Последние результаты эксперимента по поиску темных фотонов

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В сотрудничестве с: Игорь Орехов, Валерий Петухов и др.

Цель эксперимента:
поиск темных фотонов

Теорема вириала:
кинетическая энергия гравитационно связанных обьектов должна быть равна – 0.5 их потенциальной энергии

Zwicky (1937) – analyses of red shifts of the Coma Cluster of galaxies: surprisingly high mass-to-light ratio

Enigma 1: to-day, according to a combination of all data: the dark matter accounts for about **84 %** of the matter content of the Universe (Planck 2018 results)
Enigma 2: why dark matter is distributed in galaxy by a spherical halo while baryonic matter – in the plane of galaxy ?

→ CDM is not particles but **waves**,

→ $\mathbf{m_{\gamma'} < 100\ eV}$

Lam Hui arXiv:2101.11735v1

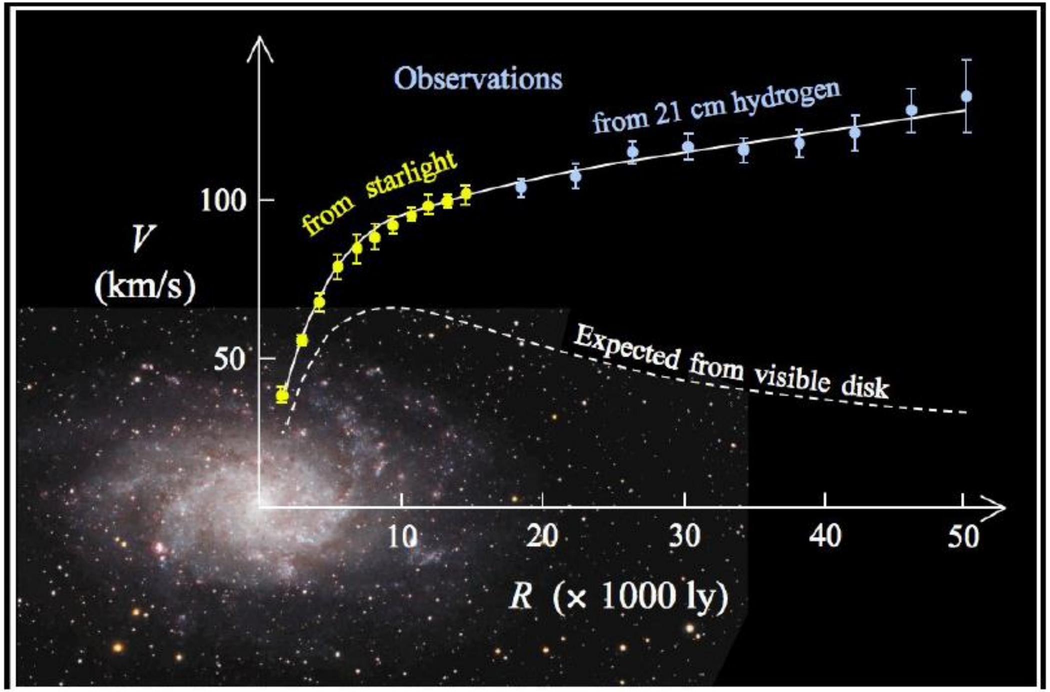


Fig. 1 The image of M33 and the corresponding rotation curve (Corbelli and Salucci 2000). What exactly does this large anomaly of the gravitational field indicate? The presence of *i)* a (new) non-luminous massive component around the stellar disk or *ii)* new physics of a (new) dark constituent?

Why Dark Matter?

The only empirical evidence for dark matter to-day is provided by astronomical observations.

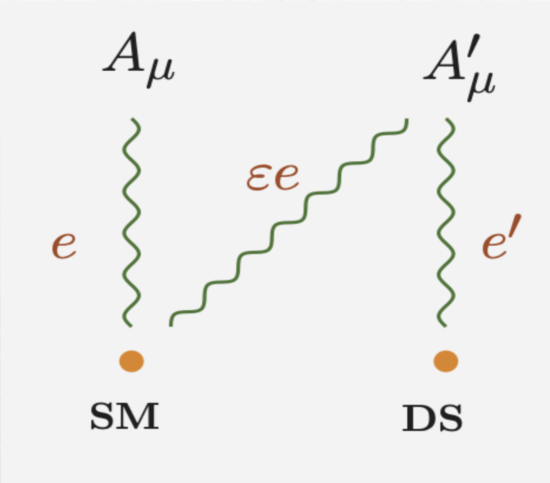
P. Salucci arXiv:1811.08843

- M.S.Turner arXiv:2109.01760

The conservative view today is that dark matter, dark energy, and inflation are simply physics beyond the standard model waiting to be clarified and understood: a new particle, a new form of elastic energy and a new scalar field. Other than neutrino mass, they are the only phenomena that cannot be explained by the standard model.[3]

There are several possible futures, all interesting, though some less satisfying. First, a detection could be right around the corner! Second, our compelling ideas could be just that – compelling, but not correct! Third, there are new ideas, including asymmetric dark matter, low-mass dark matter (1 GeV and down to tiny fractions of an eV), and the most expansive idea yet, a whole dark sector, one with its own particles and interactions, to be discovered. It could be that rather than being close to a solution, we have just seen the tip of the iceberg of a whole new sector that interacts only very weakly with the standard model particles that we are familiar with.

The dark Photon



Abstract

THE DARK PHOTON IS A NEW GAUGE BOSON whose existence has been conjectured. It is dark because it arises from a symmetry of a hypothetical dark sector comprising particles completely neutral under the Standard Model interactions. Dark though it is, this new gauge boson can be detected because of its kinetic mixing with the ordinary, visible photon. We review its physics from the theoretical and the experimental point of view. We discuss the difference between the massive and the massless case. We explain how the dark photon enters laboratory, astrophysical and cosmological observations as well as dark matter physics. We survey the current and future experimental limits on the parameters of the massless and massive dark photons together with the related bounds on milli-charged fermions.

M. Fabbrichesi, E. Gabrielli, G. Lanfranchi

The Physics of the Dark Photon, Springer Briefs in Physics (Springer, 2021)

V. Dzunushaliev, V. Folomeev, A.Tlemisov

Linear Energy Density and the Flux of an Electric Field in Proca Tubes

Symmetry 2021, *13,* 640. https://doi.org/10.3390/sym13040640

V. Dzunushaliev, V. Folomeev

Axially symmetric particlelike solutions with the flux of a magnetic field in the non-Abelian Proca-Higgs theory

arXiv:2107.11555 [hep-th]

Phys. Rev. D 104, 116027 (2021)

V. Dzunushaliev, V. Folomeev

Proca balls with angular momentum or flux of electric field

arXiv:2112.06227v.2 [hep-th] 16 Feb 2022

Phys. Rev. D 105, 06022 (2022)

Уравнения Прока и Калибровка Лоренца

Уравнения Прока:

$$\Box\Phi - \frac{\partial}{\partial t}\left(divA + \frac{\partial\Phi}{\partial t} \right) = -m^2\Phi \qquad (1)$$

$$\Box A + grad\left(divA + \frac{\partial\Phi}{\partial t} \right) = -m^2 A \qquad (2)$$

Применяем к (1) $\frac{\partial}{\partial t}$, а к (2) – div и складываем, получаем:

$$2\Box\left(divA + \frac{\partial\Phi}{\partial t} \right) = -m^2\left(divA + \frac{\partial\Phi}{\partial t} \right)$$

Или:

$$\Box\left(divA + \frac{\partial\Phi}{\partial t} \right) = -\frac{1}{2}m^2\left(divA + \frac{\partial\Phi}{\partial t} \right)$$

Обозначим:

$$\chi = \left(divA + \frac{\partial\Phi}{\partial t} \right) \qquad (3)$$

И тогда:

$$\Box\chi = -\frac{1}{2}m^2\chi \qquad (4)$$

Проверяем подстановкой, что решением уравнения (4) является,

$$\chi = \Upsilon_0(r)e^{imt} \qquad (5)$$

То есть стационарное локализованное решение, колеблющееся как e^{imt}

Действительно, после подстановки имеем:

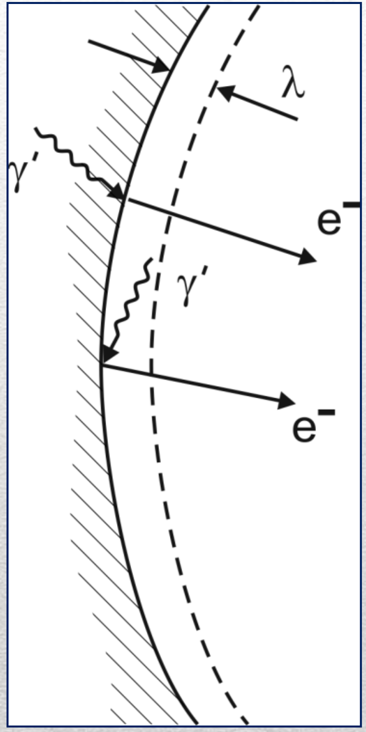
$$\Delta\Upsilon_0 + m^2\Upsilon_0 = -\frac{1}{2}m^2\Upsilon_0$$

Или:

$$\Delta\Upsilon_0 = -\frac{3}{2}m^2\Upsilon_0 \qquad (6)$$

PHELEX – PHoton-ELectron EXperiment

multicathode counter technique as an extension of a method of a dish antenna to higher masses (energies)



θ – angle between electric field of a photon and the surface
χ- dimensionless parameter quantifying a kinetic mixing

(D.Horns, J.Jackel, A.Lindner, A.Lobanov, J.Redondo, A.Ringwald , "Searching for wispy cold dark matter with a dish antenna" *Journal of Cosmology and Astroparticle Physics*, vol.4. article 16, 2013)

In our case: due to low reflectivity of the surface the photon gets absorbed and emits an electron

$\rho_{CDM} \approx 0.3$ GeV/cm^3

$\rho_{\odot}$ = (0.43 ± 0.06) GeV/cm3 (Salucci et al 2010)

Galactic dark matter halo.
But locally, near the Sun?
Primordial Solar dark matter halo?
arXiv:2007.11016
(N.B.Anderson, A.Partenheimer, and T.D.Wiser)

Sensitivity:

$$\chi = 2.9\cdot10^{-12}\left(\frac{R_{MCC}}{\eta\cdot 1Hz}\right)^{\frac{1}{2}}\left(\frac{m_{\gamma'}}{1eV}\right)^{\frac{1}{2}}\left(\frac{0.3GeV/cm^3}{\rho_{CDM}}\right)^{\frac{1}{2}}\left(\frac{1m^2}{A_{cath}}\right)^{\frac{1}{2}}\left(\frac{\sqrt{2/3}}{\alpha}\right)$$

R.B.Cairns and J.A.R.Samson Journal of optical society of America
Vol. 56, Number 11, November 1966, 1568-1573

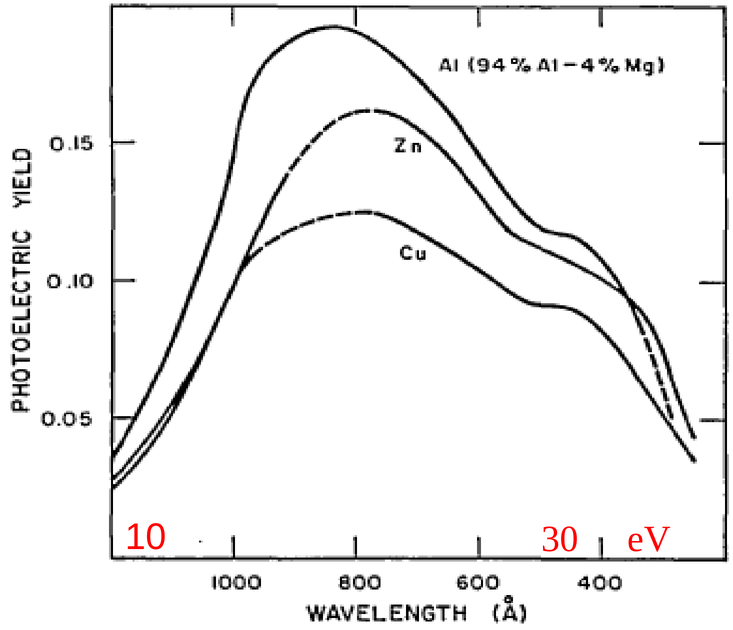


FIG. 4. Photoelectric yields of Al–Mg, Zn, and Cu.

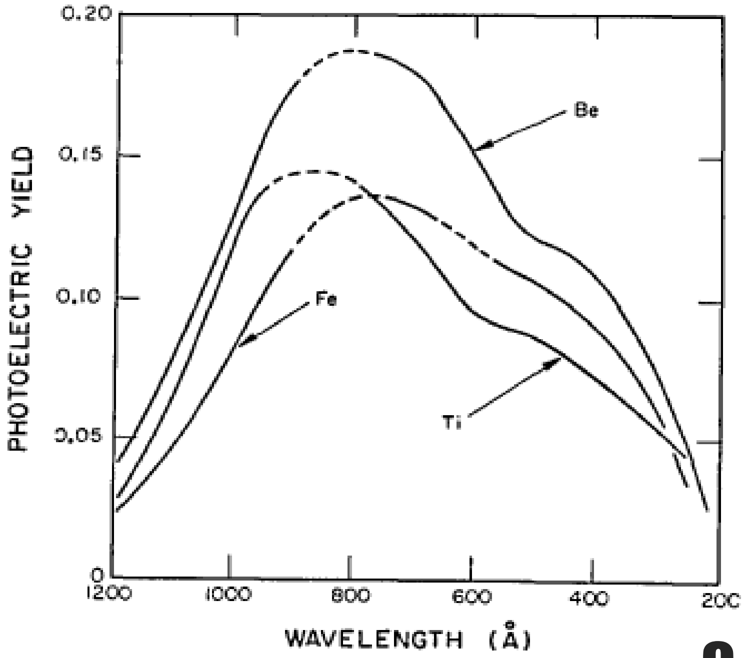
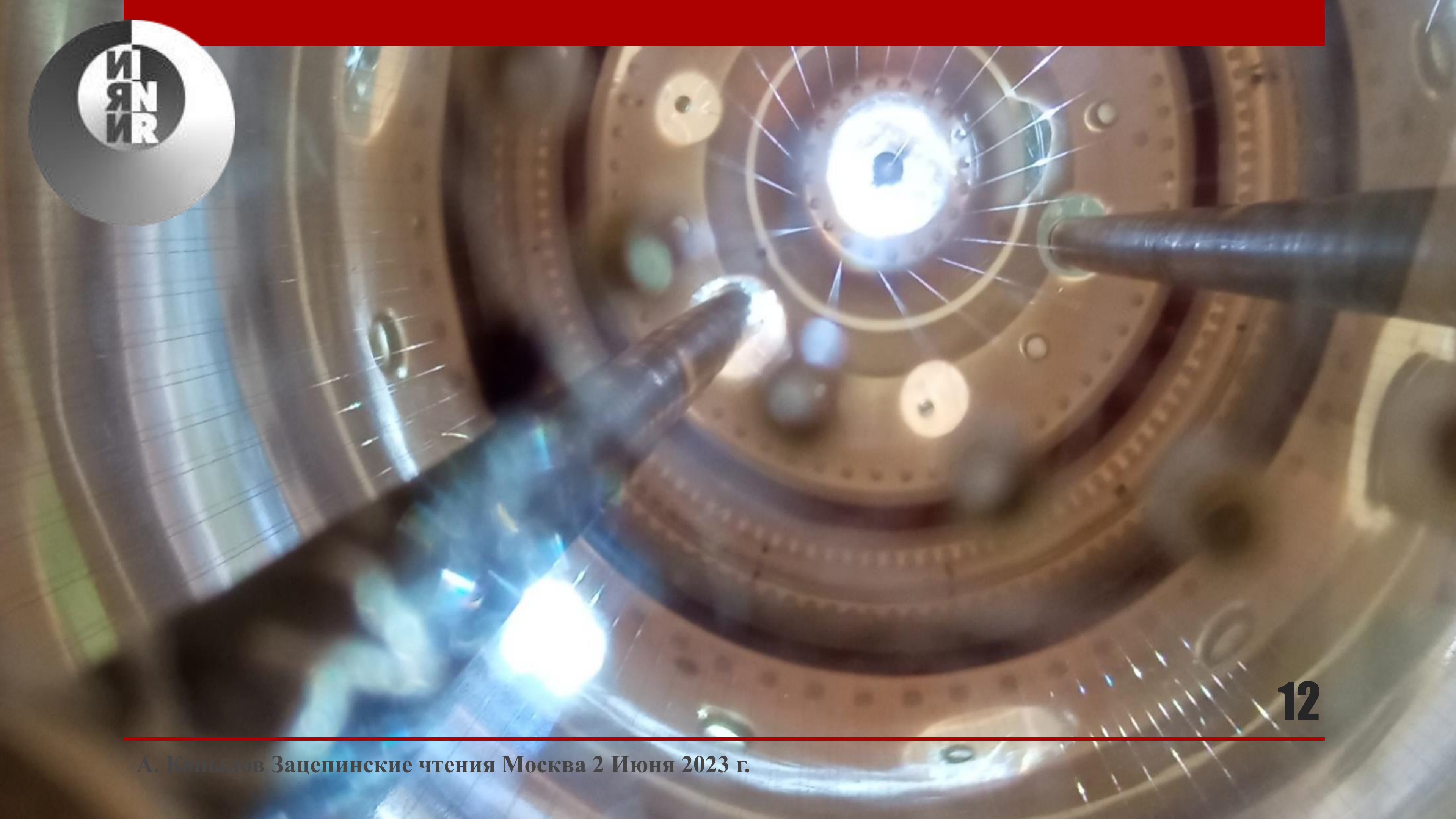


FIG. 5. Photoelectric yields of Be, Fe, and Ti.

Мультикатодный счетчик: сборка и испытания

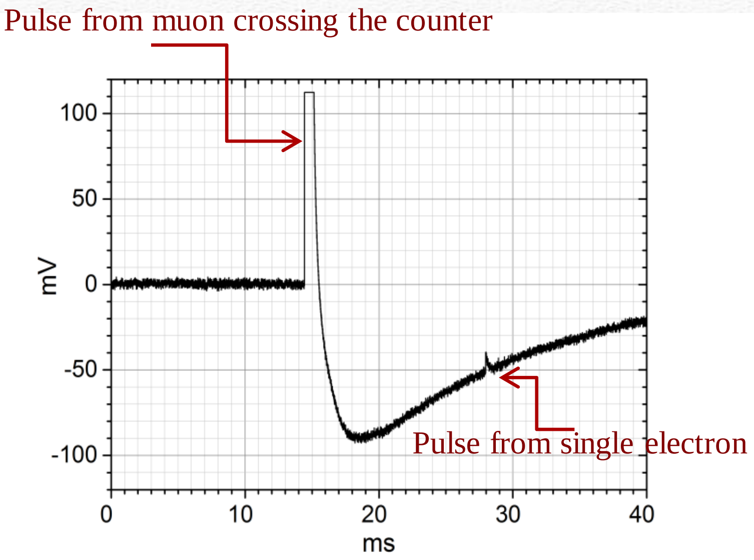

NANPino
Dubna
INTERNATIONAL WORKSHOP
on NON-ACCELERATOR NEW PHYSICS
in neutrino observations
July
19-22,
2000
Organizers:
TOPICS:
Neutrino as a key to physics beyond the Standard Model
Solar and atmospheric neutrino anomalies as
of non-zero neutrino masses and mixing

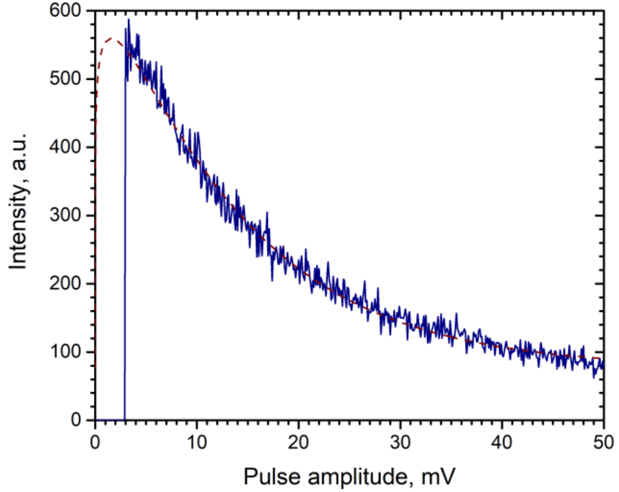


Одноэлектронные импульсы

Polya distribution

$$P(A) = C\left(\frac{A}{\bar{A}}\right)^{\theta} e^{-\left((1+\theta)\frac{A}{\bar{A}}\right)}$$

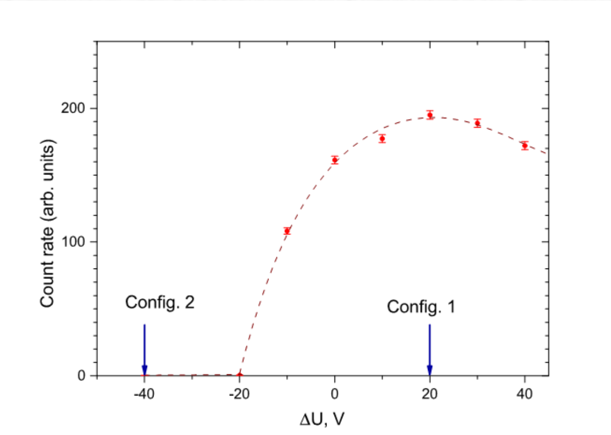


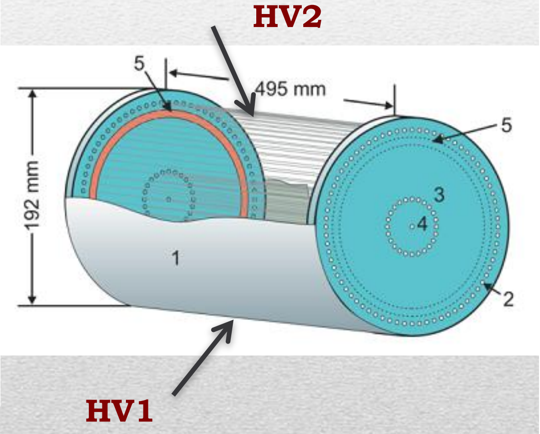


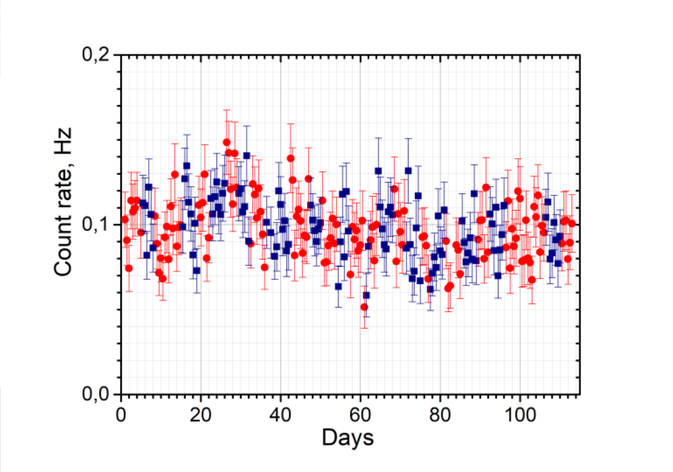
From muons at sea level: ≈ 15 pulses per second → ≈ 15% dead time (10 ms per each pulse)

Principle of a multicathode counter:
Retarding potential of the second cathode in configuration 2

The effect: $r_{MCC} = R_1 - R_2$







ΔU = HV2 – HV1

R_1 – red, R_2 - blue

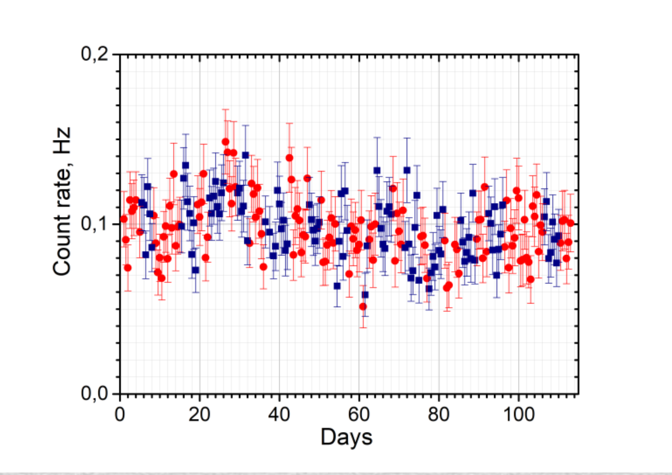
Results of measurements

with Ar +CH_4(10%) and Ne + CH_4(10%) gas mixtures

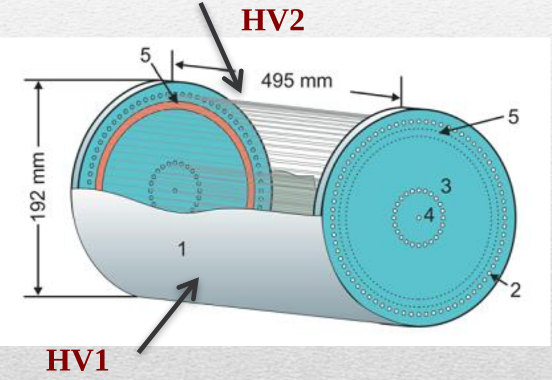
The target – free electrons of a degenerate electron gas of a metal

Result is included in compilation of the data by PDG

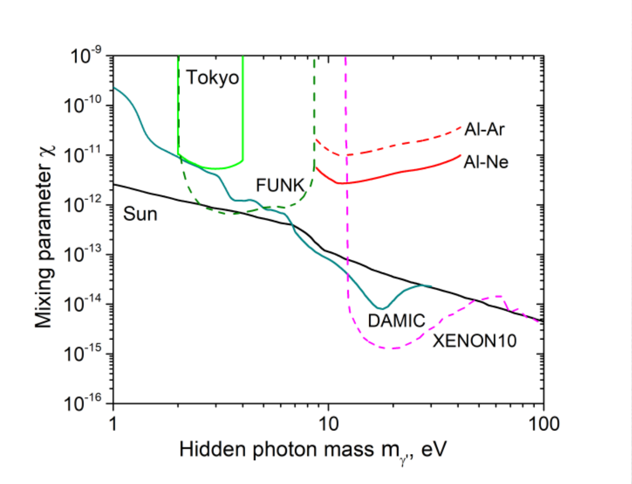
Review of Particle Physics in Prog. Theor. Exp. Phys. 2020, 083C01 (2020).



R_1 – red, R_2 - blue

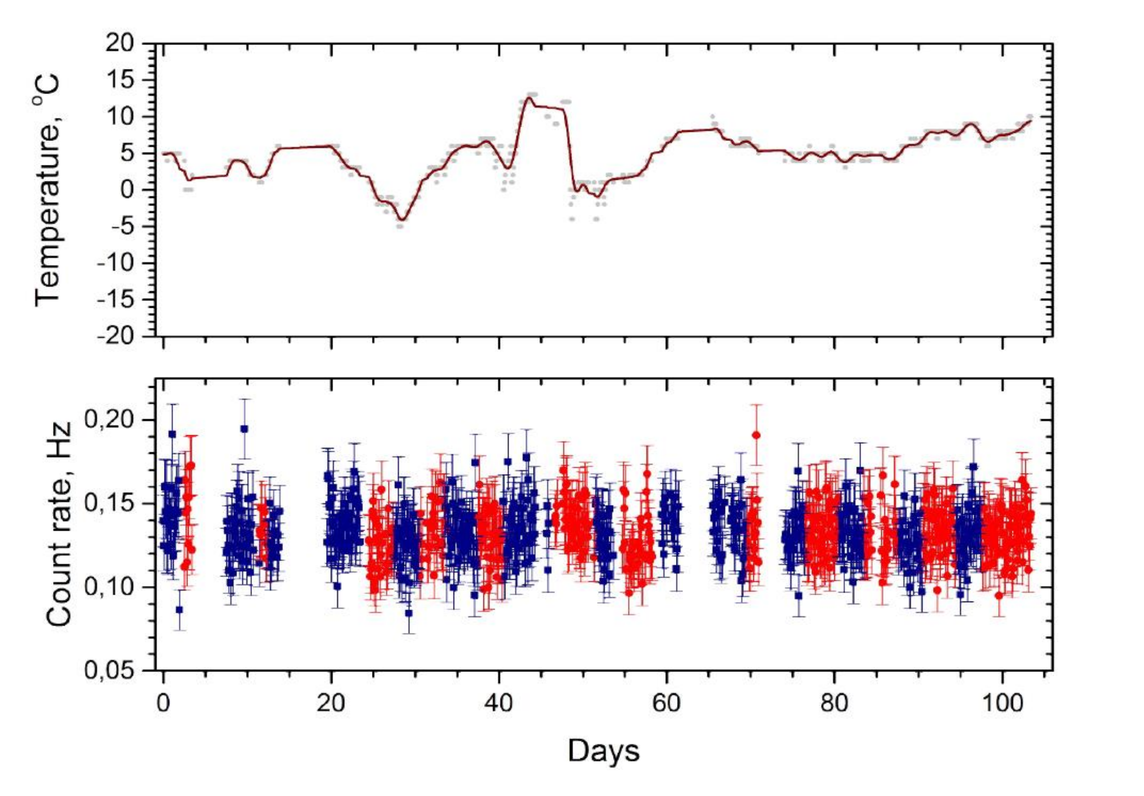


(-0.46 ± 0.67)x10^{-3} Hz



- *Target – valence electrons*

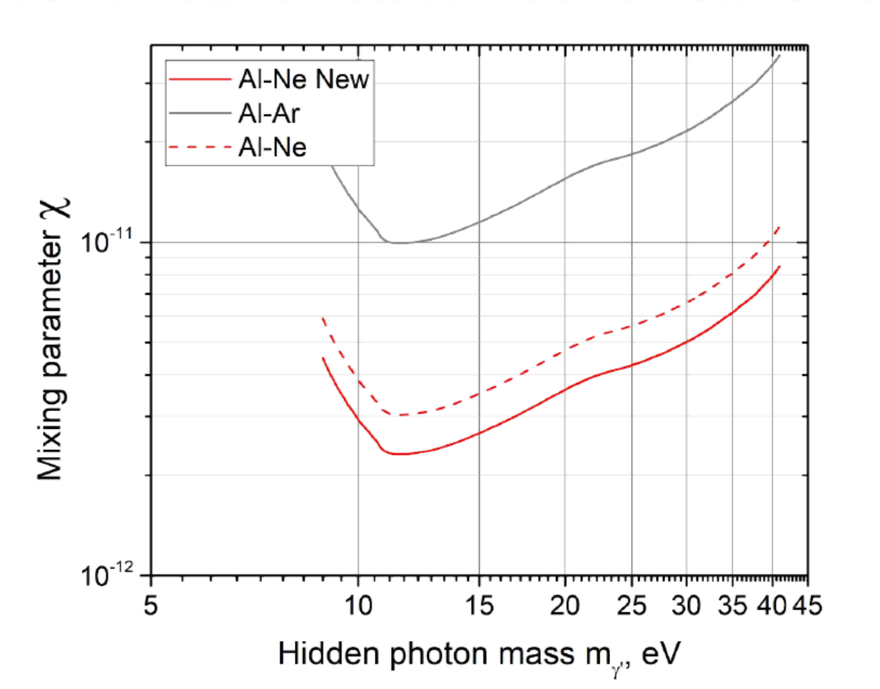
$$r_{MCC} = (-0.33 \pm 0.7)\cdot 10^{-6}\ \mathrm{Hz/cm^2}$$



Red – configuration 1
Blue – configuration 2

871 points;
In previous measurements – 200 points

New measurements Al – (Ne + CH_4(10%) 1 Bar)



New result:

C1-C2 = - 0.00018 ± 0.00101 Hz

Then @ 95 C.L.

R_{MCC} = 1.646σ/ε = 0.00164/0.608 =
= 0.0027

ε – efficiency of counting

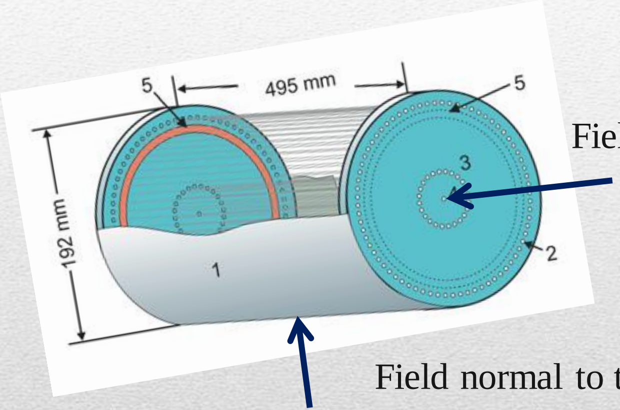
New upper limit

Result is included in compilation of the data by PDG

Review of Particle Physics in Prog. Theor. Exp. Phys. 2022, 083C01 (2022).

Directionality of the counting

θ – angle between a field of a hidden photon and the surface
χ- dimensionless parameter quantifying a kinetic mixing



Field along the axes of the counter

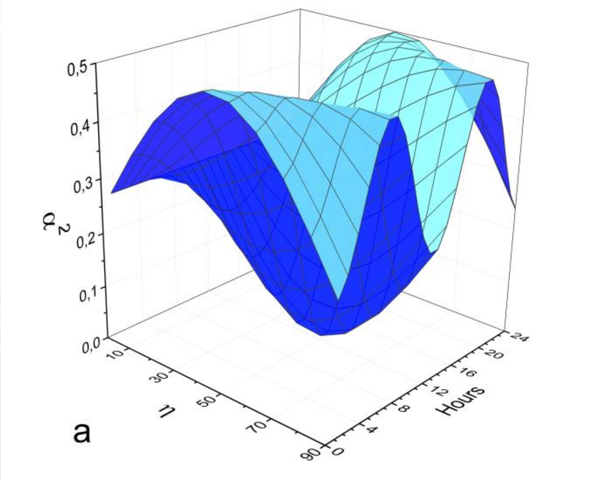
Field normal to the axes of the counter

(D.Horns, J.Jackel, A.Lindner, A.Lobanov, J.Redondo, A.Ringwald , "Searching for wispy cold dark matter with a dish antenna" *Journal of Cosmology and Astroparticle Physics*, vol.4. article 16, 2013)

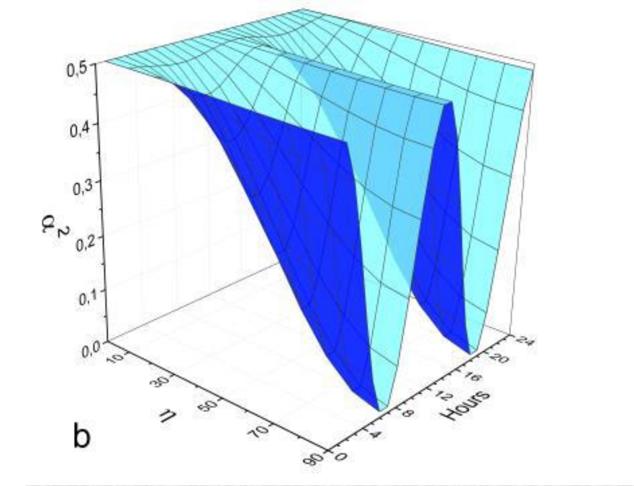
- **By rotation of the counter – variation of the count rate**

If the surface is mirror-like!
The counter with a matt surface – for the control measurements

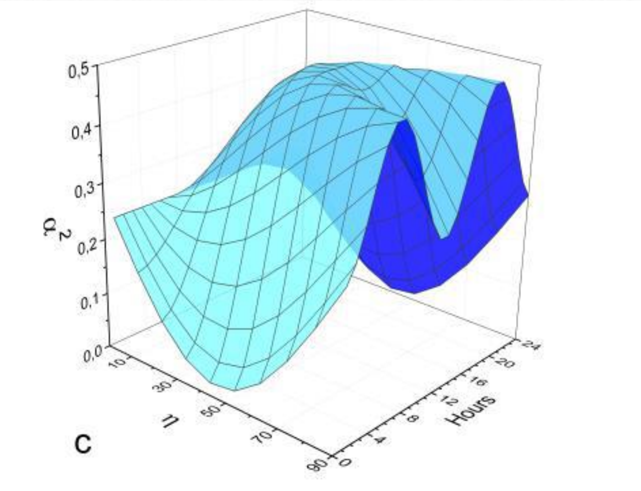
Diurnal variations, Baksan, Russia 43°



Vertical orientation

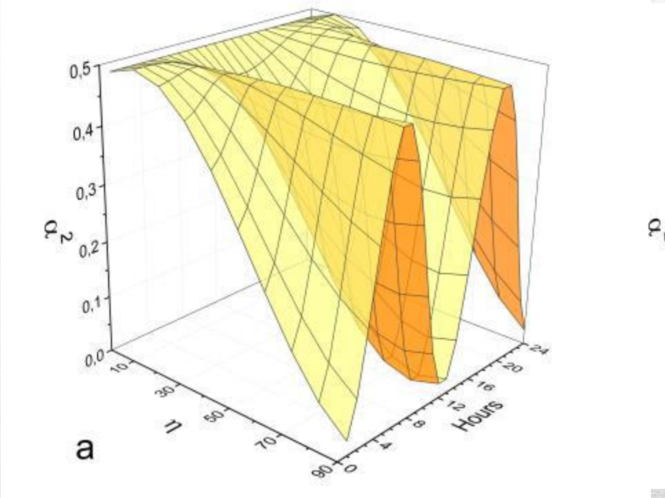


East-West orientation

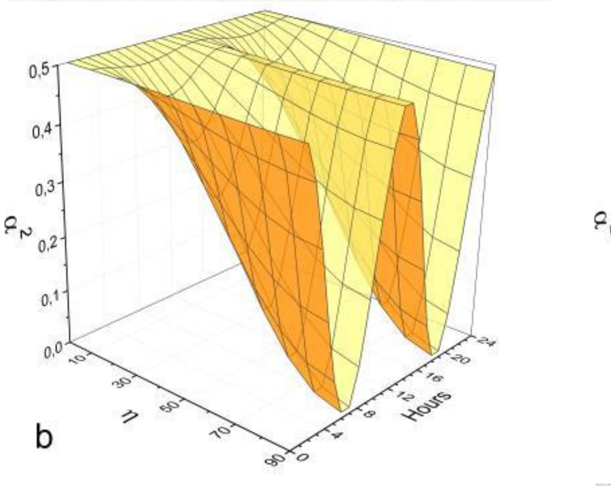


North-South orientation

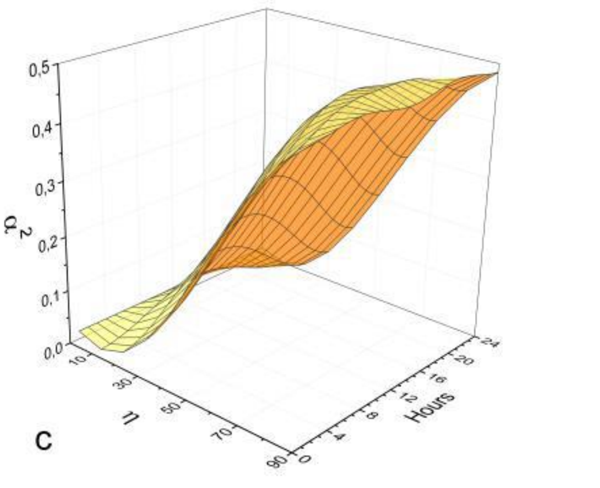
Diurnal variations, INO, India 10°



Vertical orientation

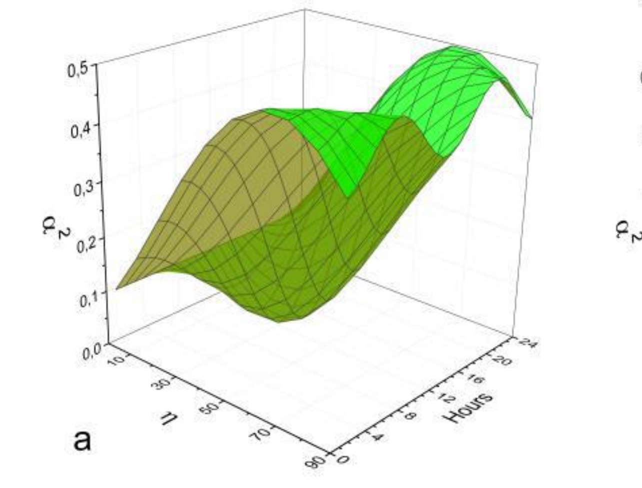


East-West orientation

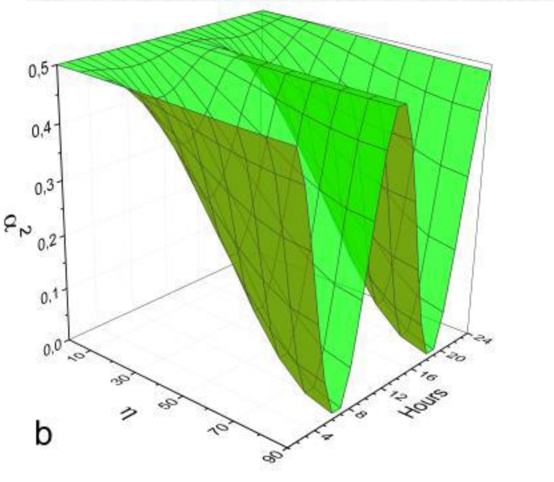


North-South orientation

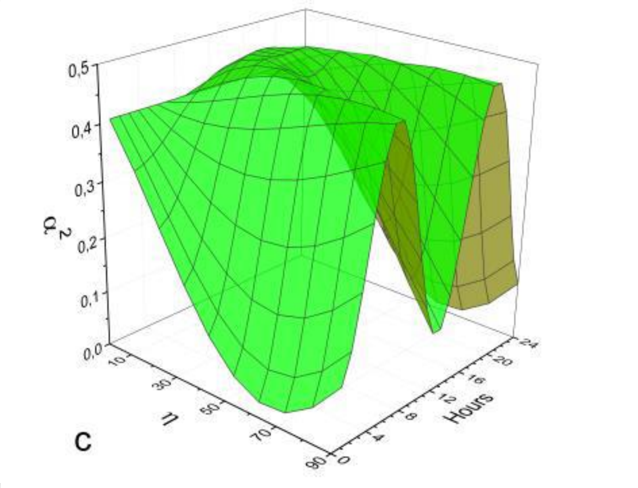
Diurnal variations, Pyhäsalmi, Finnland 64°



Vertical orientation

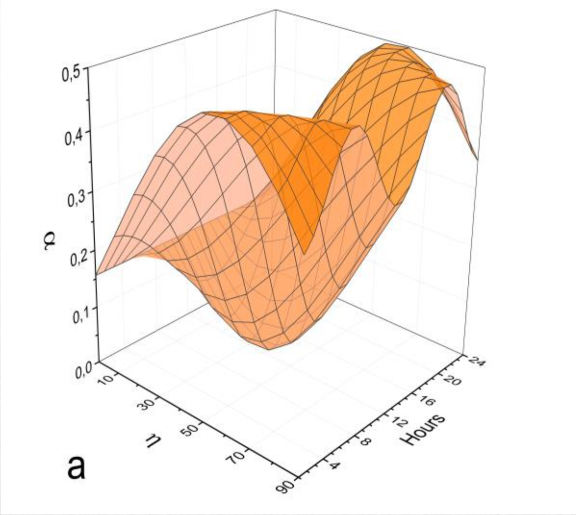


East-West orientation

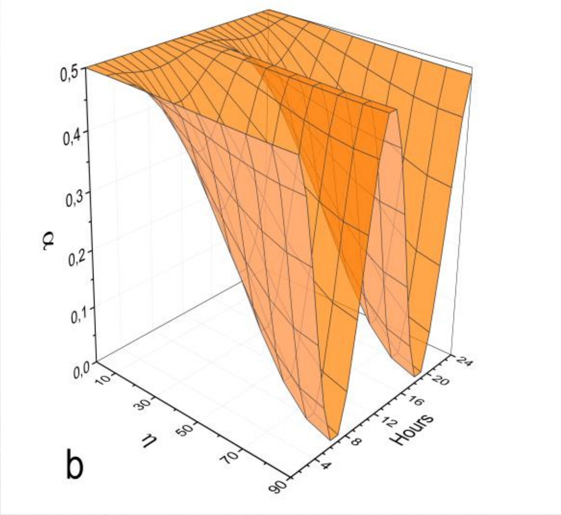


North-South orientation

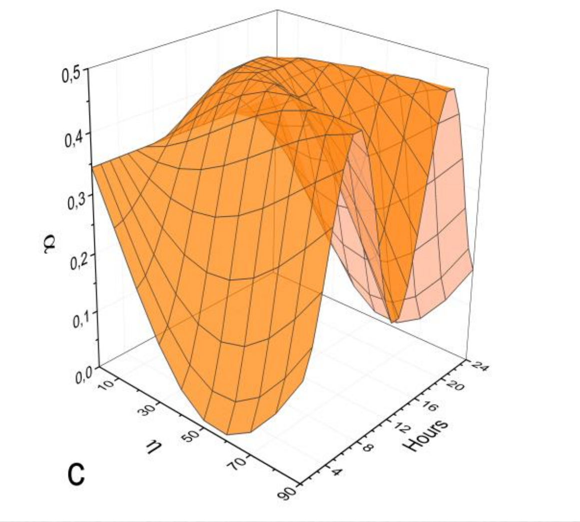
Diurnal variations, Moscow, Russia 55° 45′ N



Vertical orientation



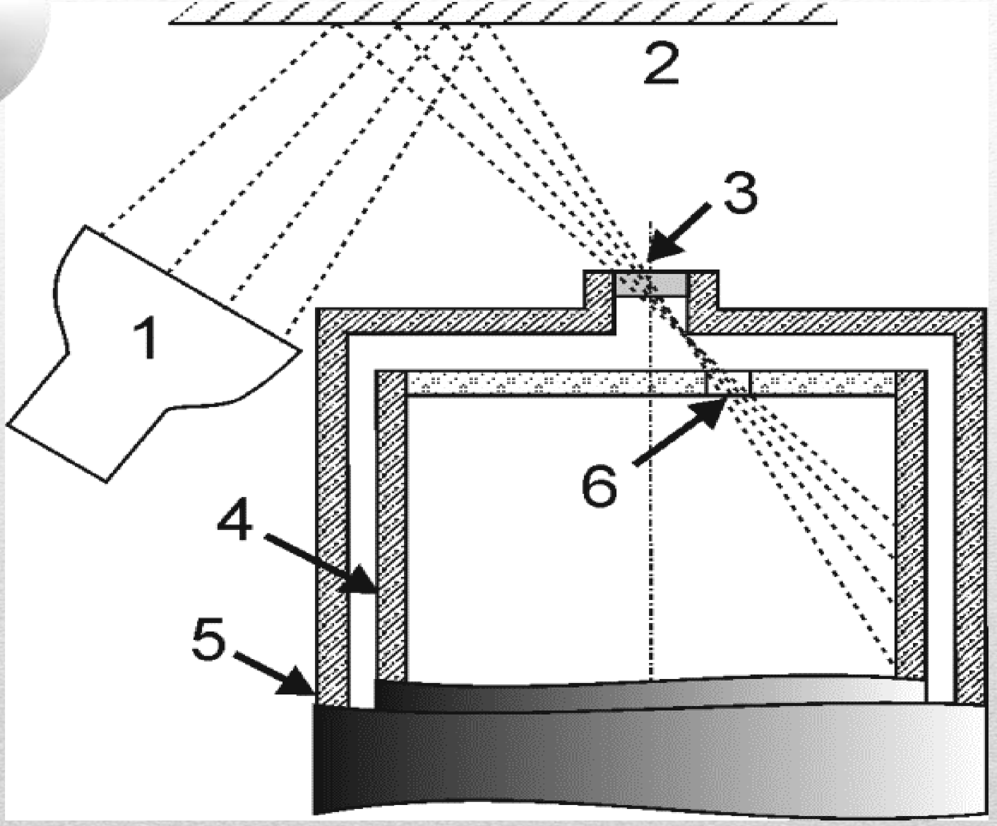
East-West orientation



North-South orientation

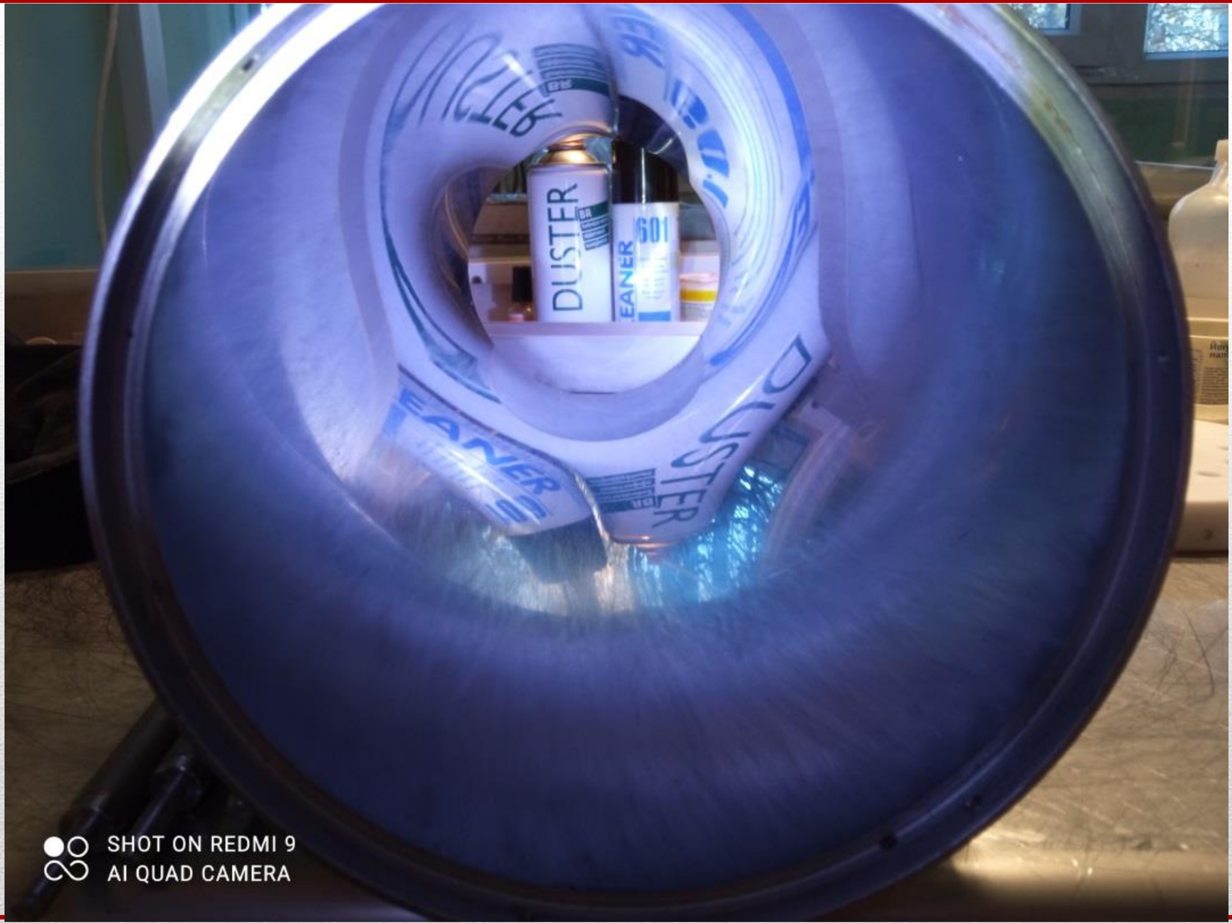
Новая конструкция счетчика

- Новый цилиндрический сплошной катод без окна для калибровки в стенке катода
- Материал катодных нитей: позолоченный вольфрам вместо нихрома
- Новый способ калибровки: с торца проекцией луча УФ на стенку катода через кварц в торце счетчика и через смещенное от центра окно
- И на будущее: низкофоновый счетчик. Все металлические детали - из титана марки ВТ1-0.



- 1. УФ источник
- 2. Экран
- 3. Кварцевое окно
- 4.Катод
- 5. Капсула
- 6. Окно со смещением от оси

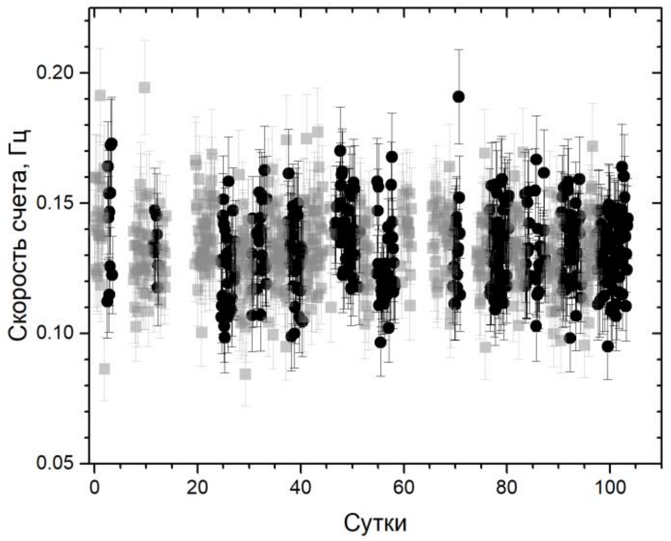
Схема калибровки
УФ источником


DUSTER
601
SHOT ON REDMI 9
AI QUAD CAMERA

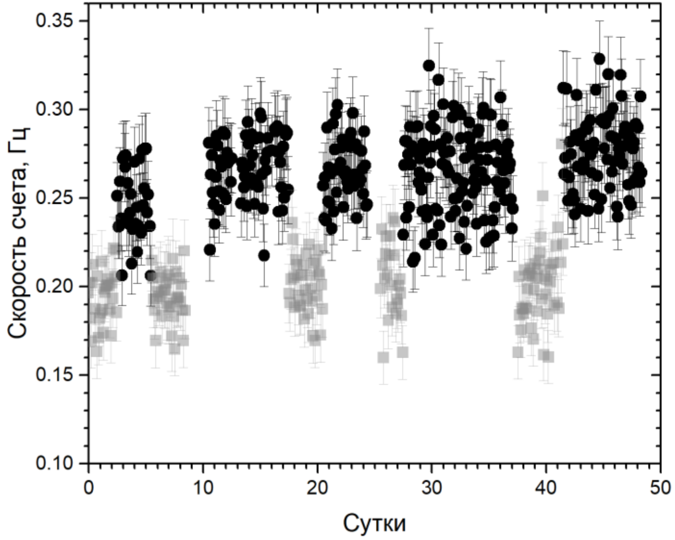
Финальный этап сборки счетчика

Вид через кварцевое окно

Счетчик с нитями из нихрома



Счетчик с нитями из вольфрам-рениевого сплава с позолотой



Скорости счета в конфигурациях 1 (черные) и 2 (серые)

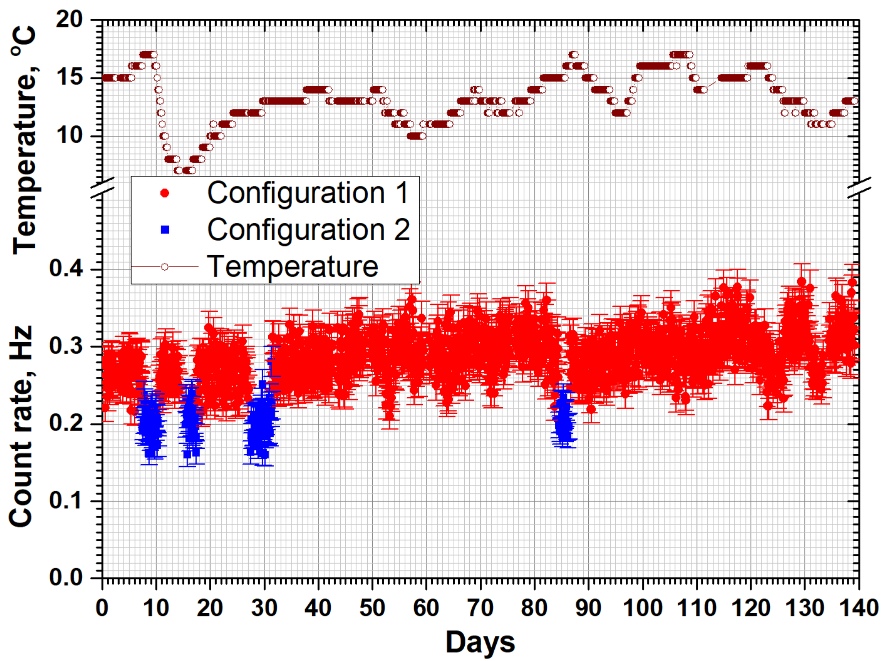
Удельная (приведенная к единице длины - метр) эмиссия одиночных электронов для 50 μm нити из вольфрам-рениевого сплава с позолотой

- $A + B = R_1$ (первая конфигурация)
- $A + kB = R_2$ (вторая конфигурация)

A – скорость счета от обьема, B – от нитей, $b = B/L = (R_1 - R_2)/(1 - k)/L$, где: R_1, R_2 – скорости счета одиночных электронов в конфигурациях 1, 2; L = 60 м – суммарная длина нитей первого и второго катодов, $k = (n_2/2 + n_1)/(n_1 + n_2) = 0.58$, где $n_1 = 20$, $n_2 = 102$ - число нитей на первом, втором катодах. Отсюда:

A = 0.10 Hz; B = 0.17 Hz (от Re187 – 76 распадов в секунду)

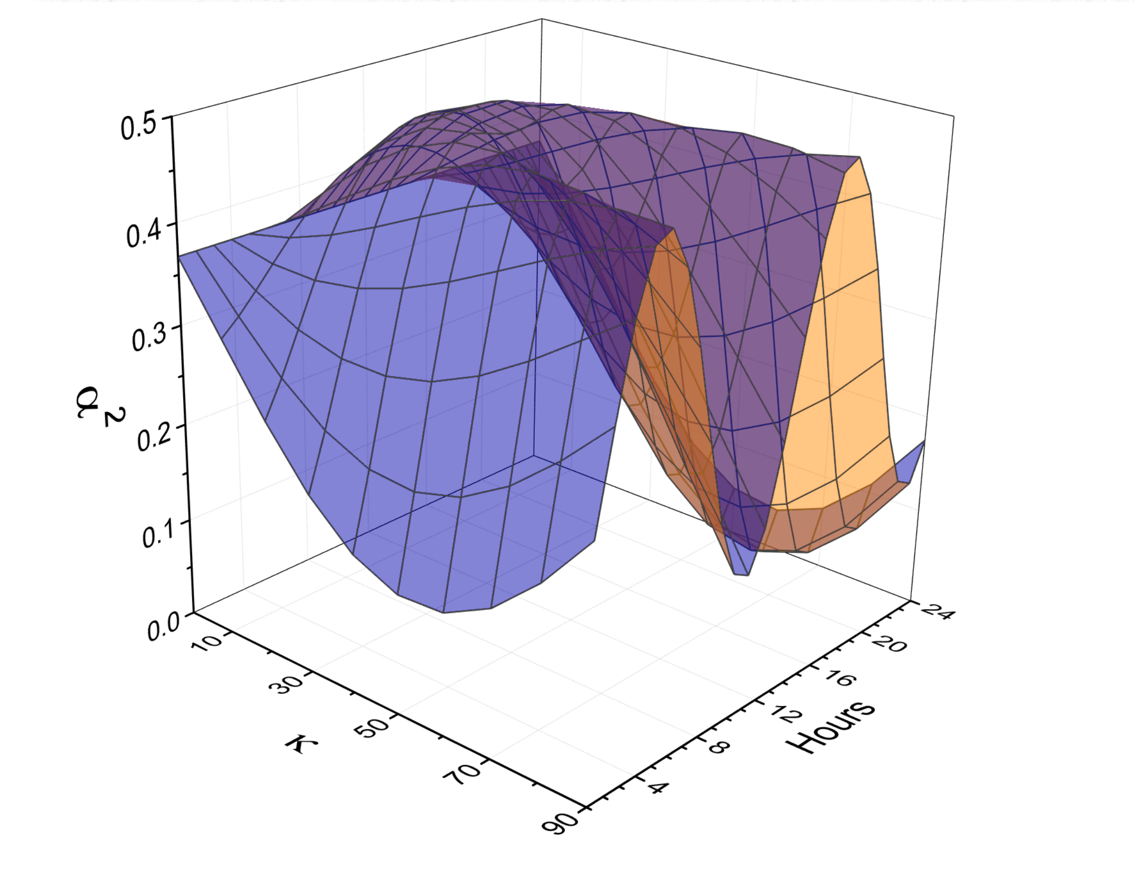
$b = 2.8 \times 10^{-3}$ Hz/m



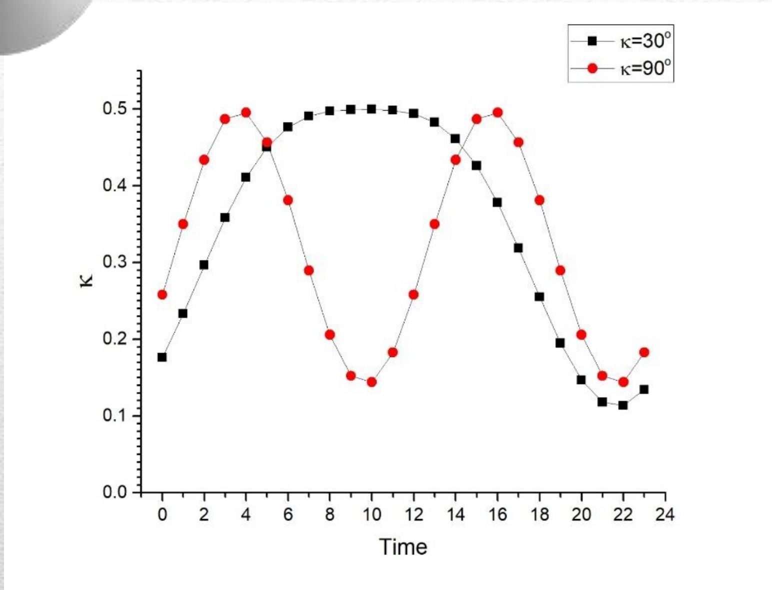
Red – configuration 1
Blue – configuration 2

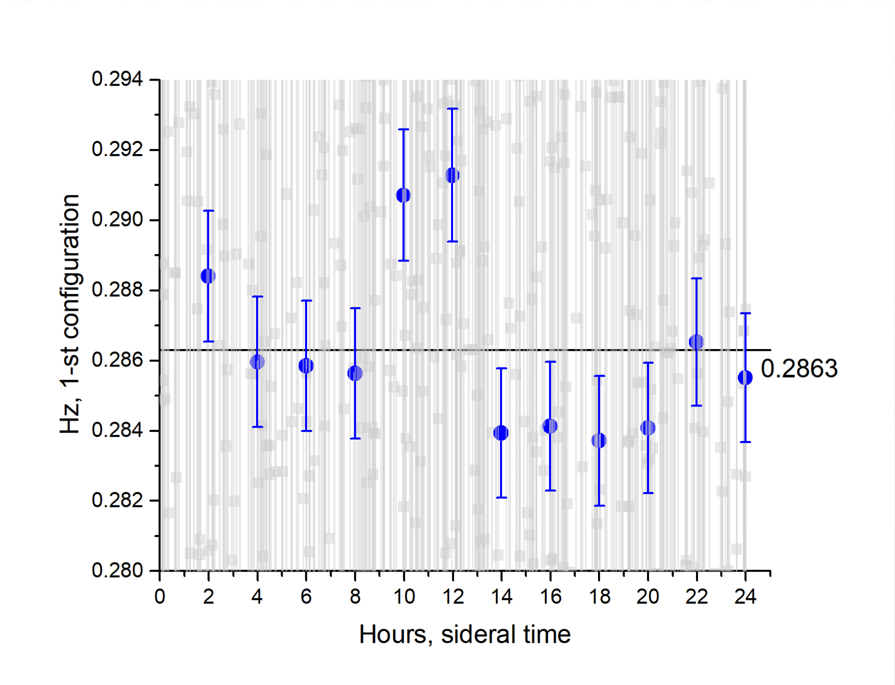
≈ 200 событий в 5120 кадрах по 0.2 сек (2M точек по 100 нсек) 12 серий (каждые 2 часа) За сутки ≈ 2400 событий в диапазоне от 3 до 50 мВ

New measurements Fe + (Ne + CH_4(10%) 1 Bar) + goldplated WRe wires



Счетчик расположен под углом α = 23^0 к оси Север-Юг



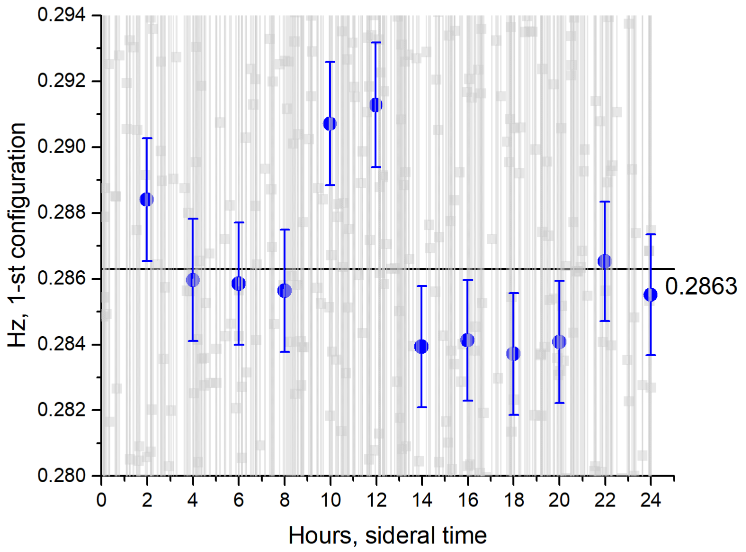


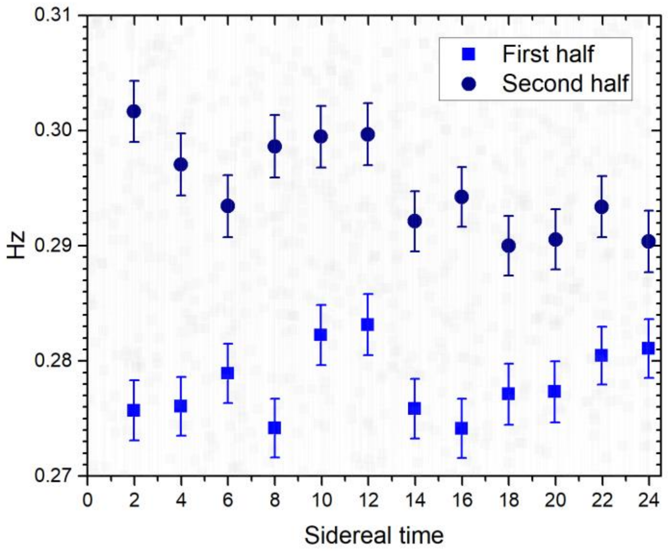
Распределения при углах к

Результаты измерений

Катод счетчика из железа

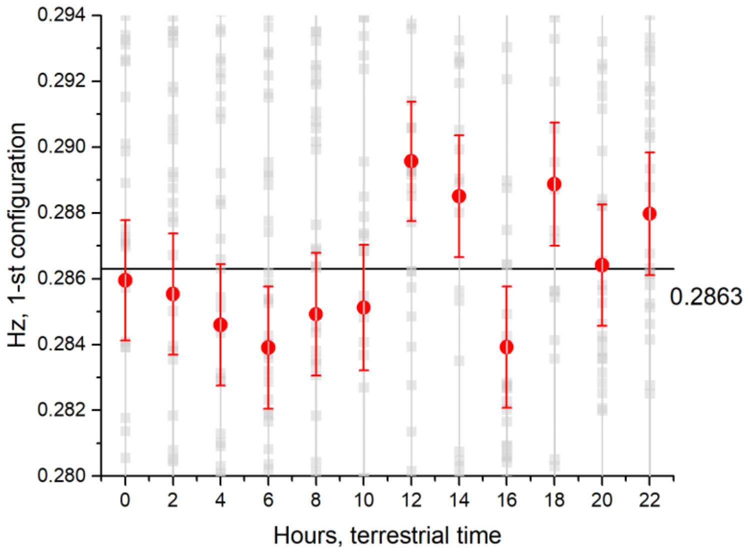
Счетчик с нитями из вольфрам-рениевого сплава с позолотой



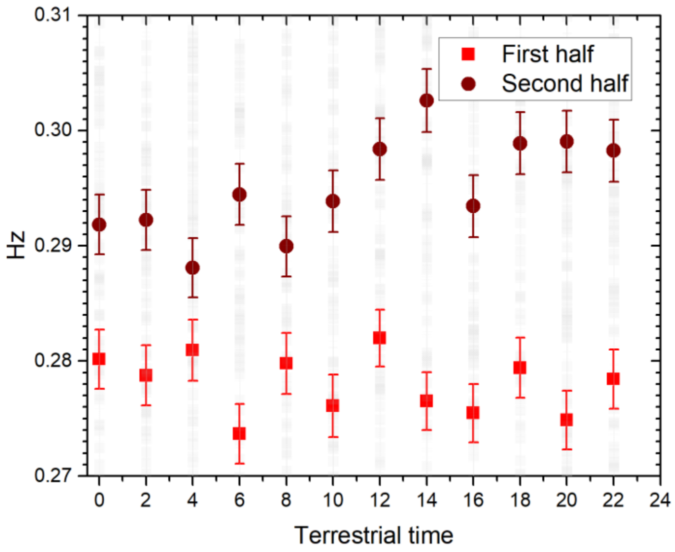


Суточные вариации в звездной системе координат за весь период измерений и с разбивкой на два полупериода

Катод счетчика из железа

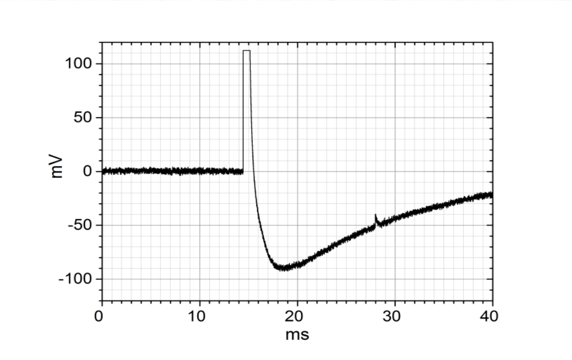


Счетчик с нитями из вольфрам-рениевого сплава с позолотой



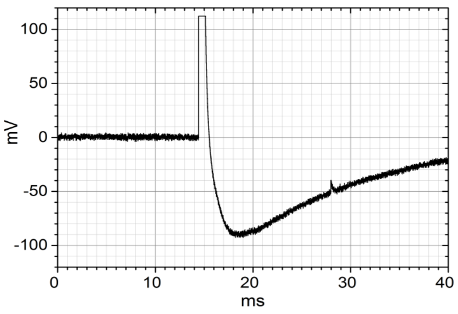
Суточные вариации в солнечной системе координат за весь период измерений и с разбивкой на два полупериода

Новая программа обработки данных.



- Оцифровка 14 бит диапазона +/- 100 mV
- Непрерывный круглосуточный набор данных
- в конфигурации 1 и 2 с временной привязкой
- событий в течение суток
- За сутки набираем ≈ 1 ТераБайт событий
- Обработка событий в off-line
- Для получения значимого результата для верхнего предела необходим набор данных в течение нескольких месяцев, а для получения значимого результата по суточным вариациям в течение нескольких лет.
- Дальнейшее увеличение чувствительности возможно путем увеличения числа детекторов и, соответственно, масштабирования всего эксперимента.

Summary



Метод показал свою эффективность, полученные результаты включены в мировую компиляцию данных PDG 2020/2022

Наблюдение (в случае успеха) суточных вариаций с характерной временной симметрией формирует доказательную базу существования темных фотонов с определенной поляризацией и позволит определить направление вектора электрического или магнитного поля в солнечной или звездной системе координат.

Для получения значимого результата по суточным вариациям необходимо провести измерения с действующим детектором в течение нескольких лет. Дальнейшее увеличение точности измерений возможно путем увеличения числа детекторов и, соответственно, масштабирования всего эксперимента.

Работа может проводиться независимыми группами в разных лабораториях на разных географических широтах.

Our publications:

1. A.K., I.Orekhov, V.Petukhov, PHELEX: Present Status, Moscow University Physics Bulletin, 2022, Vol. 77, pp, 315-318. DOI: 10.3103/S0027134922020539
2 . A.K., I.Orekhov, V.Petukhov, Diurnal Variations of the Count Rates from Dark Photons, Particles 2022, 5, 180-187. https://doi.org/10.3390/particles5020016
3. A.K., I.Orekhov, V.Petukhov, Мульти катодный счетчик как детектор скрытых фотонов, Physics of Atomic Nuclei, 2022, Vol.85, No. 6, pp 1-9, (2022). DOI: 10.31857/S0044002722060083
4. A.K., I.Orekhov, V.Petukhov, Present Status of the Experiment on the Search for Dark Photons by a Multi-Cathode Counter, Physics of Atomic Nuclei, 2021, Vol.84, No. 6, pp 860-865
5. A.K., I.Orekhov, V.Petukhov, On the possibility of observing diurnal variations in the count rate of dark photons using a multicathode counters, Physics of Particles and Nuclei, 2021, Vol.52, No.1, pp. 31 - 38
6. A.K., I.Orekhov, V.Petukhov, First results and future prospects with PHELEX, Journal of Physics, Conference Series, 1690 (2020) 012002, doi:10.1088/1742-6596/1690/1/012002
7. A.K., I.Orekhov, V.Petukhov, Results from a hidden photon dark matter search using a multi-cathode counter, JCAP, 07, 008 (2019)

Our publications:

8. A.K., I.Orekhov, V.Petukhov, Method of search for hidden photons of Cold Dark Matter using a multi-cathode counter, Physics of Atomic Nuclei, Vol.82, No. 9, pp 1-8, (2019)
9. A.K., I.Orekhov, V.Petukhov, Search for Hidden Photon Dark Matter using a Multi-Cathode Counter. Proceedings of the 4th International Conference on Particle Physics and Astrophysics (ICPPA-2018), Journal of Physics: Conference Series, 1390 (2019) 012066
10. A.K., I.Orekhov, V.Petukhov, A multi-cathode counter in a single-electron counting mode, NIM A, 910, 164 (2018)
11. A.K., I.Orekhov, V.Petukhov, Tech. Phys. Lett 42, 102 (2016)
12. A.K., I.Orekhov, V.Petukhov, Adv. High Energy Phys., 2058372 (2016)

'The new guiding principle should be "no stone left unturned": we should look for dark matter not only where theoretical prejudice dictates that we "must", but wherever we can.

G.Bertone and T.M.P.Tait A New Era in the Quest for Dark Matter arXiv:1810.01668

Спасибо за внимание

Authors: A. Kopylov, I. Orekhov, V. Petukhov
Title: Results from a Hidden Photon Dark Matter Search Using a Multi-Cathode Counter
Received: 2019-01—29 08:16:45.0
Referee report:
Their experiment is very interesting and their idea has both novelty and originality. I consider that this preprint is acceptable for publication in JCAP.

Dark photons as a Dark Matter

Search for Dark Photon Dark Matter:
Dark E-Field Radio Pilot Experiment

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Peter Graham and Kent Irwin
Physics Department, Stanford University
(Dated: January 11, 2021)

We are building an experiment to search for dark matter in the form of dark photons in the nano- to milli-eV mass range. This experiment is the electromagnetic dual of magnetic detector dark radio experiments. It is also a frequency-time dual experiment in two ways: We search for a high-Q signal in wide-band data rather than tuning a high-Q resonator, and we measure electric rather than magnetic fields. In this paper we describe a pilot experiment using room temperature electronics which demonstrates feasibility and sets useful limits to the kinetic coupling $\epsilon \sim 10^{-12}$ over 50–300 MHz. With a factor of 2000 increase in real-time spectral coverage, and lower system noise temperature, it will soon be possible to search a wide range of masses at 100 times this sensitivity. We describe the planned experiment in two phases: Phase-I will implement a wide band, 5-million channel, real-time FFT processor over the 30–300 MHz range with a back-end time-domain optimal filter to search for the predicted $Q \sim 10^6$ line using low-noise amplifiers. We have completed spot frequency calibrations using a biconical dipole antenna in a shielded room that extrapolate to a $5\,\sigma$ limit of $\epsilon \sim 10^{-13}$ for the coupling from the dark field, per month of integration. Phase-II will extend the search to 20 GHz using cryogenic preamplifiers and new antennas.

arXiv:2101.02805v1 [physics.ins-det] 8 Jan 2021

I. INTRODUCTION

The physical nature of dark matter is unknown. Sensitive searches for weakly interacting massive particles (WIMPS) have found nothing [1]. In recent years the WIMP hypothesis has dominated searches for dark matter since a generic weak-scale thermal relic could account for all of the observed dark matter in the universe [2]. Experimenters continue to probe new WIMP parameter space by developing larger and more sensitive detectors, however these tend to lose sensitivity when the mass of the dark matter particle is small, leaving a large range of parameter space open for exploration [3].

The 2014 P5 report [4] emphasizes the importance of searching for dark matter along every feasible avenue. To date, relatively little effort has been spent on detection of ultra-low mass dark matter candidates where it is best described as a wave rather than a particle [5]. This requires development of new detectors.

The *dark photon* is a hypothetical, low-mass vector boson which has been posed as a candidate for dark matter. Dark photons could account for much of the dark matter, and are theoretically motivated via fluctuations of a vector field during the early inflation epoch of our universe. A relic abundance of such a particle could be produced non-relativistically in the early universe in a similar way to axions, through either the misalignment mechanism or through quantum fluctuations of the field during inflation [6, 7].

In contrast to axions, a massive, inflation-produced vector boson like a dark photon would have a power spectrum that is peaked at a length scale of roughly 10^{10} km, and rapidly decreases in intensity at large length scales, consistent with CMB observations. Furthermore, a dark photon would adopt the adiabatic fluctuations of the inflaton making it a good dark matter candidate [7]. The high phase space density required for dark photons to constitute a significant portion of the local dark matter density implies that they would behave as an oscillating field and would oscillate with a frequency equal to the mass of the dark photon. In general, for a theory with

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Измерение индуцированного электрического поля

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As in WIMP searches, there are two unknowns: the frequency of the wave (a proxy for the mass) and its weakly coupled amplitude. We measure the induced electric field with a wideband antenna. The experiment is conducted inside a large (≈ 27.4 m^3) electromagnetically shielded room, searching for a weak narrowband signal between 30 MHz and 20 GHz from dark photons converting from within the shield. The antenna is polarization sensitive, enabling detection of the expected E-field in any direction whence aligned. The challenge is detecting a 1 ppm spectrally pure signal, varying only on 12-hour timescales (Earth rotation), at femtovolt levels, in wideband noise. Since the frequency of the line

Наш препринт: A.Kopylov, I.Orekhov, V.Petukhov. About the possibility to observe diurnal variations of the count rate of dark photons by the multicathode counters. arXiv:2006.05452

NORDITA-2021-036

Dark photon limits: a cookbook

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The dark photon is a massive hypothetical particle that interacts with the Standard Model by kinetically mixing with the visible photon. For small values of the mixing parameter, dark photons can evade cosmological bounds to be a viable dark matter candidate. Due to the similarities with the electromagnetic signals generated by axions, several bounds on dark photon signals are simply reinterpretations of historical bounds set by axion haloscopes. However, the dark photon has a property that the axion does not: an intrinsic polarisation. Due to the rotation of the Earth, accurately accounting for this polarisation is nontrivial, and highly experiment-dependent. We show that if one does account for this polarisation, and the rotation of the Earth, experimental sensitivity to the dark photon's kinetic mixing parameter can be improved by over an order of magnitude. We detail the strategies that would need to be taken to properly optimise a dark photon search. These include judiciously choosing the location and orientation of the experiment, as well as strategically timing any repeated measurements. We also point out that several well-known searches for axions employ techniques for testing signals that preclude their ability to set exclusion limits on dark photons, and hence should not be reinterpreted as such.

arXiv:2105.04565

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