Title: Everpresent Î› Cosmology

Speakers: Yasaman Kouchekzadeh Yazdi

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

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Abstract: I will discuss a number of theoretical, observational, and conceptual aspects of the Everpresent ? cosmological model arising from fundamental principles in causal set theory and unimodular gravity. In this framework the value of the cosmological constant (?) fluctuates, in magnitude and in sign, over cosmic history. At each epoch, ? stays statistically close to the inverse square root of the spacetime volume. Since the latter is of the order of H^2 today, this provides a way out of the cosmological constant puzzle without fine tuning. I will review the theoretical background of this idea. I will also describe a phenomenological implementation of this model, and discuss recent results on the statistics of its simulations and observational tests of it.

Zoom Link: https://pitp.zoom.us/j/99946149565?pwd=M2puMy9nSEtBZTg1MnRmSllHeUE0UT09

Everpresent Λ Cosmology

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Imperial College London

Work with Santanu Das & Arad Nasiri (arXiv:2304.03819)

Quantum Spacetime in the Cosmos: From Conception to Reality

Perimeter Institute

Imperial College London

May 11, 2023

LEVERHULME TRUST

Outline

- Open Questions in Cosmology and the role of Quantum Gravity
- Causal Set Theory and Everpresent Λ
- A Phenomenological Model: "Model 1"
- Statistics and Subtleties of a Stochastic Model
- Observational Constraints (SNIa and CMB)

(Some) Open Questions in Cosmology

- **Early Universe: resolution of the big bang singularity and what happens shortly after (exponential expansion? How and why?)**

- **Origin of Dark Matter and Dark Energy (cosmological constant puzzles)**

- **Tensions: e.g. Hubble tension and S_8 tension**

- **Fundamental and microscopic origin of Cosmological Horizon Entropy**

Causal Set Theory & Open Questions in Cosmology

- **Early Universe: resolution of the big bang singularity and understanding following period (exponential expansion?)**

Fundamental discreteness tames infinite curvatures and energies. Sequential growth models exhibit rapid early expansion (e.g. Sorkin arXiv:gr-qc/0003043; Ahmed and Rideout arXiv:0909.4771; Dowker and Zalel arXiv:2212.01149).

- **Origin of Dark Matter and Dark Energy (cosmological constant puzzles)**

Off-shell dark matter motivated by nonlocal quantum field theories on causal sets (e.g. Saravani and Aslanbeigi arXiv:1502.01655; Saravani and Afshordi arXiv:1604.02448). Everpresent Λ dark energy (e.g. Ahmed, Dodelson, Greene, and Sorkin arXiv:astro-ph/0209274; Sorkin arXiv:0710.1675); can in turn alleviate Hubble and S_8 tensions due to dynamical and sign changing nature.

- **Cosmological Horizon Entropy**

Causal Set Theory & Open Questions in Cosmology

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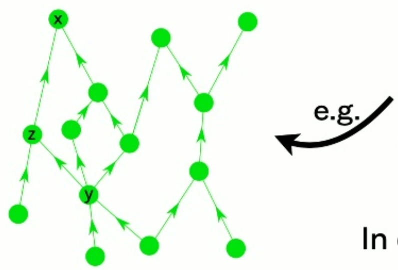
- **Cosmological Horizon Entropy**

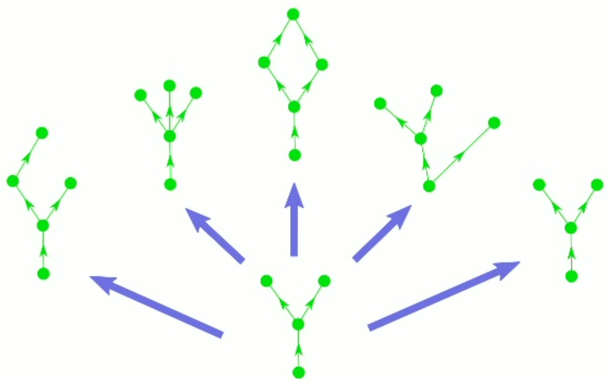
Entanglement Entropy (e.g. Sorkin and YKY arXiv:1611.10281; Surya, Nomaan, and YKY arXiv:2008.07697). Horizon Molecules (e.g. Dou and Sorkin arXiv:gr-qc/0302009; Barton et al arXiv:1909.08620)

Causal Set Theory: Growing by Number



A causal set is a locally finite partially ordered set: a set of elements $\mathscr{C}$ along with causal relations

In classical dynamical models, a causal set **grows element by element** sequentially. At stage 1, the first element is born, and subsequently at each stage n we have an n-element causal set. Each new n^{th} element selects a random subset of the existing elements to be in its causal past. While this choice is made stochastically, there are some rules to ensure that causality and a suitable analog of discrete covariance are preserved by the ancestor selection process.



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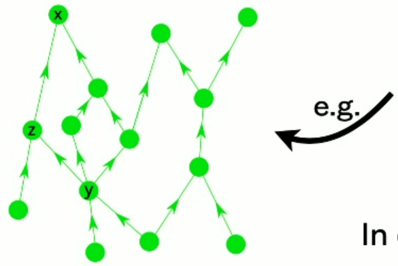

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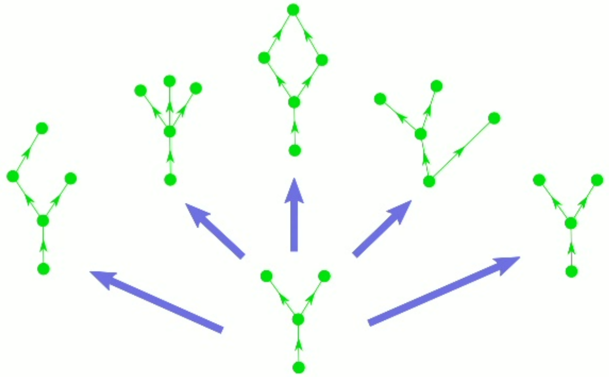


In a quantum sum over histories dynamics:

$$\mathscr{Z}(N) = \sum_{|\mathscr{C}|=N} e^{iS_{cst}[\mathscr{C}]}$$

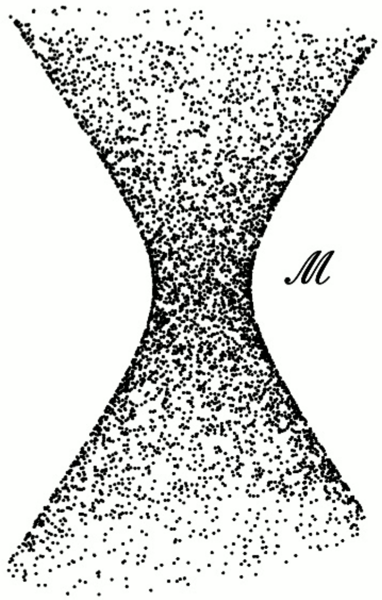
Dynamics ingredient: number of elements plays a similar role to time

Causal Set Theory: Fundamental Discreteness

A causal set is a locally finite partially ordered set: a set of elements $\mathscr{C}$ along with causal relations

Causal sets that are approximated by continuum manifolds have a **number-volume correspondence** such that: the number of elements N within any arbitrary region with volume V is statistically proportional to V. The **Poisson distribution** ensures this correspondence with minimal variance.

If we want to study causal sets that resemble a certain spacetime, we can generate them by placing points at random in $\mathscr{M}$ via a Poisson process such that $P(N) = \frac{(V)^N}{N!}e^{-V}$



Causal Set Theory: Fundamental Discreteness

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$$\langle N \rangle = V$$
$$\delta N = \sqrt{V}$$

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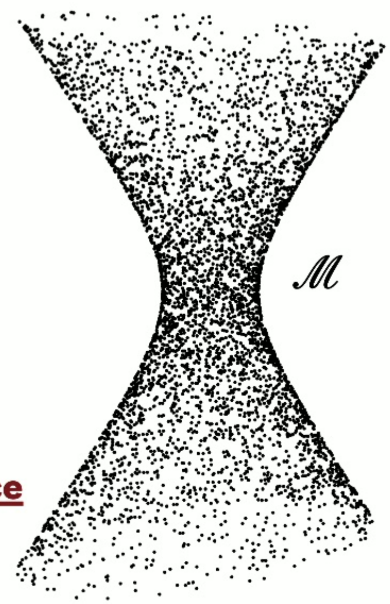

$\mathscr{M}$

Kinematics ingredient: number-volume correspondence according to the Poisson distribution

Everpresent Λ

Dynamics input: number of elements plays a similar role to time

$$\mathcal{Z}(V) \sim \int_{Vol(\mathcal{M})=V} \mathcal{D}g_{\mu\nu}\, e^{iS_G[g]} \xrightarrow{\text{Fourier Transform}} \mathcal{Z}(\Lambda) = \int dV\, e^{-i\Lambda V}\mathcal{Z}(V)$$

$$\mathcal{Z}(\Lambda) \sim \int \mathcal{D}g_{\mu\nu} \exp\left(iS_G[g] - i\Lambda \int d^4x\sqrt{-g}\right)$$

Therefore, spacetime volume V and Λ are quantum mechanically conjugate

$$\frac{\delta\Lambda}{8\pi G} \cdot \delta V \geq \frac{\hbar}{2}$$

Kinematics input: N-V correspondence according to Poisson distribution

A causal set with fixed N can be approximated by continuum spacetimes with mean $\langle V\rangle = N$ and standard deviation $\delta V = \sqrt{N} \sim \sqrt{V}$. Also: $N, V \gg 1$

$$\delta\Lambda\ \delta V \sim 1 \xrightarrow[\langle\Lambda\rangle = 0]{\text{Assume}} \Lambda \sim \delta\Lambda \sim 1/\delta V = 1/\sqrt{V} \sim H^2 \sim 10^{-121}!$$

Everpresent Λ

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1987 — **Sorkin, "A Modified Sum-Over-Histories for Gravity"** reported in the article by Brill and Smolin: "Workshop on quantum gravity and new directions", in Proceedings of the International Conference on Gravitation and Cosmology, Goa, India, 14–19 December **1987**, pp. 184–186, 1988.

1987 — **Sorkin**, **"Role of Time in the Sum-Over-Histories Framework for Gravity",** International journal of theoretical physics 33 (1994), no. 3 523–534. The text of a talk at the conference, "The History of Modern Gauge Theories," in Logan, Utah, in July **1987**.

1990 — **Sorkin, "First Steps with Causal Sets"**, in Proceedings of the Ninth Italian Conference of the same name, in Capri, Italy, September, **1990**, pp. 68–90 (World Scientific, Singapore, 1991).

1993 — **Sorkin, "Forks in the Road, on the Way to Quantum Gravity"**, talk given at the conference entitled "Directions in General Relativity", held at College Park, Maryland, May, **1993**; Int. J. Th. Phys. 36 : 2759–2781 (1997)

2004 — **Ahmed**, **Dodelson**, **Greene**, and **Sorkin**, **"Everpresent Λ"**, PRD 69, no. 10 103523, **2004**.

2013 — **Ahmed** and **Sorkin**, **"Everpresent Λ II: Structural Stability"**, PRD 87, **2013**.

2018 — **Zwane**, **Afshordi**, and **Sorkin**, "**Cosmological tests of Everpresent Λ**", CQG 35194002, **2018**.

2023 — **Das**, **Nasiri**, and **YKY**, **"Aspects of Everpresent Λ (I): A Fluctuating Cosmological Constant from Spacetime Discreteness"**, **2023**, arXiv:2304.03819.

2023 — **Das**, **Nasiri**, and **YKY**, **"Aspects of Everpresent Λ (II): Cosmological Tests of Current Models"**, **2023**, in preparation.

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A Phenomenological Model of Everpresent Λ

Ahmed, Dodelson, Greene, and Sorkin, "Everpresent Λ", PRD 69, no. 10 103523, 2004.

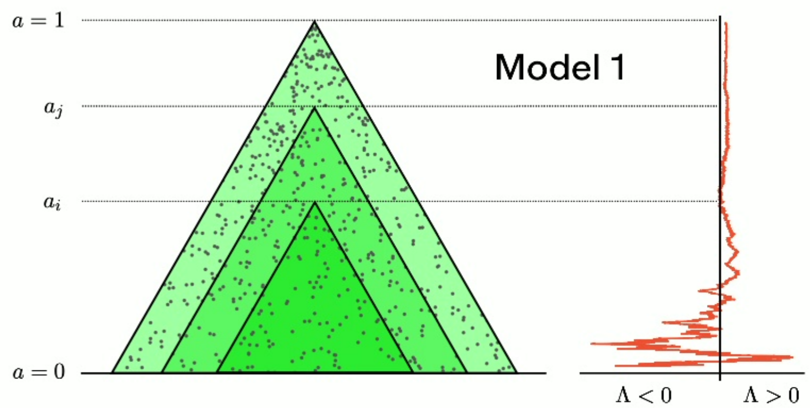
$$|\Lambda| \sim 1/\sqrt{V}$$

Each causal set element contributes a random variable with standard deviation α to S_Λ:

$$S_\Lambda|_{1\,element} = \begin{cases} \alpha, & p = \frac{1}{2} \\ -\alpha, & p = \frac{1}{2} \end{cases}$$

The effective S_Λ at time t is then the sum of all these single-element S_Λ's from elements in the **past lightcone** of an observer at t. From the central limit theorem $|S_\Lambda| \sim \alpha\sqrt{V}$ and $|\Lambda| = |S_\Lambda|/V \sim \alpha/\sqrt{V}$

$$\Lambda(t_n) = \frac{\Lambda(t_{n-1})V(t_{n-1}) + \alpha\sqrt{\Delta V_n}\,\xi_n}{V(t_n)}$$



A Phenomenological Model of Everpresent Λ

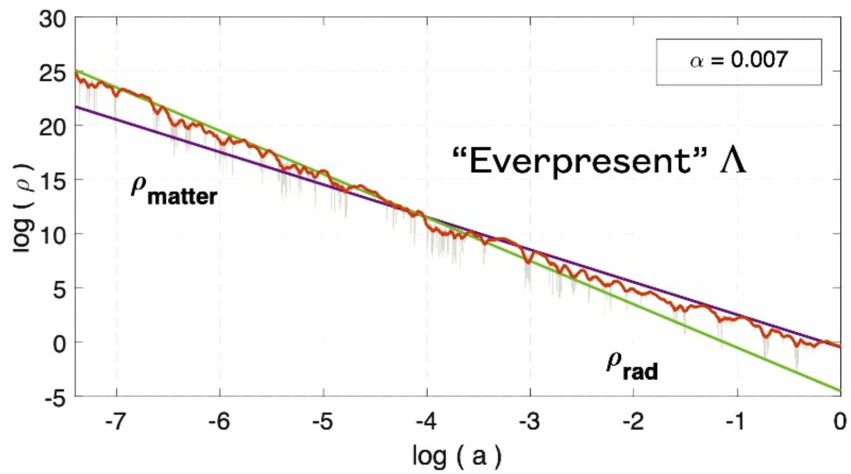
Assume a spatially flat, isotropic and homogeneous FLRW universe:

$$ds^2 = a(\tau)^2(-d\tau^2 + dr^2 + r^2 d\Omega^2)$$

Evolve V's using Friedmann eq:

$$\Lambda(t_n) = \frac{\alpha \sum_{i=1}^{n} \sqrt{\Delta V_i}\, \xi_i}{V(t_n)}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_r) + \frac{\Lambda}{3}$$



Das, Nasiri, YKY, arXiv:2304.03819.

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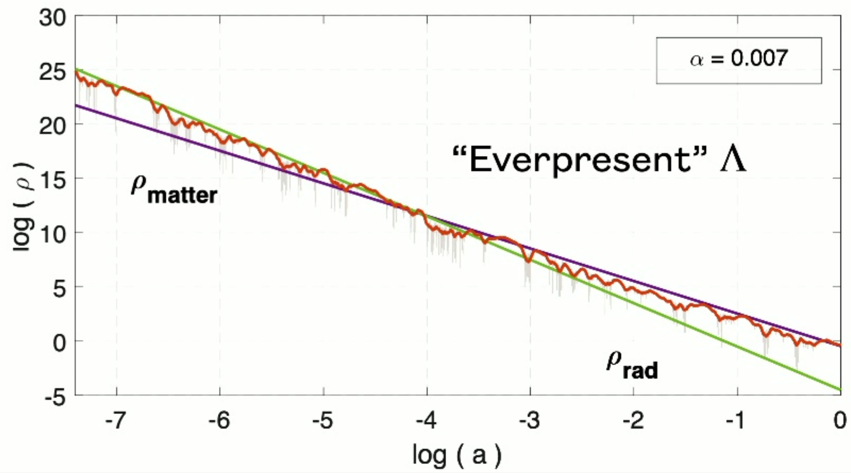
Sometimes, we encounter $H^2 < 0$ before the present. At such points, our evolution eq. is no longer valid. We discard such realizations, but finding the replacement evolution law for these cases is an **important open question** and exciting opportunity for new (quantum?) physics.



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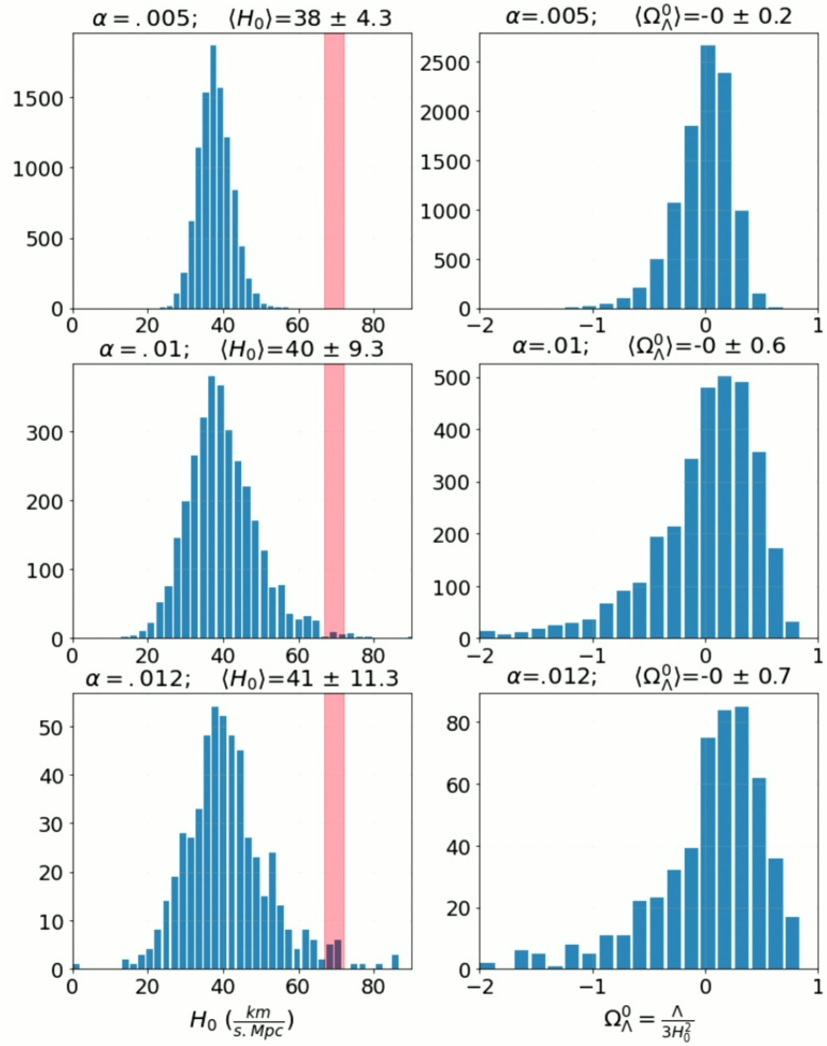


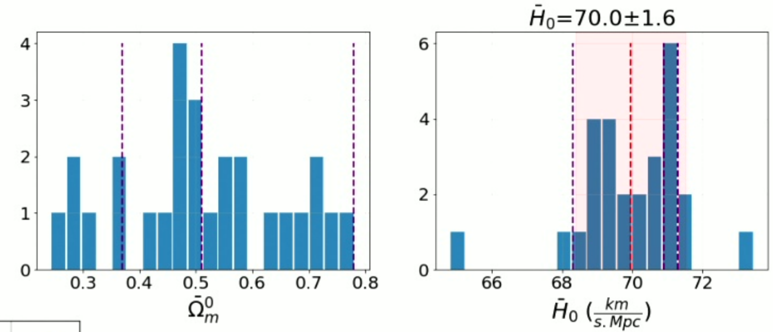
How to judge the results from a stochastic model...

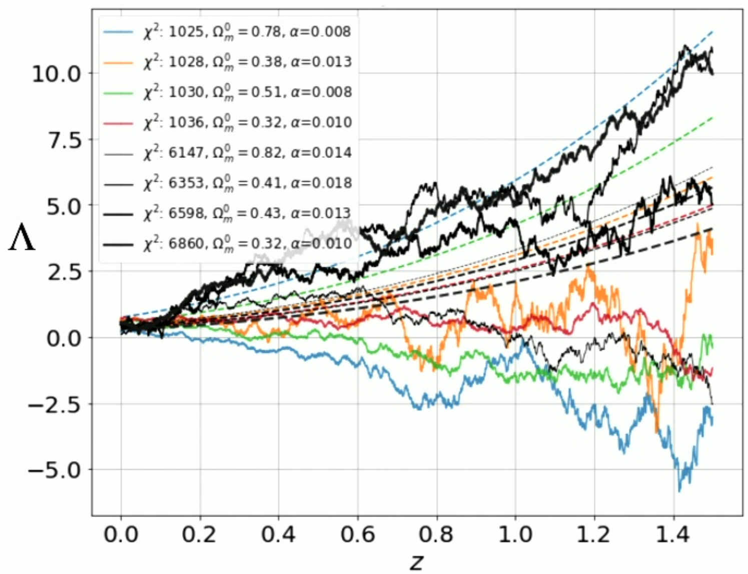
The distributions of H_0 and $\Omega_\Lambda^0 = \rho_\Lambda^0/\rho_{tot}^0$ for Model 1 with three different values for α of 0.005, 0.01, and 0.012. Shaded in red is the range $H_0 \in [67,72]$. As α increases, fewer simulations don't encounter $H^2 < 0$: 9990, 3228, and 535, each out of 10000.

Das, Nasiri, YKY, arXiv:2304.03819.

Type Ia Supernovae

Out of a sample of 20,000 seeds, 3 Everpresent Λ histories (dashed lines) yielded a better χ^2 (1025, 1028, 1030) than ΛCDM (1033).

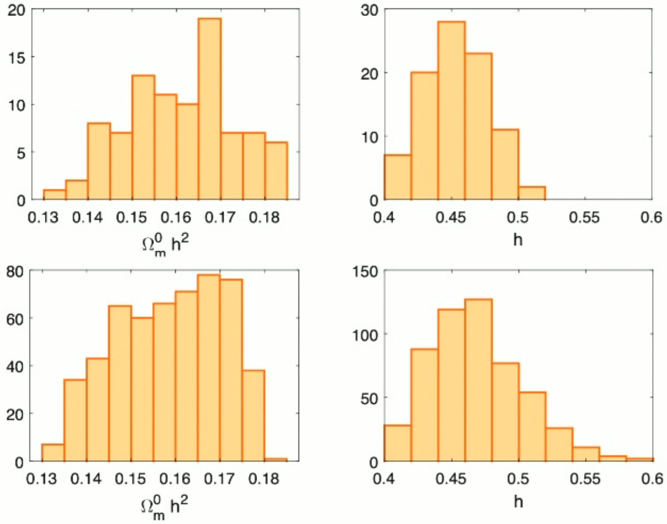




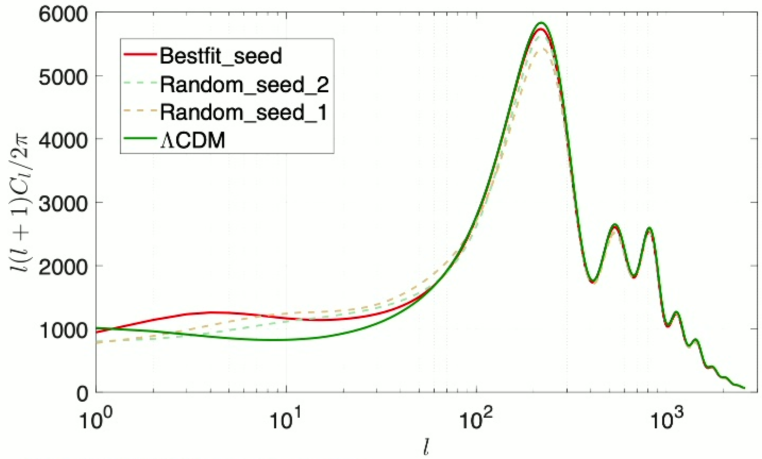
Dark energy densities that are smaller than matter density at small redshifts (colored) are favored over those with comparable or larger dark energy densities (black).

Das, Nasiri, YKY, in preparation.

Cosmic Microwave Background



Distributions for 90 seeds. 2nd row is w/ LSS suppression.



Das, Nasiri, YKY, in preparation.

Model 1 of Everpresent Λ struggles to fit CMB data better than ΛCDM. Can get better results with suppression of dark energy at the last scattering surface ($z \sim 1100$).

Ongoing work to understand why, and whether special histories can be identified which will do better with CMB.

Summary & Outlook

- Everpresent Λ: a fluctuating cosmological constant from spacetime discreteness
- Observational evidence for sign change in dark energy would be in favour of Everpresent Λ
- Many open questions remain: Why is the mean 0? What happens when $H^2 < 0$? How to judge fraction of good histories?
- Improvements: CMB data fit, quantum modifications, stochastic differential equations, incorporation of inhomogeneities
- Future work: initial Λ and the early universe