Dark matter, Mach's ether, and the QCD vacuum

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Outline

- Einstein's address at the Leiden university, may 1920: search for a **Mach's ether for general relativity**

- ΛCDM and the dark matter issue

- The QCD vacuum in a cosmological context

- The hypothesis I submit to debate:

Dark energy + Dark matter = Mach's ether

Dark matter = QCD vacuum

The Mach's ether of general relativity

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

It is true that Mach tried to avoid having to accept as real something which is not observable by endeavoring to substitute in mechanics a mean acceleration with reference to the totality of the masses in the universe in place of an acceleration with reference to absolute space. But inertial resistance opposed to relative acceleration of distant masses presupposes action at a distance; and as the modern physicist does not believe that he may accept this action at a distance, he comes back once more, if he follows Mach, to the ether, which has to serve as medium for the effects of inertia. But this conception of the ether to which we are led by Mach's way of thinking differs essentially from the ether as conceived by Newton, by Fresnel, and by Lorentz. Mach's ether not only conditions the behavior of inert masses, but is also conditioned in its state by them.

If we consider the gravitational field and the electromagnetic field from the standpoint of the ether hypothesis, we find a remarkable difference between the two. 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. (…) 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.

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.

An observational evidence for the Mach's ether: dark matter in astrophysics and cosmology

Dark matter in astrophysics

Rotation curves of stars in galaxies and galaxies in clusters of galaxies

Rotation velocities do not decrease with distance at large distance

Dark matter invented to address this issue: a medium that exerts a gravitational force that compensate the centrifugal force and prevent the rotating object to escape from the system in which it rotates

Centrifugal force $F_c=mv^2/r$, compensated by gravitational force $M(r)m/r^2$ if $M(r)=\lambda r$ i.e. the force exerted by a string with constant (independent of m and of r) string tension

Dark matter acts as an ether exerting a gravitational force which derives from a scalar potential

Dark matter in cosmology: Review of the ΛCDM standard model (WMAP confirmed by Planck 2015)

- **Planck 2015 results:**

- The Planck TT, TE, and EE spectra are accurately described with a purely adiabatic spectrum of fluctuations with a spectral tilt $n_s = 0.968 \pm 0.006$, consistent with the predictions of single-field inflationary models. Combining Planck data with BAO, we find tight limits on the spatial curvature of the Universe, $\Omega_k < 0.OO5$, again consistent with the inflationary prediction of a **spatially-flat Universe**.

- By combining the Planck TT+lowP+lensing data with other astrophysical data, including the JLA supernovae, the equation of state for dark energy is constrained to **w = -1.006 ± 0.045 and is therefore compatible with a cosmological constant, as assumed in the base ΛCDM cosmology.**

$L \propto a^2$
Radiation dominance era

$L \propto a^{1.5}$
Matter dominance era
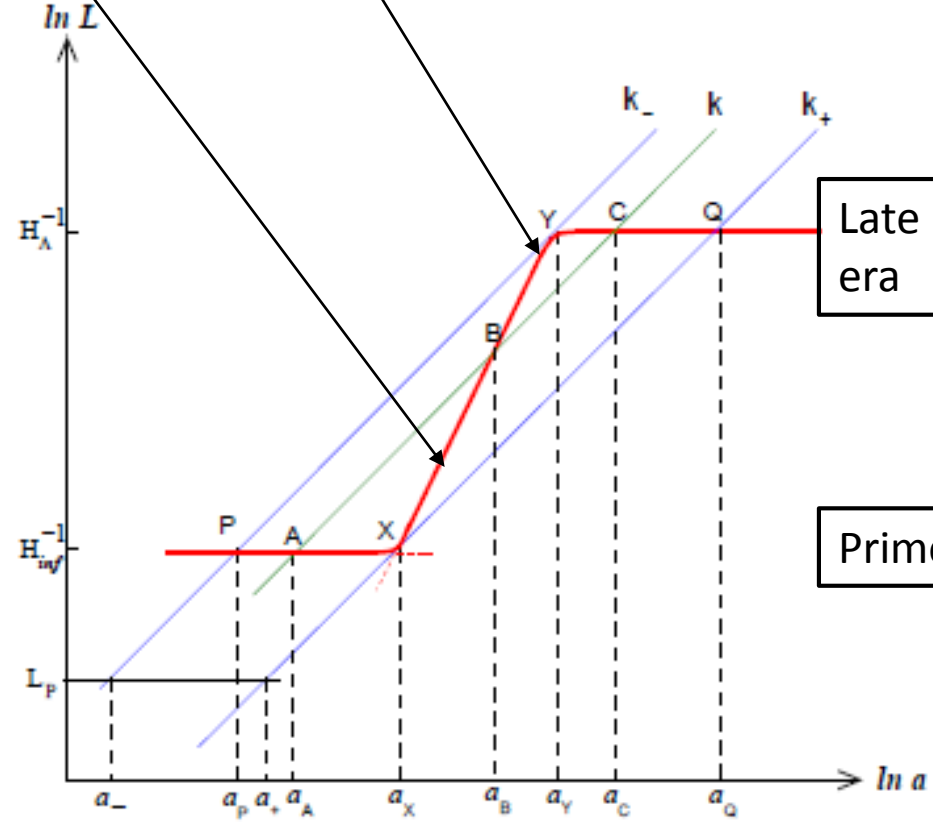
Late inflation, CC dominance era

Primordial inflation

$H_\Lambda^{-1} \approx 10^{60} L_P$

$H_{\text{inf}}^{-1} \approx 10^3 L_P$

Today, a = 1

The three stages of the ΛCDM model Hubble radius L vs scale parameter a (set at 1 today) in log scale

- Primordial inflation from a = 0 to point X. Between point P and point X about 30 orders of magnitudes: at point X space is already flat.

- Hubble expansion between point X and point Y: era with L as a^2 (radiation dominance) followed by era with L as $a^{1.5}$ (matter dominance)

- Late inflation, CC dominated between point Y and point Q
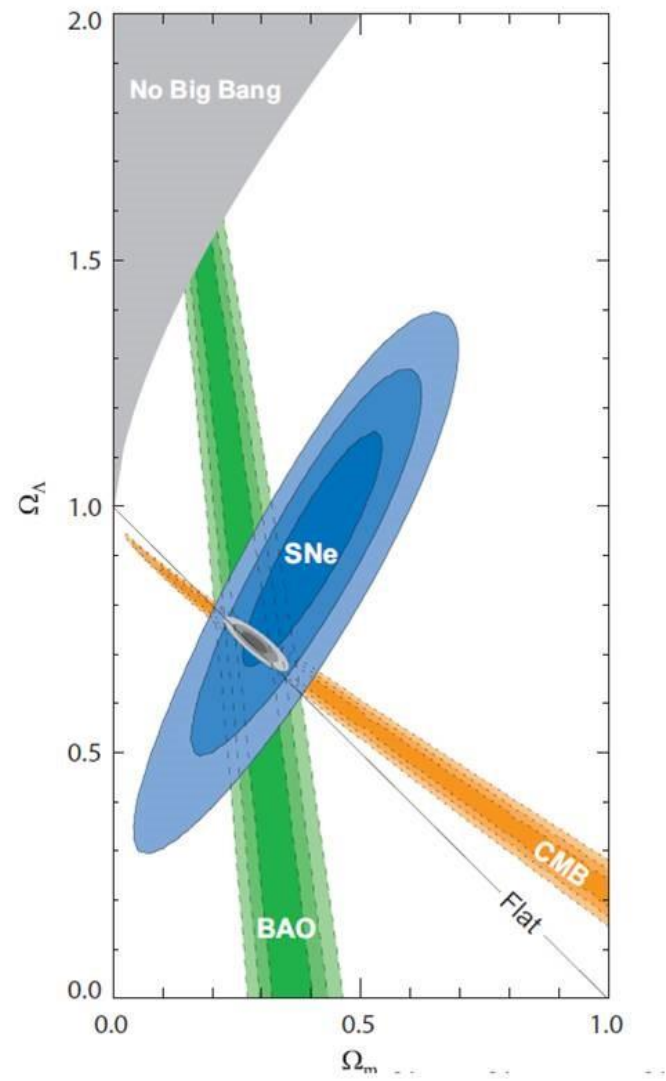
A theoretical hint about the Mach's ether: the quantum vacuum

The Friedman-Lemaître equations of motion

The Einstein equation

$$\Box_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \Box \equiv 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$\Lambda g_{\mu\nu}$ interpreted as the energy momentum tensor of the "vacuum"

Matter content of the universe, perfect fluid

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

Friedman-Lemaître equations

$$H^2 \equiv \left(\frac{\dot{R}}{R} \right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \quad (1)$$

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

The quantum vacuum is not the nothingness

« 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.» *Réponse de Blaise Pascal au très révérend père Noël, recteur de la Société de Jésus, à Paris, 29 octobre 1647 Pascal, Oeuvres complètes, La Pléiade, p 384, ed. 1998*

Consequences of the Heisenberg inequalities

- When the number of particles is well determined (for instance in the quantum vacuum where this number is zero) the space-time state of the fields is not determined: they fluctuate

- In space-time, the quantum vacuum can be assimilated to a complex medium, seat of **non scale invariant quantum fluctuations of the fields**

- **The properties of the quantum vacuum depend on the scale at which it is probed.** In cosmology, this scale is provided by the **horizon radius which depends on the cosmic time.**

- **If Mach's ether is to be assimilated to the quantum vacuum, it has to depend on the cosmic time**

Primordial inflation and the Brout Englert Gunzig mechanism

In the model proposed by Brout, Englert and Gunzig which could be compatible with the primordial inflation phase of ΛCDM "quantum creation of massy particles can occur in the cosmological context without cost of energy" R. Brout, F. Englert and E. Gunzig, The Creation of the Universe as a Quantum Phenomenon, Annals of Physics 115, 78-106 (1978) (The BEG mechanism !)

The main point of their argument is that in homogeneous and isotropic cosmologies that obey the cosmological principle, the metric is conformally flat, i.e. such that it is Minkowskian up to a multiplicative factor related to its determinant which can be treated as a scalar field ϕ in Minkowski (flat) space-time.

This field gives rise to a negative energy density such that matter carrying positive energy can be created and yet the total energy can be kept fixed and equal to the vacuum energy. This apparent paradox is solved exactly in the same away as in the Brout Englert Higgs mechanism electroweak symmetry breaking, the ghost that appears in the Landau 'tHooft gauge is canceled by the Nambu Goldstone boson in the unitary gauge.

The QCD vacuum as an ether

The QCD Lagrangian, without quarks or with massless quarks (in the so-called chiral limit), is scale invariant since the coupling constant is dimensionless. But through quantization, this symmetry is broken, one says that it is dynamically broken: this phenomenon is called conformal anomaly.
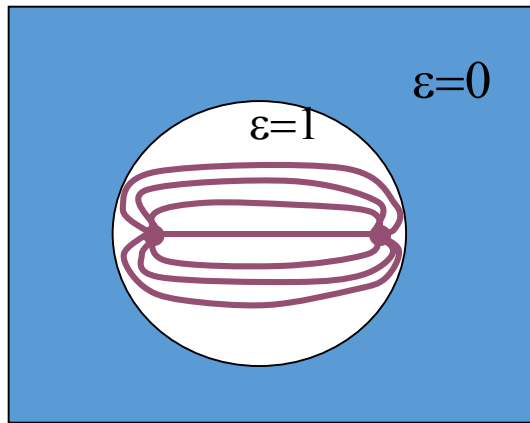
The dynamical breaking of scale invariance is apparent in the fact that "the renormalization has replaced a one-parameter family of unrenormalized theories, characterized by their values of the dimensionless unrenormalized gauge coupling, g_0 , by a one-parameter family of renormalized theories, characterized by their value of the dimension-one [renormalization group invariant] scale mass $M(g,\mu)$" (Stephen L. Adler, Einstein gravity as a symmetry breaking effect in quantum field theory Review of Modern Physics, Vol 54, No 3, 729, 1982).This feature is also known as dimensional transmutation

This scale mass, independent of the energy μ at which renormalization is performed, appears as a non-vanishing trace of the renormalized energy-momentum tensor; it is completely physical; it is related to the hadron masses; but, and this is the main point of our proposal, it does have cosmological implications. Since the variation of the action with respect to the metric, is proportional to the energy-momentum tensor, the scale factor of the metric, represented by a scalar field ϕ, is proportional to the trace of the energy-momentum tensor,

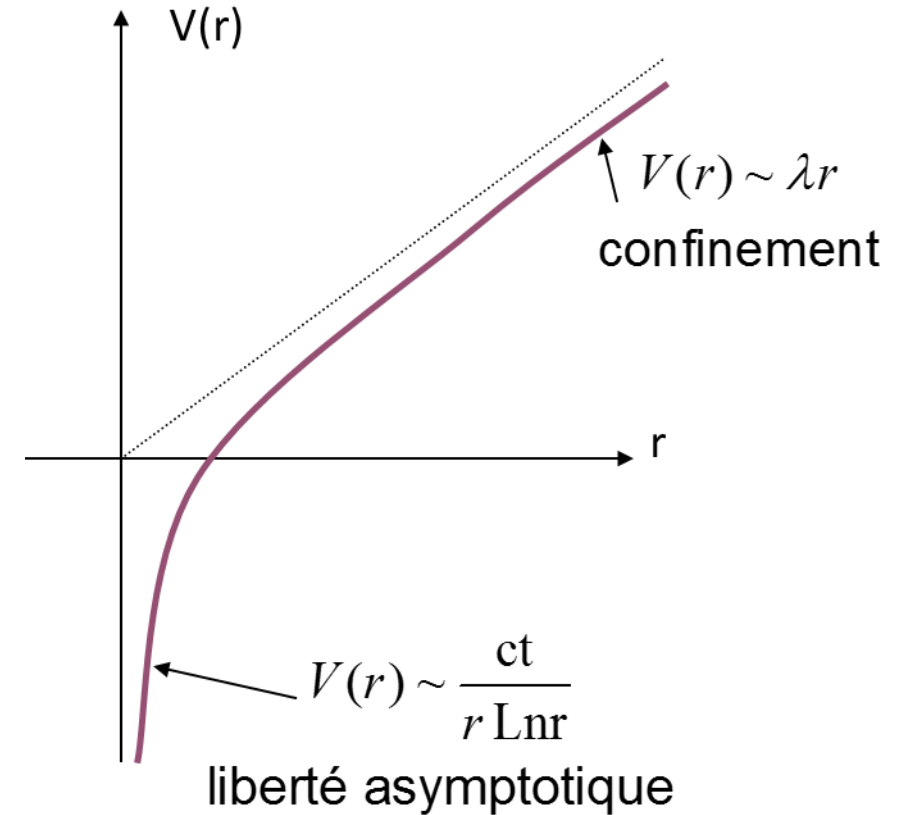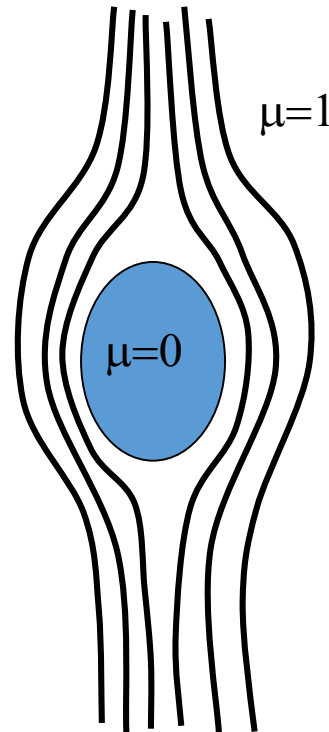# Color confinement in QCD

Confinement superconductivity analogy

QCD vacuum = perfect color diaelectric

$$V(r) = \lambda r \frac{1}{r^{\not{2}}}$$

λ= **string tension**

Superconductor = perfect diamagnetic

$V(r) \sim \lambda r$
confinement

$V(r) \sim \dfrac{ct}{r \, \mathrm{Ln} r}$
liberté asymptotique

The only way for such vacuum energy densities to contribute to the dark matter density is to be non relativistic (namely cold), stable, and with only very weak non-gravitational interactions. It seems possible to satisfy all these conditions with Bose Einstein Condensates (BEC): very low temperature at the Hubble horizon, superfluidity, a characteristic of BEC.

It turns out that DM models involving such BECs have been successfully tried in the literature (Cosmic Structure as the Quantum Interference of a Coherent Dark Wave by Hsi-Yu Schive, Tzihong Chiueh∗ & Tom Broadhurst arXiv:1406.6586). In this reference, the authors show, by means of high precision simulations, that their Axion-like model agrees with the conventional cold dark matter model in the description of large scale structures in the distribution of galaxies and works much better than the conventional one in the description of small scale structure thanks to interferences between the "dark quantum waves" and some waves arising in hydro-dynamical models (Jeans effect).

Apart from ultralight bosons like the hypothetical Axion or scalar bosons, relics of the GUT symmetry breaking or of some superstring dynamics, the only bosons susceptible to condense and to lead to observable cosmological effects are the photon and the gluon. In fact weak intermediate and Higgs bosons are unstable and decay into light particles in such a way that they contribute only to the radiation (or relativistic) component in the density budget of present time and are thus negligible. The photon can condense (see the Casimir effect), but again it contributes only to the radiation component and is negligible. **There only remains the gluon**
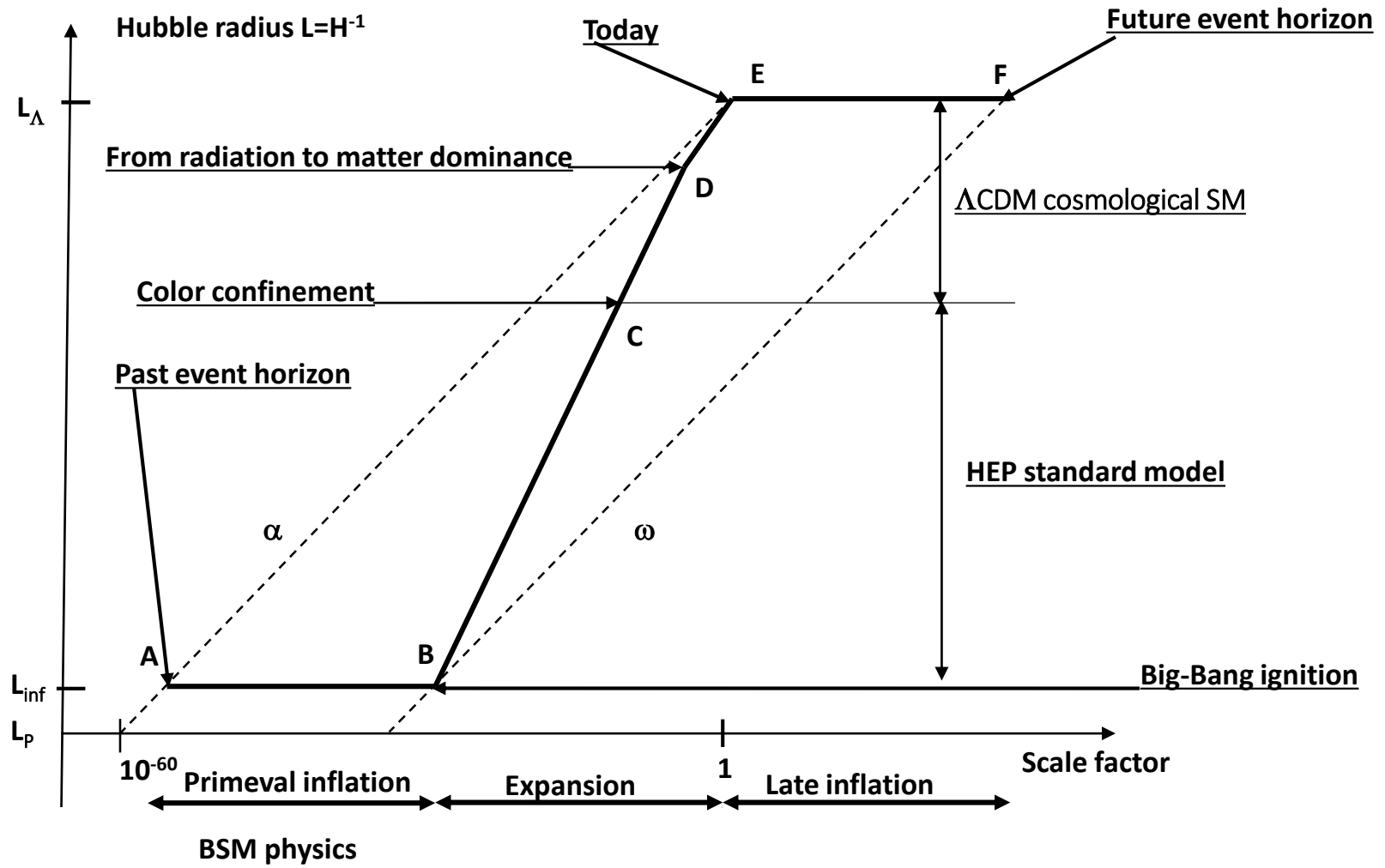
Baryonic to dark matter energy density ratio and the quark-gluon parton model

Scaling observed in deep inelastic lepton-nucleon scattering at the confinement scale (about 1.5 GeV^2) leads to the parton distribution functions used as input in the standard model:

- Three valence "constituent quarks" (with a mass about 1/3 of the nucleon mass) carrying about 15% of the momentum of the nucleon
- "Sea" quark anti-quark pairs and gluons (that is the QCD vacuum) carrying the remaining 85% of the momentum of the nucleon

Once confined, the valence quarks give rise of the baryonic matter and the QCD vacuum gives rise to the dark matter, with the good ration of energy densities

Quod erat demonstrandum!