Title: A minimal SM/LCDM cosmology based on conformal symmetry, analyticity and CPT

Speakers: Neil Turok

Series: Colloquium

Date: June 13, 2023 - 4:00 PM

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Abstract: The universe has turned out to be simpler than expected on both very small and very large scales. We propose a minimal, highly predictive framework connecting particle physics to cosmology. Instead of introducing an ``attractor" phase such as inflation we extrapolate the observed universe all the way back to the initial singularity where we impose a CPT symmetric boundary condition via a generalization of the method of images. If the hot plasma in the early universe is perfectly conformal, so is the singularity. The cosmos may then be analytically extended to a ``mirror image" universe prior to the bang. Using this new boundary condition we calculate the gravitational entropy for cosmologies with radiation, matter, Lambda and space curvature, finding it favours spatially flat, homogeneous and isotropic universes with a small positive cosmological constant in accord with observation. To maintain conformal symmetry, we include unusual Dim-0 (dimension zero) fields. They improve the SM's coupling to gravity, cancelling the vacuum energy and two local "Weyl" anomalies, without introducing additional propagating modes. They also cancel pathologies introduced into the graviton propagator by loops of SM particles. Cancellation requires precisely 3 generations of SM fermions, each with a RH neutrino. It also requires a composite Higgs, presumably built with the Dim-0 fields. One of the RH neutrinos, if stable, is a viable candidate for the dark matter which will be tested soon. The Dim-0 fields source scale-invariant curvature perturbations in the early universe. Subject to two simple but crucial theoretical assumptions, the amplitude and spectral tilt match the observations with remarkable accuracy. (See arXiv:2302.00344 and references therein).

Zoom Link: https://pitp.zoom.us/j/95784600151?pwd=dkppa2s3ZDM4NG5yb0ZVV2w5SXErdz09

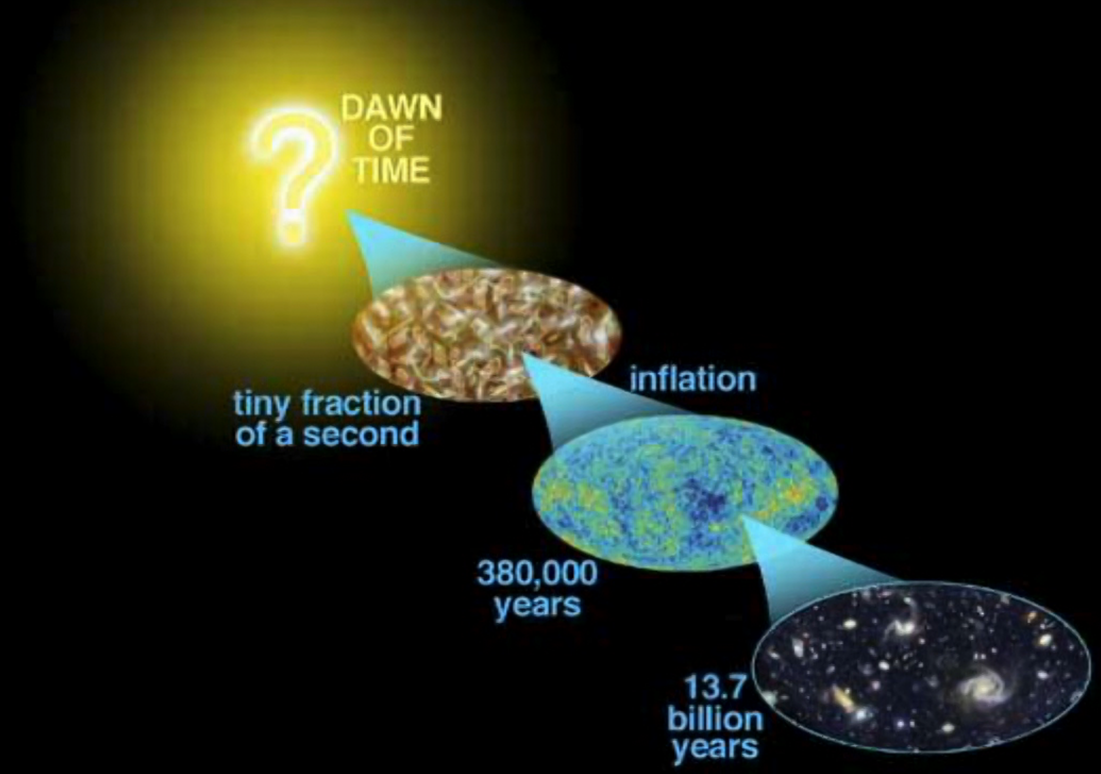
A minimal SM/LCDM cosmology

Neil Turok

University of Edinburgh
and
Perimeter Institute

with Latham Boyle (PI+Ed),
Sam Bateman and Kostas Tsanavaris

current consensus



inflation was a groundbreaking idea but

1. So far, all we see is vanilla LCDM *cf.* landscape of inflation models

2. No sign of a multiverse

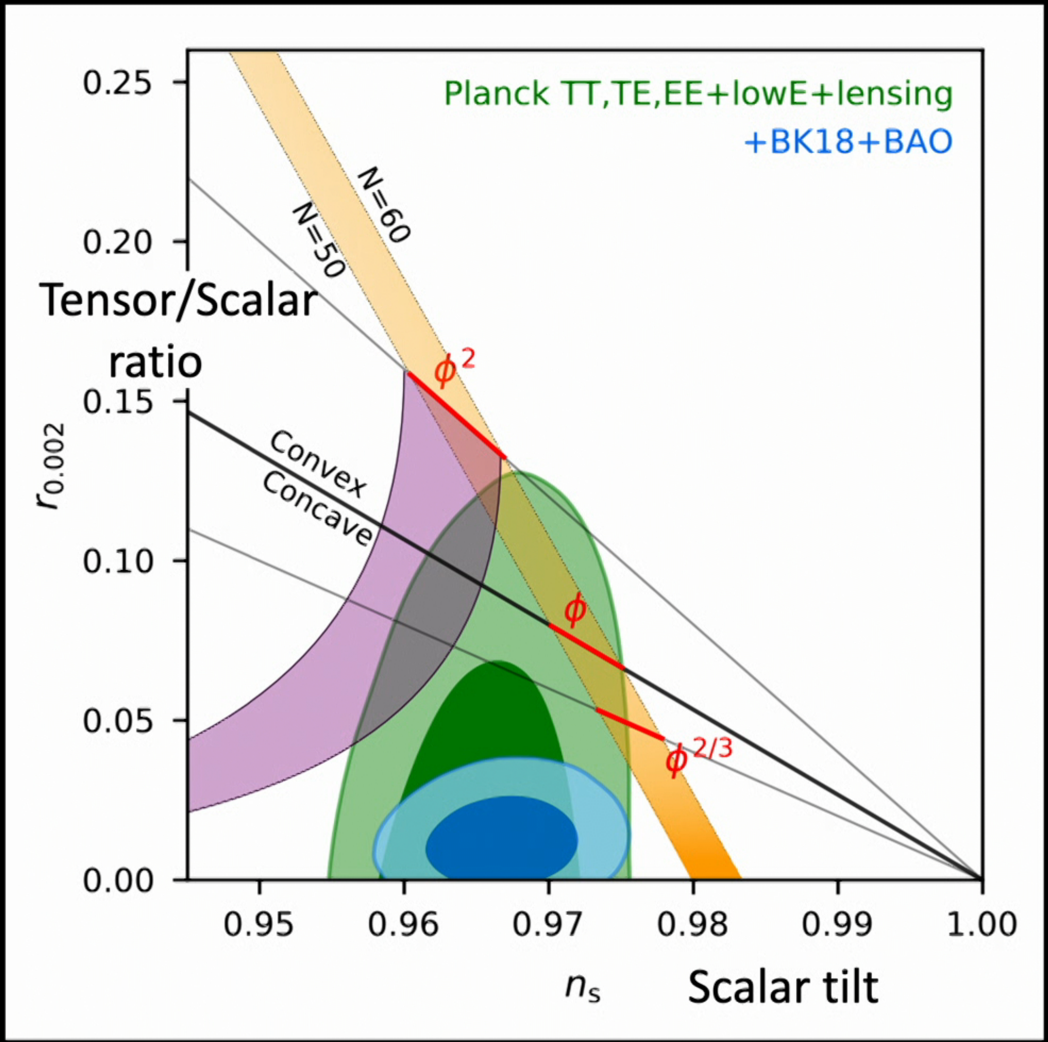
3. Upper bound on tensor modes steadily falling; ϕ^2 inflation ruled out.
   (Current bound is r<.03; CMB experimenters project r<.003 by 2027)

it is important to develop alternatives

no sign of
inflationary
tensors

BICEP/Keck
Collaboration
2203.16556
[astro-ph]

anticipated limit
r<.003
using SPT for
"delensing"
(2027)



vanilla LCDM:

just 5 fundamental physics parameters

matter/energy content

1. ρ_Λ cosmological constant
2. ρ_{DM}/ρ_B DM/baryon density
3. n_B/n_γ baryons per photon

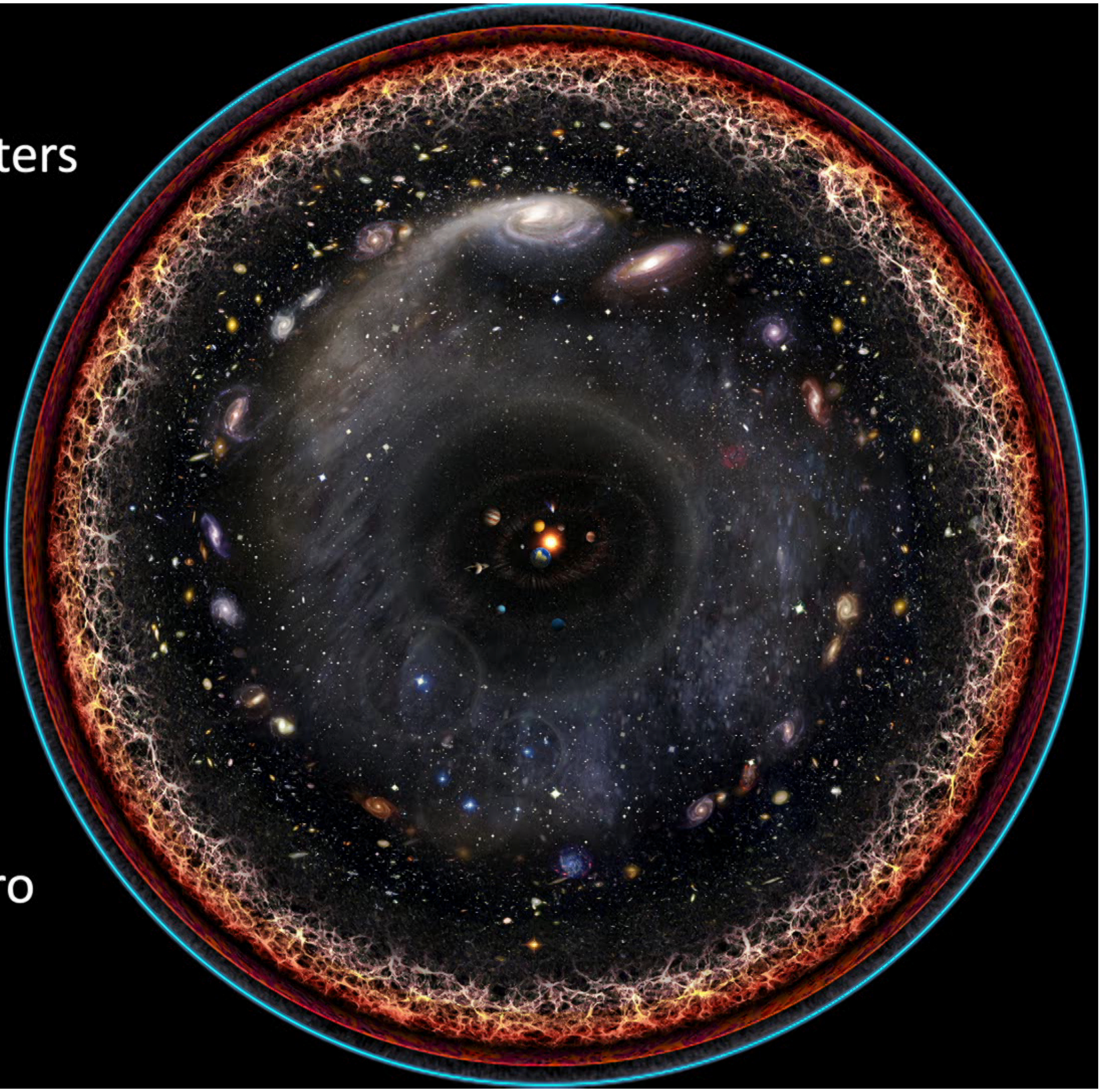
fluctuations $\langle|\Phi_k|^2\rangle = A\left(\frac{k}{k_*}\right)^{n_s-1}$ (Newtonian potential)

4. $\Phi_{rms} = \sqrt{A} \approx 3\times10^{-5}$ $(k_* \equiv 0.05\mathrm{Mpc}^{-1})$

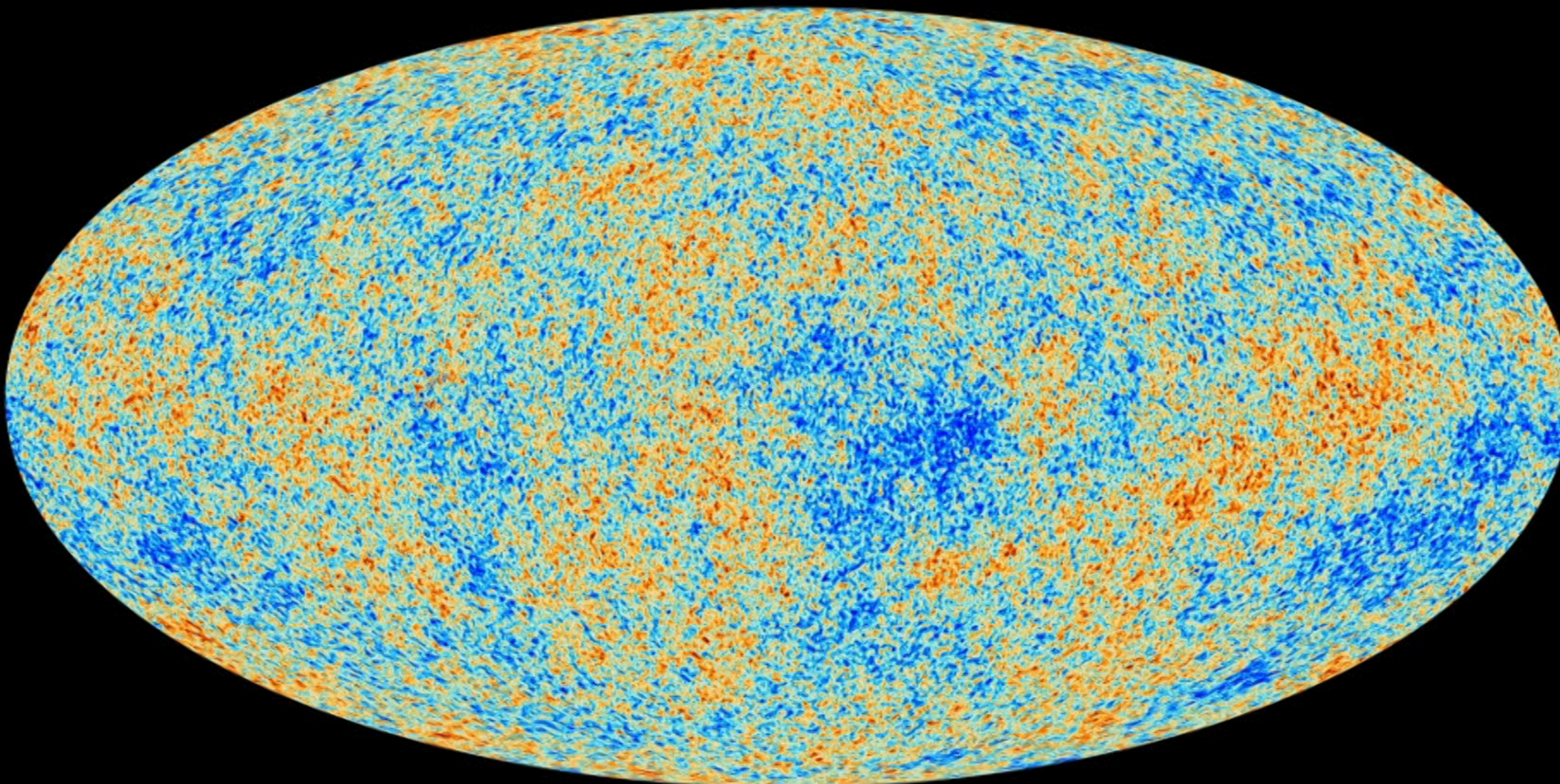
Sachs-Wolfe $\delta T/T \approx \Phi/3 \approx 10^{-5}$

5. $n_s - 1 \approx 0.96$ red tilt

many quantities consistent with zero

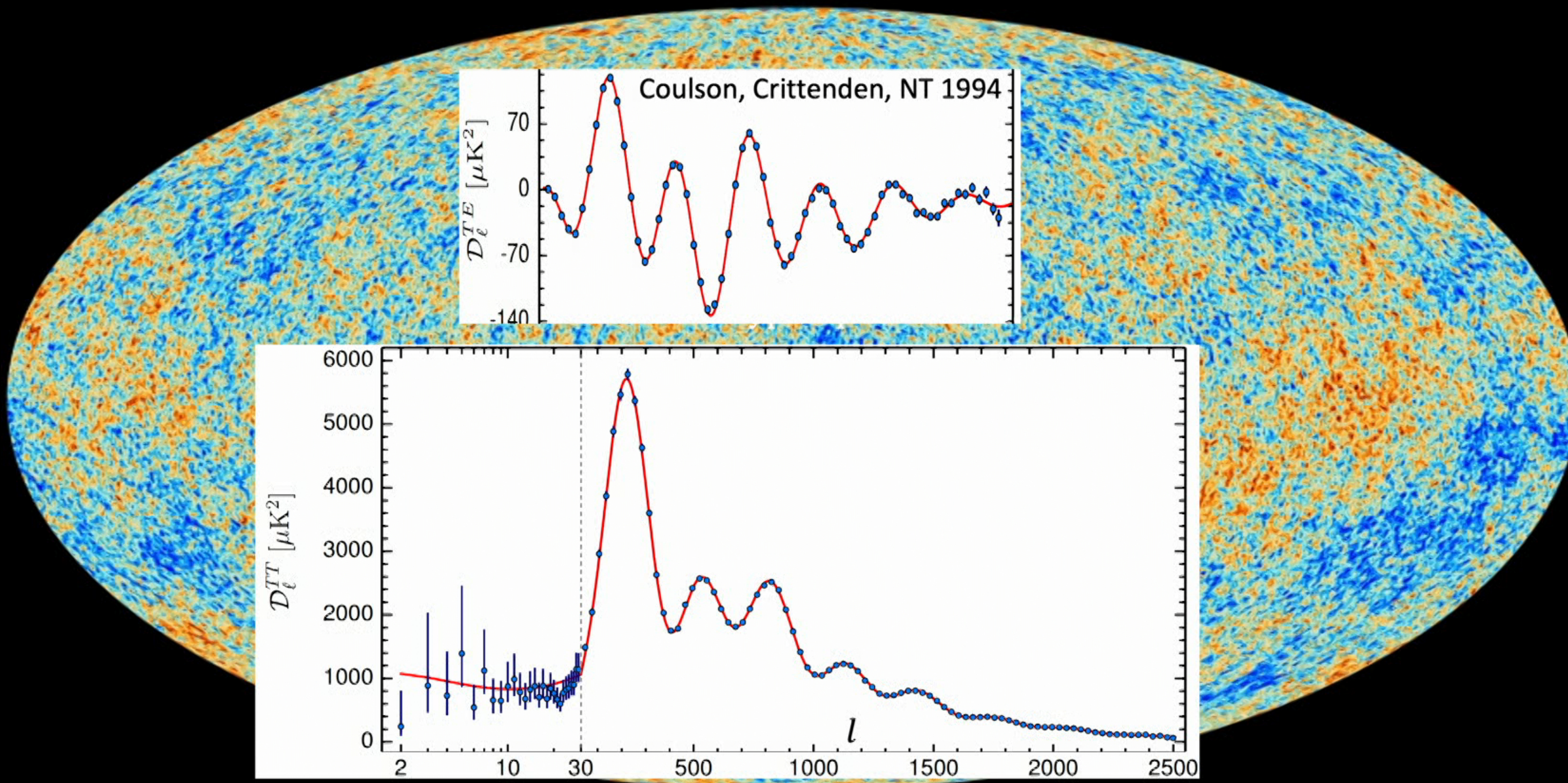


Looking back to the bang



ESA Planck satellite

Large scale perturbations

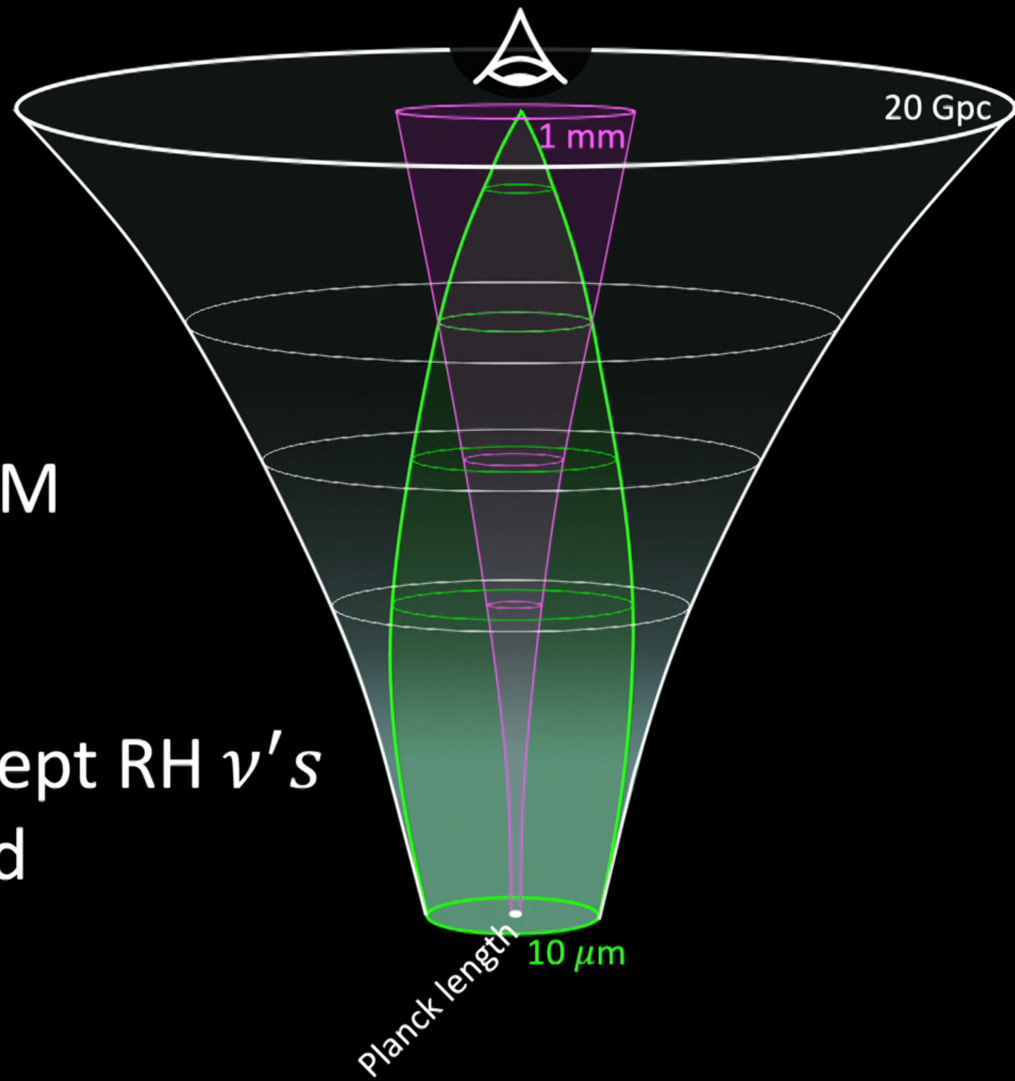


ESA Planck satellite

this talk:

a new framework connecting SM&LCDM (all 5 parameters)

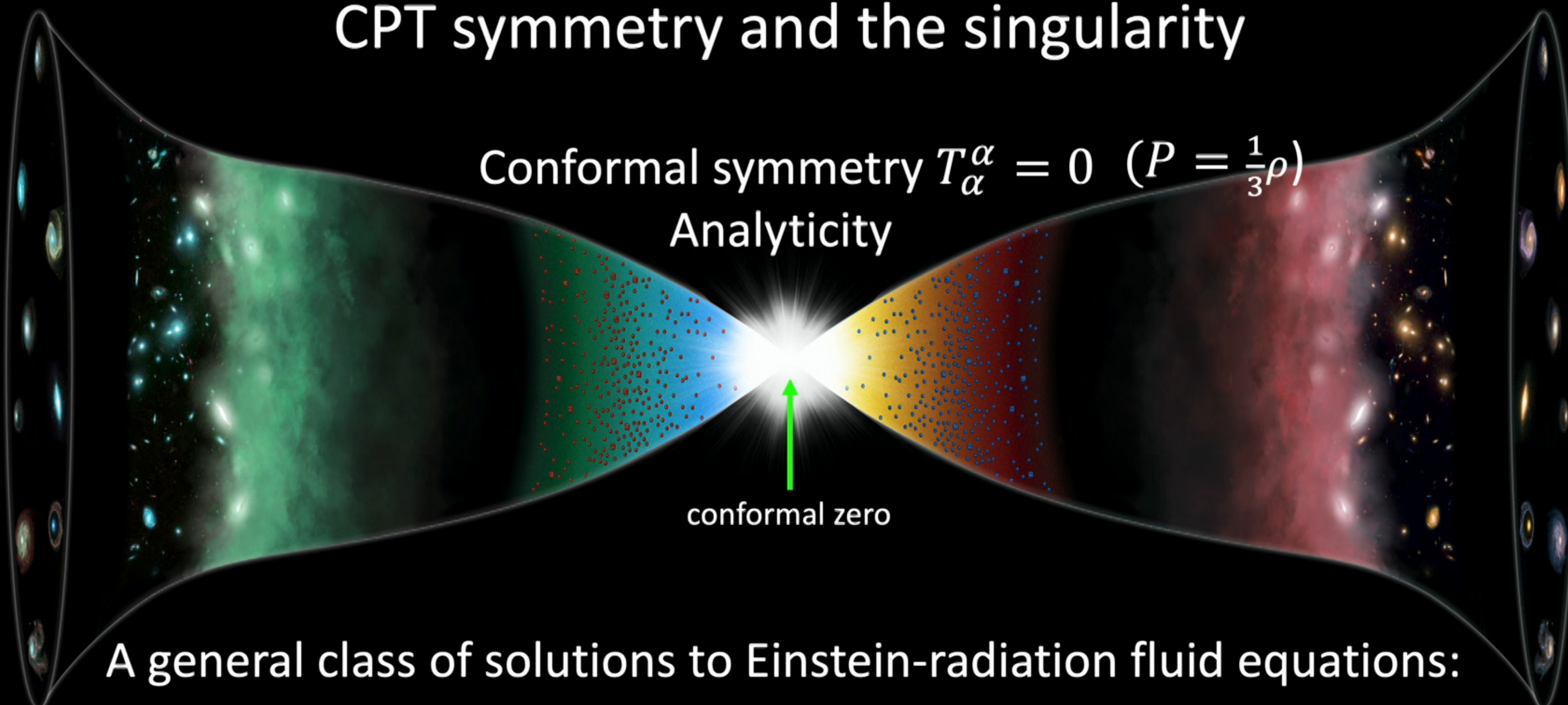
no new particles except RH $\nu's$
inflation not required



CPT symmetry and the singularity

Conformal symmetry $T^{\alpha}_{\alpha} = 0 \;\; (P = \frac{1}{3}\rho)$

Analyticity

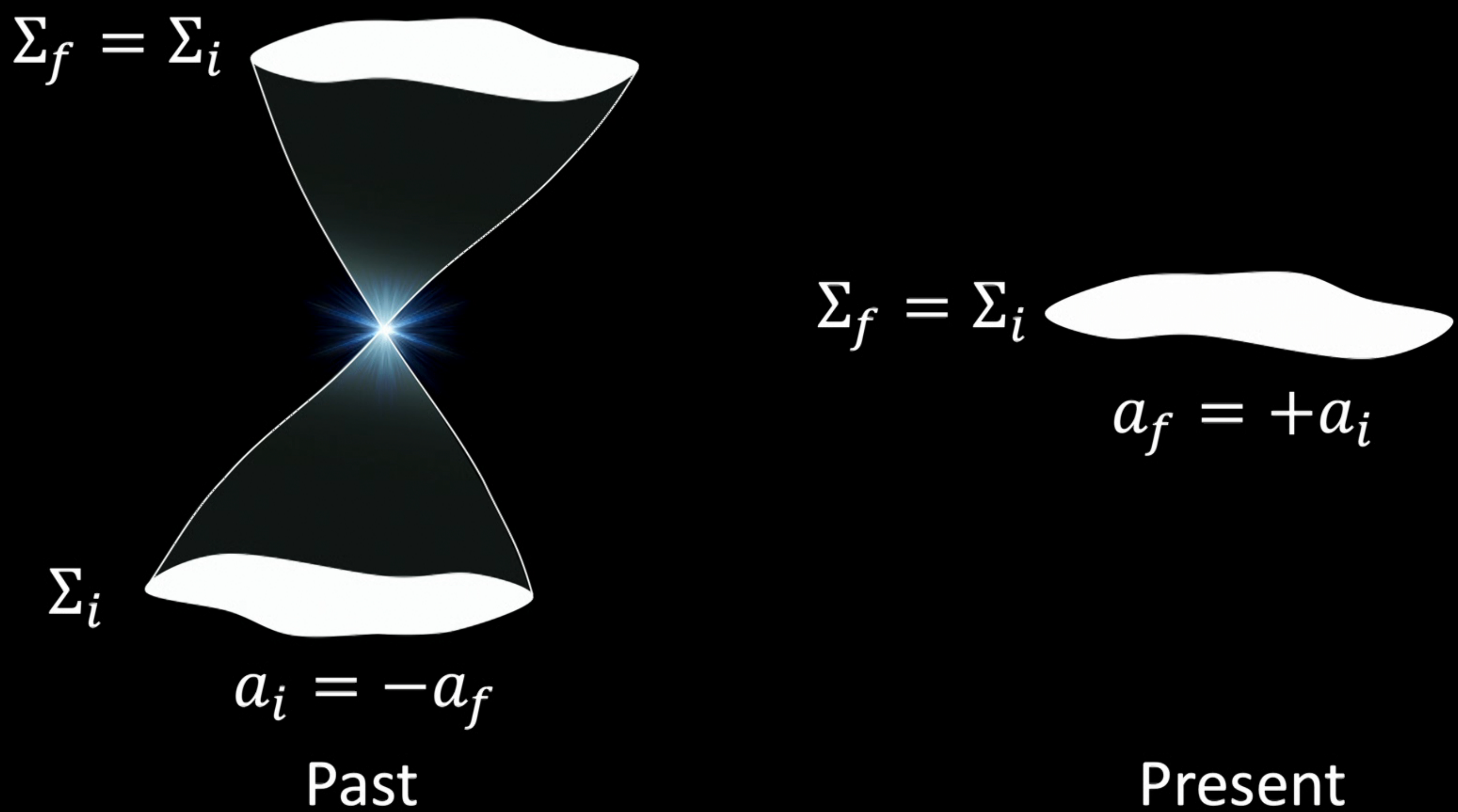


A general class of solutions to Einstein-radiation fluid equations:

$$ds^2 = t^2(-dt^2 + h_{ij}(t,x)dx^i\, dx^j);\; h_{ij}(t,x) = \underbrace{h^0_{ij}(x)}_{\text{regular 3-metric}} + t^2\, h^2_{ij}(x) + ..$$

singularity is purely conformal: extended spacetime symmetric under $t \Rightarrow -t$

Gravitational path integral with CPT symmetric boundary conditions



Penrose's ``Weyl curvature hypothesis" (late '70's) follows from the path integral for gravity with CPT symmetric boundary conditions

Start from homogeneous, isotropic backgrounds and extend to more generic metrics in (cosmological) perturbation theory

the puzzling large-scale geometry of the cosmos

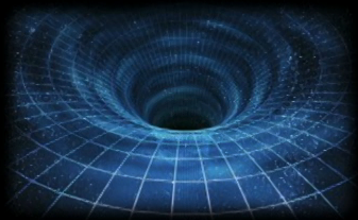
Penrose

Path integrals and gravity

gauge fields

Higgs

$$\int e^{\frac{i}{\hbar}\int\left(\frac{R}{16\pi G} - \frac{1}{4}F^2 + \overline{\psi} i \not{D}\psi - \lambda H \overline{\psi}\psi + |DH|^2 - V(H)\right)}$$

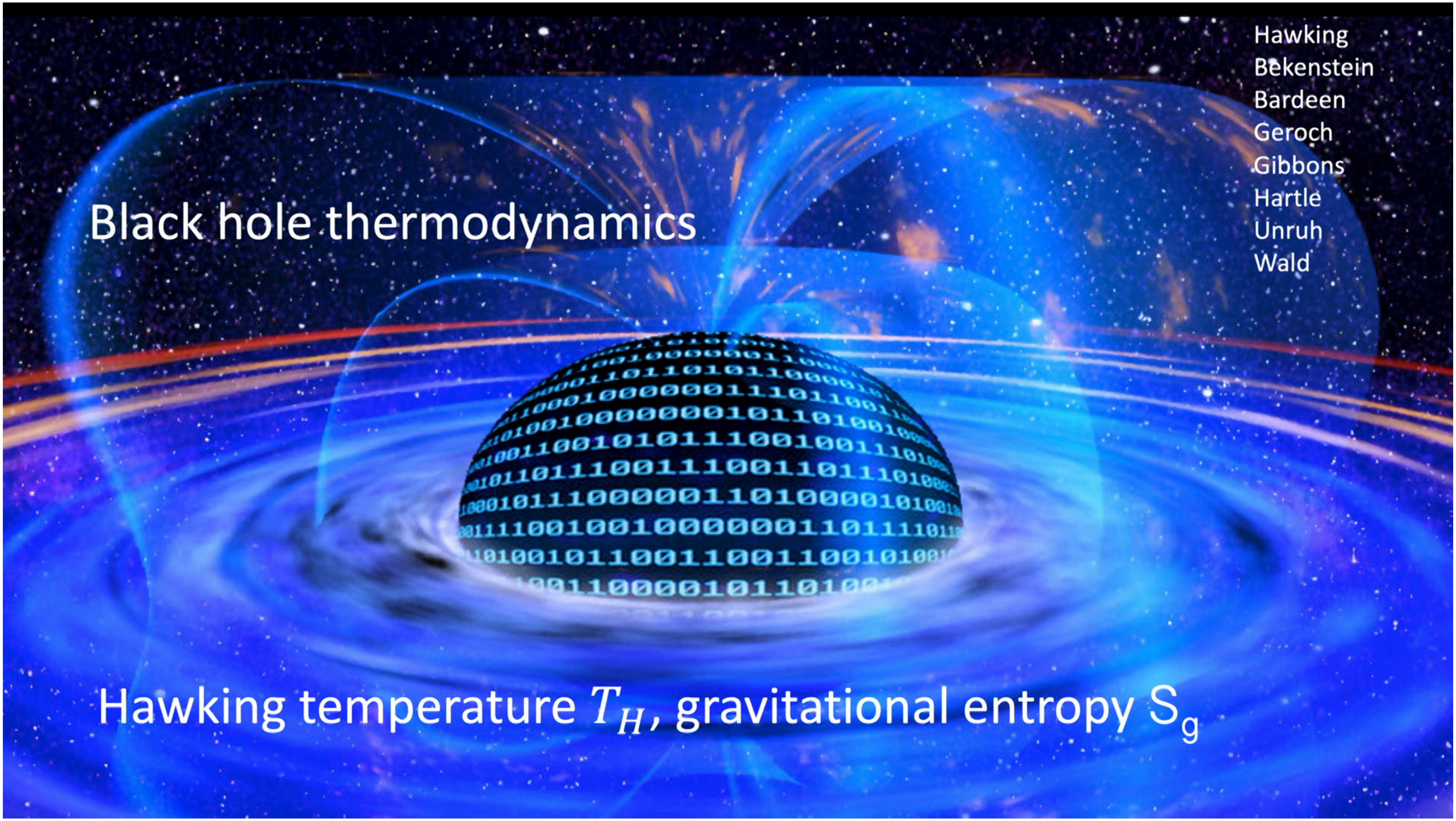


gravity

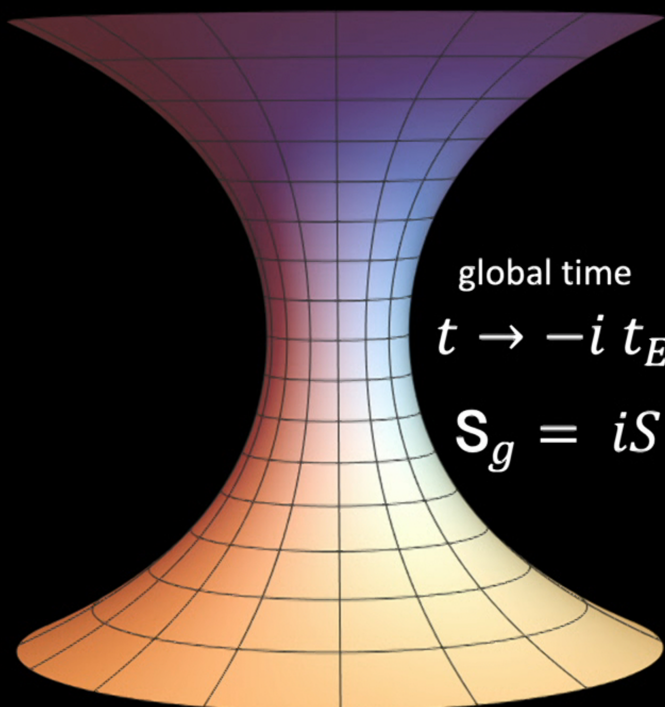
particles

gravitational entropy

With pbcs in imaginary time, $\underbrace{Z}_{\text{partition function}} = e^{S_g}$

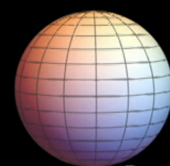

Black hole thermodynamics
Hawking
Bekenstein
Bardeen
Geroch
Gibbons
Hartle
Unruh
Wald
Hawking temperature T_H, gravitational entropy S_g

de Sitter



gravitational entropy from the Euclidean path integral

S^4



global time

$t \to -i\, t_E$

trace of Einstein

$$R = \frac{4\rho_\Lambda}{M_P^2}$$

$$\mathbf{S}_g = iS = -S_E = \int \left(\tfrac{1}{2} M_P^2 R - \rho_\Lambda\right) = \rho_\Lambda \,\mathrm{Vol} = \frac{24\pi^2 M_P^4}{\rho_\Lambda}$$

$$\equiv \mathbf{S}_\lambda \approx 3.26\times 10^{122} \text{ for measured } \rho_\Lambda$$

de Sitter Entropy

cf. entropy of radiation in our Hubble volume $\sim 10^{90}$

realistic cosmology:

scale factor

symmetric space $R^{(3)} = 6\kappa$

$$ds^2 = a(t)^2\left(-dt^2 + \gamma_{ij}dx^i dx^j\right)$$

conformal time

comoving space (assume compact)

radiation matter space curvature Lambda

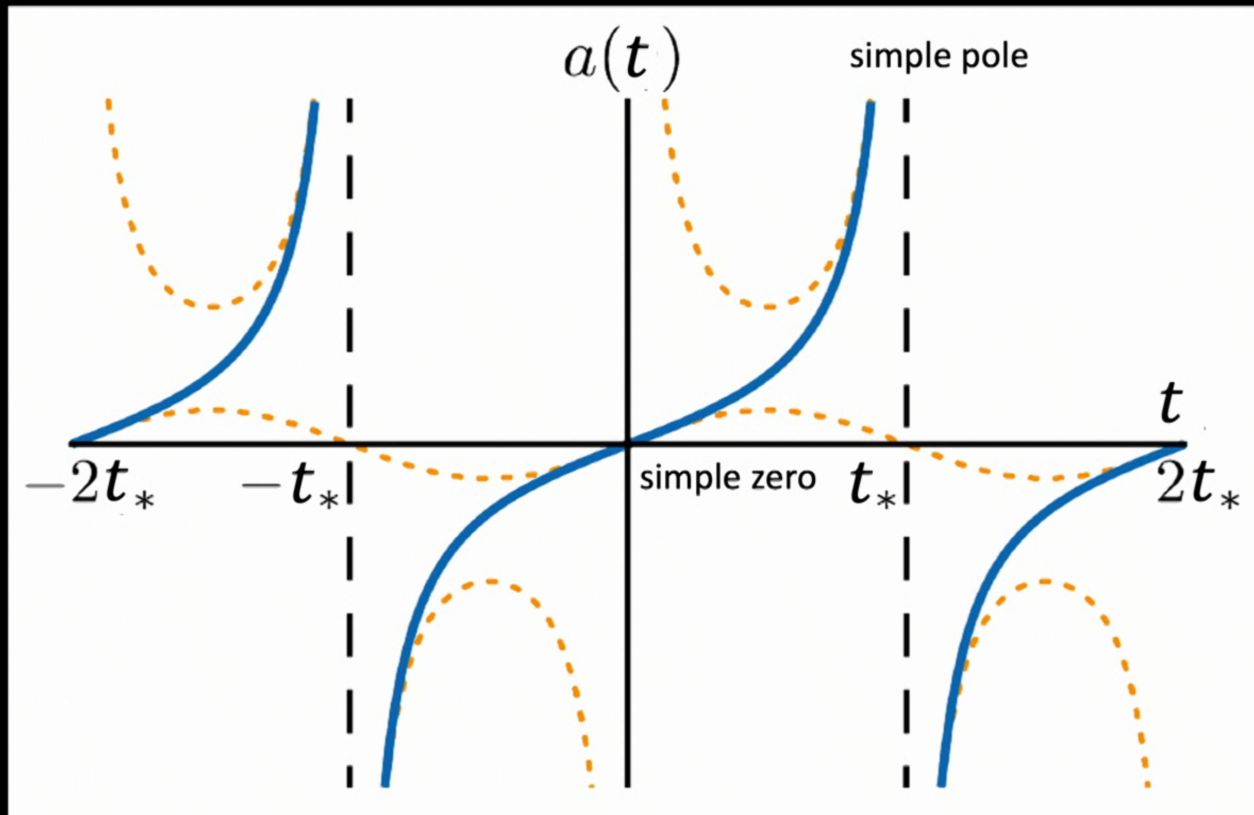
Friedmann $\dot{a}^2 = r + \mu a - \kappa a^2 + \lambda a^4$

(ignoring numerical factors)

conformal symmetry $T^{\mu}{}_{\mu} = 0 \Longrightarrow R = 0 \Longrightarrow a(t)$ analytic at $t = 0$

Einstein eq

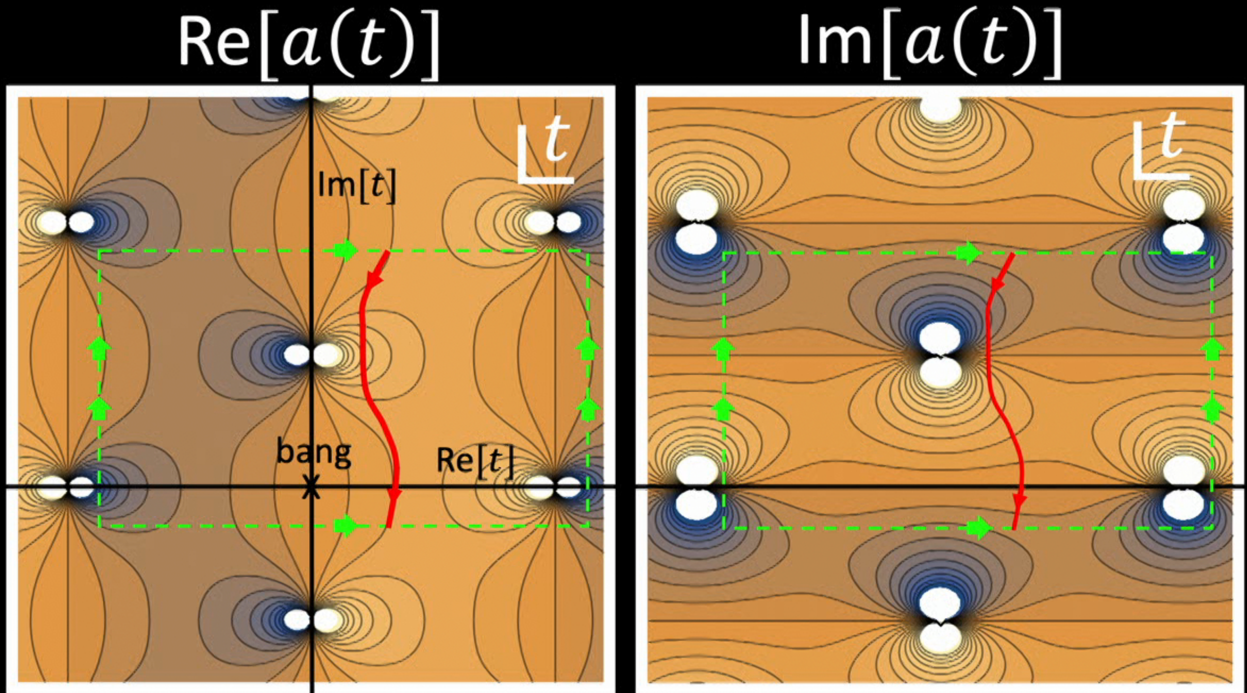
general solution has remarkable analytical properties real time

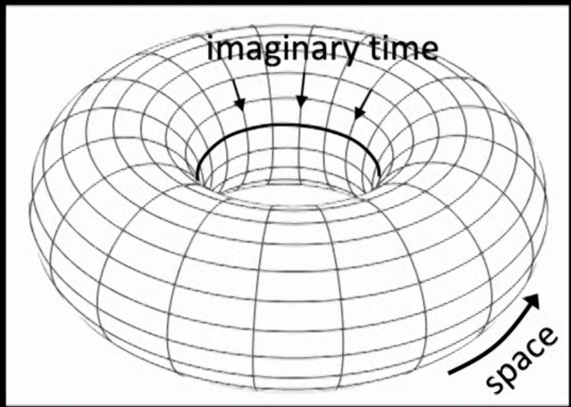


$a(t)$ is single-valued and doubly periodic in the complex t-plane

its only singularities are simple poles

$a(t)$ is periodic in imaginary time. The period and the action computed over a period determine T_H and the gravitational entropy S_g for realistic cosmologies.



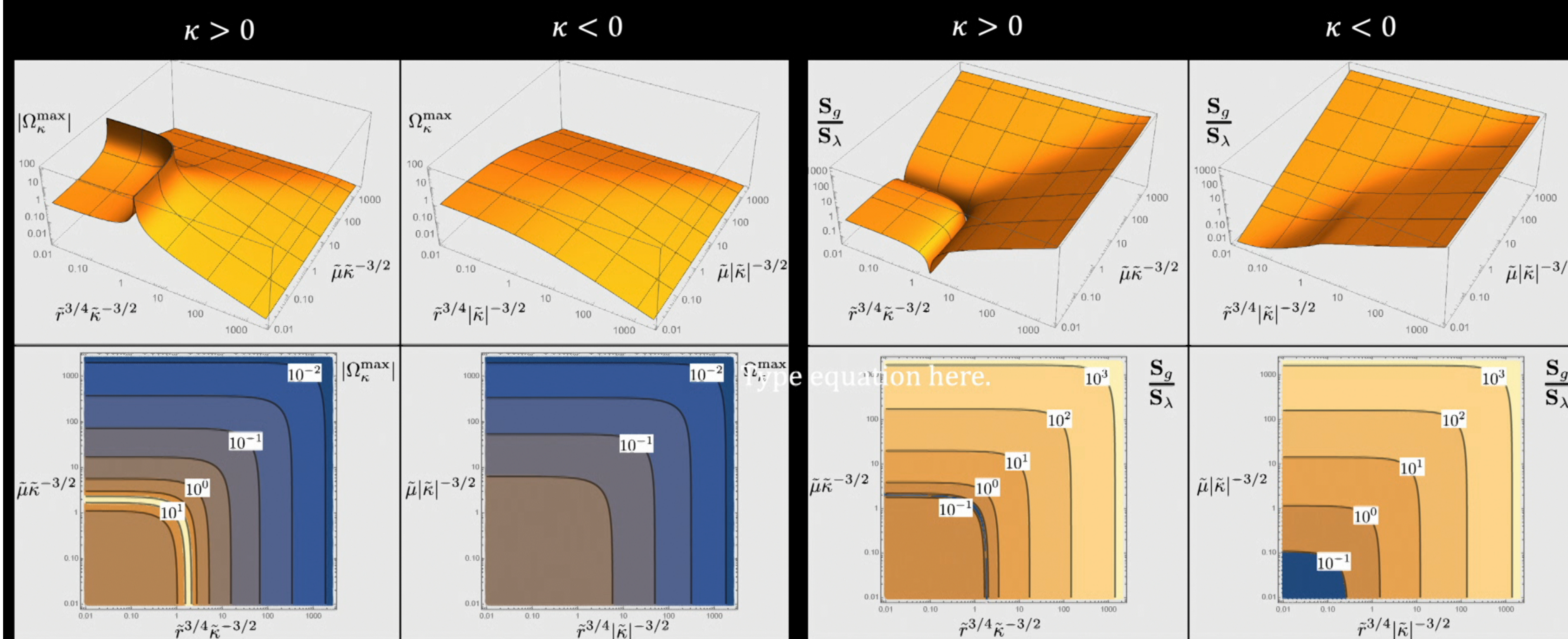


Euclidean instanton for
a closed universe
with matter, radiation, Lambda

We recently calculated S_g and found that it favours:

1. a homogeneous, isotropic, spatially flat universe
2. a small, positive cosmological constant

(echoing earlier arguments of Baum, Hawking, Coleman...)

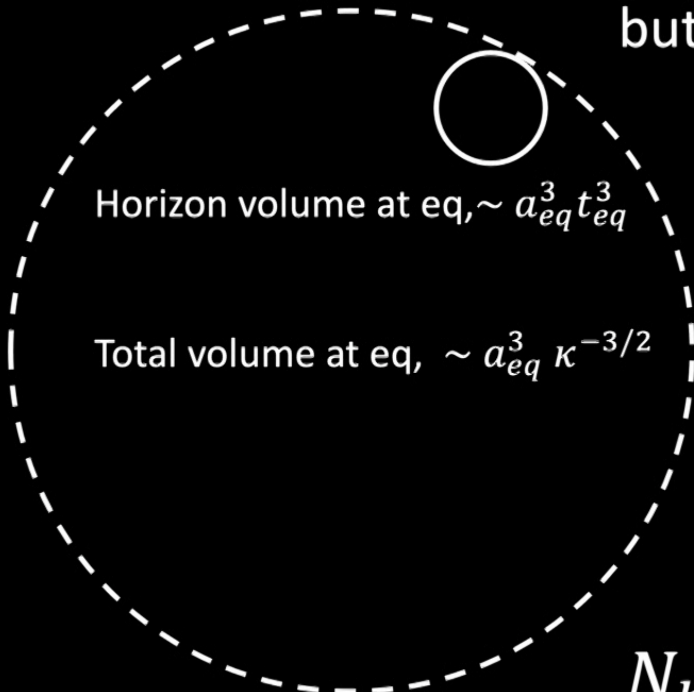


$$\tilde{r} \equiv \frac{r}{\lambda};\ \tilde{\mu} \equiv \frac{\mu}{\lambda}; \tilde{\kappa} \equiv \frac{\kappa}{\lambda}; \qquad \mathbf{S}_\lambda = \frac{24\pi^2}{L_{Pl}^2\lambda}$$

understanding in terms of horizons

$3\dot{a}^2 = -3\kappa a^2 + r + \lambda a^4$; equal Λ, radiation density at $a_{eq} = (r/\lambda)^{1/4}$

but for $a < a_{eq}$, $a \sim r^{1/2} t$ so $t_{eq} \sim 1/(r\lambda)^{1/4}$

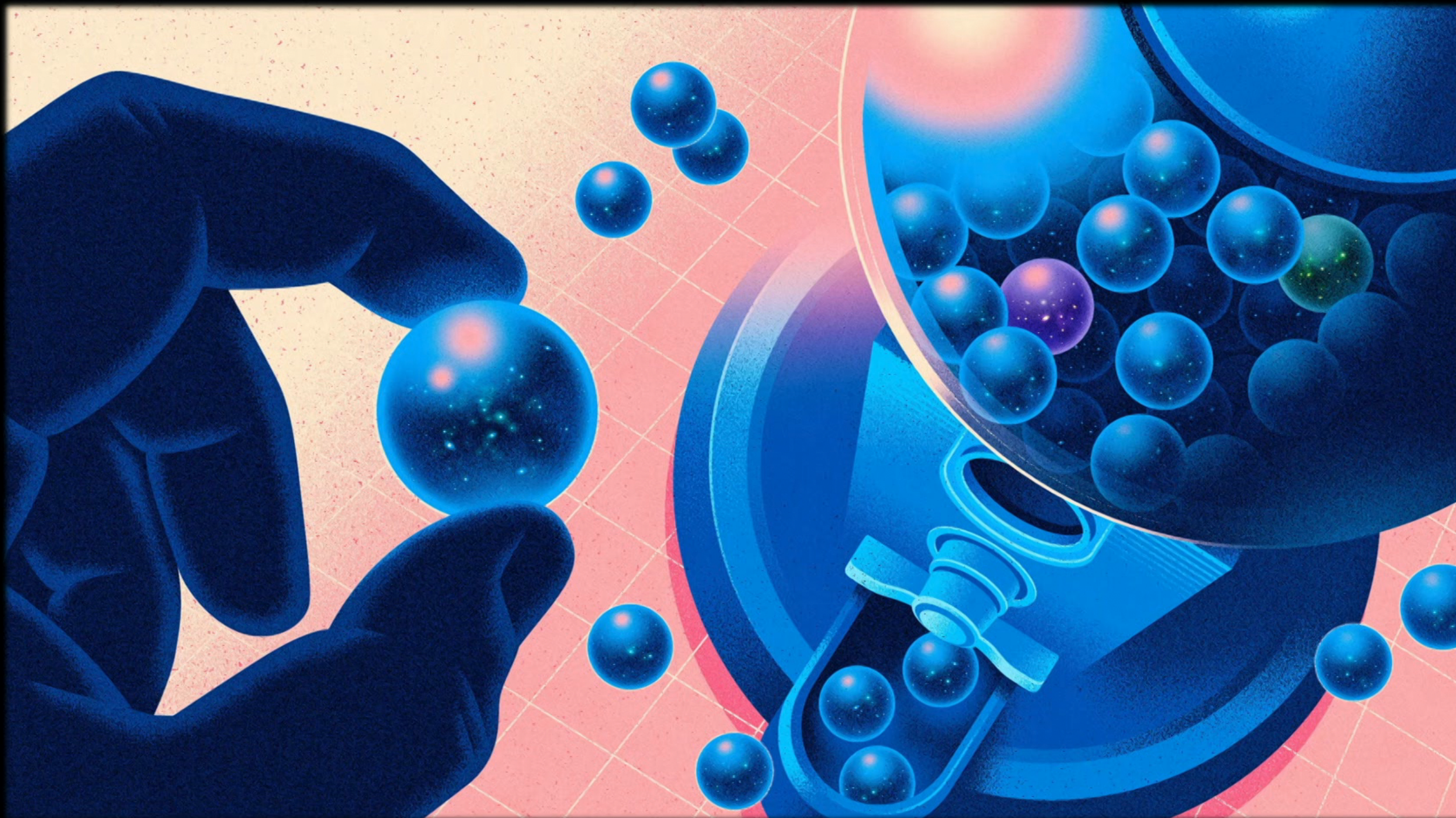


number of horizon volumes at equality

$$N_{hor} \sim (\lambda r/\kappa^2)^{3/4}$$

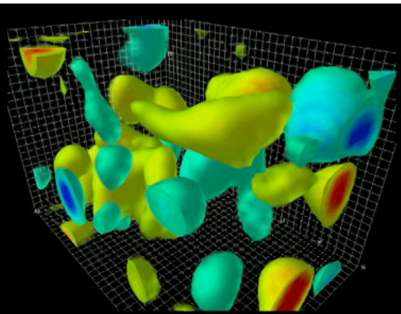
multiply by de Sitter entropy λ^{-1}

$$N_{hor}\lambda^{-1} \sim (r/\kappa^2)^{3/4}\ \lambda^{-1/4} \sim S_r S_\Lambda^{1/4}$$



Quanta Magazine, Nov 17, 2022; *WIRED*, Jan 22, 2023

Quantum fields and gravity



vacuum energy and pressure are divergent,
simple physical regularizations such as point splitting give (for, *e.g.*, Maxwell):

B.S.DeWitt, Phys. Rep. 19 (1975) 295

$$\Longrightarrow \langle T^{\mu\nu}\rangle_{vac} \sim \frac{3}{\pi^2 \Delta t^4}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix},$$

where Δt^2 = invart time-like separation

Breaks Lorentz invariance! Can be renormalized away but leaves us without a physical understanding of the QFT vacuum.

Even worse are Weyl anomalies where quantum divergences spoil the local scale invariance of Maxwell and Dirac fields: violations cannot be renormalized away

understanding in terms of horizons

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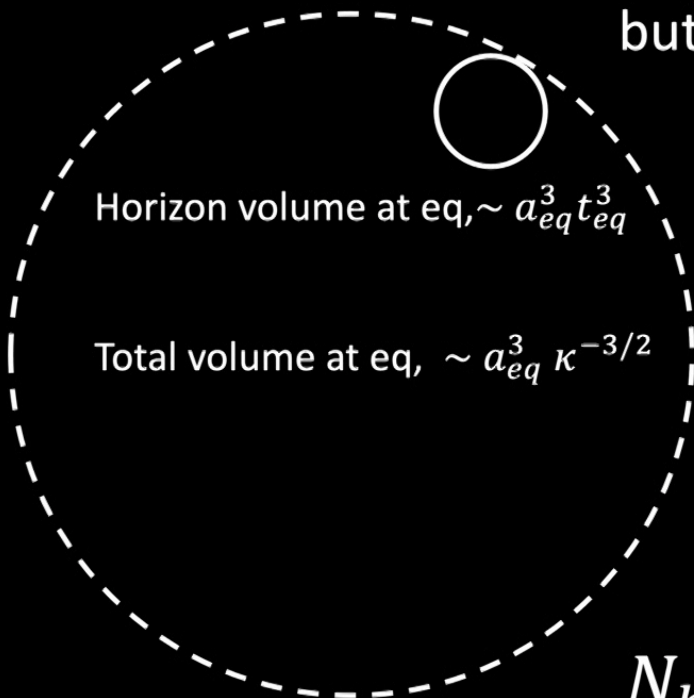

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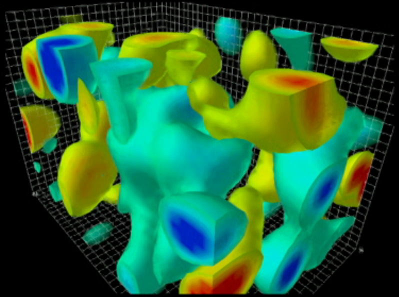

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Dimension zero scalars

Have a four-derivative, locally scale-invariant action

$$S_4 = -\frac{1}{2}\int d^4x\sqrt{-g}(\Box\varphi)^2 \qquad\qquad \varphi(x) \longrightarrow \varphi(x)$$

dates back to Heisenberg (1957), Pauli, Thirring, Nakanishi, …

- the "dipole ghost"

Bogoliubov et al (1987); Rivelles (2003)

a very interesting theory

"Dirac singleton" – predecessor of AdS/CFT (Flato+Fronsdal)

It has an infinite dimensional symmetry: $\varphi(x) \longrightarrow \varphi(x) + \alpha(x)$ with $\Box\alpha = 0$

Reminiscent of the residual gauge symmetry in covariant gauges in QED

In this case, the only physical state is the vacuum: there are no excited states

The vacuum fluctuations are scale-invariant

$$\langle\varphi(0,\boldsymbol{x})\varphi(0,\boldsymbol{y})\rangle = \int \frac{d^3\boldsymbol{k}}{(2\,\pi)^3}\frac{e^{i\boldsymbol{k}.(\boldsymbol{x}-\boldsymbol{y})}}{4\,k^3}$$

cf. Newtonian potential Φ in cosmology

Vacuum energy and conformal anomalies

$$E_{\boldsymbol{k}} = \tfrac{1}{2}\hbar k\,(\overset{\text{dim-one scalars}}{n_{s,1}} - 2\,\overset{\text{chiral fermions}}{n_F} + 2\overset{\text{gauge fields}}{n_A} + 2\overset{\text{dim-zero scalars}}{n_{s,0}})$$ per mode $\boldsymbol{k}$

$$\langle T^{\mu}{}_{\mu}\rangle = -a\,E + c\,C^2: \qquad C^2 = C^{\alpha\beta\gamma\delta}C^{\alpha\beta\gamma\delta};\quad E = R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta} - 4R_{\alpha\beta}R^{\alpha\beta} + R^2$$

$$a = \frac{1}{360(4\,\pi)^2}\left[n_{s,1} + \frac{11}{2}\,n_F + 62\,n_A - 28\,n_{s,0}\right]$$

$$c = \frac{1}{120(4\,\pi)^2}\left[n_{s,1} + 3\,n_F + 12\,n_A - 8\,n_{s,0}\right]$$

Given the SM gauge group $SU3\times SU2\times U1$, all three cancel iff

$$n_F = 4n_A = 48;\;\; n_{s,0} = 3n_A = 36;\;\; n_{s,1} = 0.$$

Requires precisely three generations, each with a RH neutrino

Also that there are no fundamental dim-1 scalars so Higgs must be composite

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Graviton propagator with 1 loop SM corrections

Tomboulis 70's
Han Willenbrook
Donoghue Menezes

Loop is given by the Fourier transform of the stress-energy correlator: for a CFT,

$$= \langle T^{\mu\nu}(x) T^{\rho\lambda}(y) \rangle = C^T \frac{1}{4\,\pi^4 x^8}\, I^{\mu\nu,\rho\lambda}(x-y)$$

where $I^{\mu\nu,\rho\lambda} = \frac{1}{2}\left(I^{\mu\rho} I^{\nu\lambda} + I^{\mu\lambda} I^{\rho\nu}\right) - \frac{1}{4}\eta^{\mu\nu}\eta^{\rho\lambda}$ and $I^{\mu\nu}(x) = \eta^{\mu\nu} - 2\frac{(x-y)^\mu (x-y)^\nu}{(x-y)^2}$

$C^T = \frac{4}{3}[n_{s,1} + 3\, n_F + 12\, n_A - 8\, n_{s,0}] \equiv \frac{4}{3} n_{eff}$ ($\propto$ coefft of Weyl squared in the trace anomaly)

Projector onto spin 2 component
- gauge invariant

Dim reg and min sub $\Rightarrow$ $$D^{\alpha\beta,\mu\nu}(k) = \frac{P^{\alpha\beta,\mu\nu}(k)}{k^2\left((1 - \frac{n_{eff}}{240\pi} G k^2 \ln(-\frac{k^2}{\mu^2})\right)}$$

These SM corrections to the graviton propagator are problematic:

1. Inconsistent with Källén-Lehmann repn. $D(k) = \int_0^\infty dm^2\, \rho(m^2) \frac{1}{k^2 - m^2 + i\varepsilon}$

   (follows from Poincare invariance and positivity of the physical Hilbert space)

2. Specifically, $D(k)$ (i) falls off as $|k|^{-4}$ at large $|k|$

   (ii) has complex (acausal) poles on physical sheet

Similarly, Dim-0 scalar loops alone violate K-L: (i) $|k|^{-4}$ fall off; (ii) a tachyonic pole

BUT SM + Dim-0 combination is consistent with Poincaré, causality and positivity

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A Minimal Explanation of the Primordial Cosmological Perturbations

Neil Turok[1,2,*] and Latham Boyle[2,†]

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[2] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5*

We outline a new explanation for the primordial density perturbations in cosmology. Dimension zero fields are a minimal addition to the Standard Model of particle physics: if the Higgs doublet is emergent, they cancel the vacuum energy and both Weyl anomalies without introducing any new particles. Furthermore, the cancellation explains why there are three generations of elementary particles, including RH neutrinos. We show how quantum zero point fluctuations of dimension zero fields seed nearly scale-invariant, Gaussian, adiabatic density perturbations. We determine their amplitude in terms of Standard Model couplings and find it is consistent with observation. Subject to two simple theoretical assumptions, both the amplitude and the tilt we compute *ab initio* agree with the measured values inferred from large scale structure observations, with no free parameters.

arXiv:2302.00344[hep-ph]

primordial perturbations from Dim-0 fields and the SM

Running couplings violate scale symmetry: at high temperature,

$$T_\beta^{SM} \equiv \langle T^{SM\mu}{}_{\mu} \rangle_\beta = 3P - \rho \approx \sum c_i \alpha_i^2\, T^4 \equiv c_\beta^{SM} T^4$$

This anomalous trace can be cancelled by introducing a coupling in the effective action,

$$\Gamma^\varphi = \sum_{j=1}^{n_{s,0}} \frac{1}{2} \int -a\varphi_j \Delta_4 \varphi_j + \left[a\left(E - \tfrac{2}{3}\Box R\right) + cC^2 - n_{s,0}^{-1} T_\beta^{SM}\right]\varphi_j$$

(generalizing sigma models in string theory viewed as a model of 2d gravity)

The last term corrects the Einstein-fluid equations, converting quantum correlations in the 36 dim-0 fields into large scale curvature fluctuations: Friedmann equation becomes

$$\dot{a}^2 = \frac{8\pi G}{3}\rho_r a^4 (1 + c_\chi \chi(x)) \text{ with } \chi(x) = n_{s,0}^{-1} \sum \varphi_j(x),\ c_\chi = c_\beta^{SM} / \left(\tfrac{\pi^2}{30}\mathcal{N}_{eff}\right),\ \mathcal{N}_{eff} \approx 106\tfrac{1}{4}$$

Conformal factor translates directly into “comoving curvature perturbation” $\mathcal{R}(x) = \frac{1}{4} c_\chi \bar{\varphi}(x)$

(adiabatic, Gaussian, scalar: no primordial tensors)

Spectral tilt

Dominated by QCD: asymptotic freedom $\Longrightarrow$ red tilt!

To understand quantitatively, consider the trace anomaly (for QCD)

$S = -\int \frac{1}{4} F^2 \Rightarrow -\int \frac{1}{4g^2} F^2$. $\alpha \equiv \frac{g^2}{4\pi}$; $\mu\partial_\mu \alpha \equiv \beta_\alpha$; $\Longrightarrow \mu\partial_\mu S = \int \frac{\beta_\alpha}{\alpha} \frac{1}{4g^2} F^2 \Rightarrow \int \frac{\beta_\alpha}{4\,\alpha} F^2$

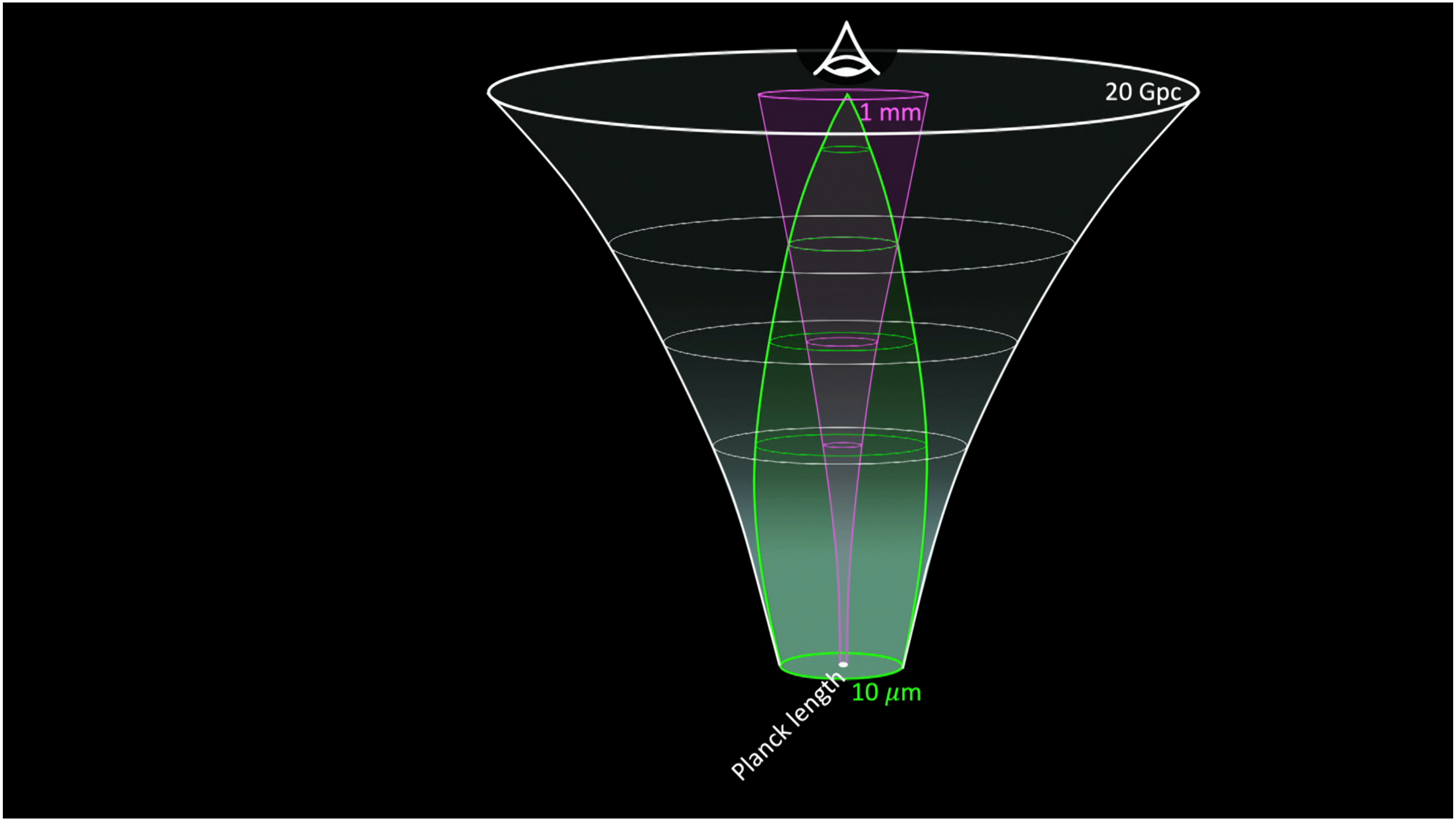
$\Longrightarrow T^\lambda_\lambda = \frac{\beta_\alpha}{4\,\alpha} F^2$; $\frac{\beta_\alpha}{\alpha} = -(11 - \frac{2}{3} n_f) \frac{\alpha}{2\pi} T^4$; $\langle F^2 \rangle_\beta = \frac{2\pi\alpha}{9}(12+5n_f)T^4$

running coupling: energy scale of φ plasma interactions: energy scale of T

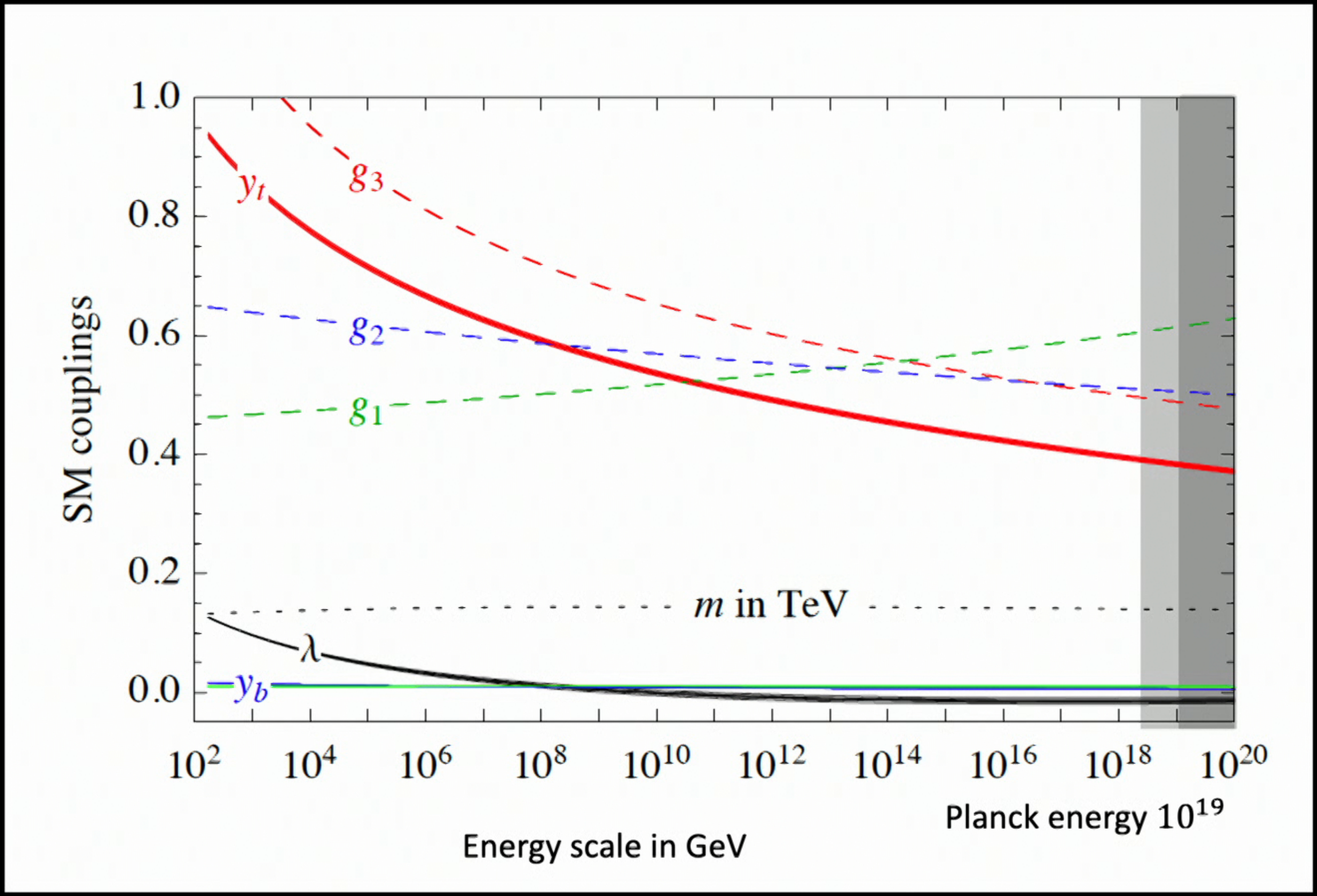
Thus, $\mathcal{P}_\mathcal{R}(k)$ scales with k as $\alpha^2(k)$; $n_s - 1 \equiv \frac{d\ln \mathcal{P}_\mathcal{R}(k)}{\mathrm{d}\ln k} = 2\frac{\beta_\alpha}{\alpha} = -\frac{7}{\pi}\alpha_{QCD}(M_P)$

The red tilt is an critical exponent which can be computed perturbatively

If so, we can extrapolate over 30 orders of magnitude in length scale…


20 Gpc
1 mm
10 μm
Planck length

Buttazzo et al
1307.3536
[hep-ph]



Comparison with observation

$\mathcal{P}_{\mathcal{R}}(k) = \frac{3^2 5^2}{7(2\pi)^4}\left(\frac{c_\beta^{SM}}{\mathcal{N}_{eff}}\right)^2 \left(\frac{k}{k_P}\right)^{-\frac{7\alpha_3}{\pi}}$; k_P= comoving Planck wavenumber

with $c_\beta^{SM} \equiv \frac{125}{108}\alpha_Y^2 - \frac{95}{72}\alpha_2^2 - \frac{49}{6}\alpha_3^2$ and $\mathcal{N}_{eff} = 106\frac{1}{4}$ (to lowest order, neglect Higgs)

Now use $(k_P/k_*)^{1-n_s} = 14.8 \pm 5.1,$ $k_* \equiv 0.05\ \mathrm{Mpc}^{-1}$

Thus, we find $\mathcal{P}_{\mathcal{R}} = A\left(\frac{k}{k_*}\right)^{n_s-1}$, $A = (13 \pm 5)\times 10^{-10}$; $n_s = 0.958$

cf. Planck satellite: $A = (21 \pm 0.3)\times 10^{-10}$; $n_s = 0.959 \pm 0.006$

Comparison with observation

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{3^2 5^2}{7(2\,\pi)^4}\left(\frac{c_\beta^{SM}}{\mathcal{N}_{eff}}\right)^2\left(\frac{k}{k_P}\right)^{-\frac{7\alpha_3}{\pi}};$$ k_P= comoving Planck wavenumber

with $c_\beta^{SM} \equiv \frac{125}{108}\alpha_Y^2 - \frac{95}{72}\alpha_2^2 - \frac{49}{6}\alpha_3^2$ and $\mathcal{N}_{eff} = 106\frac{1}{4}$ (to lowest order, neglect Higgs)

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cf. Planck satellite: $A = (21 \pm 0.3)\times 10^{-10};\ n_s = 0.959 \pm 0.006$

Comparison with observation

$$11 - \frac{2}{3} n_f$$

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{3^2 5^2}{7(2\,\pi)^4} \left(\frac{c_\beta^{SM}}{\mathcal{N}_{eff}} \right)^2 \left(\frac{k}{k_P} \right)^{-\frac{7\alpha_3}{\pi}};$$

k_P= comoving Planck wavenumber

with $c_\beta^{SM} \equiv \frac{125}{108}\alpha_Y^2 - \frac{95}{72}\alpha_2^2 - \frac{49}{6}\alpha_3^2$ and $\mathcal{N}_{eff} = 106\frac{1}{4}$ (to lowest order, neglect Higgs)

Now use $(k_*/k_P)^{n_s - 1} = 14.8 \pm 5.1$, $k_* \equiv 0.05$ Mpc^{-1}

Thus, we predict $\mathcal{P}_{\mathcal{R}} = A \left(\frac{k}{k_*} \right)^{n_s - 1}$, $A = (13 \pm 5)\times 10^{-10}$; $n_s = 0.958$

cf. Planck satellite: $A = (21 \pm 0.3)\times 10^{-10}$; $n_s = 0.959 \pm 0.006$

predictions testable as observations and theory are improved

summary

analytic extension of cosmological solutions of the Einstein equations lead to

- a new picture of the big bang singularity as a CPT “mirror”
- a calculation of the gravitational entropy for cosmological spacetimes

new explanations and predictions for

- the large-scale homogeneity, isotropy and flatness of the cosmos (and a hint about Lambda)
- the dark matter
- the arrow of time and the strong CP problem

Dimension zero scalars

- cancel the vacuum energy and both Weyl anomalies at leading order
- explain why there are 3 generations of SM fermions, including RH neutrinos
- explain the amplitude, tilt and character of the primordial perturbations
- require the Higgs to be emergent; suggest new approach to the gauge-gravity hierarchy

All without adding any new propagating degrees of freedom

These are encouraging signs but much remains to be understood