Title: What is the simplicity of the early universe trying to tell us?

Speakers: Latham Boyle

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

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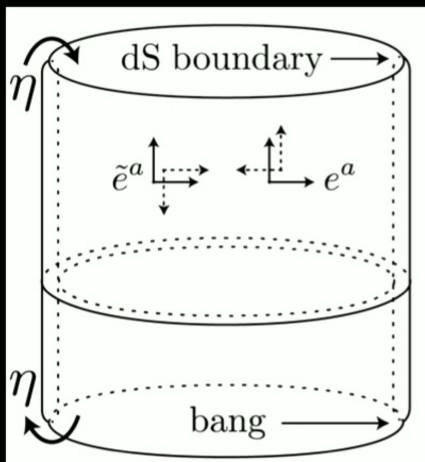
Abstract: "After reviewing some key hints and puzzles from the early universe, I will introduce recent joint work with Neil Turok suggesting a rigid and predictive new approach to addressing them.

Our universe seems to be dominated by radiation at early times, and positive vacuum energy at late times. Taking the symmetry and analyticity properties of such a spacetime seriously leads to a new formula for the gravitational entropy of our universe, and a picture in which the Big Bang may be regarded as a kind of mirror.

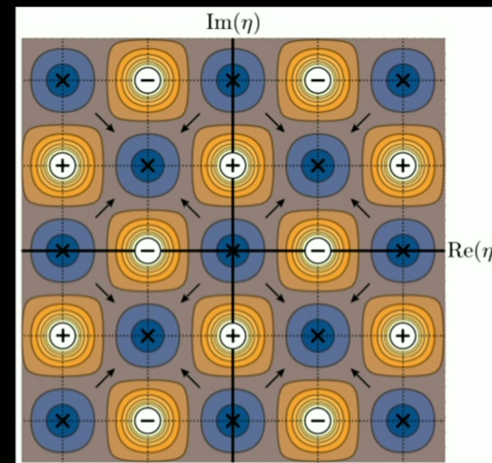
I will explain how this line of thought suggests new explanations for a number of observed properties of the universe, including: its homogeneity, isotropy and flatness; the arrow of time (i.e. the fact that entropy increases *away* from the bang); several properties of the primordial perturbations; the nature of dark matter (which, in this picture, is a right-handed neutrino, radiated from the early universe like Hawking radiation from a black hole); the origin of the
primordial perturbations; and even the existence of three generations of standard model fermions. I will discuss some observational predictions that will be tested in the coming decade, and some key open questions."

Zoom Link: https://pitp.zoom.us/j/94575380034?pwd=Y21DMTRqeFFGNnd5dnVBc1dac2tUQT09

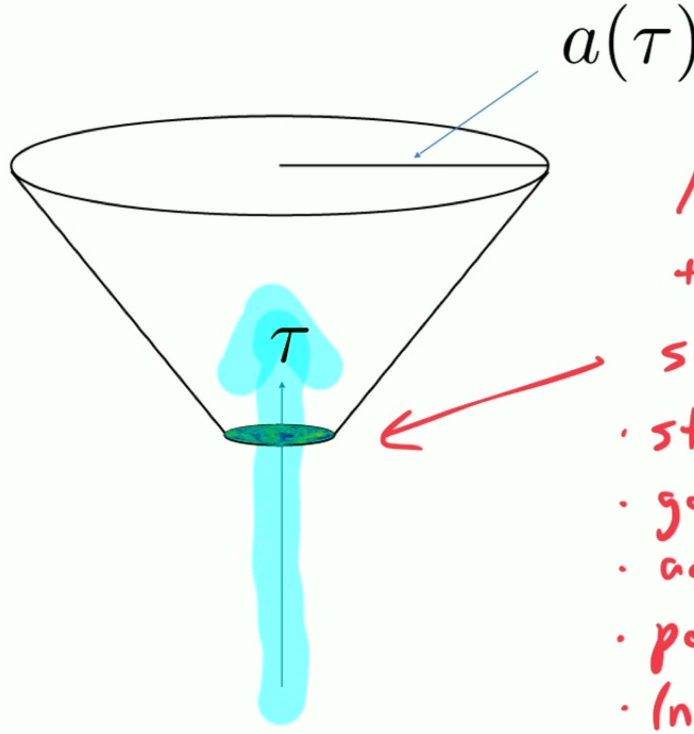
What is the simplicity of the early universe trying to tell us?



Latham Boyle
Perimeter Institute

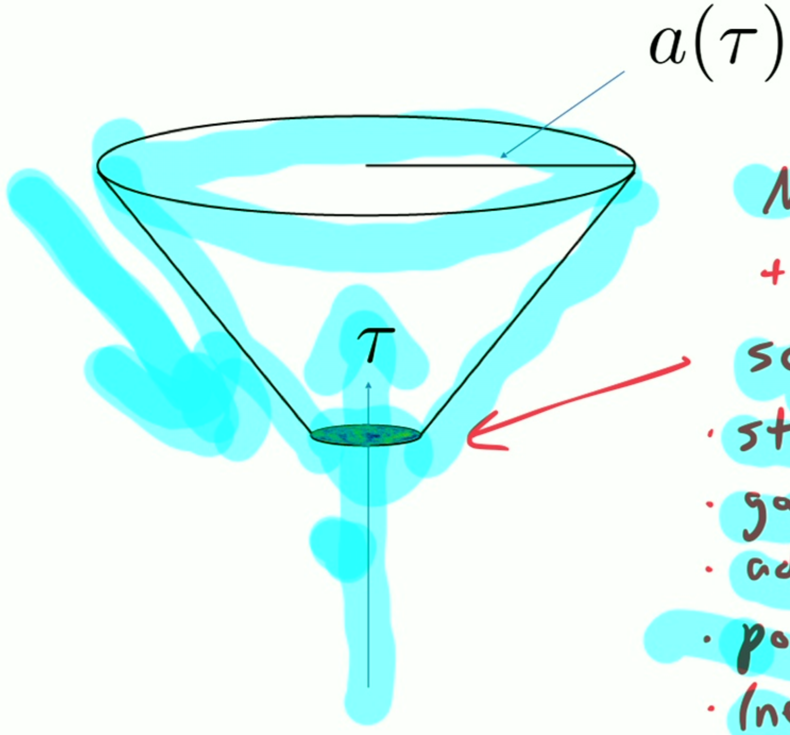


1) LB, K. Finn and N. Turok, *CPT-Symmetric Universe* arXiv:1803.08928 (Phys. Rev. Lett.)
2) LB, K. Finn and N. Turok, *The Big Bang, CPT, and neutrino dark matter* arXiv:1803.08930 (Ann. Phys.)
3) LB and N. Turok, *Two-Sheeted Universe, Analyticity & Arrow of Time,* arXiv:2109.06204
4) LB and N. Turok, *Cancelling the Vacuum Energy and Weyl Anomaly in the Standard Model with Dimension-Zero Scalar Fields,* arXiv:2110.06258
5) N. Turok and LB, *Gravitational entropy and the flatness, homogeneity and isotropy puzzles, arXiv:2201.07279*
6) LB and N. Turok, *Thermodynamic solution to the homogeneity, isotropy and flatness puzzles (and a clue to the cosmological constant),* arXiv:2210.01142
7) N. Turok and LB, *A Minimal Explanation of the Primordial Cosmological Perturbations, arXiv:2302.00344*



Maximally symmetric
+ tiny (10^{-5}) random
scalar (density) perts:

- statistically symmetric,
- gaussian,
- adiabatic,
- power law,
- (nearly) scale invariant,
- temporally synchronized (Neumann b.c.'s for ζ at the bang)



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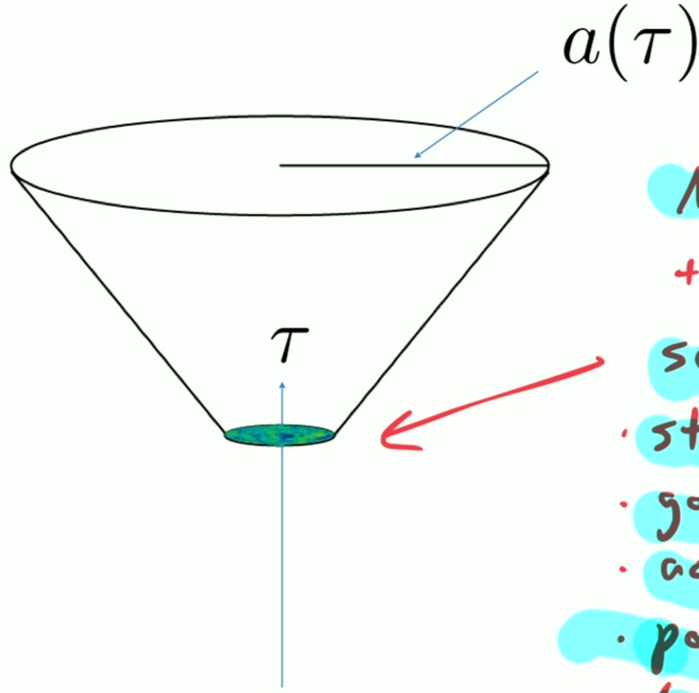

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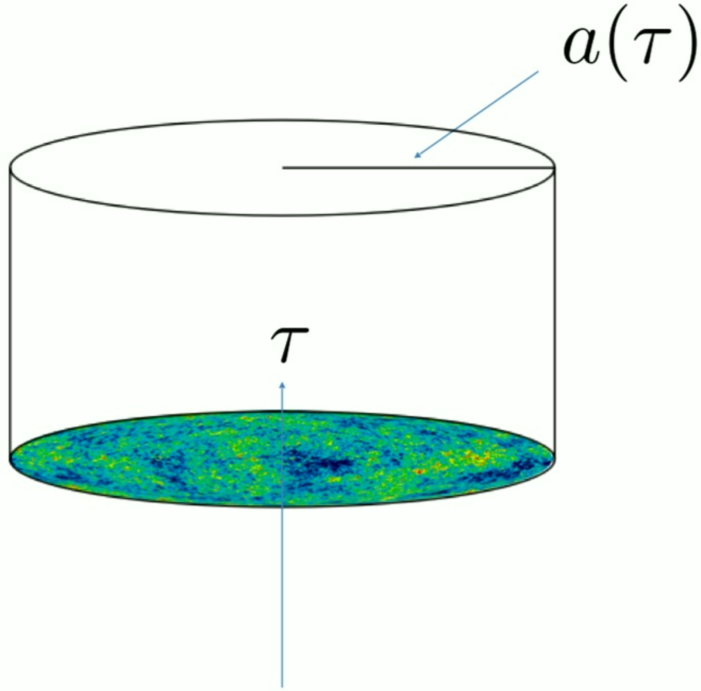
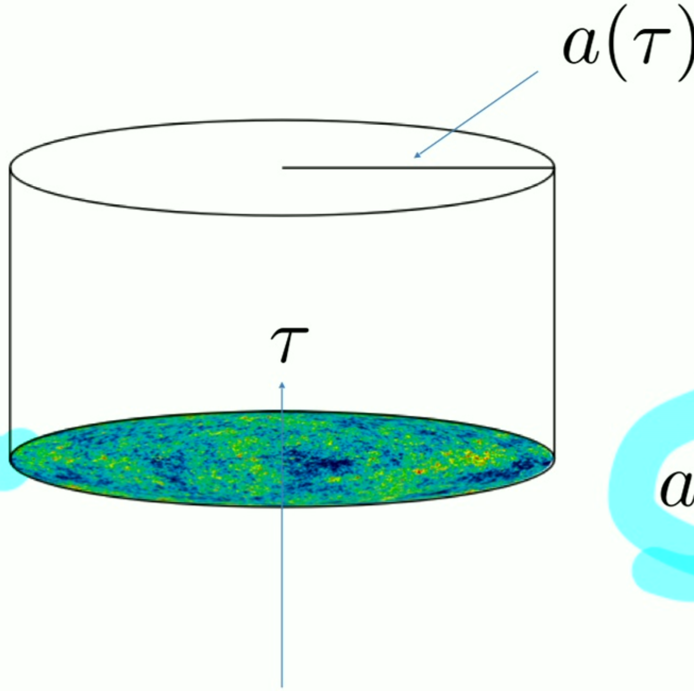

$a(\tau)$
τ

$$g_{\mu\nu} = a^2(\tau)\eta_{\mu\nu}$$



$$a(\tau) \propto \tau$$

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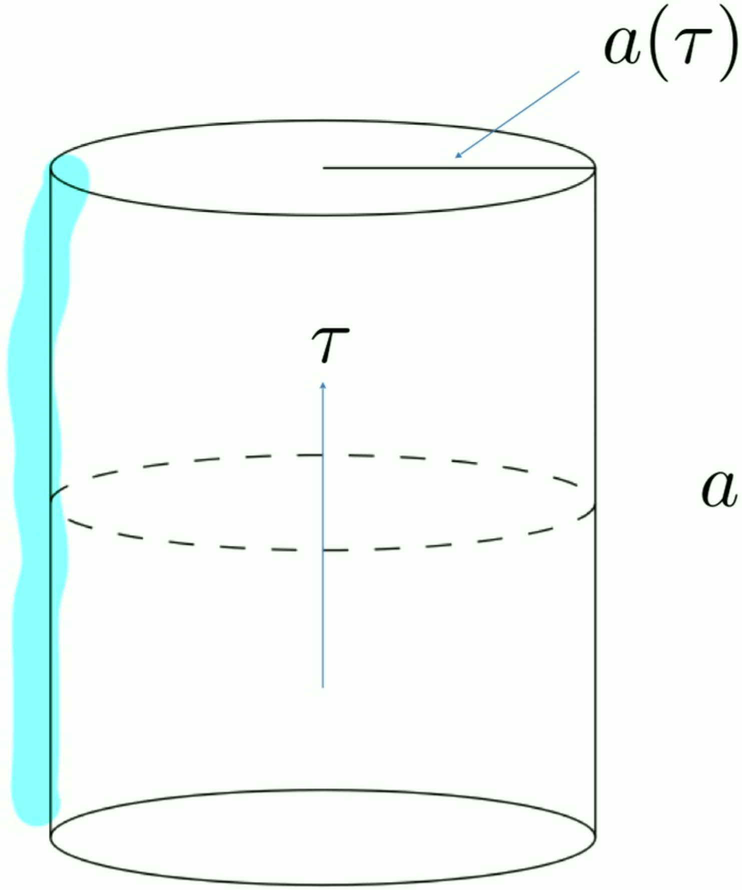

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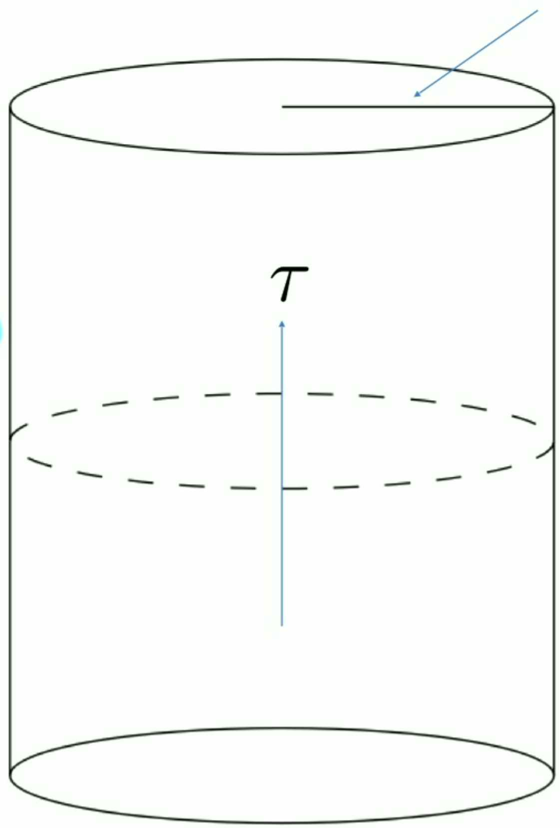


$g_{\mu\nu} = a^2(\tau)\eta_{\mu\nu}$

$a(\tau) \propto \tau$

new isometry:

$\tau \to -\tau$

preferred vacuum:

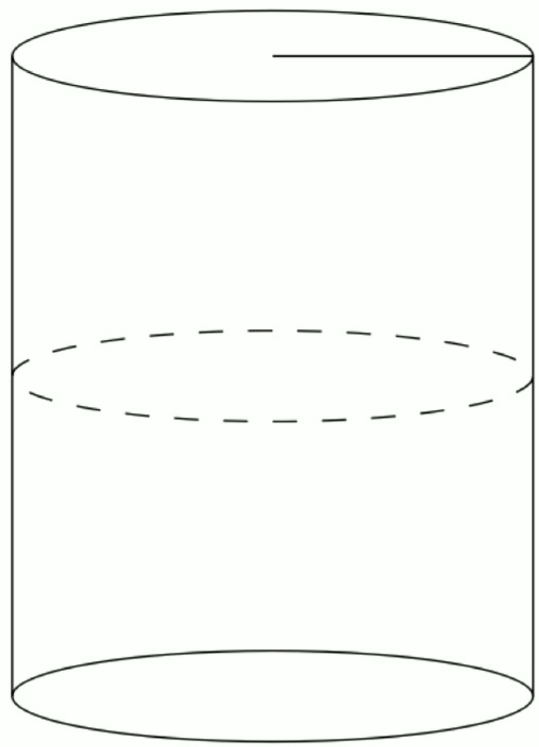
$|0_{CPT}\rangle$

hypothesis:

the universe does not spontaneously violate CPT

$$\psi(x) = \sum_h \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}} \left[a(\mathbf{p},h)\psi(\mathbf{p},h,x) + b^\dagger(\mathbf{p},h)\psi^c(\mathbf{p},h,x) \right]$$

$\psi_+(\mathbf{p},h,x)$ $\qquad a_+, b_+ \;\Rightarrow\; |0_+\rangle$



$\psi_0(\mathbf{p},h,x)$ $\qquad a_0, b_0 \;\Rightarrow\; |0_0\rangle$

$\Big(\; (\psi_0(\tau) \sim \psi_0^c(-\tau) \; \Big)$

$\psi_-(\mathbf{p},h,x)$ $\qquad a_-, b_- \;\Rightarrow\; |0_-\rangle$

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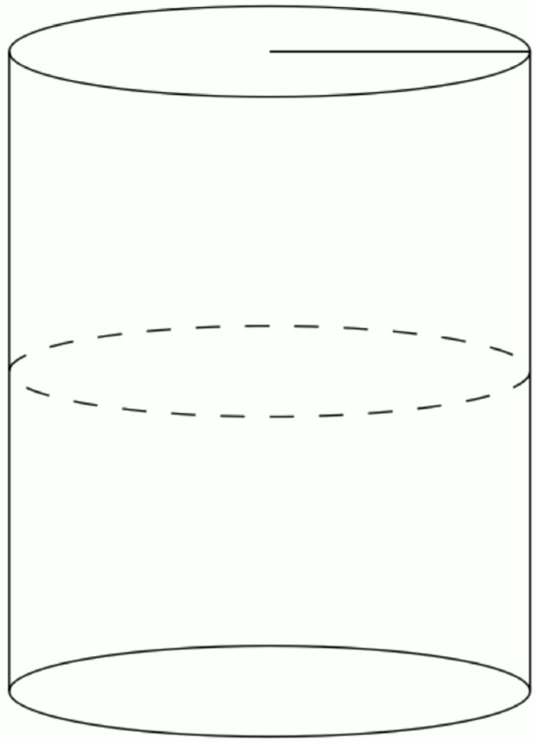

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$\Big(\, (\psi_0(\tau) \sim \psi_0^c(-\tau)\, \Big)$

$\psi_-(\mathbf{p},h,x)$ $\qquad a_-, b_- \;\Rightarrow\; |0_-\rangle$

the standard model

$$G_\mu, W_\mu, B_\mu, h$$

$$\left.\begin{matrix} d_L, u_L, d_R, u_R \\ d_L, u_L, d_R, u_R \\ d_L, u_L, d_R, u_R \\ e_L, \nu_L, e_R, \nu_R \end{matrix}\right\} \times 3$$

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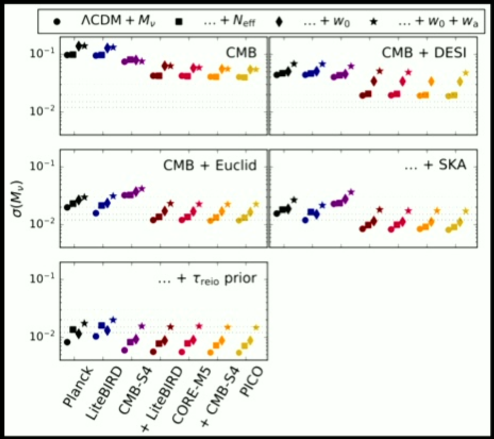
Prediction 0: dark matter neutrino is 4.8 x 10^8 GeV.

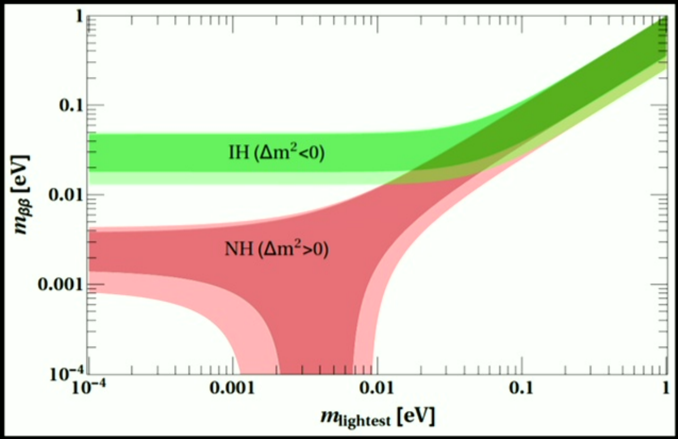
Prediction 1: one neutrino is massless

$\sum m_\nu \approx .06 eV(NH) \text{ or } .12 eV(IH)$

$0\nu\beta\beta$ decay:



(Brinckmann et al, arXiv:1808.05955)



(Dell'Oro et al, arXiv:1601.07512)

Prediction 2: dark matter is cold

Prediction 3: no primordial gravitational waves

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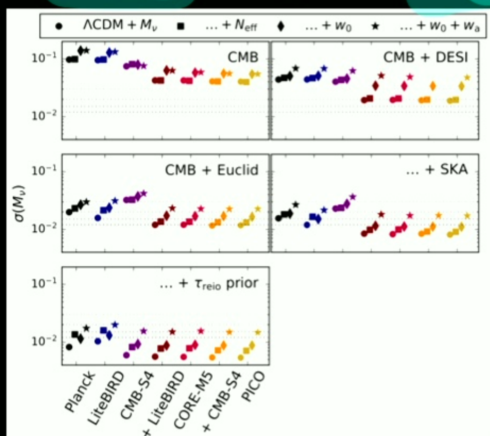

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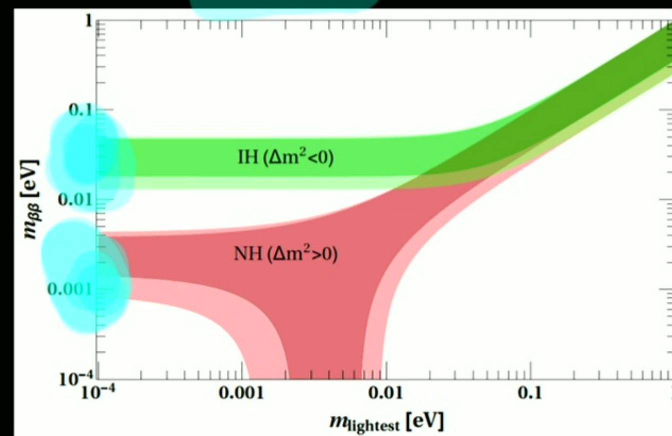

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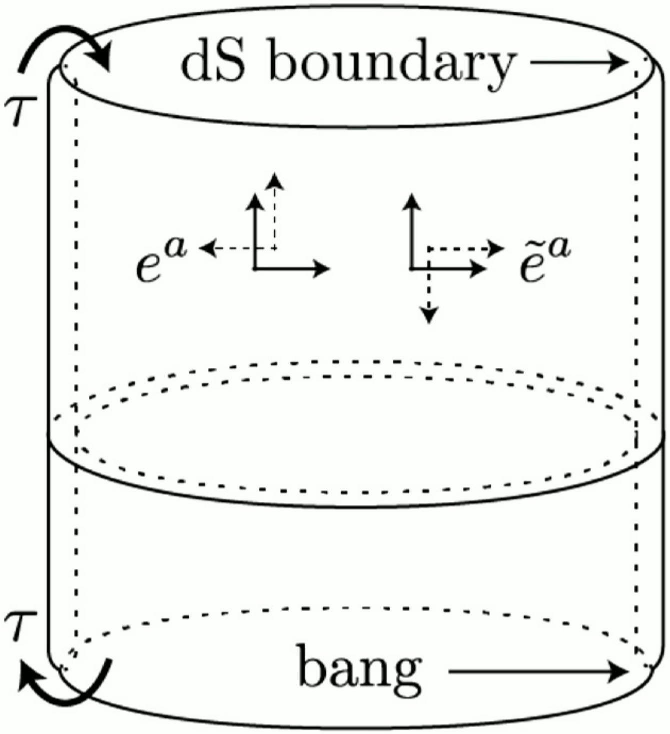
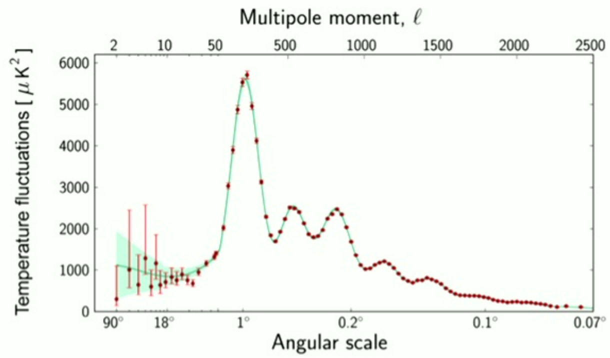
Prediction 3: no primordial gravitational waves

Consider fields on this 2-sheeted spacetime



- solns respecting background symmetry
- analytic at the bang $\Rightarrow$ reflecting b.c.
- $\Rightarrow$ no primordial vector perturbations
- $\Rightarrow$ Neumann b.c.'s for scalar perturbation ζ
- essential singularity at dS boundary $\Rightarrow$ no b.c.
- $\Rightarrow$ thermodynamic arrow of time



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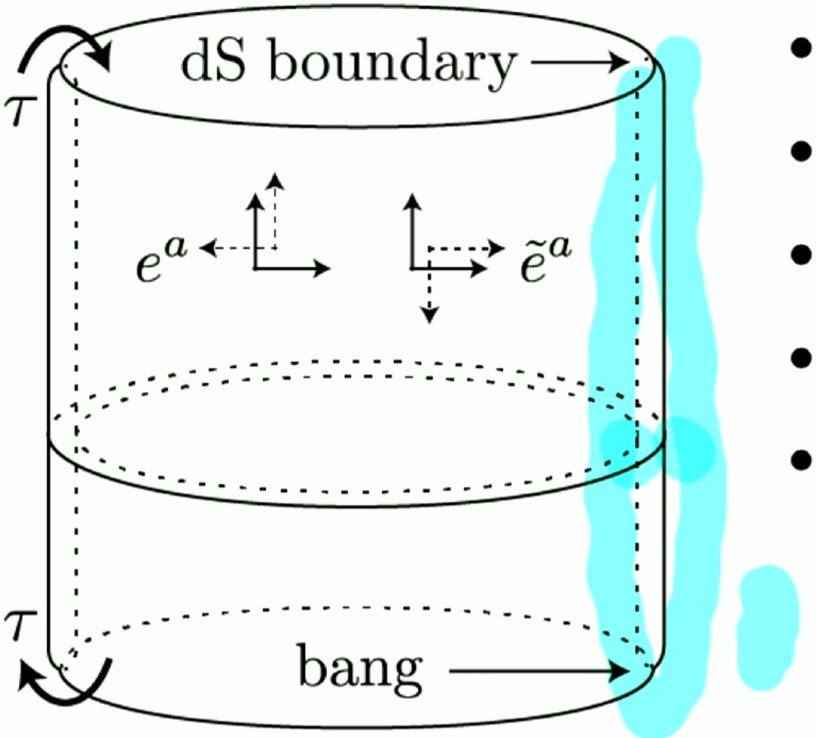

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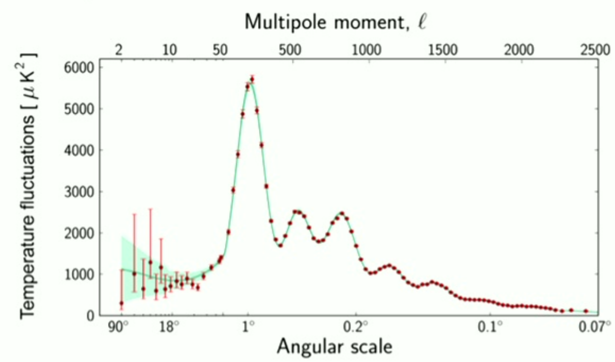


The gravitational entropy of the universe: LB and N. Turok, arXiv:2210.01142

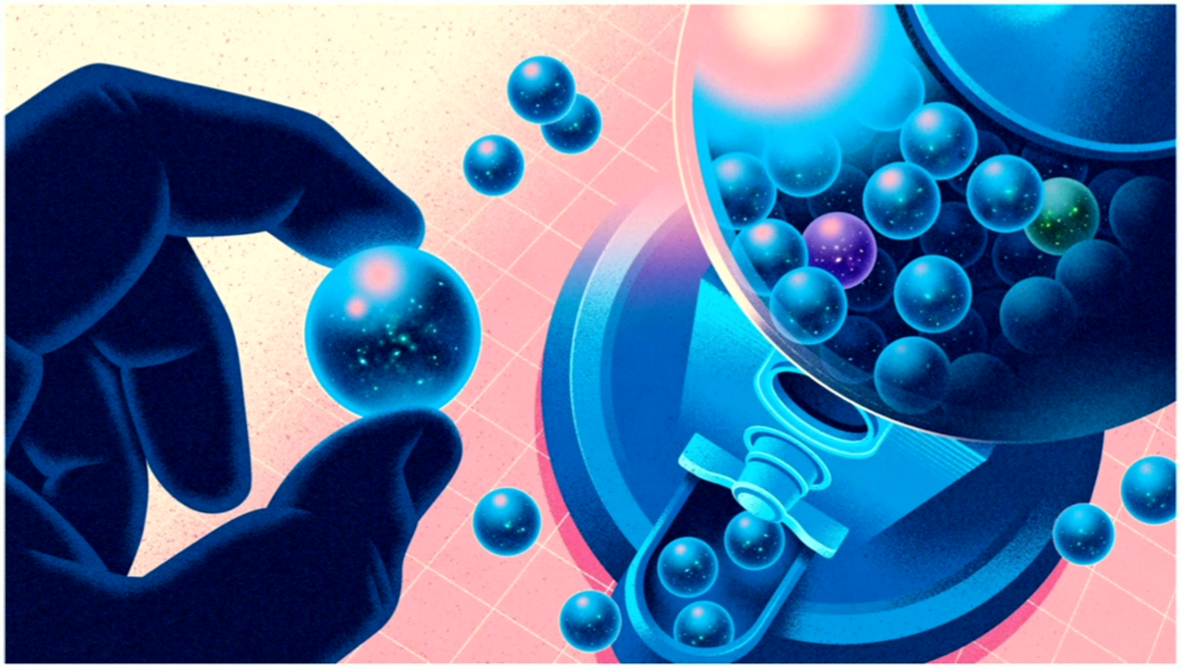
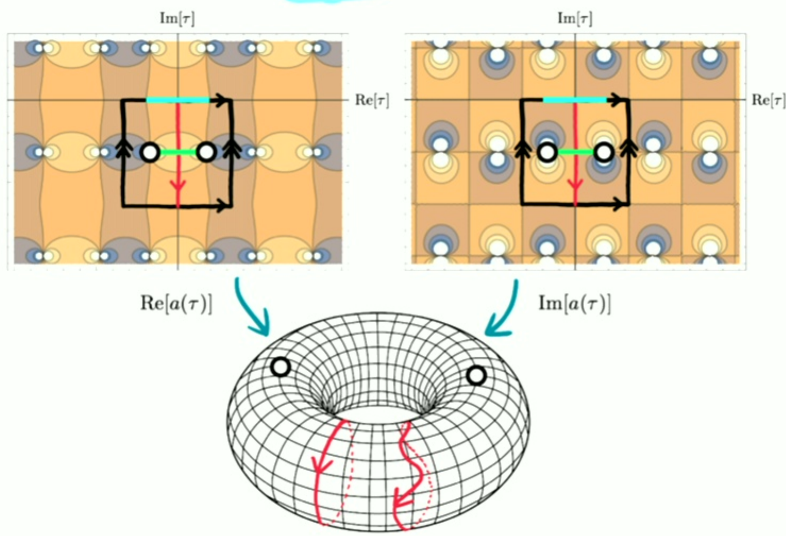


Image Credit: Quanta Magazine

Step 1. Obtain general solution for the cosmic scale factor:

$$H^2 = \frac{8\pi G}{3}\left(\frac{r}{a^4} + \frac{\mu}{a^3} + \lambda\right) - \frac{\kappa}{a^2}$$



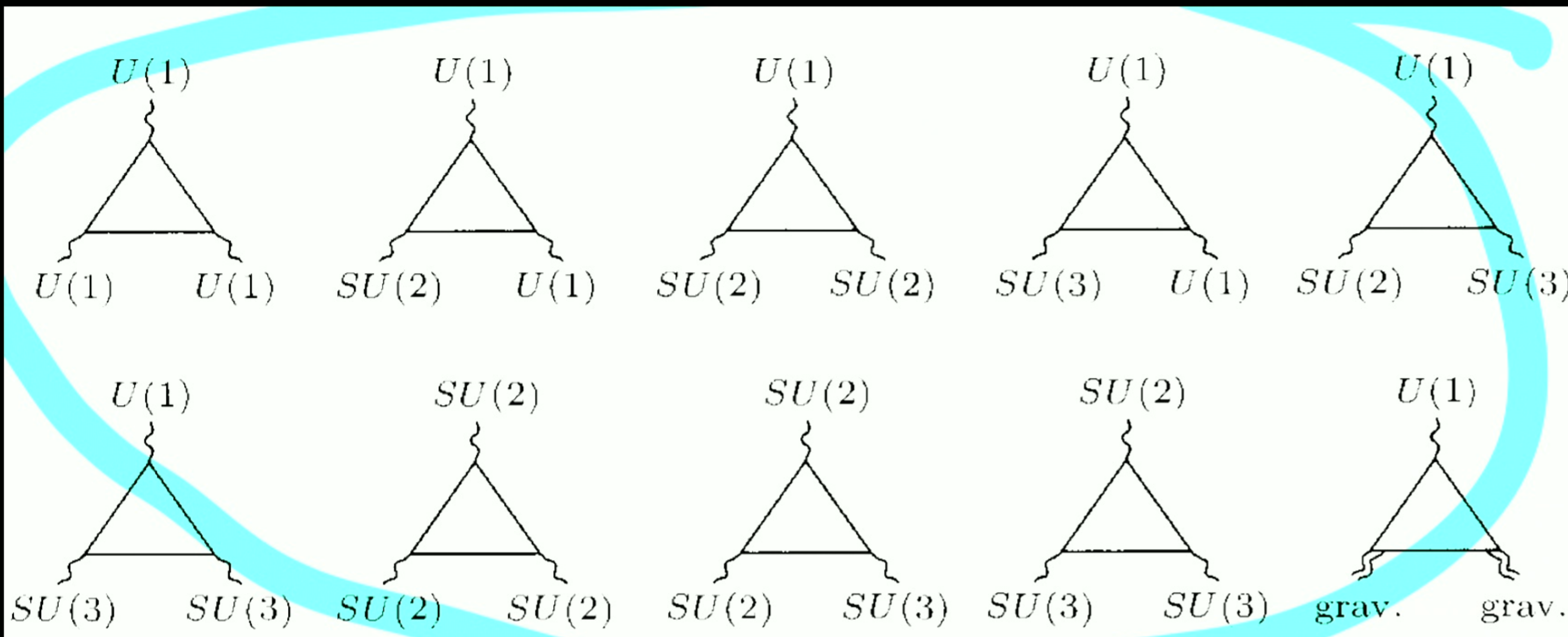
Step 2. Obtain general formula for the *gravitational* entropy of an FRW universe:

Flat universes and tiny positive Lambda are favoured!

Step 3. Add cosmological perturbations (small inhomogeneities and isotropies):

If the Big Bang is a mirror, these *cost* entropy!

In Standard Model, gauge and gravitational anomalies must cancel:



What about local scale ("Weyl") invariance?

- Emphasized by Weyl, Dirac, Dicke,…, 't Hooft:
  - Natural generalization of diff invariance (gen. covariance)
- Ignoring Higgs, Standard Model is *classically* Weyl invariant.
- But Weyl symmetry is anomalous:

$$\langle T^{\mu}_{\mu} \rangle = c\,C^2 - a\,E$$

Cancelling Weyl anomalies and Vacuum Energy?

$$a = \frac{1}{360(4\pi)^2}[\, n_0 + \frac{11}{2} n_{1/2} + 62 n_1 - 28 n_0' \,]$$

$$c = \frac{1}{120(4\pi)^2}[\, n_0 + 3\, n_{1/2} + 12 n_1 - 8\, n_0' \,]$$

$$E_{\mathbf{k}} = \frac{\hbar\omega}{2}[\, n_0 - 2n_{1/2} + 2n_1 + 2n_0' \,]$$

$$S_4[\varphi] = \frac{1}{2}\int d^4x\, \varphi\, \Box^2 \varphi$$

See Fradkin and Tseytlin, Nucl. Phys. B203 (1982), 157.

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$$n_{1/2} = 4n_1, \quad n_0' = 3n_1, \quad n_0 = 0.$$

Matches standard model!

$$n_1 = 8 + 3 + 1 = 12$$
$$n_{1/2} = 3 \times 16 = 48$$

Dimension-zero scalars: notable features

$$\langle\varphi(t,\mathbf{x})\varphi(t,\mathbf{x}')\rangle = \int \frac{d^3k}{(2\pi)^3} \mathrm{e}^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} \frac{1}{4k^3}$$

Scale invariant!

No new local degrees of freedom.

See Bogoliubov, Logunov, Oksak & Todorov (1990) and V.O. Rivelles (2003).

Primordial Power Spectrum (arXiv:2302.00344)

$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_\mathcal{R}(k_{pl})(k/k_{pl})^{n_s-1}$$

$$n_s - 1 \approx -\frac{7\alpha_3}{\pi}$$

$$\mathcal{P}_\mathcal{R}(k_{pl}) = \frac{3^2 5^3}{7(2\pi)^4}\frac{1}{\mathcal{N}_{eff}^2}\left(\frac{125}{108}\alpha_Y^2 - \frac{95}{72}\alpha_2^2 - \frac{49}{6}\alpha_3^2\right)^2$$

(SM parameters from Buttazzo et al arXiv:1307.3536])

$$n_s = 0.958 \qquad (\text{Planck}: \; n_s = 0.9587 \pm 0.0056)$$

$$\mathcal{P}_\mathcal{R}(k_*) = 12.9 \pm 4.5 \times 10^{-10} \quad (\text{Planck}: \; \mathcal{P}_\mathcal{R}(k_*) = 21 \times 10^{-10})$$

Summary

Analytic extension of the cosmological solution of the Einstein equations leads to:

1) Big Bang as a mirror
2) formula for gravitational entropy

These ideas yield new explanations/predictions for various observed features of our universe, including:

1) dark matter
2) thermodynamic arrow of time
3) absence of tensor perts (gravitational wave)
4) absence of vector perts (vorticity)
5) Neumann initial conditions for scalar (density) perts
6) The homogeneity, isotropy and flatness (and smallness of Lambda)

Finally, we saw how (without introducing new d.o.f.) 36 dimension-zero scalars can:

1) cancel both Weyl anomalies and the vacuum energy
2) explain 3 generations
3) yield a scale invariant power spectrum (without inflation)

Much still to be understood!