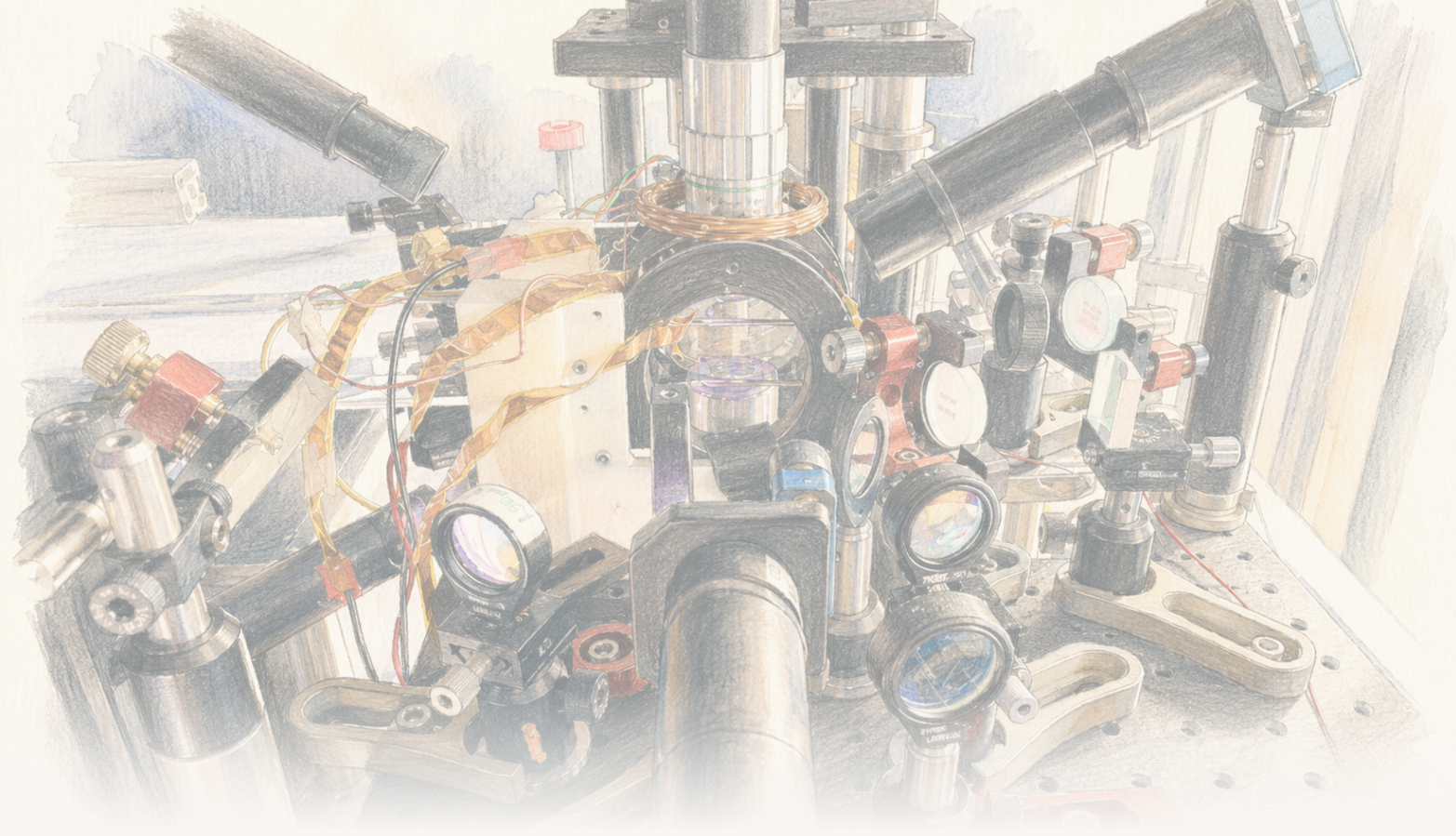




The CLEAN PAPER

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Cold-atom experiment kan test ‘problem of time’ quantum gravity — gégé bí laboratory analog, kì í ẹ answer

Nínú canonical quantum gravity, Wheeler-DeWitt equation kò ní external clock láti sequence event: ‘problem of time’. Single-author experiment kan isolate Bose-Einstein condensate, pin rẹ pẹlú thin optical barrier sí unobserved àti observed sector, ó sì build internal clock láti entropy tí ń flow láàárín wọn. ‘Entropic time’ yẹn order expansion àti recollapse observed sector, effective equation sì reproduce measured data nínú low-barrier case examined. Ó jẹ controlled testbed fún relational-time idea: ‘big bang’, ‘big crunch’ àti ‘miniuniverse’ jẹ analog label fún trapped gas, kì í ẹ real cosmology, iṣẹ náà kò sì claim láti solve problem of time tàbí quantum gravity.

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Paper: *Testing the problem of time with cold atoms*, Giovanni Barontini, Physical Review Research 8, L022047 (2026) · DOI: 10.1103/1h9j-df4k

Clock tí a kọ láti entropy, nínú trap

Nínú canonical quantum agbára walè, puzzle kan wà tó yà, tó sì stubborn: central equation kò ní àkókò nínú rẹ. Wheeler-DeWitt equation, ohun tó sunmọ Schrodinger equation jù fún gbogbo àgbáyé, kan sọ pé operator kan tí ó ọ̀ṣiṣẹ́ lórí ipò fún zero. Kò sí external parameter tó ní tick, kò sí ohun tó sequence “ṣáájú” àti “lẹ́yìn” — síbẹ̀ a experience àkókò passing kedere. Èyí ni **ìṣòro of àkókò**, ó sì ti resist resolution fún ju half century lọ.

Single-author ìwé ìwádìí nínú *Physical Review Research* kò resolve rẹ. Ohun tí ó ẹ̀ jẹ́ quieter, ó sì wúlò ní ọ̀nà tírẹ̀: ó kọ small, well-controlled yàrá ìdánwò ètò níbí tí family kan ti proposed answer lè jẹ́ **tested against gidi dátà**. Giovanni Barontini, ní University of Birmingham, gba Bose-Einstein condensate — cloud ultracold atom tí ní behave gégé bí single quantum object — ó sì yí i sí analog níbí tí idea “internal”, relational àkókò lè jẹ́ measured dípò argued. Trick ni láti kọ clock kì í ẹ̀ láti outside stopwatch, ẹ̀gbón láti entropy tí ètò ní shuffle nínú ara rẹ.

Distance láàárín “controlled analog of ìṣòro of àkókò” àti “physicist solved àkókò” ni whole ìtàn níbí, ìjìnnà náà sì gùn.

Ohun tí olùwádìí ẹ̀

Apparatus jẹ́ condensate nìkan bí **24,000 rubidium-87 atoms** tí a hold nínú conservative optical dipole trap, tí a sì set oscillating — gbogbo atom cloud ní slosh padà-síwájú kojá trap. **Thin optical barrier** — roughly 8 microns wide, painted pẹ̀lú 675 nm light ní lílo digital micromirror device — pin trap sí half méjì. Half kan ni a watch (“**bright sector**”); omíni kì í jẹ́ watched (“**dark sector**”). Kojá roughly 100-millisecond window ìdánwò, ètò kò fi hàn measurable particle loss tàbí dissipation, nítorí náà, sí good approximation, ó jẹ́ closed ètò pẹ̀lú Hamiltonian tí fúnra rẹ kò depend on àkókò.

[figure_pair pending]

Ní ọ̀sì, magneto-optical trap produce cold cloud rubidium atom nínú glass ẹ̀ẹ̀lì: early cooling stage lórí ọ̀nà sí preparing condensate. Ní ọ̀tún, Giovanni Barontini dúró lẹ́gbẹ́ optical apparatus. Àwọn yíi jẹ́ photo yàrá ìdánwò ètò lẹ́yìn ìdánwò, kì í ẹ̀ image literal miniature àgbáyé.

Tí a bá watch pẹ̀lú ordinary yàrá ìdánwò clock — absorption image every 2 ms — bright sector ẹ̀ ohun tó evocative. Atom flow kojá barrier, sector ní grow láti nothing (Barontini label moment yíi “**big bang**”), ó dé maximum extent, lẹ́yìn náà contract, ó sì empty padà sí dark side (“**big crunch**”). Gégé bí barrier height ẹ̀ rí, èyí lè repeat cyclically.

Lẹ́yìn náà ni actual kókó. Laboratory clock jẹ́ *external* sí ètò — exactly irú ohun tí Wheeler-DeWitt setting forbid. Nítorí náà Barontini beèrè: ẹ̀ history bright sector lè jẹ́ **ordered ní lílo quantity internal sí ètò nìkan**? Answer rẹ jẹ́ clock tí ó pe ní **entropic àkókò**, tí a ka taara láti kan náà image nínú step rọ̀rùn méta. First, láti absorption image kòòkan ó extract nǫ́nbà mérin fún bright sector: atom number rẹ, center of mass density profile rẹ (tí ó play role analog “scalar field”), width rẹ, àti entropy rẹ — entropy per atom, obtained ní standard ọ̀nà, multiplied pẹ̀lú atom number. Second, bí atom ẹ̀ ní cross barrier, entropy yèn rise àti fall. Third, clock tẹ̀lẹ́ entropy gradient lẹ́gbẹ́ measured center-of-mass path, counting magnitude displacement kòòkan dípò ìtọ̀sọ̀nà rẹ. Nígbà tí entropy àti center of mass rise tàbí fall together, step kòòkan advance clock kódà nígbà tí cloud reverse. Nínú dátà, èyí fún single ordering láti sector “big bang” sí “big crunch” almost everywhere, pẹ̀lú few small wiggle níbí tí coarse

sampling mú change méjèèjì disagree.

Nígbà ikẹhin, ó derive effective “**entropic-time Schrodinger equation**” — evolution equation fún bright sector tí a kọ ní terms internal clock yí dípò external ọkan — ó sì solve rẹ numerically láti wo bóyá ó reproduce ohun tí camera àkọsílẹ gangan.

Ohun tí wọn rí

èsi mètá, ní increasing order ambition.

- **Internal clock ọ́ṣẹ gégẹ bí ordering.** Entropic àkókò grow monotonically almost everywhere, speed rẹ sì set nípasẹ bí entropy ẹ ní cross barrier yára tó: ó ní run faster nígbà tí entropy exchanged, ó sì **stop entirely nígbà tí kò sí exchange**. Nínú reversible, low-barrier regime, *no internal àkókò passes at gbogbo láàárín* big crunch àti next big bang — nítorí no entropy exchanged níbẹ — bí yàrá ìdánwò clock tilẹ keep ticking. Kojá whole dataset, total entropy sector méjèèjì together stay constant nínú àṣṣe bars, gégẹ bí closed ètò require.
- **Different regime fún yàtò “àkókò”.** Turn barrier up, entropy exchange shrink, internal clock run slower. Push rẹ sí kókó níbi tí sector méjèèjì barely talk, bright sector settle toward ohun tí ìwé ìwádíí pe ní “**heat death**”: stationary ipò níbi tí entropic àkókò simply halt.
- **Effective equation reproduce dátà.** Entropic-time Schrodinger equation, fed experimental parameter, numerically recover measured evolution cloud width, pẹlú ìwé ìwádíí reporting excellent agreement fún low-barrier ọ̀ràn (níbi tí entropy-driven term dominate); explicit numerical ifiwéra ni a ẹ fún ọ̀ràn yẹn.

Kí ni “problem of time”, kí sì ni “entropic time” níbi?

Ìṣòro of àkókò ni pé master equation canonical quantum agbára walẹ (Wheeler-DeWitt) kò ní external àkókò variable. Common ìdáhùn kan jẹ *relational*: promote physical quantity kan nínú ètò sí “clock”, kí a sì describe gbogbo nkan mǐràn relative sí i. Recurring difficulty ni pé natural clock choice kì í always monotonic — recollapsing ètò ní run candidate clock forward, lẹyìn nàà backward — nítorí nàà kò lè cleanly label single ìtọ́sọ̀nà láti start sí finish.

Entropic àkókò ni Barontini’s way around that. Dípò reading position-like variable, ó build clock láti *entropy* exchanged láàárín observed àti unobserved sector, constructed kí ó má reverse. Ó close in spirit sí older “thermal àkókò” idea, ẹ̀gbọ̀n níbi ó defined operationally láti measurable entropy flow dípò abstract mathematical ìṣètò — exactly ohun tí ó mú un testable lórí gidi apparatus.

Crucially, cosmological words — “big bang”, “big crunch”, “scale factor”, “scalar field”, “miniuniverse” — jẹ **analog label**. Wọn name àbùdá trapped gas atom tí ó happen to be *structurally similar* sí equation simplified cosmological àwòṣe. Wọn kì í ẹ statement nípa actual àgbáyé.

Ohun tí èyí kò fi hàn

Níbi yí care ẹ pàtàkì jù, nítorí vocabulary invite overreach.

- **Kò solve ìṣòro of àkókò, kò sì claim bèè.** Framing ìwé ìwádíí fúnra rẹ̀ ni pé ó “establish controlled experimental setting níbi tí relational-time construction lè quantitatively tested.” Testbed kì í ẹ̀se theorem. Bóyá relational tàbí entropic àkókò ni *right* account àkókò nínú quantum agbára walẹ̀ ẹ̀si open exactly bí ó ti rí ẹ̀sáájú.
- **Ó jẹ analog, kì í ẹ̀se àgbáyé.** Kò sí cosmology tí a ní observe. Bose-Einstein condensate nínú trap ni a observe, reduced description rẹ̀ sì *mathematically similar* sí simplified (“minisuperspace”) cosmological àwòṣe. Similarity ni kókó ìdánwò; ó tún jẹ ààlà rẹ̀. Kò sí nkan níbi tó fi hàn pé early àgbáyé ní big bang irú yí, pé spacetime made of atom, tàbí pé “àkókò does not exist.”
- **Kò fi hàn pé àkókò jẹ ‘really’ entropy.** Entropic clock jẹ constructed ordering kan tó ẹ̀ṣe well lórí ètò yí. ìwé ìwádíí note conceptual kinship pẹ̀lú thermal-time hypothesis, ẹ̀ṣẹ̀bón ó explicitly leave open bóyá méjèèjì even coincide. “Internal clock built láti entropy lè order this ìdánwò” jẹ claim tó narrower púpò ju “àkókò is entropy.”
- **Effective equation jẹ modeling èsì, kì í ẹ̀se rewrite quantum mechanics.** Derived entropic-time Schrodinger equation dín kù sí ordinary quantum mechanics nígbà tí entropy flow slow, ó sì strictly usual unitary àbá-ẹ̀kọ̀ nìkan nígbà tí no entropy flows. ìwé ìwádíí position rẹ̀ as sí i gbogbogbò than standard equation *specifically when observed ètò is thermodynamically open to an unobserved ọ̀kan* — statement nípa open subsystem nínú irú setup yí, kì í ẹ̀se claim pé fundamental physics gbọ̀dọ̀ rewritten así.
- **Experiment kan, ònṁkòwé kan, clock choice kan.** èsì ní roughly 5% per-point statistical uncertainty, wọn sì lean on mean-field àti averaged-density approximation. Chosen clock àti coarse-graining jẹ deliberate modeling decision, irú ohun tí egbẹ̀ mǐràn yóò fẹ̀ probe ẹ̀sáájú drawing structural conclusion.

Báwo ni ẹ̀rí nàà ẹ̀se lágbára tó?

Fún modest thing tí ó claim gangan, ẹ̀rí clean. System genuinely well isolated lórí relevant timescale, entropy bookkeeping close (total entropy constant nínú àṣiṣe), internal clock order dátà monotonically almost everywhere, effective equation kan, derived nipasẹ̀ ònṁkòwé láti kan nàà àwòṣe pẹ̀lú parameter inferred láti dátà, reproduce measured dynamics fún low-barrier ọ̀ràn tí a apply sí. dátà openly available. Èyí jẹ gidi measurement ti gidi, controllable ètò, kì í ẹ̀se ìdánwò inú-rònú.

Weight tí ó lè ru correspondingly modest. Gbogbo nkan rest on analogy láàárín reduced condensate àwòṣe àti minisuperspace cosmology, analogy sì illuminate láisí proving. Single platform, láti single ònṁkòwé, showing ọ̀kan internal-time recipe works jẹ lágbára proof of principle àti weak basis fún claim nípa bí àkókò behaves nínú nature. Right reading ni: ọ̀nà báyi jẹ nkan tí o lè *do* nínú lab, kí o sì check.

Ìdí tí ó fi ẹ̀se pàtàkì

Debate nípa ìṣòro of àkókò ti pẹ̀ stuck ní ìpele formalism, níbi tí competing proposal ṣòro láti falsify nítorí wọn make few concrete, measurable prediction. Yíyí apá kan ti debate yẹn sí ìdánwò tí o lè run — níbi tí internal clock either order dátà rẹ̀ tàbí kò ẹ̀se, níbi tí effective equation either fit tàbí kò fit — yí character argument padà. Ó fún theorist ní bench láti ìdánwò machinery wọn.

Èyí ni genuine contribution: kì í ẹ̀se answer nípa àkókò, ẹ̀ṣẹ̀bón **ibi láti béèrè ibèèrè nàà quantitatively**. Cold-atom

platform ti tẹlẹ serve gégé bí controllable analog fún Hawking radiation, expanding àgbáyé àti false-vacuum decay; èyí add relational àkókò àti arrow of àkókò sí toolbox yẹn. Value wà nínú follow-up tí ó enable — yàtò clock choice, bouncing versus singular ìhùwàsí, ìdánwò reversibility — ọkọọkan bá yí measurement dí pò calculation nìkan.

Àkótán mímó

Physicist kan kọ Bose-Einstein condensate, pin rẹ pẹlú thin optical barrier sí observed àti unobserved half, ó sì lo entropy tí ní flow láàárín half méjèèjì láti construct internal “entropic àkókò.” Clock yẹn order expansion-and-recollapse cycle observed half, running fast nígbà tí entropy exchanged, stopping nígbà tí kò sí exchange, effective equation tí a kọ nínú internal àkókò yí sì reproduce measured dátà nínú low-barrier ọràn tí òhàkòwé examine. Setup jẹ analog ti “ìṣòro of àkókò” láti canonical quantum agbára walẹ: “big bang,” “big crunch,” àti “miniuniverse” jẹ label fún trapped gas tí mathematically similar sí simplified cosmological àwòṣe. Ó jẹ controlled testbed fún relational-time idea — kì í ṣe solution ìṣòro of àkókò, kì í ṣe claim nípa gidi àgbáyé, kò sì ṣe ẹrí pé àkókò jẹ “really” entropy.

àyèwò láìsí àṣodùn

Ohun tí iwé iwádìí náà fi hàn: Nínú ọkan well-isolated cold-atom ètò, internal clock defined láti entropy exchange lè monotonically order observed dynamics, effective “entropic-time” equation sì reproduce measured evolution nínú low-barrier ọràn examined.

Ohun tí ó ṣeé gbà ṣùgbọ́n kò shown: Pé entropic tàbí relational àkókò jẹ good account àkókò nínú gidi quantum agbára walẹ. Experiment consistent pẹlú taking such construction seriously; kò confirm wọn fún nature.

Ohun tí kò fi hàn: Pé ìṣòro of àkókò solved; pé quantum agbára walẹ resolved; pé àgbáyé began nínú big bang irú yí; pé spacetime emergent láti atom; tàbí pé “àkókò does not exist.”

Àwọn ààlà pàtàkì: Single platform, single òhàkòwé, single clock choice; roughly 5% per-point uncertainty; mean-field àti averaged-density approximation; àti, ju gbogbo rẹ lọ, reliance lórí analogy láàárín trapped condensate àti simplified cosmological àwòṣe.

Ìgboyà mélóó ni olùkà gbogbogbòò yẹ kí ó ní? Ìgboyà gígá pé ìdánwò ṣe ohun tí ó report lórí own ètò. Ìgboyà kéré fún leap kankan láti analog yí sí claim nípa àkókò nínú gidi àgbáyé.

Àwọn orísun

Barontini, Testing the problem of time with cold atoms, Physical Review Research 8, L022047 (2026)
<https://doi.org/10.1103/1h9j-df4k>