Holographic Features of a De Sitter Universe

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General Idea

EXPERIMENT: spacetime expanding at accelerating rate

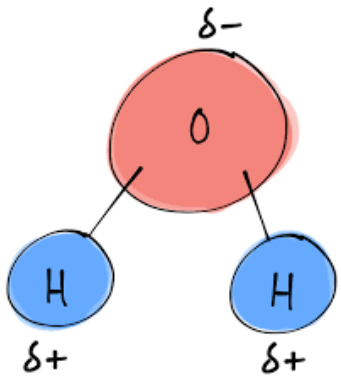
THEORY: spacetime is collective/emergent $\sim$ Holography

Consolidation?

Sakharov-'t Hooft-Polyakov-...:

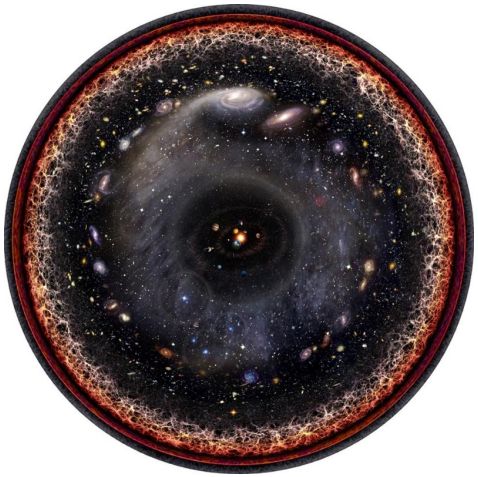
General relativity emerges in limiting sense from LARGE N constituents.

Analogy: Navier stokes equations emerging from large N atoms.



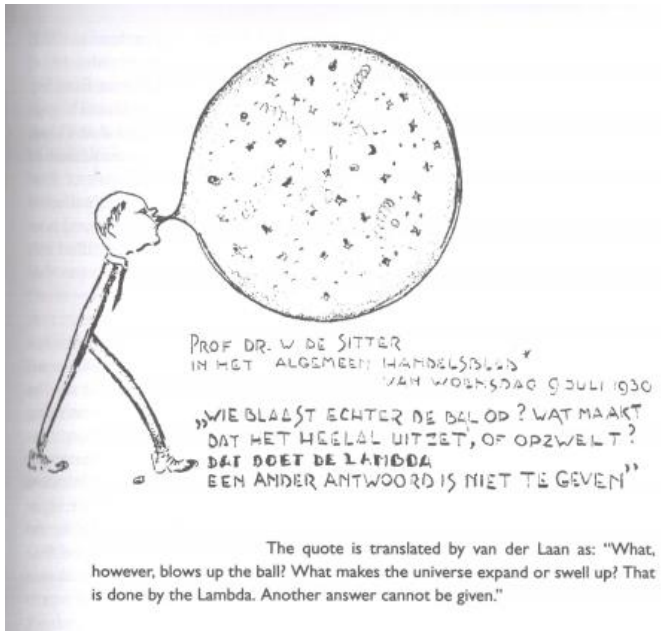
Example: ADS/CFT

...-Maldacena-...: Spacetime endowed with deep gravitational well has microscopic constituents living entirely on boundary, in form of a local (conformal) QFT.



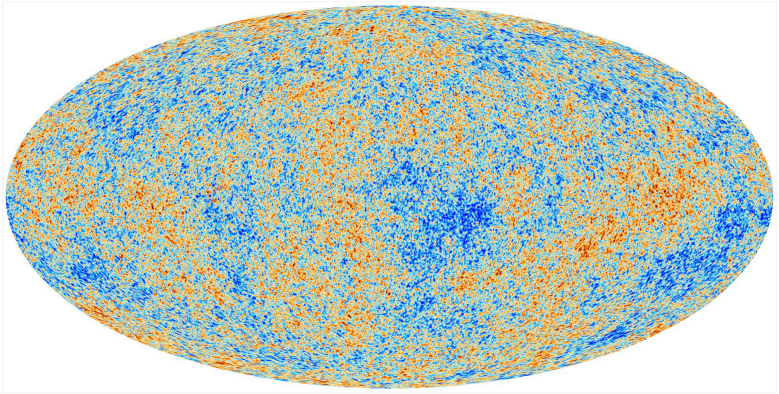
graviton $\leftrightarrow$ bounday stress tensor operator

Inflationary Picture



The quote is translated by van der Laan as: "What, however, blows up the ball? What makes the universe expand or swell up? That is done by the Lambda. Another answer cannot be given."

- Scale invariant density perturbations $\rightsquigarrow$ big bang/inflation picture.



Planck collaboration (2013)

- Expansion $\rightsquigarrow$ quantum fluctuations seed macroscopic structure.

[Guth-Linde-Albrecht,Steinhart-Starobinsky-Mukhanov-Chibishov-Guth,Pi-Hawking. . .]

PURE de Sitter geometry:

$$\boxed{ds^2 = \frac{-d\eta^2 + d\mathbf{x}^2}{\eta^2}} \,, \qquad \eta \in (-\infty, 0) \,, \qquad \mathbf{x} \in \mathbb{R}^3$$

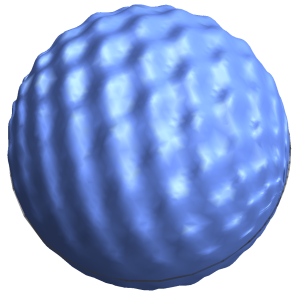
SYMMETRIES: $SO(4,1)$ with late time behaviour:

$$\boxed{\mathbf{x} \to \lambda \mathbf{x} \,, \quad \mathbf{x} \to \mathbf{\Lambda}\,\mathbf{x} + \mathbf{a} \,, \quad \mathbf{x} \to \frac{\mathbf{x} + x^2 \mathbf{b}}{1 + 2\mathbf{x}\cdot\mathbf{b} + x^2 b^2}}$$

Unitary irreps organize Hilbert space (Δ, s)

$$[\hat{\alpha}_\Delta(\mathbf{x}), \hat{\beta}_{3-\Delta}(\mathbf{y})] = i\delta(\mathbf{x} - \mathbf{y})$$

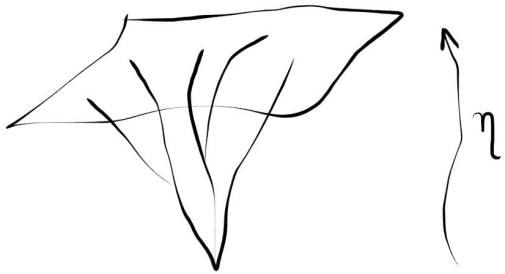
Wheeler-de Witt: There is a wavefunction $\Psi[g]$ for the geometry of space.



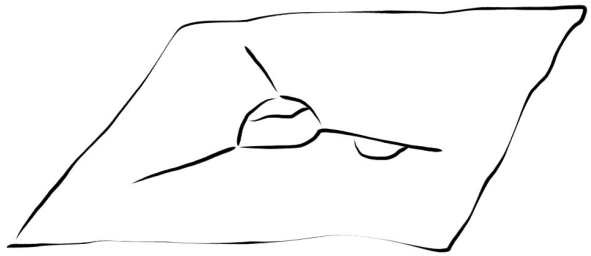
g = shape and size of space

Hartle-Hawking: Semiclassical path integral expression for $\Psi[g]$.

Correlations $\sim$ 3d CFT Ward identities $\stackrel{?}{\Longrightarrow}$ dS-CFT CORRESPONDENCE
[Hull-Strominger-Witten-Maldacena-...]



BULK: $\int \frac{d\eta}{\eta^4} \prod_i G(\mathbf{k}_i, \eta)$



BOUNDARY: $\langle \prod_i \mathcal{O}(\mathbf{k}_i) \rangle_{CFT}$

Open problem: build a complete, precise example of dS-CFT.

New direction: Vasiliev's theory of MASSLESS particles with ALL SPINS.

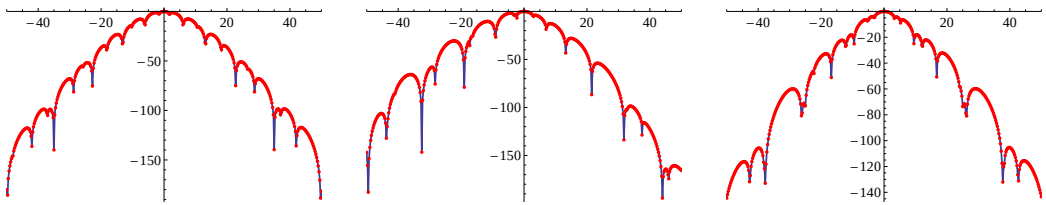
4d ✓ de Sitter vacuum ✓ No moduli stabilization problem ✓

Highly constraining mathematical structure ✓

$$\boxed{\Psi[\mathcal{B}] = \det{}^{N}\left[-\nabla^2 + \mathcal{B}\right] e^{N\,\mathrm{tr}\nabla^{-2}\mathcal{B}}} \qquad N = \frac{\ell^2}{\ell_P^2}$$

$\mathcal{B}_{\mathbf{xy}} = \delta_{\mathbf{xy}}\left(\phi_{\mathbf{x}} + A^i_{\mathbf{x}}\partial_i + g^{ij}_{\mathbf{x}}\partial_i\partial_j + \ldots\right)$ encodes profiles of all h.s. particles.

Invariant under symmetries ✓ Gaussian suppressed about dS ✓ Cubic terms ✓



Plot of $\log|\Psi|$ for various spherical harmonics of scalar.

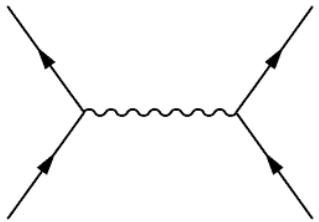
[D.A.;D.A.,Denef,Harlow;D.A.,Denef,Shaghoulian,Konstantinidis]

HS particles are COMPOSITE: $\hat{\mathcal{B}}(\mathbf{x},\mathbf{y}) = \sum_{I=1}^{N} \hat{\mathcal{Q}}^I(\mathbf{x})\hat{\mathcal{Q}}^I(\mathbf{y})$

Exact vacuum state:

$$\boxed{\Psi[\mathcal{Q}^I(\mathbf{x})] = \prod_{I=1}^{N} e^{-\int d\mathbf{x}\, \partial_{\mathbf{x}}\mathcal{Q}^I(\mathbf{x})\partial_{\mathbf{x}}\mathcal{Q}^I(\mathbf{x})}}$$

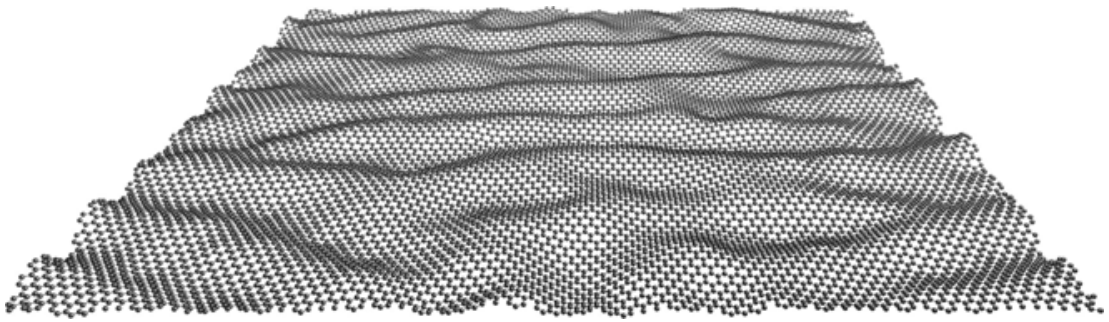
$\mathcal{Q}^I(\mathbf{x})$ measure FLAT $\Longrightarrow$ Exact formula for cosmological correlations



$$\boxed{\langle\phi(\mathbf{k_1})\phi(\mathbf{k_2})\phi(\mathbf{k_3})\phi(\mathbf{k_4})\rangle = \frac{(k_1k_2+k_3k_4)k_{21}+(k_1k_4+k_2k_3)k_{23}}{k_{21}k_{23}(k_1k_3+k_2k_4+k_{21}k_{23})} + perm.}$$

Number of $\hat{\mathcal{Q}}^I(\mathbf{x})$ operators $\ll$ number of higher spin fields

$\Longrightarrow$ Bound on # of field theoretic d.o.f: $N = \ell^2/\ell_{Pl}^2$



$\hat{\mathcal{Q}}^I(\mathbf{x})$ are 'atoms' of higher spin de Sitter Universe

Worldline Picture

De Sitter's Static Universe

Supernovae + CMB suggest we are in Λ-dominated phase.

G299 Type Ia supernova, NASA

- Eventually $\rightsquigarrow$ de Sitter's static universe.
- Size is $\ell \sim 20$ billion light years. Physics INACCESSIBLE beyond this.

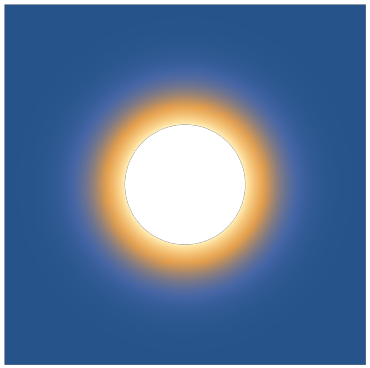
Cosmological Horizon

STATIC GEOMETRY:

$$ds^2 = -dt^2(\ell^2 - r^2) + \frac{dr^2}{(\ell^2 - r^2)} + r^2 d\Omega^2$$

Gibbons,Hawking:

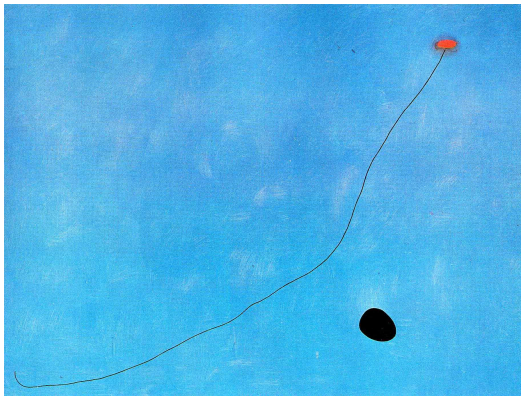
Temperature $= \frac{\hbar c}{2\pi\ell}$ & Entropy $= \frac{\ell^2}{\ell_{Pl}^2}$



Fluctuations of Cosmological Horizon

[D.A.;D.A.,Hartnoll,Hofman]

Absence of spatial/temporal boundaries $\Longrightarrow$ Focus on WORLDLINE



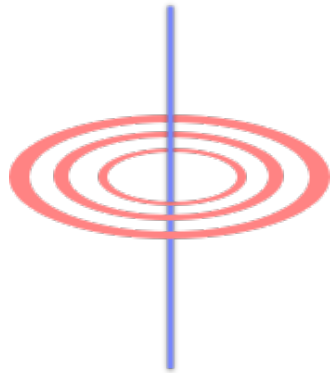
e.g. Send a localized pulse toward horizon and measure response

Brief Detour: Holographic Worldlines

Certain LARGE N Quantum Mechanics Theories are Holographic

Space emerges out of WORLDLINE

$\Longrightarrow$ NO SPATIAL BOUNDARY



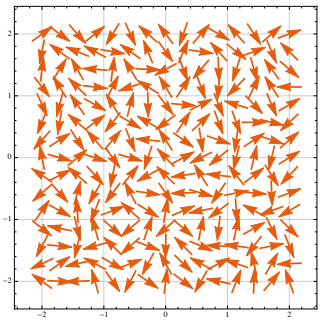
Boundary Worldline is RIGID location where QM Operators reside

Strominger-Sen: Holography $\sim$ CONFORMAL $SL(2,\mathbb{R})$ QM

$$\boxed{ds^2 = \frac{-dt^2 + dz^2}{z^2}\ , \qquad z > 0}$$

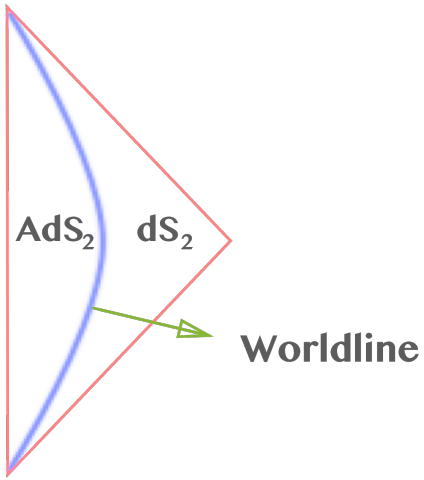
DISORDER + large N give emergent $SL(2,\mathbb{R})$ [D.A.,Anous,deLange,Cos]

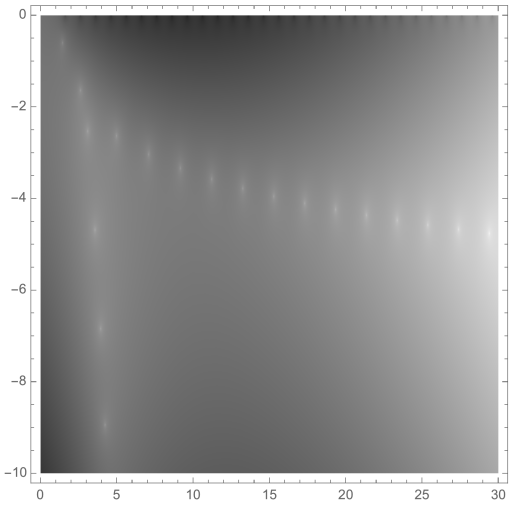
Concrete QM Model (SYK) with disordered fermions [Sachdev,Ye-Kitaev]:



- Quantum glass techniques, replica theory
- Linear T specific heat
- $SU(2)$ symmetry + rotation
- Strongly coupled, gappless 'liquid' phase

AdS_2 boundary with dS interior $\Longrightarrow$ Holographic model for static patch





Boundary correlators exhibit dS features ✓ Thermal stability ✓ Ergodicity ?

Hint For Microscopic Model

- dS static region dual to dissipative large N QM
- Conformal QM + relevant ~~$SL(2,\mathbb{R})$~~ deformation from AdS_2 fixed point

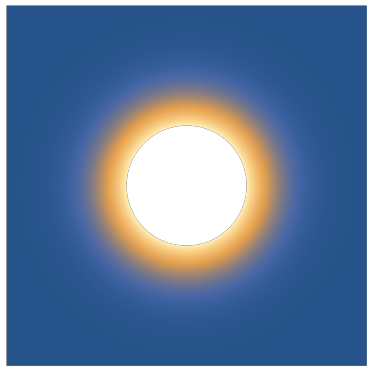
Recap

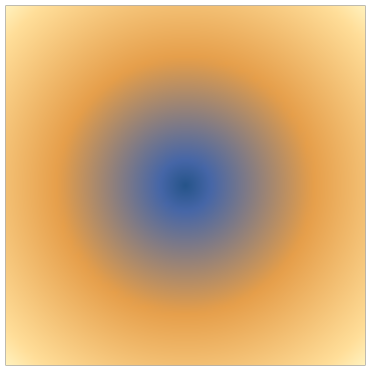
- ⋆ We can make sharp statements about an eternally inflating spacetime
- ⋆ Complete mathematical description for higher spin example
- ⋆ Insight toward de Sitter conformal bootstrap equations
- ⋆ Cosmological horizon as holographic liquid

Outlook

Different descriptions $\sim$ Exterior vs. interior horizon

Bekenstein-Susskind,Uglum,Thorlacius...: d.o.f are SAME

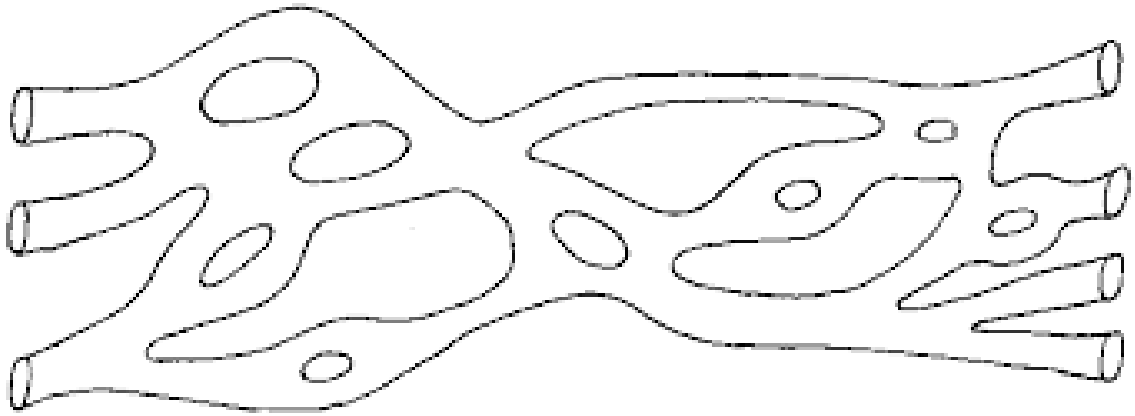




Precise realization of COMPLEMENTARITY IDEA?

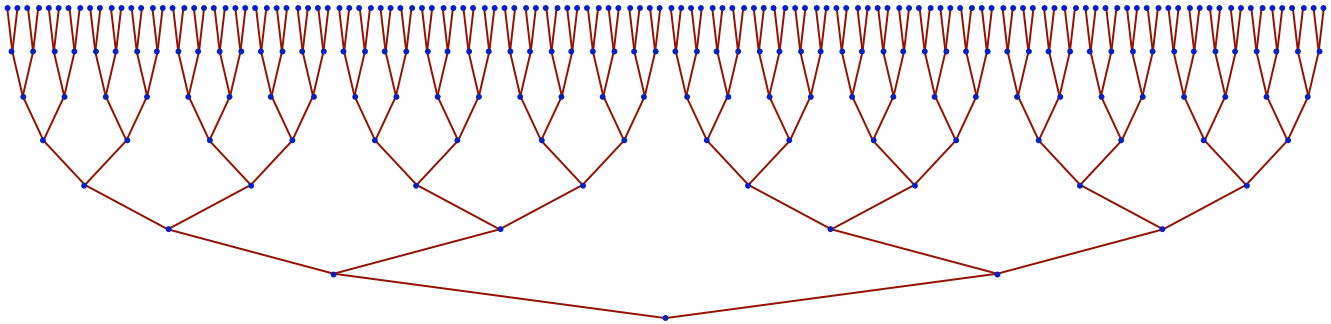
Banks-Fischler,Verlinde...: Static patch has FINITE HILBERT SPACE

't Hooft: Large N matrices $\rightsquigarrow$ string worldsheet $\rightsquigarrow$ gravity



D.A.-Silva: Study Emergent worldsheet of FERMIONIC large N matrix QM

Features of Ψ indicate it was produced by COSMOLOGICAL EVOLUTION?
[D.A.,Denef;Arkani-Hamed,Benincasa,Postnikov]



Parisi Overlap distributions of late time configs $\sim$ TREE LIKE STRUCTURE

ΕΥΧΑΡΙΣΤΩ ΠΟΛΥ!