Dragan Slavkov Hajduković

Trans-Neptunian binaries: A laboratory for testing the existence of the gravitational anomalies

Всероссийская астрометрическая конференция
"Пулково-2015" 21 - 25 сентября 2015 года

All-Russian Astrometry Conference
"Pulkovo - 2015" 21 - 25 September 2015

I am for the first time in Russia. What a pleasure to be in the country of the heroes of my childhood

Я в первый раз в России
Какое удовольствие быть в стране героев моего детства

Юрий Алексеевич Гагарин
Герман Степанович Титов
Владимир Михайлович Комаров
Валентина Владимировна Терешкова

Михаил Нехемьевич Таль
Петр Григорьевич Болотников
Валерий Николаевич Брумель
Вячеслав Иванович Старшинов

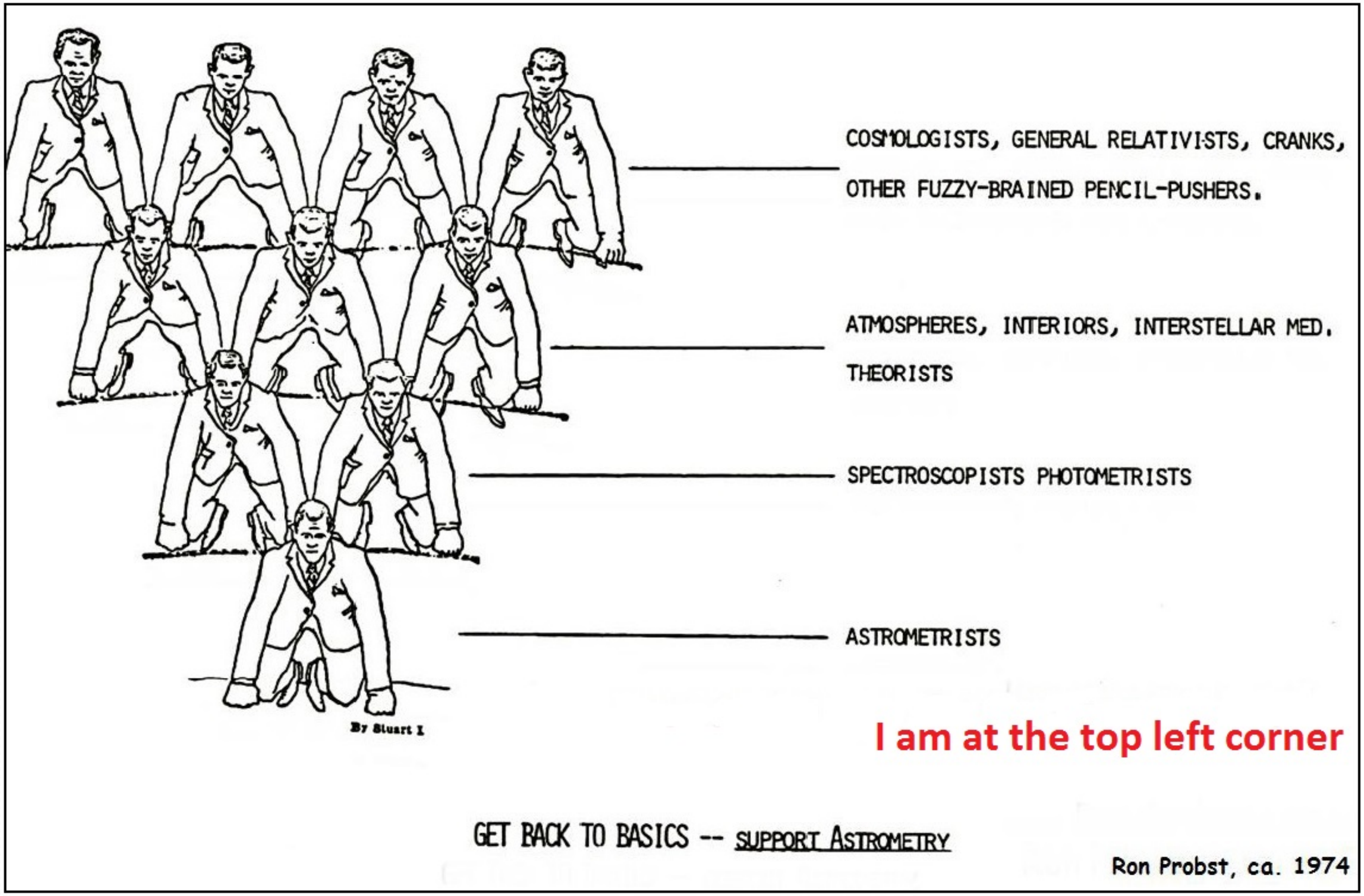
Abstract

We point out that some of trans-Neptunian binaries are a natural laboratory for testing the existence of an anomalous gravitational field as weak as 10^{-11} m/s^2 (with the next generation of telescopes the anomalous gravitational field of the order of 10^{-12} m/s^2 might be revealed). The method is based on the measurement of the perihelion precession of the orbit. The unrivalled advantage of tiny trans-Neptunian binaries is that they are the best available realisation of an isolated two body system with very weak external and internal Newtonian gravitational field. As a consequence, the known Newtonian precession might be dominated by anomalous perihelion precession. While these measurements are significant independent of any theory they were initially proposed as a crucial test of a new model of the Universe based on the hypothesis that quantum vacuum fluctuations are virtual gravitational dipoles. According to the new model, *the only* content of the Universe is the known Standard Model matter (i.e. matter made from quarks and leptons interacting through the exchange of gauge bosons) immersed in the quantum vacuum "enriched" with virtual gravitational dipoles. Apparently, what we call dark matter and dark energy, can be explained as the local and global effects of the gravitational polarization of the quantum vacuum by the immersed baryonic matter.

What a theoretical physicist with a tiny knowledge of astrometry is doing at your conference?

We have different answers!

Your answer



COSMOLOGISTS, GENERAL RELATIVISTS, CRANKS,
OTHER FUZZY-BRAINED PENCIL-PUSHERS.
ATMOSPHERES, INTERIORS, INTERSTELLAR MED.
THEORISTS
SPECTROSCOPISTS PHOTOMETRISTS
ASTROMETRISTS
By Stuart I
I am at the top left corner
GET BACK TO BASICS -- SUPPORT ASTROMETRY
Ron Probst, ca. 1974

… and my answer

- **I want to challenge and motivate astrometrists for a high-precision study of orbits of tiny satellites in trans-Neptunian binaries**

Examples of trans-Neptunian binaries

- **(55637) 2002 UX25**
- **(136199) Eris and Dysnomia**
- **(136108) Haumea, Hi'iaka, and Namaka (in fact two satellites)**
- **(50000) Quaoar and Weywot**
- **(66652) Borasisi and Pabu**
- **(42355) Typhon and Echidna**
- **(148780) Altjira**

… and my answer

- In CERN **3** experiments (AEGIS, ALPHA, GBAR) **compete** who will be the first one in the human history to reveal the gravitational properties of antimatter.
- 8 decades after the discovery of antimatter we still don’t know if in the gravitational field of the Earth, antimatter falls down or **falls up**; experiments at CERN will test it with atoms of **antihydrogen**.
- Open possibility: **matter and antimatter might have the gravitational charge of the opposite sign**.
- **High-precision study of orbits of tiny satellites in trans-Neptunian binaries can be a complementary astronomical test of the gravitational properties of antimatter**

Let us focus on (55637) 2002 UX25

- UX25 parameters

UX25 Mass	$1.25\text{x}10^{20}$ 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

- **Challenge**: **Detect a perihelion precession which can be as small as** $0.2\, arc\sec/orbit$
- **If you can do this you may be the first one to reveal that quantum vacuum has impact on orbits in binaries** (what would be in a nice analogy with the established fact that quantum vacuum has impact on the "orbits" of electrons in atoms)

What are causes of precession of an orbit

- The simplest problem in celestial mechanics is to determine orbit of a point-like body in a central gravitational field.
- The orbit is an ellipse *fixed with* respect to the centre of gravity

  if and only if

  the central gravitational field has perfect spherical symmetry and the **effective** gravitational force strictly follows the inverse square law.
- **Any departure from spherical symmetry and/or the inverse square law for the effective gravitational force, leads to the precession of the perihelion**

What are causes of precession of an orbit

general relativistic correction

- General relativistic correction can be safely neglected because trans-Neptunian binaries have very small mass and orbit far from the Sun.
- Example: For UX25 the Einstein correction to the Newtonian precession is roughly

$$\Delta\omega_{GR} \approx \frac{3\pi}{\sqrt{1-e^2}} \frac{R_S}{a} \approx 6\times10^{-8}\, arc\sec/orbit$$

R_S *and* a are respectively the Schwarzschild radius of the minor planet and the semimajor axis of the satellite

What are causes of precession of an orbit

Newtonian precession

- Newtonian precession is mainly caused by third bodies; in our case the dominant body is the Sun.
- For a minor planet (which orbits around the Sun with a period T_{Sun}) *and its satellite* (*which* orbits around the planet with a period T_p) the Newtonian precession caused by the Sun is roughly

$$\Delta\omega_N \approx \frac{3\pi}{2}\left(\frac{T_p}{T_{Sun}}\right)^2$$

- Example: For UX25, $\Delta\omega_N \approx 0.006\, arc\sec/orbit$, what, even if doubled, cannot be detected with telescopes available within the next two decades.

What are causes of precession of an orbit

Anomalous precession caused by a tiny perturbation

- We have seen that in the case of UX25 the Newtonian precession is too small to be detected with the existing telescopes; hence what we should observe is the zero Newtonian precession.
- Let us consider the central acceleration of the form

$$g(r) = \frac{GM}{r^2} + g_{qv}(r)$$

- Question: What is the value of $g_{qv}(a)$ which can produce the observable anomalous precession in the case of UX25
- Answer: $g_{qv}(a) \approx 5\times 10^{-11}\, m/s^2$; smaller than a_0 in MOND, and **exactly what can be expected if matter and antimatter have the opposite gravitational charge.**

Feasibility study for (55637) 2002 UX25

See also the Appendix

- High precision **narrow field** astrometry from ground / space A preliminary feasibility study for (55637) 2002 UX25 Mario Gai and Alberto Vecchiato: http://arxiv.org/abs/1406.3611

Presented as the Invited Talk at the following conferences

- Astrometry Futures; Institute of Astronomy, University of Cambridge, 6-8 July 2015. Slides of the talk
- 3rd Workshop on Antimatter and Gravity; University College London, 5-7 August 2015. Slides of the talk

Instead of the astrometry in the rest of the talk I will focus on an exciting physical motivation for this measurement: **If quantum vacuum is "enriched" with virtual gravitational dipoles**, what we call dark matter and dark energy can be explained as the local and global effects of the gravitational polarization of the quantum vacuum by the immersed baryonic matter.

Our best fundamental knowledge

Two cornerstones of contemporary physics

- **Standard Model of Particles and Fields**

  Everything is made from 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^o 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

Quantum vacuum
is essential part 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).

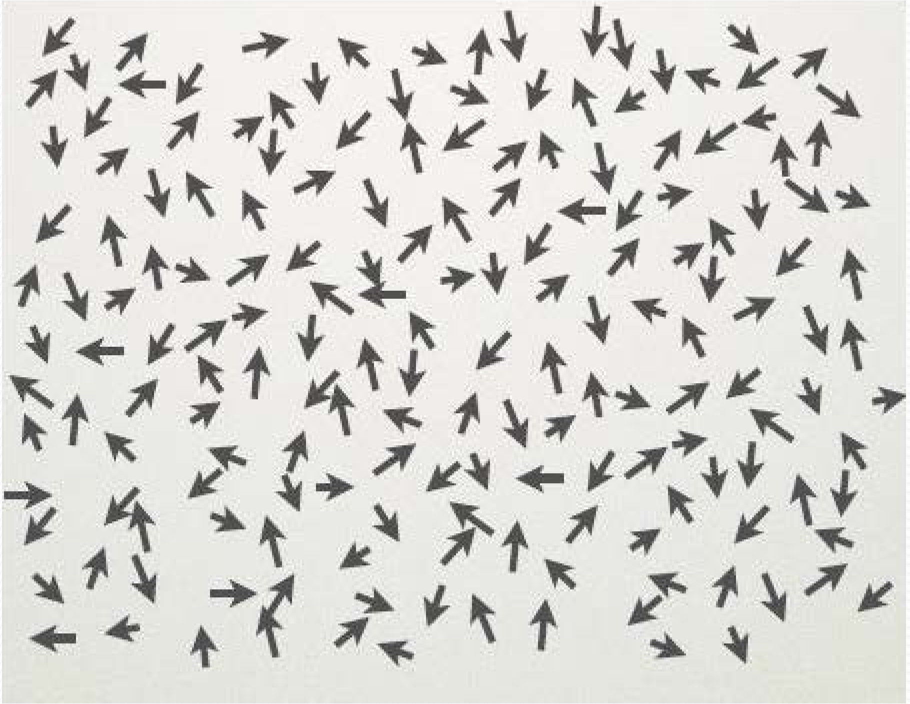
Quantum vacuum is an omnipresent state of matter-energy

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).

Quantum vacuum in QED
an “ocean” of virtual electric dipoles



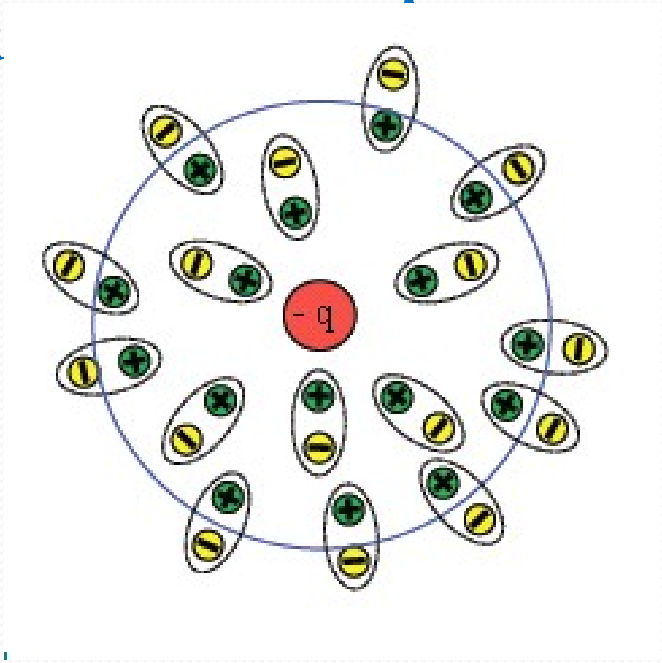
In QED quantum vacuum can be considered as an omnipresent “ocean” of virtual electric dipoles with random orientation

Quantum vacuum in QED

a **halo** of the polarized quantum vacuum

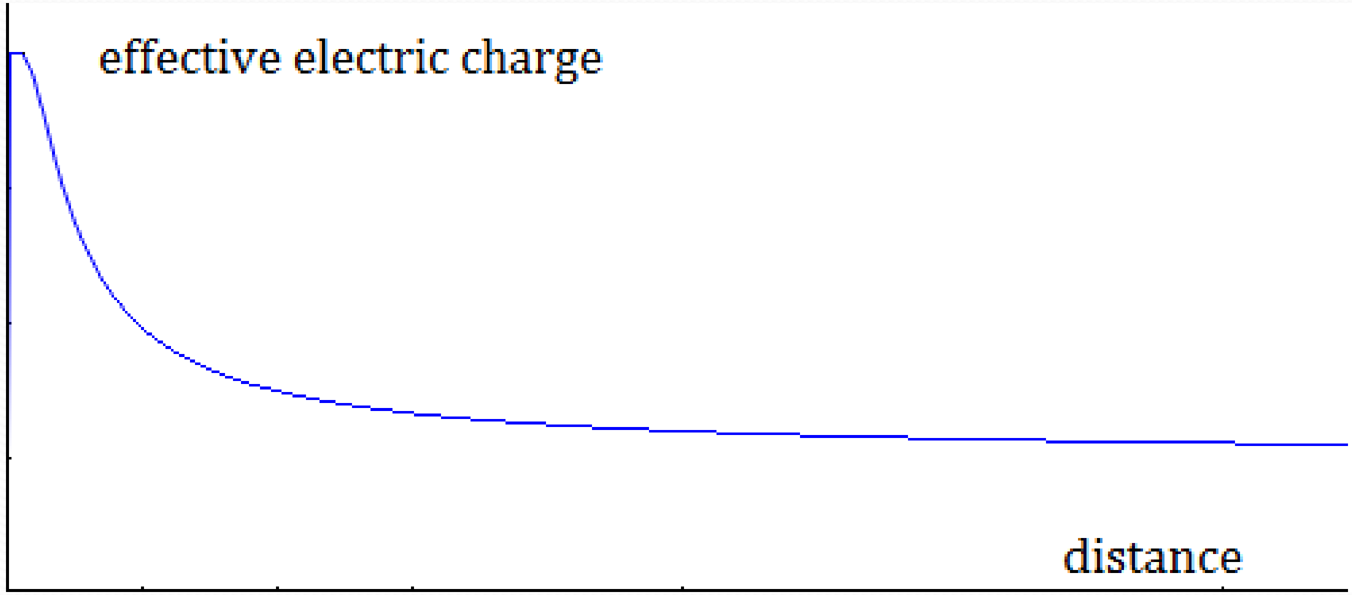
- The random orientation of virtual dipoles can be perturbed by a very strong electric field
- Example: The electric field of an electron at the distance of its Compton Wavelength is of the order of **10^{14} V/m**. Such a strong field perturbs the random orientation

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 qu**



Quantum vacuum in QED

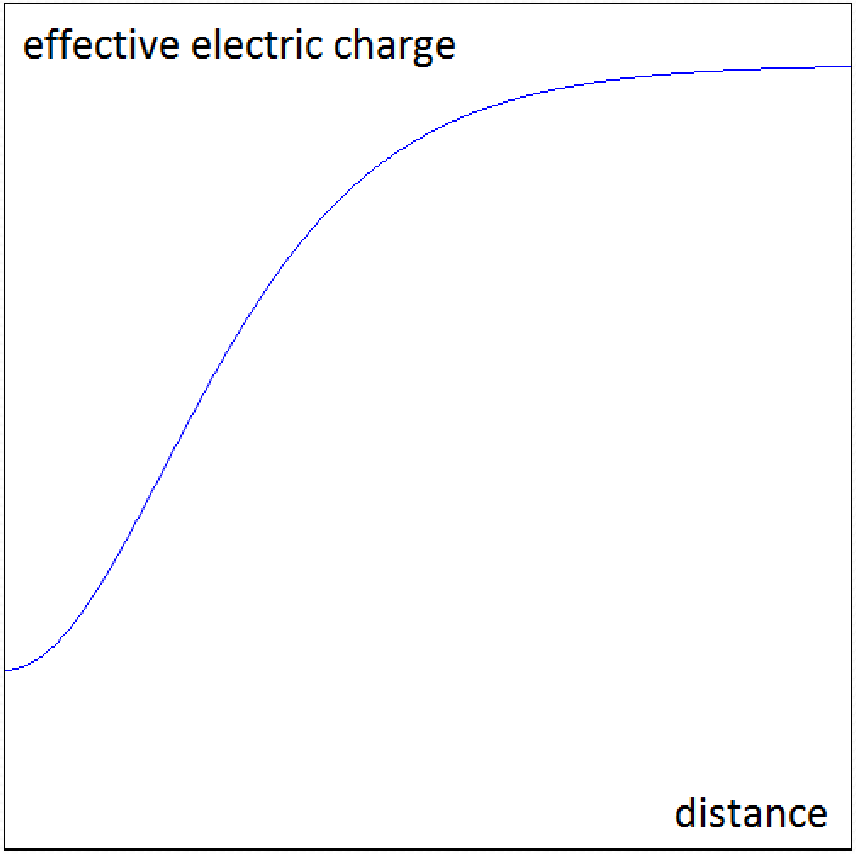
the effective electric charge of electron



- The halo screens the “bare” charge of an electron; what we measure is the effective electric charge which *decreases* with distance! Understood more than 6 decades ago by Landau (Лев Давидович Ландау).
- 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, it should be valid for gravity if quantum vacuum fluctuations are virtual gravitational dipoles!



Quantum vacuum in QED

vacuum 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)

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

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!

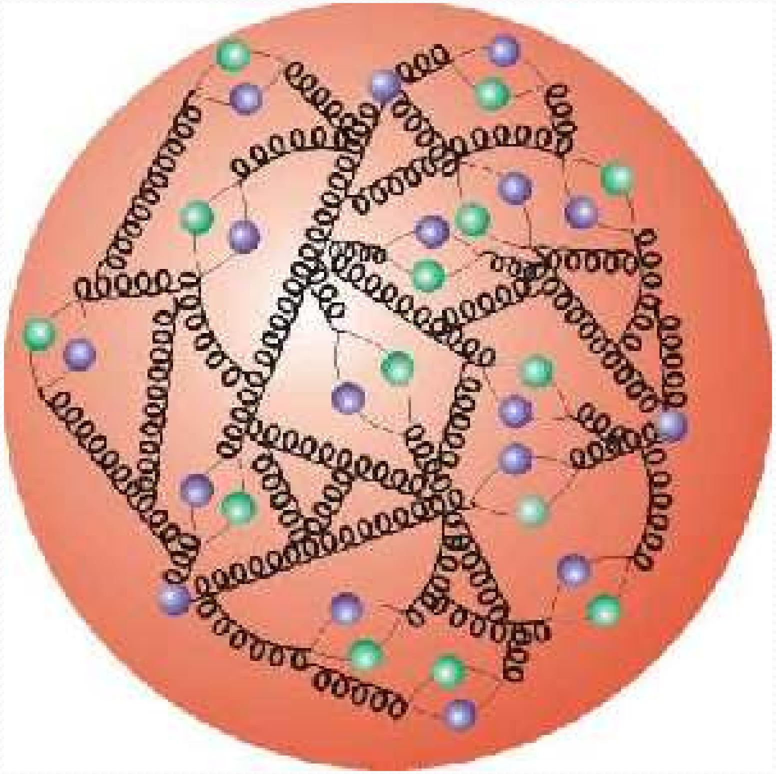
Lamb shift

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

6. 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!

Fundamental problems revealed by observations

Challenges for the Standard Model and General Relativity

Astronomical observations have revealed a series of phenomena which are a complete surprise and mystery for contemporary theoretical physics.

The first observed 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 (note that astrophysicists use "baryonic matter" as a synonym for the Standard Model matter)

The mainstream "explanation": **Dark matter** of unknown nature

The second observed phenomenon

In certain periods of its history the expansion of the Universe is accelerated; contrary to the expectation that gravity must permanently decrease the speed of expansion.

The mainstream "explanation": **Dark energy** of unknown nature.

DM + DE ≈ 95% of the content of the Universe
If so, we are composed of the exotic matter!

The third observed phenomenon

Our Universe is dominated by matter

Apparently, in the primordial Universe, something has forced the matter-antimatter asymmetry.

The mainstream "solution": A kind of CP violation, but please 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!

Additional problem

The cosmological constant problem: If there is equivalence between quantum vacuum energy density and the gravitational charge density of the quantum vacuum, then quantum vacuum must have the gravitational impact (i.e. gravitational charge density) many orders of magnitude stronger than permitted by observations.

No end to 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.

What if quantum vacuum fluctuations are virtual gravitational dipoles?

The 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 smaller than the corresponding reduced Compton wavelength

**Standard Model Matter means matter made from quarks and leptons interacting through the exchange of gauge bosons

Important Note: We do not modify the Standard Model of Particles and Fields and its understanding of quantum vacuum! Gravity is not included in the Standard Model.

Major consequences

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

$$\left|\vec{p}_g\right| < \frac{\hbar}{c}$$

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

Random orientation of dipoles

$$\vec{P}_g = 0$$

Saturation*

the gravitational polarization density has the maximal magnitude

$$P_{g\max} = \frac{A}{\lambda_m^3}\frac{\hbar}{c}$$

*Saturation is the case when as the consequence of a sufficiently strong external gravitational field, all dipoles are aligned with the field

The effective gravitational charge

- 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

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

Immediate questions

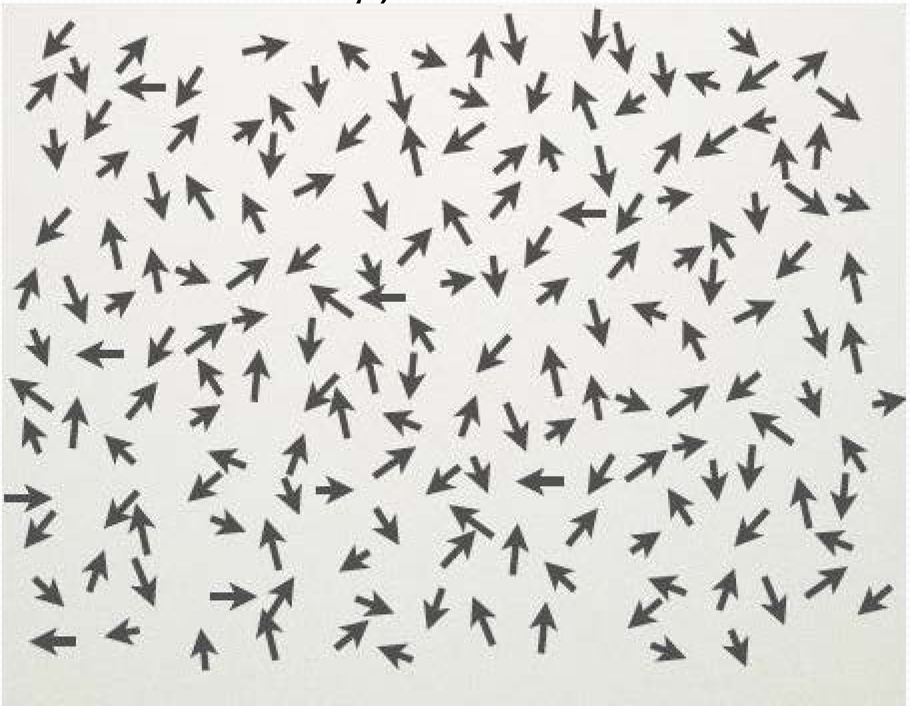
- **Can the effective gravitational charge density** of the quantum vacuum in galaxies and clusters of galaxies **explain phenomena usually attributed to dark matter**.
- **Can quantum vacuum as cosmological fluid of the effective gravitational charge explain phenomena usually attributed to dark energy**.
- What might be **effects of conversion of quantum vacuum fluctuations into real particles** in extremely strong gravitational field.

Dark matter as the local effect of gravitational vacuum polarization

References concerning this section: Hajdukovic [2,6,8,10-16]

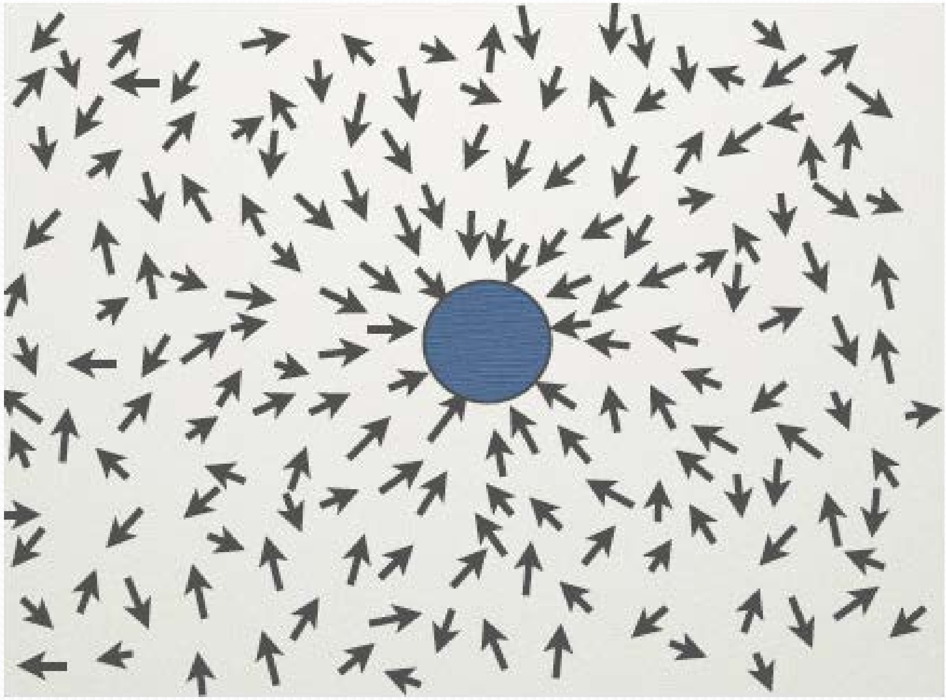
From the gravitational point of view quantum vacuum is an "ocean" of virtual gravitational dipoles

Randomly oriented gravitational dipoles (without an immersed body)



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

Halo of non-random oriented dipoles around a body (or a galaxy)



- **Random orientation** of virtual dipoles **might be broken** by the immersed Standard Model matter
- Massive bodies (stars, black holes ...) but also multi-body systems as galaxies are 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.

Gravitational field around a spherical body

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

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

reduces to

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

Problem: Function $P_g(r)$ is not known

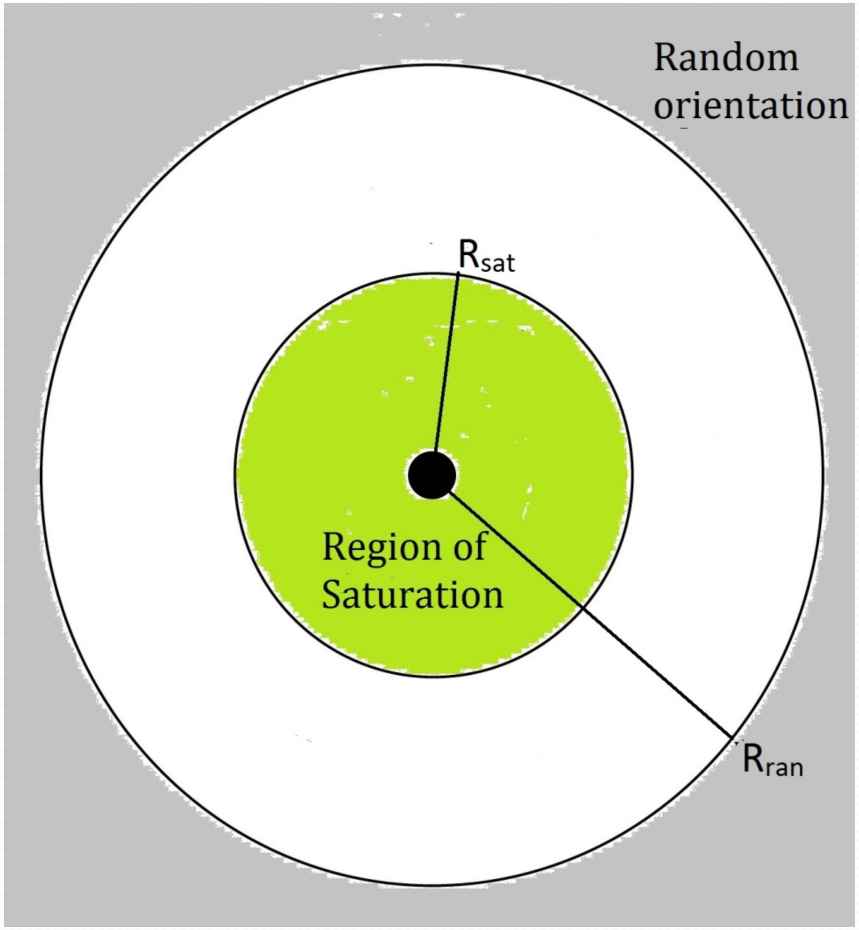
However we know that roughly there are 3 regions

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

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

Between these two regions $P_g(r)$ decreases from the maximum magnitude to zero

Schematic presentation of regions



The region of saturation

- The region of saturation: Roughly a spherical shell with the inner radius R_b (the radius of the body with the baryonic mass M_b) and the outer radius R_{sat} estimated to be

$$R_{sat} \approx \lambda_m \sqrt{\pi \frac{M_b}{m_\pi}}, \; m_\pi \; and \; \lambda_m \; correspond \; to \; a \; pion$$

- The effective gravitational charge density and the effective gravitational charge within the sphere of radius r , are

$$\rho_{qv}(r) = \frac{2P_{g\max}}{r}, \; M_{qv}(r) = 4\pi P_{g\max} r^2$$

- A good theoretical upper limit for $P_{g\max}$ (which can be used as a reasonable approximation) is

$$P_{g\max} < \frac{1}{4\pi} \frac{kg}{m^2} \approx 38 \frac{M_{Sun}}{pc^2}$$

Gravitational effect of the quantum vacuum in the region of saturation

- **Important conclusion**: as the result of the gravitational polarization of the quantum vacuum *in the region of saturation*, there is an additional anomalous constant gravitational field oriented towards the center

$$g_{v\max} = \frac{GM_v(r)}{r^2} = 4\pi G P_{g\max}$$

- If such an acceleration exists it causes a retrograde precession of the perihelion of the Satellite in a binary; precession per orbit in radians is:

$$\Delta\omega_{qv} = -2\pi\, g_{qv}\sqrt{1-e^2}\,\frac{a^2}{G\mu}$$

a -the semi-major axis of the orbit; ***e***-eccentricity, **μ**- total mass of binary

- Good news: In the case of some trans-Neptunian binaries (for instance UX25) this constant anomalous acceleration of the order of $10^{-11}\, m/s^2$ can be measured

Gravitational polarization outside the region of saturation

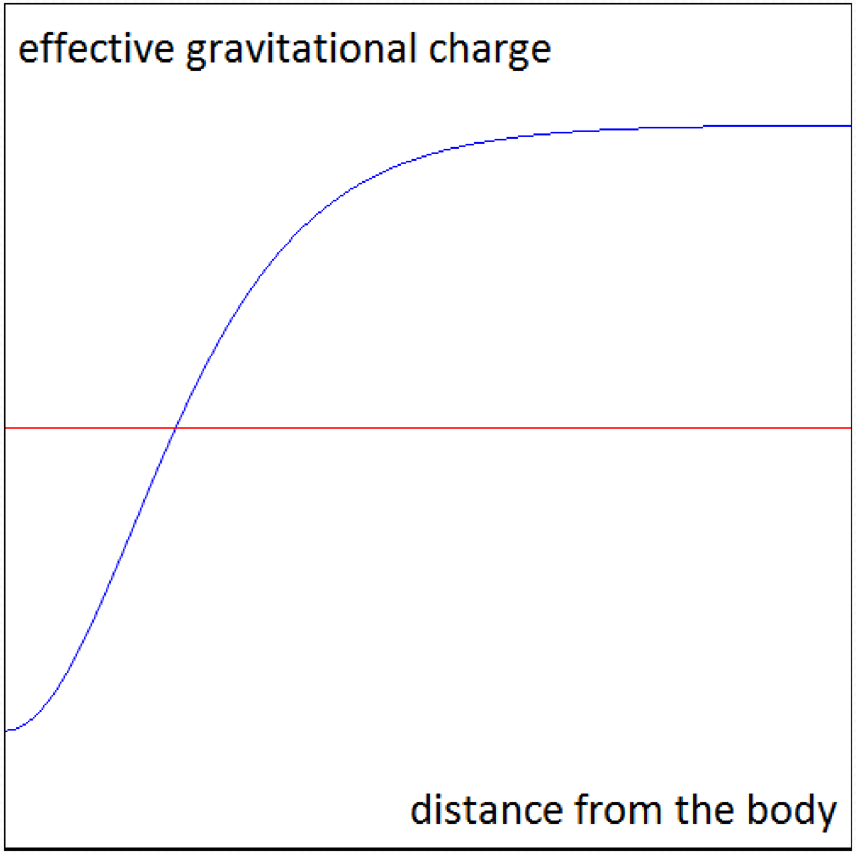
- Considering quantum vacuum as an ideal system of non-interacting gravitational dipoles in an external gravitational field (analogous to polarization of a dielectric in external electric field, or a paramagnetic in an external magnetic field) leads to

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

R_{ran} is a characteristic radius after which random orientation is dominant. For $r > R_{ran}$ the function $M_{qv}(r)$ doesn't increase more with distance and has a constant value $M_{qv\max}$.

Important note: It is obvious that gravitational field can align only quantum vacuum fluctuations which are gravitational dipoles but not electric dipoles; for instance random orientation of electron-positron pairs cannot be broken by a gravitational field, while neutrino-antineutrino pairs and gluon fluctuations might be aligned.

How the effective gravitational charge of a body depends on distance from it



- **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 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

$$\approx 2.1\times10^{-10}\, m/s^{2} \qquad *$$

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 $\sqrt{3}$

*This acceleration is only times larger than the acceleration proposed by MOND as a new universal constant. (See also the next Slide).

Comparison 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: 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, which is a consequence of relations in Slide 39, is

$$0.0069 \, M_{Sun} / pc^3$$

Comparison with the empirical evidence

Example 2: Surface density of "dark matter"

- Following Slide 39, for

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

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

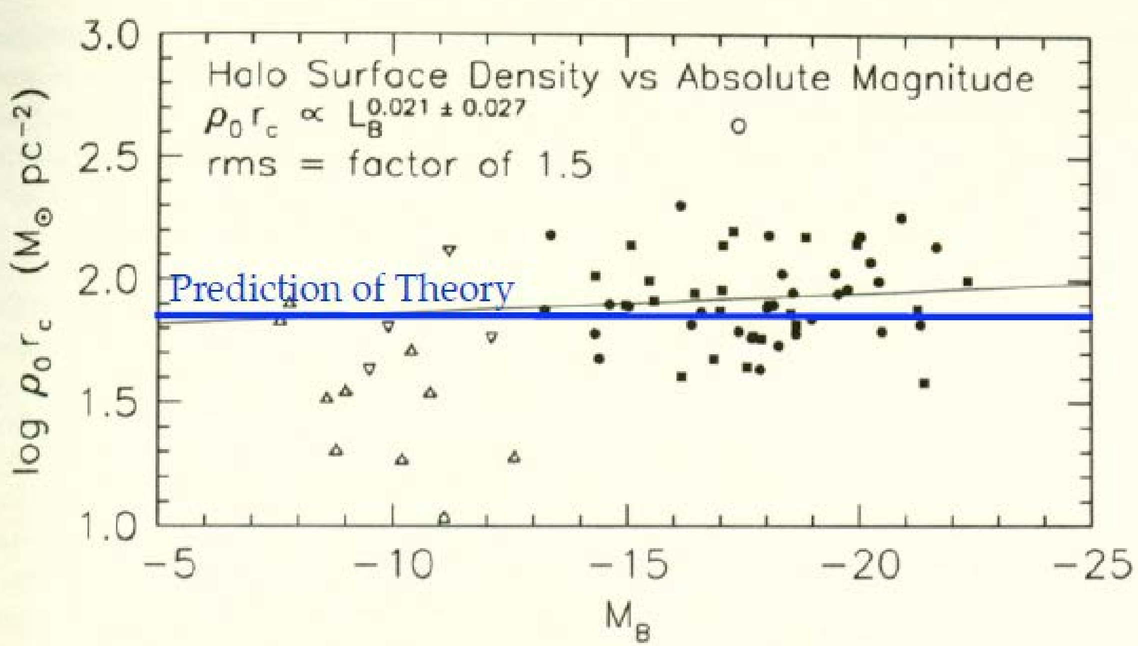


Figure 5. Logarithm of $\rho_0 r_c$, which is proportional to the projected surface density of DM halos, as a function of absolute magnitude. The symbols are the same as in Figures 2 – 4. The straight line (*key*) is a least-squares fit to the Sc – Im galaxies omitting NGC 4605. Within the errors, the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

Comparison with the empirical evidence

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

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

$$M_{MW}(260kpc) = 1.6 \times 10^{12} M_{Sun}$$

with a 90% confidence interval of

$$[1.0 - 2.4] \times 10^{12} M_{Sun}$$

- Our theoretical estimate

$$M_{MW}(260kpc) \approx 1.45 \times 10^{12} M_{Sun}$$

Dark energy as the global effect of gravitational vacuum polarization

References concerning this section: Hajdukovic [1,9,12,15,16]

Reminder:How Cosmology works

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)**.

Reminder: How Cosmology works

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

Reminder: How Cosmology works

Cosmological field equations

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

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

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

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: $p_n = -\frac{\partial U_n}{\partial V}$

$p_n = 0$

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

$p_n > 0$

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

$\mathbf{p_n < 0}$

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

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)

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

- ✓ Relativistic Standard Model matter (usually called radiation)

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

- ✓ Quantum vacuum

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

Note: Index o denotes the present day value.

Problems with the answer of the Standard Model physicists

- **Gravity is "excluded" from the Standard Model of Particles and Fields**; it is not a subject of study and a Standard Model physicist cannot tell what are the gravitational properties of the quantum vacuum.
- What the Standard Model physicist can do is to calculate **the mass-energy density of the quantum vacuum**. The result of calculations is very simple:

$$\rho_{ve} = \frac{1}{16\pi^2}\left(\frac{c}{\hbar}\right)^3 M_c^4 \equiv \frac{\pi}{2}\frac{M_c}{\lambda_{Mc}^3}$$

  For instance, for vacuum energy density in quantum chromodynamics the cut-off mass M_c is roughly mass of a pion and the density is about $5.6\text{x}10^{13}\text{kg/m}^3$.
- **The cosmological constant problem**: 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 nearly 10^{14}kg/m^3 !

Continued from the previous Slide

- The cosmological constant problem (a nice name for the worst prediction in history of physics) prevents the use of the Standard Model vacuum as the content of the Universe.
- It is unjust to blame the Standard Model for this mistake; what they estimated is the vacuum energy density, nothing more than that. The cosmological constant problem might be a hint that vacuum energy density and vacuum gravitational charge density are radically different.
- **A mathematical game**

$$\rho_{ve}^{*} = \frac{\pi}{2} \frac{M_C}{\lambda_{Mc}^3} \frac{\lambda_{Mc}}{R}$$

The above result is the result from the previous Slide multiplied by λ_{Mc} / R (R is the cosmological scale factor) what is a necessary correction if instead of gravitational monopoles there are gravitational dipoles. Calculate it! Instead of nearly $10^{14} kg/m^3$ you will get about $10^{-27} kg/m^3$ in agreement with observations. **It might be a numerical miracle but it might be the true nature of quantum vacuum as well.**

Dark energy as the global effect of the gravitational polarization of the quantum vacuum

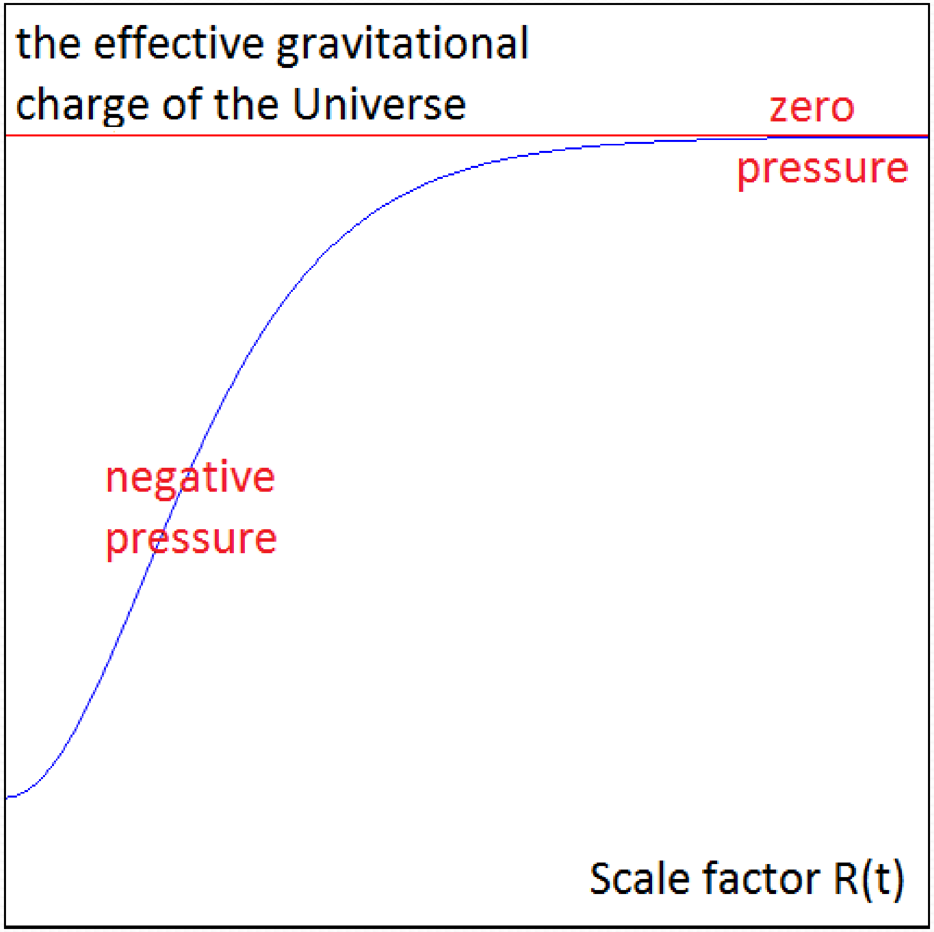
- According to General Relativistic Cosmological Field Equation (Slide 39)

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

the expansion of the Universe can be accelerated $\ddot{R} > 0$ **only if** there is a cosmological fluid with sufficiently big negative pressure, so that the sum in the above equation is negative.

- Globally quantum vacuum is a cosmological fluid with **the sum of all gravitational charges equal to zero**, but with **a large effective gravitational charge caused by the gravitational polarization**.
- There must be a period in which the size of the individual galactic halos and the total effective gravitational charge of the quantum vacuum increase with the expansion, which means that the polarized quantum vacuum behaves as a fluid with negative pressure (see the next Slide), and it is exactly what is necessary for the accelerated expansion.

How the effective gravitational charge of 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!

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

Summary: *What if quantum vacuum fluctuations are virtual gravitational dipoles*

The hypothesis stated in the title might be the basis for a new model of the Universe. According to the new model, ***the only* content of the Universe is the known Standard Model matter** (i.e. matter made from quarks and leptons interacting through the exchange of gauge bosons) *immersed in the quantum vacuum* "enriched" with virtual gravitational dipoles. Apparently, **what we call dark matter and dark energy, can be explained as the local and global effects of the gravitational polarization of the quantum vacuum by the immersed baryonic matter**. Further, **the hypothesis leads to a *cyclic model* of the Universe with cycles alternatively dominated by matter and antimatter**; with each cycle beginning with a macroscopic size and the accelerated expansion. Consequently, there is *no singularity*, *no need for inflation field*, and 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**. The forthcoming experiments (AEGIS, ALPHA, GBAR …) will reveal if particles and antiparticles have gravitational charge of the opposite sign, while study of orbits of tiny satellites in trans-Neptunian binaries (e.g. UX25) can be a reasonable test of some astronomical predictions of the theory.

Appendix
Study case UX25

The slides in this appendix have been prepared by Mario GAI and Alberto VECCHIATO

Study case: UX25

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

Trans-neptunian binary system

Newtonian precession from the Sun: $\Delta\omega_N = \frac{3\pi}{2}\left(\frac{T_P}{T_{Sun}}\right)^2 \cong 6$ mas/orbit

Estimated precession from vacuum polarisation: $\boxed{\Delta\omega_{qv} \simeq 0.23 \text{ arcsec/orbit}}$

[Hajdukovic, 2014, hal-00908554]

Cumulative effect on 5 years (~200 orbits): 46 arcsec

Previous observations...

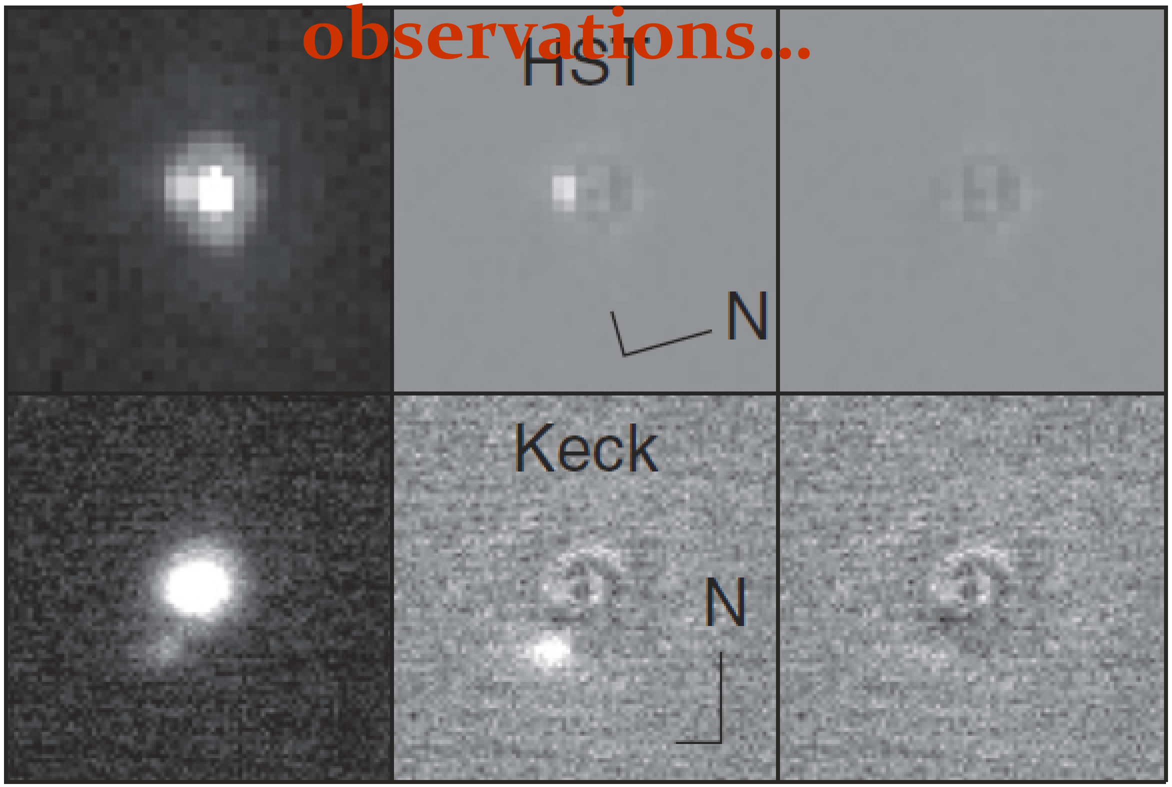
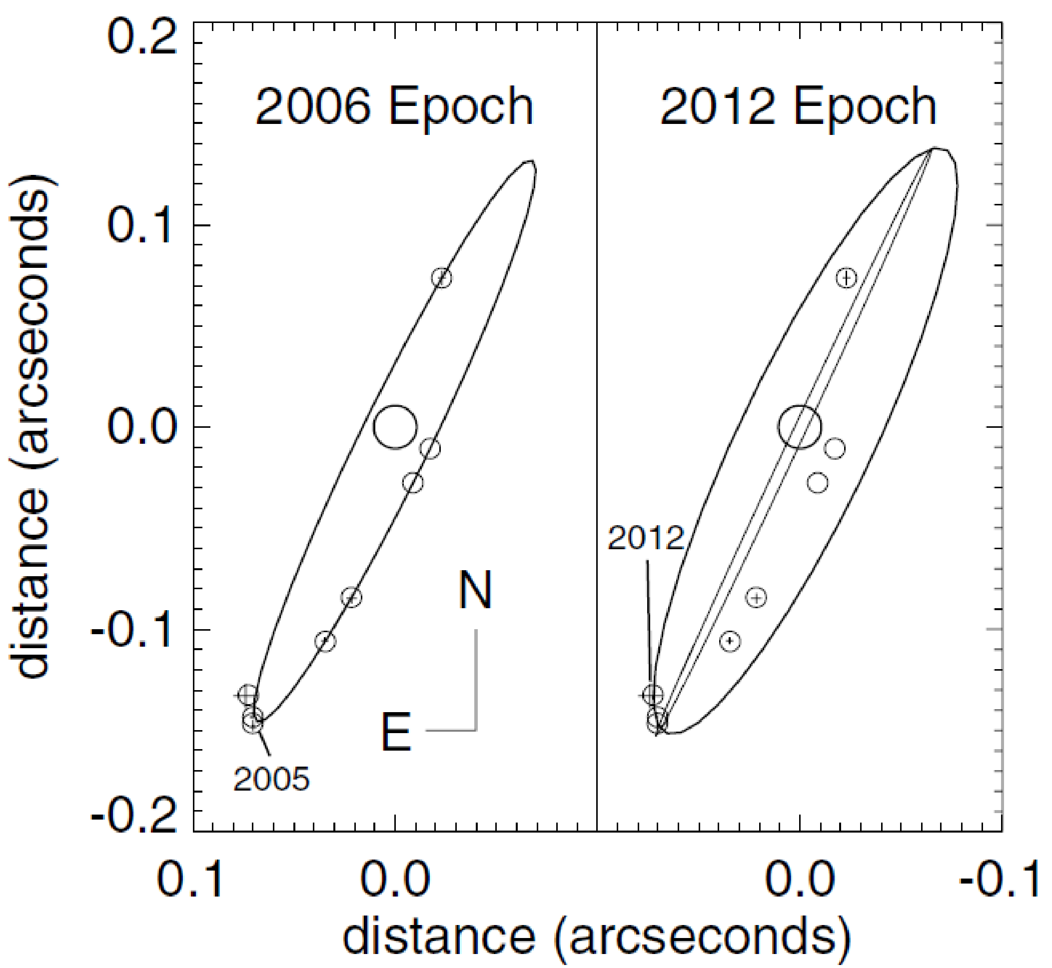


Figure 1. Observations of the 2002 UX25 system with *HST*/HRC and Keck LGS-AO/NIRC2. The northward orientation arrow is 0.25 arcsec long, for scale. In the first column, we show the image of both 2002 UX25 and its satellite. From this image we simultaneously fit a PSF to both the primary and satellite. In the the second column we show the image with the primary part of the fit subtracted. In the final column we show both components subtracted. The *HST* observation is from JD 2453939.98322 and is the most blended of the detections.

[M. E. Brown, ApJL 2013]

...and reconstructed



Semi-major axis angular amplitude: ~150 mas

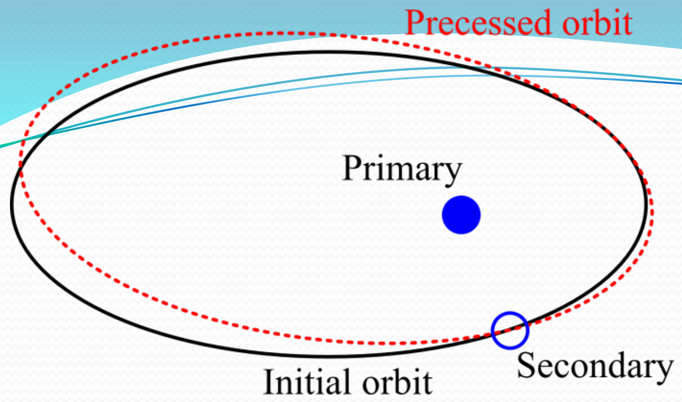
System unresolved by conventional telescopes

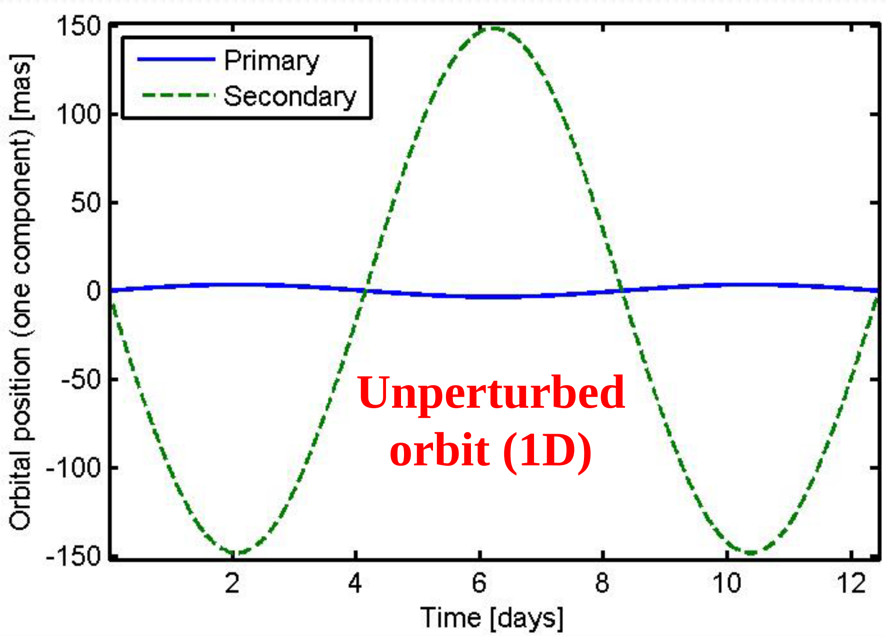
Faint visible magnitude:

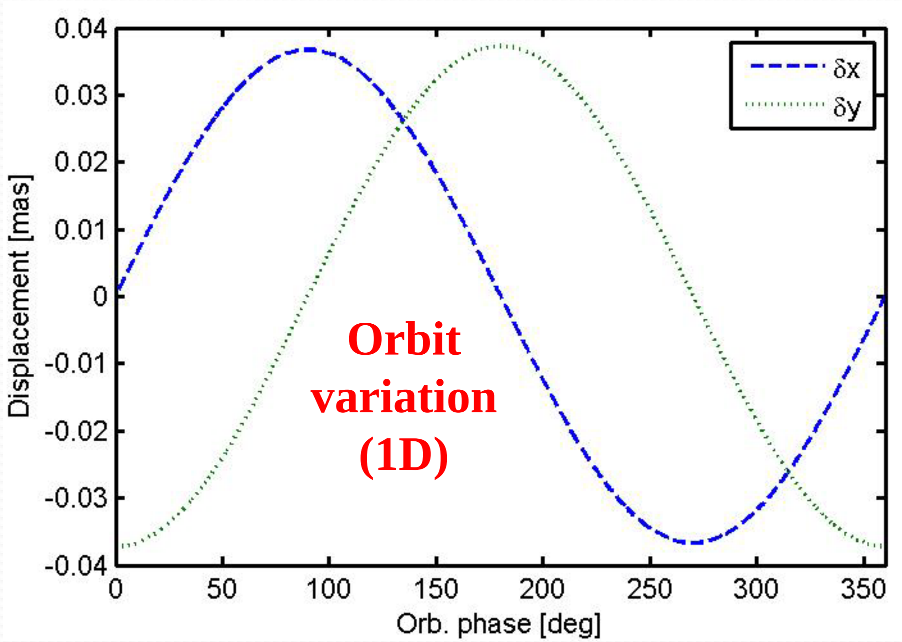
- 20 mag primary
- 22 mag secondary

Observing problem - I

Orbit variation over 5 years







Challenge: reliable μas astrometry on faint objects, narrow field

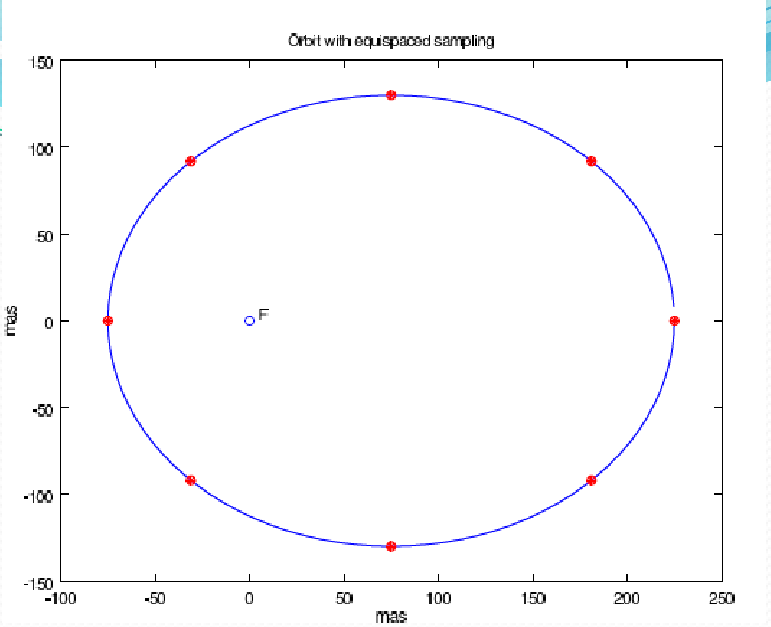
[Gai & Vecchiato, 2014, arXiv:1406.3611]

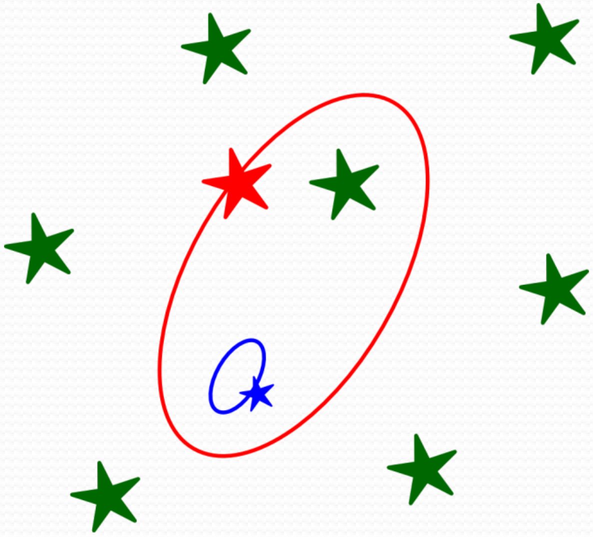
Observation setup

Multiple images taken over orbital period along several orbits

Determination of positions and velocity against field stars

Orbital fit: parameter estimate



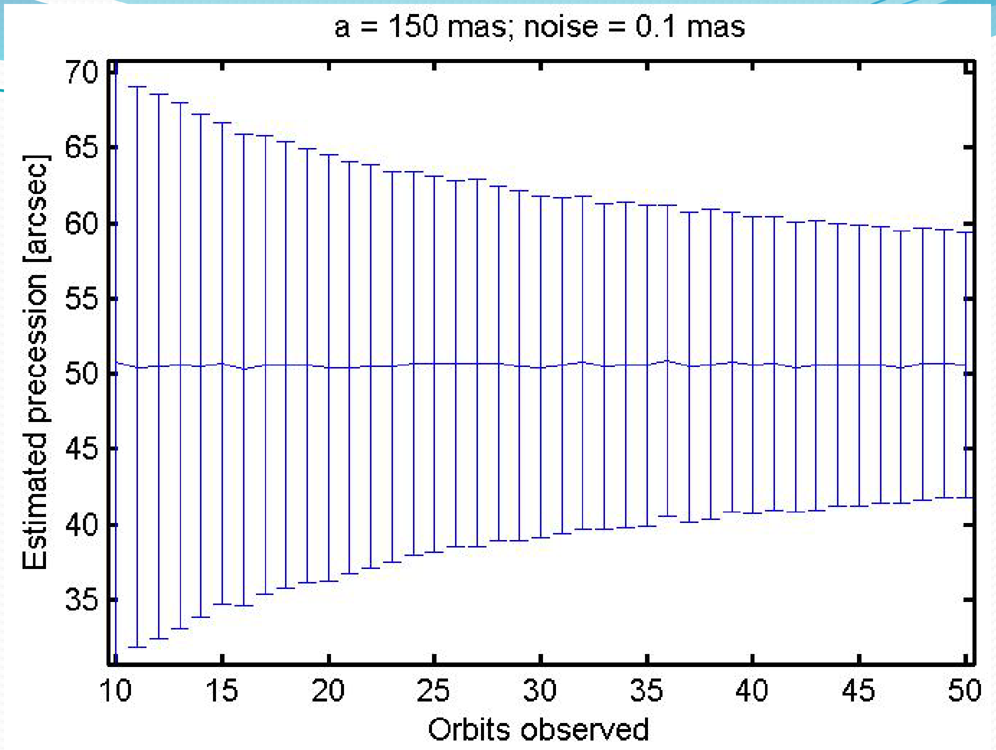


Observing problem - II

Small variation of observed vs. nominal orbital positions over a few years

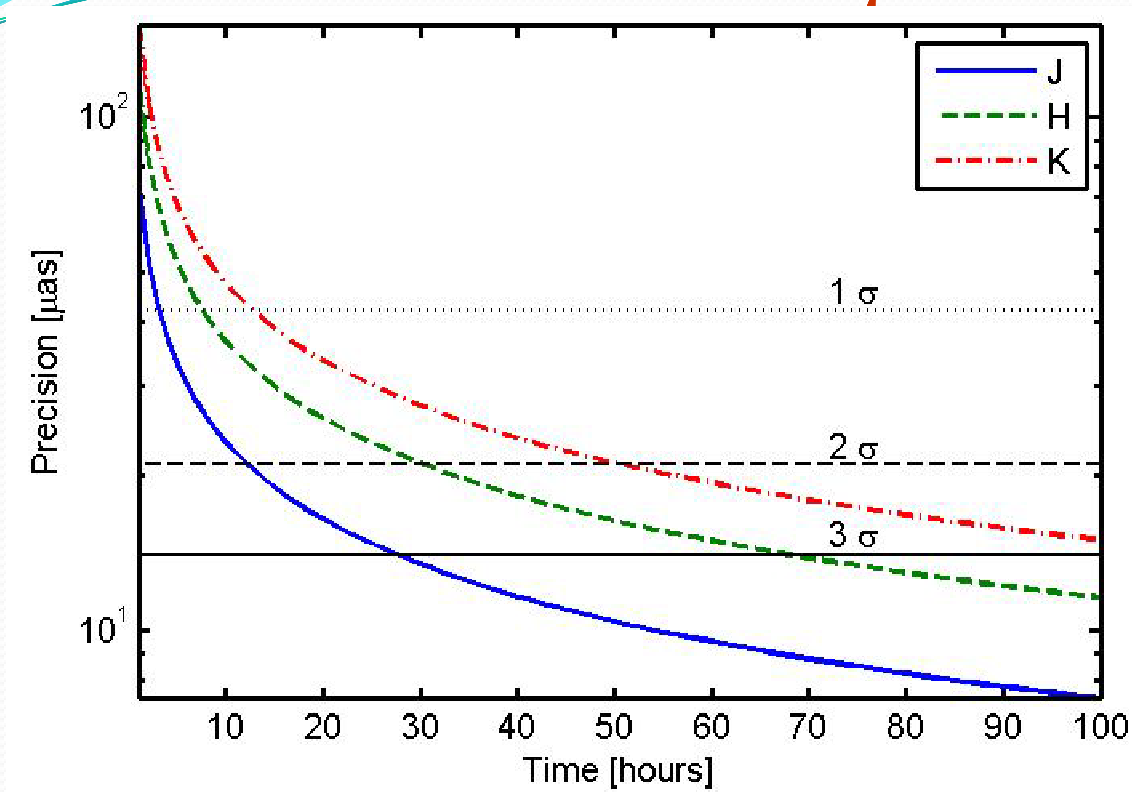
Requirement: few μas final precision

Small field (~10-20 arcmin) to have several reference stars (e.g. from Gaia)



Simulation for ~100 μas precision on individual measurements

Performance on 8 m telescope with adaptive



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

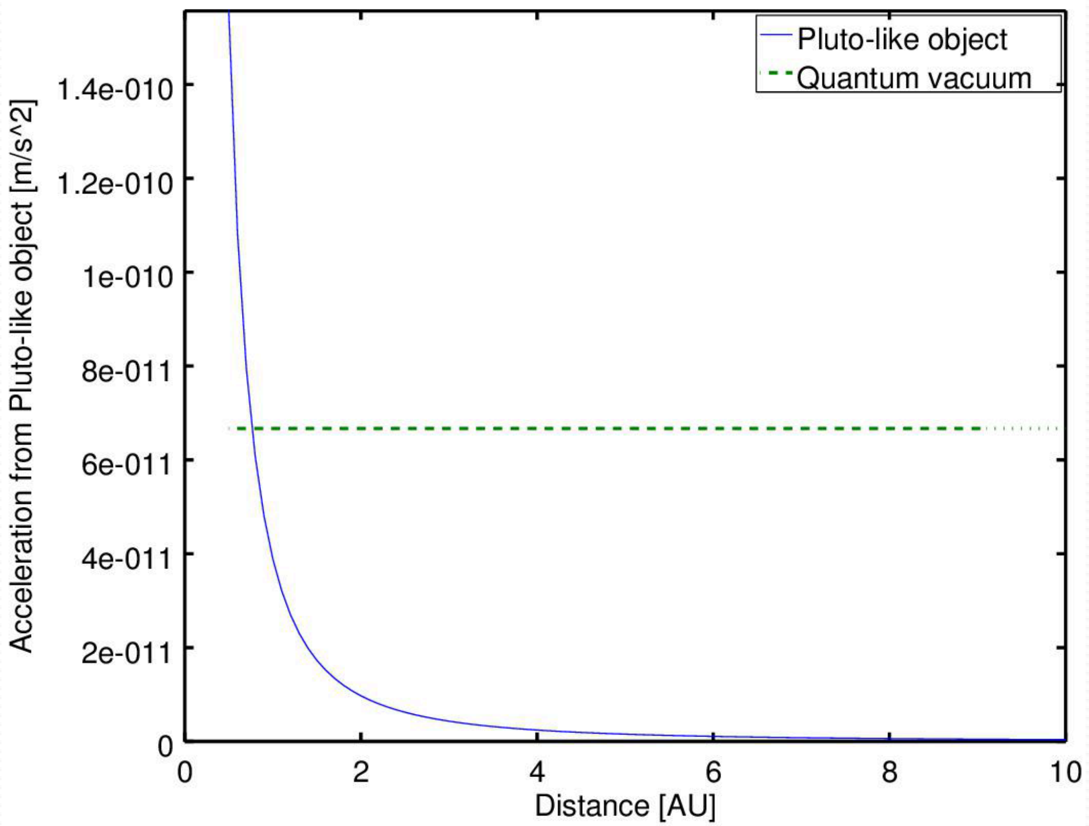
Best candidate:

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

Third-body perturbations

Need for cross-check:

precession may be induced by mass cluster in external regions of the Solar system



Sun effect estimated 10× smaller than QV effect [Hajdukovic 2014]

Measurement sensitive to any perturbation from known dynamics: MOND, unknown objects, …

Additional trans-neptunian binaries as candidates

After first detection, larger survey?

- confirm the effect
- identify dependency on system parameters

Dedicated space mission?

(55637) 2002 UX25

(136199) Eris and Dysnomia

(136108) Haumea, Hi'iaka, and Namaka

(50000) Quaoar and Weywot

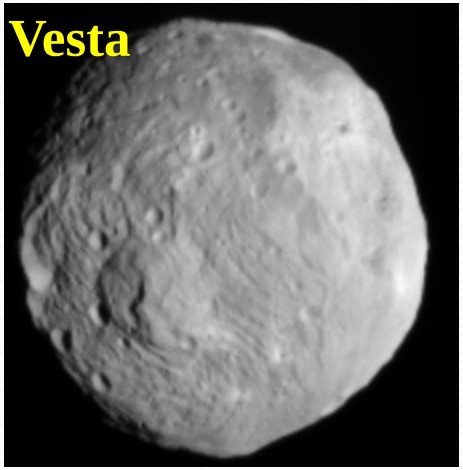
(66652) Borasisi and Pabu

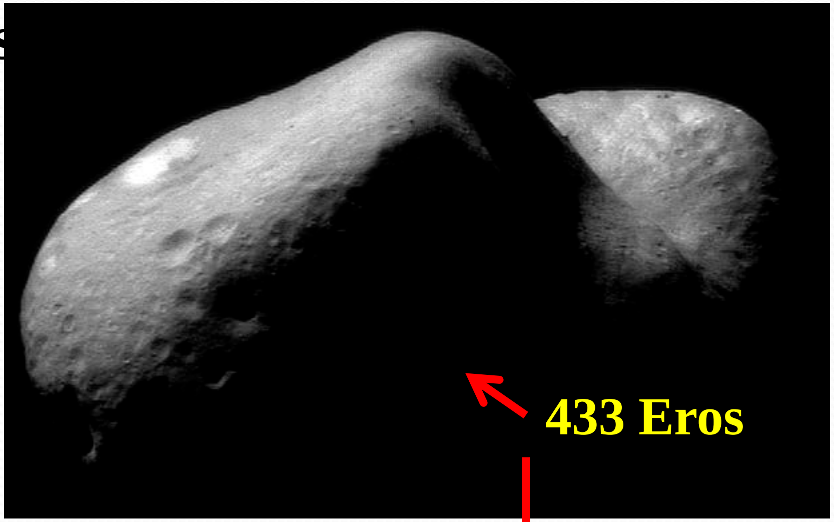
(42355) Typhon and Echidna

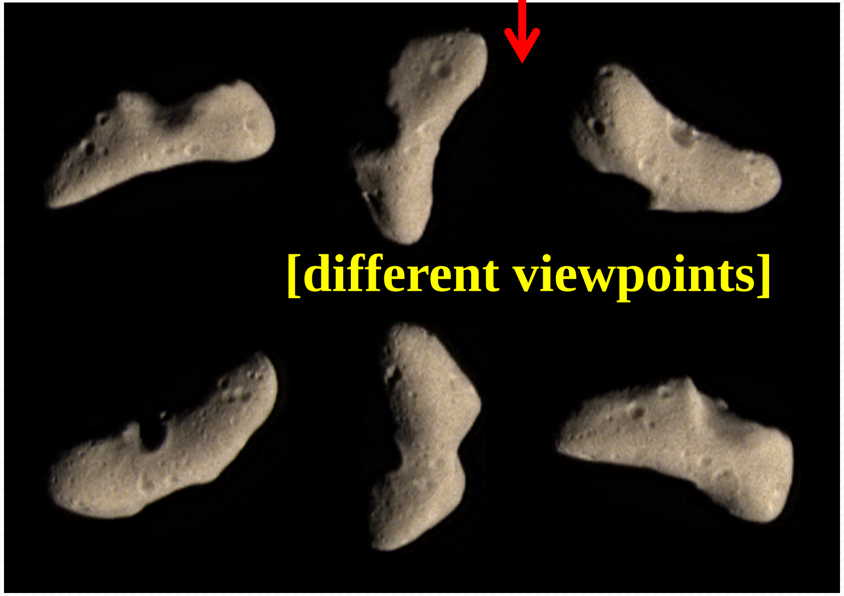
…

Orbit disturbances from object shape

Celestial bodies are neither spheres nor point sources



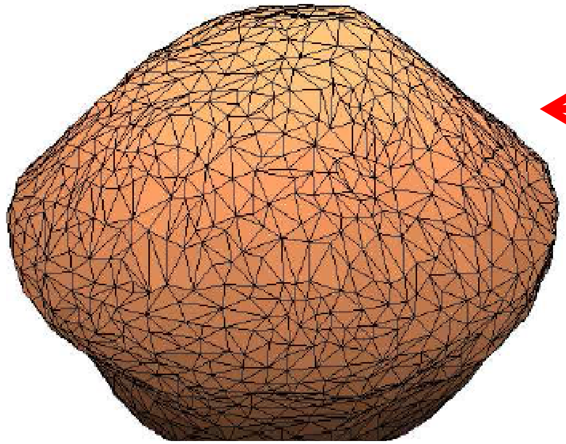




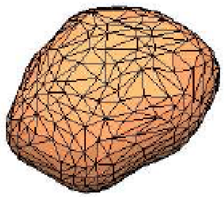
Tidal effects; orbit perturbations

Example: Polyhedron-Polyhedron Systems

Chappaz, L., and Howell, K., "Bounded Motion near Binary Systems Comprised of Small Irregular Bodies," AIAA/AAS Astrodynamics Specialist Conference, San Diego, California, August 2014.

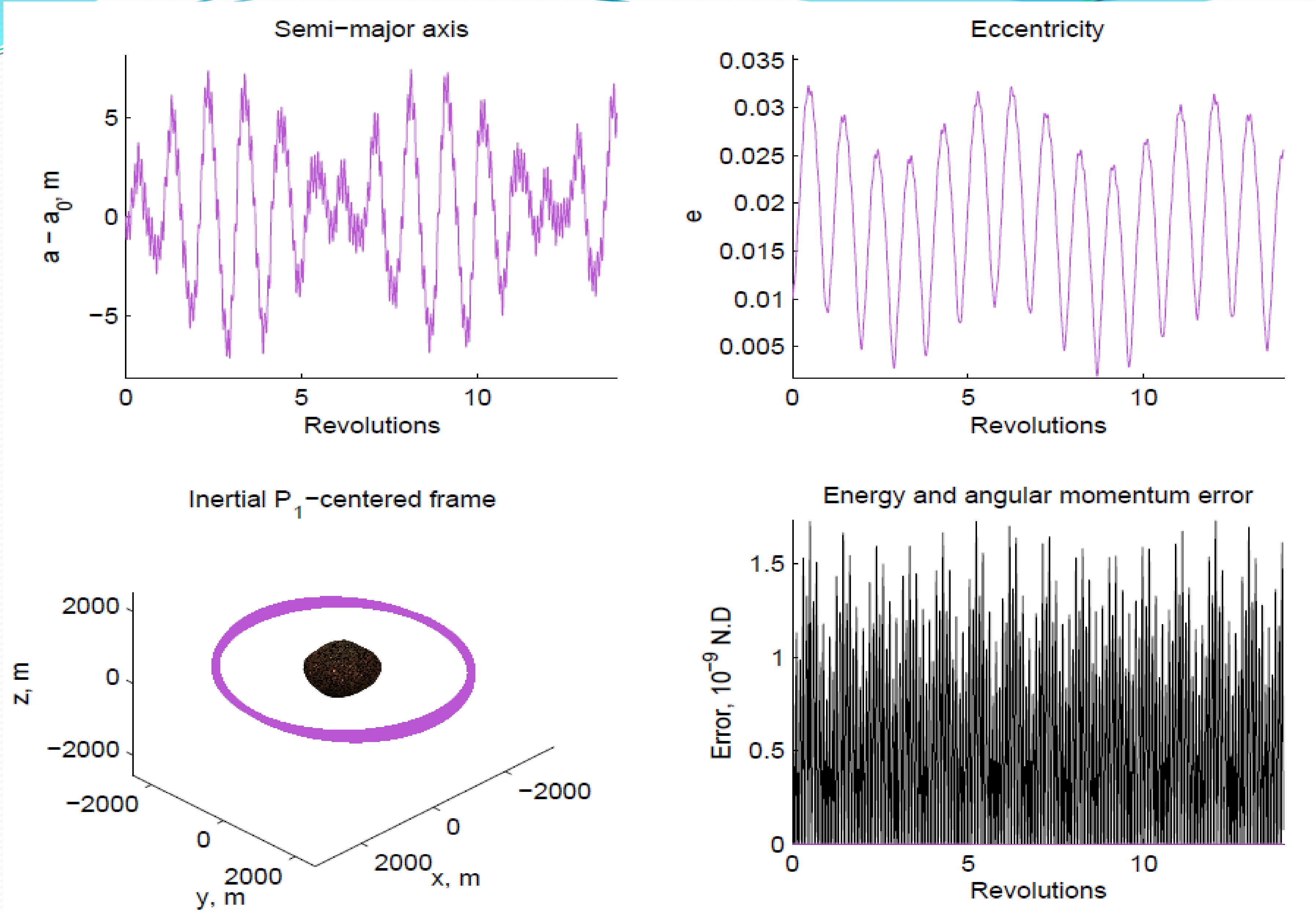


Near Earth Asteroid (NEA) 1999 KW4
Shape model [Ostro et al. 2006]:
primary and secondary



	A_X (km)	A_Y (km)	A_Z (km)	density (kg m^{-3})	rotation period (hr)
Primary	1.53	1.49	1.35	1970	2.76
Secondary	0.57	0.46	0.35	2810	17.42

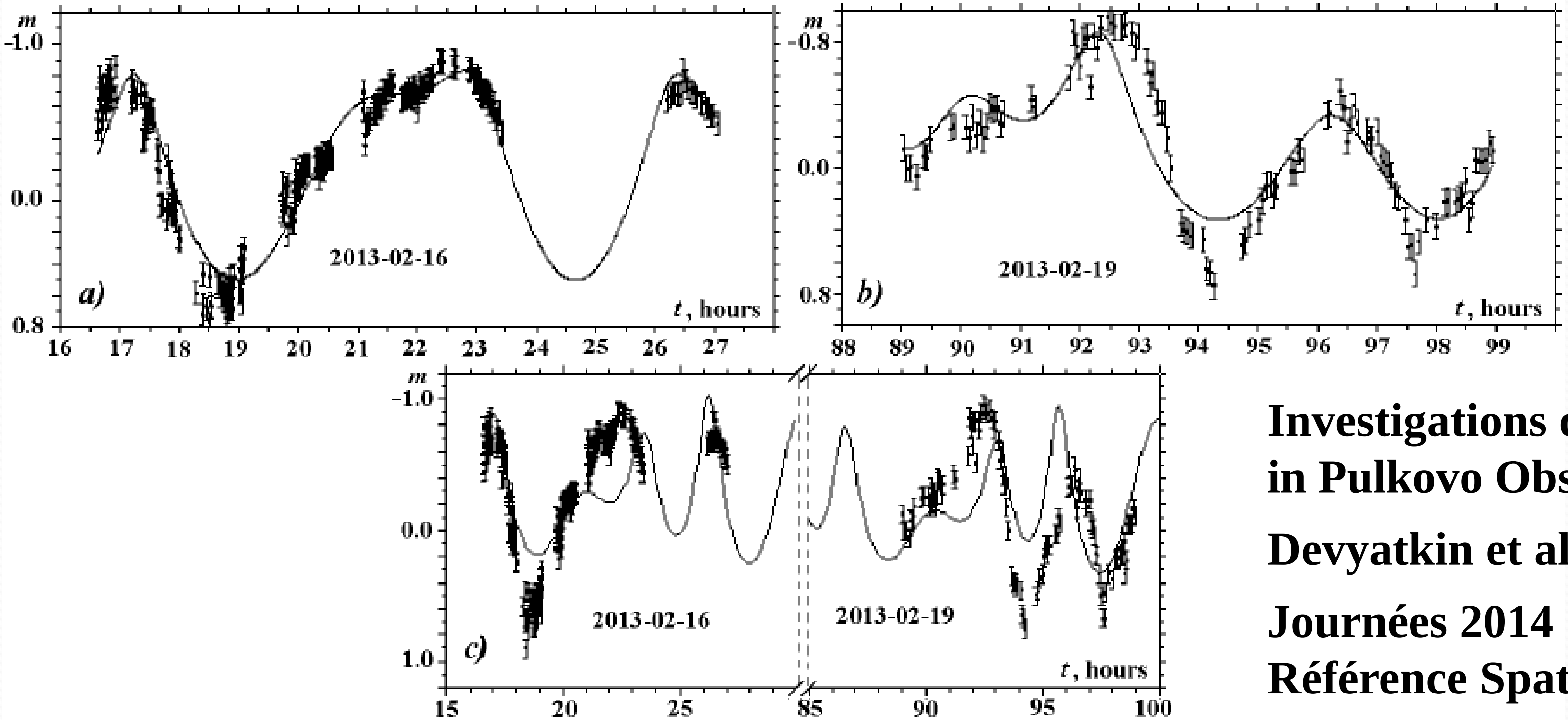
Higher-Fidelity Dynamical Models: perturbed elliptical orbit



Light curves for determination of object period / shape

Preliminary results of modeling of Duende rotation

Example



Investigations of asteroids in Pulkovo Observatory

Devyatkin et al., 2014

Journées 2014 Systèmes De Référence Spatio-Temporels

Semi-axis of body ellipsoid (NASA radar data) – 4:2:1,
semi-axis of "photometrical" ellipsoid – 10:2:1
⇒heterogeneous albedo and/or non-ellipsoidal form

Rotation of rotational axis (tumbling)

20

Sensitivity issue for trans-Neptunian objects

Devyatkin et al., 2014

Objects fainter than ~20 mag

Considerations on UX25 in-depth study

Long term monitoring with significant cadence sampling required:

- measure time sequence of positions AND velocity
- measure shape / brightness distribution
- measure albedo / surface composition
- deduce mass distribution
- cross-check actual dynamics with high fidelity model predictions

Fundamental Physics result ⇔ confidence on system parameters

Conclusions

High precision astrometry: tool for Fundamental Physics

Gravitation aspects of Quantum Vacuum need investigation

Quantum Vacuum polarisation effects close to state of the art

Experimental requirements of QV effects detection

Crucial constraints to e.g. MOND and local Dark Energy

Contributions to science case and implementation welcome!

References

Note

References to other authors are reduced to minimum; the full list of hundreds of References can be found in my publications

Boylan-Kolchin,M.; The space motion of Leo I: the mass of the Milky Way's dark matter halo, Astrophys. J. **768** (2013) 140

Donato, F. et al. A constant dark matter halo surface density in galaxies. Mon. Not. R. Astron. Soc. 397, 1169–1176 (2009) | Article

Dopita, M.; http://www.oacn.inaf.it/oacweb/oacweb_eventi/astromeeting/documenti/QuantumVacuum.pdf (2012)

Gai, M., Vecchiato, A.; Astrometric detection feasibility of gravitational effects of quantum vacuum. (2014) http://arxiv.org/abs/1406.3611v2

Kormendy, J. & Freeman, K. C. Scaling laws for dark matter halos in late-type and dwarf spheroidal galaxies. IAU Symp. Astron. Soc. Pacif. 220, 377–395 (2004)

Zhang L. et.al. The Astrophysical Journal **772** (2013) 1-14Donato, F. et al. A constant dark matter halo surface density in galaxies. Mon. Not. R. Astron. Soc. 397, 1169–1176 (2009) | Article

References to my work

[1] D.S. Hajdukovic: *On the relation between mass of a pion, fundamental physical constants and cosmological parameters*
EPL (Europhysics Letters) Volume 89 Number 4
February 2010, *EPL* **89** 49001 doi:10.1209/0295-5075/89/49001

[2] D.S. Hajdukovic: *A few provoking relations between dark energy, dark matter, and pions*
Astrophysics and Space Science
March 2010, Volume 326, Issue 1, pp 3-5

[3] D.S. Hajdukovic: What Would Be Outcome of a Big Crunch?
International Journal of Theoretical Physics
May 2010, Volume 49, Issue 5, pp 1023-1028

[4] D.S. Hajdukovic: *On the absolute value of the neutrino mass*
Modern Physics Letters A
April 2011, Vol. 26, No. 21, pp. 1555-1559

References to my work

[5] D.S. Hajdukovic: *Can the New Neutrino Telescopes Reveal the Gravitational Properties of Antimatter?*

Advances in Astronomy

June 2011, Volume 2011, Article ID 196852, doi:10.1155/2011/196852

[6] D.S. Hajdukovic: *Is dark matter an illusion created by the gravitational polarization of the quantum vacuum?*

Astrophysics and Space Science

August 2011, Volume 334, Issue 2, pp 215-218

[7] D.S. Hajdukovic: *Do we live in the universe successively dominated by matter and antimatter?*

Astrophysics and Space Science

August 2011, Volume 334, Issue 2, pp 219-223

[8] D.S. Hajdukovic: *Quantum vacuum and dark matter*

Astrophysics and Space Science

January 2012, Volume 337, Issue 1, pp 9-14

References to my work

[9] D.S. Hajdukovic: Quantum vacuum and virtual gravitational dipoles: the solution to the dark energy problem?

Astrophysics and Space Science

May 2012, Volume 339, Issue 1, pp 1-5

[10] D.S. Hajdukovic: *Trans-Neptunian objects: a laboratory for testing the existence of non-Newtonian component of the gravitational force*

arXiv:1212.2162

December 2012

[11] D.S. Hajdukovic: Can observations inside the Solar System reveal the gravitational properties of the quantum vacuum?

Astrophysics and Space Science

February 2013, Volume 343, Issue 2, pp 505-509

[12] D.S. Hajdukovic: The *signatures of new physics, astrophysics and cosmology?*

Modern Physics Letters A

August 2013, Vol. 28, No. 29, 1350124

References to my work

[13] D.S. Hajdukovic: *A new model of dark matter distribution in galaxies*
Astrophysics and Space Science
January 2014, Volume 349, Issue 1, pp 1-4

[14] D.S. Hajdukovic: *Testing the gravitational properties of the quantum vacuum within the Solar System*
HAL Id: hal-00908554
February 2014, https://hal.archives-ouvertes.fr/hal-00908554v3

[15] D.S. Hajdukovic: Virtual gravitational dipoles: The key for the understanding of the Universe?
Physics of the Dark Universe, *Volume 3, April 2014, Pages 34-40*
April 2014, *Volume 3, Pages 34-40*

[16] D.S. Hajdukovic, The basis for a new model of the universe
HAL Id: hal-01078947
November 2014, https://hal.archives-ouvertes.fr/hal-01078947v2