Title: Cosmology, Quantum Gravity and a Constant

Speakers: Stephon Alexander

Collection/Series: Lee's Fest: Quantum Gravity and the Nature of Time

Date: June 02, 2025 - 1:00 PM

URL: https://pirsa.org/25060032

Abstract:

Cosmological data is consistent with a positive cosmological constant. In this talk I discuss an approach pioneered by Smolin that uses a non-perturbative exact quantization of gavity with a cosmological constant in the Ashtekar formalism. I discuss follow up work by the Author and his collaborators that address some conceptual and potential physical predictions of this approach. I end with a discussion of Smolin's cosmic natural selection as a predictive mechanism which also had consequences in particular Anthrophic landscape realizations in string theory.

A Cosmic Journey with Lee

Stephon H.S. Alexander

Brown Theoretical Physics Center

Brown University

Lee's Fest

BROWN

What do we know?

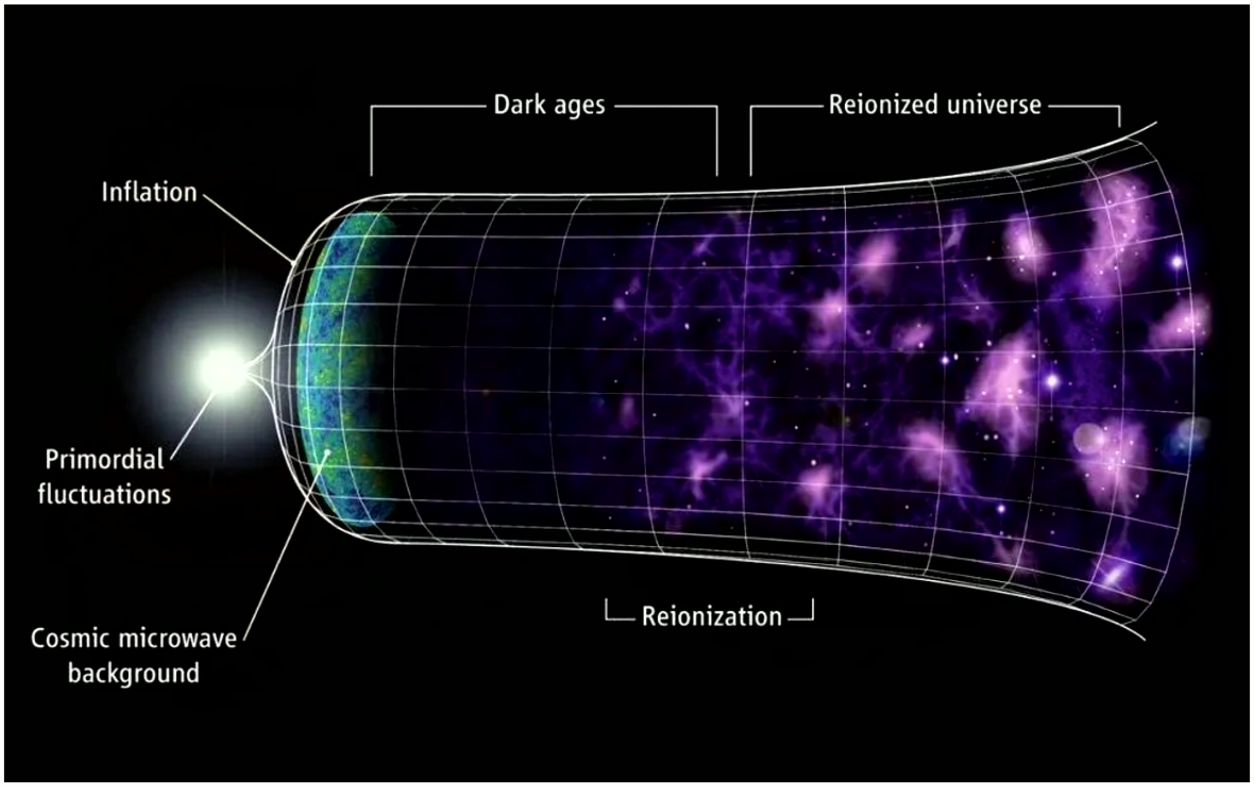
- General Relativity
- The Standard Model of Particle Physics

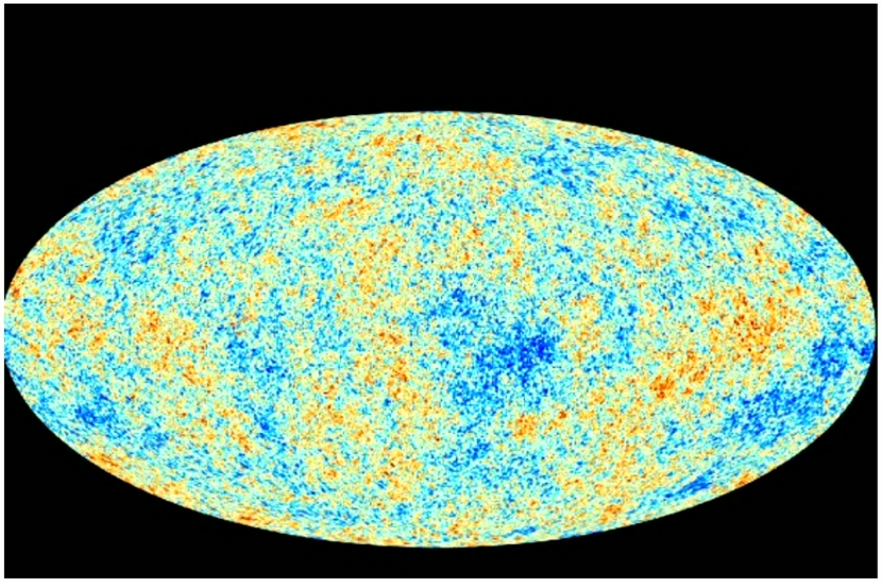
Principles

- SYMMETRY!
- General Relativity elevates the equivalence principle to general coordinate invariance.
- Standard Model has gauge invariance and is chiral.
- General Relativity is not-chiral: it does not distinguish between right- and left-handed states.

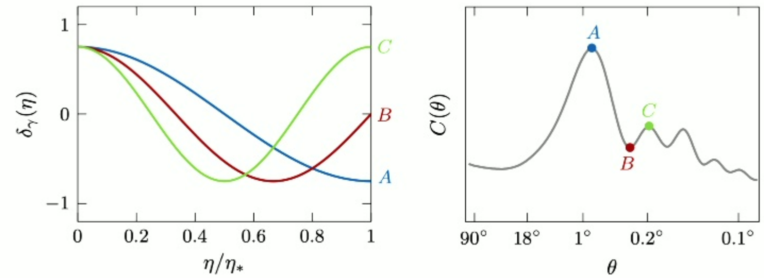
But there is a subtle exception!

Cosmic History





Acoustic Peaks

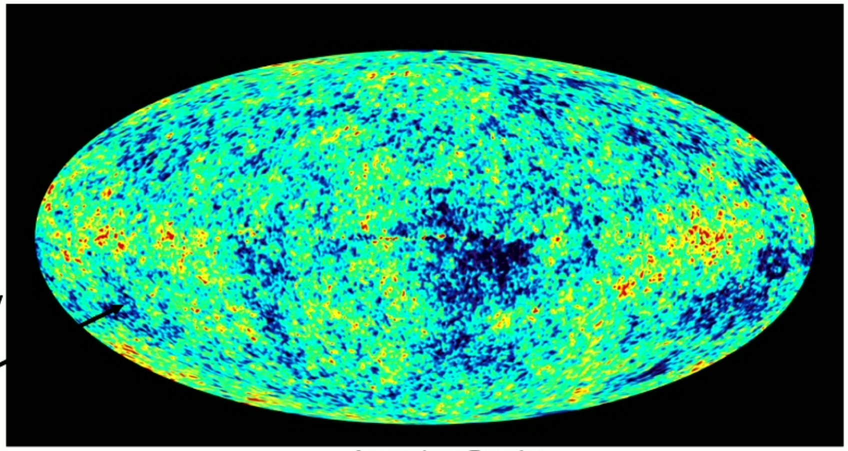


$$\delta_\gamma'' + \frac{R'}{1+R}\delta_\gamma' - \frac{1}{3(1+R)}\nabla^2\delta_\gamma = \frac{4}{3}\nabla^2\Psi + 4\Phi'' + \frac{4R'}{1+R}\Phi'$$

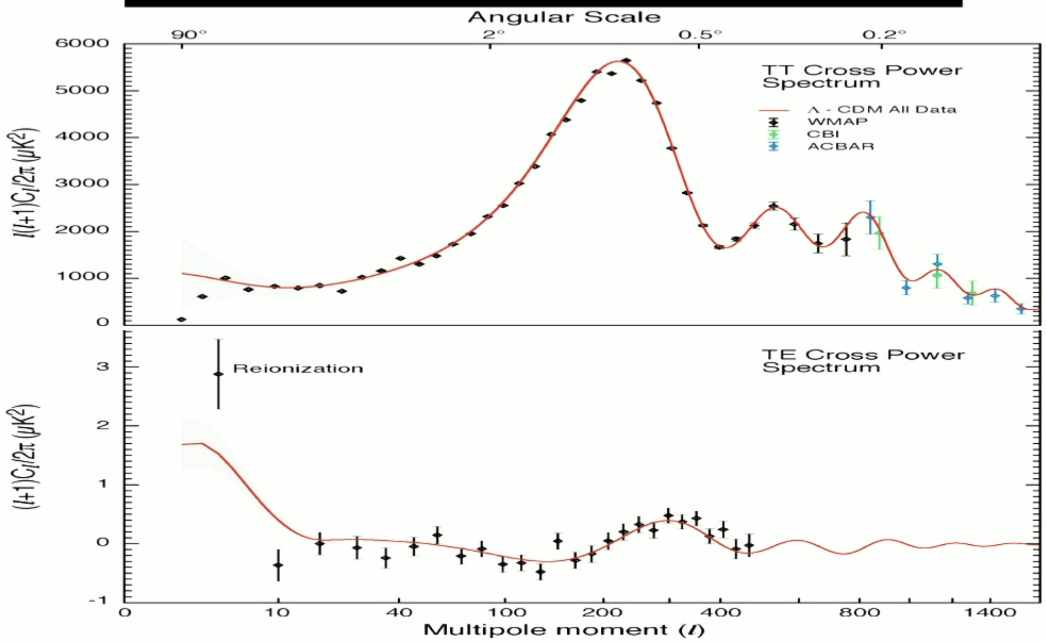
What causes these fluctuations?

Black dots - experimental results.

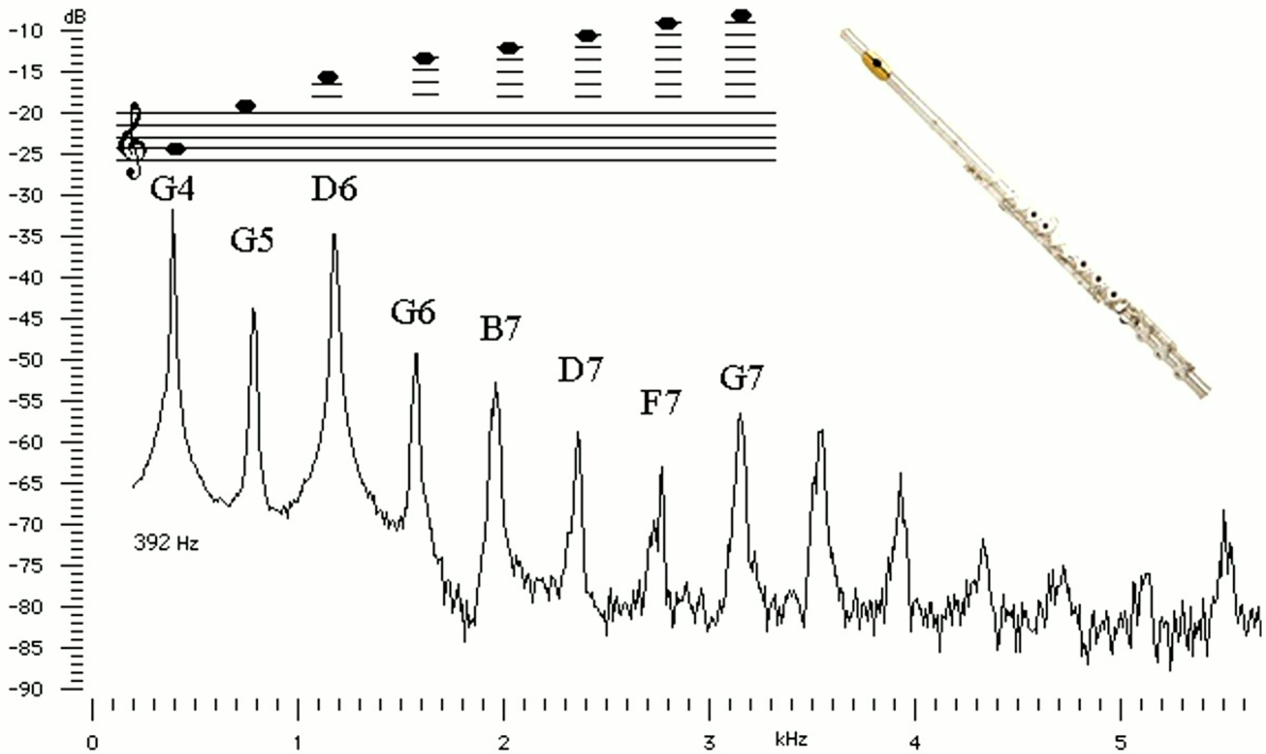
Red line - predictions of inflationary theory



Fluctuations grow into galaxies

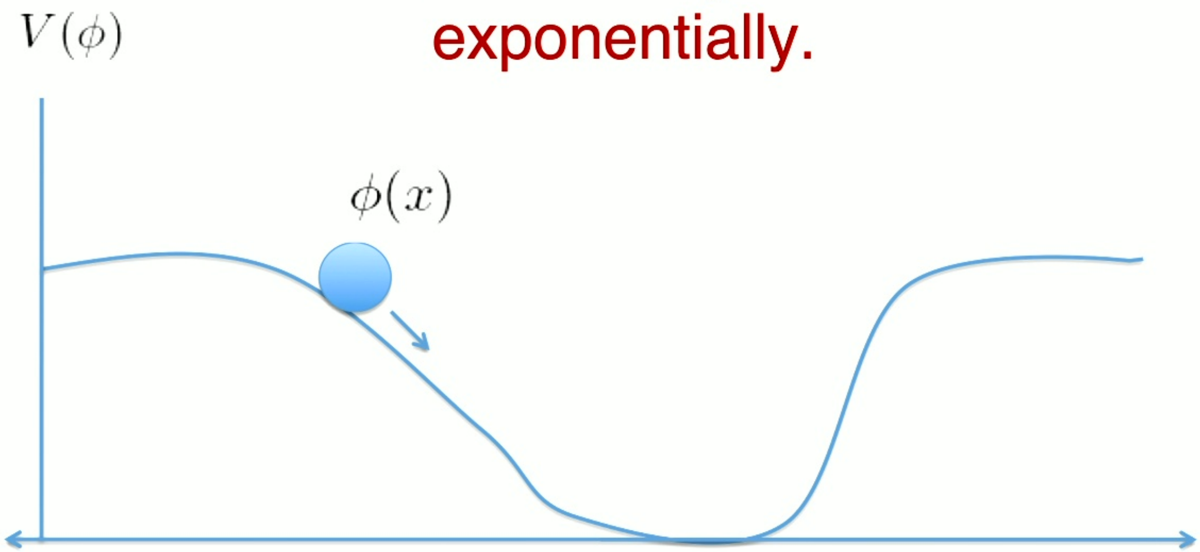


Power Spectrum of A Flute



Cosmic Inflation

The Inflation field's false vacuum energy yields a repulsive force that stretches space exponentially.



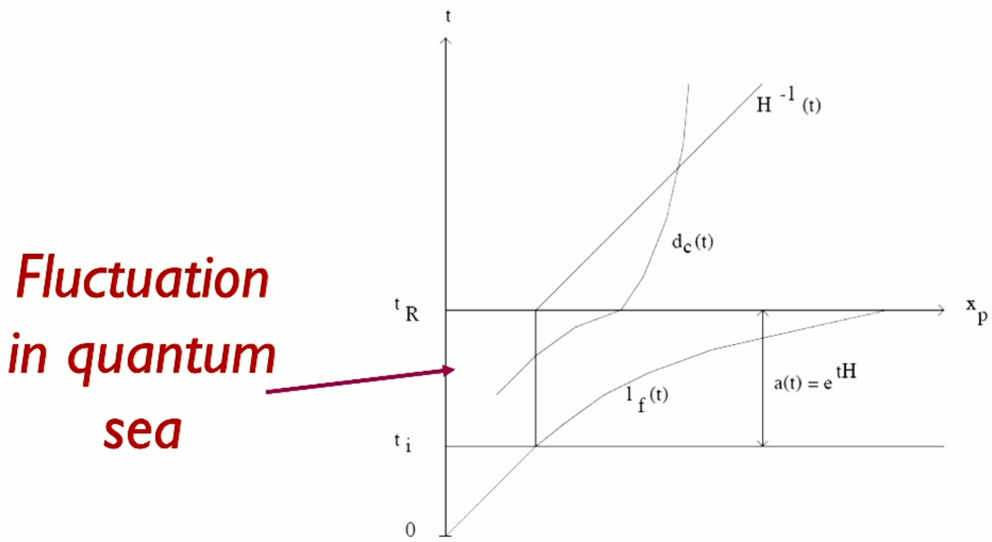
But it is hard to get a field with these properties in our standard model of particle physics

*The Inflaton could be the Higgs
S.A, Sarbinowski, Gilmer, Freese (2023)

Major Bonus!

Inflation and Structure Formation

Inflation provides us with a causal and predictive
Mechanism for generating the primordial perturbations
Required for galaxies, clusters and super-clusters (LSS)



Quantum Gravity and deSitter

- The inflationary quantum fluctuations are generated in de Sitter space
- But backreaction can render these perturbations to be O(1)
- We are motivated to study non perturbative, background independent quantization of de Sitter (Positive CC)
- The Guth-Vilenkin-Borde theorem: inflationary spacetimes inflation alone is geodesically incomplete.

Gravity Waves and Inflation

- Scalar field experiences quantum fluctuations during inflation
  - These source gravitational potentials → cosmic structure.
- Space-time (metric-field) also undergoes quantum fluctuations: Gravitational Waves.
- What is the physical role of Gravitational Waves?

$$\mathrm{d}\ell^2 = e^{2Ht}\left[(1+\zeta)\delta_{ij} + h_{ij}\right]\mathrm{d}x^i \mathrm{d}x^j$$

expansion (e^{2Ht}): $H(t) \approx const$

scalar (ζ): *isotropic stretching*

tensor (h_{ij}): *anisotropic stretching*

PHYSICAL REVIEW D, VOLUME 65, 023507

Inflation from D-$\bar{\mathrm{D}}$ brane annihilation

Stephon H. S. Alexander
Theoretical Physics Division, Imperial College, The Blackett Laboratory Prince Consort Road, London, SW7 2BZ United Kingdom
(Received 22 May 2001; published 21 December 2001)

We demonstrate that the initial conditions for inflation are met when a D5-$\bar{\mathrm{D}}$5 brane annihilates. This scenario uses Sen's conjecture that a codimension two vortex forms on the worldvolume of the annihilated 5-brane system. Analogous to a "big bang," when the five branes annihilate, a vortex localized on a 3-brane forms and its false vacuum energy generates an inflationary space-time. We also provide two possible mechanisms for ending inflation via the decay of a metastable vortex, or radiation of the cosmological constant into the bulk space-time.

DOI: 10.1103/PhysRevD.65.023507 PACS number(s): 98.80.Cq

- Lee at Jaron's in Tribeca
- Calculated the de Sitter Temperature using

The KMS Conditon in the Kodama State

Lessons from Leon Cooper

Ashtekar Formalism

$$S_{\text{EH}} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\; R$$
$$= \frac{1}{16\pi G}\int dtd^3y\; N\sqrt{q}\left(R^{(3)} + K^{ab}K_{ab}K^{ab} - K^2\right)$$

$$A_a^i = \Gamma_a^i - \frac{1}{\beta}K_a^i$$

$$H_{\text{Ashtekar}} = \int d^3x\left(N\tilde{\mathcal{H}} + N^a\mathcal{H}_a + \lambda^i\mathcal{G}^i\right)$$

$$\tilde{\mathcal{H}} = \frac{\beta^2}{16\pi G\sqrt{|\tilde{E}|}}\epsilon^{ijk}\tilde{E}_i^a\tilde{E}_j^b\left(F_{ab}^k + \frac{\Lambda}{3}\epsilon_{abc}\tilde{E}_k^c\right)$$

$$\hat{\tilde{\mathcal{H}}}\Psi[A] = 0.$$

$$\left(F_{ab\ k} - i\frac{\Lambda 8\pi G\hbar\beta}{3}\epsilon_{abc}\frac{\delta}{\delta A_c^k}\right)\Psi[A] = 0.$$

$$\Psi[A] = \mathcal{N}e^{-\frac{3i}{2\beta\Lambda\ell_{\mathrm{Pl}}^2}\mathrm{CS[A]}}$$

$$\mathrm{CS}[A] = \int_{\Sigma_3}\mathrm{Tr}\left(A\wedge dA + \frac{2}{3}A\wedge A\wedge A\right)$$

Issues

Thiemann (book), Witten gr-qc/0306083

- This state is non-normalizable in naive inner product.
- ”not invariant” under large gauge transformations
- Reality Conditions
- What about time?

PHYSICAL REVIEW D **70**, 044025 (2004)

Quantum gravity and inflation

Stephon Alexander
Stanford Linear Accelerator Center and ITP Stanford University, Stanford, California 94309, USA

Justin Malecki
Department of Physics, University of Waterloo, Ontario, Canada and Perimeter Institute for Theoretical Physics, Waterloo, Canada

Lee Smolin
Perimeter Institute for Theoretical Physics, Waterloo, Canada
(Received 22 October 2003; published 20 August 2004)

Using the Ashtekar-Sen variables of loop quantum gravity, a new class of exact solutions to the equations of quantum cosmology is found for gravity coupled to a scalar field that corresponds to inflating universes. The scalar field, which has an arbitrary potential, is treated as a time variable, reducing the Hamiltonian constraint to a time-dependent Schrödinger equation. When reduced to the homogeneous and isotropic case, this is solved exactly by a set of solutions that extend the Kodama state, taking into account the time dependence of the vacuum energy. Each quantum state corresponds to a classical solution of the Hamiltonian-Jacobi equation. The study of the latter shows evidence for an attractor, suggesting a universality in the phenomena of inflation. Finally, wave packets can be constructed by superposing solutions with different ratios of kinetic to potential scalar field energy, resolving, at least in this case, the issue of normalizability of the Kodama state.

DOI: 10.1103/PhysRevD.70.044025 PACS number(s): 04.60.Ds

We seek a non-perturbative, background independent Quantization of Inflation

By gauge fixing the "slow roll" conditions

$$\mathcal{H}^{\mathrm{grav}} = \frac{1}{l_p^2}\epsilon_{ijk}E^{ai}E^{bj}\left(F_{ab}^k + \frac{GV(\phi)}{3}\epsilon_{abc}E^{ck}\right)$$

$$H = \pm\frac{\sqrt{2}}{l_p^2}\int_{\mathcal{S}}[-\mathcal{H}^{\mathrm{grav}} - \mathcal{H}^{\Psi}]^{1/2}. \quad \Longrightarrow \quad i\frac{\partial\Psi}{\partial T} = \hat{H}\Psi$$

$$S_u(A,T) = \frac{R^3 A^3}{3 l_p V}[1 + u(T)].$$

$$i \frac{\partial \Psi}{\partial T} = \hat{H} \Psi$$

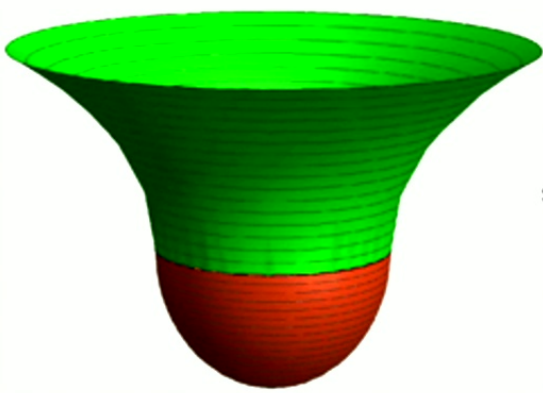
$$\Psi(A,T) = e^{(6\sqrt{3}/l_p)\int_{T_0}^{T} \sqrt{-u(t)}dt + i(A^3 R^3/3Vl_p)(1+u)}$$

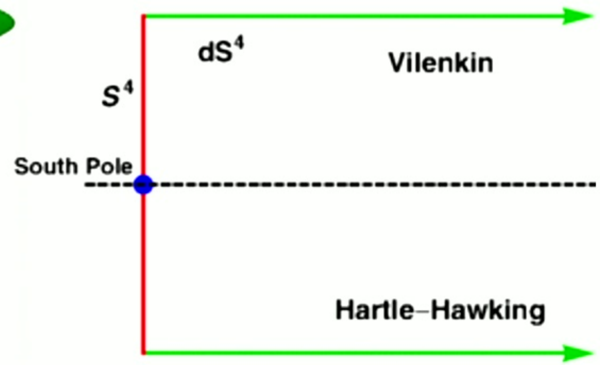
$$\dot{u} = \frac{\dot{V}}{V}(1+u) + \frac{18i}{l_p}(1+u)\sqrt{3u}.$$

The Prosecco Island Conference

Inflationary Quantum Perturbations Reloaded

- Magueijo demonsrated that the Kodama state encodes both Hartle-Hawking and Vilenkin *Phys.Rev.D* 102 (2020)





Perturbed Perturbation Theory

Volume 198, number 2 PHYSICS LETTERS B 19 November 1987

THE EUCLIDEAN VACUUM: JUSTIFICATION FROM QUANTUM COSMOLOGY

Raymond LAFLAMME
Department of Applied Mathematics and Theoretical Physics, Silver Street, Cambridge CB3 9EW, UK

Received 26 June 1987; revised manuscript received 28 August 1987

We evaluate the wave function of the universe for a de Sitter minisuperspace with inhomogeneous matter perturbations from a massive scalar field. From the Wheeler–DeWitt equation, we derive Schrödinger equations for the matter modes. We show that

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY
Class. Quantum Grav. **21** (2004) 3831–3844 PII: S0264-9381(04)77126-9

The linearization of the Kodama state

Laurent Freidel[1,2] and Lee Smolin[3]

[1] Perimeter Institute for Theoretical Physics, 35 King Street North, Waterloo N2J 2G9, Ontario, Canada
[2] Laboratoire de Physique, UMR 5672 du CNRS, École Normale Supérieure de Lyon, 46 allée d'Italie, 69364 Lyon Cedex 07, France
[3] Perimeter Institute for Theoretical Physics, 35 King Street North, Waterloo N2J 2G9, Ontario, Canada

E-mail: lfreidel@perimeterinstitute.ca and lsmolin@perimeterinstitute.ca

Received 4 March 2004
Published 23 July 2004

PRL **106,** 121302 (2011) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2011

Chiral Vacuum Fluctuations in Quantum Gravity

João Magueijo and Dionigi M. T. Benincasa
Theoretical Physics, Blackett Laboratory, Imperial College, London, SW7 2BZ, United Kingdom
(Received 18 October 2010; published 21 March 2011)

We examine tensor perturbations around a de Sitter background within the framework of Ashtekar's variables and its cousins parameterized by the Immirzi parameter γ. At the classical level we recover standard cosmological perturbation theory, with illuminating insights. Quantization leads to real novelties. In the low energy limit we find a second quantized theory of gravitons which displays different vacuum fluctuations for right and left gravitons. Nonetheless right and left gravitons have the same (positive) energies, resolving a number of paradoxes suggested in the literature. The right-left asymmetry of the vacuum fluctuations depends on γ and the ordering of the Hamiltonian constraint, and it would leave a distinctive imprint in the polarization of the cosmic microwave background, thus opening quantum gravity to observational test.

DOI: 10.1103/PhysRevLett.106.121302 PACS numbers: 04.60.Bc, 04.60.Ds, 98.80.−k

PRL 101, 141101 (2008) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2008

Anomalous Cosmic-Microwave-Background Polarization and Gravitational Chirality

Carlo R. Contaldi,[1] João Magueijo,[1] and Lee Smolin[2]

[1]*Theoretical Physics, Imperial College, Prince Consort Road, London, SW7 2BZ, United Kingdom*

[2]*Perimeter Institute, 31 Caroline Street North, Waterloo, Ontario N2L 2Y5, Canada*

(Received 18 June 2008; published 2 October 2008)

We consider the possibility that gravity breaks parity, with left and right-handed gravitons coupling to matter with a different Newton's constant and show that this would affect their zero-point vacuum fluctuations during inflation. Should there be a cosmic background of gravity waves, the effect would translate into anomalous cosmic microwave background polarization. Nonvanishing temperature-magnetic (TB) mode [and electric-magnetic mode] components emerge, revealing interesting experimental targets. Indeed, if reasonable chirality is present a TB measurement would provide the easiest way to detect a gravitational wave background. We speculate on the theoretical implications of such an observation.

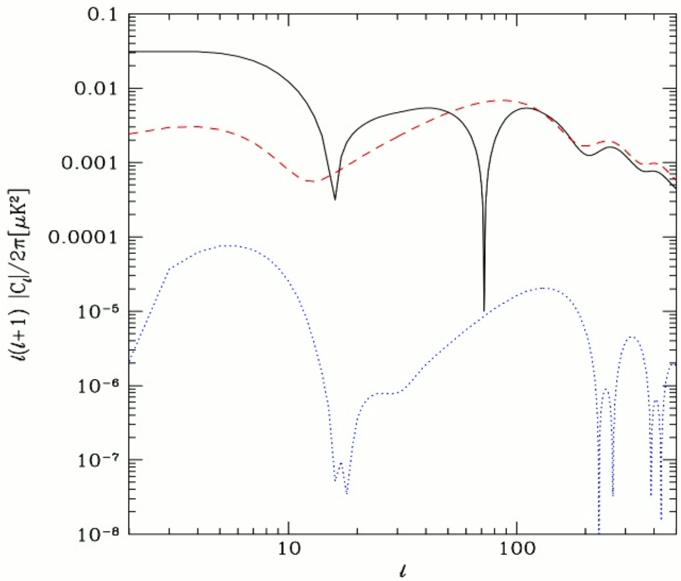


FIG. 1 (color online). Tensor contribution to the TB (solid, black), BB (dashed, red), and EB (dotted, blue) spectra for a standard ΛCDM model with tensor-to-scalar ratio $r = 0.1$ and chirality parameter $\gamma = 10$.

IOP Publishing Classical and Quantum Gravity

Class. Quantum Grav. **40** (2023) 145010 (23pp) https://doi.org/10.1088/1361-6382/acde3d

An inner product for 4D quantum gravity and the Chern–Simons–Kodama state

Stephon Alexander[1], **Gabriel Herczeg**[1,*] **and Laurent Freidel**[2]

[1] Brown Theoretical Physics Center Department of Physics, Brown University, Providence, RI 02912, United States of America

[2] Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario N2L 2Y5, Canada

We implement the reality conditions quantum mechanically

$$(\hat{E}^a_i)^\dagger = \hat{E}^a_i,$$

$$\hat{E}^a_i \Psi = \ell^2_{\rm Pl} \frac{\delta \Psi}{\delta A^i_a}, \qquad \hat{A}^i_a \Psi(A) = A^i_a \Psi(A)$$

$$\hat{A}^i_a + (\hat{A}^i_a)^\dagger = 2\hat{\Gamma}^i_a.$$

$$\langle \Psi | \Psi \rangle = \int_{\mathcal{C}\times\bar{\mathcal{C}}} DAD\bar{A}\, \exp\left(-S(\Re A)\right) |\Psi(A)|^2$$

$$\exp\left(-S(\Re A)\right) := \int DE \exp\left(-\frac{1}{\ell^2_{\rm Pl}} \int e_i \wedge {\rm d}_{\Re A} e^i\right)$$

To Appear
with grad students
Jake Kuntzleman & Max Pezzelle

- We perform a self-consistent functional perturbation using the graviton-antigraviton decomposition of Magueijo et al.

$$e^{-S(\Re A)} = \int DH\Big(1 - \int d^3x d^3y \eta_{ia}(\mathbf{x})\big(\delta^{(3)}(\mathbf{x}-\mathbf{y})\epsilon^{ikj}\epsilon^{acb}\Re A_{kc}(\mathbf{x})\big)\eta^j_b(\mathbf{y}) + ...\Big) \times \exp\Big[-\int d^3x d^3y \eta_{ia}(\mathbf{x})\mathcal{M}^{ia}{}_j{}^b(\mathbf{x},\mathbf{y})\eta^j_b(\mathbf{y})\Big].$$

Graviton Fock Space Factorizes into CPT sectors

$$\tilde{\Psi}_{dSK}[E] = \mathcal{N}_0\tilde{\Psi}_+[E]\tilde{\Psi}_-[E]$$

$$\hat{C}\hat{P}\hat{T}\Psi^+_K[E] = [\Psi^-_K[E]^*]^{-1}.$$

symmetry

MDPI

Article

The Quantum Cosmological Constant

Stephon Alexander [1], Joao Magueijo [2] and Lee Smolin [3,*]

[1] Department of Physics, Brown University, Providence, RI 02906, USA
[2] Theoretical Physics Group, The Blackett Laboratory, Imperial College, Prince Consort Rd., London SW7 2BZ, UK
[3] Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2J 2Y5, Canada
* Correspondence: lsmolin@perimeterinstitute.ca

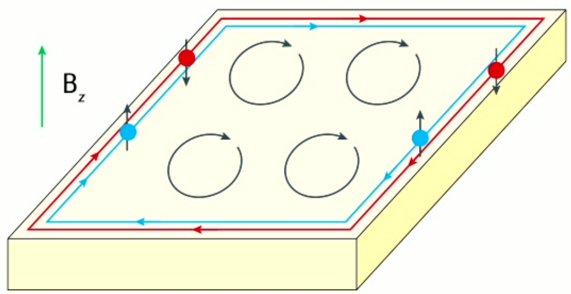
Observational Consequences

$6\pi/(\Lambda \ell_{\rm Pl}^2) \in \mathbb{Z}$. In one lens, fixing θ "quantizes" $1/\Lambda$

Conversely, experimental measurements of Λ determine the choice of topological θ-sector.

Like Yang-Mills, the theta sector cannot receive quantum corrections

The Quantum Gravitational Hall Effect



Despite impurities and noise Hall conductivity

$$\sigma_H = \frac{e^2}{h}\nu$$

Measured to 1 part in a Billion

The Problem of Time

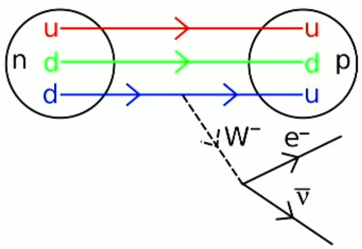
•Lee Smolin(Penn State U.
•Chopin Soo(Penn State U.
Nucl.Phys.B 449 (1995) 289-316

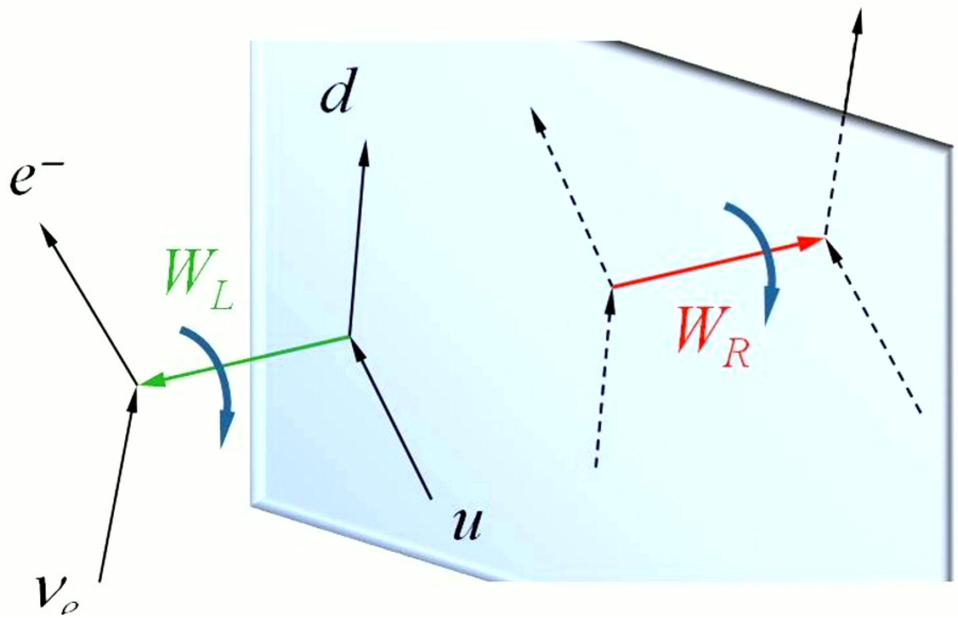
- Soo and Smolin showed that the imaginary part of the Chern-Simons functional, can be interpreted as the *time parameter* in classical cosmology.
- The Imaginary part of the Chern-Simoms invariant is related to the Lorentzian signature of spacetime (it encodes extrinsic curvature).
- ImY(A)=T, evolves monotonically along classical solutions of the Einstein equations with $\Lambda>0$

- **In Quantum Gravity:** Im(YCS) provides a natural *internal time* variable in the semiclassical quantum gravity context.
- This contrasts with the usual problem of time in quantum gravity: here, time emerges from the structure of the gravitational phase space itself.

Chirality and Parity Violation

The weak sector distinguishes left- and right- handed interactions (i.e., it's chiral)





Gravi-Weak Unification

Percacci, Nesti, S. Alexander (2004)
S. A, Marciano, Smolin (2012), P. Woit, S.A, B.
Alexandre, Magueijo, Pezzelle, Tobago Horse (2025)

- Idea: View Gravity as a gauge theory with a connection valued in

$$SO(3,1;C) = \mathrm{SL}(2,\mathbb{C})_L \times \mathrm{SL}(2,\mathbb{C})_R$$

- This is realized by the fact that the Complex Ashtekar-Sen variable is Chiral.

Weak interaction inherits parity violation and chirality from the other handed connection.

Cosmological Natural Selection

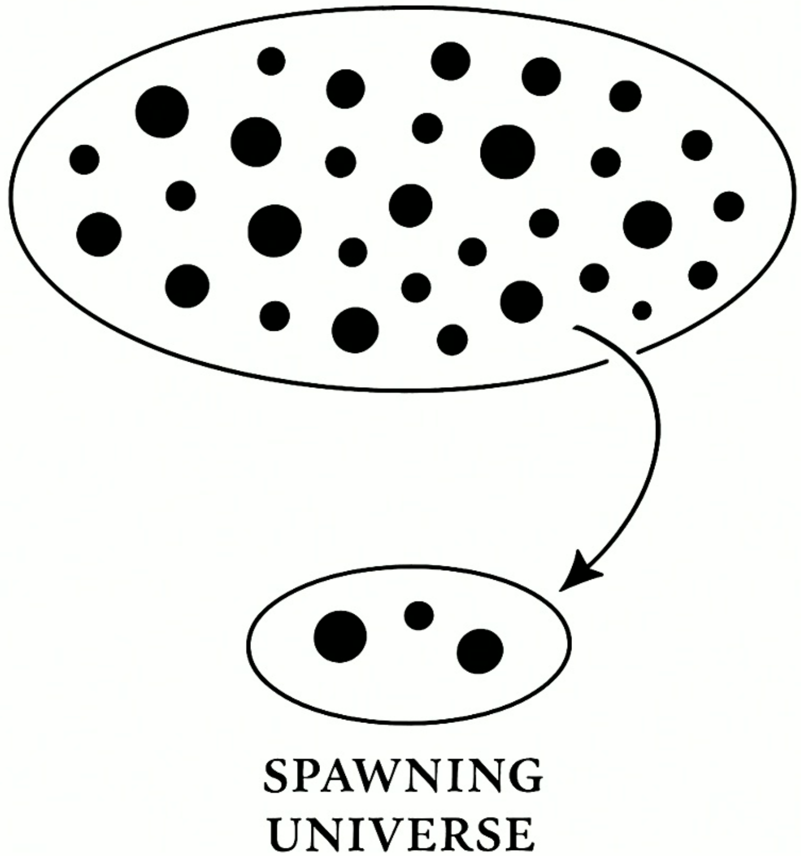
L. Smolin Class.Quant.Grav. 9

- The idea of the Landscape in particle physics was first instantiated in this work.
- The Universe is subject to a generalized Darwininan natural selection evolutionary process.

Mechanism

- Black hole singularities bounce, leading to new expanding regions of spacetime, one per each black hole.
- After reproduction, dimensionless parameters of the standard model differ by a small random change from those in the region in which the black hole formed
- Was one of the first cosmological model to address the issue of complexity in the universe from fundamental physics.

Parent Universe



Thank You
Lee!

The Fun
has just
started!