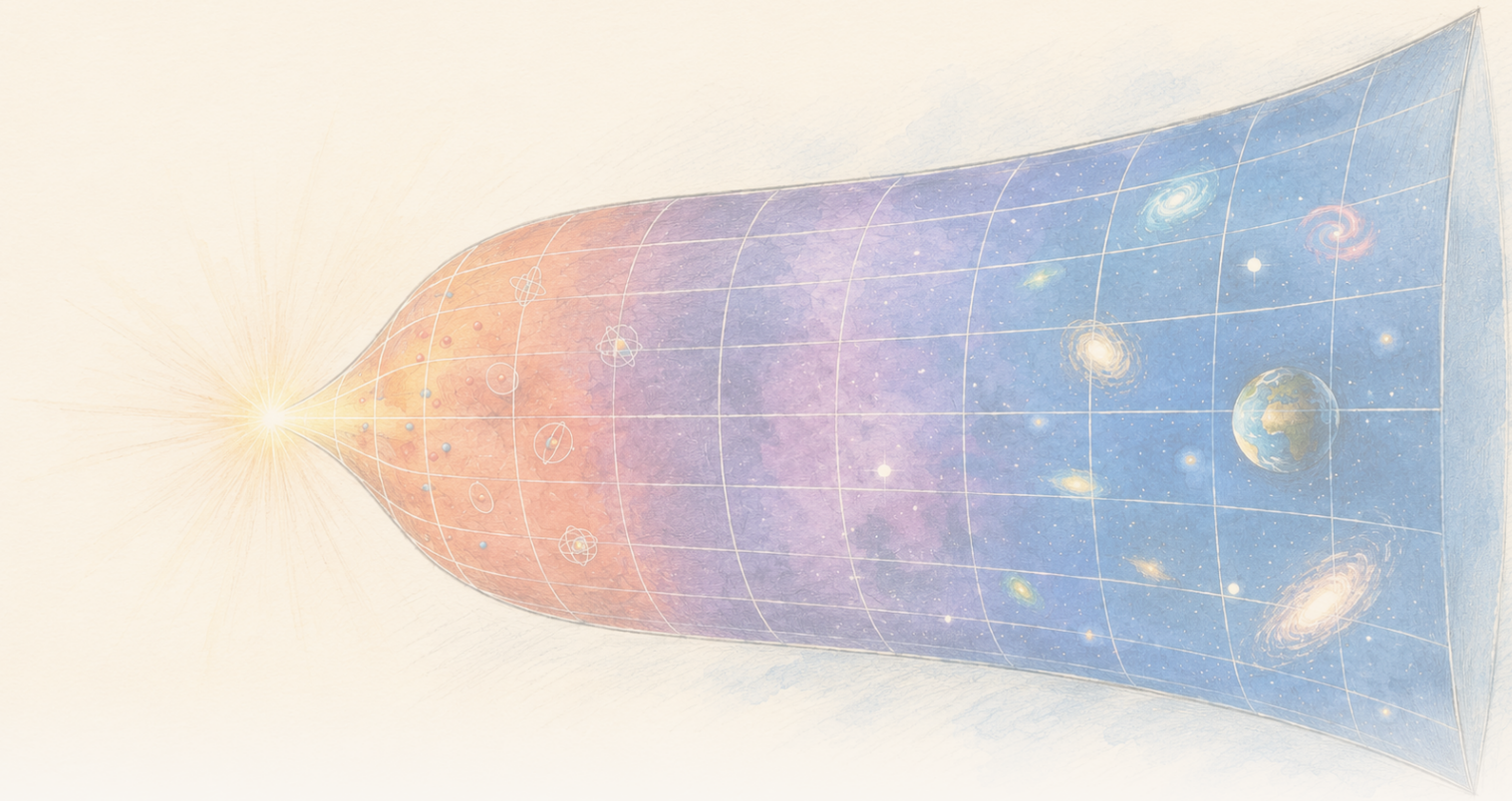

The Clean Paper

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

A cikin entropy-based gravity model, local entropy density yana raguwa yayin da total ke ƙaruwa

Wata takarda a Physical Review D ta samo temperatures, pressures da first law a cikin Gravity From Entropy, wani proposed modified-gravity framework. A late-time, low-curvature Friedmann approximation, local entropy da energy densities na model suna raguwa yayin da expansion ke sa total entropy ya ƙaru. Lissafin yana da cikakken ma'ana a cikin framework d'in, amma yana da sharaɗi: Friedmann cosmologies ba exact solutions na full theory ba ne, kuma wannan ba observational evidence cewa gravity ta fito daga entropy ba, ba explanation na measured dark energy ba, kuma ba completed quantum-gravity theory ba.

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Faɗaɗar girma na iya rage density amma ta ƙara jimilla

Idan entropy density a wannan samfurin tana raguwa yayin da sararin samaniya yake faɗaɗa, ta yaya jimillar entropy za ta iya ƙaruwa?

Ka yi tunanin sararin samaniya mai faɗaɗawa da aka raba zuwa ƙananan cells. Adadin wani abu a kowace cell zai iya raguwa, amma idan yankin da ake ƙirgawa yana ƙara girma, jimillar adadin a duk yankin na iya ƙaruwa. Raguwar density da ƙaruwa a jimilla ba su saba wa juna idan volume ɗin kansa yana canzawa.

Wannan ƙaramin lissafin ne yake tsakiyar wata takardar ka'ida mai buri sosai. A *Physical Review D*, masanin mathematical physics Ginestra Bianconi ya gina bayanin thermodynamics na **Gravity From Entropy** (GfE), wani sabon samfurin da aka gabatar inda gravity ake wakilta ta wata alaƙar information theory tsakanin matter da geometry. A nan "information-theoretic" yana nufin cewa samfurin ya fara ne daga ma'aunin lissafi na bambancin descriptions biyu na geometry: geometry na zahiri da kuma geometry da matter da curvature suka haifar.

Takardar ta fitar da local quantities da ake kira k-entropies, k-energies, k-temperatures da k-pressures. Harafin k yana raba sassa daban-daban na geometry a cikin samfurin; ba nau'ikan abu ko lokutan sararin samaniya ba ne. Alaƙarsu ta first law tana da tsarin lissafi iri ɗaya da na thermodynamics: canjin energy yana da alaƙa da temperature sau canjin entropy, sannan a cire pressure sau canjin volume.

$$\delta\epsilon_k = \theta_k\,\delta s_k - \pi_k\,\delta v$$

Sannan takardar ta ƙididdige waɗannan quantities a kan Friedmann cosmologies masu faɗaɗawa: samfuran sararin samaniya na ka'ida waɗanda a manyan ma'auni suke homogeneous da isotropic. A yanayin ƙaramin energy da ƙaramin curvature, misalan da matter ko radiation suka mamaye suna da local entropy density da energy density masu raguwa, amma faɗaɗar volume tana isa ta sa **jimillar entropy ta ƙaru**. Jimillar energy kuma tana kusantar wata ƙima mai dindindin a leading order — wato bayan a riƙe babban term da yake mamaye lissafi a dogon lokaci, a yi watsi da terms da suke ɓacewa da sauri.

Wannan sakamako ne na lissafi mai tsabta. Amma iyakarsa ma tana da muhimmanci: an yi lissafin **a cikin wata ka'ida da aka gabatar**, kuma Friedmann cosmologies da aka yi amfani da su a misalan ba cikakkun solutions na full GfE equations ba ne — approximations ne kawai. Full equations ɗin suna fitowa ne daga varying GfE action kuma suna haɗa dynamical G-field da higher-order geometric sectors waɗanda ba sa cikin ordinary Friedmann equations. Takardar ba ta lura kai tsaye da entropy tana samar da gravity ba, ba ta gano dark energy na sararin samaniyarmu ba, kuma ba ta kammala ka'idar quantum gravity ba.

Abin da Gravity From Entropy take ɗauka

General relativity tana bayyana gravity ta geometry na spacetime. Matter yana sa spacetime ya karkata, kuma wannan curvature tana tsara yadda matter yake motsi. GfE ta fara daga wani proposed action dabam: tana ɗaukar objects masu alaƙa da metric a matsayin quantum operators kuma tana gina Lagrangian ɗinta daga **Geometric Quantum Relative Entropy** (GQRE).

Kalmomi uku cikin minti biyu

Quantum operator wata ka'idar lissafi ce da ke aiki a kan quantum state kuma tana wakiltar quantity ko transformation. GfE tana ɗauka cewa objects masu alaƙa da metric ɗinta za a iya kula da su haka; ba a buƙatar mai karatu ya sake gina wannan tsarin.
Lagrangian gajeriyar hanyar lissafi ce da ke ɗauke da dokokin motsin wata ka'ida. A haɗa ta a kan spacetime a samu action, sannan a vary action ɗin don fitar da field equations.
GQRE ita ce Lagrangian takamaimai da GfE ta zaɓa. Tana daidaita ra'ayin quantum relative entropy don kwatanta physical metric da higher-order metric da matter da curvature suka haifar. Kiran wannan "entropy" ba ya sa ta zama entropy na zafi na yau da kullum.

Relative entropy galibi ma'aunin yadda probability distributions biyu ko quantum states biyu suke bambanta. A GfE, kwatantawar tana tsakanin physical metric da higher-order metric da matter da curvature suka haifar. "Higher-order" ba ya nufin ƙarin spacetime dimensions. Yana nufin samfurin yana tattara scalar, vector-type da bivector-type geometric sectors cikin wani object mafi faɗi. Wani **G-field** mai motsi yana haɗa waɗannan sassa kuma yana "dress" metric da ake amfani da ita a ɓangaren gravity da matter. An gina tsarin yadda a limit na ƙaramin energy da ƙaramin curvature, action ɗinsa ya koma Einstein-Hilbert action na general relativity tare da matter action.

Wannan jumla ta ƙarshe tana da saukin wuce gona da iri wajen fassara ta. Samun Einstein equations a wani limit wani gwajin daidaito ne ga proposal ɗin. Ba ya nuna cewa nature tana amfani da wannan ka'ida mafi faɗi a wajen wannan limit.

Field equations na GfE suna kuma ɗauke da dynamical term da tsarin ke kira **emergent effective dark-energy term**. A wannan takardar, Bianconi ya haɗa internal-energy density na samfurin da wannan term. "Effective dark energy" yana bayyana rawar term ɗin a equations. Ba shaidar cewa shi ne dark energy da cosmological observations suka nuna ba.

Ma'anoni uku na kalmar "entropy"

Ordinary thermodynamic entropy tana da alaƙa da yawan microscopic arrangements da za su iya ba da macroscopic state ɗaya. **Quantum relative entropy** tana auna bambanci tsakanin quantum states biyu. **GQRE** a wannan takardar kuwa wani geometric construction ne na wannan samfurin, wanda aka yi wahayi daga relative entropy kuma ake amfani da shi a matsayin gravitational Lagrangian. Kama suna ba ya sa quantities ɗin su zama abu ɗaya; takardar tana fitar da alaƙar da take amfani da ita a cikin GfE.

Sakamakon thermodynamics da yake daidai a cikin samfurin

Takardar ta fara ne a matakin tsarin GfE kansa. Ga kowane order da type na geometric degree of freedom, wanda k ke wakilta, tana bayyana:

- local k-entropy daga GQRE;
- local k-energy daga internal-energy density na samfurin;

- k-temperature mai conjugate da ita;
- da k-pressure.

Waɗannan quantities suna bin local first law. A notation na takardar,

$$\delta\epsilon_k = \theta_k\,\delta s_k - \pi_k\,\delta v$$

Index k ba jerin nau'ikan matter ko lokutan Universe ba ne. A lissafin homogeneous da isotropic yana wakiltar entries biyar: scalar entry ɗaya; timelike da spacelike entries daban daga vector-type sector; da time-space da space-space entries daban daga bivector-type sector. Scalar ba shi da directional index; vector-type entries suna bambanta time da space; bivector kuma ana gina shi daga pairs na directions. Kowane sector na iya samun temperature da pressure nasa. K-temperature ma na iya zama positive ko negative, gwargwadon component na G-field da yake wakilta.

Waɗannan ba temperatures da za a auna da thermometer kusa da cosmological horizon ba ne. Standard de Sitter quantum-field temperature tana scale da H: **Gibbons-Hawking temperature** ana danganta ta da cosmological horizon, yayin da **Bunch-Davies vacuum** shi ne standard de Sitter-invariant quantum state wanda field correlations ɗinsa suke ba da thermal response. Takardar ta bambanta su sarai daga geometric k-temperatures ɗinta, waɗanda a misalin de Sitter suke scale da H^2. A nan kalmar "temperature" tana nufin thermodynamic conjugate variable da aka samo daga definitions na entropy da energy na samfurin.

Saboda haka first-law identity ɗin derivation ne na gaske, amma **sakamako ne na cikin ka'idar**: idan an karɓi GfE action da definitions ɗinta, wannan tsarin thermodynamics yana biyo baya.

Me ya sa lissafin Friedmann approximation ne

Don mayar da formalism ɗin zuwa misalin cosmology, takardar tana amfani da homogeneous da isotropic Friedmann-Robertson-Walker (FRW) spacetimes. "Homogeneous" yana nufin samfurin a manyan ma'auni yana da matsakaicin properties iri ɗaya a kowane wuri; "isotropic" yana nufin yana kama iri ɗaya a duk directions. Scale factor ɗaya yana bayyana yadda distances suke girma da lokaci, matter ana wakilta shi a matsayin smooth perfect fluid, kuma Hubble parameter H yana taƙaita expansion rate. Wannan idealized background ne, ba taswirar individual galaxies ba.

Amma akwai rashin dacewa a tsarin. Friedmann universes suna warware Einstein equations. Gaba ɗaya ba sa warware full higher-order GfE equations, waɗanda suke kuma bin scalar, vector-type da bivector-type sectors da derivatives na G-field. Einstein equations suna sake fitowa ne kawai a first-order, low-energy, small-curvature limit na proposal ɗin.

Takardar ta faɗi wannan kai tsaye kuma tana ɗaukar Friedmann solutions a matsayin approximations, ta hanyar da ta kwatanta da saka mean-field solution cikin wata cikakkiyar ka'ida domin a ga inda approximation ɗin ke ci gaba da aiki. Yanayin yana buƙatar ƙaramin energy da ƙaramin curvature, wanda aka taƙaita da $l_P H \ll 1$, inda l_P yake Planck length. Wani sharadi na biyu yana buƙatar product na induced higher-order metric da inverse physical higher-order metric ya kasance positive definite.

Saboda haka sakamakon ba “GfE ta hango tarihin sararin samaniyarmu” ba ne. Ya fi kama da: **idan GfE universe za a iya kusantarta da familiar Friedmann cosmology a wannan regime, ga yadda full GfE quantities ke scale a thermodynamics.**

Bambanci tsakanin local da jimilla

A cikin wannan regime, leading local quantities suna da scaling mai sauƙi:

- entropy density na samfurin tana scale da H^2;
- energy density na samfurin tana scale da H^4;
- a misalan Friedmann da ba de Sitter ba a late times, waɗannan suna zama kusan t^{-2} da t^{-4}.

Saboda haka densities biyu suna raguwa yayin da universe take faɗaɗa. Amma density ba ita ce jimilla ba.

Da takardar ta integrate quantities ɗin a kan yankin spacetime da yake ƙara girma, faɗaɗar volume ta canza amsar. A misalan matter-dominated da radiation-dominated da muka fi sani a cosmology, **jimillar entropy tana ƙaruwa da lokaci ko da entropy a kowace unit volume tana raguwa**. Jimillar energy ba ta ci gaba da ƙaruwa; a leading order tana kusantar wata constant.

Wannan shi ne sakamakon conceptual da ya fi amfani a takardar. Rage local entropy density ba lallai ya saba wa global second law ba. Wani yanki zai iya samun ƙarancin entropy a kowane unit volume, yayin da integrated entropy ke ƙaruwa saboda spacetime volume yana girma da sauri fiye da raguwar density.

Lissafin bai tabbatar cewa wannan shi ne microscopic explanation na thermodynamic arrow a real Universe ba. Ya nuna cewa proposed framework ɗin zai iya ɗaukar bambancin local-global ba tare da contradiction ba a Friedmann approximation ɗinsa.

Kwatantawa da de Sitter, amma da temperature dabam

Takardar ta kuma duba de Sitter space, idealized spacetime da ke faɗaɗawa exponentially tare da constant H. Ga observer guda, tana integrate ne kawai a finite **causal diamond**: overlap tsakanin future light cone na earlier event da past light cone na later event, wanda ke iyakance region na spacetime da zai iya shiga observations tsakanin lokutan biyu. A wannan diamond, jimillar GfE entropy tana scale da H^{-2}, scaling iri ɗaya da familiar Gibbons-Hawking entropy. Jimillar GfE energy tana da order one a units na samfurin.

> **Iyali ɗaya na cosmological backgrounds**
>
> FRW iyali ne na homogeneous da isotropic geometries, ba wani wuri dabam ba. Matter-dominated da radiation-dominated universes misalan FRW ne da suka bambanta da abin da ke cika samfurin. De Sitter space ma za a iya rubuta ta a FRW form, amma tana wakiltar vacuum-dominated case da constant H da exponential expansion. Causal diamond finite region ne da aka zaɓa a cikin wannan spacetime ga observer

> guda; ba wani sabon nau'in universe ba ne.

Daidaiton scaling ba daidai yake da nuna cewa objects ɗin biyu abu ɗaya ne ba. GfE k-temperature da ke da alaƙa da wannan sakamakon tana scale da H^2, ba kamar standard de Sitter temperature ba, wadda take scale da H. Takardar tana fassara wannan bambanci a matsayin alamar cewa k-temperature tana cikin geometry na spacetime, ba quantum fields da suke rayuwa a kan background ɗin ba.

Sannan ta ba da shawarar cewa irin wannan temperature **mai yiwuwa** tana da alaƙa da graviton radiation maimakon ordinary particle emission. Wannan tambaya ce ta bincike na gaba, ba sakamakon wannan takardar ba. Sai an fara quantize ka'idar kafin a iya tabbatar ko temperatures ɗinta suna da alaƙa da radiation ko a'a.

Abin da wannan binciken bai tabbatar ba

- Bai nuna ta observation cewa gravity tana fitowa daga entropy ba.
- Bai tabbatar cewa effective term na samfurin shi ne dark energy da aka auna a cosmology ba.
- Bai maye gurbin general relativity da wata ka'ida da aka gwada kuma ta fi ta ba. General relativity tana fitowa a nan ne a matsayin low-energy, small-curvature limit na proposal ɗin.
- Bai sa Friedmann cosmologies su zama exact solutions na GfE ba. Approximations ne da aka yi amfani da su wajen kiyasta thermodynamic behavior na samfurin.
- Bai fitar da cikakken microscopic count na spacetime degrees of freedom ba.
- Bai ba da cikakkiyar quantum-gravity theory ko gano gravitons ba.
- Bai nuna cewa negative k-temperatures ordinary negative thermometer readings ba ne.

Yaya ƙarfin sakamakon yake?

Wannan takarda ce ta ka'ida da aka yi peer review, don haka "shaida" a nan tana da ma'ana dabam da ta gwaji. Tambayoyin da suka dace su ne ko definitions suna da haɗin kai, ko derivations suna bin lissafi, da ko approximations an bayyana iyakokinsu kuma ana sarrafa su.

A wannan matakin, takardar tana ba da cikakken thermodynamic dictionary ga GfE kuma tana fitar da first-law structure maimakon dogaro da analogy kawai. Haka kuma tana bayyana iyakar approximation sosai: Friedmann solutions an aro su daga general relativity, an saka su cikin GfE quantities, sannan an takaita amfani da su zuwa regime inda induced metric take ci gaba da kasancewa mai kyau.

Manyan ikiraran physical har yanzu a buɗe suke. Tsarin sabo ne, wannan takardar ba ta kwatanta cosmology ɗinsa da bayanan observation ba, kuma wasu daga cikin abubuwan da suka fi ban sha'awa — quantization, contact-geometric dynamics da yiwuwar graviton radiation — an gabatar da su a matsayin abubuwan bincike na gaba. Internal consistency abu ne da sabuwar ka'idar gravity take buƙata. Amma shi kaɗai bai isa ya nuna cewa ka'idar tana bayyana nature ba.

Me ya sa wannan yake da muhimmanci

Alaƙar gravity da thermodynamics tsohuwa ce kuma mai zurfi, tun daga entropy na black holes zuwa temperature na de Sitter space. Yawancin waɗannan sakamakon suna juyawa ne a kan horizons. GfE kuwa tana ƙoƙarin gina local, volumetric information measure kai tsaye daga alaƙar matter da geometry.

Ko proposal ɗin zai jure gwaje-gwajen gaba har yanzu tambaya ce a buɗe. Amma wannan aikin thermodynamics yana bayyana wata manufa mai amfani ga kowace irin ka'ida: ya kamata ta iya bayyana yadda local structure da raguwar local entropy density za su iya kasancewa tare da ƙaruwa a jimillar entropy a universe mai faɗaɗawa.

Wannan takarda tana nuna hanya ɗaya ta lissafi da hakan zai iya faruwa. Darajarta ba cewa ta rufe matsalar gravity-entropy ba ce. Tana juya wani ɓangaren matsalar zuwa equations da za a iya bayyana zato, iyaka da gwaje-gwajen gaba a sarari.

Takaitaccen bayani

Bianconi ta fitar da bayanin thermodynamics a cikin **Gravity From Entropy**, wani proposed modified-gravity framework da aka gina a kan geometric quantum relative entropy. Local entropy, energy, temperature da pressure na samfurin suna bin first law. Idan aka ƙididdige full GfE quantities a kan Friedmann approximations na low-energy da small-curvature, local entropy da energy densities suna raguwa yayin da universe take faɗaɗa, amma **jimillar entropy tana ƙaruwa** saboda spacetime volume tana girma; a misalan matter- da radiation-dominated, jimillar energy tana kusantar constant a leading order. De Sitter causal diamond yana ba da entropy scaling da H^{-2}, amma temperature na samfurin ya bambanta da standard horizon temperature. Waɗannan sakamakon lissafi ne masu sharadi a cikin GfE — ba observation cewa gravity tana fitowa daga entropy ba, ba ma'aunin dark energy ba, kuma ba cikakkiyar quantum-gravity theory ba.

Majiyoyi

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