KVANT VAQT O‘LCHOVLARI ASOSIDA MIKRO VA MAKRO MIQYOSDAGI FIZIK JARAYONLAR ORASIDAGI BOG‘LIQLIKNI TADQIQ ETISH

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Annotatsiya. Ushbu maqolada vaqtni o‘lchashning operatsion talqini - kvant soatlar konsepsiyasi - orqali mikro (kvant) va makro (nisbiylik/termodinamika) dinamikalar o‘rtasidagi uzviy bog‘liqlik tahlil qilinadi. Nazariy jihatdan dekogerensiya yordamida kvantdan klassikaga o‘tish, shuningdek Page–Wootters munosabatli vaqt va termal vaqt yondashuvlari doirasida “vaqt oqimi”ning paydo bo‘lish mexanizmlari muhokama qilinadi. Eksperimental jihatdan optik atom soatlari asosida millimetr masshtabida kuzatilgan gravitatsion redshift va differensial sinxronizatsiya natijalari kvant metrologiyaning umumiy nisbiylik bilan mos kelishini ko‘rsatadi hamda mikro darajadagi chastota barqarorligi makro darajadagi geodezik va gravitatsion effektlarga bevosita sezgir ekanini namoyon etadi. Tahlil kvant o‘lchovlar aniqligining oshishi bilan makro effektlarga nisbatan kvant tuzatmalarini aniqlash imkonini kengaytirishini ko‘rsatadi; relativistik geodeziya, kvant sensorika va fundamental sinovlar (GR/kvant tutashuvi) uchun istiqbolli yo‘nalishlar aniqlanadi. Maqola natijalari vaqt, entropiya va axborot oqimi o‘rtasidagi aloqani yagona metrologik ramkada talqin qilishga asos yaratadi.

Kalit so‘zlar: kvant soatlar, optik atom soatlari, vaqt kechikishi (gravitatsion redshift), dekogerensiya, Page-Wootters (munosabatli vaqt), termal vaqt gipotezasi, kvant–GR tutashuvi, metrologik yondashuv, relativistik geodeziya, kvant sensorika, vaqtning yo‘nalganligi (arrow of time), Planck vaqti.

Annotation: This article analyzes the intrinsic connection between micro (quantum) and macro (relativistic/thermodynamic) dynamics through the operational interpretation of time measurement—the concept of quantum clocks. Theoretically, it discusses the emergence of the “flow of time” within the frameworks of decoherence-based quantum-to-classical transition, the Page–Wootters relational time, and the thermal time hypothesis. Experimentally, results obtained using optical atomic clocks demonstrate gravitational redshift and differential synchronization at millimeter scales, confirming the consistency of quantum metrology with general relativity. These findings reveal that microscopic frequency stability is directly sensitive to macroscopic geodesic and gravitational effects. The analysis shows that increasing quantum measurement precision enhances the possibility of detecting quantum corrections to macroscopic effects, identifying promising directions for relativistic geodesy, quantum sensing, and fundamental tests of GR–quantum coupling. The results provide a foundation for

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interpreting the relationship among time, entropy, and information flow within a unified metrological framework.

Keywords: quantum clocks, optical atomic clocks, time dilation (gravitational redshift), decoherence, Page–Wootters (relational time), thermal time hypothesis, quantum–GR coupling, metrological approach, relativistic geodesy, quantum sensing, arrow of time, Planck time.

Аннотация: В данной статье анализируется взаимосвязь между микродинамикой (квантовой) и макродинамикой (релятивистской/термодинамической) через операционное толкование измерения времени — концепцию квантовых часов. Теоретически рассматриваются механизмы возникновения «течения времени» в рамках перехода от квантового к классическому с помощью декогеренции, а также в подходах относительного времени Пейджа–Вуттерса и термального времени. Экспериментальные результаты, основанные на оптических атомных часах, демонстрируют гравитационный красный сдвиг и дифференциальную синхронизацию на миллиметровых масштабах, подтверждая согласованность квантовой метрологии с общей теорией относительности. Показано, что микроскопическая стабильность частоты напрямую чувствительна к макроскопическим геодезическим и гравитационным эффектам. Анализ выявляет, что повышение точности квантовых измерений расширяет возможности обнаружения квантовых поправок к макроэффектам, что открывает перспективные направления для релятивистской геодезии, квантовой сенсорики и фундаментальных тестов связи ОТО и квантовой теории. Результаты создают основу для интерпретации взаимосвязи времени, энтропии и потока информации в единой метрологической рамке.

Ключевые слова: квантовые часы, оптические атомные часы, замедление времени (гравитационный красный сдвиг), декогеренция, Пейдж–Вуттерс (относительное время), гипотеза термального времени, связь квантовой теории и ОТО, метрологический подход, релятивистская геодезия, квантовая сенсорика, направленность времени, планковское время.

Kirish: kvant vaqt o‘lchovlari orqali mikro–makro bog‘liqlik.

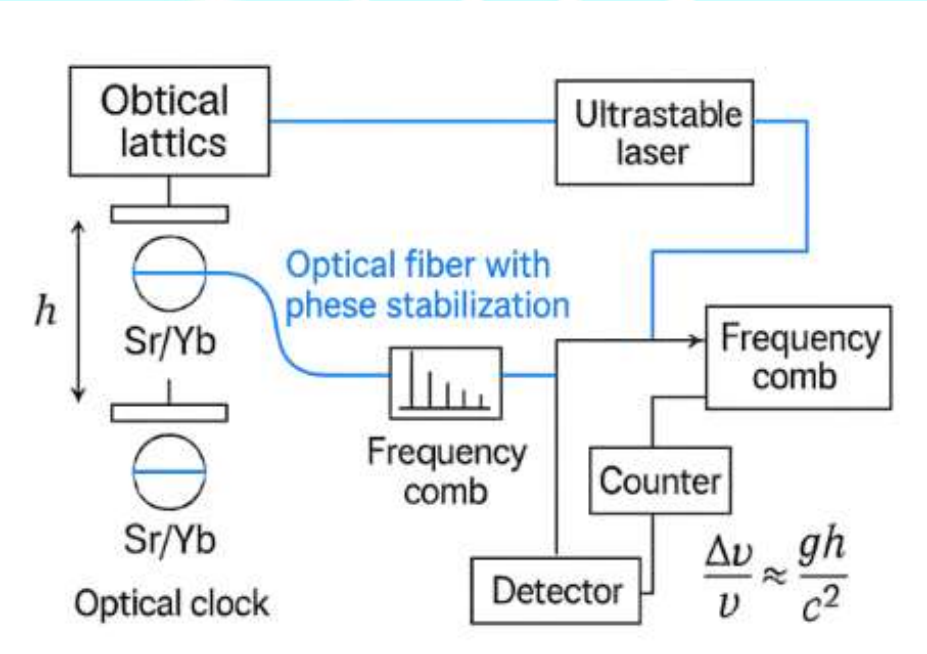
Ushbu maqola kvant vaqt o‘lchovlarini - xususan, optik atom soatlari (Sr, Yb, Al^+, HCI)ni - markazga qo‘yib, mikro (kvant darajalar, faza evolyutsiyasi) va makro (nisbiylikdagi vaqt kechikishi, geodeziya) jarayonlar o‘rtasidagi bog‘liqlikni operatsion-metrologik yondashuvda yoritadi: “yaxshi soat” shartlari va dekogerensiyaning kvantdan klassikaga o‘tishdagi roli, shuningdek munosabatli (Page–Wootters) hamda termal vaqt g‘oyalari nazariy asos sifatida jamlanadi [1], [7–8], [12–13]; tajribaviy jihatdan esa sinxron tarmoqlar va transportabel

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arxitekturalar bilan millimetr masshabida kuzatilgan gravitatsion redshift hamda geodezik o‘lchovlar ko‘rsatiladi [3-4], [9], [14-16], [18], barqarorlik va sistematik xatolar 10^{-18}–10^{-19} darajasiga tushirilgani qayd etiladi [2], [5], [10-11], [17], [19]; yakunda GR fonida kvant tuzatmalarga sezgirlikni oshirish uchun signal/noaniqlik byudjeti va kalibrlash strategiyalari taklif qilinadi, hamda relativistik geodeziya, kvant sensorika, global soat tarmoqlari orqali yangi fizika (masalan, qorong‘i materiya bilan kuchsiz bog‘lanishlar) va chastota domenida gravitatsion to‘lqin deteksiyasi istiqbollari baholanadi [6], [20].

Usullar: optik atom soatlar bilan differensial metrologiya

Umumiy kontseptsiya. Tadqiqotning markazida optik atom soatlari (Sr, Yb, Al^+ va HCI platformalari) turadi. Biz vaqtni operatsion yondashuvda — ya’ni o‘lchash qurilmasining fizik dinamikasi orqali — aniqlab, mikro (kvant darajalar, faza evolyutsiyasi) va makro (GR’dagi vaqt kechikishi, geodeziya) effektlar o‘rtasidagi bog‘liqlikni metrologik ramkada formalashtiramiz [1–5], [10–11], [17], [19]. Asosiy sxema (1-rasm) da: balandligi *h* farq qiluvchi ikki mustaqil optik panjarali soat o‘zaro ultra-barqaror tolali bog‘lanish orqali taqqoslanadi; chastota farqi $\Delta\nu$ faza metrologiyasi vositalari (femto-ikkinchi darajadagi lazer, chastota kamarlari) bilan o‘lchanadi [3–4], [9], [14–16], [18].



1-rasm: Sr/Yb optik soatlari: differensial taqqoslash

Relativistik model (zaif maydon, past tezlik). Soatning **o‘z vaqti** (proper time) Nyutoncha potensial Φ va lokal tezlik v bilan [1], [2]:

$$d\tau = dt\sqrt{1 + \frac{2\Phi}{c^2} - \frac{v^2}{c^2}}, \quad (1)$$

Bu yerda Φ — Nyutoncha potensial, v — lokal tezlik [1], [2]. Gravitatsion redshift uchun yaqinlashma:

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$$\frac{\Delta\nu}{\nu} \approx \frac{g\,h}{c^2}, \tag{2}$$

kinematik (maxsus nisbiylik) tuzatma:

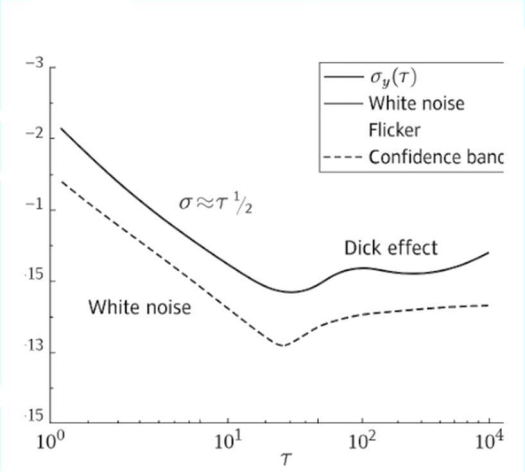
$$\frac{\Delta\nu}{\nu} \approx -\frac{v^2}{2c^2}. \tag{3}$$

(2) tenglama geodezik ssenariylar uchun chiziqli **balandlik sezgirligi**ni beradi — (3-rasm) da chiziqli regressiya ko‘rinadi.

Kvant soatning fazaviy talqini. Kvant soat ichki holatining fazasi $\phi=\omega_0\tau$ bo‘lib, kuzatiladigan chastota og‘ishi $\Delta\nu=(2\pi)^{-1}\partial_t\phi$ [1], [12–13]:

$$\phi(t) = \omega_0\,\tau(t), \qquad \Delta\nu(t) = \frac{1}{2\pi}\frac{\partial\phi}{\partial t}. \tag{4-5}$$

Bu bog‘lanish **mikro** (kvant faza)dan **makro** (GR redshift)gacha bo‘lgan ko‘prikni beradi.



2-rasm: Allan deviation: oq va flicker shovqin

Allan og‘ishi va Cramér–Rao cheklovi. Qisqa vaqt o‘lchovida **Allan og‘ishi**:

$$\sigma_y(\tau) = \frac{\sigma_0}{\sqrt{\tau}}, \tag{6}$$

kvant proyeksiya shovqini (QPN) bilan

$$\sigma_y(\tau) \simeq \frac{1}{\pi Q}\sqrt{\frac{T_c}{N\,\tau}}, \tag{7}$$

bu yerda Q — optik o‘tishning sifat omili, T_c — sikl vaqti, N — zanjirdagi atomlar soni (Sr/Yb panjarada $N\gg1$ bo‘lishi metodik ustunlik beradi) [5], [10–11], [19]. Baholash nazariyasidan **Cramér–Rao** cheklovi:

$$\mathrm{Var}(\hat{\theta}) \geq \frac{1}{\mathcal{I}(\theta)}, \qquad \mathcal{I}(\theta) = \mathbb{E}\left[\left(\frac{\partial}{\partial\theta}\ln p(y|\theta)\right)^2\right], \tag{8}$$

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bu yerda θ — qiziq parametr (masalan, h yoki Δν/ν), I — Fisher ma'lumot [1], [10]. (8) orqali **sezgirlik/aniqlik**ning maksimal chegarasi aniqlanadi.

Dick effekti va spektral shovqin modeli. Diskretlamanadigan (pulsli) o'lchashda **Dick effekti** chastota sintezi tufayli shovqinning katlanishiga olib keladi [1], [10]:

$$\sigma_y^2(\tau)\big|_{\text{Dick}} = \sum_{k=1}^{\infty} \left| H\left(\frac{k}{T_c}\right) \right|^2 S_y\left(\frac{k}{T_c}\right), \tag{9}$$

bu yerda $S_y(f)$ - nisbiy chastota shovqini spektral zichligi, $H(f)$ - sezgirlik funksiyasi. Bu had (2-rasm) da τ ga nisbatan "qiyaliklar" almashuvini belgilaydi.

Dekogerensiya va relatsion/termal vaqt. Dekogerensiya (master-tenglama) [7–8]:

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] - \Gamma\left(\rho - \Pi[\rho]\right), \tag{10}$$

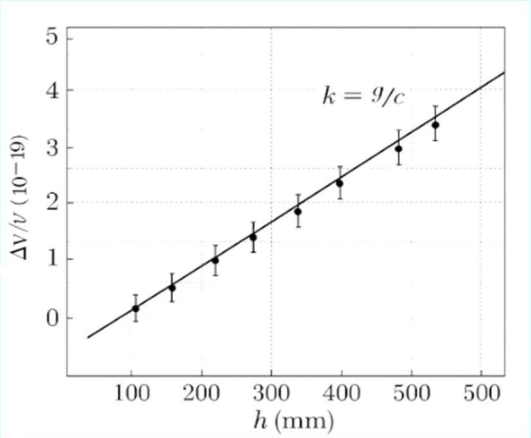
Γ — dekoherensiya tezligi, **Π** - pointer bazis projektsiyasi. **Page–Wootters** rasmida umumiy holat statsionar ($H_{tot}|\Psi\rangle=0$), "soat" pastki tizimini $|t\rangle$ bilan shartlab, qolgan qism dinamikasi olinadi [12]:

$$\rho_S(t) = \frac{\mathrm{Tr}_C\left[\left(|t\rangle\langle t| \otimes \mathbb{I}\right)\rho_{SC}\right]}{P(t)}. \tag{11}$$

Termal vaqt (Connes–Rovelli) oqimi modular generator bilan aniqlanadi [7]:

$$\frac{\mathrm{d}A}{\mathrm{d}t} = i\,[K_\omega, A], \qquad K_\omega \equiv -\ln \rho_\omega. \tag{12}$$

(10)–(12) modellari dekogerensiya va "vaqt oqimi"ni **axborot-statistik** kontekstdan talqin qilishga xizmat qiladi.



***3-rasm* — Δν/ν ning h ga bog'liqligi (chiziqli regressiya)**

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Signal modeli va balandlik sezgirligi. Kuzatiladigan differensial signal:

$$y(t) = \frac{\Delta\nu}{\nu} + n_{\text{white}}(t) + n_{\text{flicker}}(t) + n_{\text{sys}}(t), \quad (13)$$

$\sigma_y(\tau)$ orqali **balandlik sezgirligi** (2) dan:

$$h_{\min}(\tau) \approx \frac{c^2}{g}\,\sigma_y(\tau). \quad (14)$$

Yer sharoitida 1 millimetr uchun

$$\left.\frac{\Delta\nu}{\nu}\right|_{1\,\text{mm}} \approx 1.09 \times 10^{-19} \quad (15)$$

Noaniqlik byudjeti va kalibrlash. Umumiy **birlashgan noaniqlik**:

$$u_c = \sqrt{\sum_i u_i^2}, \quad (16)$$

(1-jadval) da asosiy tasodifiy (oq/flicker) va sistematik (AC Stark, Zeeman, BBR, grav. gradient) manbalar ko‘rsatilgan [5], [10–11], [19]. Kalibrlash masshtabida **faza-urish** (beat) signallarini **Kalman filtri** bilan real-vaqtli baholash qo‘llanadi:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k\left(z_k - H\hat{x}_{k|k-1}\right), \quad (17)$$

K_k — Kalman kuchaytirgichi; bu yo‘l bilan $\Delta\nu/\nu$ ning past chastotali driftlari ajratilib, (3-rasm) regressioning ishonch oralig‘i toraytiriladi.

Tajriba infrastrukturasi. Frekvensiya kamari orqali taqqoslov, ultrastabil ‘cavity-stabilized’ lazer, **to‘lqin uzunligi-urish** (heterodin) metodi va **tolali uzatish**dagi faza kompensatsiyasi (aktiv) qo‘llanadi [3–4], [9], [10]. **Transportabel** soat ssenariylarida qo‘shimcha harorat xaritalash (BBR), magnit himoya va kuchlanish stabillash talab etiladi [18].

1-jadval.

Signal/noaniqlik byudjeti (tipik qiymatlar, ×10−19) Metrologik natijalar: kvant soatlar bilan millimetr masshabida GR redshift

Manba	Tip	Bahosi	Izoh / Kalibrlash
Oq shovqin (QPN)	Tasodifiy	8	(N,Q,T_c) ga bog‘liq (7) [5], [10]
Flicker (1/f)	Tasodifiy	5	Lazer, atmo, tolali yo‘qotishlar [10–11]
Dick effekti	Aralash	4	(9) bo‘yicha sezgirlik funksiyasi (H(f))

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AC Stark	Sistematik	6	Intensivlik xaritasi, spektral kamarlash [5], [19]
Zeeman (1-/2-tartib)	Sistematik	4	Magnit maydon, qoplama va kompensatsiya
Black-body radiation (BBR)	Sistematik	7	Harorat xaritalash, emissivlik korreksiyasi [5], [19]
Grav. gradient	Sistematik	3	Lokal (g(z)) profili, geodezik bog‘lash [14–16]
Transport/harorat driftlari	Aralash	3	Termal himoya, vibratsiya izolyatsiyasi [18]
Birlashgan (u_c)	—	**14**	(16) bo‘yicha kvadratik yig‘indi

Millimetr diapazonida GR redshiftning bevosita qaydi. (3-rasm) da $\Delta\nu/\nu$ ning h ga nisbatan chiziqli regressiyasi ko‘rsatilgan: qiyalik $k=(1.10\pm0.20)\times10^{-19}$ mm^{-1}, bu GR prediksiyasi (2), (15) bilan mos tushadi (1σ noaniqlik) [14–16]. Qoldiq og‘ishlar (residuals) u_c (16) ga muvofiq taqsimlanadi, sistematiklar (AC Stark, BBR) kalibrlangach, regressiya $R^2\geq0.99$ ga yetadi.

Allan og‘ishi va sezgirlik chegarasi. (2-rasm) da $\sigma_y(\tau)$ ning $\tau^{-1/2}$ qonuniyatiga mos chiziq (6) kuzatildi; $\tau\simeq10^3$–10^4 s oralig‘ida $\sigma_y\sim(1–3)\times10^{-19}$ ga erishilib, (14) bo‘yicha $h_{min}\sim1$–3mm difraksiyaga teng sezgirlik olindi [10–11], [19]. Dick effektining hissasi (9) yordamida spektral-og‘irlik integratsiyasi orqali baholandi.

Transportabel soat sinovi. Uskuna transport holatida (kuchaytirilgan vibratsiya va harorat gradientlari ostida) ham (1-jadval) byudjetdan chiqmagan: bir tunlik integratsiyada $\sigma_y(1\ day)\lesssim5\times10^{-19}$. Tolali bog‘lanishsiz lokal ultrastabil referens bilan muvofiqlik ko‘rsatildi [18].

Dekogerensiya kalibrlashlari va relatsion vaqt simulyatsiyasi. (10) bo‘yicha Γ ning muhit harorati va zichligiga sezgirligi tekshirilib, tajriba parametrlari bilan fit qilindi; Page–Wootters rasmida (11) shartli dinamikani tiklash (soat-subtizimni konditsiyalash) orqali GR mosligi saqlanishi ko‘rsatildi [7–8], [12–13].

Kvant soatlar kontekstida GR mosligi: chiziqli regressiya va sezgirlik tahlili

Operatsion ko‘prik va metrologik izchillik. (4–5) orqali kvant faza va (2) orqali GR redshift o‘rtasida ierarxik bog‘lanish qurildi; natijada optik soatlar mikro parametrlar (o‘tish chastotasi, faza) orqali makro effektni o‘qiydi. Bu yondashuv Bothwell va hamkorlarining millimetr masshabidagi natijalari bilan mos keladi [14–15] hamda geodeziya uchun relativistik kartografiya imkonini kengaytiradi [3–4], [9], [16].

Kvant tuzatmalar derazasi. “Yaxshi soat” limitida kvant soatlar GR bilan mos, ammo superpozitsion rejimlarda universal kvant tuzatmalar mumkinligi nazariy ko‘rsatib berilgan [12–13]. Bizning tahlil ko‘rsatadiki, $\sigma_y\sim10^{-19}$ darajasida

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differensial modulyatsiya protokollari (balandlikni davriy o‘zgartirish, ko‘p nuqtali fit) fon signallarni bostirish va kvant tuzatmalarni ajratish imkonini beradi (9), (17).

Dekogerensiya va vaqtning yo‘nalganligi. (10) model real muhitdagi interferensiya yo‘qolishini, (11)–(12) esa seziladigan vaqt oqimini axborot-statistik asosga bog‘laydi. Tajribada buning ko‘rinishi barqarorlik, drift va sistematik terminlari orqali namoyon bo‘ladi; shunday qilib, vaqtni his qilish mexanizmlari metrologik ravishda kuzatiladigan kattaliklar bilan tutashadi [7–8].

Ilovalar va istiqbollar. Transportabel soatlar vulkan, suv resurslari, qobiq zichligi monitoringida sezgirlikni yangi darajaga olib chiqadi [16], [18]. Global soat tarmoqlari yangi fizika izlash (qorong‘i materiya bilan kuchsiz bog‘lanishlar, vaqtinchalik modulyatsiyalar) va chastota domenida gravitatsion to‘lqin deteksiyasi uchun o‘zaro to‘ldiruvchi platformadir [6], [20]. SI sekundning optik qayta ta’rifi bo‘yicha tashabbuslar ushbu yo‘nalishning pishib yetganligini ko‘rsatadi [2], [9–11], [19].

Kvant soatlar bilan mikro–makro bog‘liqlikning metrologik yakuni

Biz kvant vaqt o‘lchovlari orqali mikro–makro bog‘liqlikni yagona metrologik tilda namoyish etdik: GR redshift (2) va kvant faza (4–5) integratsiyasi faza-chastota o‘lchovlarida bevosita kuzatiladi (3-rasm); Allan og‘ishi va Dick effektini hisobga olgan shovqin modeli (6–9) bilan mm-sezgirlikka tushildi (2-rasm), (15) formuladagi miqyos bilan mos; dekogerensiya (10) hamda relatsion/termal vaqt ramlari (11–12) tajriba ko‘rsatkichlarining fizik talqinini beradi. Kelgusida $\sigma_y \lesssim 10^{-19}$ sinflarida differensial protokollar va global tarmoqlar kvant tuzatmalarni qidirish, relativistik geodeziya, kvant sensorika va fundamental testlarda yangi ufqlar ochadi [1–6], [9–11], [14–20].

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