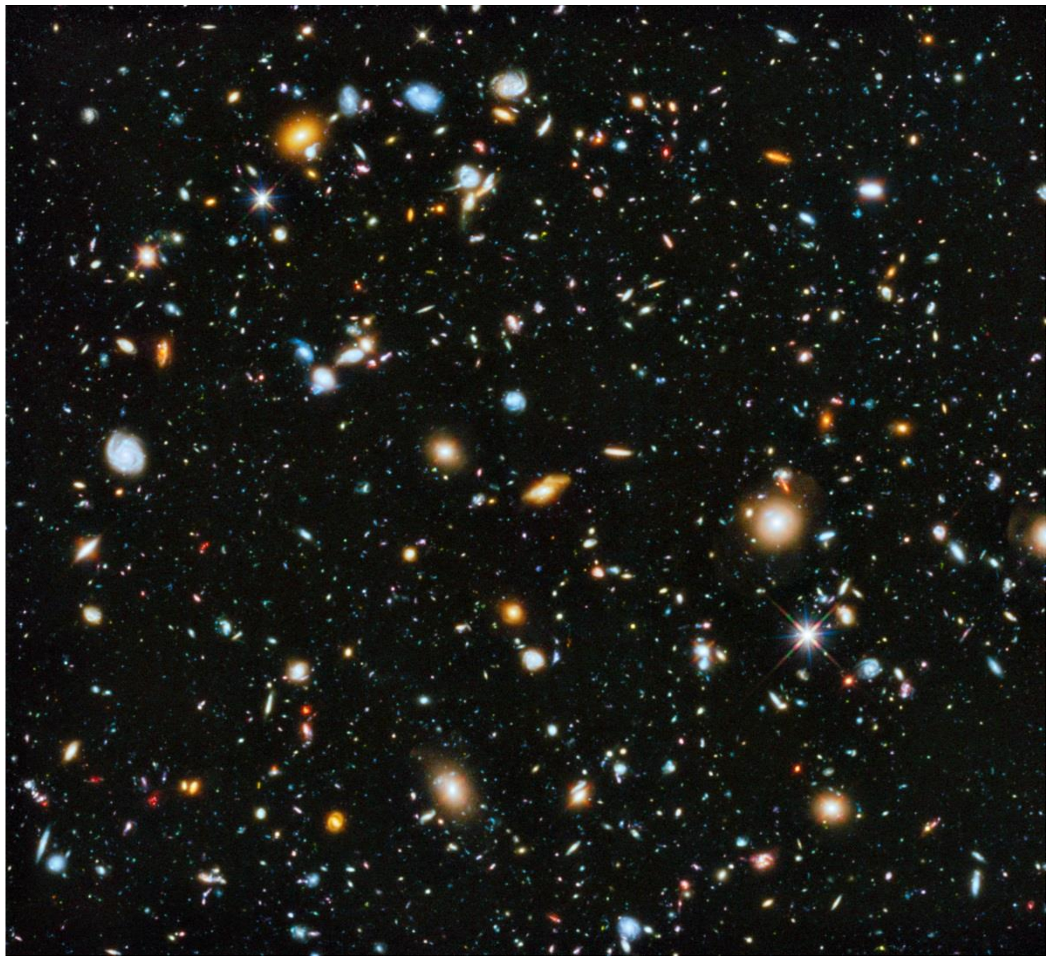
Quantum Vacuum and Antimatter Gravity

The basis for a New Model of the Universe?



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Abstract

- We present the astonishing astrophysical and cosmological consequences of the following hypotheses:

(1) *The Standard Model matter* (i.e. matter made from quarks and leptons interacting through the exchange of gauge bosons) *is the only content of the Universe*

(2) *Quantum vacuum fluctuations are virtual gravitational dipoles* (i.e. systems composed from one positive and one negative gravitational charge)

- The first hypothesis excludes dark matter and dark energy from astrophysics and cosmology, while the second hypothesis postulates quantum vacuum as a cosmological fluid free of the cosmological constant problem.

Abstract

- The phenomena usually attributed to hypothetical dark matter, may be considered as a consequence of the local gravitational polarization of the quantum vacuum by the immersed Standard Model matter; i.e. a galactic halo of dark matter can be replaced by the halo of the polarized quantum vacuum. Globally "quantum vacuum" may be viewed as a cosmological fluid, which during expansion of the Universe converts from a fluid with negative pressure - allowing an accelerated expansion of the Universe - to a fluid with zero pressure, which physically means the end of the accelerated expansion. This, for the first time, suggests that quantum vacuum may explain both phenomena; phenomena for which we have invoked dark matter and phenomena for which we have invoked dark energy.

Abstract

- Furthermore, as a consequence of the hypothesis of virtual gravitational dipoles, together with the gravitational version of the Schwinger mechanism, the possibility exists that we live in a cyclic universe with cycles alternatively dominated by matter and antimatter. Consequently, at least mathematically, there is no initial singularity, there is no need for cosmic inflation and there is an elegant explanation of the matter-antimatter asymmetry in the universe: our universe is dominated by matter because the previous cycle was dominated by antimatter (and the next cycle would be dominated by antimatter again).
- The eventual evidence of gravitational effects of the quantum vacuum “enriched” with virtual gravitational dipoles can be revealed, among other ways, through the gravitational experiments with antihydogen , muonium and positronium, and by the study of orbits of tiny satellites in trans-Neptunian binaries, for instance UX 25.

Prelude

Overview of the Standard Cosmology

Prelude 1: Mysteries

- Astronomical observations have revealed a series of phenomena which are a complete surprise and mystery for contemporary theoretical physics (i.e. General Relativity and the Standard Model of Particles and Fields)

What is the nature of
what we call Dark Energy

The first observed phenomenon

(a global phenomenon)

- **In certain periods of its history expansion of the Universe is accelerated,** contrary to the common sense expectation that gravity must decrease the speed of expansion.
- The mainstream “explanation”: **Dark energy** of unknown nature.

What is the nature of what we call Dark Matter

The second observed phenomenon

(a local phenomenon)

- **In galaxies and clusters of galaxies, the gravitational field is much stronger than it should be according to our theory of gravitation and the existing amount of the Standard Model matter** (i.e. matter made of quarks and leptons interacting through the exchange of gauge bosons)
- The mainstream "explanation": **Dark matter** of unknown nature or **modification** of our law of gravity (for instance MOND)

The matter-antimatter asymmetry in the Universe

- The Big Bang should have created equal amounts of matter and antimatter. But today, there is far more matter than antimatter in the Universe.

The third observed phenomenon

- **Our Universe is dominated by matter**

  What is the cause of this matter-antimatter asymmetry.
- The mainstream “solution”: A kind of CP violation,

- The overplus of matter caused by known CP violation would be sufficient just for a few galaxies and there are billions of galaxies in the Universe.
- Hence, do not be misled by the known CP violation; it must be an unknown type of CP violation, many orders of magnitude stronger than the known one!

No end of troubles
Inherent problems of the Big Bang model

- **The *initial singularity***
- **Conflict with observations!**

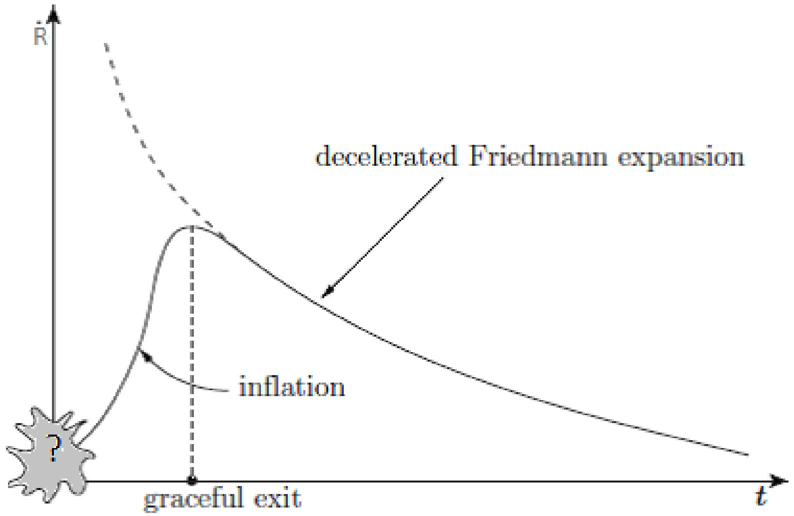
For instance, the old Big-Bang theory predicts the existence of the cosmic microwave background (CMB), but contradicts its major characteristics: high level of homogeneity and isotropy.

- Mainstream “solution”: **cosmic inflation**, i.e. an accelerated expansion of the early Universe, within the first 10^{-30} seconds, with a speed more than twenty orders of magnitude greater than the speed of light!

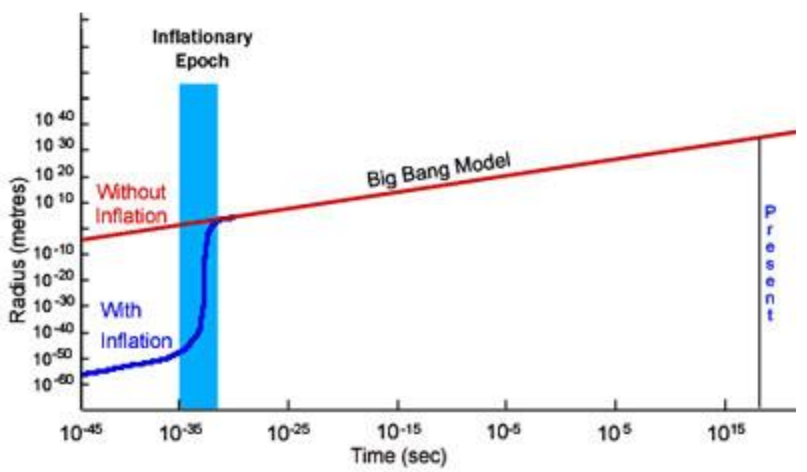
- The first content of the Universe was not matter but **inflation field**; the creation of matter has happened *after* inflation, at a macroscopic size, when the energy concentrated in the inflation field was converted into particle-antiparticle pairs.

The cosmic inflation

The radical change introduced by cosmic inflation: a tremendous accelerated expansion, Before the “graceful exit” (roughly less than 10^{-30} s).



During the inflation (in less than **10^{-30}** seconds) the scale factor of the Universe) increases from less than a Planck length to a macroscopic size.



Prelude 2: Quantum vacuum of the Standard Model

- Two cornerstones of contemporary physics
- Quantum vacuum - the hearth of the Standard Model
- The Quantum Vacuum in QED
- The Quantum Vacuum in QCD

Two cornerstones of contemporary physics

- Standard Model of Particles and Fields

  Everything is made of apparently structureless fermions (**quarks and leptons**) which interact through the exchange of **gauge bosons** (photons for electromagnetic, gluons for strong, and W^+, W^- and Z^0 for weak interactions)

- General Relativity

  Our best theory of gravitation

So far, the Standard Model is the most successful and the *best tested theory* of all time. The recent LHC experiments at CERN have been a new triumph for the Standard Model contrary to the mainstream conviction that experiments will be a triumph of supersymmetric theories

What is the Universe made of?
The Standrard Model matter

Three generations of matter (fermions)

Quarks (spin ½)	**Leptons** (spin ½)

First Generation

u up ≈2.4 MeV/c^2 2/3	**e** electron ≈0.511 MeV/c2 -1
d down ≈4.8 MeV/c^2 - 1/3	**ν_e** e-neutrino <2.2 eV/c^2 0

Second Generation

c charm ≈1.28 GeV/c^2 2/3	**μ** muon ≈105.7 MeV/c^2 -1
s strange ≈95 MeV/c^2 -1/3	**ν_μ** μ-neutrino

Third Generation

t top ≈172.4 GeV/c^2 2/3	**τ** tau ≈1.78 GeV/c^2 -1
b bottom ≈4.18 GeV/c2 -1/3	**ν_τ** τ-neutrino

Bosons

Gauge Bosons
(spin 1)

g gluon 0 0	**ϒ** photon 0 0
Z Z boson ≈91.19 GeV/c^2 0	**W** W boson ≈80.39 GeV/c^2 ±1

Scalar Bosons
(spin 0)

H Higgs
≈125.09 GeV/c^2
0

Quantum vacuum
The hearth of the Standard Model

"Nothing is plenty"

Physical vacuum is plenty of ***quantum vacuum fluctuations***, or, in more popular wording, of short-living virtual particle-antiparticle pairs which in permanence appear and disappear (as is allowed by time-energy uncertainty relation).

Quantum vacuum is an omnipresent state of matter-energy

apparently as real as the familiar states:
gas, liquid, solid, plasma in stars, quark-gluon plasma…

- ❑ Quantum vacuum is a state with perfect *symmetry* between matter and antimatter; a particle *always* appears in pair with its antiparticle

- ❑ The lifetime of a quantum vacuum fluctuations is extremely *short* (for instance, a virtual electron-positron pair "lives" only about 10^{-21} seconds).

Energy density of the quantum vacuum

- Within the Standard Model of Particles and Fields, the mass-energy density of the quantum vacuum is of the order of

$$M_c / \lambda_{Mc}^3$$

- It is uncertain what to use as a cut-off mass M_c . While some people think that for M_c we must use the Planck mass, let us consider the vacuum energy density in quantum chromodynamics with M_c roughly equal to mass of the lightest quark-antiquark pair (a neutral pion). The density is of the order of **10^{14}kg/m^3** .
- Of course you have right to think that vacuum energy density and vacuum gravitational charge density are the same thing, but in that case each cubic meter of the quantum vacuum behaves as if it has the mass of about 10^{14}kg/m^3 .

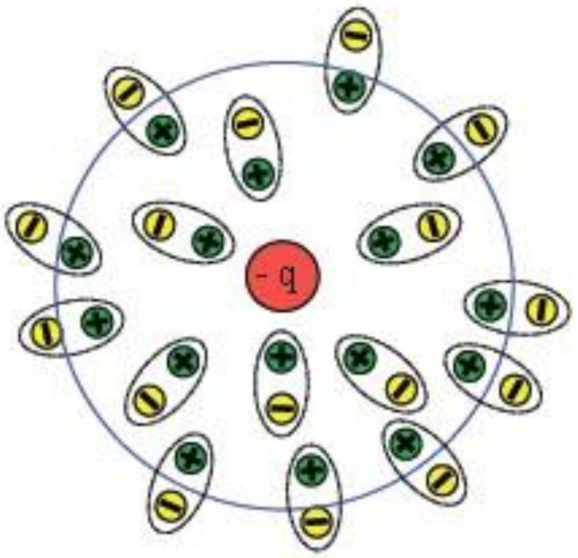
Mental picture 1: Quantum vacuum in QED
an “ocean” of virtual electric dipoles

In QED quantum vacuum can be considered as an omnipresent “ocean” of virtual electric dipoles with random orientation

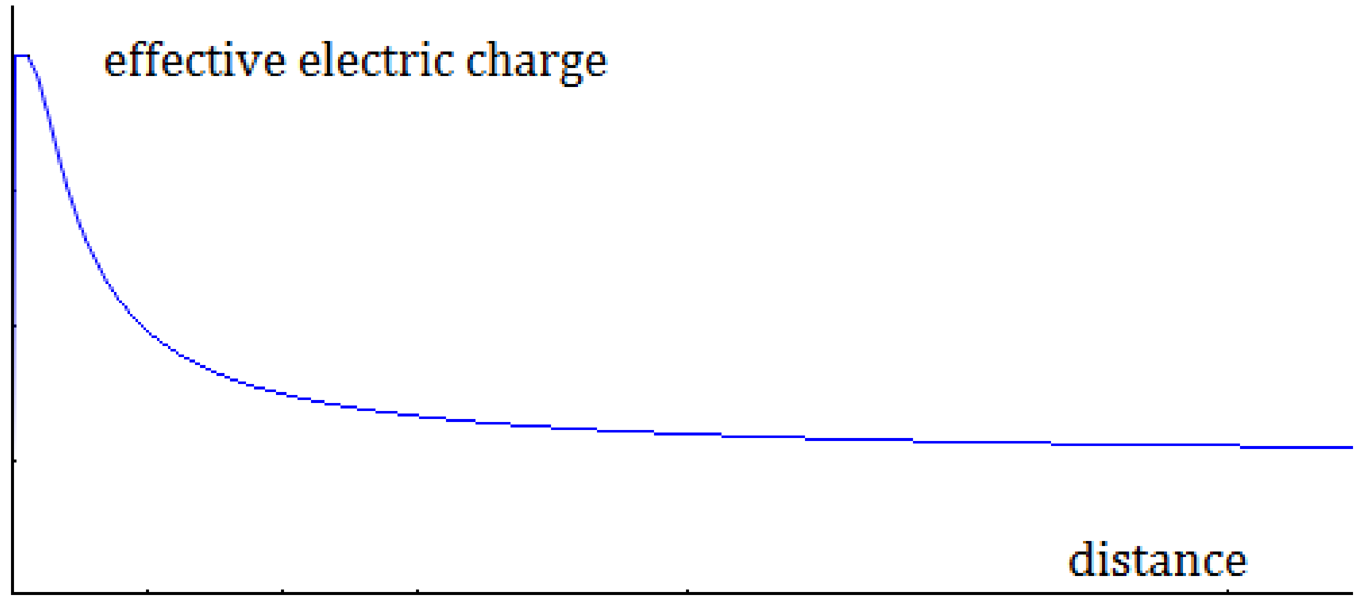
Mental picture 2: a **halo**
of the polarized quantum vacuum

- The random orientation of virtual electric dipoles can be perturbed by a very strong electric field
- Example: The electric field of an electron at the distance of its Compton Wavelength is of the order of **10^{14} V/m**. Such a strong field perturbs the random orientation

Electron "immersed" in the quantum vacuum produces around itself **a halo** of non-random oriented virtual electric dipoles, i.e. **a halo of the polarized quantum vacuum**.



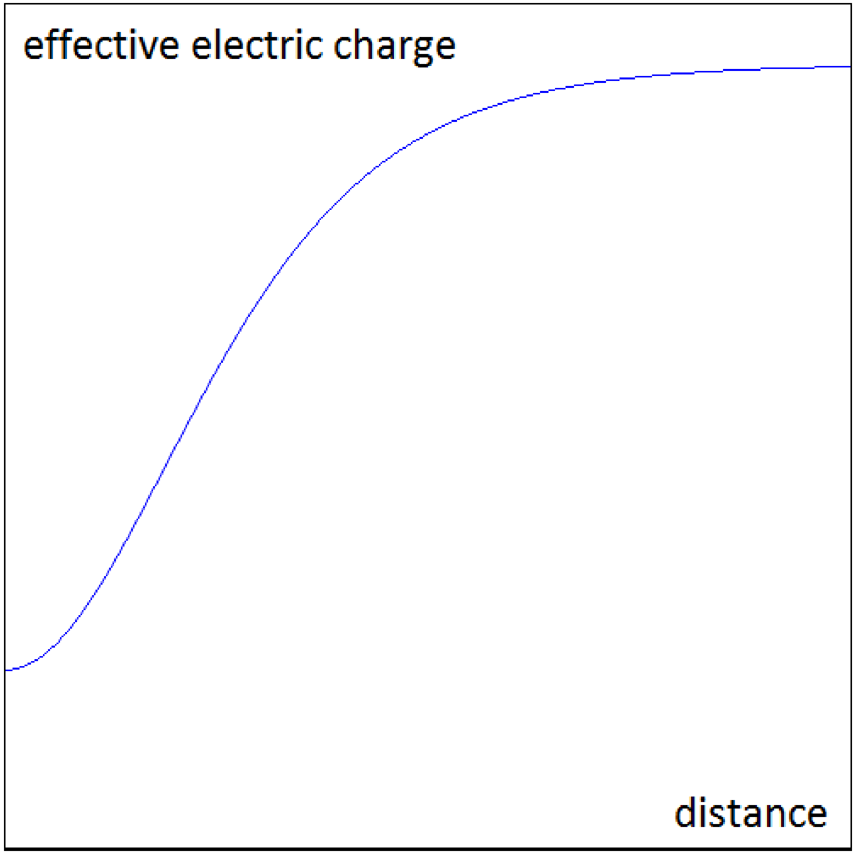
The effective electric charge of an electron



- The halo screens the "bare" charge of an electron; what we measure is the effective electric charge which *decreases* with distance!
- The effects of screening are not significant after a characteristic distance (which is of the order of the Compton wavelength)

Mathematical game with the effective electric charge of electron

- **Mathematical game**: What if there is attraction between charges of the same sign and repulsion between charges of the opposite sign?
- In this purely mathematical , non-physical case, the effect of the halo is **anti-screening**, the effective charge increases with distance.
- However, this should be valid for gravity if quantum vacuum fluctuations are virtual gravitational dipoles!



Vacum fluctuations
can be converted into real particles

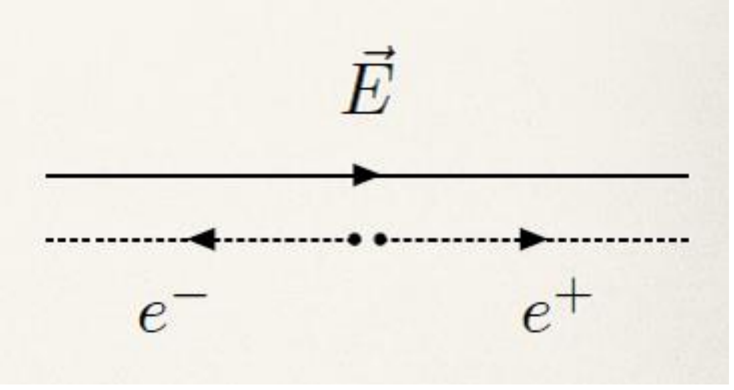
Dynamical Casimir effect

- Theoretical prediction: **Virtual photons might be converted into directly observable real photons**.
- Confirmed by experiments
  Wilson, C. M. *et al*. Nature 479, 376–379 (2011)
- For the first time, we have created light from darkness!

The Schwinger mechanism

- A virtual electron-positron pair can be converted to a real one by an external field which, during their short lifetime, can separate particle and antiparticle to a distance of about one reduced Compton wavelength
- Awaiting experimental confirmation

More about the Schwinger mechanism



- External electric field E (with the magnitude of the force equal to eE) accelerates *virtual* electrons and positrons in opposite directions. The virtual pair would become real if, as a result of acceleration, the energy gained from the electric field is at least equal to

$$2m_ec^2$$

- or in a different but equivalent wording if virtual particle and antiparticle are separated for about one reduced Compton wavelength of electron.

More about the Schwinger mechanism

For a constant acceleration *a* (which corresponds to a constant electric field) the particle creation rate per unit volume and time, can be written as

$$\frac{dN_{m\bar{m}}}{dtdV} = \frac{c}{\lambda\!\!\!^{-}{}^{4}}\left(\frac{a}{a_{cr}}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\frac{a_{cr}}{a}\right), \quad a_{cr} \equiv \pi \frac{c^2}{\lambda\!\!\!^{-}{}_m}$$

$$\lambda\!\!\!^{-}{}_m = \frac{\hbar}{mc}, \textit{ the reduced Compton wavelength}$$

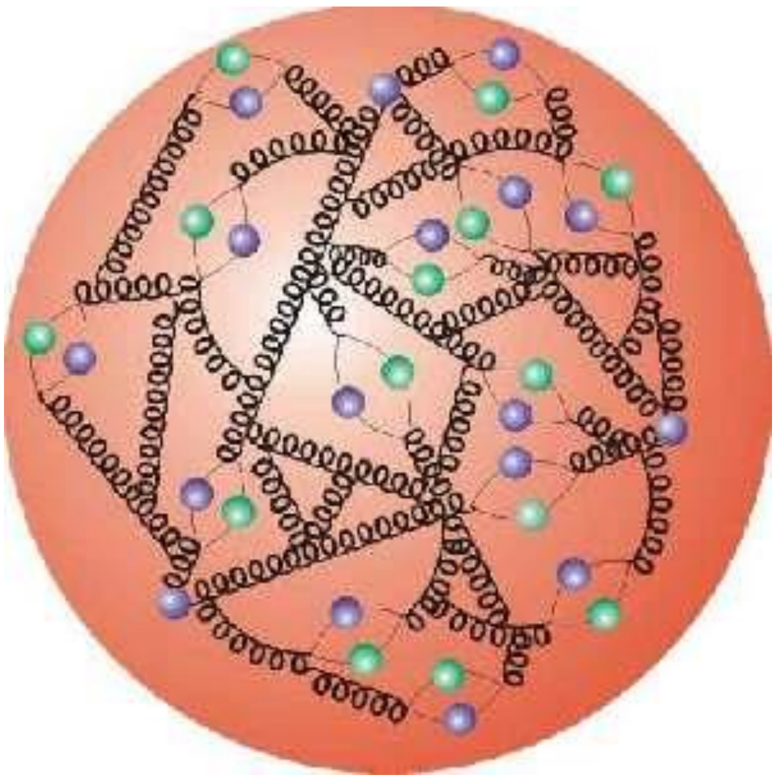
Valid for gravity if there are virtual gravitational dipoles!

Lamb shift: Quantum vacuum has impact on orbits of electrons in atoms

- Quantum vacuum, as "ocean" of virtual electric dipoles **has a tiny impact (but impact!) on the "orbits" of electrons in atoms**. It is known as the Lamb shift.
- Of course the best system to study the Lamb shift is the atom of antihydrogen because it is a binary system without complications of a many-body system.
- Immediate question: Can quantum vacuum as an eventual "ocean" of virtual gravitational dipoles have impact on orbits of satellites in binaries.

Quantum Chromodynamics
Illuminating example: the structure of proton

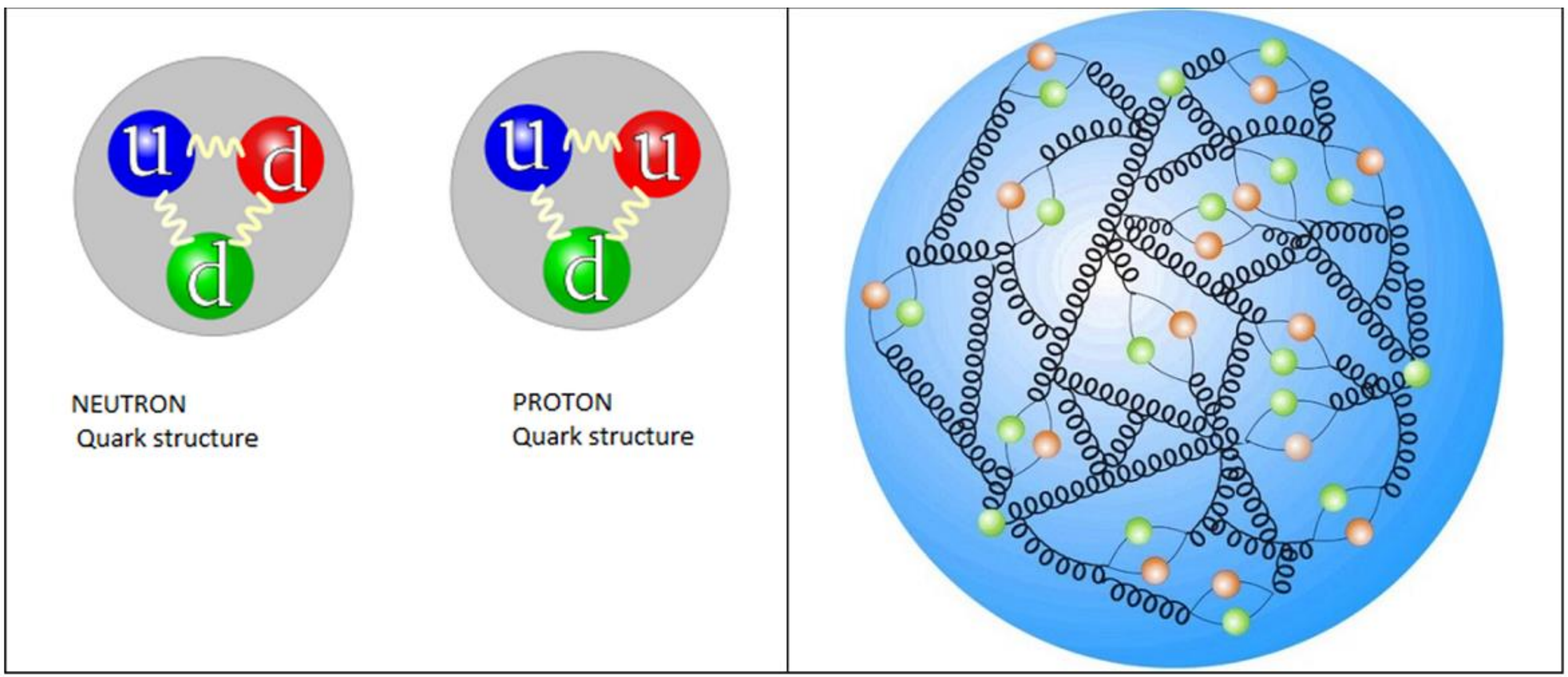
Inner structure of a proton revealed at HERA



- Black spirals represent gluons while purple-green particles denote *virtual* quark-antiquark pairs (up to 100 of these quark/anti-quark pairs are "visible" at any instant!). Note that there are three more quarks (two up, one down) than anti-quarks. These are the three valence quarks we would normally refer to when speaking of the proton
- Switching off the quantum vacuum in the Universe would destroy protons and neutrons! Quantum vacuum is the root of our existence!

What if quantum vacuum is „switched off”

Left-hand side presents structure of protons and neutrons with neglected quantum fluctuations. Right-hand side shows real inner structure of a proton revealed at HERA.



Prelude 3: How Cosmology works

- Friedman-Lemaitre-Robertson-Walker (FLRW) metric
- Einstein equation and energy-momentum tensor
- The Cosmological Field Equations
- The content of the Universe

FLRW metric

The cosmological principle (i.e. the statement that at any particular time the Universe is isotropic about every point) determines the Friedman-Lemaitre-Robertson-Walker (FLRW) metric

$$ds^2 = c^2 dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\vartheta^2\right)\right]$$

where k=+1, k=-1 and k=0 correspond respectively to closed, open and flat Universe.

The dynamics of the above space-time geometry is entirely characterised by the *scale factor* **R(t)**.

Einstein equation and energy-momentum tensor

The scale factor **R(t)** is solution of the Einstein equation

$$G_{\mu\nu} = -(8\pi G / c^4) T_{\mu\nu}$$

Einstein tensor **$G_{\mu\nu}$** is determined by FLRW metric, but in order to solve Einstein equation we must know *Energy-momentum tensor* **$T_{\mu\nu}$**

Key point

Energy-momentum tensor **$T_{\mu\nu}$** is approximated by the energy-momentum tensor of a **perfect fluid**; characterised at each point by its proper density **ρ** and pressure **p** .

Attention: Pressure p is important in GR

Cosmological field equations

If cosmological fluid consists of several distinct components denoted by ***n***, the final results are cosmological field equations

$$\ddot{R} = -\frac{4\pi G}{3} R \sum_n \left(\rho_n + \frac{3p_n}{c^2} \right)$$

$$\dot{R}^2 = \frac{8\pi G}{3} R^2 \sum_n \rho_\mathrm{n} - kc^2$$

The cosmological field equations can be solved only if we know the content of the Universe: ***the number of different cosmological fluids and the corresponding functions*** ρ_n ***and*** p_n .

Demand and promise of cosmologists to physicists: ***Tell us the content of the Universe and we will tell you how the Universe evolves in time.***

Before we continue

About pressure of cosmological fluids

Reminder: $p_n = -\frac{\partial U_n}{\partial V}$ derivative of matter-energy content of a fluid

$p_n = 0$

If the matter-energy content of a fluid is a constant

$p_n > 0$

If the matter-energy content of a fluid decreases with the increase of the scale factor *R(t)* of the Universe

$p_n < 0$

If the matter-energy content of a fluid increases with the increase of the scale factor *R(t)* of the Universe

In principle, Cosmological field equations
can describe the accelerated expansion

According to the cosmological field equation

$$\ddot{R} = -\frac{4\pi G}{3} R \sum_n \left(\rho_n + \frac{3p_n}{c^2} \right)$$

the accelerated expansion ($\ddot{R} > 0$) is possible only if

$$\sum_n \left(\rho_n + \frac{3p_n}{c^2} \right) < 0$$

The key fact to remember

The necessary condition for the accelerated expansion is the existence of a fluid with negative pressure, i.e. **a fluid with mass-energy content** (or better to say gravitational charge) **which increases with expansion.**

Cosmologists: Tell us the content of the Universe and we will tell you how the Universe evolves in time

The answer of a Standard Model physicist

The content of the Universe are **three** cosmological fluids

- ✓ Non-relativistic Standard Model matter (usually called **pressureless** matter or dust)

$$\rho_{\mathrm{m}} = \rho_{\mathrm{m0}} \left(\frac{R_0}{R} \right)^3 , \;\; p_m = 0$$

- ✓ Relativistic Standard Model matter (usually called radiation)

$$\rho_{\mathrm{r}} = \rho_{\mathrm{r0}} \left(\frac{R_0}{R} \right)^4 , \;\; p_r = \frac{1}{3} \rho_r c^2$$

- ✓ Quantum vacuum

$$\rho_{\mathrm{qv}} \equiv \mathrm{constant}, \;\; p_{qv} = -\rho_{qv} c^2$$

Note: Index 0 denotes the present day value.

Problems with the answer of the Standard Model physicists

- The use of the quantum vacuum is prevented by the cosmological constant problem. For instance quantum vacuum between Earth and Sun would have the gravitational impact as minimum 10^{18} solar masses.
- Instead of quantum vacum, cosmological fluid called dark energy is used (with the same equation of state but density inhered from observations).
- Phenomena usualy attributed to dark matter cannot be explained
- Phenomena usualy attributed to cosmic inflation cannot be explained.
- Matter-antimatter assymetry remains a mistery.

Antimatter gravity

A common explanation of all mysteries?

90 years after discovery of antimatter

The gravitational properties of antimatter are still not known

Waiting the experimental answer

- **Already active experiments**

Three competing experiments at CERN (ALPHA-g; AEGIS and GBAR) work on the measurement of the gravitational acceleration of antihydrogen . Hopefully, the ALPHA-g experiment will determine *the sign* of the gravitational acceleration of antihydrogen before the end of 2021.

- **Forthcoming experiments** with positronium (at UCL, London) and muonium (MAGE experiment at PSI).
- The unexpected shock would be if experiments reveal a gravitational repulsion between matter and antimatter (hence, forcing us to attribute a negative gravitational charge to antimatter).

How antimatter can have a major impact in a Universe without antimatter?

- According to our best knoweledge we live in a **Universe dominatted by matter.**
- Hence, the first thought is that, in spite of an eventual negative gravitational charge, the non-existing antimatter cannot play any major role in the present day Universe.
- But attention, this reasoning neglects the existence of the quantum vacuum. Quantum vacuum contains equal (and enormous) amounts of matter and antimatter in form of quantum vacuum fluctuations (or, if you prefere, virtual particle-antiparticle pairs).
- Consequently, from the gravitational point of view, physical vacuum (the quantum vacuum) must be considered as a cosmological fluid composed of virtual gravitational dipoles.

Towards a New Model of the Universe

What if quantum vacum fluctuations are virtual gravitational dipoles?

Two working hypotheses

(1) Quantum vacuum fluctuations are virtual gravitational dipoles

(2) The Standard Model matter and quantum vacuum are ***the only*** *matter-energy content of the Universe*

- A virtual gravitational dipole is defined in analogy with an electric dipole: two gravitational charges of the opposite sign at a distance **d** smaller than the corresponding reduced Compton wavelength.

- Of course, from the point of view of our best physics (General Relativity and The Standard Model of Particles and Fields) this is a completely „wild" hypothesis, but, as we will see, the hypothesis is very reach in consequences which are both astonishing and reasonable.

A quantum vacuum fluctuation

- A quantum vacuum fluctuation is a system with zero gravitational charge, but a non-zero gravitational dipole moment

$$\mathbf{p_g} = m_g \mathbf{d}, \quad |\mathbf{p_g}| < \frac{\hbar}{c}$$

m_g denotes the magnitude of the gravitational charge

d is directed from the antiparticle to the particle, and has a magnitude d equal to the distance between them.

The inequalityy follows from the fact that the size d of a quantum fluctuation is smaller than the reduced Compton wavelength, i.e.

$$d < \lambda\!\!\!^{-}_g = \hbar / m_g c$$

The number density of quantum vacuum fluctuations is rougly $1/\lambda_g^3$

Gravitational Polarization Density

- **Gravitational polarization density** $\mathbf{P}_g$ i.e. the gravitational dipole moment per unit volume, *can be attributed to the quantum vacuum*.

- For **random** orientation of dipoles $\left|\mathbf{P}_g\right| = 0$

- In the region of saturation*, the gravitational polarization density has the maximal magnitude $\left|\mathbf{P}_g\right| = P_{g\,\max}$

$$0 \le \left|\mathbf{P}_g\right| \le P_{g\,\max}$$

*Saturation is the case when all dipoles are aligned with the field

Note: $P_{g\,\max}$ can be expressed thorough characteristics of dipoles

$$P_{g\,\max} \equiv \frac{A}{\lambda_g^3}\frac{\hbar}{c}$$

The effective gravitational charge density

(the gravitational bound charge density)

- In a dielectric medium the spatial variation of the electric polarization generates a charge density known as the bound charge density. In an analogous way, the gravitational polarization of the quantum vacuum should result in

the effective gravitational charge density of the physical vacuum

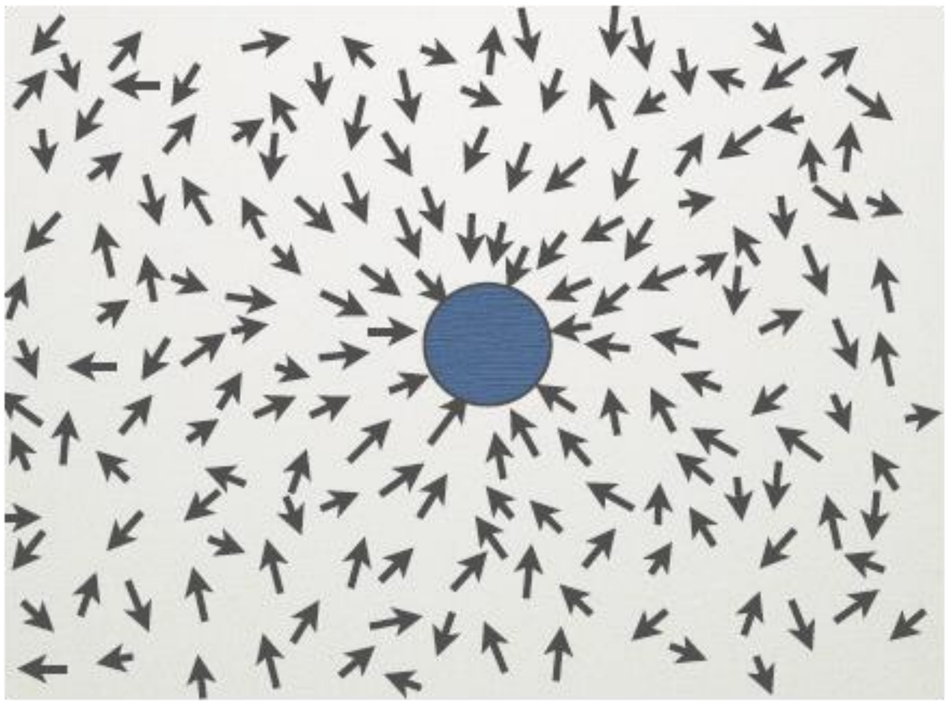
$$\rho_{qv} = -\nabla \cdot \mathbf{P}_g$$

The first mental picture: the quantum vacuum as an “ocean” of virtual gravitational dipoles

Randomly oriented gravitational dipoles (without an immersed body)

The gravitational charge density of the quantum vacuum is zero, what is the simplest possible solution to the cosmological constant problem. A tiny, **effective gravitational charge density** might appear as the result of the immersed Standard Model matter

The second mental picture: A Halo of non-random oriented dipoles around a body



- **Random orientation** of virtual dipoles **can be broken** by the immersed Standard Model matter
- A body is surrounded by an invisible ***halo of the gravitationally polarized quantum vacuum*** (i.e. a region of *non-random* orientation of virtual gravitational dipoles)
- The halo of the polarized quantum vacuum acts as an **effective gravitational charge**

This halo is well mimicked by the artificial stuff called dark matter! I joke, but it might be true. Gravitational polarization of the quantum vacuum might be the true nature of what we call dark matter.

The effective gravitational charge density in the case of spherical symmetry

In the case of spherical symmetry the general equation for the effective gravitational charge density

$$\rho_{qv} = -\nabla \cdot \vec{P}_g$$

reduces to

$$\rho_{qv}(r) = \frac{1}{r^2}\frac{d}{dr}\left(r^2 P_g(r)\right); \quad P_g(r) \equiv \left|\vec{P}_g(r)\right| \geq 0$$

The point-like source of gravity immersed in a gravitationally *featureless* classical vacuum

The simplest source of gravity is a point-like body of mass M_b.

Newton

$$\mathbf{g}_N = -\frac{\mathrm{GM_b}}{r^2}\mathbf{r}_0$$

General Relativity (Schwarzschild Metric)

$$ds^2 = c^2\left(1 - \frac{2GM_b}{c^2 r}\right)dt^2 - \left(1 - \frac{2GM_b}{c^2 r}\right)^{-1} dr^2 - r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

The point-like source of gravity immersed in quantum vacuum

$$M_{tot}(r) = M_b + \int_0^r \rho_{qv}(r)dV = M_b + 4\pi r^2 P_g(r)$$

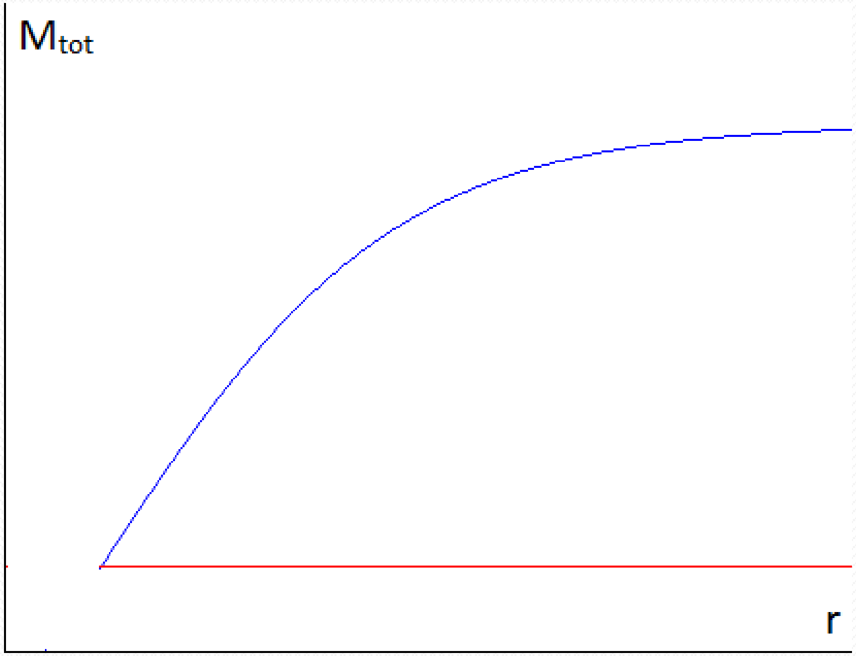
$$\mathbf{g}_{tot} = \mathbf{g}_N + \mathbf{g}_{qv} = -\frac{GM_b}{r^2}\mathbf{r}_0 - 4\pi G P_g(r)\mathbf{r}_0$$

The emerging picture

There is no dark matter and there is no modification of gravity; instead of it quantum vacuum acts as an additional (so far „forgotten) source of gravity

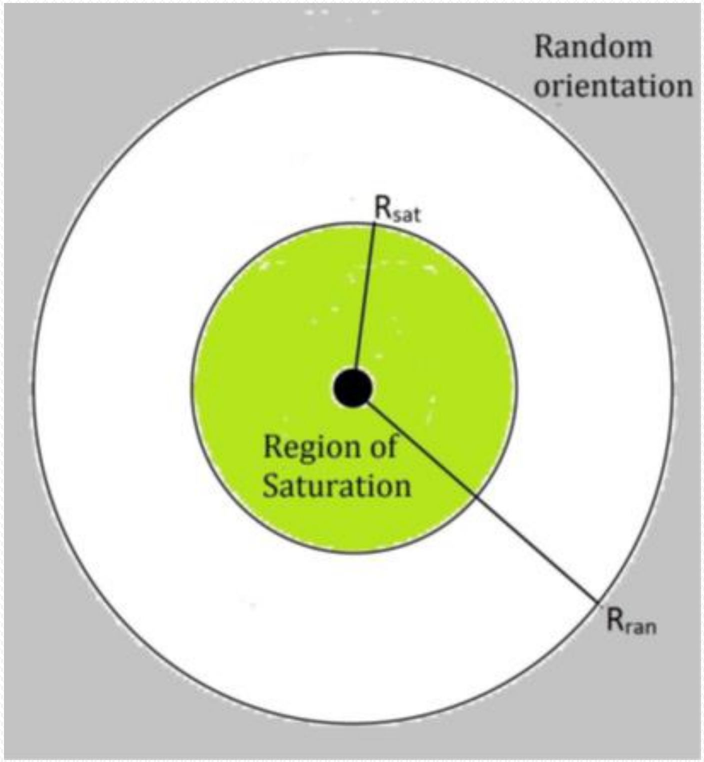
$$\mathbf{g}_{qv} - 4\pi G P_g(r)\mathbf{r}_0$$

The third mental picture
The total gravitational charge of a point-like body



- Total mass (gravitational charge) measured within a sphere with radius r. Red line is total mass with the neglected quantum vacuum. Blue line is the gravitational charge (mass) with the included quantum vacuum. Both lines begin at the surface of the body.

The forth mental picture
Schematic presentation of regions around a body



The region of saturation: the gravitational polarization density can be approximated by its maximal magnitude $P_{g\,\max}$.

The region dominated by random orientation, $P_g(r)=0$

Between these two regions $P_g(r)$ decreases from the maximum magnitude to zero. The effects usually attributed to **dark matter** are significient only in the region between saturation and random orientation.

The simplest approximation for $P_g(r)$

- Considering quantum vacuum as an ideal system of non-interacting gravitational dipoles in an external gravitational field (analogous to polarization of a dielectric in external electric field, or a **paramagnetic** in an external magnetic field) leads to

$$P_g(r) = P_{g\,\max} \tanh\left(\frac{R_{sat}}{r}\right), \quad r < R_{ran}; \; R_{sat} \approx \sqrt{\frac{M_b}{4\pi P_{g\,\max}}}$$

Note: In general hyperbolic tangent function should be replaced by the Brillouin function

$$B_{n_\varepsilon}(x) = \frac{n_\varepsilon}{n_\varepsilon - 1}\coth\left(\frac{n_\varepsilon}{n_\varepsilon - 1}x\right) - \frac{1}{n_\varepsilon - 1}\coth\left(\frac{1}{n_\varepsilon - 1}x\right)$$

Integer n_ε denotes the number of differant energy levels of a dipole in external field.

The effective gravitational charge of the quantum vacuum within a sphere

$$M_{qv}(r) = 4\pi r^2 P_{g\max} \tanh\left(\frac{R_{sat}}{r}\right) \quad for\ \ r < R_{ran}$$

$$g_{qv}(r) = 4\pi G P_{g\max} \tanh\left(\frac{R_{sat}}{r}\right) \quad for\ \ r < R_{ran}$$

- Maximal magnitude of the gravitational acceleration that can be caused by the quantum vacuum appears *in the region of saturation*

$$g_{qv\max} = 4\pi G P_{g\max}; \ \ r << R_{sat}$$

- The maximal magnitude of the gravitational acceleration can be eventually determined bu study of orbits of tiny satellites in trans-Neptunian binaries!

Rough estimation for $P_{g\max}$ and $g_{qv\max}$

- The maximal magnitude of the gravitational acceleration can be eventually determined by study of orbits of tiny satellites in trans-Neptunian binaries! The expected values are roughly

$$P_{g\max} \approx 0.07\, kg/m^2 \approx 33\, M_{Sun}/pc^2$$

$$g_{qv\max} \approx 6\times 10^{-11}\, m/s^2$$

The surface and radial density of the effective gravitational charge of the quantum vacuum

$$M_{qv}(r) = 4\pi r^2 P_{g\max} \tanh\left(\frac{R_{sat}}{r}\right) \quad for\ r < R_{ran}$$

- In the region of saturation there is nearly a constant surface density (See Appendix 1 for empirical evidence)

$$\frac{M_{qv}(r)}{4\pi r^2} = P_{g\max} \tanh\left(\frac{R_{sat}}{r}\right) \approx P_{g\max} \quad for\ r < R_{sat}$$

- Outside og the region of saturation there is nearly a constant radial density (See Appendix 1 for empirical evidence)

$$\frac{M_{qv}(r)}{r} = 4\pi P_{g\max} R_{sat} \approx \frac{1}{\lambda_\pi}\sqrt{m_\pi M_b}$$

Determination of $|\mathbf{P}_g| = P_{g\max}$ from orbits of tiny satellites in trans-Neptunian binaries

- In the region of saturation, the gravitational polarization of the quantum vacuum produces the following perihelion shift per orbit:

$$\Delta\omega_{qv} = -8\pi^2 \frac{a^2}{\mu} P_{g\max}$$

where a *and* μ are respectively the semi-major axis of the orbit and the total mass of the binary.

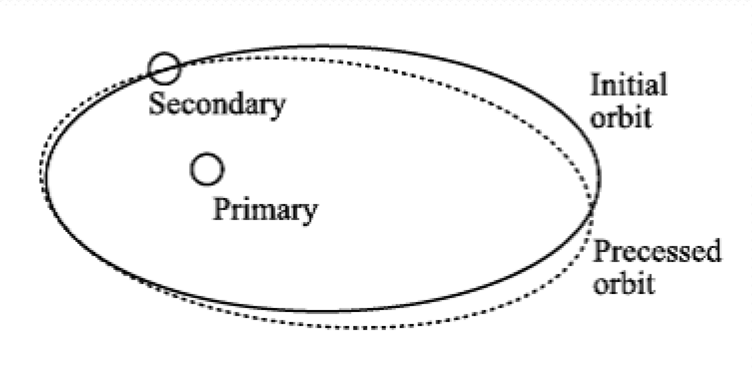
- A fascinating possibility: using the above proportionality, we can determine the maximum magnitude of the gravitational polarization density of the quantum vacuum by the measurement of the perihelion precession! It should be possible with High precision **narrow field** astrometry from ground / space.
- The expected value: $P_{g\max} \approx 0.07\, kg/m^2 \approx 33\, M_{Sun}/pc^2$

A promising Trans-Neptunian binary (55637) 2002 UX25

- UX25 parameters

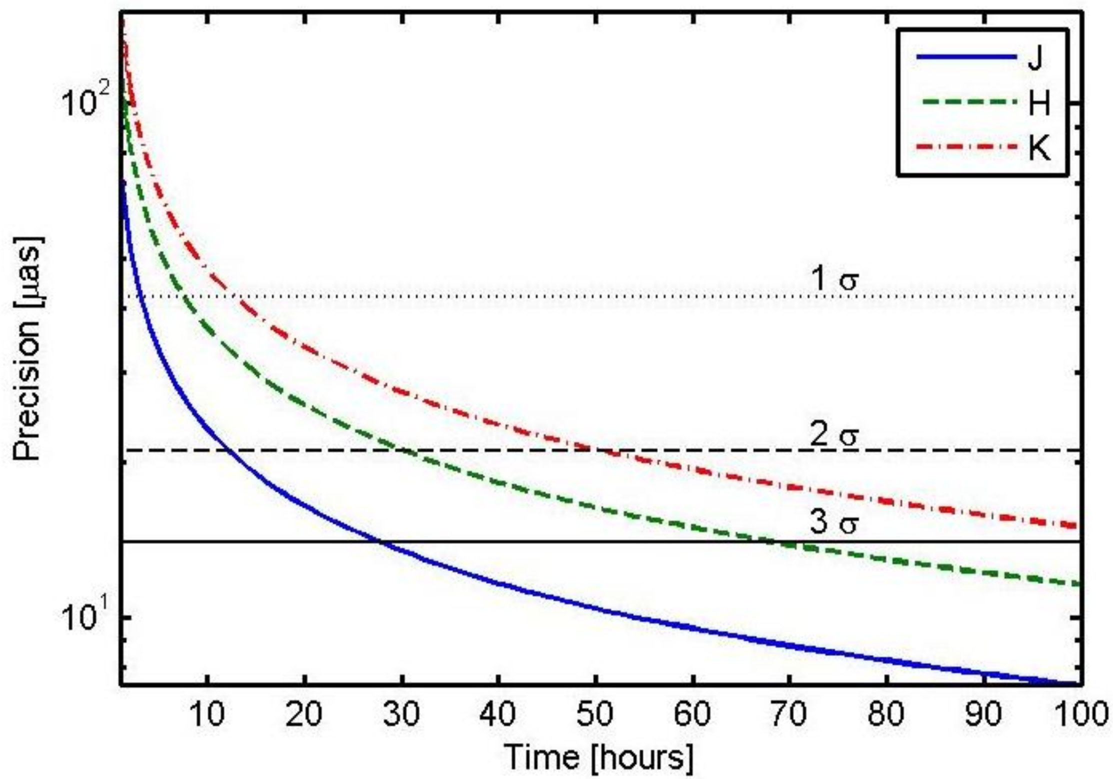
UX25 Mass	1.25×10^{20} kg
UX25 Semimajor axis	42.869 AU
UX25 Orbital Period	280.69 years
Satellite Semimajor axis	4770 km
Satellite Orbital Period	8.3094 days
Satellite Eccentricity	0.17

- Newtonian precession from the Sun (≈6 mas/orbit) is much smaller than the eventual precessioon precession caused by quantum vacuum (≈0.2arcsec/orbit).



- **Observable Cumulative effect on 5 years (~200 orbits): 40 arcsec**

Performance on 8 m telescope with



[Gai & Vecchiato, 2014]

Observation in near infrared bands

Photon noise, near diffraction limited imaging

Exploit best instrument performance

Feasible with 8 m AO telescope from ground – 10 nights/year

Best candidate:

James Webb Space Telescope (~2020) – 30 hours/year

The case of a Galaxy

An astonishing agreement with MOND and Dark matter results

Two schools of thinking: Dark matter and MOND

Two schools of thinking

- **Dark matter**: Our law of gravity is correct but the Standard Model of Particles and Fields is wrong about the content of the Universe.
- **MOND**: The content of the Universe predicted by the Standard Model of Particles and Fields is correct, but the law of gravity is wrong and must be modified.
- Apparently, MOND is a little bit better fit at scale of a galaxy, while dark mater performs better at scale of a cluster of galaxies
- For a galaxy, predictions of these two competing theories are so close that the current astronomical observations cannot distinguish between them. So, it is sufficient to compare quantum vacuum with one of them, for instance MOND.

Distribution of „dark matter” in a galaxy

- In the absence of physical understanding of the phenomenon, the distribution of (real or effective) dark matter in a galaxy is usually described by empirical laws. For instance the Burkert and NFW profile

$$\rho_B(r)=\frac{\rho_0}{\left(1+\frac{r}{r_0}\right)\left[1+\left(\frac{r}{r_0}\right)^2\right]},\quad \rho_{\mathrm{NFW}}(r)=\frac{\rho_0}{\left(1+\frac{r}{r_0}\right)\left[\frac{r}{r_0}+\left(\frac{r}{r_0}\right)^2\right]}$$

- Density ρ_0 and characteristic radius r_0 are *two* free parameters determined to give the best possible fit of observational findings for considered galaxies. Note spherical symmetry of distributions what is of course a rough approximation. Consequently our approximation can be used!

Alternative – Modified Newtonian Dynamics (MOND)

- MOND starts with ad-hoc assumption that, for a point-like source of gravity, the ratio of the total and Newtonian acceleration (g_{tot}/g_N) is a function of the ratio (a_0/g_N) of a universal acceleration a_0 and the Newtonian acceleration , i.e.

$$\frac{g_{tot}}{g_N} = f\left(\frac{a_0}{g_N}\right) > 1;\ a_0 \approx 1.2\times 10^{-10}\, m/s^2$$

- In order to fit observations two limits are imposed on the function $f(a_0/g_N)$

$$f\left(\frac{a_0}{g_N}\right) \to 1 \ \ when \ \ \frac{a_0}{g_N} \to 0; \qquad f\left(\frac{a_0}{g_N}\right) \to \sqrt{\frac{a_0}{g_N}} \ \ when \ \ \frac{a_0}{g_N} \to \infty$$

Interpolating functions in MOND

- MOND uses the following (very successful) interpolating functions

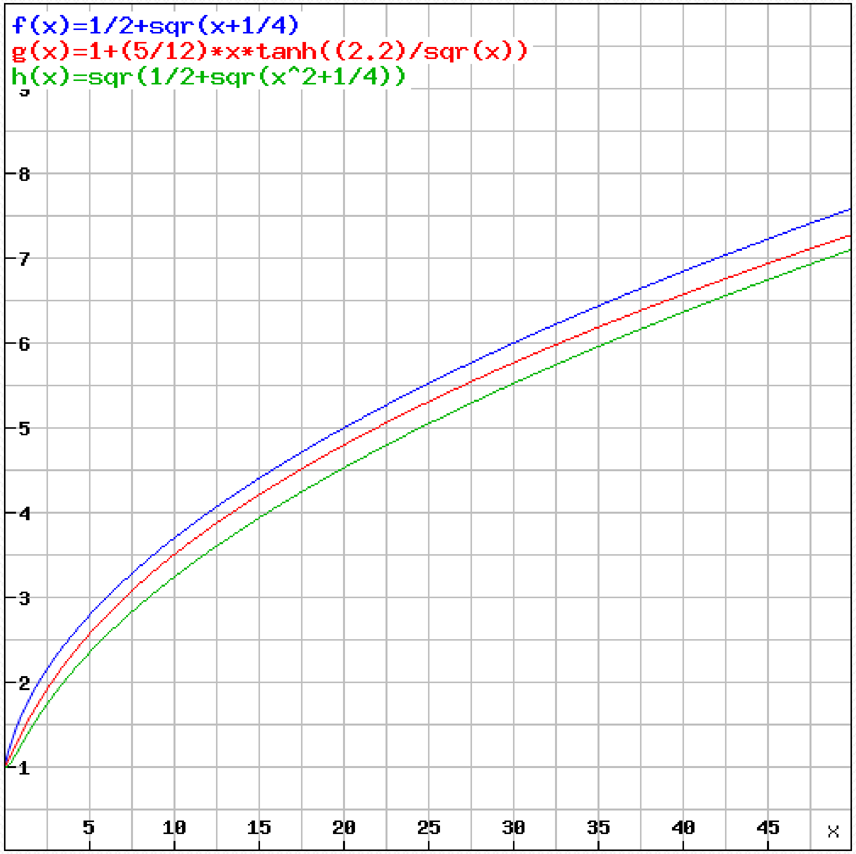
$$f_{smp}\left(\frac{a_0}{g_N}\right)=\frac{1}{2}\left(1+\sqrt{4\frac{a_0}{g_N}+1}\right),\quad f_{std}\left(\frac{a_0}{g_N}\right)=\frac{1}{\sqrt{2}}\sqrt{1+\sqrt{4\left(\frac{a_0}{g_N}\right)^2+1}},$$

$$f_{rar}\left(\frac{a_0}{g_N}\right)=\frac{1}{1-e^{-\sqrt{g_N/a_0}}}$$

- These interpolating functions should be compared with the corresponding result for the quantum vacuum

$$f_{qv}\left(\frac{a_0}{g_N}\right)=1+\frac{g_{qv}}{g_N}\tanh\left(\frac{R_{sat}}{r}\right)=1+\alpha_1\frac{a_0}{g_N}\tanh\left(\alpha_2\sqrt{\frac{g_N}{a_0}}\right)$$

Comparaison with MOND



- The simple and the standard interpolating functions in MOND (respectively blue and green) compared with the prediction of the polarized quantum vacuum : (red line). In all functions

$$x = a_0 / g_N$$

- Apparently, a halo of the polarized quantum vacuum can explain phenomena (in a galaxy) as well as MOND and Dark matter.

How strong must be an external field to produce vacuum polarization?

- The electric field of an electron at the distance of its Compton Wavelength is of the order of

$$10^{14} V/m$$

- The gravitational acceleration produced by a pion (roughly a typical mass in the physical vacuum of quantum chromodynamics) at the distance of its Compton wavelength is

$$\approx 1.9 \times 10^{-10} m/s^2 \quad *$$

The mean distance between two dipoles which are first neighbours is one Compton wavelength. Hence, the above electric and gravitational field can be used as a rough approximation of the external field needed to produce the effect of saturation for the corresponding dipoles. While the gravitational field needed for polarization is very weak, the needed electric field is very strong. In fact the electric polarization of macroscopic volumes is suppressed because the electromagnetic interactions are too strong; only a weak interaction as gravity can polarize large volumes

*This acceleration is not very differant from the acceleration proposed by MOND as a new universal constant.

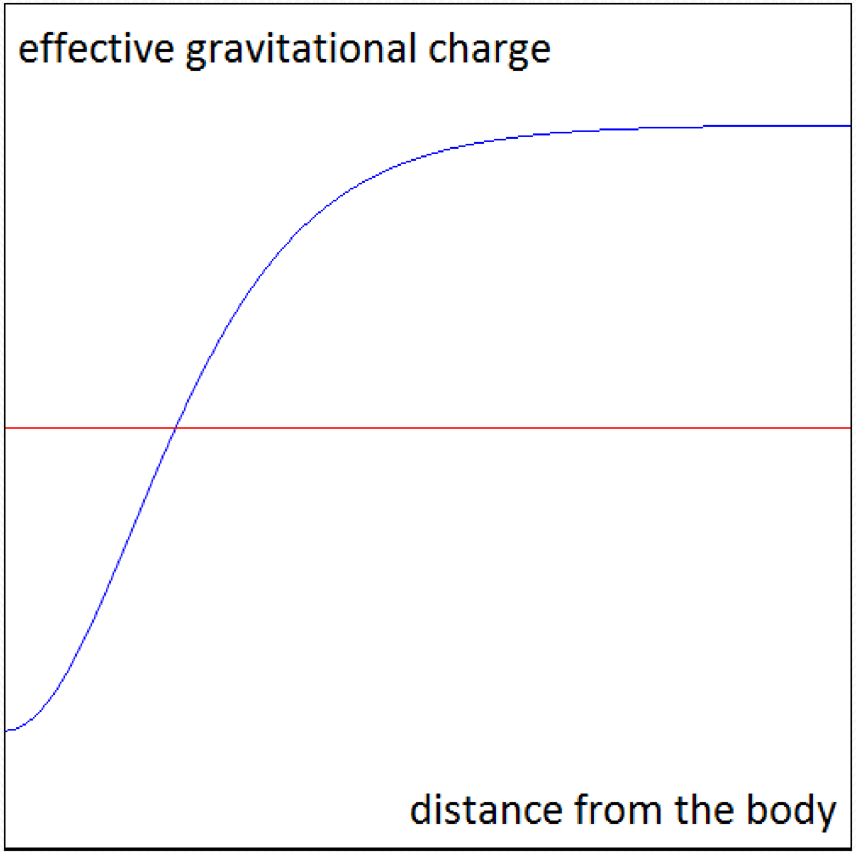
Three qualitative pictures

- Dark energy as the global effect of the gravitational vacuum polarization
- A cyclic Universe alternatively dominated by matter and antimatter
- Black-White Holes

The size of a halo

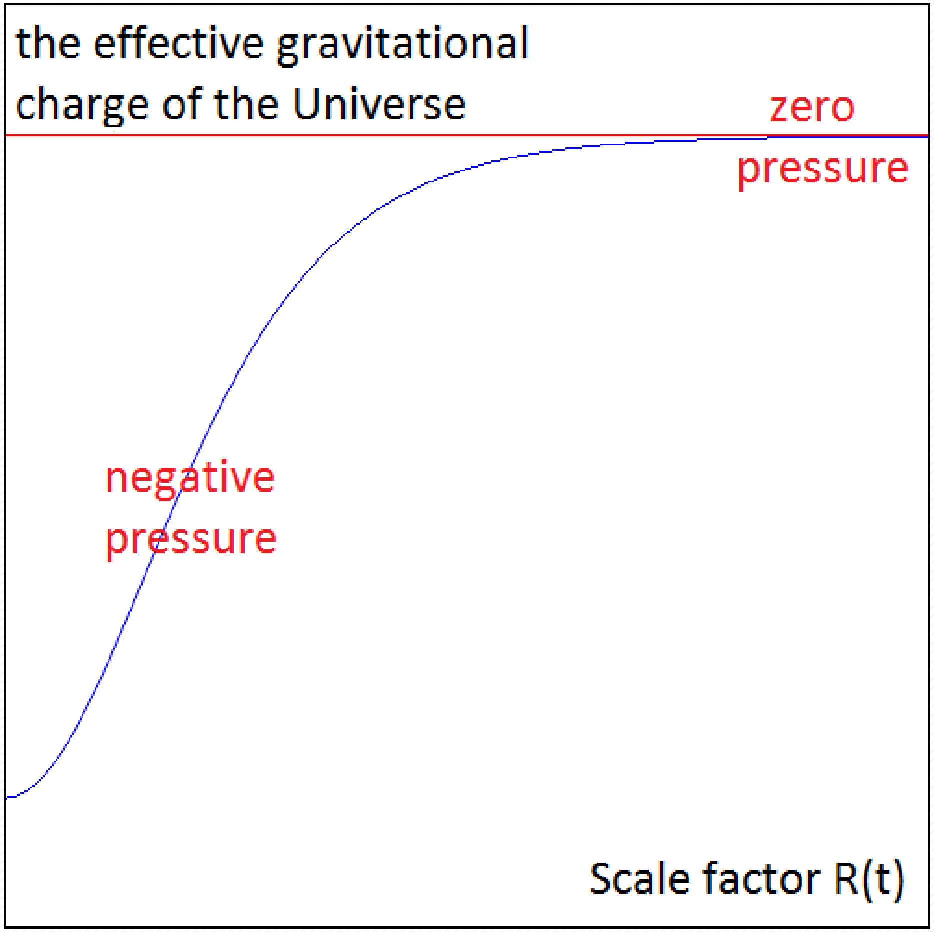
- There is a *maximum size of the halo* for each massive body, galaxy or cluster of galaxies; after a characteristic size the random orientation of dipoles dominates again. However, because of the proximity of other bodies, many halos are smaller than the maximum size.
- A halo of the maximum size can be formed *only if* other bodies, competing in the polarization of the quantum vacuum, are sufficiently far away.
- Consequently, with the expansion of the universe, galactic halos must increase in size and the content of the *effective gravitational charge* caused by the polarization of the quantum vacuum must also *increase*. However, it is not an endless increase; once the halos have reached their maximum size they remain unchanged with the further expansion.

How the effective gravitational charge depends on the distance from other bodies



- **The effective gravitational charge** of a body (blue line) increases from the "**bare**" charge measured at its surface to a constant maximum charge at a large distance from the body
- Competing gravitational field of other bodies can prevent the effective gravitational charge to increase above a limit presented by the red line
- The maximum effective charge can be reached only if other bodies are sufficiently far

How the effective gravitational charge of the Universe depends on the scale factor R(t)



The effective gravitational charge of the quantum vacuum in the Universe depends on the scale factor R(t). Note that with the expansion of the Universe the polarized quantum vacuum converts from a cosmological fluid with negative pressure to a presureless fluid!

Key points about quantum vacuum replacing dark energy

- The *increase* of the effective gravitational charge of the quantum vacuum means that the polarized quantum vacuum behaves as a fluid with *negative pressure*, and, according to the cosmological equations (see Slide 20) it is a necessary condition, for the accelerated expansion of the Universe.
- A second major feature is that the qualitative behaviour presented in the previous slide *prevents* eternal accelerated expansion predicted by the current ΛCDM cosmology. Namely, when the effective gravitational charge of the quantum vacuum is close to constant value, the pressure is nearly zero and the accelerated expansion is no longer possible; deceleration and an eventual contraction become possible.

The gravitational version of the Schwinger mechanism

$$\frac{dN_{m\bar{m}}}{dtdV} = \frac{1}{4\pi^3}\frac{c}{\lambda_m^4}\left(\frac{g}{g_{cr}}\right)^2 \sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n\pi\frac{g_{cr}}{g}\right), \quad g_{cr} = \frac{c^2}{\lambda_m}$$

Ilustration: For the Scale factor of the Universe $R = 10^9\,m$ (about the size of the Sun), the Cosmological equations for the radition dominated Universe gives

$$\ddot{R} = -\frac{8\pi G\rho_{r0}}{3}\frac{R_0^4}{R^3} \propto 10^{42}\, m/s^2$$

The corresponding particle creation rate (for particles of let’s say mass of a nucleon) is

$$\frac{\mathrm{d}N_{m\bar{m}}}{\mathrm{dtd}V} \approx 10^{90}\ particles/sm^3 \approx 10^{33}\, M_{Sun}/sm^3$$

A cyclic Universe alternatively dominated by matter and antimatter

- During the expansion of the Universe **quantum vacuum converts from a cosmological fluid with negative pressure to nearly pressureless fluid**. According to the cosmological field equations it means that **the accelerated expansion converts to the decelerated one**.
- The eventual collapse of the Universe cannot end in singularity. There is an ultimate mechanism to prevent it: the gravitational version of the Schwinger mechanism i.e. conversion of quantum vacuum fluctuations into real particles, by an extremely strong gravitational field
- An extremely strong gravitational field would create a huge number of particle-antiparticle pairs from the physical vacuum; with the additional feature that matter tends to reach toward the eventual singularity while antimatter is violently ejected farther and farther from singularity. The amount of created antimatter is equal to the decrease in the mass of the collapsing matter Universe.

Continue on the next Slide

Continued from the previous Slide

- Hence, the quantity of matter decreases while the quantity of antimatter increases by the same amount; the final result might be conversion of nearly all matter into antimatter. If the process of conversion is very fast, it may look like a Big Bang but it is not a Big Bang: it starts with a macroscopic initial size without singularity and without need for inflation field of unknown nature.
- In addition, there is an elegant explanation of the matter-antimatter asymmetry in the universe:

our universe is dominated by matter
because the previous cycle of the universe
was dominated by antimatter

Black-White Holes

- If particles and antiparticles have gravitational charge of the opposite sign a black hole is also a white hole. A black hole made from matter is a black hole for matter but a white hole for antimatter, while a black hole made from antimatter is a black hole for antimatter but a white hole for matter.
- The name black-white hole would be inevitable for such objects; if black-white holes exist, Hawking's black hole radiation will remain a great intellectual achievement but not the way in which nature works.

Astonishing coincidences or signatures of new physics, astrophysics and cosmology

Dirac's relation

- The original and modified Dirac's relation

$$m_{\pi}^{3} \propto \frac{\hbar^{2}}{c}\frac{H_{0}}{G}, \quad m_{\pi}^{3} \propto \frac{\hbar^{2}}{c}\frac{H}{G}\left\{\frac{\Omega_{\Lambda}}{\sqrt{\Omega_{tot}-1}}\frac{R_{0}}{R}\right\}$$

- The original (incomplete?) Dirac's equation. On the left-hand side is the mass of a typical particle, such as a pion. On the right-hand side is a simple expression entirely composed from the fundamental constants $\hbar, c, G$ and the Hubble constant H_0 (i.e. the present day value of the cosmological parameter related to the expansion of the Universe). Dirac's intuition was that this is not a coincidence.
- The completed Dirac's relation includes other cosmological parameters and there is no need (as in the original Dirac's work) to keep constant the ratio *H/G*.

New Dirac’s type relations

- Dirac’s relation is not a consequence of any previous theory; simply someone has noticed an astonishing numerical similarity that might be a coincidence but also may have some fundamental physical significance. Hence, we can say that relation comes from nowhere and it is an advantage; the usual opposition to relations coming from a radically new theory is minimized and the open-minded thinking is facilitated.
- We present a series of other astonishing relations which, just as Dirac’s “coincidence”, relate a typical Standard Model mass, of the order of mass of a pion, with different cosmic phenomena. Considered separately, each of the forthcoming relations is intriguing, but all together they impress much more and it is very likely that nature tell us something through them.
- How the mass of a quark-antiquark pair (or something else similar to pion within the Standard Model of Particles and Fields) can be related to cosmological parameters describing the large-scale Universe. Let me paraphrase Einstein, all these relations suggest a spooky communication at a distance.

The radial density of dark matter in a galaxy

- The astronomical observations have revealed that (out of a small central part) the quantity of dark matter within a sphere divided by the radius of the sphere is a constant; i.e. $M_{dm}(r)/r$ is a constant for all *r*. For a galaxy, with the baryonic mass , the astonishing coincidence, of similar beauty and simplicity as Dirac's coincidence is:

$$\rho_r \equiv \frac{M_{dm}(r)}{r} \approx \frac{\sqrt{m_\pi M_b}}{\lambda_\pi}$$

- An amusing rule: Find the geometrical mean $\sqrt{m_\pi M_b}$ of mass m_π of a microscopic fluctuation and the gigantesque Standard Model mass M_b (usually called baryonic mass) of a galaxy and divide it by the Compton wavelength of fluctuation; what you get is very close to the value of the radial dark matter density.

The surface density of dark matter in a galaxy

- The astronomical observations suggest that in the central part of a galaxy, the quantity of dark matter within a sphere divided by the surface of the sphere $M_{dm}(r)/4\pi r^2$ is a constant which is the same for all galaxies; i.e. is a constant independent of the mass of galaxy. The coincidence is:

$$\frac{M_{qv}(r)}{4\pi r^2} \approx \frac{m_\pi}{4\pi\lambda_\pi^2}$$

Dark energy density in the present-day Universe

- Dark energy, a content of the Universe apparently completely different from dark matter, can also be expressed through mass of a pion. The coincidence is:

$$\rho_{de}\left(R_0\right) \propto \frac{m_\pi}{\lambda_\pi^2}\frac{1}{R_0}$$

- Hence, dark energy density of the present-day Universe is apparently determined by mass of a pion and the scale radius .

- Note: Remember that, if not composed from virtual gravitational dipoles. quantum vacuum in quantum chromodinamics has the gravitational charge density of the order of m_π / λ_π^3 . If quantum vacuum is composed from dipoles this result should be multiplied by .

The characteristic acceleration

- Empirical evidence has revealed that if Newtonian acceleration is very small it is only a fraction of the total acceleration. This empirical fact must be separated from attempts to explain it. This effect becomes significant when acceleration is close to a “critical” acceleration a_0 . The coincidence is:

$$a_0 \propto \frac{Gm_\pi}{\lambda_\pi^2}$$

- Hence, the fact that Newtonian acceleration is a fraction of the total acceleration emerges when acceleration caused by such big system as galaxies has the same value as the acceleration caused by a pion at the distance of its Compton wavelength.
- And so on; there are more coincidences than space to present them

Appendix 1

Comparison with the empirical evidence for galaxies

Comparaison with the empirical evidence
Example 1:Tully-Fisher relation

- **Tully-Fisher relation** is one of the most robust **empirical results**, unexplained by "dark matter"; basically it is a scaling relation of the same form as our analytical result

$$V_{rot}^4 = G^2 \frac{m_\pi M_b}{\pi \lambda_\pi^2}$$

(relating limit of rotation velocity in disk galaxies with the baryonic content of the galaxy)

- Let us note that at this point (Tully-Fisher relation) MOND is more successful than "dark matter" theory. The significant success of MOND is a sign that there is something special about their acceleration $a_0 \approx 1.2 \times 10^{-10}\, m/s^2$. However, according to our model **there is no any modification of the Newton's law**, as proposed by MOND, for gravitational fields weaker than a_0 . In our model, a_0 is rather **a transition point**, **from saturation in stronger fields to non-saturated polarization in weaker fields**.

Comparison with the empirical evidence
Example 2: Surface density of "dark matter"

- In the region of saturation

$$\frac{M_{qv}(r)}{4\pi r^2} \approx P_{g\,\max} \equiv \text{constant}$$

which is a prediction universally valid for all galaxies!

- It is exactly what has been observed [Kormendy and Freeman 2004, Donato 2009]. Let us note that astronomers have no any physical interpretation of the critical distance and that so far this result escapes explanation within dark matter theory.
- Next Slide contains comparison of our result and observations

Continued from the previous Slide

Dopita (2012) has found, as he said the excellent agreement, between our theoretical result (blue line) and observations

Scaling Laws for Dark Matter Halos of Galaxies 391

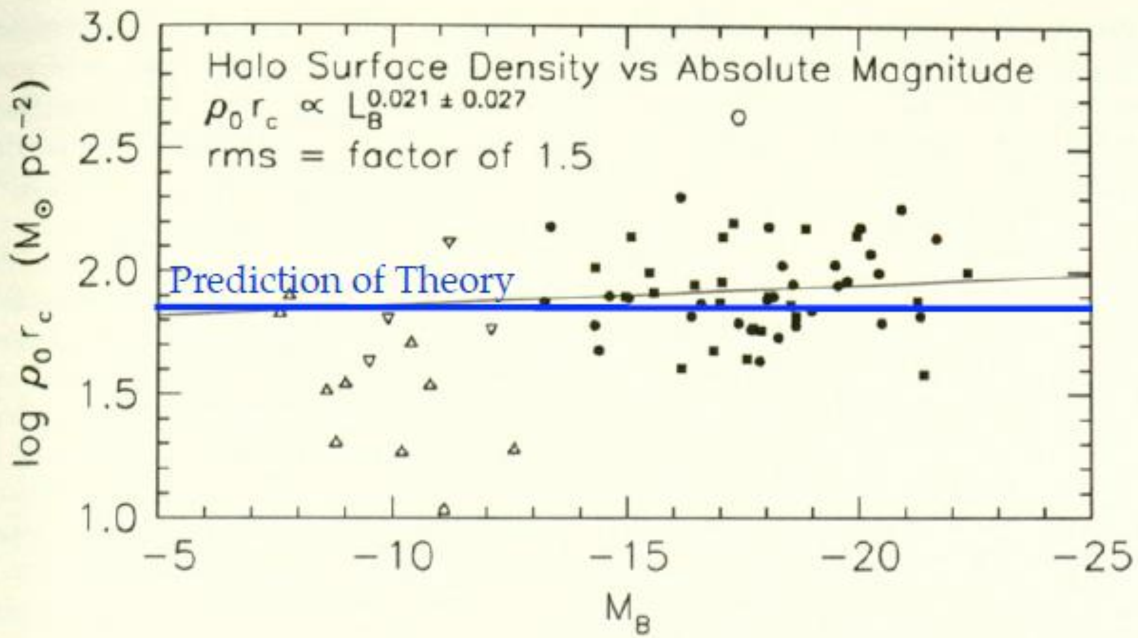


Figure 5. Logarithm of $\rho_0 r_c$, which is proportional to the projected surface density of DM halos, as a function of absolute magnitude. The symbols are the same as in Figures 2 – 4. The straight line (*key*) is a least-squares fit to the Sc – Im galaxies omitting NGC 4605. Within the errors, the surface densities of DM halos of late-type galaxies are independent of galaxy luminosity.

Comparison with the empirical evidence

Example 3: The local “dark matter” density

The local effective gravitational charge density

- The local dark matter density is an average over a small volume, typically a few hundred parsecs around the Sun.
- Apparently, the best estimate of the local dark matter density [Zhang et al. 2013] is

$$0.0075 \pm 0.0021 M_{Sun} / pc^3$$

- Our theoretical result (Sun is in the region of saturation) is

$$\rho_{qv}(r) = \frac{2P_{g\max}}{r} = \frac{57 M_{Sun} / pc^2}{8kpc} \approx 0.0071 \frac{M_{Sun}}{pc^3}$$

Comparison with the empirical evidence

Example 4:The total mass of Milky Way within 260kpc

- According to astronomical observations [Boylan-Kolchin 2013] the median Milky Way mass within 260kpc is

$$M_{MW}(260kpc) = 1.6\times10^{12} M_{Sun}$$

with a 90% confidence interval of

$$[1.0-2.4]\times10^{12} M_{Sun}$$

- Our theoretical estimate (using $M_b = 6\times10^{10} M_{Sun}$)

$$M_{MW}(260kpc) \approx 1.45\times10^{12} M_{Sun}$$