The dark universe and the quantum vacuum

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The Einstein's equation

The unknown: the metric of space-time

$$R_{\mu\nu}(x) - \frac{1}{2} g_{\mu\nu}(x) R + \Lambda g_{\mu\nu}(x) = -\kappa T_{\mu\nu}(x)$$

Space-time curvature

The cosmological constant

Energy tensor of matter

Proportionality constant
$\kappa = G / c^2$

Matter tells space-time how it must be curved; space-time tells matter how it must move

The Friedman Lemaître equations

The Einstein equation

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\mathcal{R} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Matter content of the universe, perfect fluid

$$T_{\mu\nu} = -p g_{\mu\nu} + \left(p + \rho\right) u_\mu u_\nu$$

$u = \left(1, 000\right)$ velocity vector for the isotropic fluid in comoving coordinates

Friedman-Lemaître equations

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}$$

Energy conservation, via $T^{\mu\nu}_{;\mu} = 0$

$$\dot{\rho} = -3H\left(\rho + p\right)$$

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G}{3}\left(\rho + 3p\right)$$

Definition of cosmological parameters

$$\rho_c \equiv \frac{3H^2}{8\pi G_N}$$

$$\Omega_{\mathrm{tot}} = \rho / \rho_c$$

$$k / R^2 = H^2 \left(\Omega_{\mathrm{tot}} - 1\right)$$

$$k / R_0^2 = \left(\Omega_{\mathrm{M}} + \Omega_{\mathrm{R}} + \Omega_{\mathrm{V}} - 1\right)$$

In ΛCDM

$$k = 0$$

$$\Omega_{\mathrm{M}} = \Omega_{\mathrm{b}} + \Omega_{\mathrm{DM}}$$

$$\Omega_{\mathrm{tot}} = \Omega_{\mathrm{b}} + \Omega_{\mathrm{R}} + \Omega_{\mathrm{DM}} + \Omega_{\mathrm{DE}} = 1$$

Vanishing of spatial curvature = vanishing of "total energy"?

Big bang cosmology,

K. Nakamura et al. (PDG), JP G 37 0750021 (2010)

"Eq. (19.8) has a simple classical mechanical analog if we neglect (for the moment) the cosmological term Λ. By interpreting $-k/R^2$ Newtonianly as a 'total energy', then we see that the evolution of the Universe is governed by a competition between the potential energy, $8\pi G_N\rho/3$, and the kinetic term $(H_0)^2$."

However, "the usage of referring $-k/R_0^2H_0^2$ as Ω_k is unfortunate: it encourages one to think of curvature as a contribution to the energy density of the Universe, which is not correct"

Emergent perspective of gravity and dark energy

T. Padmanabhan ArXiv: 1207,0505
***Gravity and/is thermodynamics* ArXiv:1512,06546**
***Exploring the nature of gravity* ArXiv: 1602.011474**

In the conventional approach, gravity is treated as a field which couples to the energy density of matter. The addition of a cosmological constant — or equivalently, shifting of the zero level of the energy — is not a symmetry of the theory and the field equations (and their solutions) change under such a shift. In the emergent perspective, it is the *entropy density* rather than the *energy density* which plays the crucial role.

In Friedman universe in expansion, there is a horizon with radius H^{-1} to which is associated an entropy

$S = \left(A/4L_p^{\,2}\right) = \left(\pi / H^2 L_P^{\,2}\right)$ and a temperature $T = \hbar H / 2\pi$

During time interval *dt* the change of gravitational entropy is

$\left(dS/dt\right) = \left(1/4L_P^{\,2}\right)\left(dA/dt\right)$ and the corresponding heat flux

$$T\left(dS/dt\right) = \left(H/8\pi G_N\right)\left(dA/dt\right)$$

Gibbs-Duhem relation for matter

entropy density for matter is $s_m = (1/T)(\rho + P)$

with correspondig heat flux $Ts_m A = (\rho + P)A$

balancing matter and gravitational heat fluxes leads to

$TdS/dt = (\rho + P)A$ which becomes

$\frac{H}{8\pi G_N}\frac{dA}{dt} = (\rho + P)A$, which with $A = 4\pi / H^2$ gives

$$\dot{H} = -4\pi G_N(\rho + P)$$

Which is the correct Friedman equation

Energy conservation for matter

$$\frac{d(\rho a^3)}{dt} = -P\frac{da^3}{dt}$$

$$\dot{\rho} = -3H(\rho + P) = \frac{3H\dot{H}}{4\pi G_N}$$

$$\rho = \frac{3H^2}{8\pi G_N} + \text{ constant} = \rho + \rho_\Lambda$$

The entropy balance condition correctly reproduces the field equation but with an arbitrary cosmological constant acting as an integration constant : the entropy density vanishes for the cosmological constant: ρ_Λ= - P_Λ

When the space-time responds in a manner maintaining entropy balance, it responds to

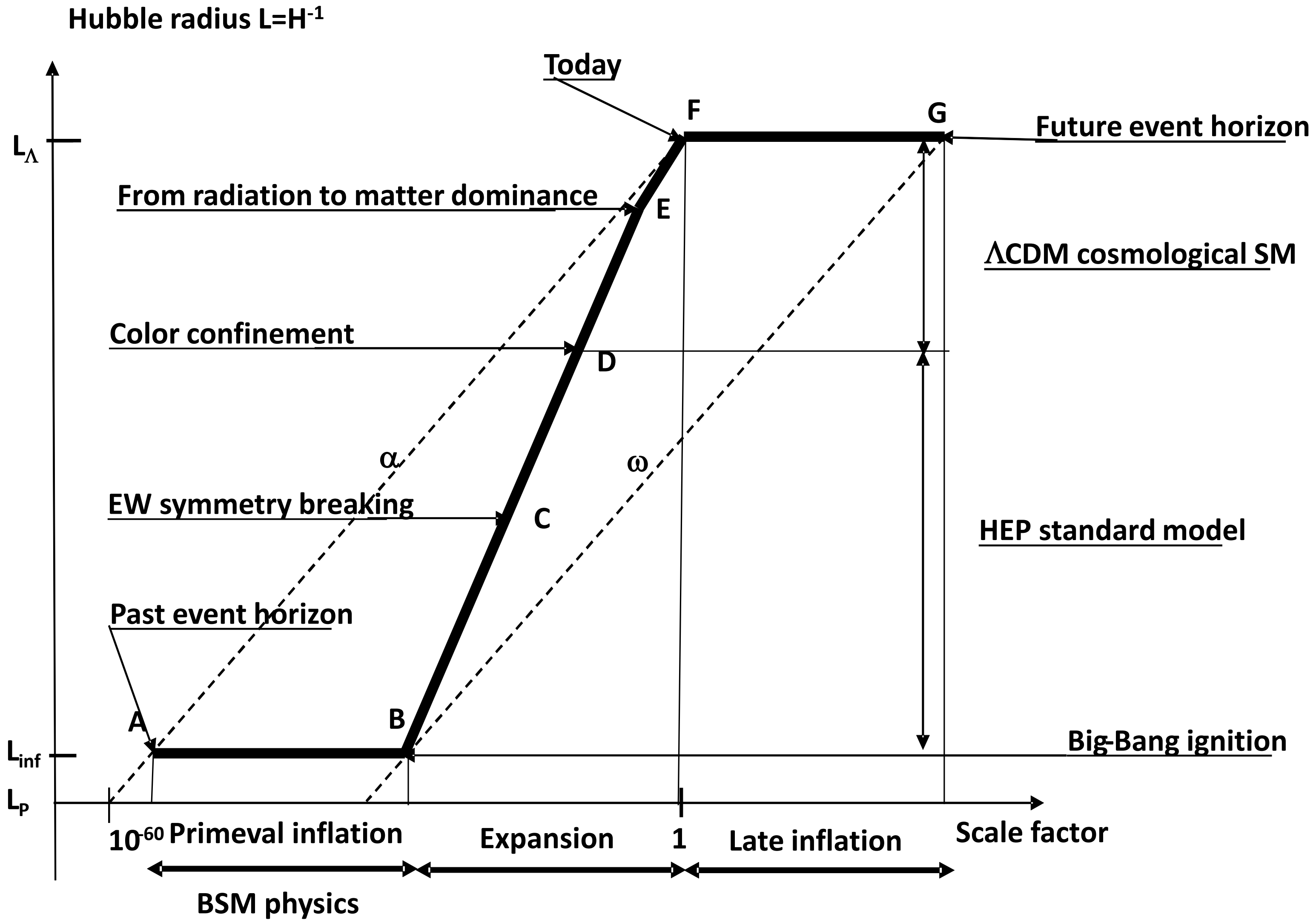
$\rho + P$ or more generally to $T_{\mu\nu} l^{\mu} l^{\nu}$ (where l is a null 4-vector)

which vanishes for the cosmological constant

In other words, shifting the zero level of the energy is the symmetry of the theory in the emergent perspective and gravity does not couple to the cosmological constant. The vanishing of CC would be a direct consequence of this symmetry. The smallness of CC arises as a consequence of the smallness of the symmetry breaking (**'t Hooft naturalness criterion**)

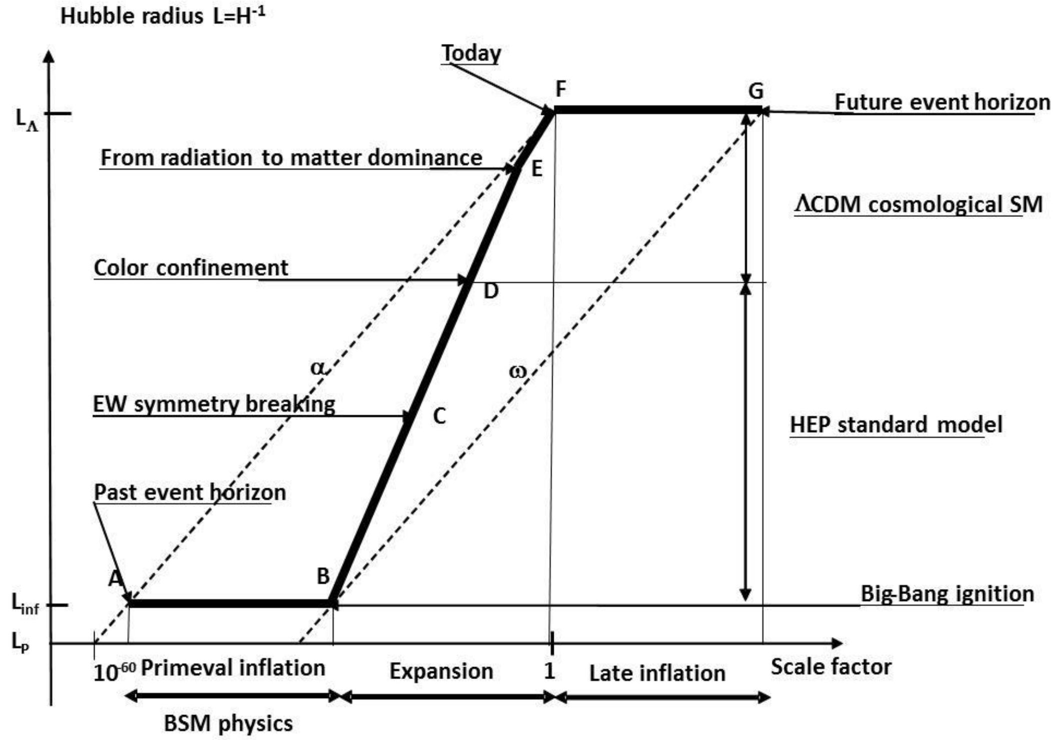
Interpreting the ΛCDM cosmology in the emergent perspective of gravity has led T. Padmanabhan to a solution of the CC problem, and, as we are going to show, could lead to a new approach of the dark matter problem

The ΛCDM cosmology



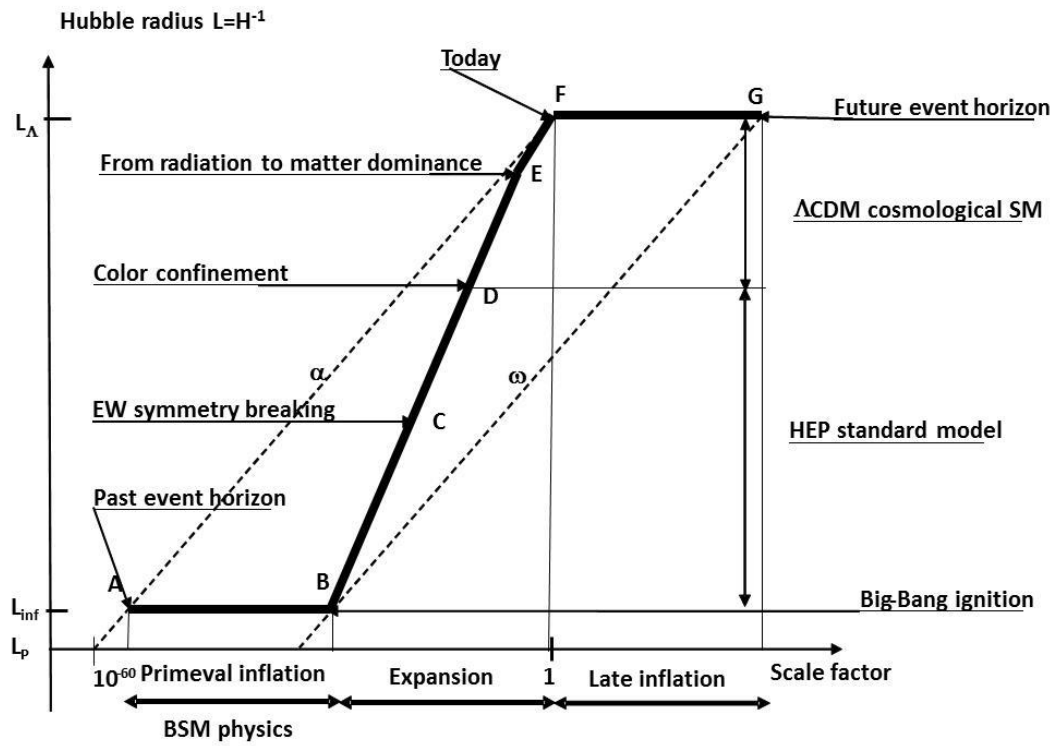
ΛCDM in the emergent perspective of cosmology

- **A conservation law in ΛCDM**: all the modes that exit from the horizon between A and B go through the horizon between B and F and the re-exit the horizon between F and G
- **This conservation law applies to degrees of freedom, that is to entropy and not to energy**
- This means that **the emergent perspective of gravity applies to ΛCDM**

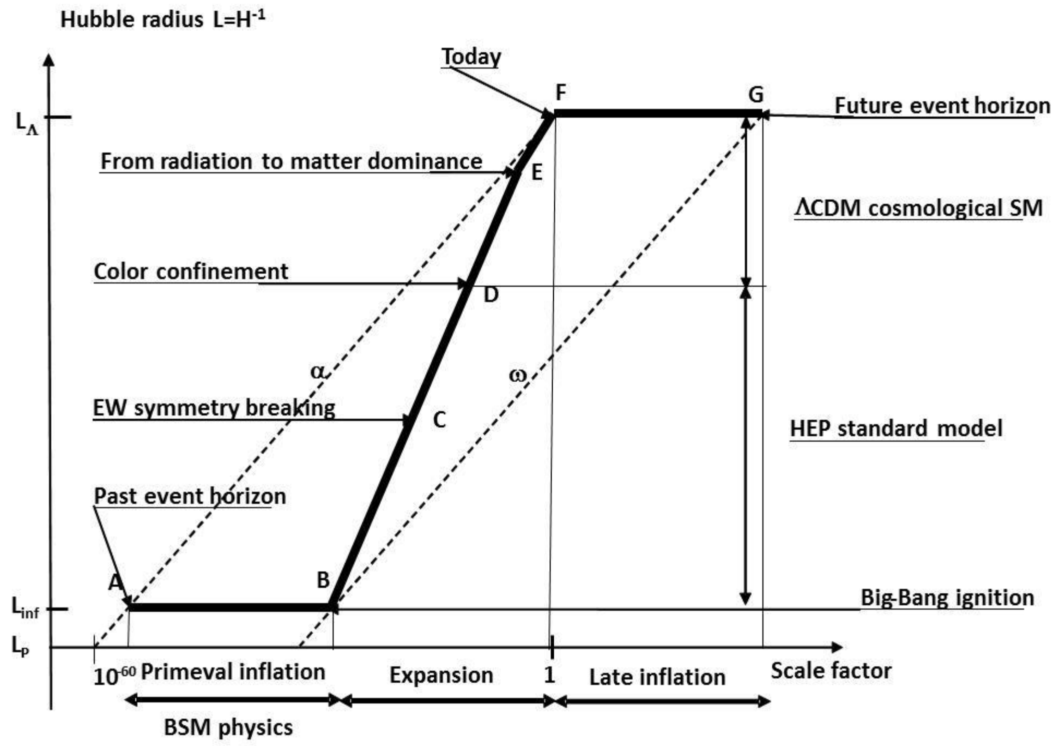


The three stages of the ΛCDM cosmology

- **The primordial inflation stage (AB)**
  - A BSM (beyond the standard model) phase (Quantum gravity? GUT?, SUSY? Superstrings?, Baryo- and lepto-genesis? Axions and axion-like particles?) that replaces the “big bang”
  - Relaxation of the **quantum vacuum** after a quantum fluctuation of matter and gravitational fields that occurred in the remote past: all the particles of the SM (supposed to be mass less before the BEH mechanism) and possible BSM particles are **virtual**
  - the scale factor grows exponentially while the Hubble radius of order of a GUT scale remains constant (de Sitter space-time geometry)
  - Inflation stops at B when the lightest non massless particles of the SM, possibly the neutrinos (with masses of about 1/100 eV, of order of the CC scale) decohere. Point B is called in the literature the **reheating** point. (Bjorken calls it the **ignition of the big bang**).



- **The conventional FLRW phase (BF)**
  - Radiation dominated phase (BE), with L proportional to a^2 that goes through
    - the breaking of the electroweak symmetry at C by means of the BEH mechanism when all SM particles except photons and gluons became massive
    - The confinement of color at D when colorless hadrons (baryons and mesons) were formed.
  - Pressure-less matter dominated phase (EF), with L proportional to $a^{1.5}$, a phase in which occurred the events of the conventional big bang model.
- **The late inflation phase (FG)**
  - The acceleration of the expansion observed today is interpreted as due to a **non vanishing CC**
  - Asymptotically in the future, CC implies the existence of an event horizon at G beyond which the whole matter will be unobservable



The de Sitter geometry of the quantum vacuum

- Before A (**the past event horizon**) and after G (**the future event horizon**), space-time of the observable universe is empty of matter: ρ (matter)=k=0. Inflation is driven by a cosmological constant, an effective CC for the primordial inflation and the observed CC for the late inflation; **the geometry is the one of a de Sitter's universe**
- **A space-time empty of matter is not the nothingness**: it is the quantum vacuum; i.e. a complex medium in which the quantum fields of the standard model, and possibly a quantized gravitational field are subject to **quantum fluctuations**.
- Such a complex medium can be considered as **a perfect fluid with an equation of state $\rho + P = 0$**
- To describe phenomenologically such a medium, we have to include besides the quantum fields of the standard model a (quantum) field to account for gravitation
- In homogeneous and isotropic cosmologies, which are **conformally flat**, the relevant gravitational field is not the metric itself but a **scalar field** related to the determinant of the metric, the **dilaton field ϕ**

ΛCDM in the emergent perspective of gravity

With the **dilaton field ϕ** we write the Friedman equation that translates the **balancing of the heat fluxes of matter and gravity through the horizon**

$$\left\{T_{\mu\nu}(\phi)+T_{\mu\nu}(\text{Matter})\right\}l^{\mu}l^{\nu}=0$$

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

In the conventional model

$$P(\text{Matter})\approx 0$$

$$\rho(\text{Matter})=\rho_{\text{B}}+\rho_{\text{DM}}$$

$$\rho(\phi)=\rho_{\text{DE}}$$

$$P(\phi)=-\frac{3H^2}{8\pi G_N}=-\rho_{\text{c}}$$

$$\rho_{\text{B}}+\rho_{\text{DM}}+\rho_{\text{DE}}=\rho_{\text{c}}$$

The flatness sum rule !

Dark matter associated with matter, not with vacuum

Dark energy (CC) only component associated with vacuum

Our model

$$\left\{T_{\mu\nu}(\phi)+T_{\mu\nu}(\text{Matter})\right\}l^{\mu}l^{\nu}=0$$

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

$$P(\text{Matter})\approx 0$$

$$\rho(\text{Matter})=\rho_{\text{B}}$$

$$\rho(\phi)=\rho_{\text{DE}}+\rho_{\text{DM}}$$

Dark matter and dark energy that have no non-gravitational interactions are components of the **quantum vacuum** and not of the non-vacuum matter

$$P(\phi)=-\frac{3H^2}{8\pi G_N}=-\rho_{\text{c}}=-\frac{\Lambda_{\text{eff}}}{8\pi G_N}$$

The **critical density** is identified with the contribution of an effective **« running » CC**

$$\rho_{\text{B}}+\rho_{\text{DM}}+\rho_{\text{DE}}=\rho_{\text{c}}$$

The flatness sum rule !

Dark energy and sterile neutrinos

- The masses of the neutrinos and the BEH mechanism
  - The SM is compatible with mass less neutrinos: right handed neutrinos would be isospin singlet, and hypercharge neutral and thus sterile with respect to the SM. If no right handed neutrinos the Yukawa couplings of the BEH does not lead to massive neutrinos.
  - If neutrinos are not mass less, one needs some BSM physics.
  - Simplest assumption: there exist right handed neutrinos, sterile with respect to the SM
- The seesaw mechanism leading to very small masses for the neutrinos (Ramond *Neutrinos: precursors of new physics,* C. R. Physique 6 (2005) 719-728)

- Yukawa couplings to the BEH boson gives Dirac masses to neutrinos
- Right handed neutrinos can get Majorana masses
- Seesaw mechanism between a large Majorana mass (of the order of lepton number breaking, i.e. GUT or primordial inflation scale) and the Dirac mass, of the order of EW symmetry breaking, leads to
  - Neutrino masses much smaller than charged particle masses
  - A small sterile component of each physical neutrino**, possible candidates for the dark energy particles**

- Through the so-called "sphaleron" mechanism, breaking of lepton number can lead to breaking of baryon number at the GUT scale, and thus to the breaking of the matter-antimatter symmetry. (W. Buchrnüller, *Neutrinos in the early universe* C. R. Physique 6 (2005) 798-809)

The BEH boson as the electroweak dark matter

The well known interpretation of the BEH mechanism that generates masses to all the particles coupled to the BEH field with a coupling proportional to the mass or the squared mass, shows that the BEH boson acts as a (massive) dilaton, i.e. as anEW ether or EW dark matter

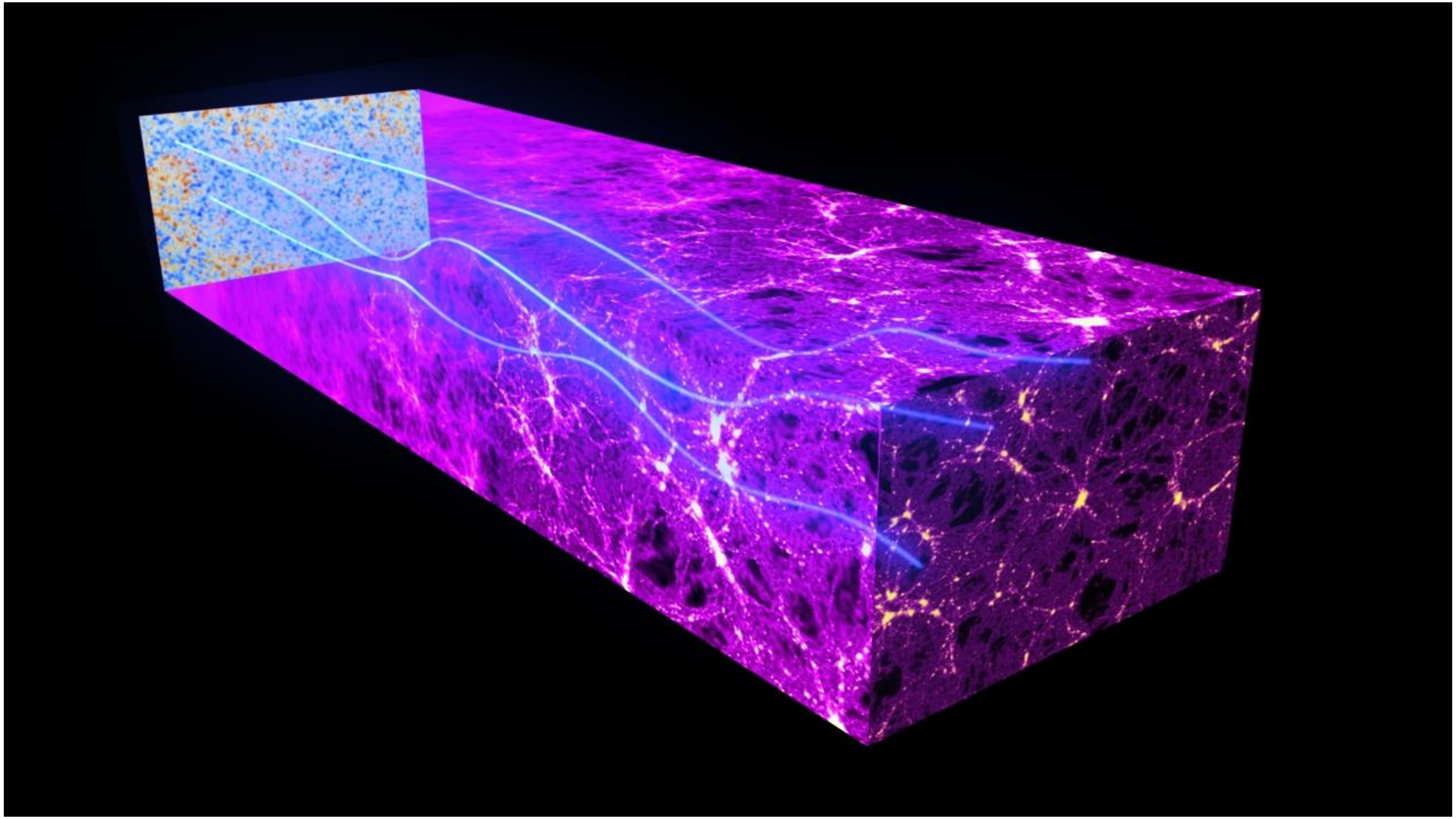
Dark matter and the QCD vacuum

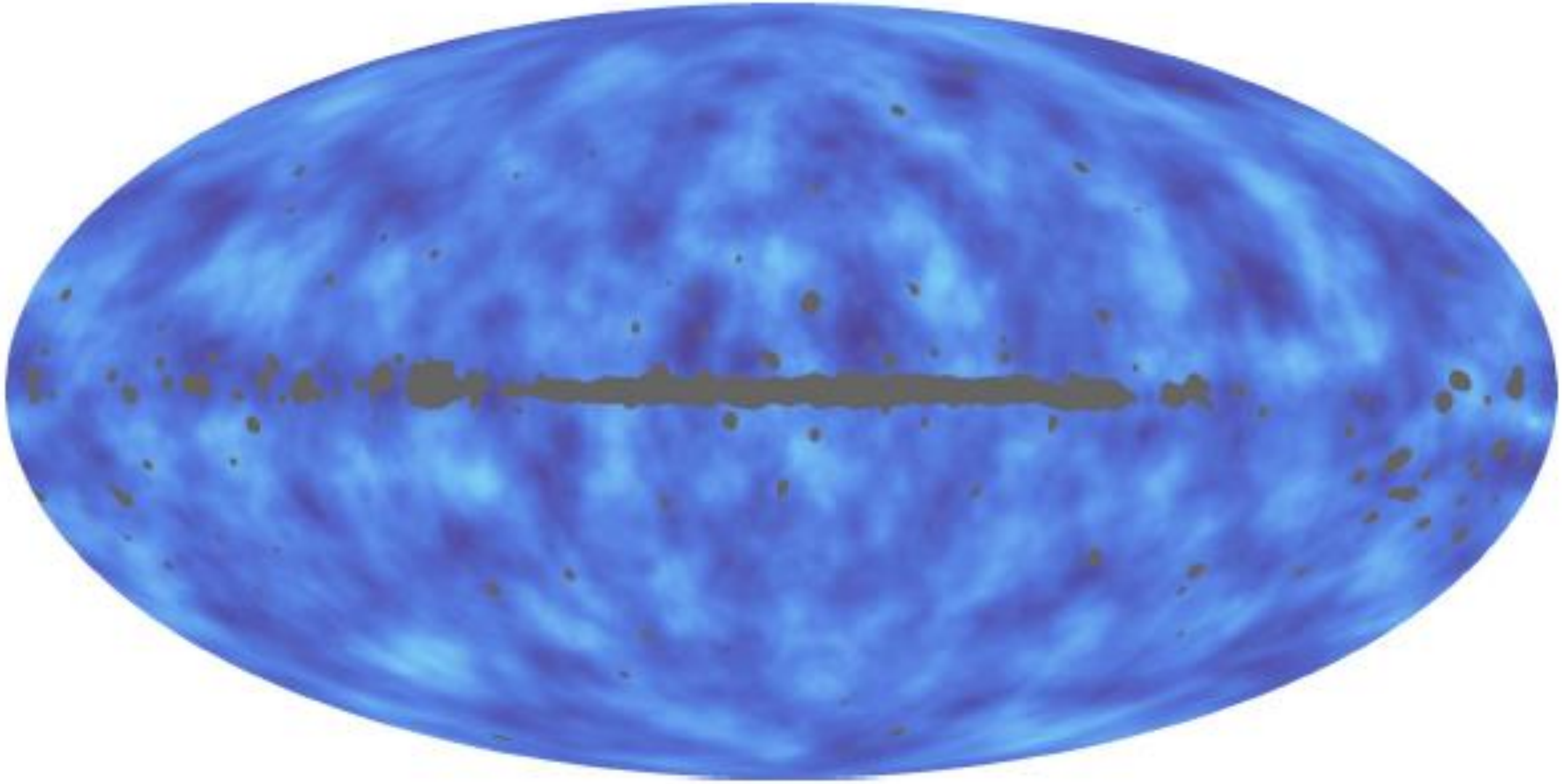
- As an unbroken Yang Mills theory, QCD with no quarks or with mass less quarks, is **scale invariant**
- But, because of infrared divergences, this symmetry is spontaneously broken through the **trace anomaly** and dynamically realized
- In a cosmological context, **the Nambu-Golstone boson of this spontaneous symmetry breaking is our field ϕ**
- At the color confinement scale (about 1 GeV), since dark energy is negligible, dark matter density is the density of the QCD vacuum.
- **The known parton distribution functions of the nucleon at Q^2 about 1 GeV^2 show that the energy-momentum carried by the vacuum (gluons plus sea quark pairs) is about five times the one carried by the valence quarks: a factor 5 that is quite comparable with the observed ratio of dark to baryonic matter**

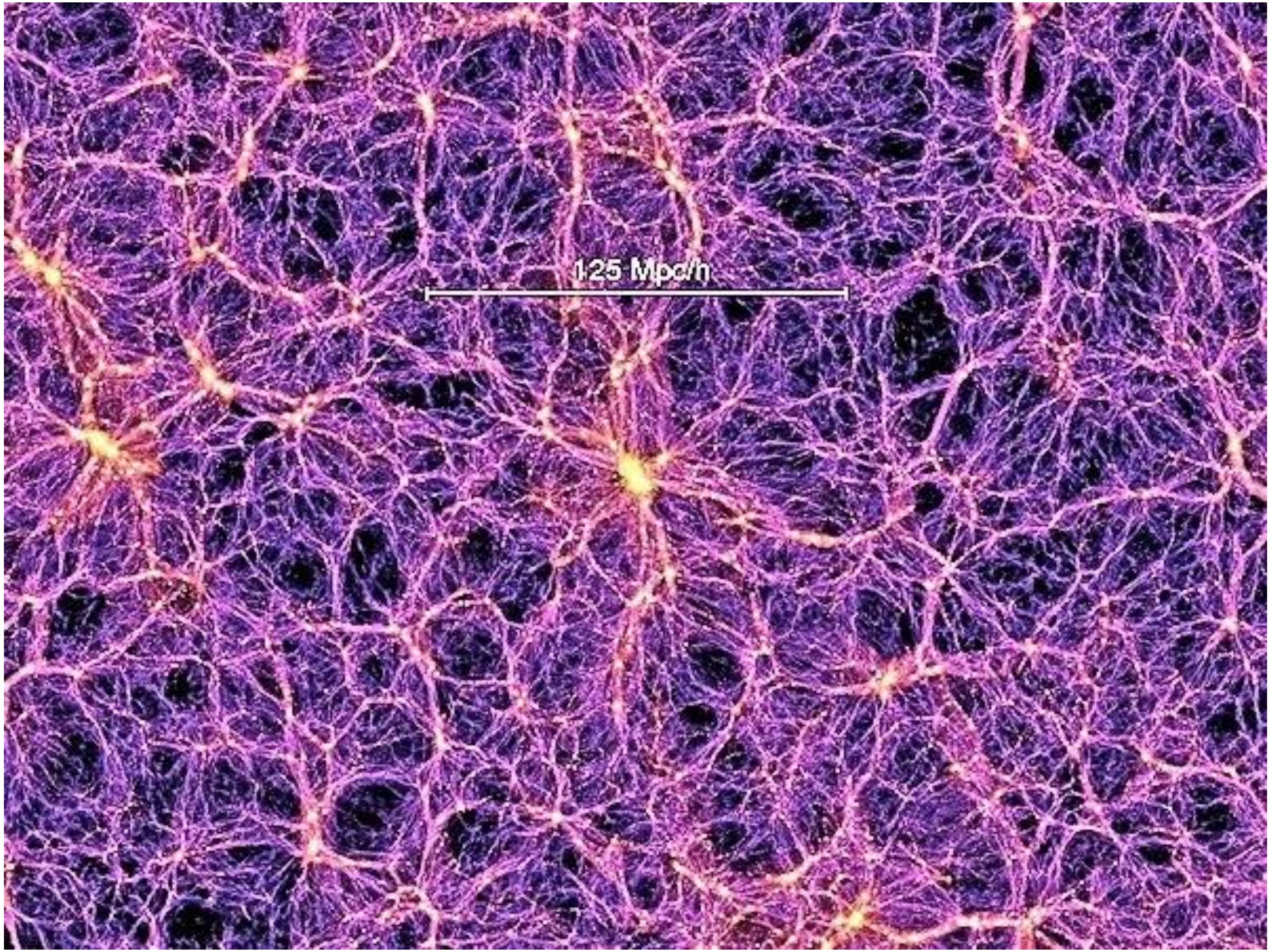
A QUANTUM LIQUID MODEL FOR THE QCD VACUUM

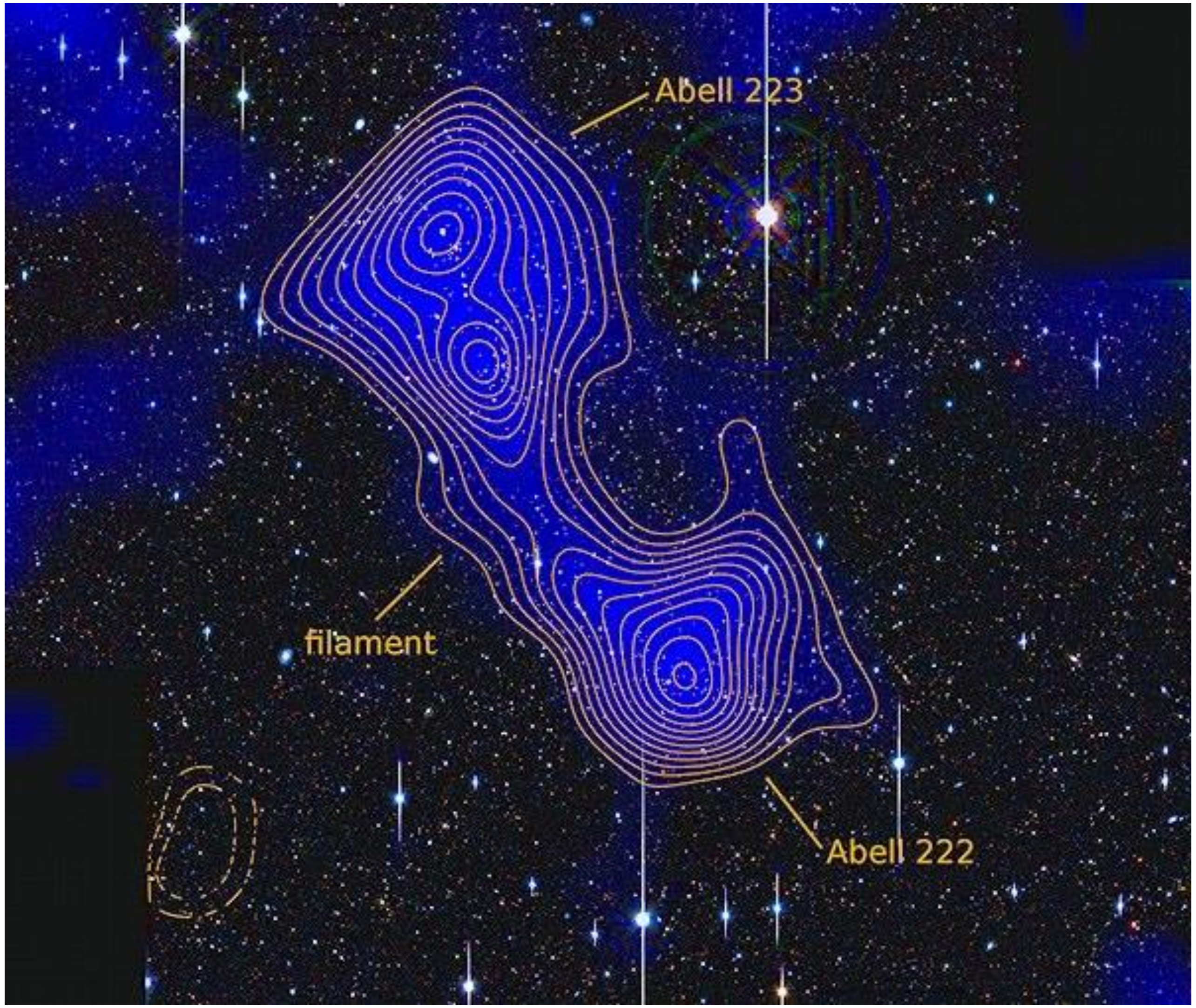
H.B. NIELSEN and P. OLESEN Nuclear Physics B160 (1979) 380-396

- "We show that domains are formed in a homogeneous SU(2) color magnetic field. Due to quantum fluctuations the domains have fluid properties. It is then argued that, quantum mechanically superpositions of such domains must be considered. The resulting state is gauge and rotational invariant, in spite of the fact that the original color magnetic field breaks these invariances. We point out that in our model for the QCD vacuum, color magnetic monopoles are not confined"
- **The magnetic tubes therefore form a three-dimensional pattern which resembles spaghetti.**






125 Mpc/h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filament
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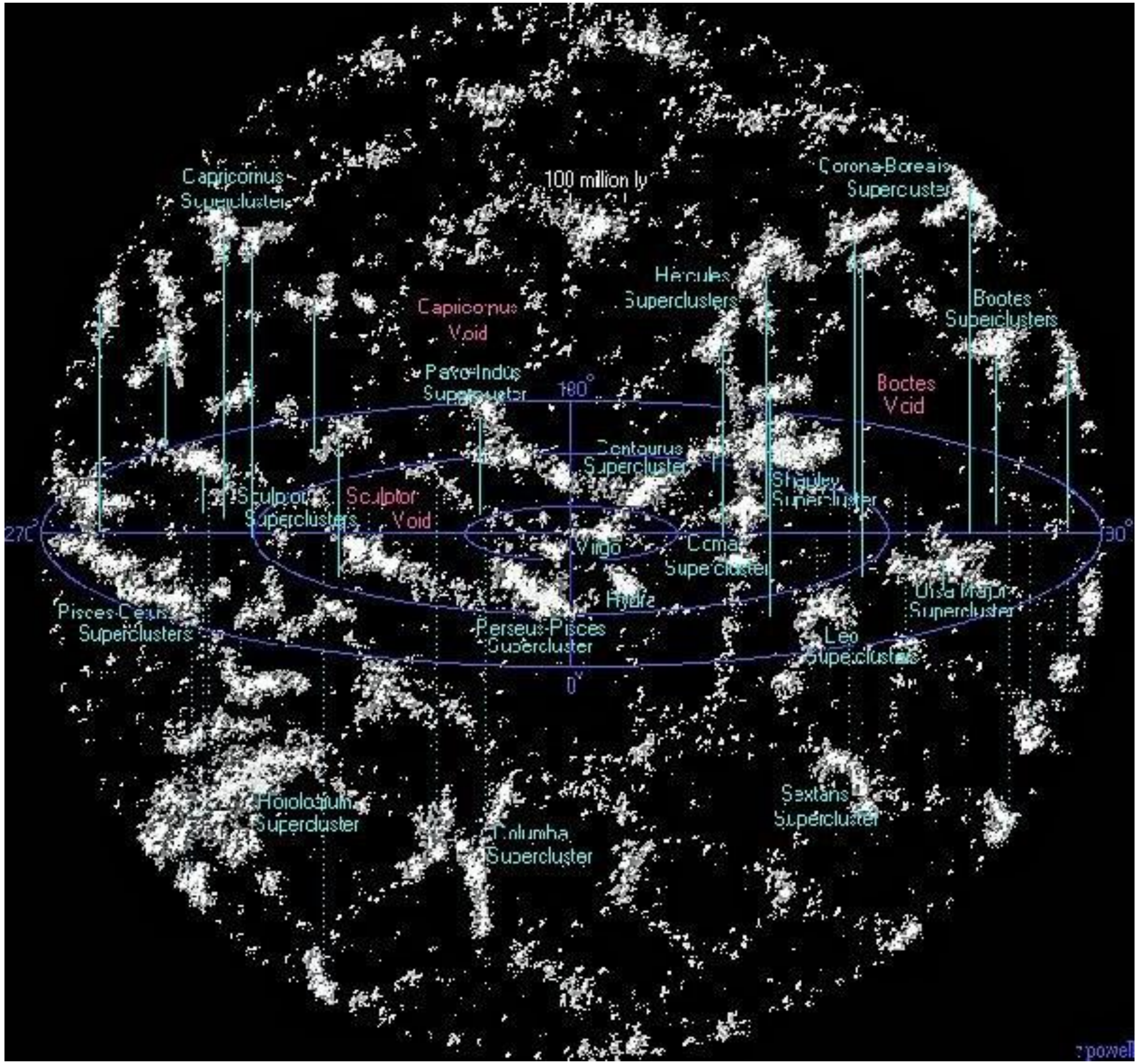


100 million ly
Capricornus Superclusters
Void
Pavo-Indus
Sculptor Void
Superclusters
Pisces-Cetus
Superclusters
Perseus-Pisces
Supercluster
180°
0°
270°
Hercules
Superclusters
Corona Borealis
Bootes
Superclusters
Bootes
Void
Centaurus
Supercluster
Shapley
Virgo
Supercluster
Hydra
Ursa Major
Supercluster
Leo
Sextans
Supercluster
Horologium
Supercluster
Columba
Supercluster

Le vide quantique, le lieu de la reconciliation de la relativité et de la quantique

- **« D'où l'on peut voir qu'il y autant de différence entre le néant et l'espace vide, que de l'espace vide au corps matériel ; et qu'ainsi l'espace vide tient le milieu entre le matière et le néant. C'est pourquoi la maxime d'Aristote dont vous parlez, "que les non-êtres ne sont point différents", s'entend du véritable néant, et non pas de l'espace vide. »** Réponse de Blaise Pascal au très révérend père Noël, recteur de la Société de Jésus, à Paris, 29 octobre 1647 Pascal, Œuvres complètes, La Pléiade, p 384, ed. 1998

Louis de Broglie, cours à la Sorbonne 1957-1958

Ces constatations ont amené la Physique quantique contemporaine à devenir de plus en plus consciente du fait que ce que nous nommons le vide n'est pas du tout un milieu dénué de propriétés physiques, mais bien plutôt une sorte d'immense réservoir d'où peuvent émerger au niveau microphysique des unités ou des paires corpusculaires et où aussi ces unités et ces paires disparaissant du niveau microphysique peuvent s'engloutir.

Si cette conception est exacte (et il semble bien aujourd'hui qu'elle le soit), il y aurait trois niveaux de la réalité physique :

- le niveau macrophysique des phénomènes macroscopiques directement observables à notre échelle qui est le domaine propre de la Physique dite "classique";

- le niveau microphysique ou quantique qui est celui des molécules, des atomes, des noyaux ou plus généralement des particules élémentaires, qui est le domaine propre de la Physique quantique ;

- le niveau le plus profond, hypomicrophysique ou subquantique pourrait-on dire, constitué par ce "vide" réservoir immense d'énergie sous-jacente dont nous ignorons encore presque tout. (,,,)

L'expression "substratum universel" (ou une autre de ce genre) serait meilleure. J'emploierai cependant habituellement le mot vide couramment usité, mais vous devez imaginer qu'il doit être mis entre guillemets ("le vide'').

Nous ne savons pas si, quand un boson apparaît au niveau microphysique sortant du "vide", il existait déjà dans ce substratum à l'état préformé, ou s'il est "créé" au moment de son apparition. Nous ne savons pas davantage si, quand un boson disparaît du niveau microphysique pour s'engloutir dans le "vide", il subsiste dans ce substratum dans un état indécelable ou s'il est "détruit" au moment de sa disparition.

On est évidemment amené à penser que toute particule, même quand elle nous paraît isolée, est en contact avec un milieu subquantique caché qui constitue une sorte d'invisible thermostat ..... La particule échangerait ainsi continuellement de l'énergie et de la quantité de mouvement avec ce milieu subquantique.

Dès qu'on a admis l'existence d'un "milieu subquantique" caché, on est amené à se demander quelle est la nature de ce milieu. Il a certainement une nature très complexe. En effet, il doit d'abord ne pas pouvoir servir de milieu de référence universel, ce qui serait en opposition avec la théorie de la Relativité. De plus nous verrons qu'il se comporte non pas comme un thermostat unique, mais plutôt comme un ensemble de thermostats dont les températures seraient reliées aux énergies propres des diverses sortes de particules.

The Mach's ether

"**There can be no space nor any part of space without gravitational potentials; for these confer upon space its metrical qualities, without which it cannot be imagined at all**. The existence of the gravitational field is inseparably bound up with the existence of space. On the other hand a part of space may very well be imagined without an electromagnetic field; thus in contrast with the gravitational field, the electromagnetic field seems to be only secondarily linked to the ether, the formal nature of the electromagnetic field being as yet in no way determined by that of gravitational ether. From the present state of theory it looks as if the electromagnetic field, as opposed to the gravitational field, rests upon an entirely new formal motif, as though nature might just as well have endowed the gravitational ether with fields of quite another type, for example, with fields of a **scalar potential**, instead of fields of the electromagnetic type."

A. Einstein, Einstein, *L'éther et la théorie de la relativité* Œuvres choisies, 5, Vol. 5 Science, éthique, philosophie, pp. 81-88, Le Seuil, CNRS, 1991

Albert Einstein
An address delivered in 1920, at the University of Leiden

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.

Of course it would be a great advance if we could succeed in comprehending the gravitational field and the electromagnetic field together as one unified conformation. Then for the first time the epoch of theoretical physics founded by Faraday and Maxwell would reach a satisfactory conclusion. The contrast between ether and matter would fade away, and, through the general theory of relativity, the whole of physics would become a complete system of thought, like geometry, kinematics, and the theory of gravitation. An exceedingly ingenious attempt in this direction has been made by the mathematician H. Weyl; but I do not believe that his theory will hold its ground in relation to reality. **Further, in contemplating the immediate future of theoretical physics we ought not unconditionally to reject the possibility that the facts comprised in the quantum theory may set bounds to the field theory beyond which it cannot pass.**

Figure from T. Padmanabhan, The atoms of space, gravity and CC, arXiv:1603.08658

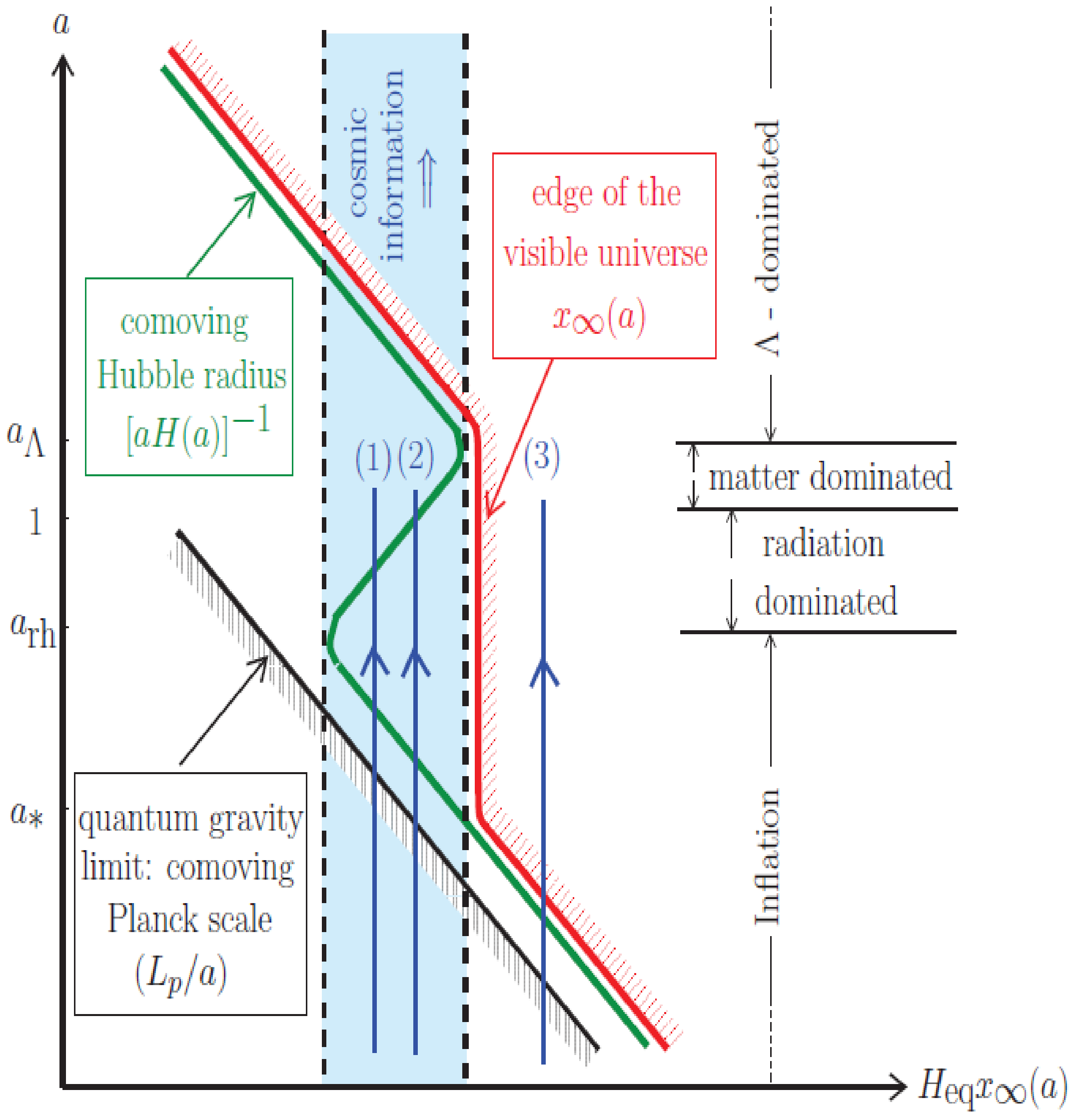
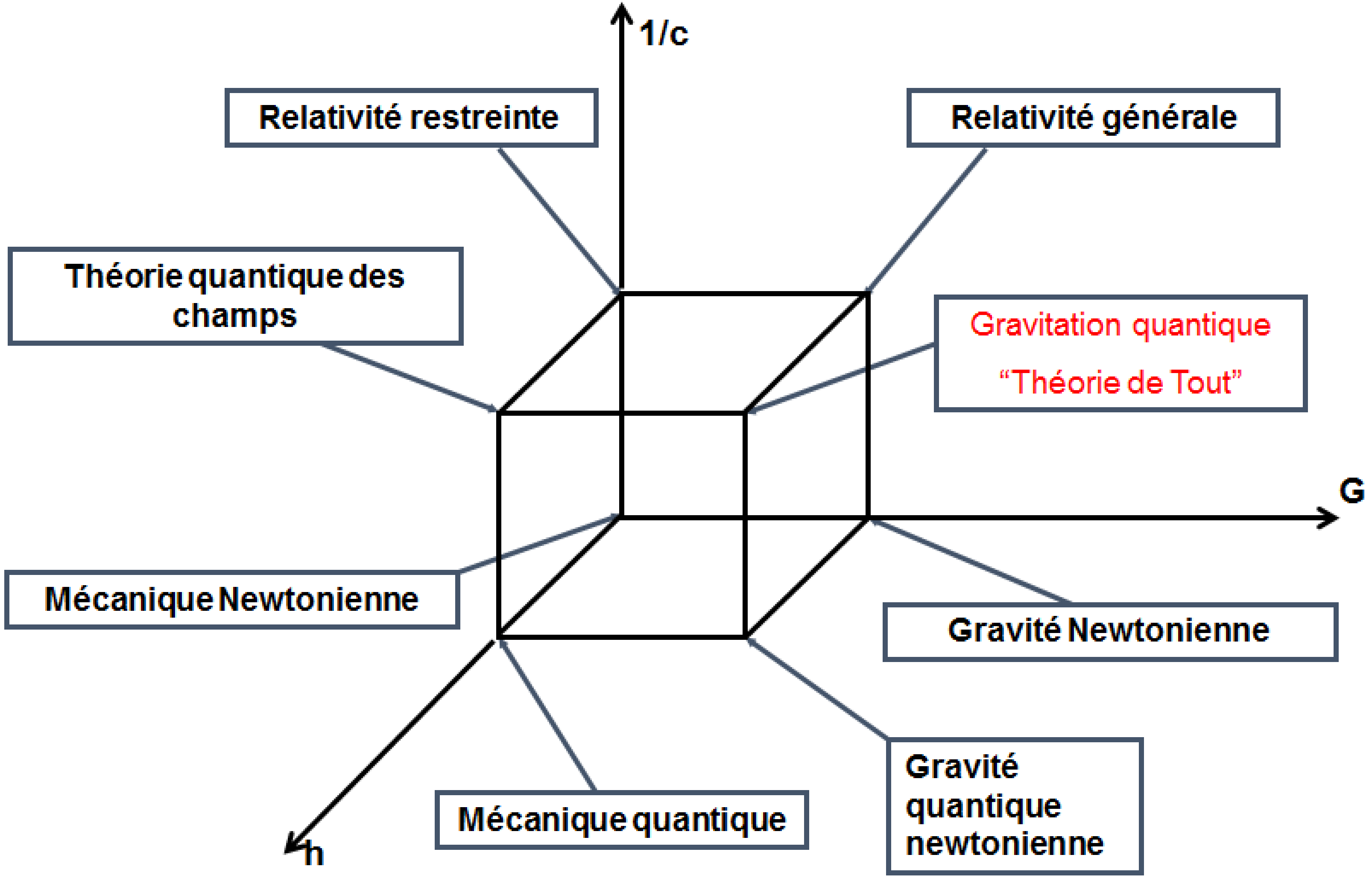
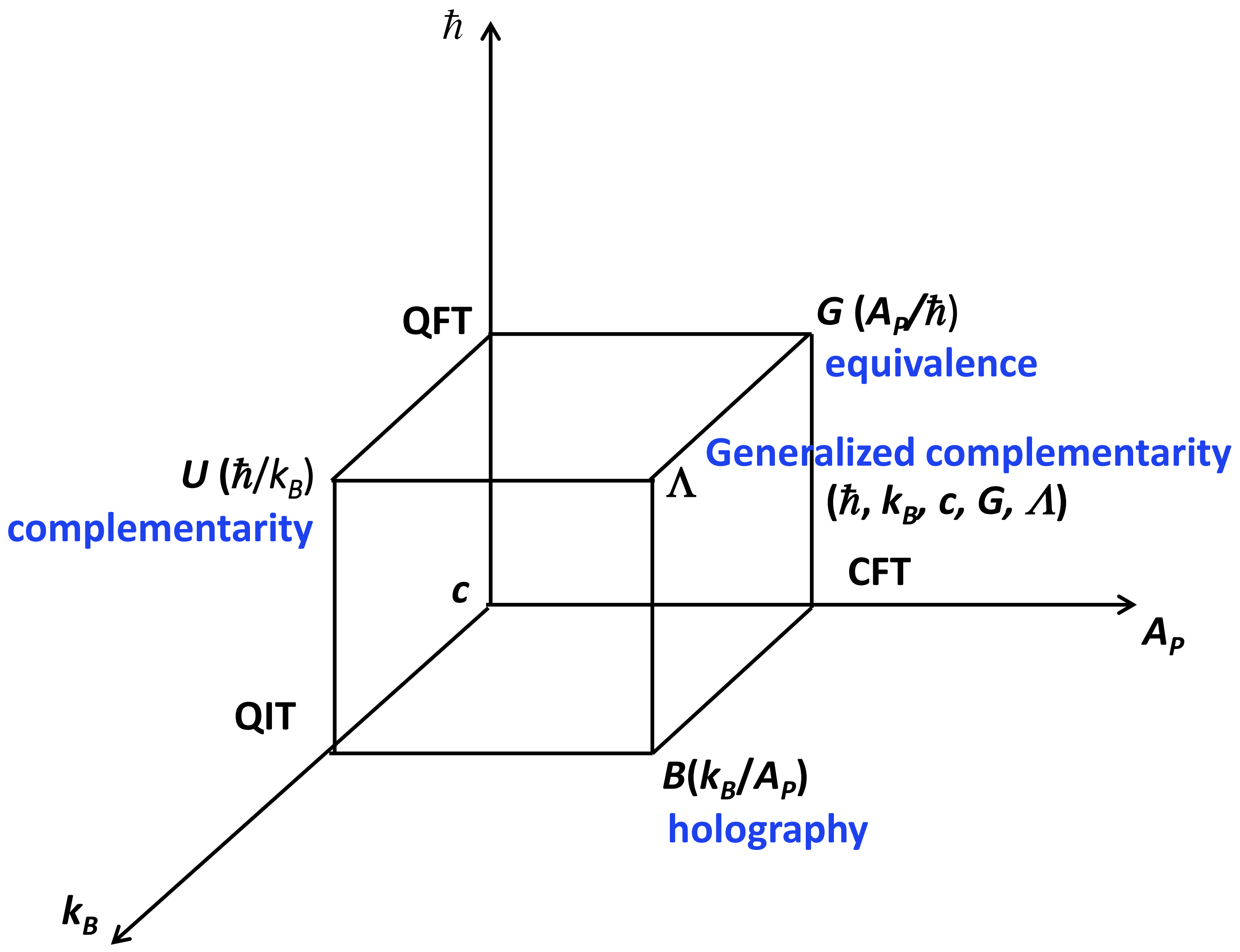


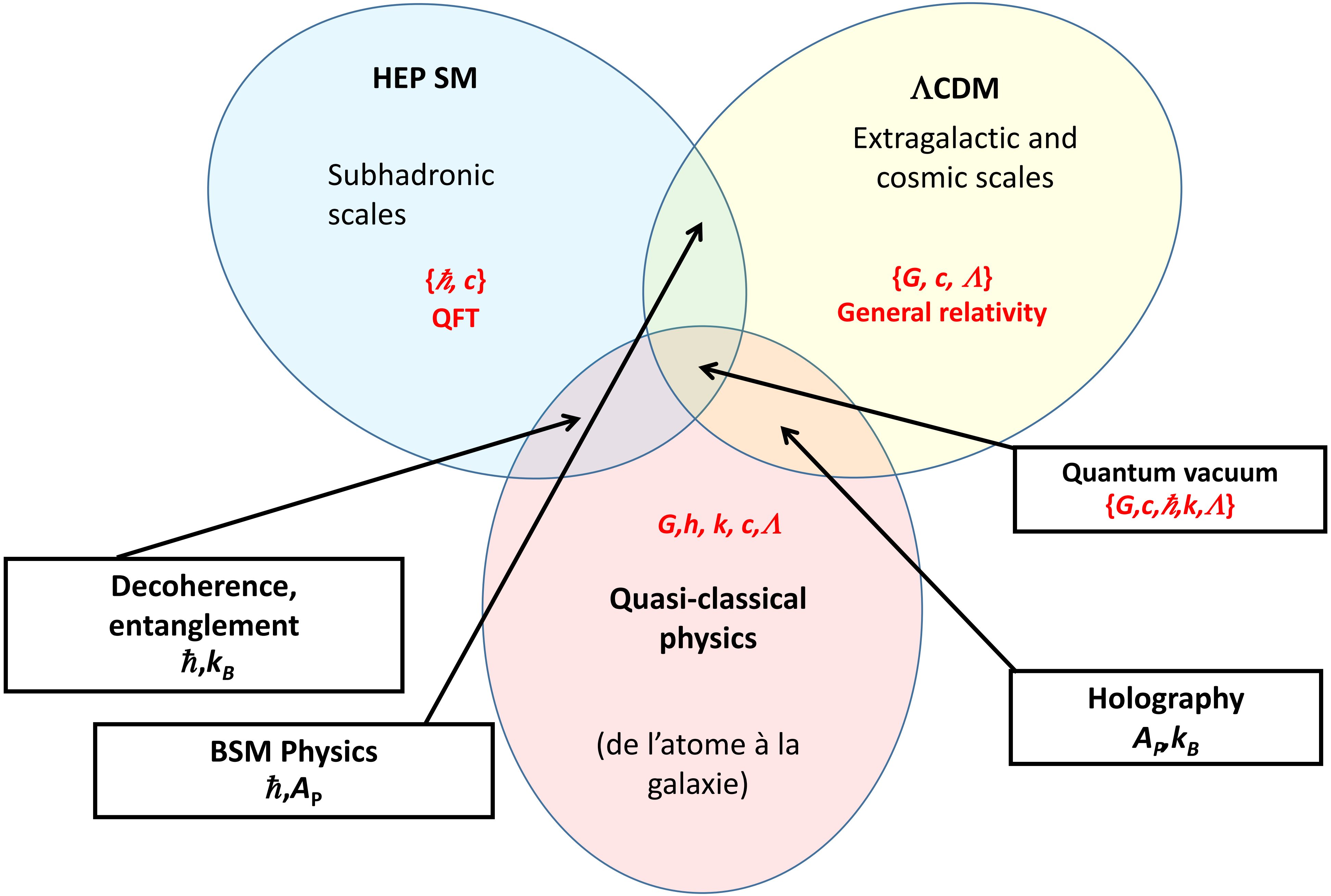
Figure 3: The various length scales in a universe with an inflationary phase and a non-zero cosmological constant. The red curve gives the maximum comoving size of a region from which signals can reach an observer at very late times. The information in the shaded region to the right of the red curve is not accessible to an observer even if she waits forever. The green curve denotes the comoving Hubble radius. The slanted black curve is the comoving scale corresponding to the Planck length and the shaded region below the black line is dominated by quantum gravitational effects. The vertical lines correspond to different proper length scales which cross the Hubble radius and the horizon. The two lines marked 1 and 2 exit the Hubble radius during inflation and re-enter it during the radiation/matter dominated epoch. These are within the horizon of the observer at the origin (red curve) and are visible to her at, say, $a = a_{\rm rh}$. The line marked 3 corresponds to a proper length scale which goes out of, not only the Hubble radius, *but also the horizon* and hence will be inaccessible to the observer at, say, $a = a_{\rm rh}$. So the relevant part of the cosmic information is contained within the blue vertical band, defined by the two vertical lines which are tangential to the comoving Hubble radius at its turning points. The arrows at the top denote the direction of flow of the cosmic information.



Le cube des théories



The triple quantization or generalized complementarity



HEP SM
Subhadronic scales
{ħ, c}
QFT
ΛCDM
Extragalactic and cosmic scales
{G, c, Λ}
General relativity
G,h, k, c,Λ
Quasi-classical physics
(de l'atome à la galaxie)
Quantum vacuum
{G,c,ħ,k,Λ}
Decoherence, entanglement
ħ,k_B
BSM Physics
ħ,A_P
Holography
A_P,k_B

Was the 1917 Einstein's universe so wrong?

- **ΛCDM can be interpreted as a quasi-classical, quasi-Newtonian, quasi "perfect", quasi-Machian** Einstein's universe, in which dark matter and energy and a "running" cosmological constant, exactly compensate, at all epochs, the effects of gravity
- Such an unstable equilibrium would be unacceptable if the universe was static
- But in an expanding universe, such an equilibrium is perfectly admissible, because it is **dynamical**
- Rather that "running", the CC in such an Einstein's universe should be said **"biking"**