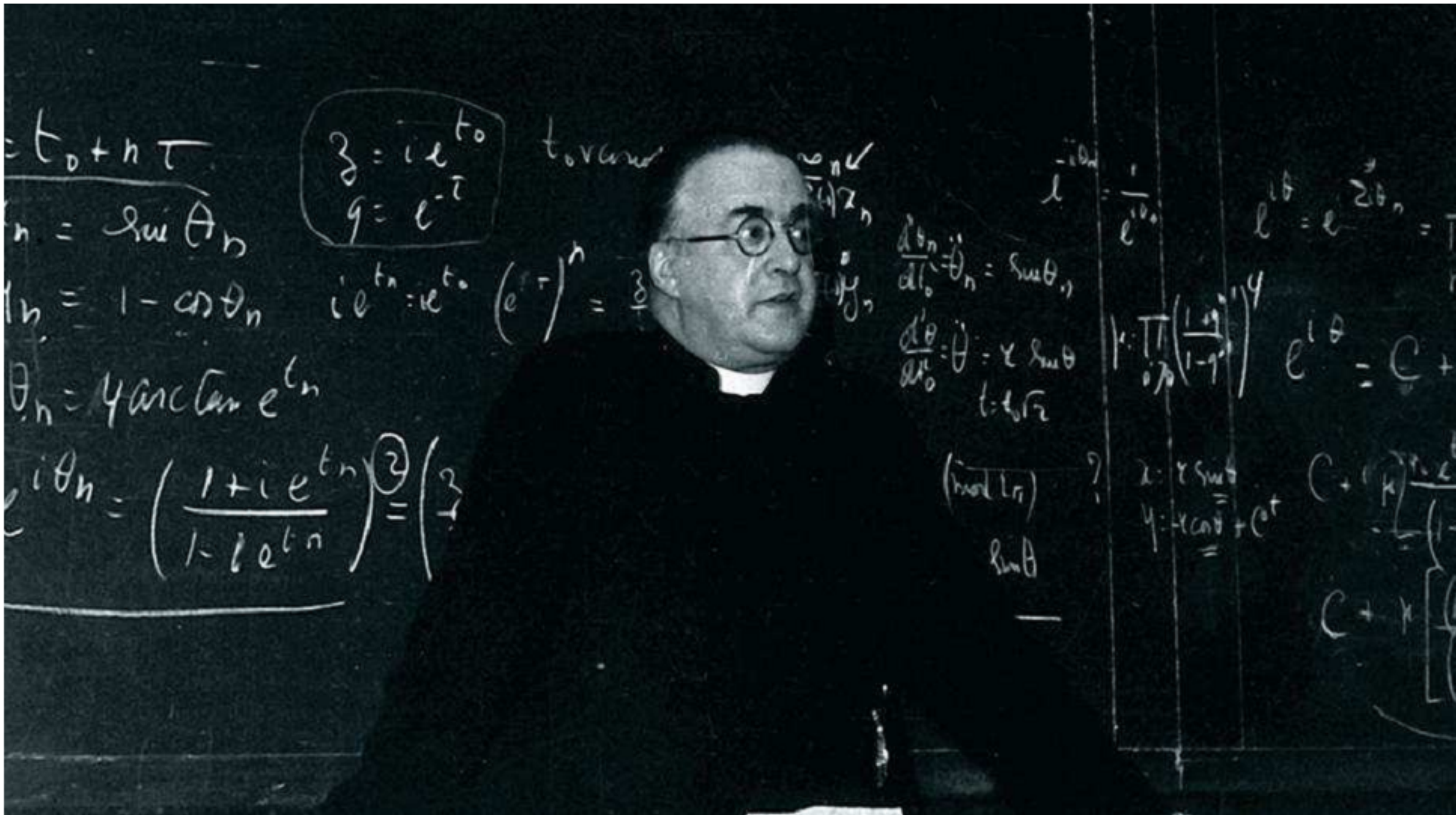


$$(t,s) \to \begin{cases} Y_0(t,s) &= \frac{\xi_0}{\xi_3} &= \mathrm{sn}(t,k)\ \mathrm{dc}(s,k), \\ Y_1(t,s) &= \frac{\xi_1}{\xi_3} &= \mathrm{cn}(t,k)\ \mathrm{nc}(s,k), \\ Y_2(t,s) &= \frac{\xi_2}{\xi_3} &= \mathrm{dn}(t,k)\ \mathrm{sc}(s,k) \end{cases}$$

Epilogue 2

- Up to the beginning of the ‘30 everybody believed in a static universe
- The fundamental papers by Friedmann - 1922 and 1924 – and the independent work by Lemaître en 1927 were largely ignored
- Einstein even published a note claiming a mistake in Friedmann’s work.
- Once more he was wrong.
- In his retractation he said (sentence suppressed in the final vesion) *Friedmann's paper while mathematically correct is of no physical significance*
- « *Vos calculs sont corrects, mais votre physique est abominable* » Einstein to Lemaitre, 1927

Epilogue 3: Lemaitre's discovers Hubble's law



ARCHIVES GEORGES LEMAÎTRE/CATHOLIC UNIV. LOUVAIN/TECLIM

Georges Lemaître giving a lecture at the Catholic University of Louvain in Belgium.

Dear Professor Eddington

I just read the February No of the Observatory and ~~the discussion on~~ your suggestion of ~~the~~ investigating ~~the intermediary~~ non statistical intermediary solution between those of Einstein and de Sitter.

I made these investigation two years ago. I consider an universe of curvature constant in space but ~~variable~~ increasing with time. And ~~I looked~~ I emphasize the existence of a solution for which the ~~apparent receding~~ motion of the nebulae ~~has exist from~~ is always ~~from~~ a receding one ~~from time the and~~ from time minus infinity to the infinity.

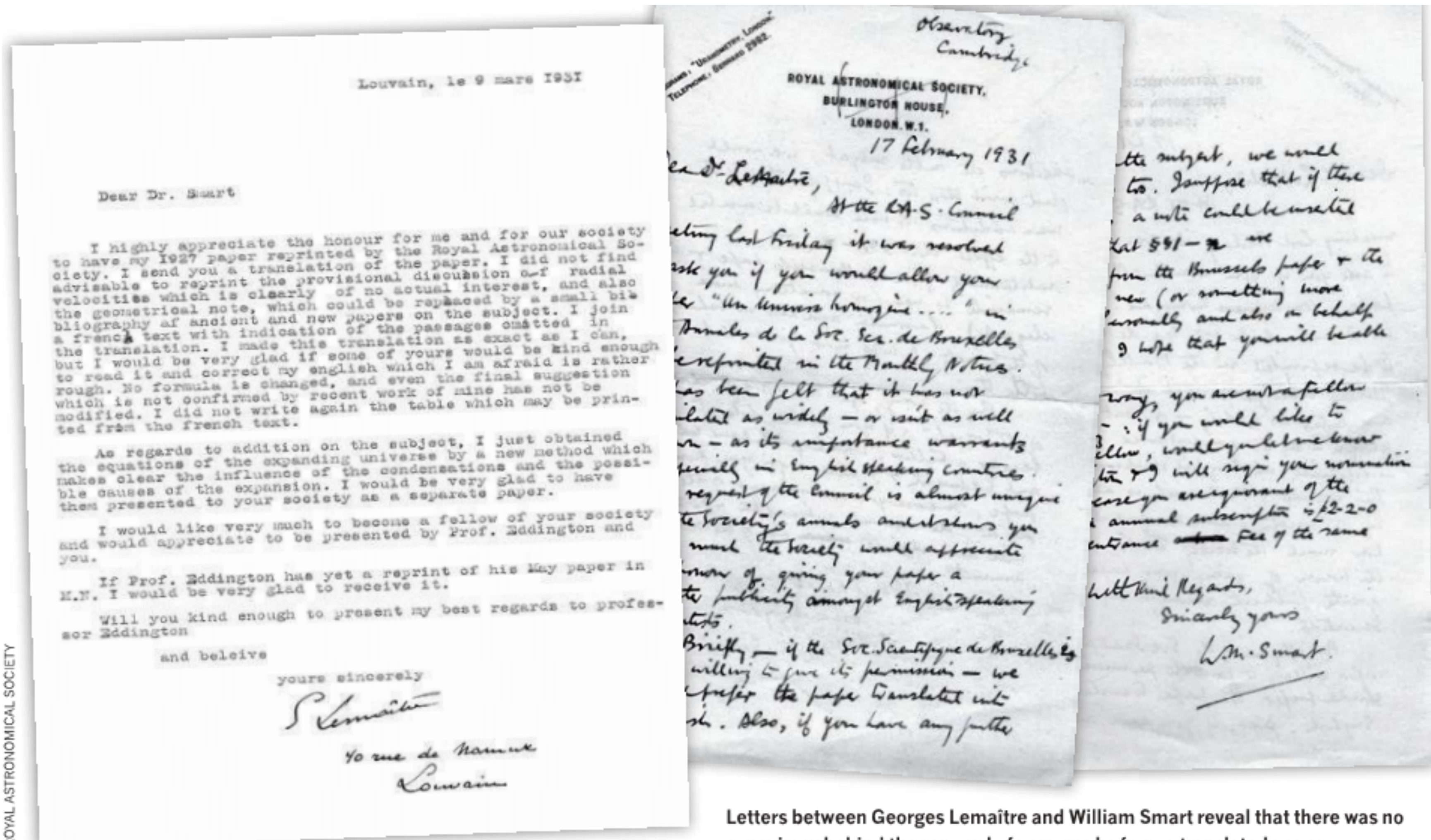
This solved the question put forward by de Sitter why the nebulae are on the receding branch of the hyperbola.

The result is as follows.

~~This is the~~ The receding motion of the nebulae is a measure of the initial or non asymptotic radius for time $-\infty$ by the formulae

$R_0 \cong \frac{rc}{v\sqrt{3}}$ strictly [$\frac{v^2}{r^2c^2} = \frac{1}{3R_0^2} + \frac{1}{R^2} - \frac{2}{3}\frac{1}{R_E^2}$ see later the whole]

M Livio solves the Hubble-Lemaitre affaire



Louvain, le 9 mars 1931

Dear Dr. Smart

I highly appreciate the honour for me and for our society to have my 1927 paper reprinted by the Royal Astronomical Society. I send you a translation of the paper. I did not find advisable to reprint the provisional discussion of radial velocities which is clearly of no actual interest, and also the geometrical note, which could be replaced by a small bibliography of ancient and new papers on the subject. I join a french text with indication of the passages omitted in the translation. I made this translation as exact as I can, but I would be very glad if some of yours would be kind enough to read it and correct my english which I am afraid is rather rough. No formula is changed, and even the final suggestion which is not confirmed by recent work of mine has not be modified. I did not write again the table which may be printed from the french text.

As regards to addition on the subject, I just obtained the equations of the expanding universe by a new method which makes clear the influence of the condensations and the possible causes of the expansion. I would be very glad to have them presented to your society as a separate paper.

I would like very much to become a fellow of your society and would appreciate to be presented by Prof. Eddington and you.

If Prof. Eddington has yet a reprint of his May paper in M.N. I would be very glad to receive it.

Will you kind enough to present my best regards to professor Eddington

and beleive

yours sincerely

G. Lemaître

40 rue de Namur

Louvain

Observatory
Cambridge

ROYAL ASTRONOMICAL SOCIETY,
BURLINGTON HOUSE,
LONDON, W.1.

17 February 1931

Dear Dr Lemaître,

At the R.A.S. Council meeting last Friday it was resolved to ask you if you would allow your paper "Un Univers homogène ...." in the Annales de la Soc. Sci. de Bruxelles to be reprinted in the Monthly Notices. It has been felt that it has not been circulated as widely — or isn't as well known — as its importance warrants, especially in English speaking countries. The request of the Council is almost unique in the Society's annals and it shows you how much the Society would appreciate the honour of giving your paper a greater publicity amongst English-speaking scientists.

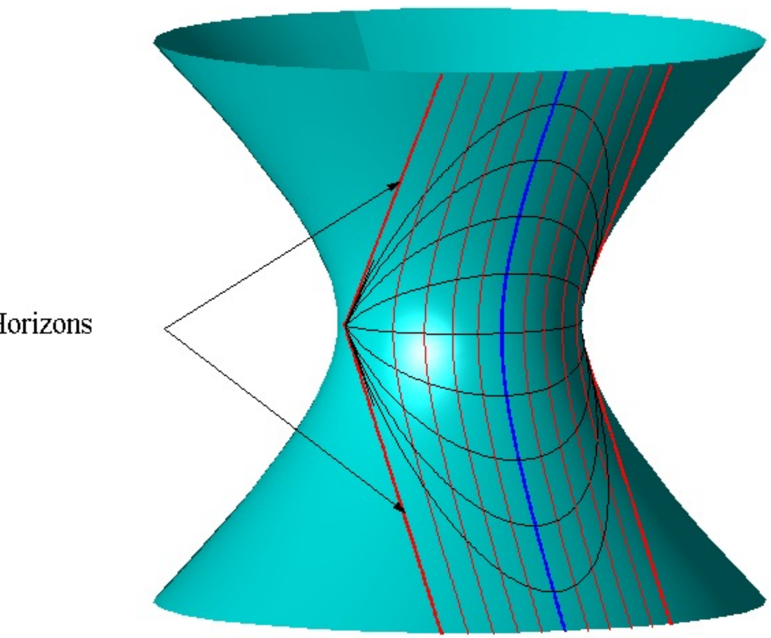
Briefly — if the Soc. Scientifique de Bruxelles is willing to give its permission — we would prefer the paper translated into English. Also, if you have any further ... the subject, we would ... to. I suppose that if there ... a note could be inserted ... that §§1— ... are ... from the Brussels paper & the new (or something more ... personally and also on behalf ... I hope that you will be able ...

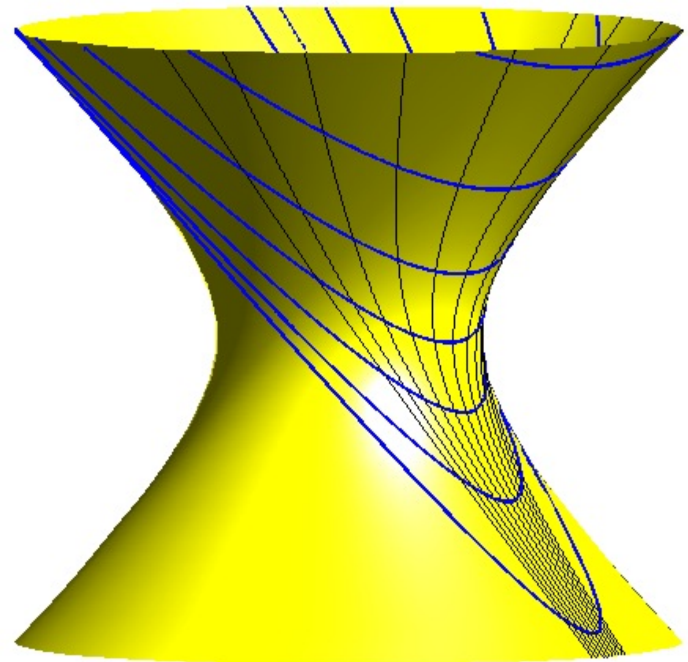
... way, you are not a fellow ... ; if you would like to ... Fellow, would you let me know ... & I will sign your nomination ... case you are ignorant of the ... annual subscription is £2-2-0 ... entrance fee of the same ...

With kind regards,
Sincerely yours
W. M. Smart.

Letters between Georges Lemaître and William Smart reveal that there was no conspiracy behind the removal of paragraphs from a translated paper.

Two years later

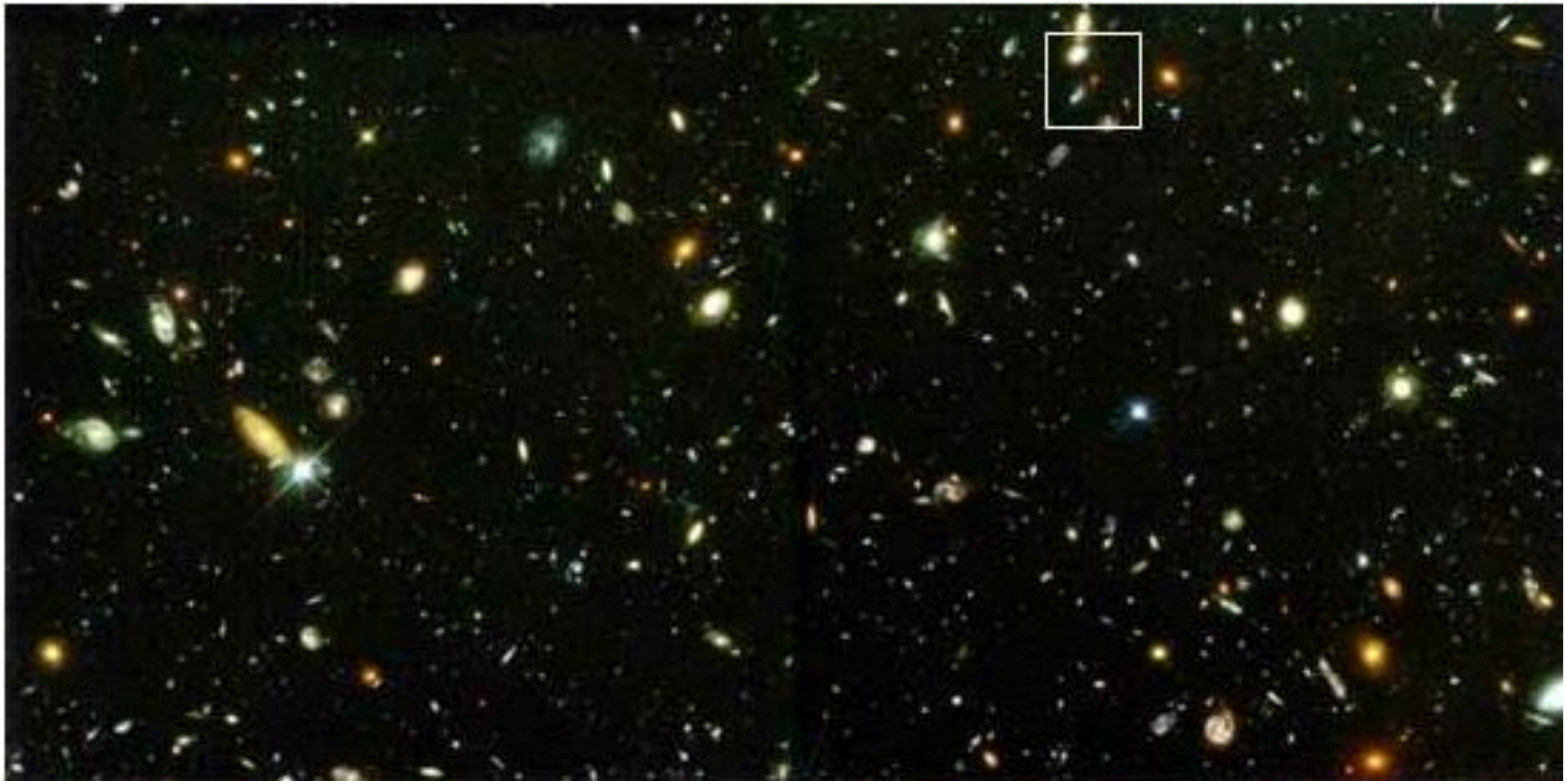




Hubble explains the redshifts of the nebulae by using the de Sitter model, as suggested by Eddington. Il ignored Lemaître (Eddington too, but not Einstein)

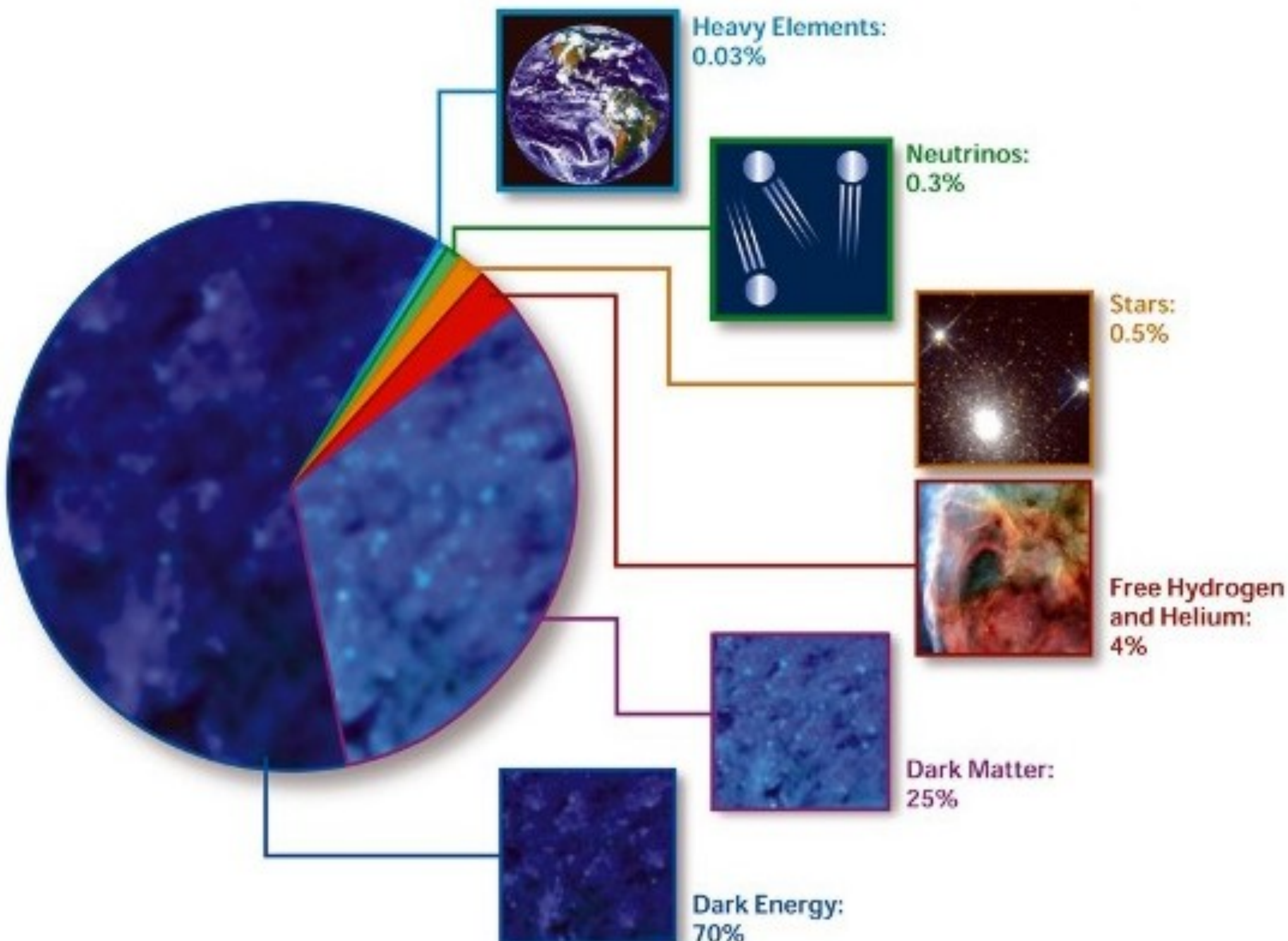
BONUS TRACK

Supernova SN1997 ff



SN 1997 → Sidereus Nuncius 1997

1997: The cosmological constant strikes back

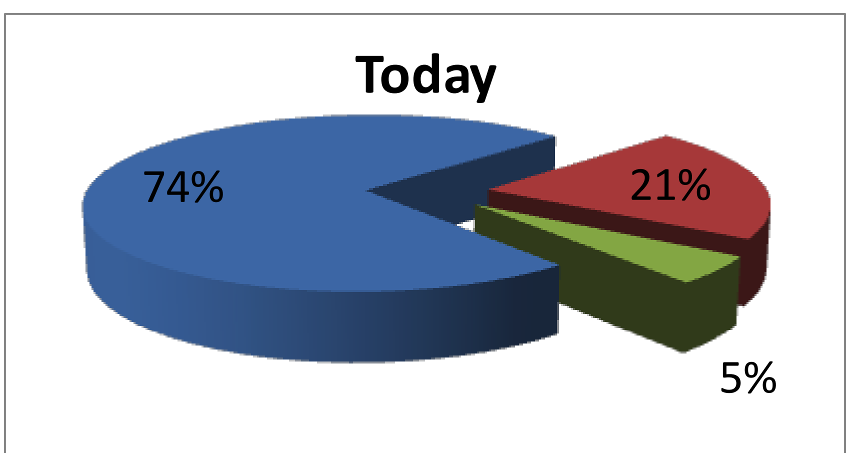


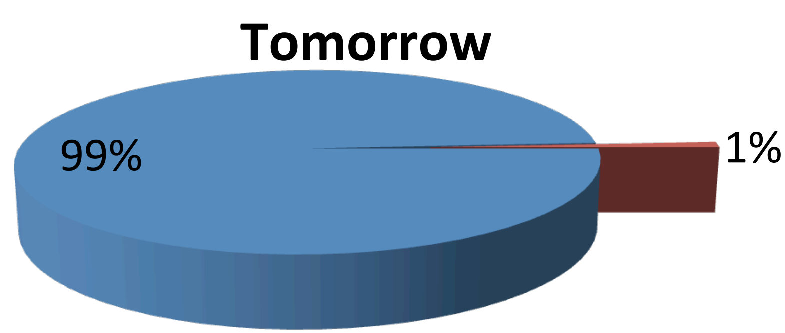
De Sitter is forever!

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8}{3}\pi G(\rho_M + \rho_R + \rho_\Lambda) - \frac{K}{a^2}$$

$$p_M = 0, \quad p_R = \frac{1}{3}\rho_R, \quad p_\Lambda = -\rho_\Lambda,$$

$$H^2 = \frac{\Omega_M}{a(t)^3} + \frac{\Omega_R}{a(t)^4} + \Omega_\Lambda + \frac{\Omega_K}{a(t)^2}$$





Epilogue IV

- The introduction of such a constant implies a considerable renunciation of the logical simplicity of the theory... Since I introduced this term, I had always a bad conscience... I am unable to believe that such an ugly thing should be realized in nature

  —*Einstein to Lemaître, 1947*

- The history of science provides many instances of discoveries which have been made for reasons which are no longer considered satisfactory. It may be that the discovery of the cosmological constant is such a case.

  —*Lemaître to Einstein, 1949*

Epilogue III

The moral: never admit you're wrong.

If only Einstein had not admitted he was wrong, he would have been famous

Rocky Kolb (APS, Tampa, 2005)