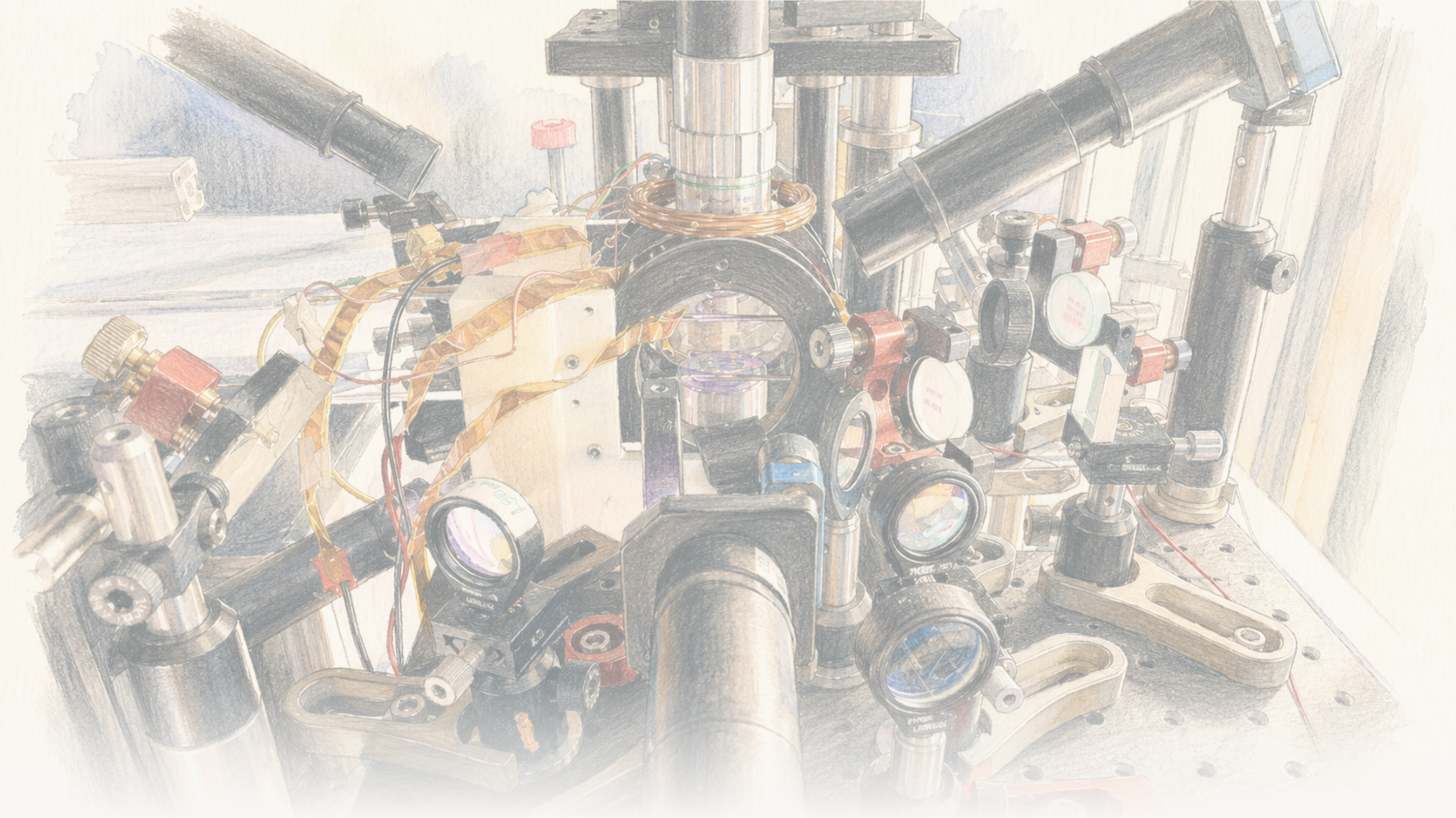

The Clean Paper

WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

Gwajin cold atoms yana gwada “problem of time” na quantum gravity — a matsayin laboratory analog, ba amsa ba

A canonical quantum gravity, Wheeler-DeWitt equation ba ta da external clock da zai jera events: “problem of time”. Wani experiment mai author guda ya isolate Bose-Einstein condensate, ya split shi da thin optical barrier zuwa unobserved da observed sector, sannan ya gina internal clock daga entropy da ke flow tsakanin su. Wannan “entropic time” yana order expansion da recollapse na observed sector, kuma effective equation tana reproduce measured data a low-barrier case da aka examine. Controlled testbed ne ga relational-time ideas: “big bang”, “big crunch” da “miniuniverse” analog labels ne ga trapped gas, ba real cosmology ba, kuma aikin ba ya claim ya solve problem of time ko quantum gravity.

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Agogon da aka gina daga entropy, a cikin tarko

A tsarin quantum gravity na canonical akwai wata matsala mai ban mamaki kuma mai taurin kai: babban equation ɗin tsarin ba ya ƙunshe da lokaci. Wheeler-DeWitt equation, wanda shi ne mafi kusa da Schrodinger equation ga dukan sararin samaniya, yana cewa kawai wani operator idan ya yi aiki a kan state ɗin tsarin sakamakon ya zama sifili. Babu wani external parameter da ke bugun lokaci, babu abin da zai tsara "kafin" da "bayan" - duk da haka mu kan ji lokaci yana wucewa. Wannan shi ake kira **problem of time**, kuma fiye da rabin ƙarni ba a samu cikakkiyar mafita ba.

Wata takarda mai marubuci guda ɗaya a *Physical Review Research* ba ta warware wannan matsala ba. Abin da ta yi ya fi ƙanƙanta, amma yana da amfani ta wata hanya: ta gina ƙaramin tsarin gwaji da ake iya sarrafawa sosai, inda za a iya **gwada da ainihin bayanai** ɗaya daga cikin ra'ayoyin da aka gabatar a matsayin mafita. Giovanni Barontini na University of Birmingham ya ɗauki wani Bose-Einstein condensate - gajimaren atoms masu matuƙar sanyi da ke aiki kamar quantum object guda ɗaya - ya mai da shi analogue inda za a iya auna ra'ayin lokaci na "ciki", ko relational time, maimakon tattauna shi kawai a ka'ida. Dabarar ita ce a gina agogo ba daga stopwatch na waje ba, sai daga entropy da tsarin yake musanyawa a cikin kansa.

Bambancin da ke tsakanin "analogue da ake sarrafawa na problem of time" da "masana physics sun warware lokaci" shi ne ainihin labarin nan - kuma bambancin yana da girma sosai.

Abin da mai binciken ya yi

Na'urar gwajin ta ƙunshi condensate na kusan **24,000 rubidium-87 atoms** da aka riƙe a cikin conservative optical dipole trap, sannan aka sa dukan gajimaren atoms ɗin yana motsi gaba da baya a cikin tarkon. Wani **siririn optical barrier** - faɗinsa kusan microns 8, an zana shi da haske mai 675 nm ta amfani da digital micromirror device - ya raba tarkon gida biyu. Ana lura da rabin ɗaya ("**bright sector**"); ɗayan kuma ba a lura da shi ("**dark sector**"). A cikin taga ta gwaji ta kusan milliseconds 100, ba a ga asarar particles ko dissipation da za a iya aunawa ba. Saboda haka, a kusanci mai kyau, tsarin rufaffe ne kuma Hamiltonian ɗinsa ba ya dogara da lokaci da kansa.

[figure_pair pending]

A hagu, magneto-optical trap yana samar da gajimaren rubidium atoms masu sanyi a cikin glass cell: wannan mataki ne na farko na sanyaya kafin a shirya condensate. A dama, Giovanni Barontini yana tsaye kusa da optical apparatus. Waɗannan hotunan tsarin gwaji ne a dakin bincike, ba hotunan wani ƙaramin sararin samaniya na zahiri ba.

Idan aka lura da bright sector ta agogon dakin gwaji na yau da kullum - absorption image ɗaya a kowane 2 ms - ana ganin wani yanayi mai kama da labarin cosmology. Atoms suna ketare barrier, sector ɗin ya fara daga babu komai (Barontini ya kira wannan lokacin "**big bang**"), ya kai mafi girman faɗi, sannan ya sake matsewa ya zube zuwa dark side ("**big crunch**"). Gwargwadon tsayin barrier, wannan zagayowar na iya maimaituwa.

Sai a nan ne muhimmin batu ya shigo. Agogon dakin gwaji yana *waje* da tsarin - daidai irin abin da tsarin Wheeler-DeWitt ba ya ba da dama a yi amfani da shi. Don haka Barontini ya tambaya: shin za a iya **tsara tarihin bright sector ta amfani da quantities da suke cikin tsarin kawai**? Amsarsa ita ce agogon da ya kira **entropic time**, wanda ake fitarwa kai tsaye daga hotuna ta matakai uku. Na farko, daga kowane absorption image yana fitar da lambobi huɗu na bright sector: yawan atoms, center of mass na density profile ɗinsa (wanda ke taka rawar analogue na "scalar field"), faɗinsa, da entropy ɗinsa - entropy per atom da aka samu ta hanyar da aka saba amfani da ita, sannan aka ninka da yawan atoms. Na biyu, yayin da atoms ke ketare barrier, entropy ɗin yana ƙaruwa ko raguwa. Na uku, agogon yana bin entropy gradient tare da hanyar center of mass da aka auna, yana ƙirga girman kowane displacement maimakon alkiblarsa. Idan entropy da center of mass suna ƙaruwa tare ko suna raguwa tare, kowane mataki yana ciyar da agogon gaba ko da gajimaren ya juya ya koma baya. A bayanan gwajin, wannan ya ba da tsari guda ɗaya daga "big bang" na sector zuwa "big crunch" kusan ko'ina, sai 'yan ƙananan tangarɗa inda ƙarancin yawan samples ya sa canje-canjen biyu suka ɗan saba wa juna.

A ƙarshe, ya samo wani effective **"entropic-time Schrodinger equation"** - equation na evolution na bright sector da aka rubuta da wannan agogon cikin tsarin maimakon agogon waje - sannan ya warware shi ta hanyar numerical calculation don ganin ko zai sake samar da abin da kamara ta auna a zahiri.

Abin da aka gano

Akwai sakamako uku, daga mafi sauƙi zuwa mafi girman da'awa.

- **Agogon cikin tsarin yana aiki wajen tsara abubuwan da suka faru.** Entropic time yana ƙaruwa a hanya guda kusan ko'ina, kuma saurin tafiyarsa yana dogara da yadda entropy ke ketare barrier: yana sauri idan ana musayar entropy, kuma **yana tsaya gaba ɗaya idan babu musayar entropy**. A reversible, low-barrier regime, *babu internal time da ke wucewa kwata-kwata* tsakanin big crunch da big bang na gaba - saboda babu entropy da ake musanyawa a wannan lokacin - ko da yake agogon dakin gwaji yana ci gaba da tafiya. A dukkan dataset, jimillar entropy na sectors biyu tare ta tsaya daidai cikin error bars, kamar yadda ake tsammani ga tsarin rufaffe.
- **Regimes daban-daban suna ba da "lokuta" daban-daban.** Idan aka ɗaga barrier, musayar entropy tana raguwa, saboda haka agogon cikin tsarin yana tafiya a hankali. Idan aka kai inda sectors biyu kusan ba sa hulɗa, bright sector yana kusantar yanayin da takardar ta kira "**heat death**": stationary state inda entropic time ya tsaya kawai.
- **Wani effective equation yana sake samar da bayanan gwajin.** Entropic-time Schrodinger equation, idan aka ba shi parameters na gwajin, yana iya sake samar da evolution da aka auna na faɗin gajimaren ta numerical calculation. Takardar ta rahoto daidaito mai kyau sosai a low-barrier case (inda ɓangaren da entropy ke tukawa ya fi rinjaye); wannan ne case ɗin da aka yi explicit numerical comparison a kai.

> **Menene "problem of time", kuma menene "entropic time" a nan?**
>
> **Problem of time** shi ne cewa babban equation na canonical quantum gravity (Wheeler-DeWitt) ba shi da external time variable. Wata amsa da aka saba bayarwa ita ce *relational*: a ɗauki wani physical quantity da ke cikin tsarin a matsayin "agogo", sannan a bayyana sauran abubuwa dangane da shi. Matsala mai maimaituwa ita ce natural clock choices ba koyaushe suke tafiya a hanya guda ba - tsarin da ya faɗaɗa sannan ya sake rushewa zai sa clock candidate ɗin ya fara tafiya gaba sannan ya koma baya - don haka ba zai iya lakafta alkibla guda daga farko zuwa ƙarshe ba.

> **Entropic time** ita ce hanyar Barontini ta kauce wa wannan matsalar. Maimakon karanta wani variable mai kama da position, ya gina agogon daga *entropy* da ake musanyawa tsakanin observed da unobserved sectors, ta hanyar da aka tsara kada ya koma baya. Ra'ayin yana da kusanci a ruhu da tsofaffin "thermal time" ideas, amma a nan an bayyana shi operationally daga entropy flow da za a iya aunawa, maimakon daga abstract mathematical structure - wannan ne ya sa za a iya gwada shi da ainihin apparatus.
> Muhimmin abu: kalmomin cosmology - "big bang", "big crunch", "scale factor", "scalar field", "miniuniverse" - **sunaye ne na analogue**. Ana amfani da su ne don wasu siffofi na gajimaren atoms da aka kama a tarko waɗanda equations ɗinsu suke da kama ta tsari da na simplified cosmological models. Ba magana ake yi game da ainihin sararin samaniya ba.

Abin da wannan bai tabbatar ba

A nan ne taka-tsantsan ya fi muhimmanci, domin kalmomin da ake amfani da su suna iya sa a wuce gona da iri.

- **Bai warware problem of time ba, kuma takardar ba ta yi wannan da'awar ba.** Takardar ta bayyana abin da ta yi a matsayin kafa wani controlled experimental setting inda za a iya quantitatively test relational-time constructions. Testbed ba theorem ba ne. Ko relational time ko entropic time shi ne *daidai* bayanin lokaci a quantum gravity ya ci gaba da zama buɗaɗɗiyar tambaya.
- **Analogue ne, ba sararin samaniya ba.** Ba a lura da cosmology a nan. Ana lura da Bose-Einstein condensate a cikin tarko, kuma reduced description ɗinsa yana da *mathematical similarity* da simplified ("minisuperspace") cosmological model. Wannan kamanceceniya ita ce manufar gwajin; ita ce kuma iyakarsa. Babu abin da ke nuna cewa farkon sararin samaniya ya yi big bang irin wannan, cewa spacetime an gina shi da atoms, ko cewa "lokaci ba ya wanzu."
- **Bai nuna cewa lokaci a zahiri entropy ne ba.** Entropic clock ɗin wani constructed ordering ne da ke aiki da kyau a wannan tsarin. Takardar ta ambaci kusanci na ra'ayi da thermal-time hypothesis, amma ta bar a buɗe ko ma su biyun sun yi daidai. "Agogon cikin tsarin da aka gina daga entropy na iya tsara wannan gwajin" ƙaramin da'awa ce idan aka kwatanta da "lokaci entropy ne."
- **Effective equation ɗin sakamakon modeling ne, ba sake rubuta quantum mechanics ba.** Entropic-time Schrodinger equation da aka samo yana komawa zuwa ordinary quantum mechanics idan entropy flow ya yi jinkiri, kuma yana zama daidai usual unitary theory ne kawai idan babu entropy flow kwata-kwata. Takardar ta gabatar da shi a matsayin wanda ya fi standard equation faɗi *musamman idan observed system yana thermodynamically open ga unobserved one* - magana ce game da open subsystems a irin wannan setup, ba da'awar cewa fundamental physics dole ne a sake rubuta shi haka ba.
- **Gwaji guda ɗaya ne, marubuci guda ɗaya, da clock choice guda ɗaya.** Sakamakon yana da kusan 5% statistical uncertainty ga kowane point, kuma yana dogara da mean-field da averaged-density approximations. Zaɓin agogo da coarse-graining shawarwari ne na modeling da sauran ƙungiyoyi za su so su gwada kafin a fitar da manyan structural conclusions.

Yaya ƙarfin shaidar yake?

Ga ƙaramar da'awar da takardar take yi a zahiri, shaidar tana da tsabta. Tsarin ya kasance isolated sosai a timescale da ya dace; lissafin entropy ya rufe (jimillar entropy ta tsaya constant cikin error); agogon cikin tsarin ya tsara bayanai monotonically kusan ko'ina; kuma effective equation da marubucin ya samo daga samfurin, da parameters da aka inferred daga bayanan gwaji, ya sake samar da dynamics da aka auna a low-barrier case da aka yi amfani da shi a kai. Bayanai kuma suna samuwa a buɗe. Wannan ainihin ma'auni ne na ainihin tsarin da ake iya sarrafawa, ba thought gwaji ba.

Amma nauyin da shaidar za ta iya ɗauka yana daidai da wannan ƙaramar da'awar. Komai yana dogara da analogy tsakanin reduced condensate model da minisuperspace cosmology, kuma analogies suna taimakawa wajen fahimta amma ba sa tabbatarwa. Platform guda ɗaya, daga marubuci guda ɗaya, da ya nuna cewa internal-time recipe guda ɗaya yana aiki, hujja ce mai ƙarfi ta proof of principle amma tushe ne mai rauni ga kowace babbar da'awa game da yadda lokaci yake a cikin yanayi. Karatun da ya dace shi ne: yanzu wannan hanya ta zama abin da za a iya *yi* a dakin gwaji kuma a duba ko tana aiki.

Me ya sa wannan yake da muhimmanci?

Tattaunawa game da problem of time ta daɗe tana makale a matakin formalism, inda competing proposals suke da wahalar falsification saboda suna samar da kaɗan daga cikin concrete, measurable hasashe. Juya ko da wani ƙaramin ɓangare na wannan muhawara zuwa gwajin da za a iya gudanarwa - inda internal clock ko dai ya tsara bayanai ko bai tsara ba, inda effective equation ko dai ya dace da bayanai ko bai dace ba - yana sauya yanayin muhawarar. Yana ba theorists wani bench na gwaji da za su iya gwada kayan aikinsu a kai.

Wannan shi ne ainihin gudummawar: ba amsa game da lokaci ba, sai dai **wurin da za a iya tambayar tambayar da lambobi da gwaji**. Cold-atom platforms sun riga sun zama controllable analogs don Hawking radiation, expanding universes, da false-vacuum decay; wannan aikin ya ƙara relational time da arrow of time cikin wannan toolbox. Muhimmancinsa yana cikin follow-up gwaje-gwaje da zai ba da dama - clock choices daban-daban, bouncing versus singular behavior, tests of reversibility - kowanne yanzu yana iya zama ma'auni maimakon calculation kawai.

Takaitaccen bayani

Wani physicist ya gina Bose-Einstein condensate, ya raba shi da siririn optical barrier zuwa rabin da ake lura da shi da rabin da ba a lura da shi, sannan ya yi amfani da entropy da ke gudana tsakanin rabin biyu don gina internal "entropic time." Wannan agogon yana tsara zagayowar faɗaɗawa da sake rushewar observed half, yana tafiya da sauri idan ana musayar entropy kuma yana tsayawa idan babu musayar entropy. Wani effective equation da aka rubuta da wannan internal time kuma ya sake samar da measured bayanai a low-barrier case da marubucin ya bincika. Setup ɗin analogue ne na "problem of time" daga canonical quantum gravity: "big bang", "big crunch", da "miniuniverse" sunaye ne ga trapped gas wanda lissafinsa yake da kama da simplified cosmological model. Wannan controlled testbed ne don relational-time ideas - ba mafita ga problem of time ba, ba da'awa game da ainihin sararin samaniya ba, kuma ba shaida cewa lokaci a zahiri "entropy" ne ba.

Binciken ba tare da ƙarin hayaniya ba

Abin da takardar ta nuna: A cikin wani well-isolated cold-atom system guda ɗaya, internal clock da aka bayyana daga entropy exchange zai iya tsara observed dynamics a hanya guda kusan ko'ina, kuma effective "entropic-time" equation yana sake samar da measured evolution a low-barrier case da aka bincika.

Abin da yake da yiwuwa amma ba a nuna ba: Cewa entropic ko relational time kyakkyawan bayani ne na lokaci a ainihin quantum gravity. Gwajin yana dacewa da ɗaukar irin waɗannan constructions da muhimmanci; bai tabbatar da su ga yanayi ba.

Abin da bai nuna ba: Cewa problem of time ya warware; cewa quantum gravity ta samu mafita; cewa sararin samaniya ya fara da big bang irin wannan; cewa spacetime ya fito daga atoms; ko cewa "lokaci ba ya wanzu."

Manyan iyakoki: Platform guda ɗaya, marubuci guda ɗaya, clock choice guda ɗaya; kusan 5% uncertainty ga kowane point; mean-field da averaged-density approximations; kuma sama da komai, dogaro da analogy tsakanin trapped condensate da simplified cosmological model.

Yaya yawan amincewar da mai karatu na yau da kullum ya kamata ya yi? Babba cewa gwajin ya yi abin da ya rahoto a cikin nasa tsarin. Ƙarami ga duk wani tsalle daga wannan analogue zuwa da'awa game da lokaci a ainihin sararin samaniya.

Majiyoyi

Barontini, Testing the problem of time with cold atoms, Physical Review Research 8, L022047 (2026)
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