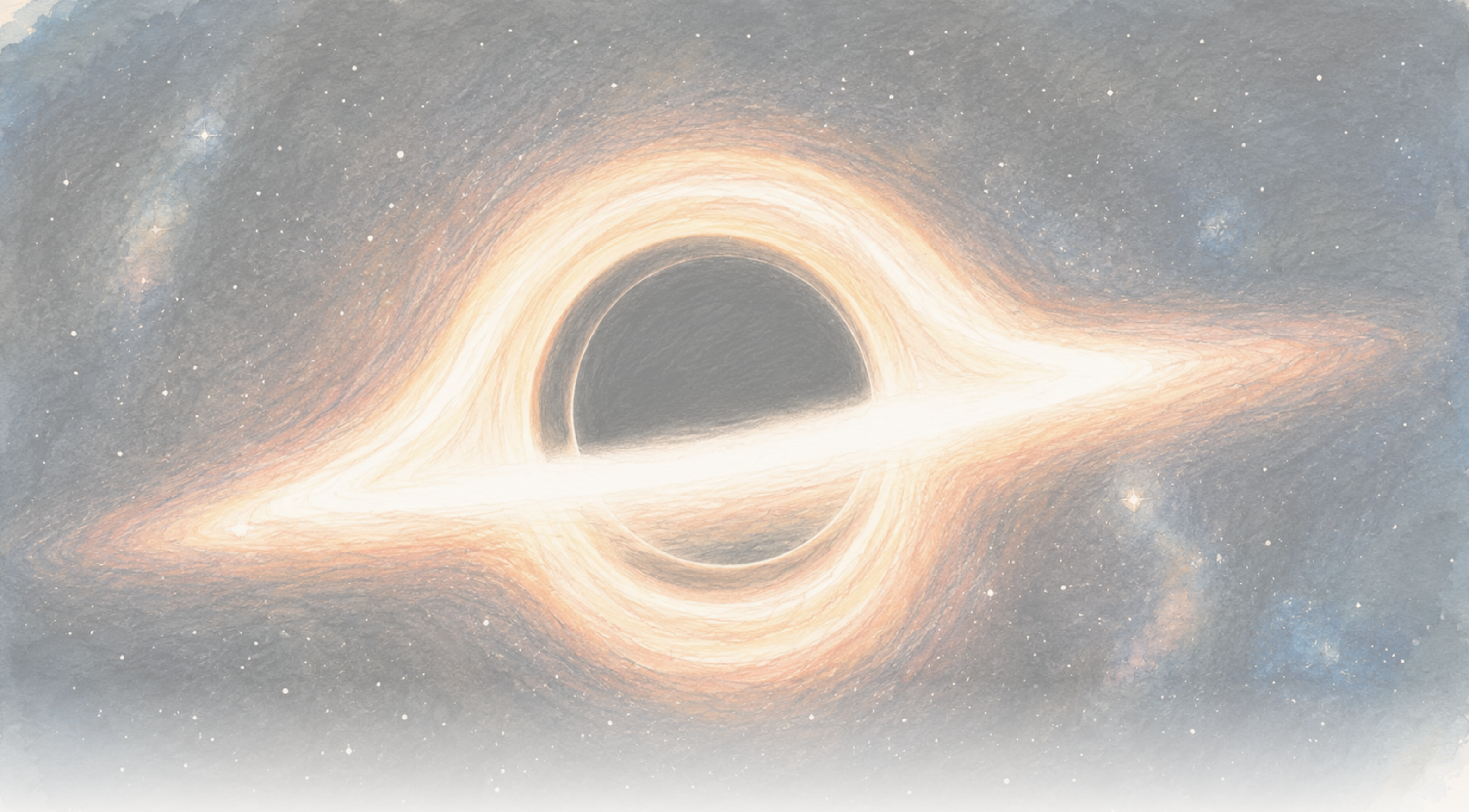

The Clean Paper

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

Black holes suna bin thermodynamic “laws” — sabon sakamako ya faɗaɗa su zuwa black holes da suke nesa sosai da equilibrium

Tun farkon shekarun 1970 an san cewa black holes suna bin dokoki masu kama da thermodynamics, amma mafi tsabtar sigar waɗannan dokokin ta shafi black holes da suke cikin equilibrium ne kawai. Wata sabuwar takarda a Physical Review Letters ta faɗaɗa first da second laws zuwa black holes da suke canzawa da sauri — suna haɗiye matter, suna merger ko suna radiating — ta amfani da locally defined ‘dynamical horizons’. Wannan yana ba physicists damar bayyana temperature da entropy ko ga black hole da ke violently evolving. Mathematical result ne a classical general relativity, ba sabon quantum gravity ba, ba observation ba, kuma ba mafita ga black-hole information puzzle ba.

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Black holes suna da “dokoki” masu kama da thermodynamics. Tsarin da ya yi kyau a takarda yana aiki ne kawai idan komai yana cikin equilibrium

Ɗaya daga cikin abubuwan da suka fi ban mamaki a physics shi ne cewa black holes suna nuna halaye kamar abubuwa masu zafi. A farkon shekarun 1970, Bekenstein da Hawking sun lura cewa equations da ke sarrafa black holes suna daidaita, ɓangare zuwa ɓangare, da dokokin thermodynamics: black hole yana da entropy da ya yi proportional da area na horizon ɗinsa, kuma yana da temperature da ya yi proportional da surface gravity. Daga baya Hawking ya nuna cewa temperature ɗin ba kwatanci kawai ba ne—black hole da gaske yana fitar da faint thermal radiation.

Mene ne Hawking radiation?

A classical physics, babu abin da zai tsere daga black hole, don haka ya kamata ya kasance cikakken baki kuma ba shi da temperature. A 1974 Stephen Hawking ya nuna cewa wannan yana sauyawa idan aka haɗa quantum theory kusa da horizon: black hole yana fitar da faint thermal glow kuma saboda haka yana rasa mass a hankali, wato yana “evaporate.” Spectrum ɗin thermal ne a Hawking temperature, yayin da tafiyarsa ta curved spacetime ke sauya radiation da ke isa infinity. A wani sanannen heuristic picture—ba ainihin derivation na Hawking ba—quantum fluctuations kusa da horizon suna samar da pair inda ɗaya ya tsere a matsayin radiation, ɗayan kuma ya faɗa ciki.

Muhimmin fasali shi ne cewa wannan temperature yana da **inverse proportionality** da mass na black hole: idan hole ɗin ya ƙanƙanta, temperature ɗinsa ya fi girma. Ga duk black hole da telescope zai iya gani, temperature ɗin ƙasa ƙwarai yake—ya fi empty space da ke kewaye da shi sanyi sosai—saboda haka radiation ɗin ba shi da tasiri a aikace kuma ba a taɓa auna shi kai tsaye ba. Muhimmancinsa na ra’ayi ne: Hawking radiation ne ya mai da *analogy* tsakanin black-hole mechanics da thermodynamics zuwa ainihin thermodynamics. Saboda hole ɗin da gaske yana da temperature, “temperature” da “entropy” a waɗannan dokoki physical thermodynamic quantities ne, ba formal coincidence ba. (Wannan background ne ga takardar yanzu, ba sakamakonsa ba.)

Wannan haɗin yana da ginshiƙi a sakamakon da ake kira **na farko law of black hole mechanics** (Bardeen, Carter da Hawking, 1973). A kalmomi, yana cewa: idan ka matsar da black hole daga steady state guda zuwa wani steady state mai kusa, canjin mass ɗinsa yana daidai da temperature ɗinsa sau canjin entropy, tare da ƙarin term domin spin. Wannan shi ne nau’in black-hole na “heat in equals temperature times change in entropy.”

Amma akwai matsala a kalmar *nearby steady state*. Dokar 1973 mai tsabta tana kwatanta black holes biyu da suke zaune a equilibrium ba tare da hayaniya ba, bambancinsu kuma infinitesimal ne. Ba ta bayyana wani **process** na gaske ba—black hole yana haɗiye star, black holes biyu suna merger, ko sabon black hole yana ring down bayan violent birth. Waɗannan su ne yanayin da muke son fahimta sosai, kuma su ne akasin “zama cikin natsuwa.” Dokar mai sauƙi tana yin shiru a daidai lokacin da black hole ya fi ban sha’awa.

Me ya sa gyaran da ya fi bayyana ba ya aiki

Za a iya tunanin mafita tana da sauƙi: kawai a kalli horizon yana ƙaruwa yayin da matter ke faɗa ciki. Matsalar ita ce: **wane horizon?**

Horizon da yawancin mutane suke tunani—**event horizon**, ainihin point of no return—yana da wata siffa mai rikitarwa: an ayyana shi da duk future history na universe. Domin sanin inda event horizon yake **yanzu**, dole ne ka san duk abin da zai taɓa faɗawa black hole har abada. Wannan ba technical detail kaɗai ba ne. Event horizon zai iya fara ƙaruwa a wani yankin sarari da babu matter kuma locally flat ne **kafin** matter da zai ciyar da black hole ya isa, kawai saboda matter ɗin zai zo daga baya. Area ɗinsa zai iya ƙaruwa inda, a local sense, babu wani abu da ke faruwa.

Ta yaya horizon zai iya ƙaruwa kafin matter ya iso?

Sunan kimiyya na wannan matsala shi ne **teleological nature of the event horizon**, ana kuma kiransa **global definition**. A nan "teleological" ba yana nufin horizon yana da wata manufa, yana hango future, ko yana aika influence baya cikin lokaci ba. Yana nufin cewa za a iya yanke hukunci ko wani event yana cikin horizon ne kawai idan an san complete future history na spacetime.

Formal definition yana faɗin abu iri ɗaya cikin taƙaitacciyar hanya. Ka yi tunanin **future null infinity**—ana kiransa "I-plus" kuma ana rubuta $\mathcal{I}^+$—a matsayin inda light da ya tsere har abada zai dosa a infinitely distant future. Event horizon shi ne boundary tsakanin events da outward light signal zai iya daga ƙarshe isa wannan destination da events da babu irin signal ɗin da zai taɓa iya isa. A standard notation na general relativity, shi ne boundary of the causal past of future null infinity: $\partial J^-(\mathcal{I}^+)$. Saboda kalmar *ever* tana cikin definition ɗin, ma'auni da aka yi a nan da yanzu kaɗai ba zai iya gano event horizon daidai ba.

Collapsing spherical shell yana sa abin ya bayyana. Kafin shell ɗin ya iso, yankin cikinsa zai iya zama empty kuma locally flat. Aika outward light rays daga centre a lokuta masu jere: waɗanda suka fara da wuri suna tserewa, waɗanda suka fara daga baya kuma suna haɗuwa da collapsing shell a geometry da ba za su iya fita ba. Event horizon shi ne boundary da ke raba sakamako biyu. Idan aka bi wannan boundary baya, yana farawa daga centre yana faɗaɗa cikin interior da har yanzu empty kuma flat ne kafin shell ɗin ya kai gare shi. Ƙaruwar area ɗinsa ba ta nuna local flow na matter a can; tana rikodin waɗanne escape routes ne suka rage a completed spacetime.

Babu wani abu a wannan hoton da ke aiki baya cikin lokaci. Idan aka karkatar da shell ɗin kuma black hole bai samuwa ba, completed spacetime zai zama dabam kuma wancan earlier region ba zai kasance wani ɓangare na event horizon ba. Darasin ba cewa future yana sauya past ba ne, sai dai cewa event horizon **global causal boundary** ne, ba surface da nearby observer zai gano a instant guda ba. Wannan ne ya sa physicists ke amfani da quasi-local ko dynamical horizons idan suna son bibiyar black hole yayin da yake sauyawa.

Wannan yana sa event horizon ya zama mara amfani a matsayin running account na "state" na black hole. Ko a computer simulation, ba za ka iya gano shi daidai ba sai simulation ta ƙare; saboda haka ba za ka iya amfani da shi wajen bibiyar temperature ko entropy daga lokaci zuwa lokaci ba.

Matakin da takardar ta ɗauka: horizon da za a iya ayyana a local level

Sabon takarda na Abhay Ashtekar, Daniel Paraizo da Jonathan Shu ya gina sakamakonsa a kan wani nau'in horizon dabam—**quasi-local horizon**, wanda geometry a neighbourhood ɗinsa kaɗai ke ayyana shi, ba tare da komawa ga infinite future ba. Waɗannan "dynamical horizon segments" su ne surfaces da numerical relativists suke amfani da su wajen gano black holes a merger simulations, saboda local ne kuma suna ba da bayani kai tsaye: area ɗinsu yana ƙaruwa ne inda energy ta ketare su a zahiri.

Daga nan marubutan suka warware wani ɓangaren da ya fi wahala. A thermodynamics na yau da kullum, system da yake nesa da equilibrium yana da wahalar bayyana da temperature ko pressure guda, domin irin waɗannan quantities suna da ma'ana sosai ne idan system ya daidaita. Black holes suna da wannan matsalar—amma marubutan sun nuna cewa wani fasali na general relativity yana ba da hanya. Black hole **a equilibrium**—Kerr black hole—ana iya ayyana shi da lambobi biyu kaɗai: girma da spin. Saboda haka marubutan sun gina map da ke ɗaukar duk evolving, out-of-equilibrium horizon sannan a kowane instant ya karanta lambobin equilibrium black hole da ya fi kama da shi. Ta wannan map, za a iya ba wa black hole mai violent change **time-dependent temperature da spin**.

Da waɗannan kayan—locally defined energy da ke ketare horizon, da instantaneous intensive quantities—sun faɗaɗa na farko law zuwa black holes da suke nesa da equilibrium gwargwadon hali. Muhimmin abu shi ne sabon law yana bayyana **finite changes da real physical processes suka jawo**—matter da gravitational waves suna ketare horizon—ba infinitesimal steps tsakanin frozen states biyu ba. Sun haɗa shi da na biyu law mai dacewa wanda yanzu yake quantitative: horizon area yana ƙaruwa da adadin da ya danganta kai tsaye da energy da ta shiga. Idan aka haɗa na farko da na biyu laws, conclusion ɗin yana zama mai tsabta: ko da black hole yana tsakiyar violent event, ma'aunin entropy da ya dace har yanzu area na horizon ɗinsa ne.

Abin da wannan **bai** tabbatar ba

- Bai warware **quantum gravity** ba. Wannan sakamako ne a *classical* general relativity, yana amfani da standard identification na horizon area da entropy. Ba ya samo entropy daga wani abu mafi fundamental.
- Bai ƙidaya microstates ko bayyana **me** ke samar da black-hole entropy ba. Yana faɗaɗa bookkeeping na black-hole thermodynamics; ba ya buɗe microscopic degrees of freedom.
- Bai warware black-hole information paradox ba. Wannan matsalar tana cikin quantum theory; takardar ba ta shiga cikinta ba.
- Ba observation ko ma'auni ba ne. Babu telescope, bayanai ko gravitational-wave signal a sakamakon—mathematics ne. "Temperature" na merging black hole a nan precisely defined quantity ne a equations, ba abin da thermometer zai auna ba.
- Bai rushe Bekenstein da Hawking ba. Yana **faɗaɗa** hotonsu zuwa dynamical regime inda equilibrium-only law na asali ba ta da abin cewa.

Yaya ƙarfin shaidar yake?

Mai ƙarfi, idan aka yi la'akari da irin shaidar da ake magana a kai: careful, internally consistent mathematical physics daga ƙungiya mai babban matsayi a fannin, an buga shi a matsayin *Editors' Suggestion* a Physical Review Letters; companion takarda kuma yana gabatar da dogayen derivations.

Caveats na gaskiya suna game da **nau'in** sakamakon, ba ingancinsa ba:

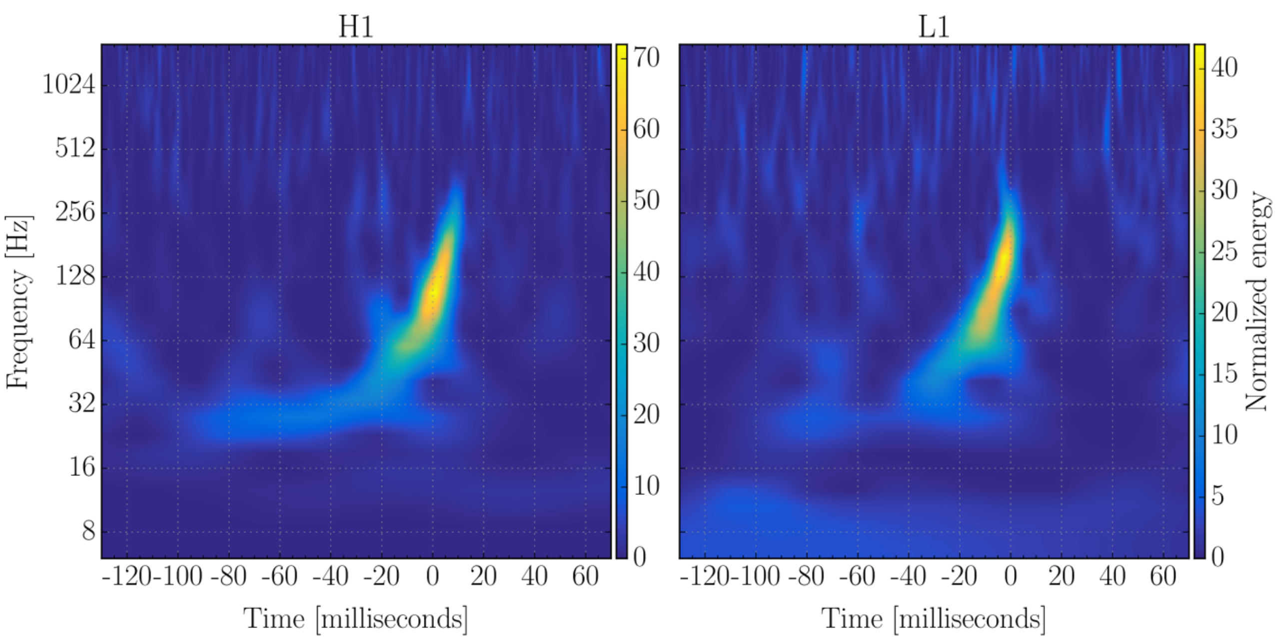
- Yana dogara da conventional assumption cewa horizon area **shi ne** entropy (area divided by four times Newton's constant and Planck's constant). Idan full quantum theory of gravity ta sauya wannan identification, interpretation ɗin zai sauya tare da ita.
- kanun labarai calculations an yi su ga common case—spacelike dynamical horizons masu axial symmetry. Marubutan suna jayayya cewa restrictions ba essential ba ne, amma fully general statement yana dogara da sakamako a companion work.
- “Entropy equals horizon area even out of equilibrium” compelling **identification** ne da sabbin na farko da na biyu laws suka sa ya zama natural, ba theorem da aka samo daga microscopic statistics ba.

Saboda haka: rigorous extension na tsari mai shekaru hamsin, ba experimental discovery ba kuma ba sabon law of nature da ake jira a gwada ba.

Me ya sa wannan yake da muhimmanci

Dalilai biyu ne: ɗaya practical, ɗaya conceptual.

A aikace, black holes da muke nazari yanzu—waɗanda LIGO da Virgo suke jin merging—suna ciyar da muhimman lokutansu nesa da equilibrium. Quantities a wannan takarda an gina su daga locally defined horizons iri ɗaya da simulations suke bibiyewa. Saboda haka wannan yana ba da principled way na magana game da entropy da temperature na black hole **yayin** merger ko collapse, ba kafin da bayan kawai ba.



GW150914, gravitational-wave signal na farko da aka gano kai tsaye, ya fito daga black holes biyu suna merger. Waɗannan time-frequency maps suna nuna signal ɗin a LIGO Hanford (hagu) da LIGO Livingston (dama): a detectors biyu, bright trace yana hawa yayin da frequency na signal ke karuwa zuwa merger. Wannan ainihin misali ne na black-hole system da yake nesa da equilibrium; context ne ga sabon thermodynamic tsari, ba observational shaida ga tsarin ba.

A ra’ayi, thermodynamic behavior na black holes yana ɗaya daga cikin ’yan concrete clues da muke da su game da quantum gravity—wurin da gravity, quantum theory da thermodynamics suke haɗuwa a fili. Fayyaɗa daidai ma’anar “entropy” da “temperature” ga black hole da ke sauyawa cikin violent way yana ƙara bayyana target da kowace future quantum theory dole ta cimma. Bai amsa zurfin tambayar menene black-hole entropy a zahiri ba. Ya bayyana tambayar daidai fiye—kuma a wannan ɓangaren physics, wannan babban ɓangare ne na aikin.

Taƙaitaccen bayani

Black holes suna bin dokoki masu kama da thermodynamics, amma clean “na farko law” na 1973 ya kwatanta black holes ne kawai da suke zaune a equilibrium kuma bai iya bayyana ainihin process ba. Ashtekar, Paraizo da Shu sun faɗaɗa na farko da na biyu laws zuwa black holes da suke nesa da equilibrium—merging, feeding, ringing down—ta amfani da locally defined “dynamical horizons” da map da ke ba changing black hole instantaneous temperature da spin. Babban sakamakon shi ne cewa horizon area yana ci gaba da zama ma’aunin entropy da ya dace ko da yayin violent events. Rigorous sakamako ne a classical general relativity, ba quantum gravity ba, ba observation ba, ba ƙidayar microstates ba, kuma ba mafita ga information paradox ba.

Binciken ba tare da ƙarin gishiri ba

Abin da takardar ta nuna: Mathematically consistent extension na na farko da na biyu laws na black-hole mechanics zuwa fully dynamical, far-from-equilibrium black holes, wanda aka gina a quasi-local dynamical horizons. Yana ayyana finite, process-based na farko law da quantitative na biyu law, kuma yana sa identification na entropy na dynamical black hole da horizon area ya zama natural.

Abin da yake na gaske amma interpretive: Identification "entropy = horizon area" a wajen equilibrium. Sabbin dokokin suna sa ya zama compelling, amma yana gaji standard classical area-entropy assumption maimakon ya derive shi.

Abin da bai nuna ba: Quantum theory of gravity; microscopic origin ko "count" na black-hole entropy; resolution na information paradox; observational ko experimental sakamako; ko temperature da za a iya auna da thermometer.

Manyan iyakoki: Classical general relativity gaba ɗaya; kanun labarai sakamako an tabbatar da su ga common spacelike, axisymmetric case, yayin da generality ake jayayya da companion work; area-entropy identification assumption ne, ba proof daga statistical mechanics ba.

Yaya yawan amincewa ya kamata mai karatu gaba ɗaya ya yi? Babban amincewa cewa wannan solid, well-regarded theoretical advance ne da gaske ya faɗaɗa black-hole thermodynamics zuwa dynamical regime. Haka kuma babban amincewa cewa **ba** sabon observation ba ne, ba quantum gravity ba ne, kuma ba resolution na famous information puzzle ba ne. Matsayin da ya dace: mataki na gaske wajen fahimta, wanda aka ɗauka da lissafi ba telescope ba.

Majiyoyi

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