Lambda, the fifth foundational constant considered by Einstein

BIPM 09/07/2017

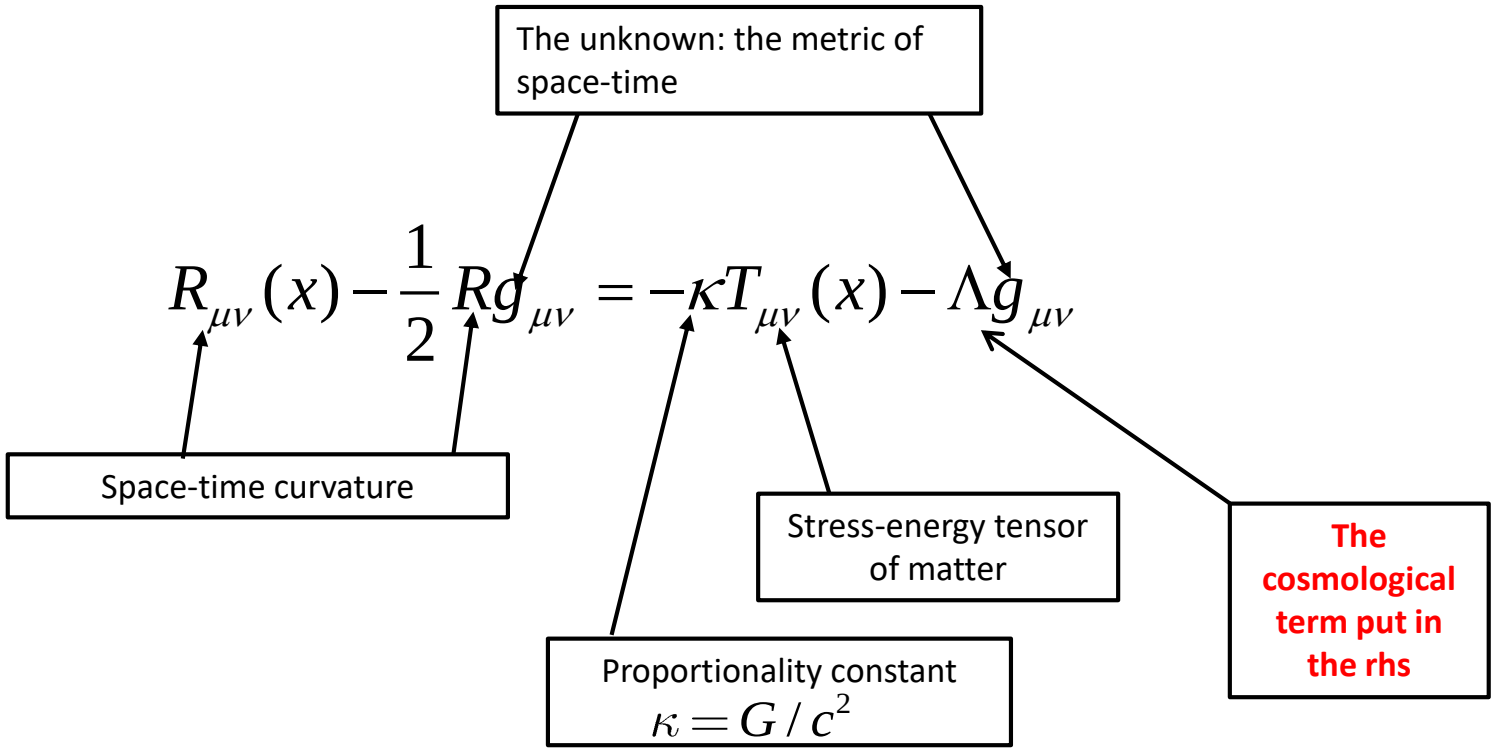
Gilles Cohen-Tannoudji

IRFU, CEA, Université Paris-Saclay

The comeback of Λ

Λ, the Einstein-de Sitter-Lemaître constant

- **A. Einstein**, *Cosmological considerations about the general theory of relativity,* Akademie de wissenschaften, Sitzungssberichte, 194-17,p. 142-152; in French: Albert Einstein, *Oeuvre choisies, Tome 3, Relativités.* p.91 Le Seuil, Paris (1993)
- **W. de Sitter**, *On the relativity of inertia. Remarks concerning Einstein's latest hypothesis,* KNAW Proceedings, 1911- 1917, pp. 1217-1225
- Alexandre Friedman et **Georges Lemaître** *Essai de cosmologie, Textes choisis et présentés par J.P. Luminet et A. Grib* Le Seuil 1997



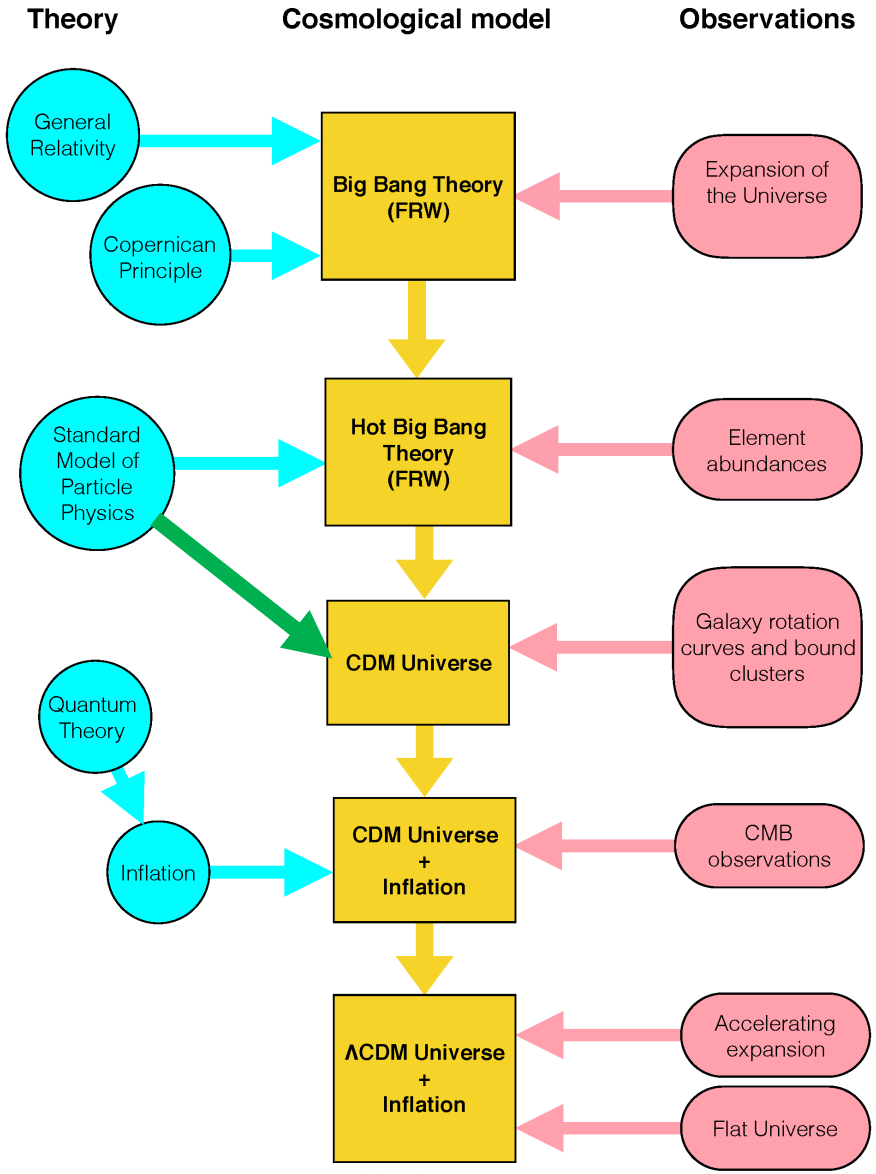
Matter tells spacetime how it must curve;
spacetime tells matter how it must move

The Einstein's equation with a cosmological term

FROM BBM TO ΛCDM
(Ivan Debono and George F. Smoot)

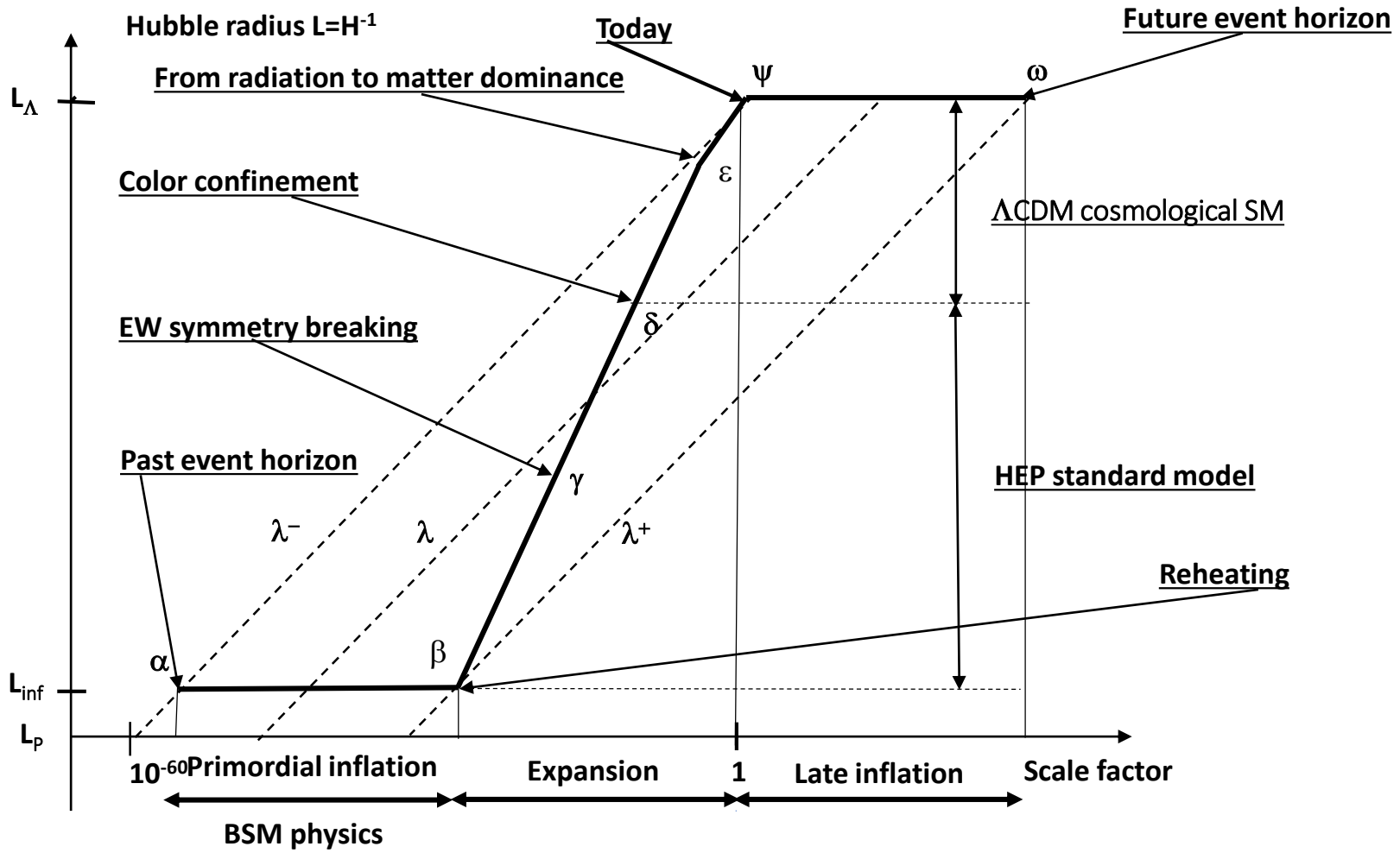
Georges Fitzgerald
Smoot, Prix Nobel 2006

Saul Perlmutter, Brian Schmidt, Adam Riess, Prix Nobel 2011



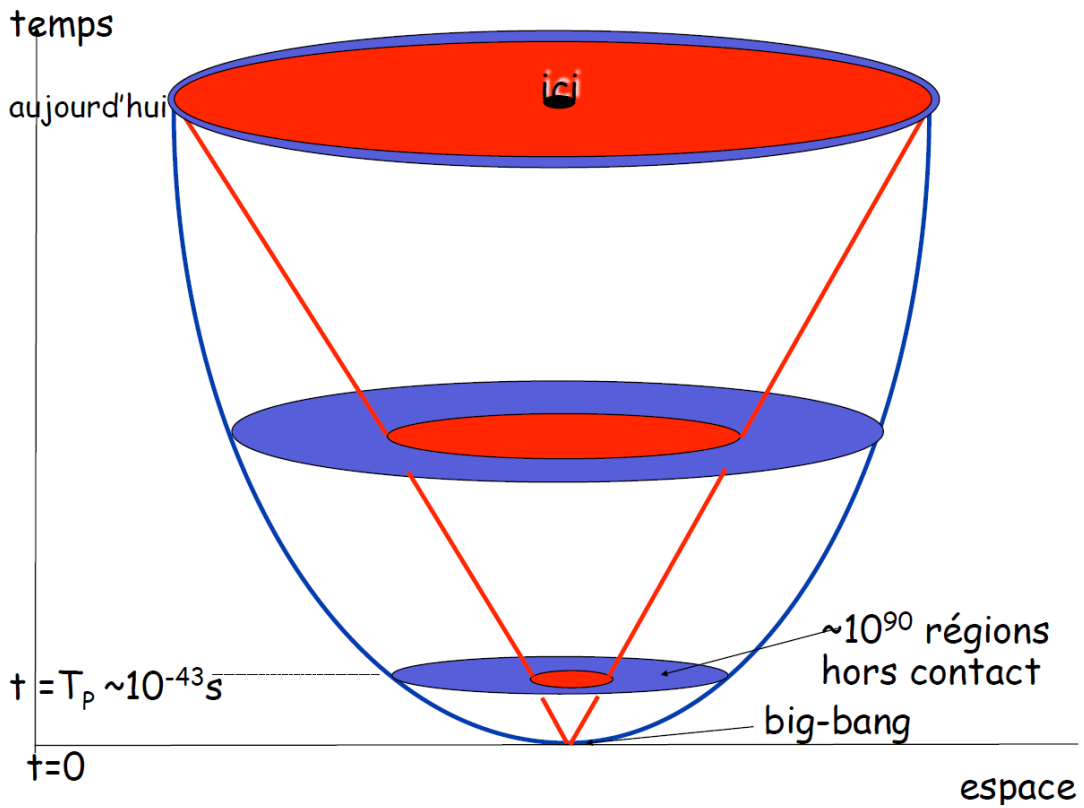
From BBM to ΛCDM
Figure from *General Relativity and Cosmology: Unsolved Questions and Future Directions*.
http://www.mdpi.com/2218-1997/2/4/23

Modified by adding the green arrow from SMPP to CDM universe


Hubble radius L=H-1
Today
Future event horizon
From radiation to matter dominance
ψ
ω
LΛ
Color confinement
ε
ΛCDM cosmological SM
δ
EW symmetry breaking
Past event horizon
γ
HEP standard model
λ−
λ
λ+
Reheating
α
β
Linf
LP
10-60Primordial inflation
Expansion
1
Late inflation
Scale factor
BSM physics

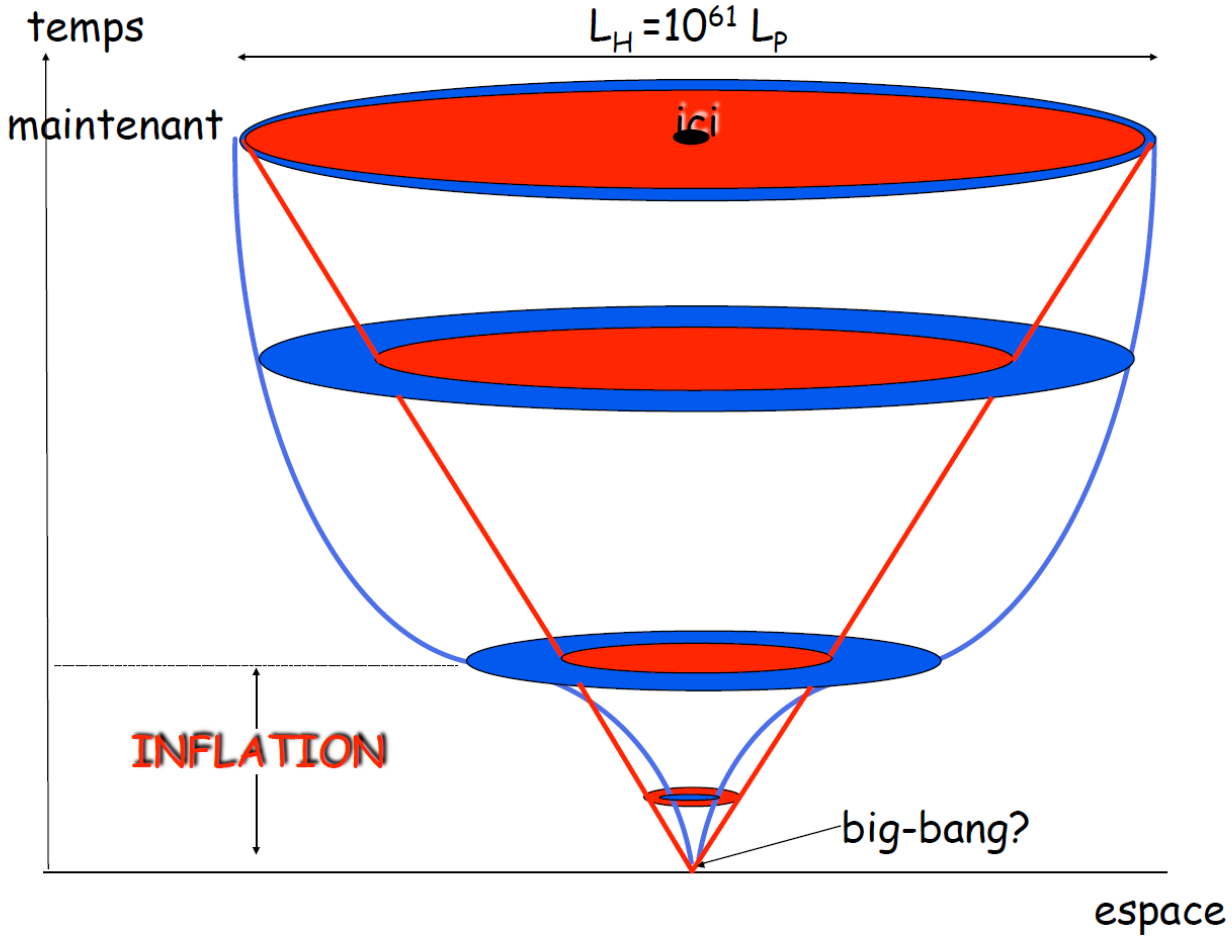
The BBM: « the universe is too large for its age »

(many thanks to Gabriele Veneziano)



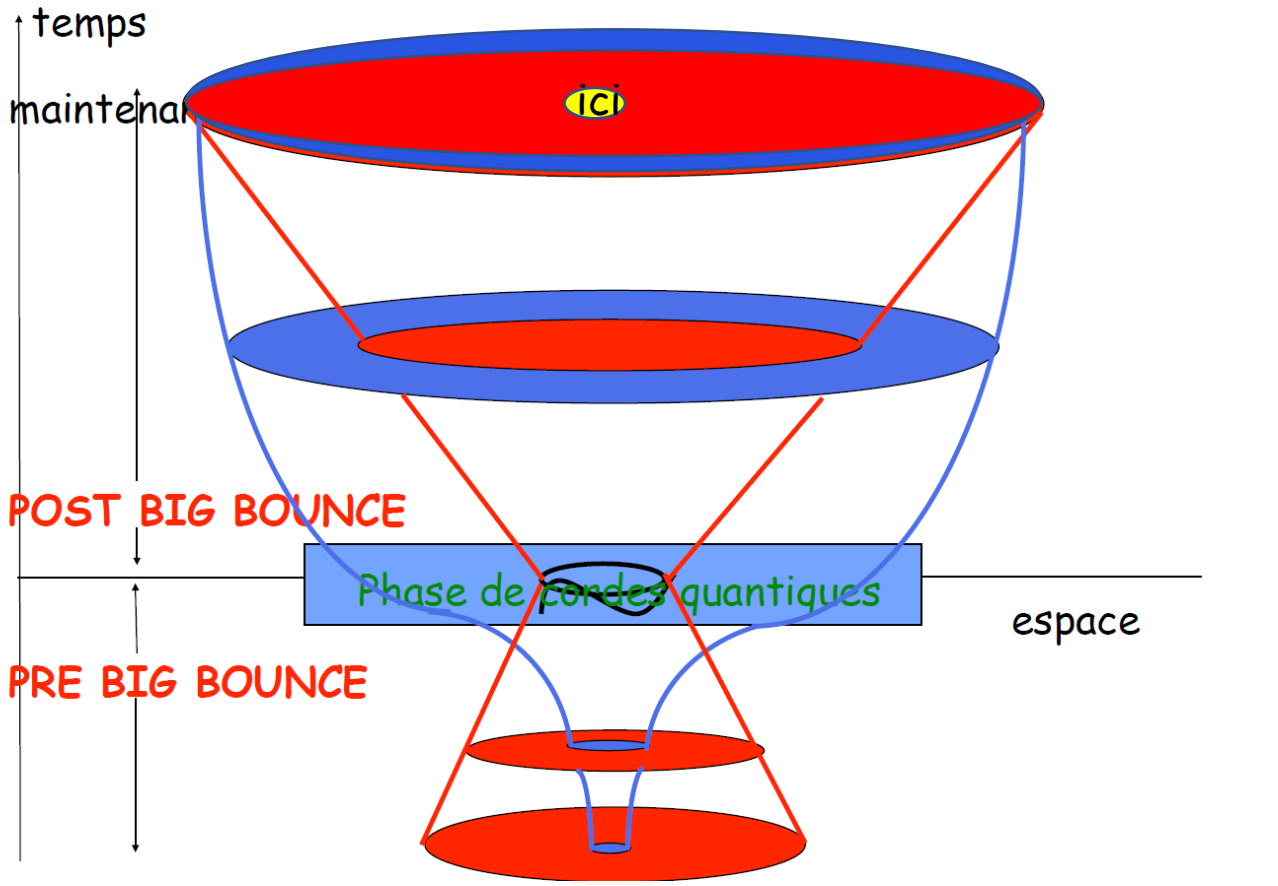
From BBM to inflationary model

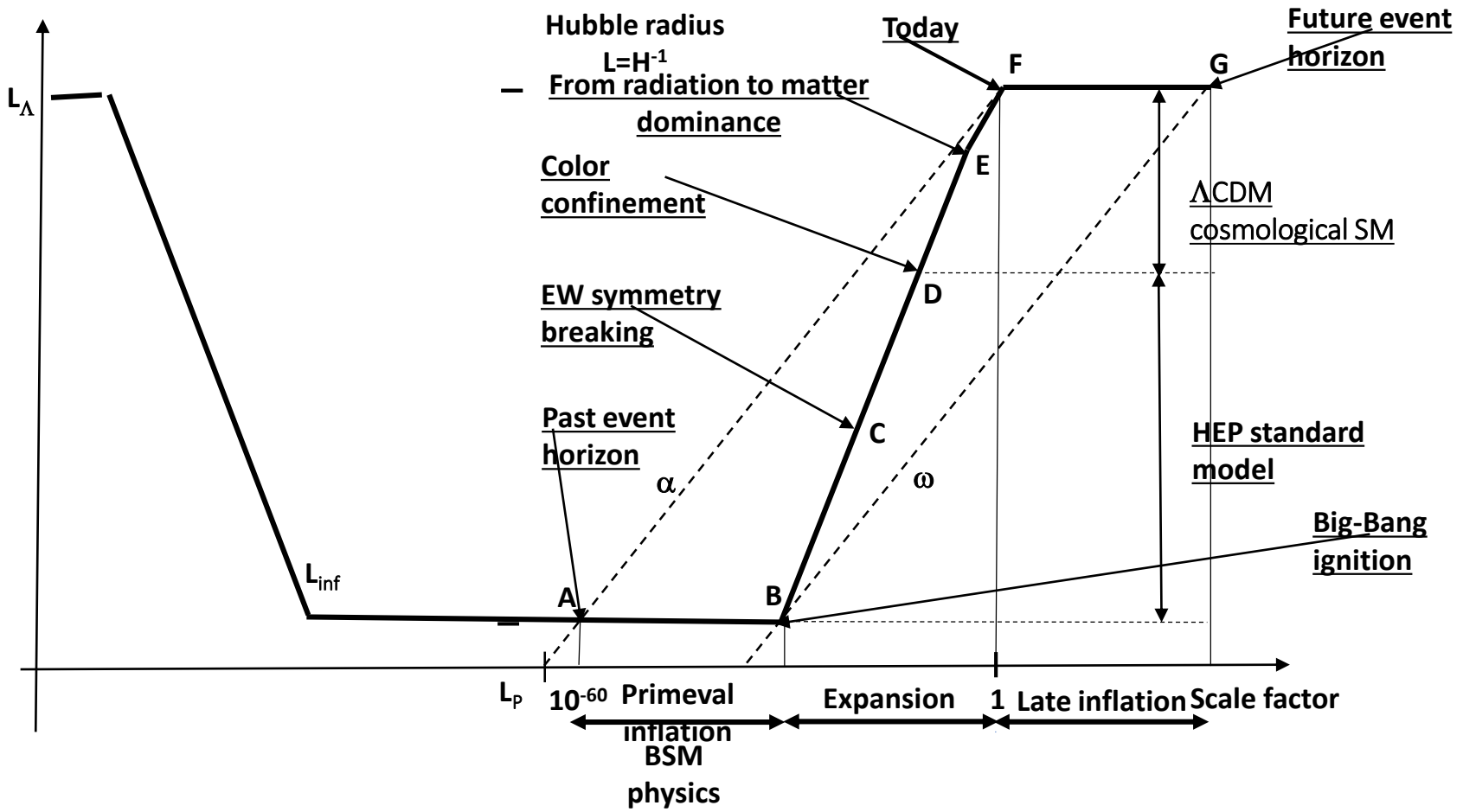
(many thanks to Gabriele Veneziano)



Th e « big bounce model »

(many thanks to Gabriele Veneziano)

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Λ and the principle of the relativity of inertia

Postscript

Prof. Einstein, to whom I had communicated the principal contents of this paper, writes "to my opinion, that it would be possible to think of a universe without matter is unsatisfactory. On the contrary the metric field *must be determined by matter, without which it cannot exist* [underlined by de Sitter] This is the core of what I mean by the **postulate of the relativity of inertia**". He therefore postulates what I called above the logical impossibility of supposing matter not to exist. I can call this the "material postulate" of the relativity of inertia. This can only be satisfied by choosing the system A, with its **world-matter**, i.e. by introducing the constant λ, and assigning to the time a separate position amongst the four coordinates.

On the other hand, we have the "mathematical postulate" of the relativity of inertia, i.e. the postulate that the shall be invariant at infinity. This postulate, which, as has already been pointed out above, has no physical meaning, makes no mention of matter. It can be satisfied by choosing the system B, without a world-matter, and with complete relativity of the time. But here also we need the constant λ. **The introduction of this constant can only be avoided by abandoning the postulate of the relativity of inertia altogether.**

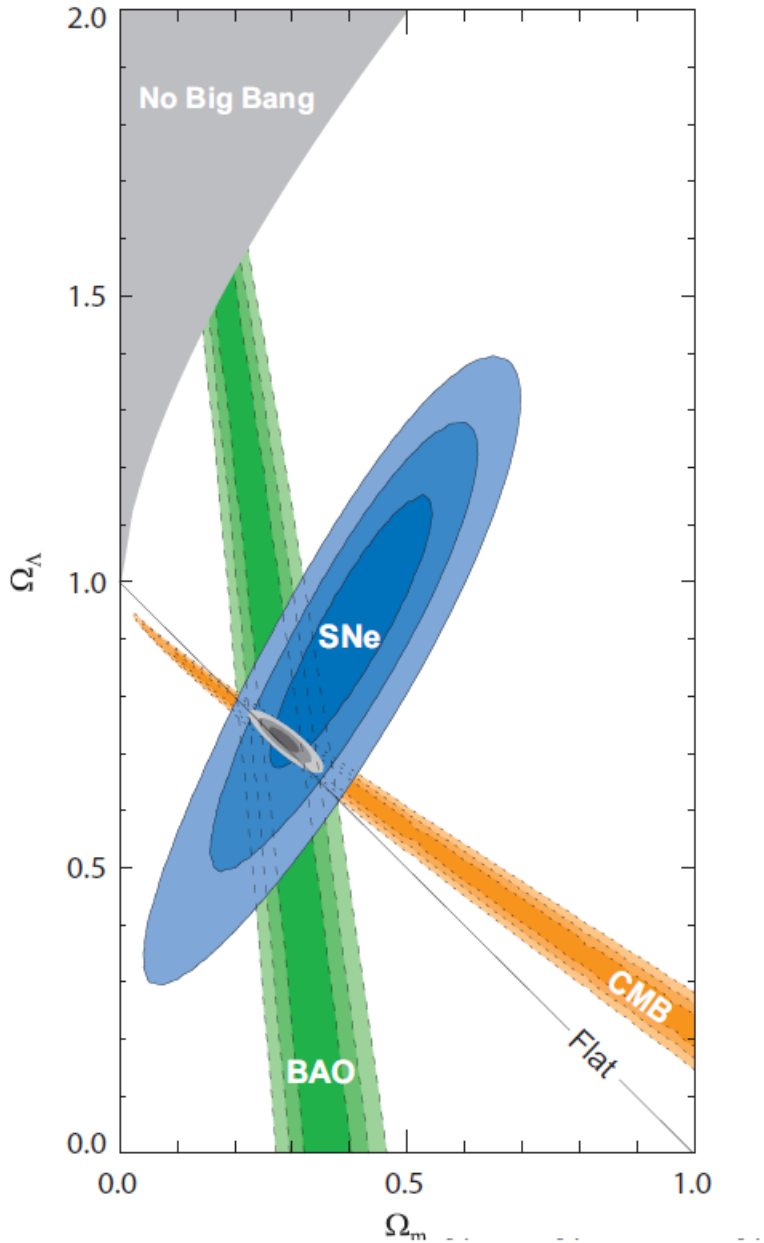
De Sitter *KNAW Proceedings 1917*

and no gravitational field is present. The assumption of the complete physical equivalence of the systems of co-ordinates, K and K', we call the "principle of equivalence;" this principle is evidently intimately connected with the theorem of the equality between the inert and the gravitational mass, and signifies an extension of the principle of relativity to co-ordinate systems which are in non-uniform motion relatively to each other. In fact, through this conception we arrive at the unity of the nature of inertia and gravitation. For according to our way of looking at it, the same masses may appear to be either under the action of inertia alone (with respect to K) or under the combined action of inertia and gravitation (with respect to K'). The possibility of explaining the numerical equality of inertia and gravitation by the unity of their nature gives to the general theory of relativity, according to my conviction, such a superiority over the conceptions of classical mechanics, that all the difficulties encountered in development must be considered as small in comparison.

Einstein, *Princeton conference,* 1921

Although all of these effects are inaccessible to experiment, because κ is so small, nevertheless they certainly exist according to the general theory of relativity. We must see in them a strong support for Mach's ideas as to the relativity of all inertial actions. If we think these ideas consistently through to the end we must expect the *whole* inertia, that is, the *whole* $g_{\mu\nu}$-field, to be determined by the matter of the universe, and not mainly by the boundary conditions at infinity.

Einstein, *1921 Princeton conference*


2.0
1.5
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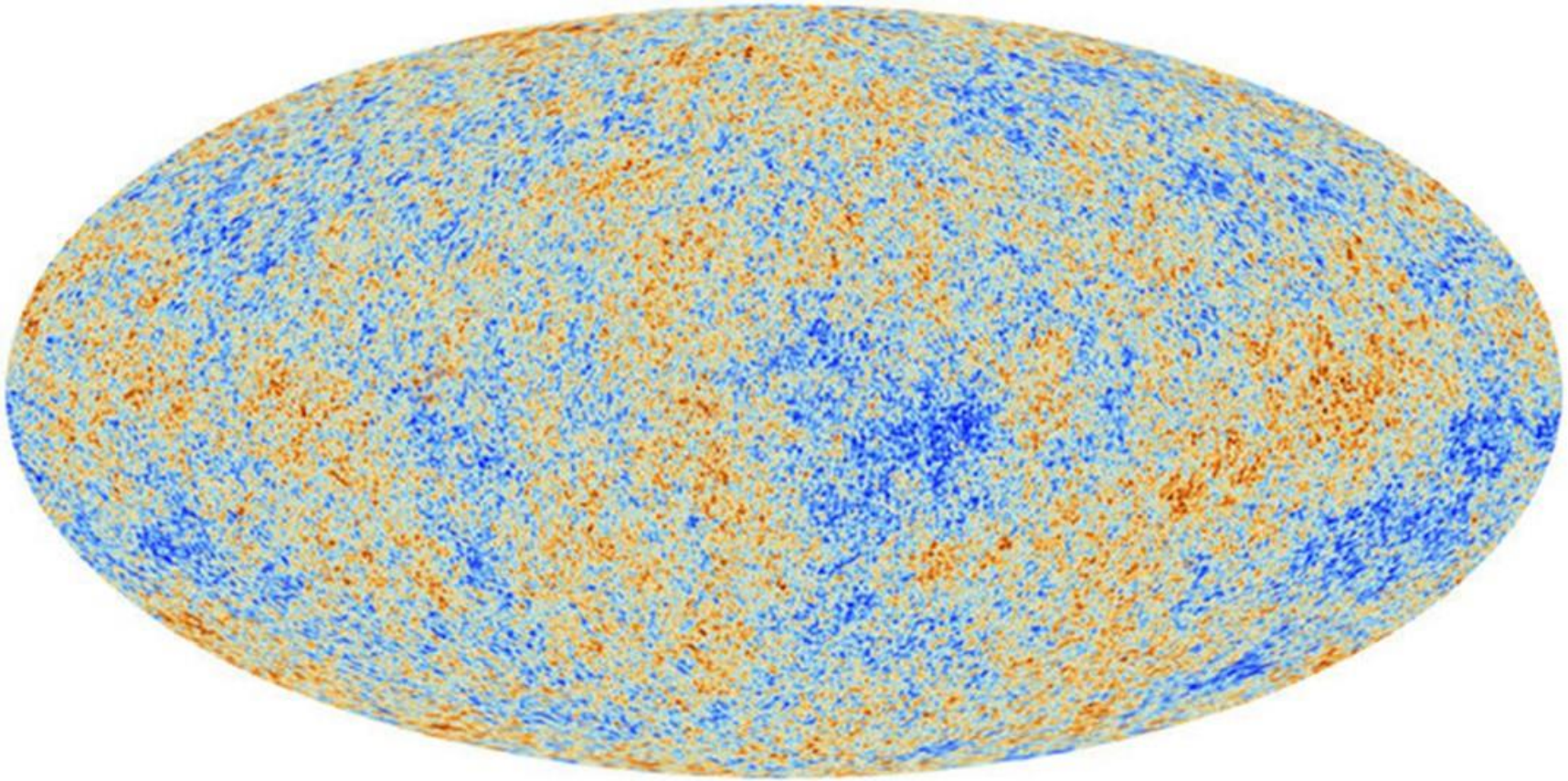
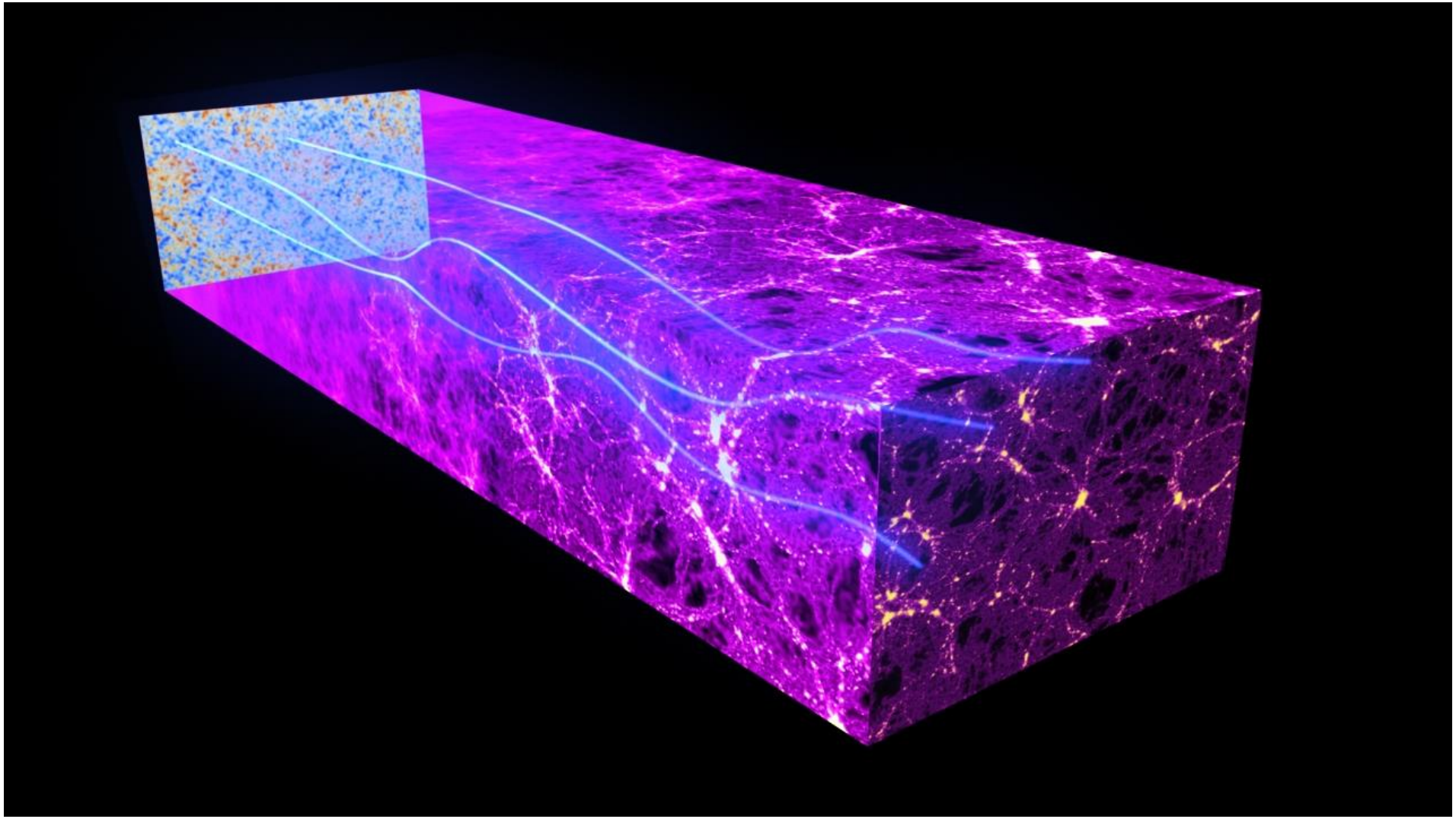
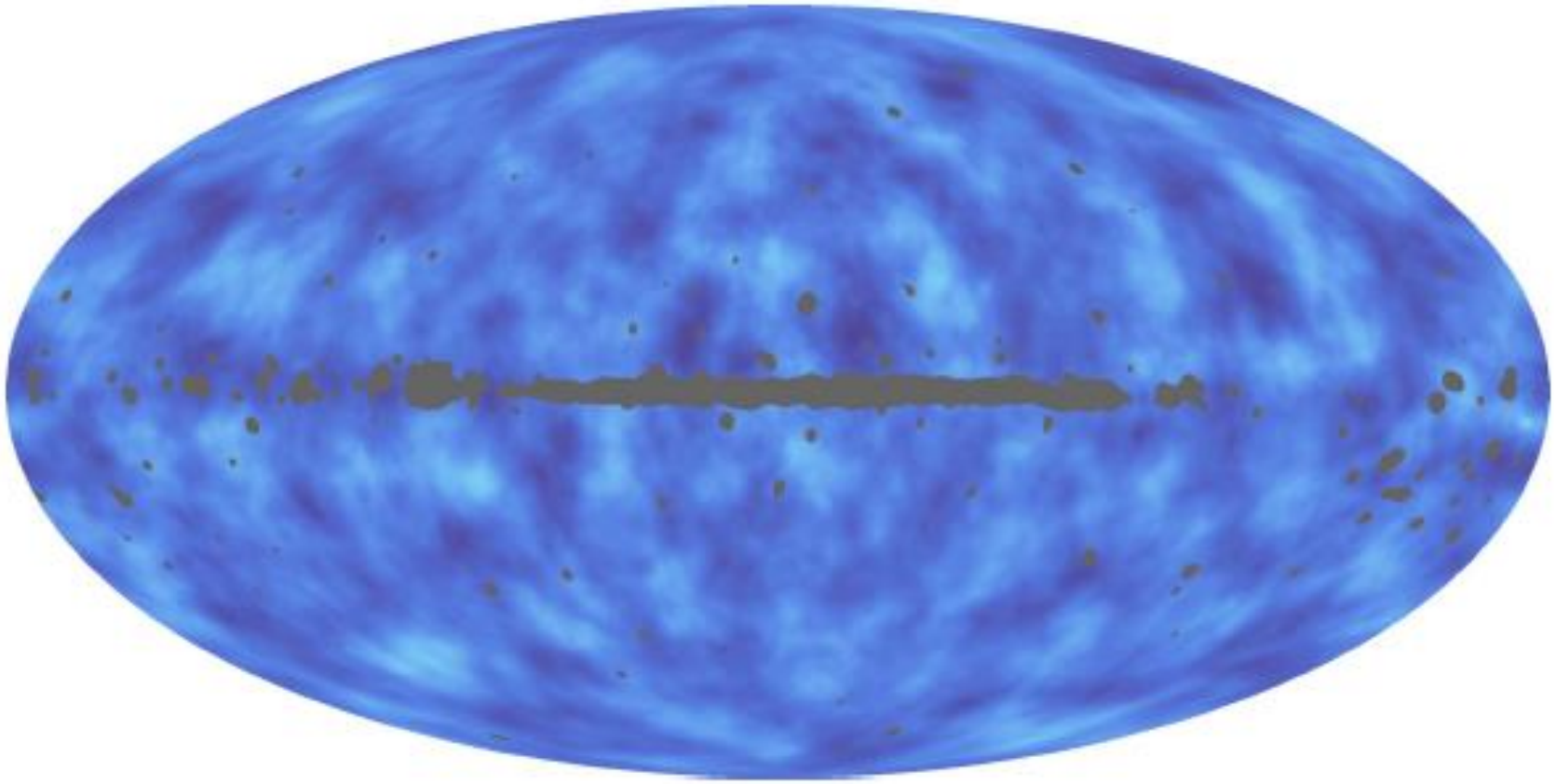
Ω_Λ
Ω_m
No Big Bang
SNe
CMB
BAO
Flat

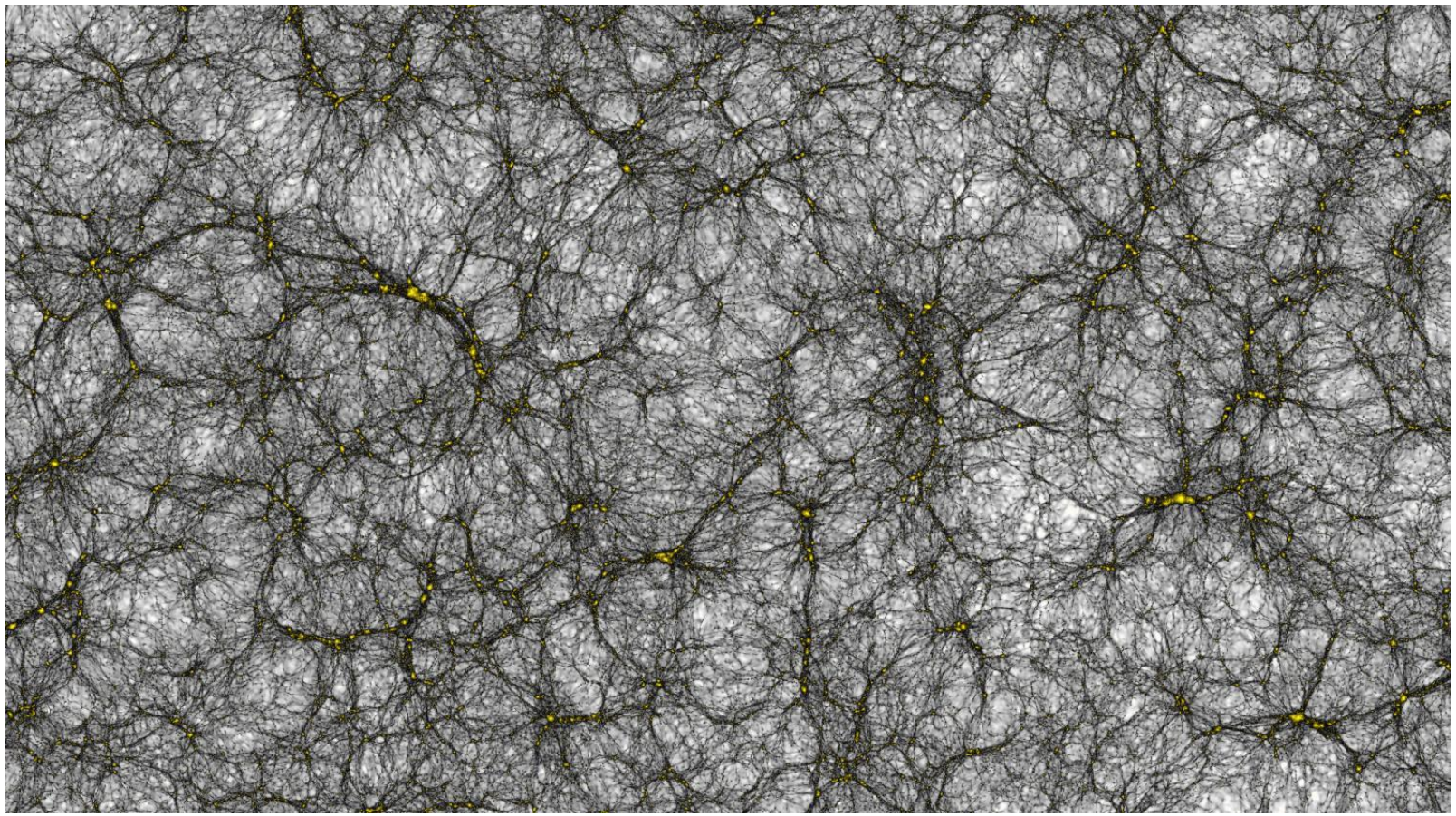


Planck 2015 CMB Map

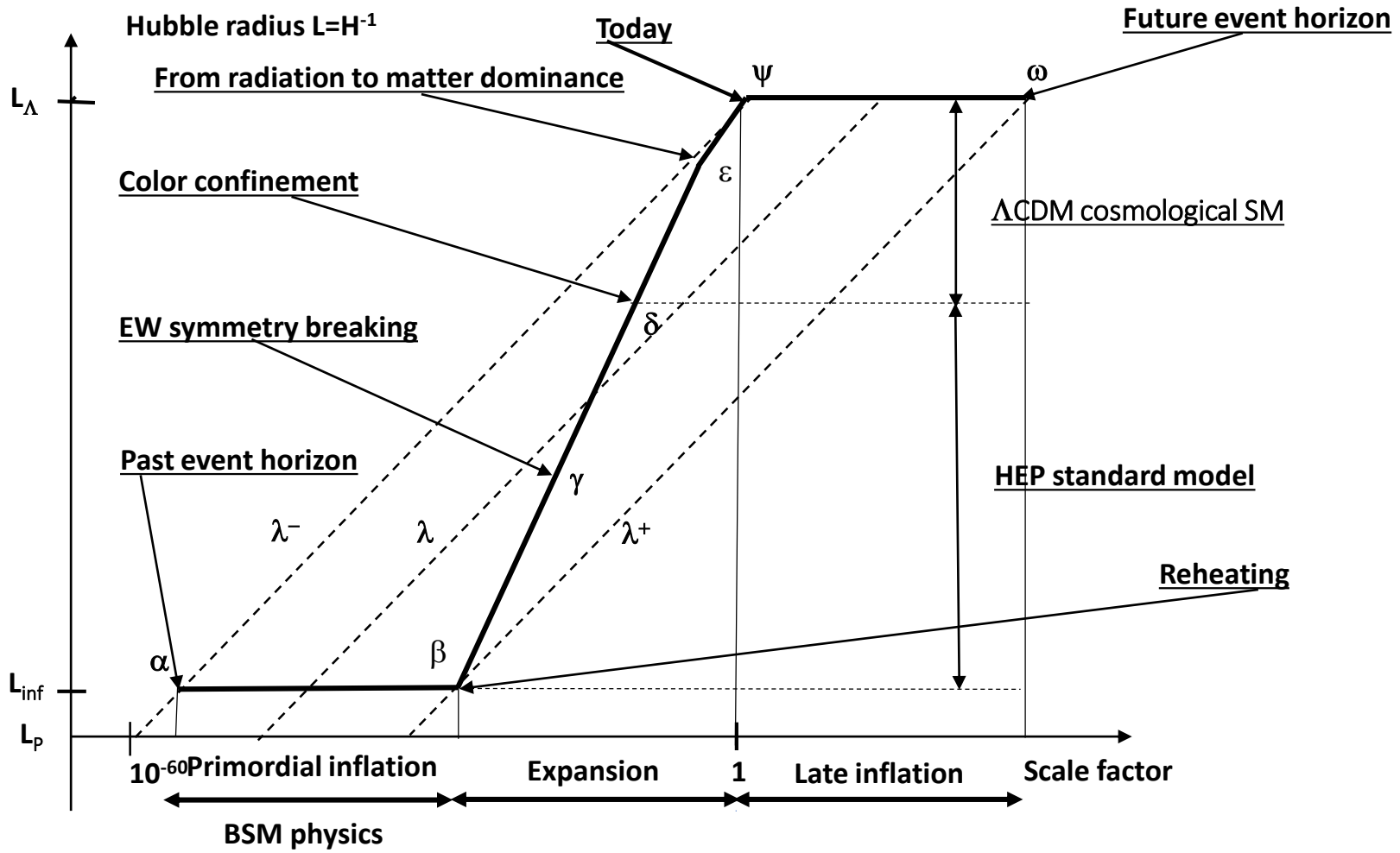




Map of the lensing potential from Planck 2015 result overview



THE LARGEST VIRTUAL UNIVERSE EVER SIMULATED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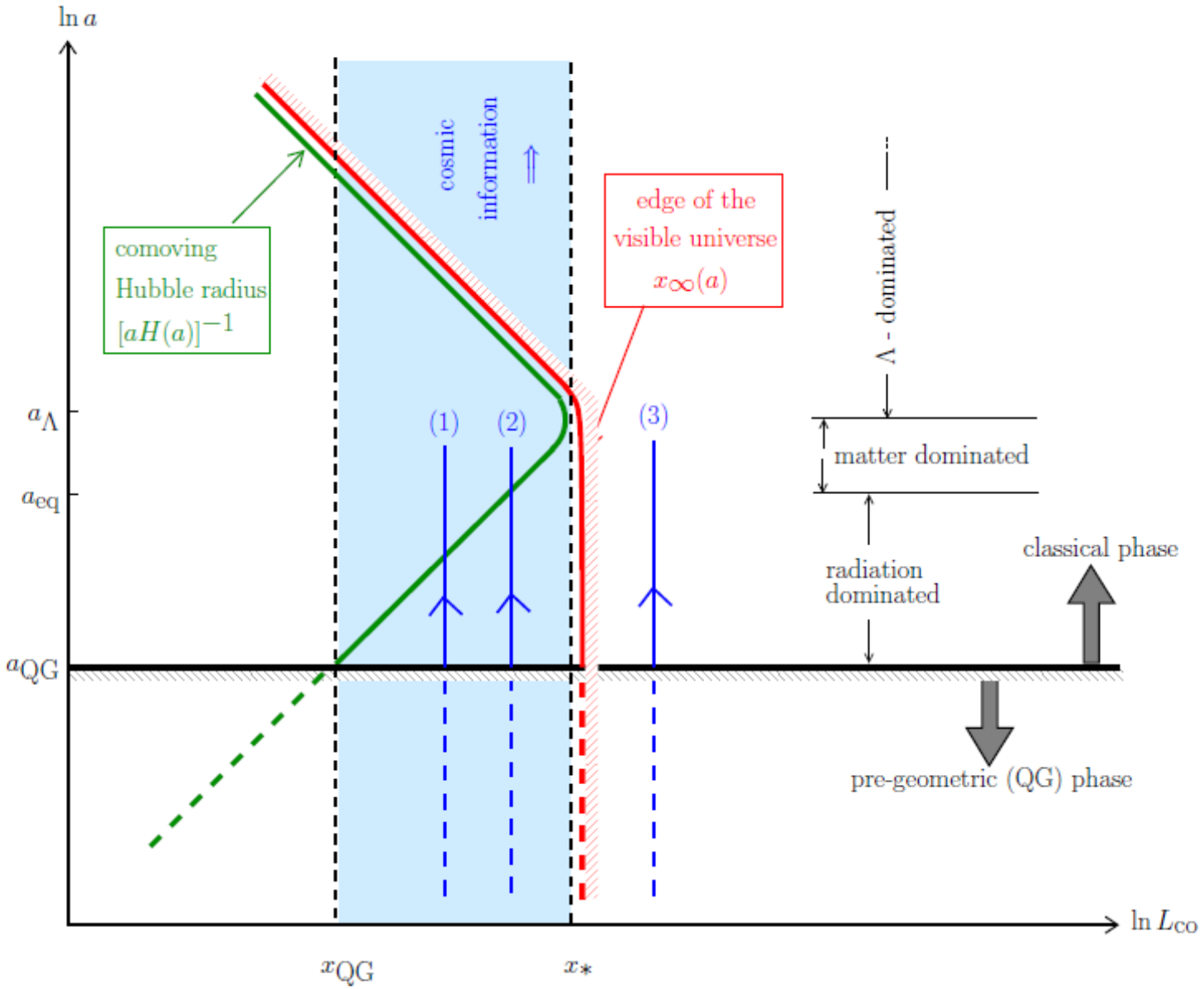


Figure 1: Various length scales of interest in cosmological evolution. See text for discussion.

The simplest way to ensure that $(\rho+3p) < 0$ at late times without invoking untested physics (like e.g., quintessence) is to introduce a non-zero cosmological
constant, with energy density ρ_Λ. The expansion of such a universe, for, $a > a_{QG}$ is driven by the energy density of matter $\rho_M \propto a^{-3}$, radiation $\rho_R \propto a^{-4}$ and the cosmological constant ρ_Λ

We show that (i) the numerical value of the cosmological constant, as well as (ii) the amplitude of the primordial, scale invariant, perturbation spectrum can be determined in terms of a single free parameter, a_{QG} which specifies the energy scale at which the universe makes a transition from a pre-geometric phase to the classical phase. For a specific value of the parameter, we obtain the correct results for both (i) and (ii).

Cosmic Information, the Cosmological Constant and the Amplitude of primordial perturbations T. Padmanabhan & H. Padmanabhan
https://arxiv.org/abs/1703.06144v1

ΛCDM and the principle of relativity of inertia

The flatness sum rule

$$\left(\Omega_k \equiv -k / R_0^2 H_0^2 = 0.0008^{+0.0040}_{-0.0039}\right)$$

$$\rho_{\mathrm{M}} + \rho_{\mathrm{R}} + \rho_{\mathrm{DM}} + \rho_{\mathrm{DE}} = \rho_{\mathrm{c}}$$

$$\rho_{\mathrm{c}} \equiv 3H^2 / 8\pi G_N$$

$$\rho_{\mathrm{DE}} = \rho_{\Lambda} = \Lambda / 8\pi G_N$$

Relativity of inertia

$$\rho(\text{Matter}) = \rho(\text{Inertia})$$

$$\rho(\text{Matter}) = \rho_{\mathrm{M}} + \rho_{\mathrm{R}} + \rho_{\mathrm{DM}}$$

$$\rho(\text{Inertia}) = \rho(\text{World-Matter}) = \rho_{\mathrm{c}} - \rho_{\Lambda}$$

(Λ constant of integration)

$$\rho(\text{World-Matter}) = -P(\text{World-Matter})$$

$$\left(w = -1.019^{+0.075}_{-0.080}\right)$$

$$\rho(\text{Matter}) + P(\text{World-Matter}) = 0$$

Vanishing of volume entropy

The foundational role played by the five constants, *c, h, k, G* and Λ, considered by Einstein

when they are brought together. In this the physical assumption is essential that the relative lengths of two measuring rods and the relative rates of two clocks are independent, in principle, of their previous history. But this assumption is certainly warranted by experience; if it did not hold there could be no sharp spectral lines; for the single atoms of the same element certainly do not have the same history, and it would be absurd to suppose any relative difference in the structure of the single atoms due to their previous history if the mass and frequencies of the single atoms of the same element were always the same.

Einstein, *Princeton conference,* 1921

Recapitulating, we may say that according to the general theory of relativity space is endowed with physical qualities; in this sense, therefore, there exists an ether. According to the general theory of relativity space without ether is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this ether may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

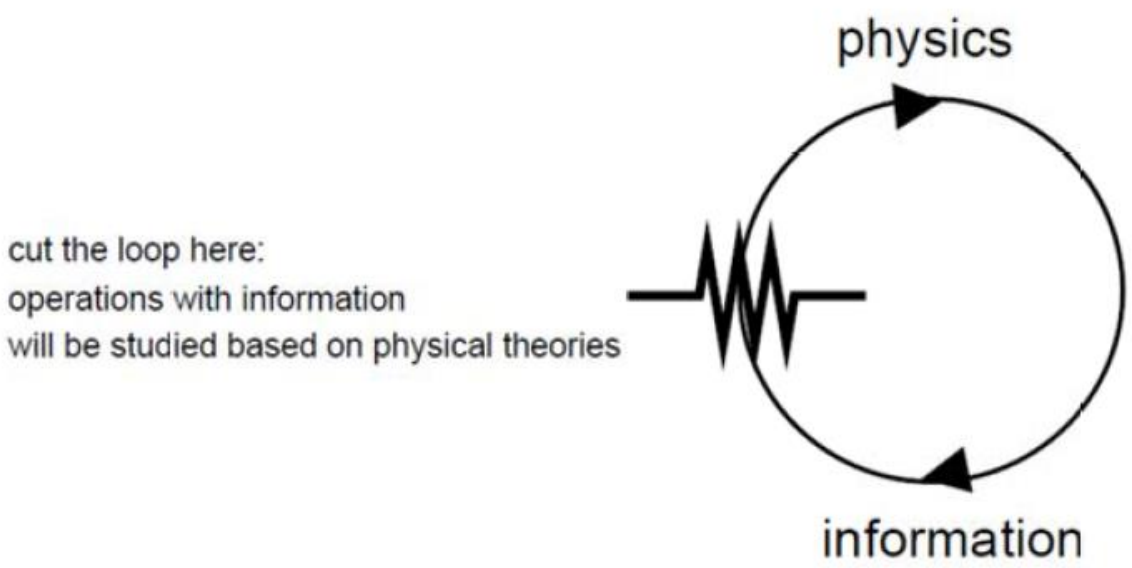
Einstein, *University of Leyden,* 1921

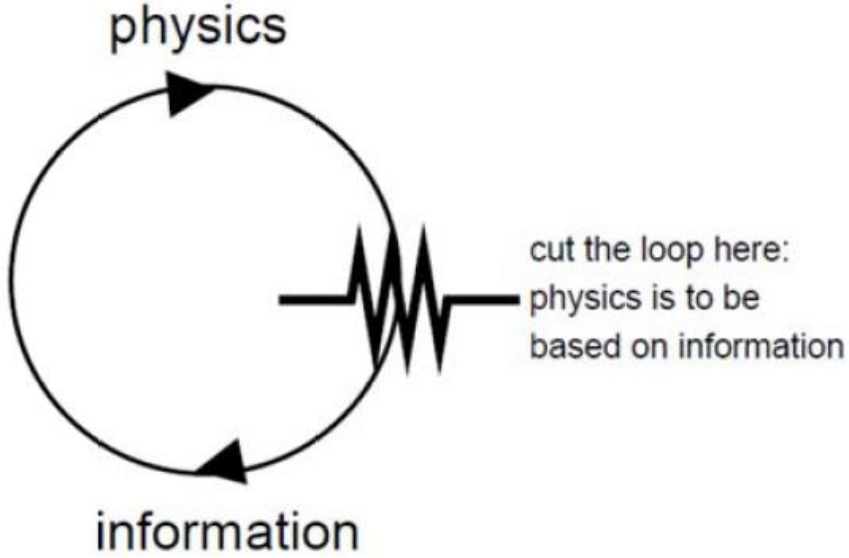
On epistemological modesty

"One is struck [by the fact] that the theory [of special relativity] Introduces two kinds of physical things, i.e., (1) measuring rods and clocks, (2) all other things, e.g., the electromagnetic field, the material point, etc. This, in a certain sense, is inconsistent; strictly speaking measuring rods and clocks would have to be represented as solutions of the basic equations (objects consisting of moving atomic configurations), not, as it were, as theoretically self-sufficient entities. However, the procedure justifies itself because it was clear from the very beginning that the postulates of the theory are not strong enough to deduce from them sufficiently complete equations in order to base upon such a foundation a theory of measuring rods and clocks." (Einstein, 1969, p. 59)

A. Grinbaum, Philosophica 83 (2010) pp. 139-150

Two ways of cutting the epistemic loop implied by the existence of two elementary quanta in physics and in information

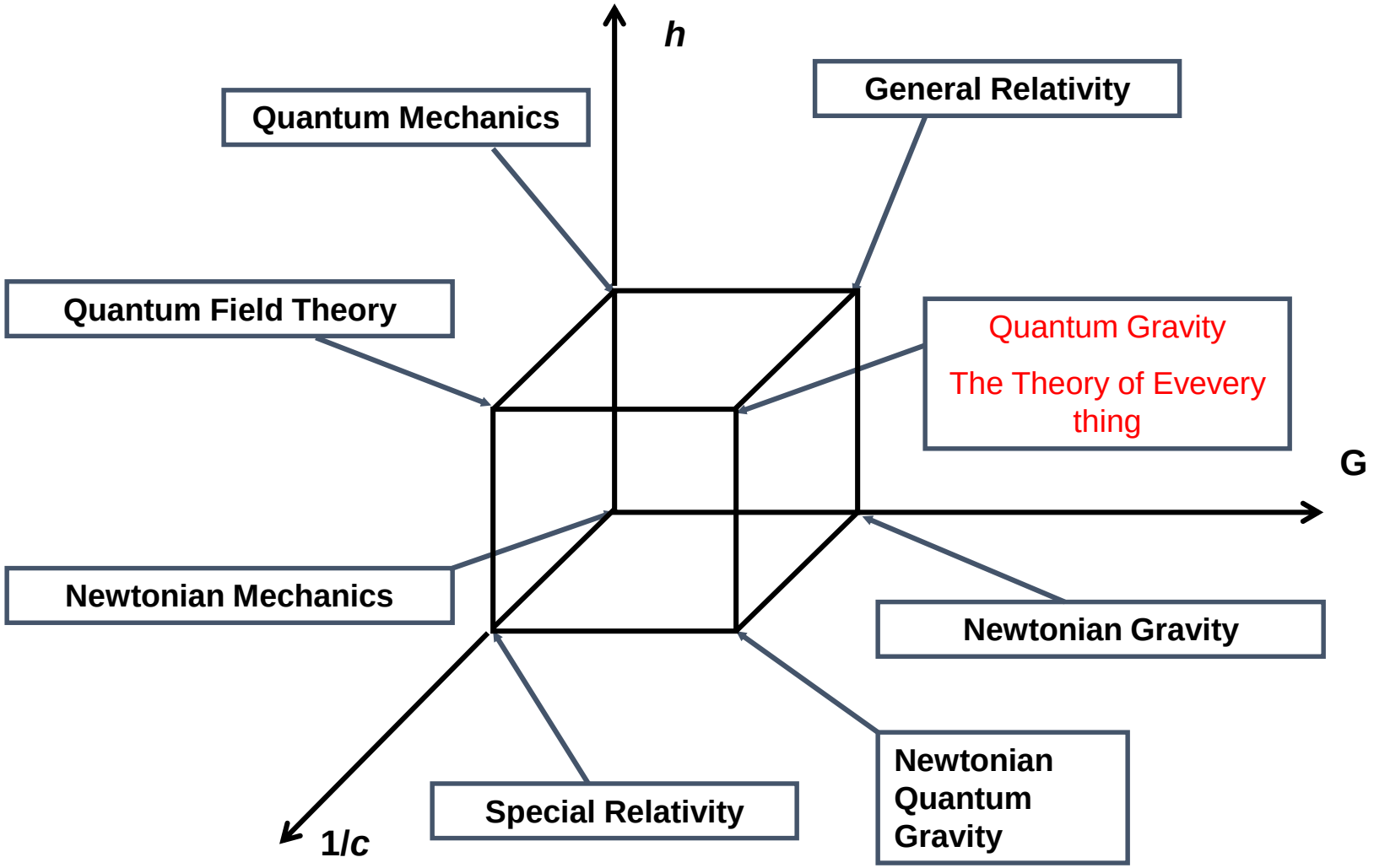


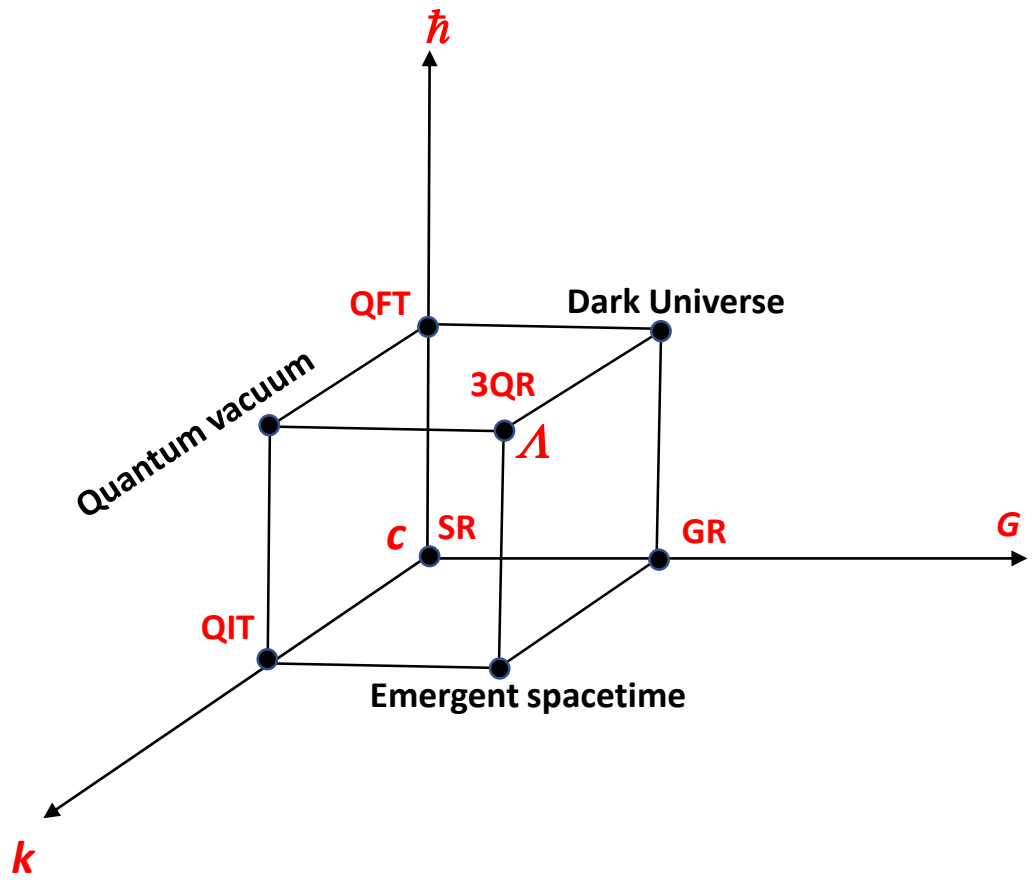


Information is physical

Physics is informational

THE CUBE OF THEORIES





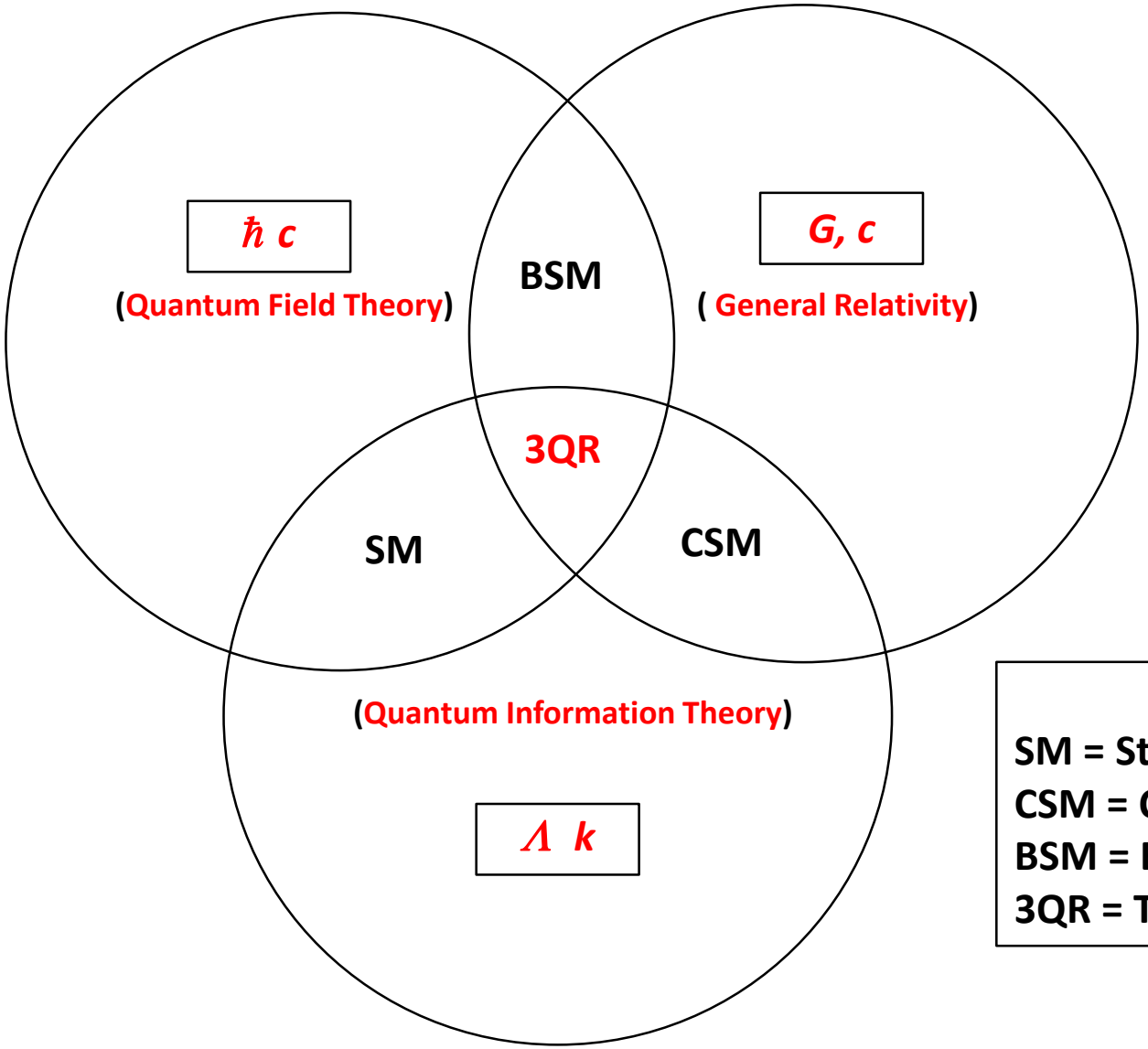
Caption

QFT = Quantum Field Theory
3QR = Thrice Quantized Relativity
SR = Special Relativity
GR = General Relativity
QIT = Quantum Information Theory

$$\text{CosmIn} = \frac{3c^3k}{\hbar G\Lambda}$$

large but finite

THE CUBE OF THRICE QUANTIZED RELATIVITY



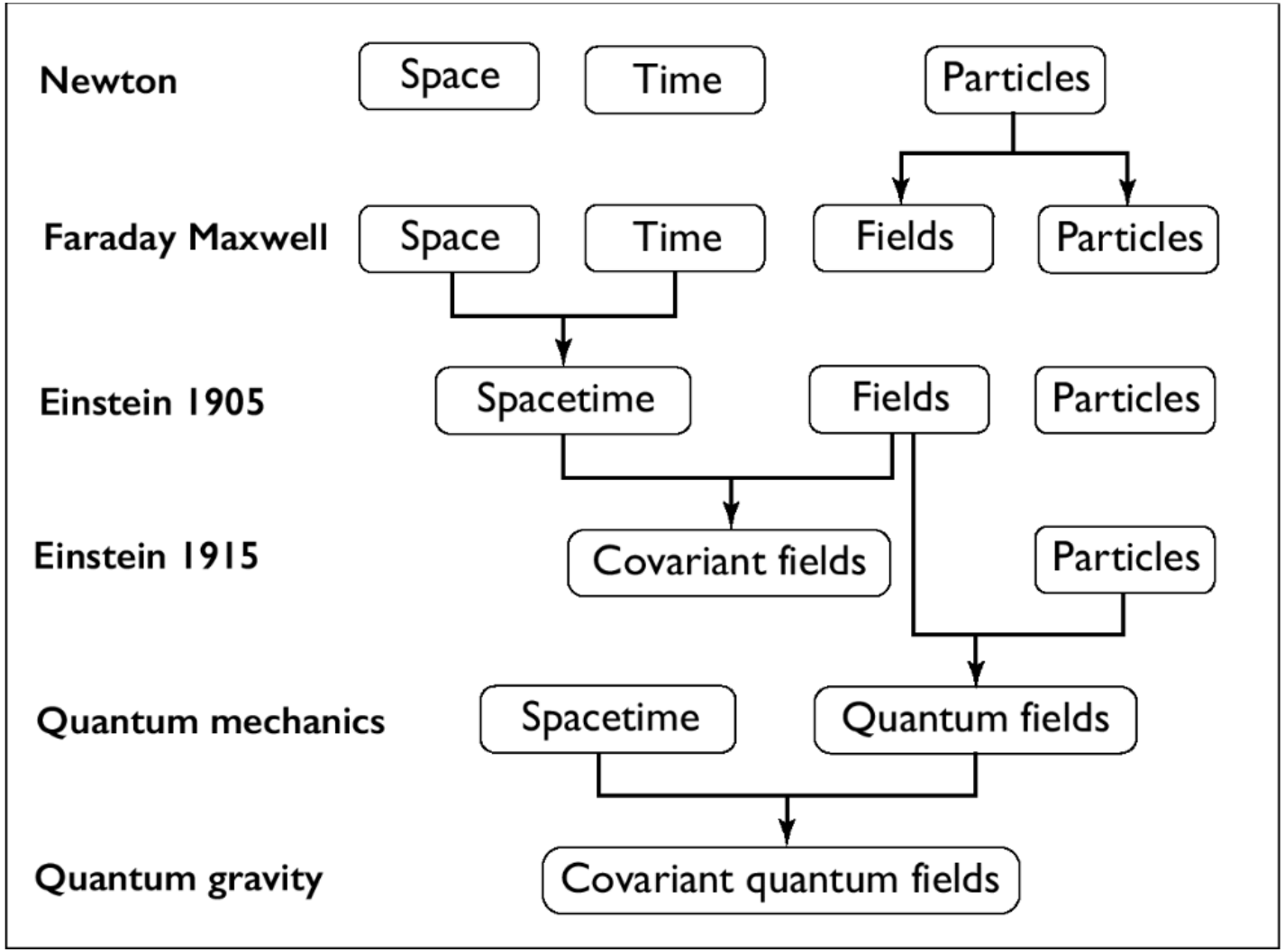
$$\text{CosmIn} = \frac{3c^3 k}{\hbar G \Lambda}$$

large but finite

Caption

SM = Standard Model
CSM = Cosmological Standard Model
BSM = Beyond the Standard Models
3QR = Thrice Quantized Relativity

THE PHENOMENOLOGICAL LANDSCAPE



From Carlo Rovelli, *Reality is not what it seems*

The informational turn of foundational physics

"Nature is earlier than man, but man is earlier than natural science". (**Von Weizsäcker, quoted by Heisenberg)**

"In contrast to the theories of relativity, quantum mechanics is not yet based on a generally accepted conceptual foundation. It is proposed here that the missing principle may be identified through the observation that all knowledge in physics has to be expressed in propositions and that therefore the most elementary system represents the truth value of one proposition, i.e., it carries just one bit of information. Therefore an elementary system can only give a definite result in one specific measurement. The irreducible randomness in other measurements is then a necessary consequence ."

"The universe is participatory at least in the sense that the experimentalist by choosing the measurement apparatus, defines out a set of mutually complementary observables which possible property of a system can manifest itself as reality and the randomness of individual events stems from the finiteness of information. (…) In conclusion, it may be very well said that information is the irreducible kernel from which everything else flows. Then the question why nature appears quantized is simply a consequence of the fact that information itself is quantized by necessity ."

Anton Zeilinger

The speed of light *c* is a quantity which intervenes as a 'universal constant' in the equations of physics. But if one takes as a unit of time, not the second, but the time that light takes to go 1 cm, c no longer appears in the equations. In this sense, Ie the constant *c* is only an apparent universal constant. It is manifest, and universally admitted, that it would also be possible to eliminate universal constants by introducing instead of the gram and the centimeter, adequately selected 'natural' units (e.g. mass and and the radius of the electron).

Imagine that this has been realized [elimination of two universal constants to the benefit, for example of the mass and the radius of the electron]; then there appear in the fundamental equations of physics only dimensionless constants. About them, I would like to enunciate a principle which, provisionally, cannot be based on nothing else than on my confidence in the simplicity, or rather in the intelligibility of Nature: there is no arbitrary constant of this type. In other words: Nature is such that it is logically possible to establish laws that are so strongly defined that only constants susceptible of a complete rational determination appear in them (there are therefore no constants whose numerical values can be modified without the theory being destroyed)

Einstein, *Scientific Autobiography*

The very fact that the totality of our sense experiences is such that by means of thinking (operations with concepts, and the creation and use of definite functional relations between them, and the coördination of sense experiences to these concepts) it can be put in order, this fact is one which leaves us in awe, but which we shall never understand. One may say "the eternal mystery of the world is its comprehensibility." It is one of the great realisations of Immanuel Kant that the setting up of a real external world would be senseless without this comprehensibility.

Einstein, *Physics and reality, 1935*

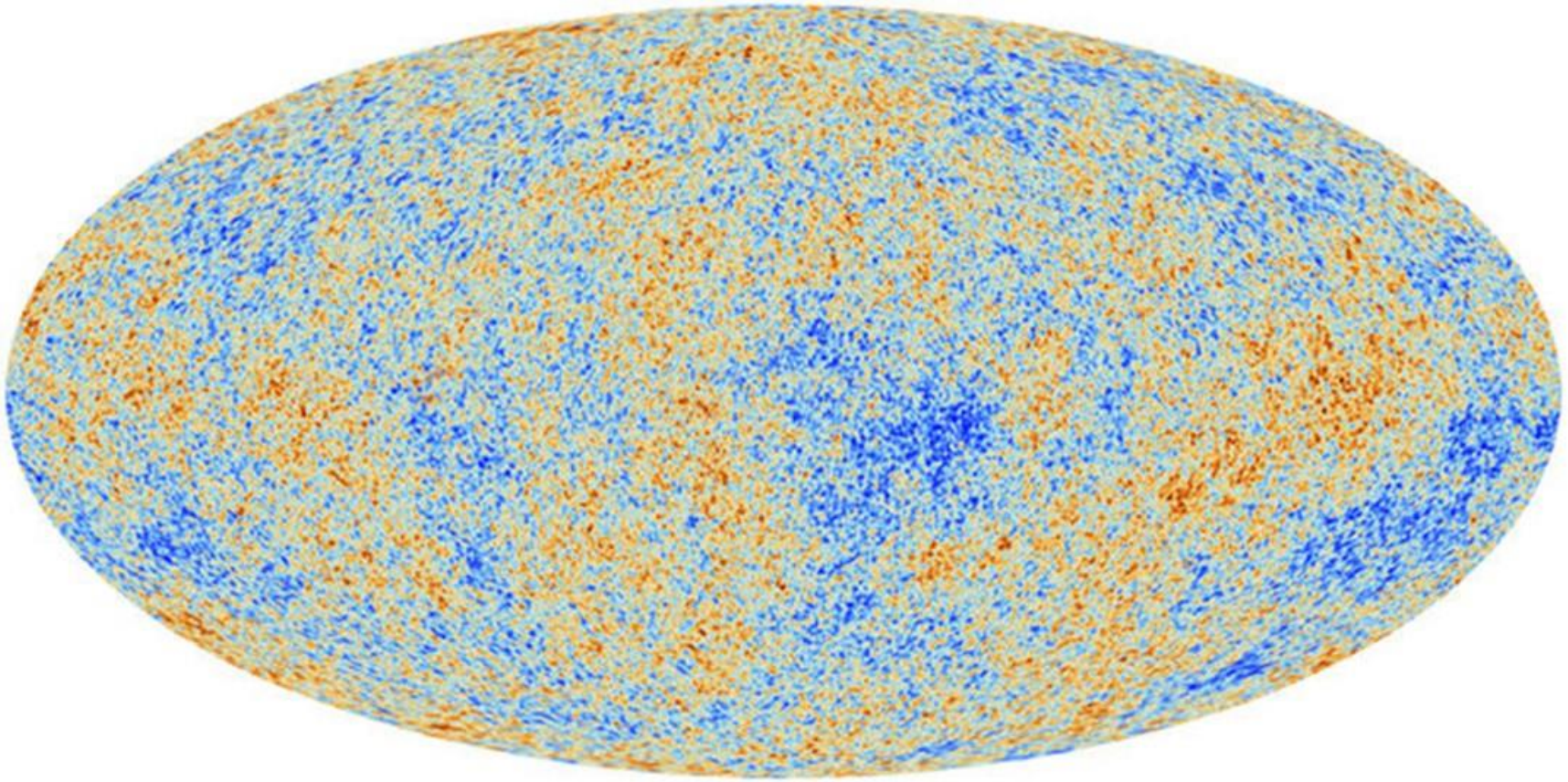
$$\mathrm{CosmIn} = \frac{3c^3 k}{\hbar G \Lambda}$$

large but finite

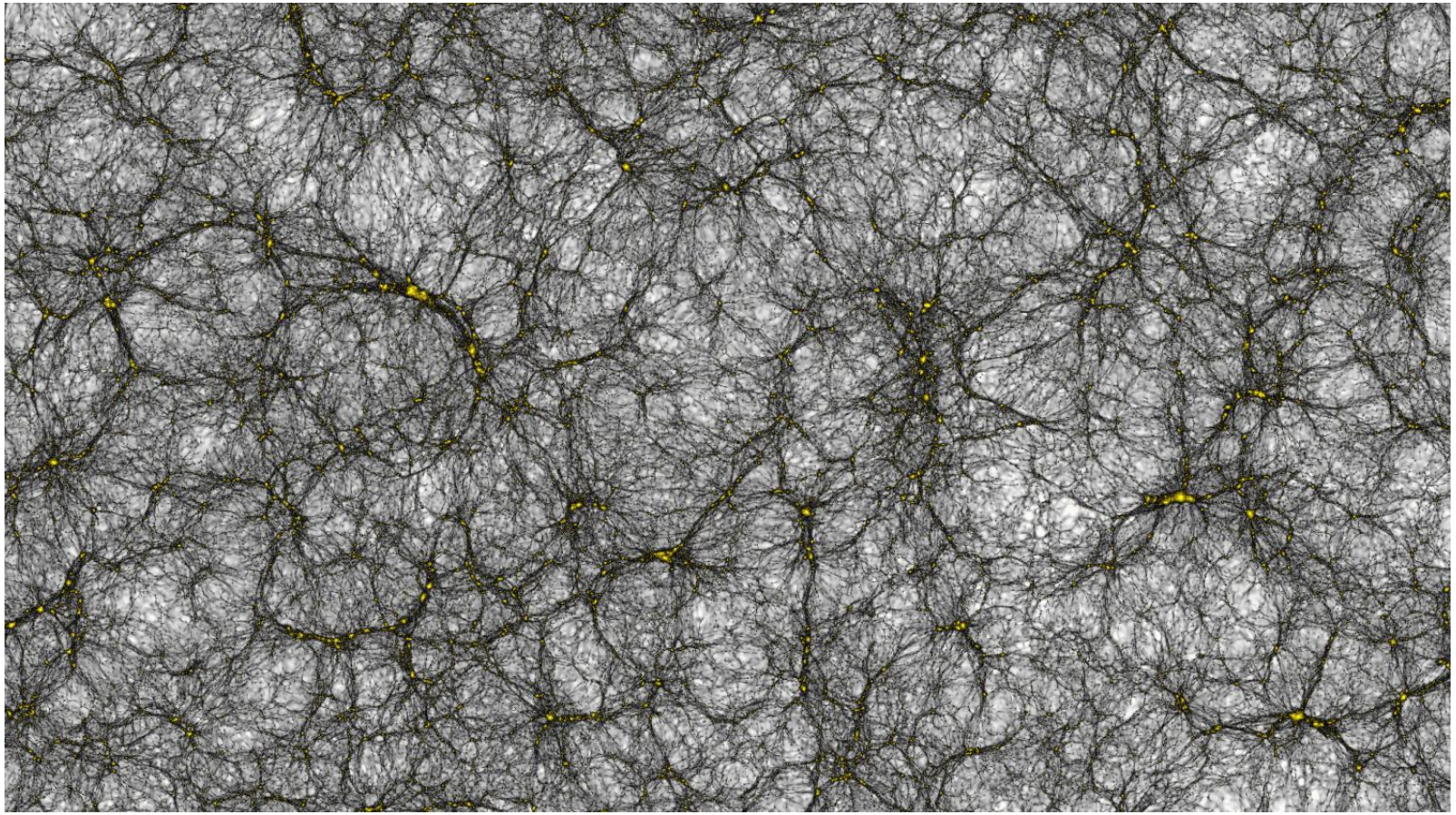
ΛCDM is a quasi-classical (*h* small), quasi-Newtonian (*c* large), quasi-perfect (*G*, Λ, *k* small), cosmology

but it is not a universe!


Ceci n'est pas une pipe.



This is not a universe



This is not a universe