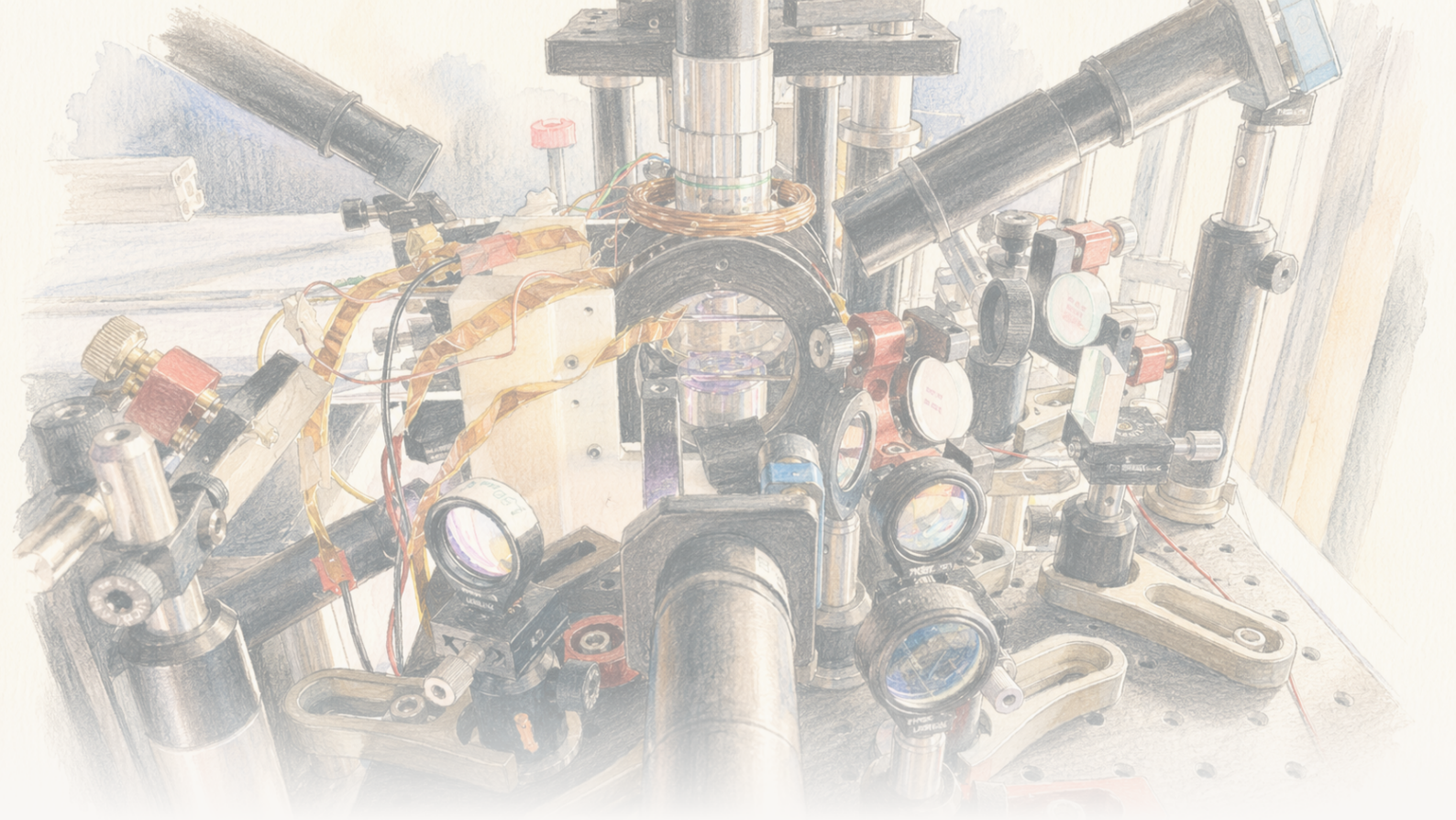

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# Cold-atom experiment kan test ‘problem of time’ quantum gravity — gẹ́gẹ́ bí laboratory analog, kì í ṣe answer

*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 rẹ̀ pẹ̀lú 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 jẹ́ controlled testbed fún relational-time idea: ‘big bang’, ‘big crunch’ àti ‘miniuniverse’ jẹ́ analog label fún trapped gas, kì í ṣe real cosmology, iṣẹ́ 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 walẹ, puzzle kan wà tó yà, tó sì stubborn: central equation kò ní àkókò nínú rẹ̀. Wheeler-DeWitt equation, ohun tó sunmọ́ Schrodinger equation jù fún gbogbo àgbáyé, kan sọ pé operator kan tí ó ṣiṣẹ́ lórí ipò fún zero. Kò sí external parameter tó ń 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 rẹ̀. Ohun tí ó ṣe jẹ́ quieter, ó sì wúlò ní ọ̀nà tirẹ̀: ó kọ small, well-controlled yàrá ìdánwò ètò níbi 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 ń behave gẹ́gẹ́ bí single quantum object — ó sì yí i sí analog níbi tí idea "internal", relational àkókò lè jẹ́ measured dípò argued. Trick ni láti kọ clock kì í ṣe láti outside stopwatch, ṣùgbọ́n láti entropy tí ètò ń shuffle nínú ara rẹ̀.

Distance láàárín "controlled analog of ìṣòro of àkókò" àti "physicist solved àkókò" ni whole ìtàn níbí, ijìnnà náà sì gùn.

# Ohun tí olùwádìí ṣe

Apparatus jẹ́ condensate nǹkan bí **24,000 rubidium-87 atoms** tí a hold nínú conservative optical dipole trap, tí a sì set oscillating — gbogbo atom cloud ń slosh padà-síwájú kọjá 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**"); omíì kì í jẹ́ watched ("**dark sector**"). Kọjá 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 rẹ̀ kò depend on àkókò.

[figure_pair pending]

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

Tí a bá watch pẹ̀lú ordinary yàrá ìdánwò clock — absorption image every 2 ms — bright sector ṣe ohun tó evocative. Atom flow kọjá barrier, sector ń grow láti nothing (Barontini label moment yìí "**big bang**"), ó dé maximum extent, lẹ́yìn náà contract, ó sì empty padà sí dark side ("**big crunch**"). Gẹ́gẹ́ bí barrier height ṣe 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 béèrè: ṣé history bright sector lè jẹ́ **ordered ní lílo quantity internal sí ètò nìkan**? Answer rẹ̀ jẹ́ clock tí ó pe ní **entropic àkókò**, tí a ka taara láti kan náà image nínú step rọrùn mẹ́ta. First, láti absorption image kọ̀ọ̀kan ó extract nọ́ńbà mẹ́rin fún bright sector: atom number rẹ̀, center of mass density profile rẹ̀ (tí ó play role analog "scalar field"), width rẹ̀, àti entropy rẹ̀ — entropy per atom, obtained ní standard ọ̀nà, multiplied pẹ̀lú atom number. Second, bí atom ṣe ń cross barrier, entropy yẹn rise àti fall. Third, clock tẹ̀lé entropy gradient lẹ́gbẹ̀ẹ́ measured center-of-mass path, counting magnitude displacement kọ̀ọ̀kan dípò ìtọ́ṣọ́nà rẹ̀. Nígbà tí entropy àti center of mass rise tàbí fall together, step kọ̀ọ̀kan 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 níbi 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 yìí dípò external ọ̀kan — ó sì solve rẹ̀ numerically láti wo bóyá ó reproduce ohun tí camera àkọsílẹ̀ gangan.

# Ohun tí wọ́n rí

èsì mẹ́ta, ní increasing order ambition.

- **Internal clock ṣiṣẹ́ gẹ́gẹ́ bí ordering.** Entropic àkókò grow monotonically almost everywhere, speed rẹ̀ sì set nípasẹ̀ bí entropy ṣe ń cross barrier yára tó: ó ń 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 níbẹ̀ — bí yàrá ìdánwò clock tilẹ̀ keep ticking. Kọ̀já whole dataset, total entropy sector méjèèjì together stay constant nínú àṣìṣe bars, gẹ́gẹ́ bí closed ètò require.
- **Different regime fún yàtọ̀ “àkókò”.** Turn barrier up, entropy exchange shrink, internal clock run slower. Push rẹ̀ sí kókó níbi tí sector méjèèjì barely talk, bright sector settle toward ohun tí ìwé ìwádìí 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, pẹ̀lú ìwé ìwádìí reporting excellent agreement fún low-barrier ọ̀ràn (níbi tí entropy-driven term dominate); explicit numerical ìfiwéra ni a ṣe fún ọ̀ràn yẹn.

> **Kí ni “problem of time”, kí sì ni “entropic time” níbí?**
>
> **ìṣòro of àkókò** ni pé master equation canonical quantum agbára walẹ̀ (Wheeler-DeWitt) kò ní external àkókò variable. Common ìdáhùn kan jẹ́ *relational*: promote physical quantity kan nínú ètò sí “clock”, kí a sì describe gbogbo nkan mìíràn relative sí i. Recurring difficulty ni pé natural clock choice kì í always monotonic — recollapsing ètò ń run candidate clock forward, léyìn náà backward — nítorí náà kò lè cleanly label single ìtọ́ṣọ́nà 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, ṣùgbọ́n níbí 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” — jẹ́ **analog label**. Wọ́n name àbùdá trapped gas atom tí ó happen to be *structurally similar* sí equation simplified cosmological àwòṣe. Wọ́n kì í ṣe statement nípa actual àgbáyé.

# Ohun tí èyí kò fi hàn

Níbi yìí care ṣe pàtàkì jù, nítorí vocabulary invite overreach.

- **Kò solve ìṣòro of àkókò, kò sì claim bẹ́ẹ̀.** Framing ìwé ìwádìí fúnra rẹ̀ ni pé ó "establish controlled experimental setting níbi tí relational-time construction lè quantitatively tested." Testbed kì í ṣe theorem. Bóyá relational tàbí entropic àkókò ni *right* account àkókò nínú quantum agbára walẹ̀ ṣi open exactly bí ó ti rí ṣáájú.
- **Ó jẹ́ analog, kì í ṣe àgbáyé.** Kò sí cosmology tí a ń 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 jẹ́ ààlà rẹ̀. Kò sí nkan níbí tó fi hàn pé early àgbáyé ní big bang irú yìí, pé spacetime made of atom, tàbí pé "àkókò does not exist."
- **Kò fi hàn pé àkókò jẹ́ 'really' entropy.** Entropic clock jẹ́ constructed ordering kan tó iṣẹ́ well lórí ètò yìí. ìwé ìwádìí note conceptual kinship pẹ̀lú thermal-time hypothesis, ṣùgbọ́n ó explicitly leave open bóyá méjèèjì even coincide. "Internal clock built láti entropy lè order this ìdánwò" jẹ́ claim tó narrower púpọ̀ ju "àkókò is entropy."
- **Effective equation jẹ́ modeling èsì, kì í ṣe 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-ẹ̀kọ́ nìkan nígbà tí no entropy flows. ìwé ìwádìí 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 yìí, kì í ṣe claim pé fundamental physics gbọdọ̀ rewritten así.
- **Experiment kan, òǹkọ̀wé kan, clock choice kan.** èsì ní roughly 5% per-point statistical uncertainty, wọ́n sì lean on mean-field àti averaged-density approximation. Chosen clock àti coarse-graining jẹ́ deliberate modeling decision, irú ohun tí ẹgbẹ́ mìíràn yóò fẹ́ probe ṣáájú drawing structural conclusion.

# Báwo ni ẹ̀rí náà ṣe 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 àṣìṣe), internal clock order dátà monotonically almost everywhere, effective equation kan, derived nipasẹ̀ òǹkọ̀wé láti kan náà àwòṣe pẹ̀lú parameter inferred láti dátà, reproduce measured dynamics fún low-barrier ọ̀ràn tí a apply sí. dátà openly available. Èyí jẹ́ gidi measurement ti gidi, controllable ètò, kì í ṣe 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 láìsí proving. Single platform, láti single òǹkọ̀wé, showing ọ̀kan internal-time recipe works jẹ́ lágbára proof of principle àti weak basis fún claim nípa bí àkókò behaves nínú nature. Right reading ni: ọ̀nà báyìí jẹ́ nkan tí o lè *do* nínú lab, kí o sì check.

# Ìdí tí ó fi ṣe pàtàkì

Debate nípa ìṣòro of àkókò ti pẹ́ stuck ní ìpele formalism, níbi tí competing proposal ṣòro láti falsify nítorí wọ́n 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 ṣe, 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 ṣe answer nípa àkókò, ṣùgbọ́n **ibi láti béèrè ìbéèrè náà quantitatively**. Cold-atom

platform ti tẹlẹ serve gẹ́gẹ́ 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 — yàtọ̀ clock choice, bouncing versus singular ìhùwàsí, ìdánwò reversibility — ọkọọkan báyìí measurement dípò calculation nìkan.

# Àkótán mímọ́

Physicist kan kọ Bose-Einstein condensate, pin rẹ̀ pẹ̀lú thin optical barrier sí observed àti unobserved half, ó sì lo entropy tí ń 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 yìí sì reproduce measured dátà nínú low-barrier ọ̀ràn tí òǹkọ̀wé examine. Setup jẹ́ analog ti “ìṣòro of àkókò” láti canonical quantum agbára walẹ̀: “big bang,” “big crunch,” àti “miniuniverse” jẹ́ label fún trapped gas tí mathematically similar sí simplified cosmological àwòṣe. Ó jẹ́ controlled testbed fún relational-time idea — kì í ṣe solution ìṣòro of àkókò, kì í ṣe claim nípa gidi àgbáyé, kò sì ṣe èrí pé àkókò jẹ́ “really” entropy.

# àyẹ̀wò láìsí àsọdùn

**Ohun tí ìwé ìwádìí náà fi hàn:** Nínú ọ̀kan 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 ọ̀ràn examined.

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

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

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

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

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## Àwọn orísun

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