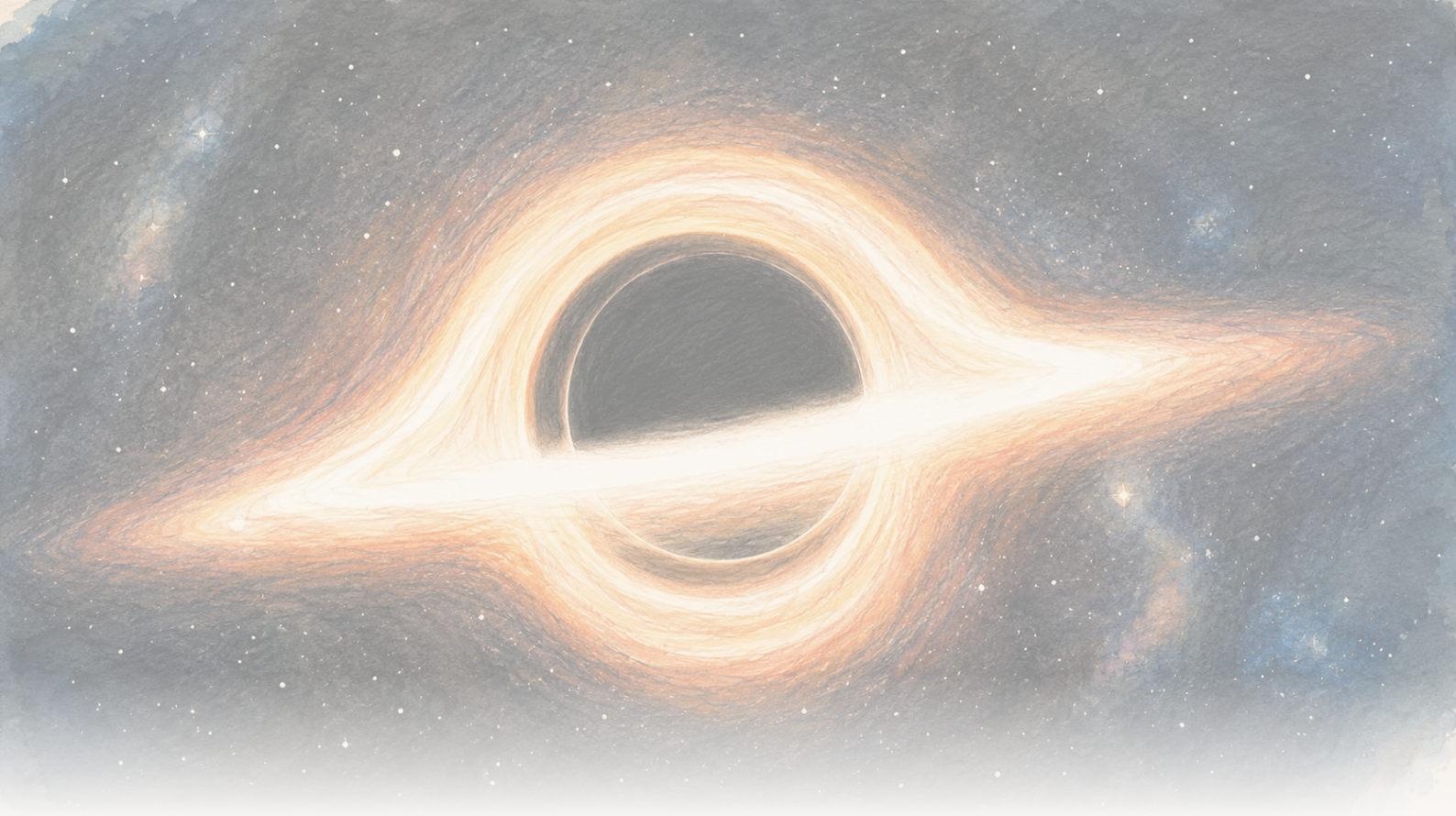




The CLEAN PAPER

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

Black holes seera thermodynamics hordofu — result
haaraan black holes equilibrium irraa violently
fagaatanitti seerota sana bal'isa

Bara 1970s irraa, black holes laws thermodynamics mirror godhan akka hordofan beekama, garuu version qulqulluun black holes equilibrium keessatti callisanii taa'an qofaaf hojjeta ture. Paper Physical Review Letters haaraan first fi second laws black holes saffisaan jijjiiraman — matter liqimsan, merge godhan, radiate godhan — tti locally defined 'dynamical horizons' fayyadamuun bal'isa. Physicists violently evolving black hole'f illee temperature fi entropy assign gochuu dan-deessisa. Kun mathematical result classical general relativity keessaa; quantum gravity haaraa miti, observation miti, black-hole information puzzle furmaata miti.

Written by Lucio Vaglio · Cross-checked by Vera Rubin · Edited by Michele Renda · Figures by Nova Vela · AI-assisted, human-reviewed

Paper: *Thermodynamics of Black Holes, Far from Equilibrium*, Abhay Ashtekar, Daniel E. Paraizo, Jonathan Shu, Physical Review Letters 136, 251405 (2026) · DOI: 10.1103/3c1r-v8f1

Gurraacha boollota “seera” teermoodaynaamikii fakkaatu qabu. Gosa qulqulluun isaa garuu yeroo homtuu hin ta’in qofa hojjeta ture.

Fiiziksii keessatti facts nama ajaa’iban keessaa tokko gurraacha boollota akka wanta ho’aa behave gochuu isaanii. Bara 1970s jalqabaa keessatti, Bekenstein fi Hawking equations gurraacha boollota to’atan term-by-term seerota teermoodaynaamikii waliin akka wal siman hubatan: gurraacha boolla entiroopii bal’ina horizonii isaa waliin proportional, ho’a immoo fuula gravity isaa waliin proportional qaba. Hawking sana booda ho’a kun hiika gadi fageenyaan dhugaa ta’uu agarsiise — gurraacha boolla dhugumaan baay’ee dadhabinaan thermal radiation’n ifa.

Hawking radiation maal?

Kilaasikaalaa fiiziksii keessatti homtuu gurraacha boolla keessaa hin miliqu, kanaaf perfectly gurraacha fi ho’a homaa hin qabu ta’uu qaba. Bara 1974 Stephen Hawking quantum tiyoorii horizonii bira yeroo fudhatamu kun akka jijjiiramu agarsiise: gurraacha boolla faint thermal glow baasa, kanaaf maassaa isaa suuta suuta dhaba, ykn “evaporates.” Speektrumii Hawking ho’a irratti thermal dha; propagation curved yeroo-iddoo keessa immoo radiation infinity ga’u jijjiira. Heuristic picture yeroo baay’ee fayyadamu — Hawking derivation dhugaa miti — keessatti, quantum fluctuations horizonii alaa zarraawwan pairs uumu, partner tokko radiation ta’ee miliqa, kan biraa immoo keessaa kufa.

Amaloota ijoo: ho’a kun gurraacha boolla maassaa isaa waliin *inverse* proportional dha: gurraacha boolla xiqqaan caalaatti ho’aa dha. Gurraacha boolla teleskooppiin argu danda’u kam iyyuu ho’a baay’ee, baay’ee gadi-aanaa qaba — duwwaa space naannoo isaa caalaa qabbanaa’aa — kanaaf practice keessatti glow isaa negligible dha, kallattiin hin safaramne. Barbaachisummaa isaa conceptual dha: Hawking radiation’n *analogy* black-hole makaanikaa fi teermoodaynaamikii gidduu jiru gara dhugaa teermoodaynaamikii’tti jijjiira. Gurraacha boolla dhugumaan ho’a waan qabuuf, “ho’a” fi “entiroopii” seerota kana keessaa dhugaa teermoodaynaamikii hangawwan dha, idilee coincidence qofa miti. (Kun duubbee barruu ammaa ti, bu’aa isaa miti.)

Wal-simni kun bu’aa **jalqabaa seera makaanikaa boolla gurraachaa** (Bardeen, Carter fi Hawking, 1973) jedhuun cime. Jecha salphaatti: gurraacha boolla steady haala tokko irraa gara steady haala itti dhihoo, xiqqoo adda ta’etti yoo nudge goote, jijjiirama maassaa isaa ho’a $\times$ jijjiirama entiroopii isaa, plus term spin isaa, waliin walqixa. Kun black-hole gosa “ho’a in = ho’a yeroowwan jijjiirama in entiroopii” ti.

Garuu catch tokko phrase *nearby steady haala* keessa dhokata. Seera 1973 qulqulluun gurraacha boollota lama madaallii tasgabbaa’aa keessatti callisanii taa’an, infinitesimally qofa adda ta’an, walbira qaba. **Adeemsa** tokko — gurraacha boolla urjii tokko liqimsu, gurraacha boollota lama merge godhan, ykn newborn boolla violent birth booda ring down godhu — hin ibsu. Kun situations nuti caalaatti hubachuu barbaannu, fi “quietly sitting” faallaa guutuu dha. Seera qulqulluun yeroo gurraacha boolla nama hawwatu ta’u sirriitti callisa.

Fix obvious maaliif hin hojjenne

Tarii fix’n salphaa fakkaata: barbaachisaa keessaa kufaa yeroo deemu horizonii guddatu ilaali. Rakkoon *horizonii kam* jedhu.

Horizonii namoonni baay’een yaadan — **horizonii taateerii**, qabxii of lakki return dhugaa — amaloota subtle fi awkward tokko qaba: guutuu fuuldura addunyaa’n define godhama. horizonii taateerii *amma* eessa akka jiru beekuuf, forever keessa homtuu boolla keessa kufu hundumaa beeku qabda. Kun technicality miti. horizonii taateerii duwwaa, flat naannoo space keessatti *barbaachisaa isa nyaachisu hin ga’in dura* guddachuu jalqabuu danda’a, sababni barbaachisaa sun boodaa dhufuuf destiny qaba. Bal’ina isaa bakka locally homtuu hin ta’in keessatti ol ka’uu danda’a.

Horizon barbaachisaa hin ga’in dura akkamitti guddachuu danda’a?

Maqaan saayinsawaa puzzle kanaa **amaloota teeleolojikaalaa daangaa taatee**, ykn **waliigalaa hiika** jedhama. As “teleological” jechuun horizonii kaayyoo qaba, fuuldura tilmaama, ykn dhiibbaa yeroo keessatti backwards erga jechuu miti. Event tokko horizonii keessa jira moo ala jechuun guutuu fuuldura seenaa yeroo-iddoo irraa qofa murtaa’uu danda’a jechuu dha.

Idilee hiika jecha gabaabaadhaan sanuma dubbata. **Fuuldura null infinity** — “I-plus” jedhamee waamamu, $\mathcal{I}^+$ jedhamee barreeffamu — bakka ga’umsaa ifa forever miliqee duwwaa fuuldura infinitely distant keessatti ga’u yaadi. horizonii taateerii daangaa events outward ifa mallattoo eventually bakka ga’umsaa sana ga’uu danda’an fi events mallattoo akkasii *ever* hin ga’in gidduu jiru. Istaandaardii notation waliigalaa relativity keessatti, daangaa sababa-qabeessa darbe fuuldura null infinity: $\partial J^-(\mathcal{I}^+)$. Sababni jechi *ever* hiika keessaa waan jiruuf, safartuu here-and-amma qofa horizonii taateerii exactly arguu gochuu hin danda’u.

Kufaa jiru spherical qola strangeness kana ifa godha. Qola hin ga’in dura naannoo inside duwwaa fi locally flat ta’uu danda’a. Giddugala irraa outward ifa rays yeroo itti aanu itti aanu ergi: rays duraa miliqu; rays boodaa kufaa jiru qola ji’oometirii keessaa ba’uu hin dandeenye keessatti qunnamu. horizonii taateerii daangaa bu’aawwan lamaan addaan baasu dha. Backwards trace godhamuun, daangaa sun giddugala irraa jalqabee still-empty, flat interior keessa qola hin ga’in dura babal’ata. Bal’ina isaa guddachuun naannoo keessaa barbaachisaa flow achitti jiru hin gabaasu; completed yeroo-iddoo keessatti miliquu routes kamtu banaa akka hafe galmeessa.

Picture kana keessatti homtuu yeroo keessatti backwards hin hojjetu. Qola divert godhamee gurraacha boolla hin uumamne taanaan, completed yeroo-iddoo adda ta’a; earlier naannoo sun horizonii taateerii keessaa hin ta’u ture. Lesson fuuldura darbe jijjiira jechuu miti; horizonii taateerii **waliigalaa sababa-qabeessa daangaa** dha, fuula nearby observer instant tokko keessatti adda baasuu miti. Kanaaf physicists yeroo gurraacha boolla changing hordofu barbaadan quasi-local ykn socho’aa horizons fayyadamu.

Kun horizonii taateerii gurraacha boolla “haala” isaa running account ta’ee faayidaa hin qabne godha. Kompiitara fakkeessuu keessatti illee fakkeessuu xumuramee booda qofa arguu gochuu dandeessa; ho’a ykn entiroopii moment-by-moment hordofuuf immoo caalaatti hin mijatu.

Move: horizonii locally define gochuu dandeessu

Barruu haaraan Abhay Ashtekar, Daniel Paraizo fi Jonathan Shu irraa bu’aa isaa notion horizonii adda ta’e irratti ijaara — **quasi-local** horizonii, ji’ometirii naannoo isaa qofa irraa define godhamu, infinite fuuldura tokko illee hin barbaadne. “Socho’aa horizonii segments” kun fuulota lakkoofsaa relativists walitti makamu fakkeessuwwan keessatti gurraacha boollota argachuuf duraan fayyadaman; sababni isaanii naannoo keessaa fi honest ta’uu: bal’ina isaanii bakka anniisaa dhugumaan ce’utti qofa guddata.

Kana irratti, barreessitoonni kutaa rakkoo caalaatti rakkisaa furu. Idilee teermoodaynaamikii keessatti, sirna far irraa madaallii tasgabbaa’aa baay’ee slippery dha: tokko ho’a ykn dhiibbaa qulqulluun kennuun hin danda’amu, sababni hangawwan sun yeroo sirna settle godhu qofa well-defined ta’aniif. Gurraacha boollota rakkoo walfakkaataa qabu — garuu, barreessitoonni akka agarsiisanitti, addaa amaloota waliigalaa relativity fayyadamuun furmaata argamu. Gurraacha boolla madaallii tasgabbaa’aa keessa jiru (Kerr gurraacha boolla) lakkoofsota lama qofa — hammamtaa fi spin — tiin guutumaan determined. Kanaaf barreessitoonni kaartaa tokko ijaaru: horizonii wildly evolving, out-of-equilibrium kam iyyuu instant tokko tokko keessatti madaallii tasgabbaa’aa gurraacha boolla isa yeroo sana fakkaatu lakkoofsota lama dubbisa. Kaartaa sanaan, gurraacha boolla violently changing tokko **time-dependent ho’a fi spin** qabaachuu danda’a.

Pieces kanaan — locally defined anniisaa horizonii ce’u fi instantaneous intensive hangawwan — jalqabaa seera gurraacha boollota arbitrarily far irraa madaallii tasgabbaa’aa’tti bal’isu. Crucially, seera haaraan **daangeffame jijjiiramoota dhugaa fiizikaalaa adeemsoota** irraa dhufan (barbaachisaa fi gravitational waves horizonii ce’u) ibsa; infinitesimal tarkaanfiiwwan dhaabbataa taasifame haalawwan lama gidduu miti. Matching lammaffaa seera waliin walitti qabu; statement isaa amma *quantitative*: horizonii bal’ina anniisaa flowed in waliin kallattiin tied amount’n guddata. Waliin, jalqabaa fi lammaffaa seerota xumura ifaa tokko irratti geessu — even gurraacha boolla middle of irra caalaa violent event imaginable keessatti, entiroopii safartuu sirrii ammallee bal’ina horizonii isaa dha.

Kun maal *hin mirkaneessu*

- quantum gravity **hin furu**. Kun bu’aa *kilaasikaalaa* waliigalaa relativity keessaa, istaandaardii identification horizonii bal’ina = entiroopii fayyadame. Entiroopii sana maal irraa bu’uuraan dhufu hin keessaa baasu.
- Haala xixiqqoo **hin lakkaa’u**, ykn gurraacha boolla entiroopii *maal irraa ijaarame* hin ibsu. Book-keeping black-hole teermoodaynaamikii bal’isa; box banee microscopic degrees of freedom hin mul’isu.
- Black-hole odeeffannoo walfaallaa **hin furu**. Puzzle sun quantum tiyoorii keessa jira; barruu kun hin tuqu.
- **Ilaalcha ykn safartuu miti**. Teleskooppii, daataa, gravitational-wave mallattoo hin jiru — mathematics dha. Merging gurraacha boolla “ho’a” walqixxaattoo keessatti keessatti sirriitti defined hanga dha; thermometer irraa dubbistu miti.

- Bekenstein fi Hawking **hin overturn godhu**. Picture isaanii socho'aa haala jalqabaa equilibrium-only seera keessatti homaa hin jenneetti *extends* godha.

Ragaan hammam cimaa dha?

Wanta inni ta'eef cimaa dha: herregaa fiiziksii careful fi internally wal-simu, garee damee keessatti leading keessaa tokko irraa, Fiizikaalaa Gamaaggama Letters keessatti *Editors' Suggestion* ta'ee maxxanfame (companion barruu derivations dheeraa irratti hojjeta).

Caveats honest qulqullina irratti miti, *kind* irratti:

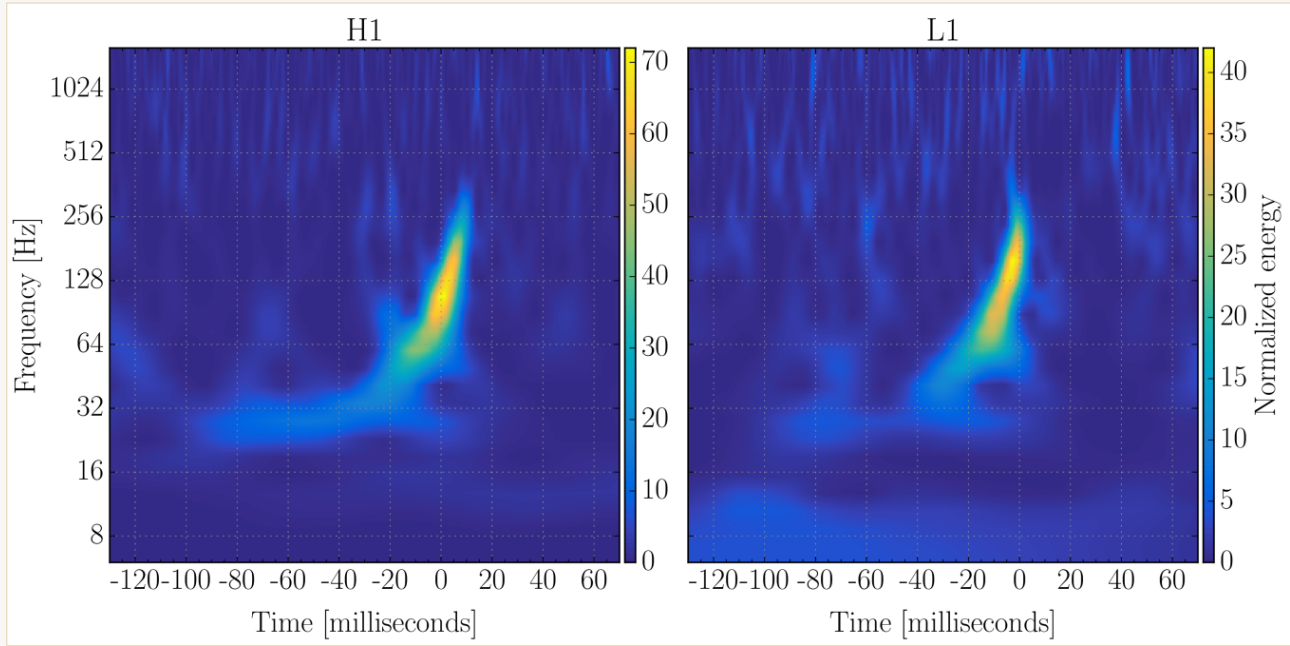
- Conventional yaada bu'uura horizonii bal'ina *entiroopii dha* jedhu irratti hunda'a (bal'ina divided by four yeroowwan Newton's dhaabbataa fi Planck's dhaabbataa). Guutuu quantum gravity tiy-oorii'n identification sana yeroo tokko revise godhe, hiika isaas waliin sochoosa.
- mata-duree shallaggiwwan baramaa haala (spacelike socho'aa horizons, axially symmetric) irratti worked out; barreessitoonni restrictions essential miti jedhu, garuu guutummaatti waliigalaa statement bu'aawwan elsewhere irratti hirkata.
- "Entiroopii equals horizonii bal'ina, even out of madaallii tasgabbaa'aa" compelling *identification* seerota haaraan natural godhan dha; microscopic istaastikii irraa theorem ragaa godhame miti.

Kanaaf: bu'uura waggaa shantama dursanii jiru rigorous extension; yaalii discovery miti, seera nature haaraa qormaata eeggatu miti.

Maaliif barbaachisaa dha

Sababoota lama: tokko hojiirra oolu, tokko conceptual.

Hojiirra oolu ahaan, gurraacha boollota nuti amma dhugumaan qorannoo goonu — kan LIGO fi Virgo merge yeroo godhan dhaga'an — moments isaanii barbaachisoo keessatti far irraa madaallii tasgabbaa'aa dha. Hangawwan barruu kana keessaa horizons locally defined fakkeessuuwwan duraan hordofan sanuma irraa ijaaraman; kanaaf gurraacha boolla *yeroo* walitti makamu ykn collapse entiroopii fi ho'a isaa principled way'n dubbachuuf carraa kenna, dura fi booda qofa miti.



GW150914, kallattiin detected gravitational-wave mallattoo jalqabaa, gurraacha boollota lama merge godhan irraa dhufe. Time-frequency kaartawwan kun mallattoo LIGO Hanford (bita) fi LIGO Livingston (mirga) keessatti agarsiisu: detectors lamaan keessatti, bright trace frequency mallattoo walitti makamu'tti dhiyaachaa yeroo ol ka'u upward sweep godha. Kun black-hole sirna far irraa madaallii tasgabbaa'aa dhugaa fakkeenya dha; bu'uura teermoodaynaamikii haaraaf haala qofa, observational ragaa miti.

LIGO Scientific Collaboration and Virgo Collaboration / Classical and Quantum Gravity, Fig. 10 CC BY 3.0

Conceptual ahaan, teermoodaynaamikii amala gurraacha boollota quantum gravity irratti clues ifa ta'e muraasa qabnu keessaa tokko — bakka gravity, quantum tiyoorii fi teermoodaynaamikii ifatti wal qunnamu. Gurraacha boolla violently changing tokkoof “entiroopii” fi “ho'a” exactly maal jechuu akka ta'e sharpen gochuun galma fuuldura quantum tiyoorii kam iyyuu hit gochuu qabu cimsu. Gurraacha boolla entiroopii dhugumaan maal akka ta'e gaaffii gadi fagoo hin deebisu. Gaaffii sana caalaatti sirrii godha — fiiziksii corner kana keessatti, kun hojii keessaa harki guddaan.

Cuunfaa gabaabaa

Gurraacha boollota seerota teermoodaynaamikii mirror godhan hordofu, garuu “jalqabaa seera” ifaa 1973 gurraacha boollota madaallii tasgabbaa'aa keessatti amma iyyuu taa'an qofa walbira qabee dhugaa adeemsa hin ibsu ture. Ashtekar, Paraizo fi Shu jalqabaa fi lammaffaa seerota lamaan gurraacha boollota arbitrarily far irraa madaallii tasgabbaa'aa — merging, feeding, ringing down — tti bal'isu, locally defined “socho'aa horizons” fi kaartaa changing gurraacha boolla'f instantaneous ho'a fi spin kennu fayyadamuun. Bu'aan: horizonii bal'ina violent events keessatti illee entiroopii safartuu sirrii ta'ee hafa. Kun rigorous bu'aa kilaasikaalaa waliigalaa relativity keessaa; quantum gravity miti, ilaalcha miti, haala xixiqqoo count miti, odeeffannoo walfaallaa furmaata miti.

Sakatta'a ifaa

Wanti barruu agarsiisu: Jalqabaa fi lammaffaa seerota black-hole makaanikaa guutummaatti socho'aa, madaallii tasgabbaa'aa irraa fagoo gurraacha boollota'tti mathematically wal-simu extension, quasi-local socho'aa horizons irratti ijaarame. Daangeffame, process-based jalqabaa seera fi quantitative lammaffaa seera define godha; socho'aa gurraacha boolla entiroopii horizonii bal'ina waliin adda baasu natural godha.

Wanti dhugaa garuu interpretive: “Entiroopii = horizonii bal'ina” out of madaallii tasgabbaa'aa identification. Seerota haaraan compelling godhu, garuu istaandaardii kilaasikaalaa area-entropy yaada bu'uura dhaala; derive hin godhu.

Wanti inni hin agarsiifne: Quantum tiyoorii gravity; microscopic origin ykn “count” black-hole entiroopii; odeeffannoo walfaallaa furmaata; observational ykn yaalii bu'aa; ho'a physically safaramuu danda'u.

Daangaawwan ijoo: Kilaasikaalaa waliigalaa relativity qofa; mata-duree bu'aawwan baramaa space-like, axisymmetric haala keessatti mirkaneesse, generality companion hojii'n argued; area-entropy identification assumed dha, istaatistikii makaanikaa irraa mirkaneesse miti.

Dubbisaan waliigalaa hammam amantaa qabaachuu qaba? Kun jajjabaa, well-regarded tiyoorii advance black-hole teermoodaynaamikii socho'aa haala'tti dhugumaan extend godhu irratti amantaa guddaa. Akkasuma haaraa ilaalchawwan himannaa miti, quantum gravity miti, famous odeeffannoo puzzle furmaata miti. Stance sirrii: understanding keessatti tarkaanfii dhugaa, chalk'n fudhatame — telescope'n miti.

Maddoota

Ashtekar, Paraizo & Shu, Thermodynamics of Black Holes, Far from Equilibrium, Phys. Rev. Lett. 136, 251405 (2026)

<https://doi.org/10.1103/3c1r-v8f1>