Title: A minimal SM/LCDM cosmology

Speakers: Neil Turok

Collection: Puzzles in the Quantum Gravity Landscape: viewpoints from different approaches

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Abstract: Recent observations point to a surprisingly economical description of the universe on both very small and very large scales. Stimulated by these findings, Boyle and I have proposed a new, potentially more complete theoretical framework than currently popular paradigms. Our search has so far led to 1) the simplest-yet explanation for the cosmic dark matter, soon to be tested by galaxy surveys, 2) a thermodynamic explanation for the large scale geometry of the cosmos, based on the concept of gravitational entropy à la Hawking, 3) a new account of the big bang singularity as a "mirror" enforcing CPT-symmetric boundary conditions, realising Penrose's "Weyl curvature hypothesis" and 4) a new mechanism for cancelling the divergent vacuum energy and the trace anomalies in the Standard Model (SM). The new mechanism successfully predicts the primordial density perturbations in terms of the SM's gauge couplings. It also explains why there are 3 generations of elementary particles, each including a RH neutrino, one of which is stable and comprises the dark matter. I'll outline the challenges the new picture faces and the opportunities it presents, ranging from solving the gauge hierarchy problem to an improved description of quantum gravity along with prospective observational tests.

A minimal SM/LCDM cosmology

Neil Turok

Higgs Centre, University of Edinburgh
and
Perimeter Institute for Theoretical Physics

with Latham Boyle

vanilla LCDM:
just 5 fundamental physics parameters

the matter/energy content

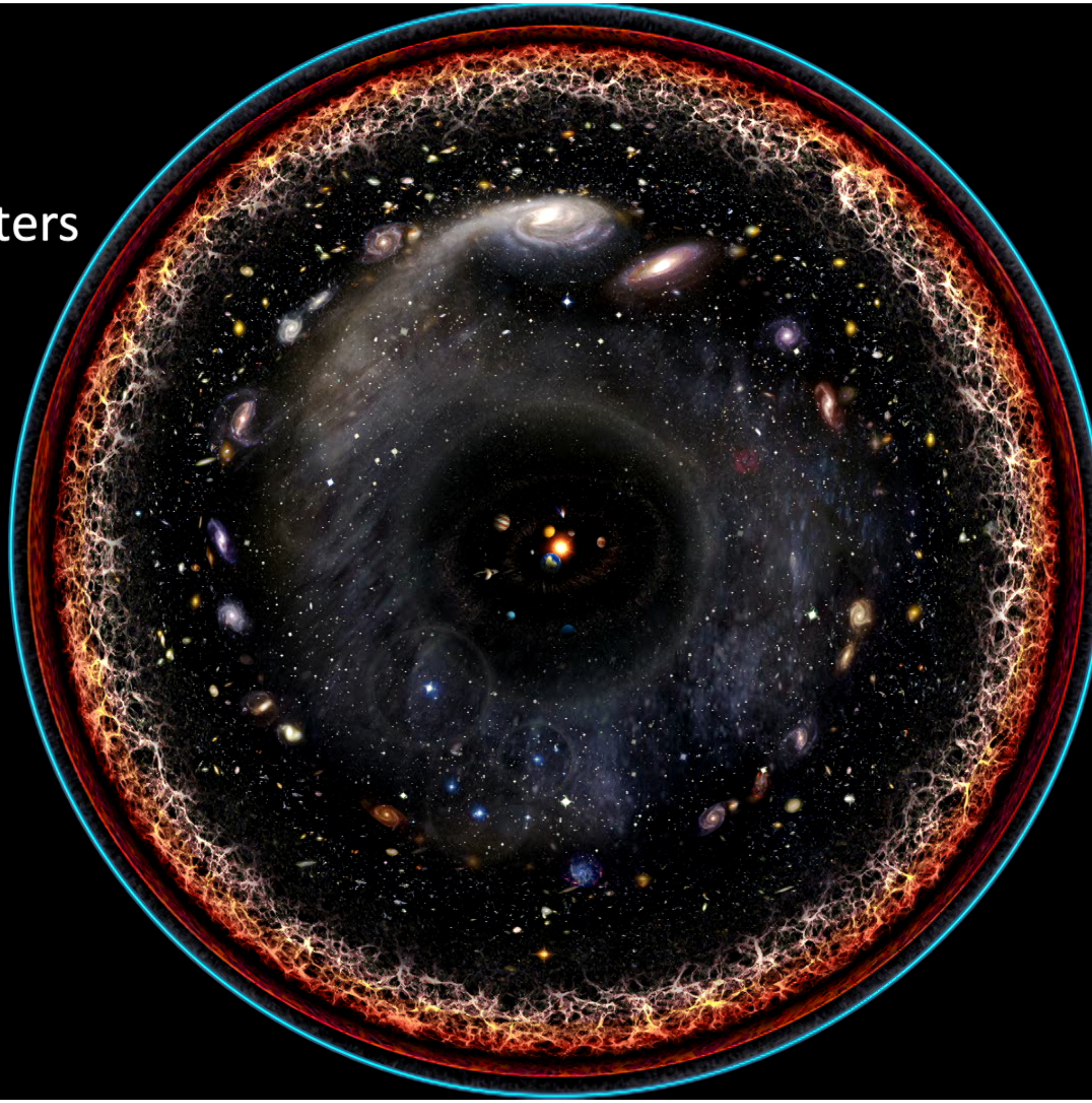
1. ρ_Λ cosmological constant
2. ρ_{DM}/ρ_B DM/baryon density
3. n_B/n_γ baryons per photon

the fluctuations

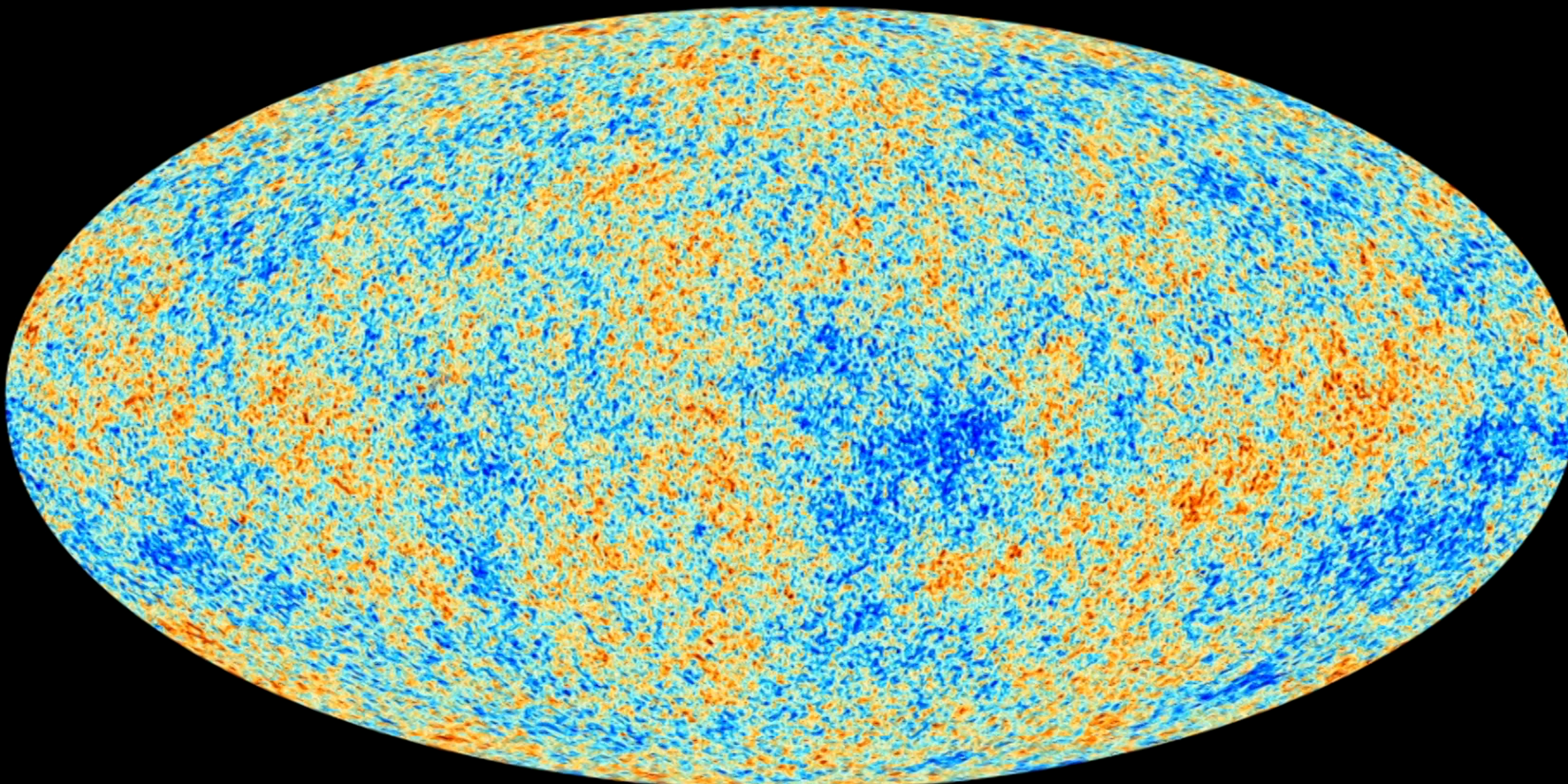
Large scale Newtonian potential

$$\langle \Phi^2 \rangle = \int \frac{dk}{k} A \left(\frac{k}{k_*}\right)^{n_s - 1} \quad (k_* \equiv 0.05\mathrm{Mpc}^{-1})$$

4. $A \approx 10^{-9}$
5. $n_s - 1 \approx -0.04 \pm .006$

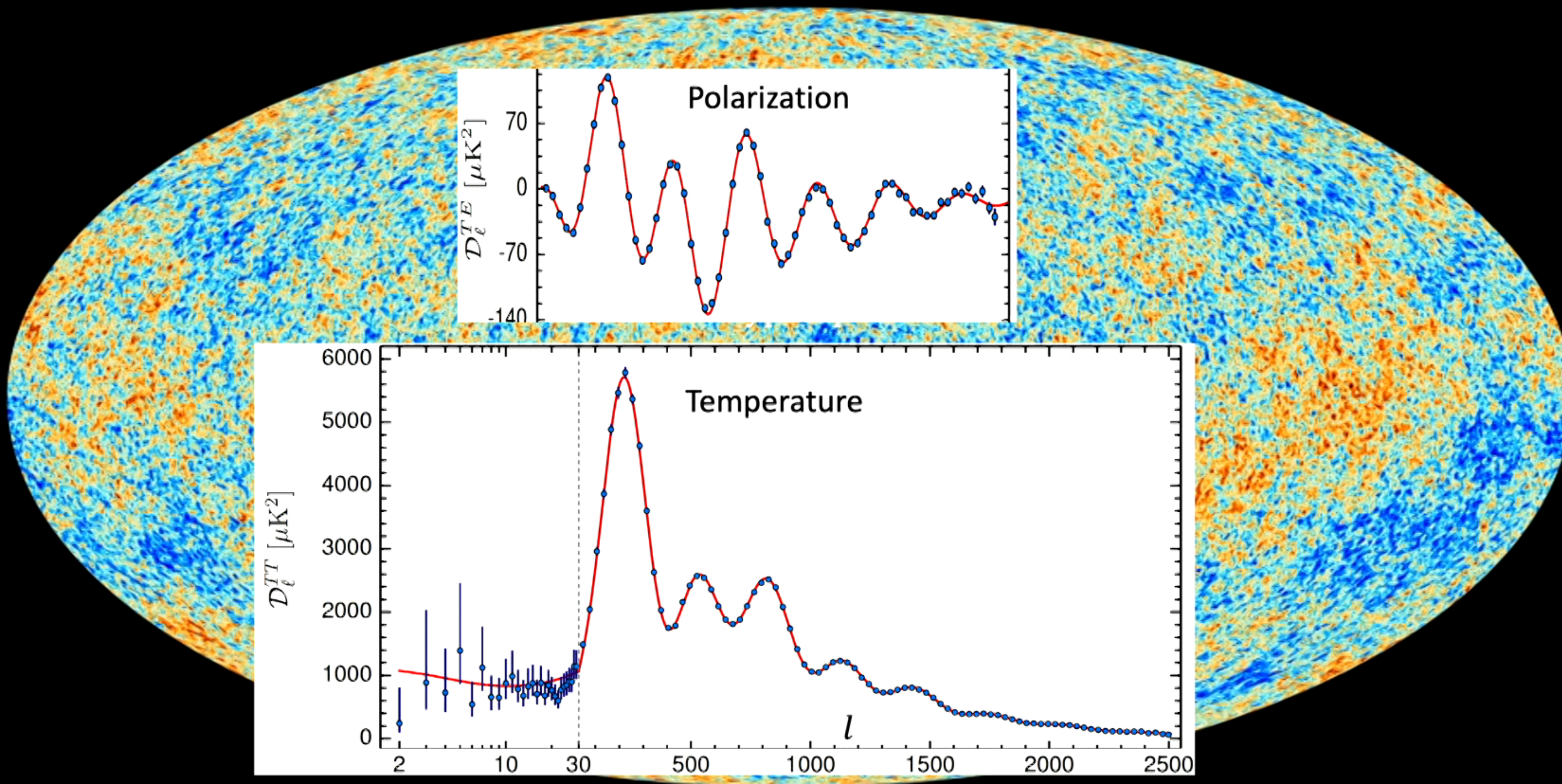


Looking back to the bang



ESA Planck satellite

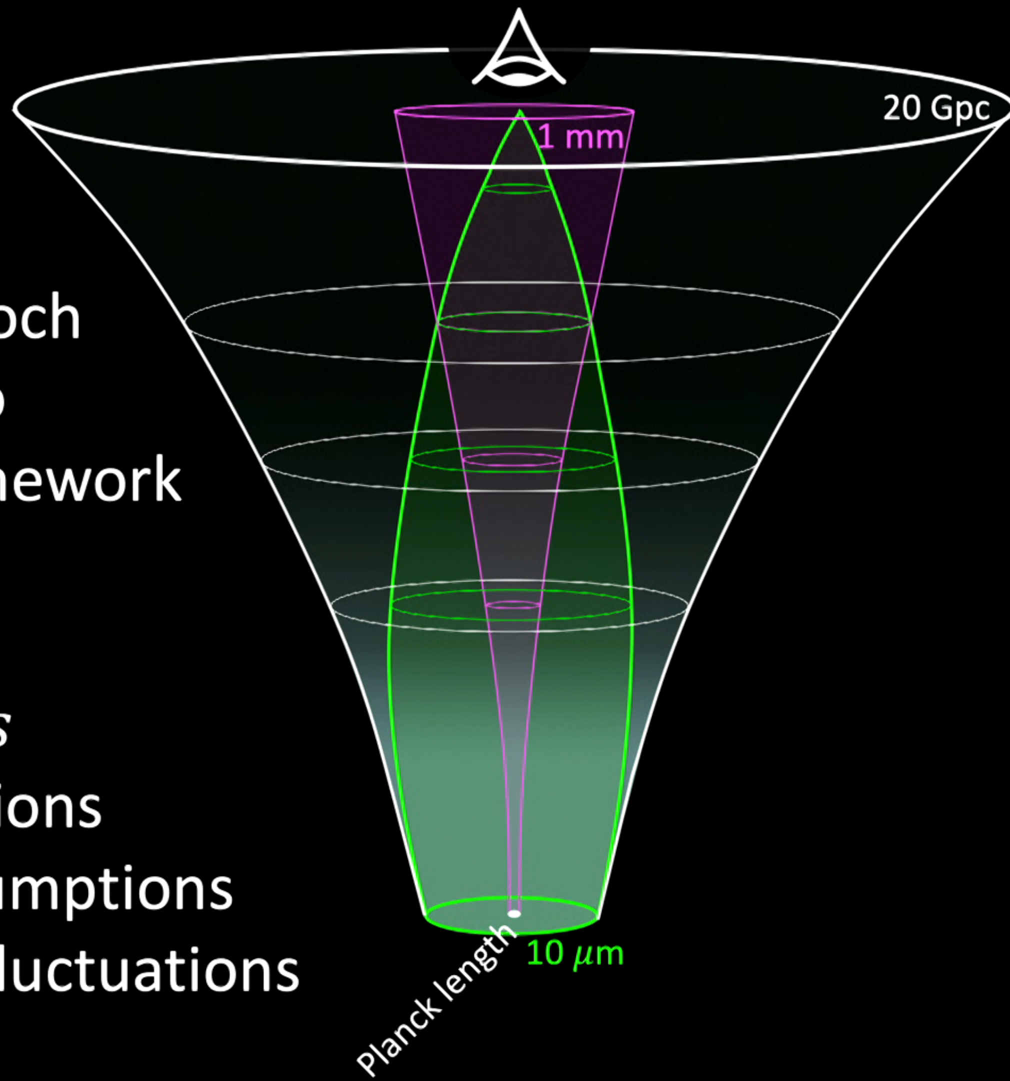
Large scale perturbations



ESA Planck satellite

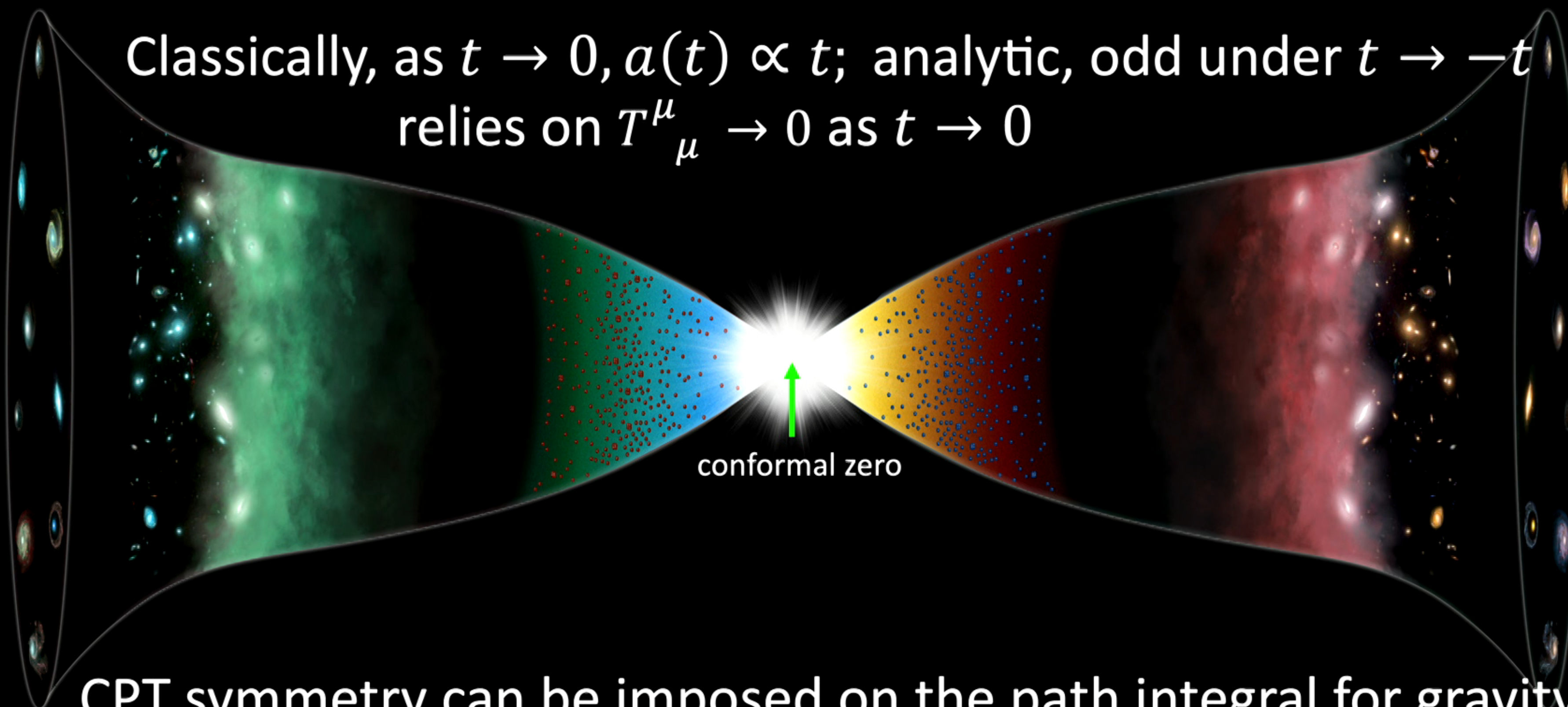
This talk:
a unified framework based on extrapolating the radiation epoch and the SM all the way back to the singularity, within the framework of a CPT-symmetric ensemble.

no new particles except RH $\nu's$
new explanation for 3 generations
with minimal (but crucial) assumptions
we quantitatively predict the fluctuations



Basic hypothesis: the universe respects CPT symmetry

Classically, as $t \to 0, a(t) \propto t$; analytic, odd under $t \to -t$
relies on ${T^{\mu}}_{\mu} \to 0$ as $t \to 0$



CPT symmetry can be imposed on the path integral for gravity via the "method of images"

For a perfect radiation fluid, $T^{\mu}{}_{\mu} = 0$ $(P = \frac{1}{3}\rho)$, *i.e.*, local conformal symmetry, there are ∞^3 solutions to the Einstein-fluid equations which are analytic at $t = 0$,

$$ds^2 = t^2(-dt^2 + h_{ij}(t,\boldsymbol{x})dx^i\, dx^j);\; h_{ij}(t,\boldsymbol{x}) = h^0_{ij}(\boldsymbol{x}) + t^2\, h^2_{ij}(\boldsymbol{x}) + \ldots,$$

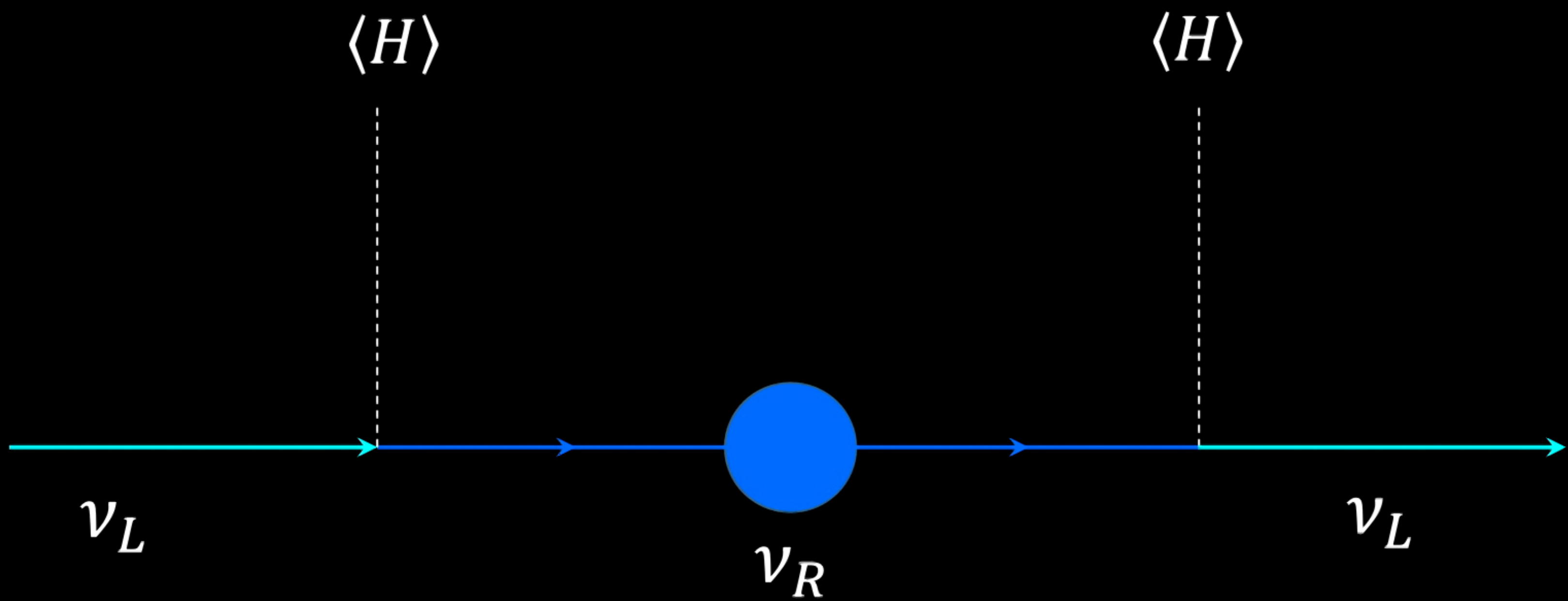
regular 4-metric — regular 3-metric — determined by Einstein eqns

These are saddles of the real-time path integral for gravity with CPT-symmetric boundary conditions. They all have a global isometry $t \leftrightarrow -t$.

The big bang singularity is *conformal*: the Weyl tensor $C^{\lambda}{}_{\mu\nu\rho}$ vanishes at $t = 0$. Penrose's "Weyl curvature hypothesis" is thus a consequence of CPT symmetry.

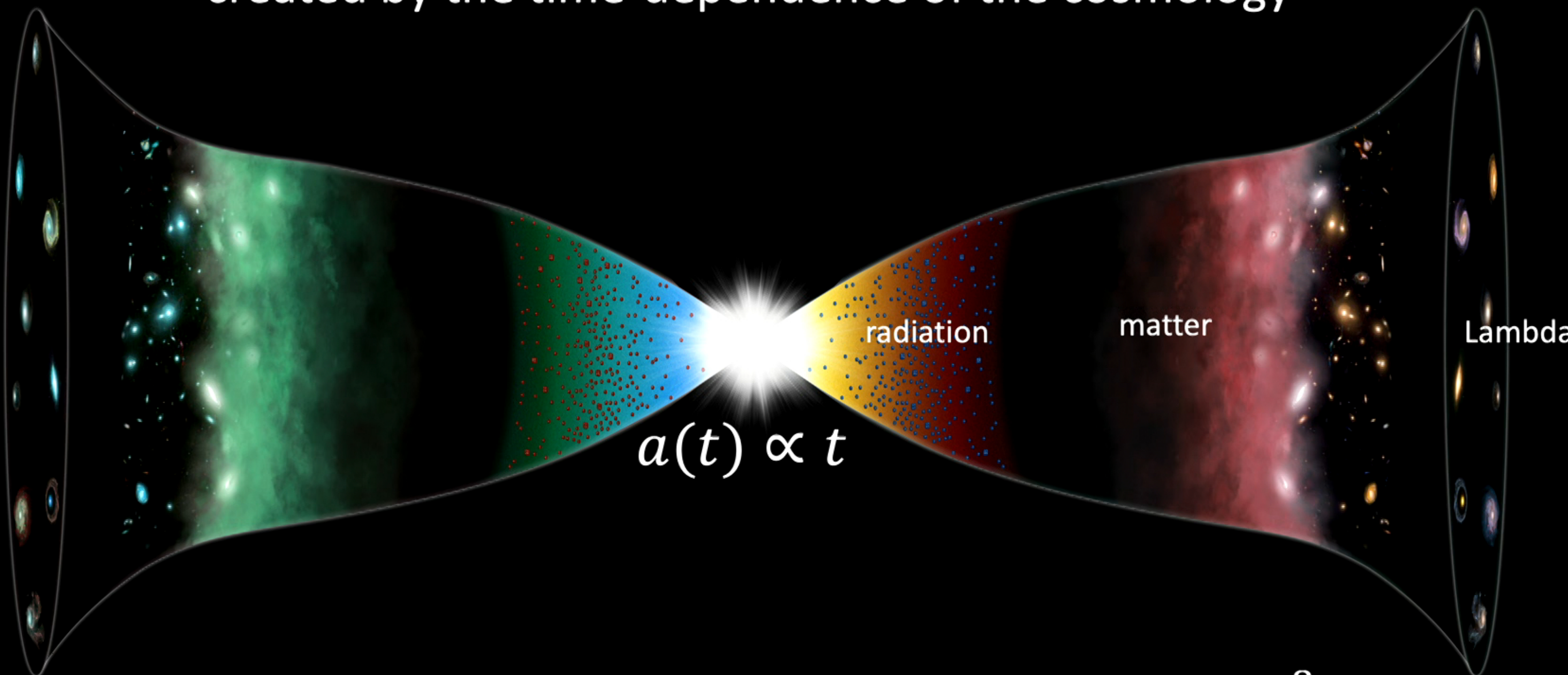
BKL or Mixmaster excluded because they are singular hence not genuine saddles simplest-yet explanation for the dark matter

Right-handed neutrinos:



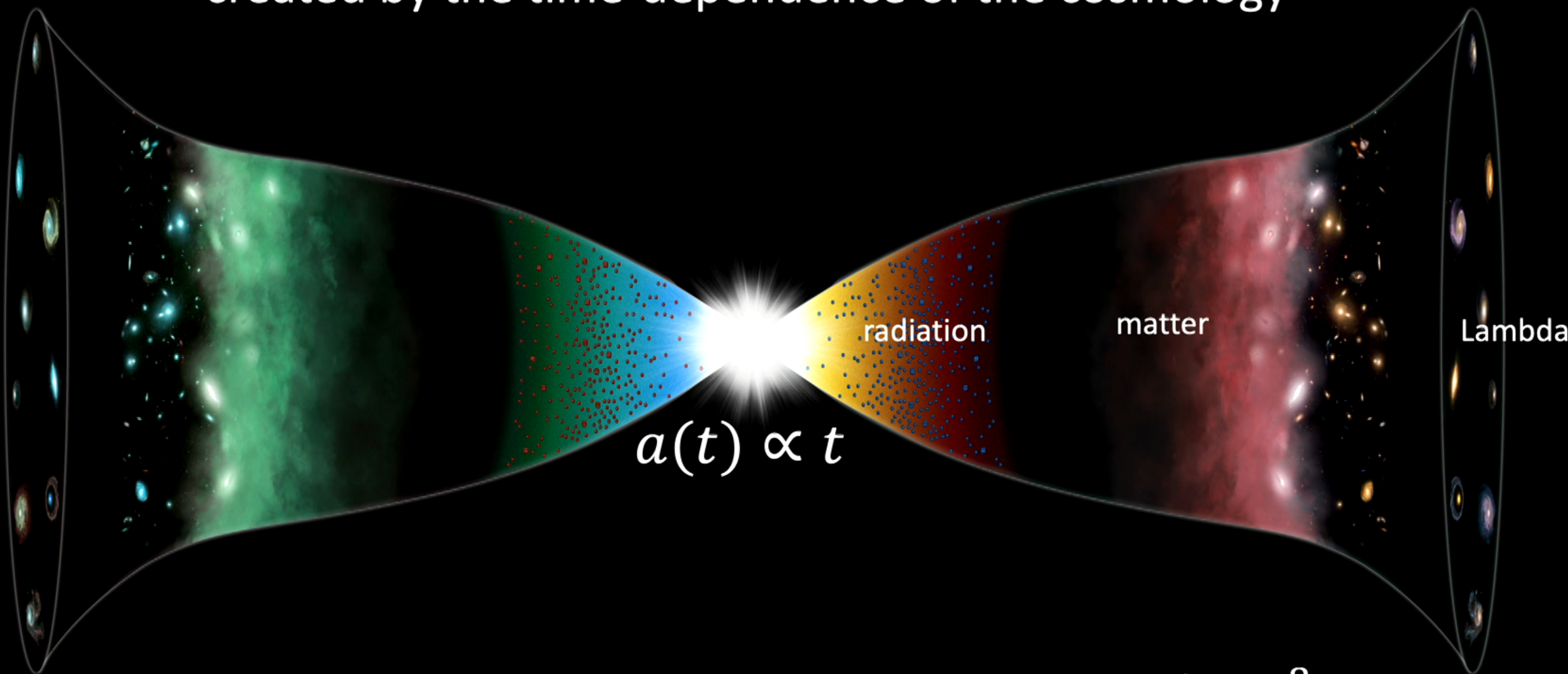
explain observed light neutrino masses (70's)
(seesaw mechanism)

CPT-symmetric vacuum ⇒ abundance of RH neutrinos determined created by the time-dependence of the cosmology



match Ω_{DM} if one RH neutrino is stable, with mass $5\times10^{8} GeV$

CPT-symmetric vacuum ⇒ abundance of RH neutrinos determined created by the time-dependence of the cosmology



match Ω_{DM} if one RH neutrino is stable, with mass $5{\times}10^{8}GeV$

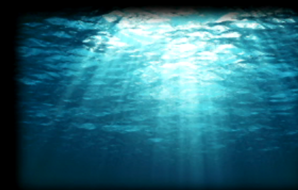
the puzzling large-scale geometry of the cosmos

Penrose

Path integrals and gravity

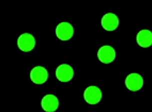
gauge fields

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

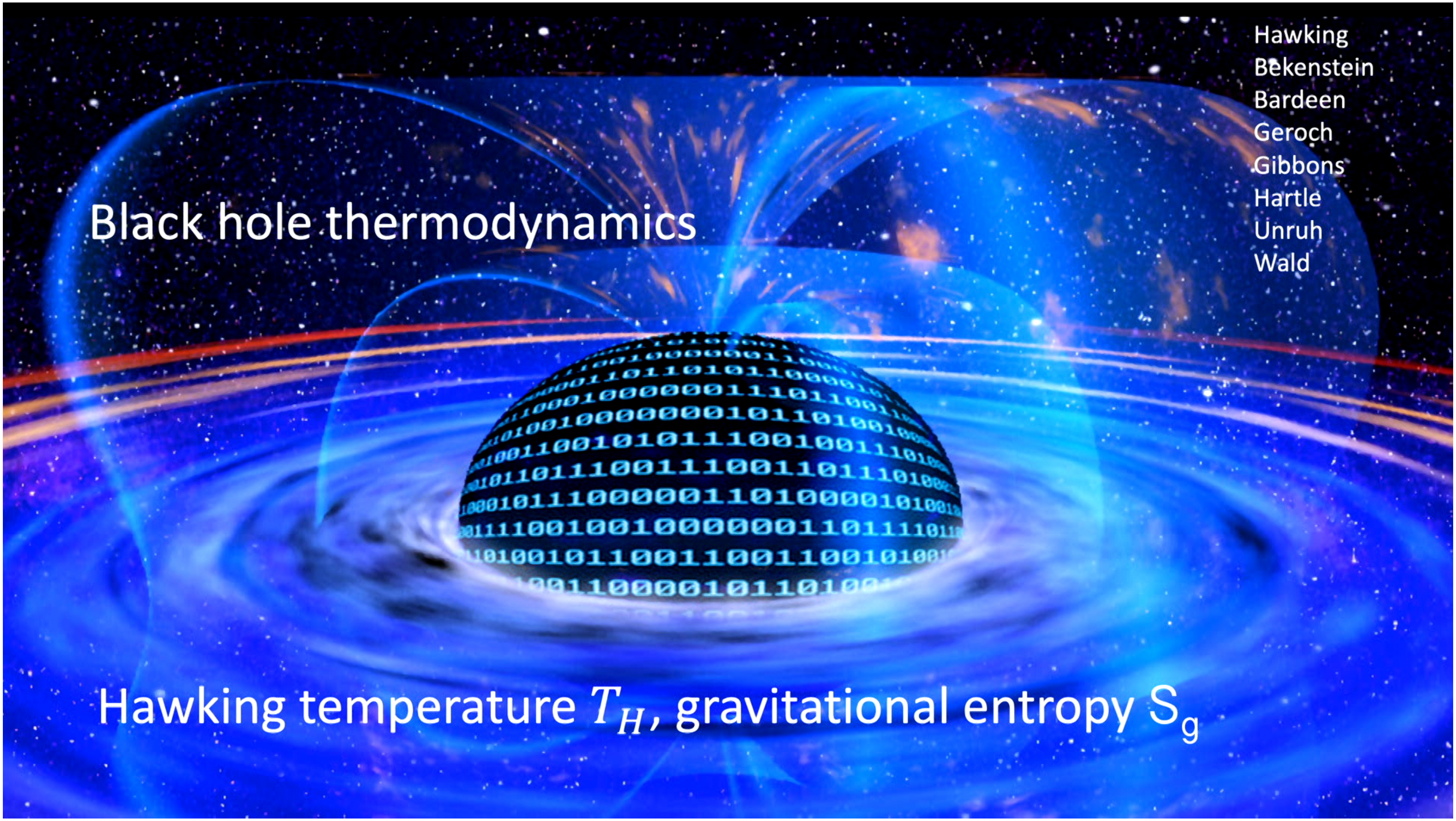


particles

gravitational entropy

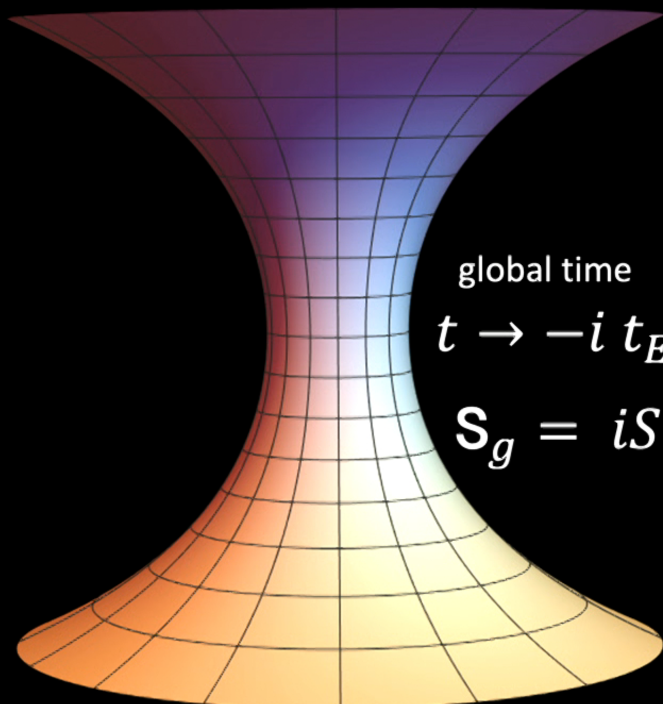
With pbcs in imaginary time, $Z = e^{S_g}$

partition function

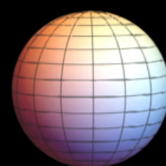

Black hole thermodynamics
Hawking
Bekenstein
Bardeen
Geroch
Gibbons
Hartle
Unruh
Wald
Hawking temperature T_H, gravitational entropy S_g

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

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)

In Planck units

radiation — matter — space curvature — Lambda

Friedmann $$3\dot{a}^2 = r + \mu a - 3\kappa a^2 + \lambda a^4$$

general solution (Jacobi elliptic function) has remarkable analytical properties

We have calculated S_g analytically for a general cosmology with radiation, matter, space curvature and a cosmological constant (*i.e.*, all the conserved quantities).

Inhomogeneities and anisotropies are treated in cosmological perturbation theory.

S_g is greatest for:

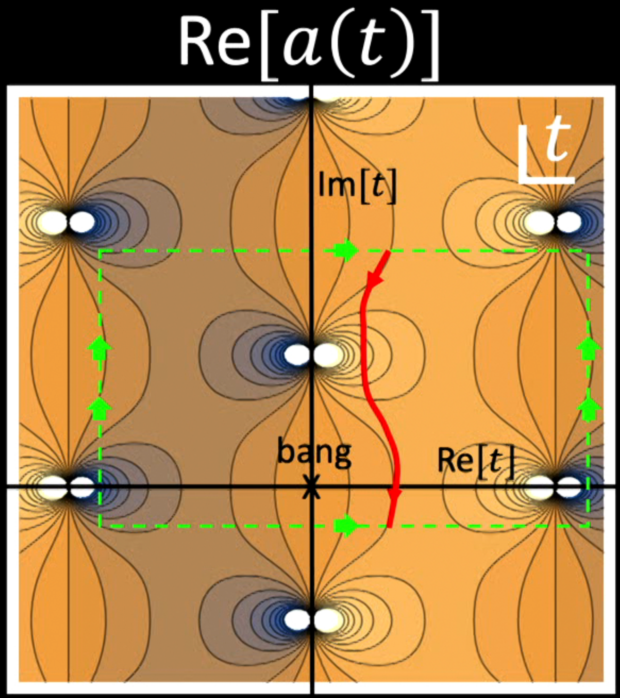
1. a spatially flat, homogeneous, isotropic universe
2. a small, positive cosmological constant

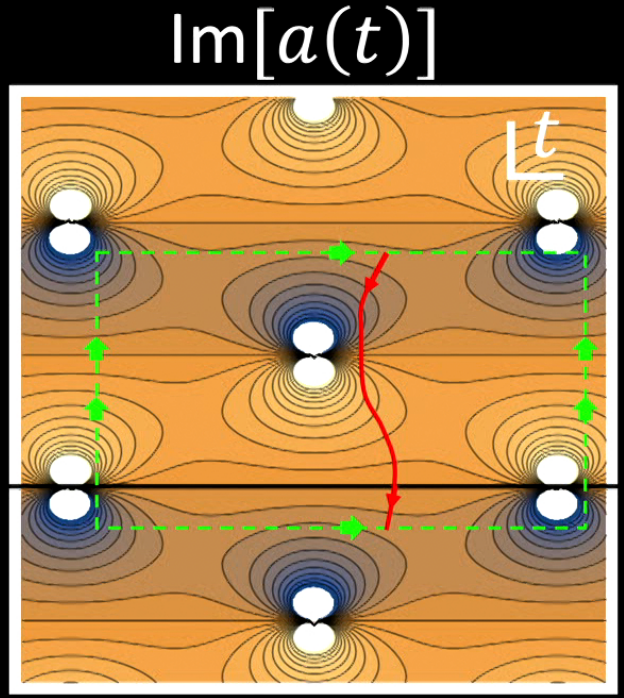
(echoing earlier arguments of Baum, Hawking, Coleman...)

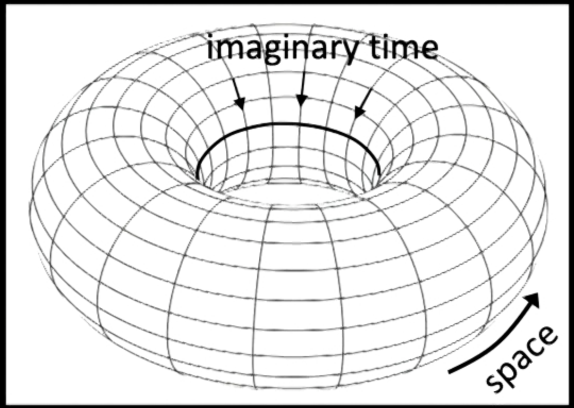
Note: S_g is the *global* entropy for the entire spacetime. It is independent of real time via Cauchy's theorem.

This is a thermodynamic explanation of the large-scale geometry of the universe. No additional smoothing or flattening mechanism is required.

$a(t)$ is single-valued and doubly periodic in the complex t-plane: its only singularities are simple poles. The imaginary time period and the action computed over a period determine T_H and the gravitational entropy S_g







Euclidean instanton for a universe w/radiation, matter, curvature, Lambda

Connections with recent advances in nonequilibrium statistical mechanics.

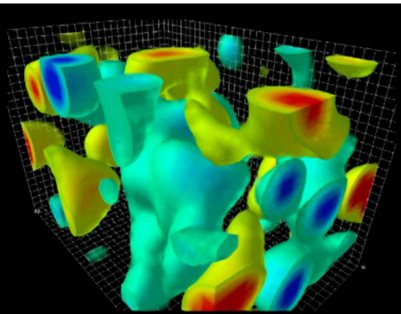
Entropy of the trajectory of a particle interacting with a thermal medium: proof that total entropy increases. Employs the time-reversed trajectory.

(Udo Seifert, *e.g.*, arXiv:cond-mat/0503686)

cf. entropy of a 4-geometry interacting with its material contents

Can one prove an analog of the 2nd law of black hole thermodynamics?

Quantum fields and gravity



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

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

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

where Δt^2 = invart time-like separation

Can be renormalized away but this leaves us with little physical understanding

Similarly, quantum divergences spoil the local scale (Weyl) invariance of Maxwell and Dirac fields: trace anomalies. These cannot be renormalized away.

Dimension zero scalars

A four-derivative, Weyl-invariant (*i.e.,* locally scale-invariant) action

$$S_4 = -\frac{1}{2}\int d^4x\sqrt{-g}\varphi\Delta_4\varphi; \quad \Delta_4 = \Box^2 + \ldots$$

Heisenberg (1957), Pauli, Thirring, Nakanishi, …
Flato, Fronsdal ('70s , '80s) forerunner of AdS/CFT
Moschella+Strocchi (1989), Rivelles (2003), Holdom (2023)

Bogoliubov *et al.* recognized this as the simplest gauge theory (1987 QFT text, Ch. 10)

Infinite-dimensional symmetry: $\varphi(x) \longrightarrow \varphi(x) + \alpha(x)$ with $\Box\alpha = 0$

Allows one to remove negative norm states (via Gupta-Bleuler or BRST):

Unique physical state is the vacuum: 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 in cosmology

A numbers game

Dim 1 scalars | fermions | gauge bosons | Dim 0 scalars

1. Vacuum energy $\propto n_{s,1} - 2n_F + 2n_A + 2n_{s,0}$
2. Conformal anomaly (Euler) $\propto n_{s,1} + \frac{11}{2} n_F + 62\, n_A - 28\, n_{s,0}$
3. Conformal anomaly (Weyl²) $\propto n_{s,1} + 3\, n_F + 12\, n_A - 8\, n_{s,0}$

1) All three vanish iff $n_{s,1} = 0 \Longrightarrow$ no fundamental dimension one scalars allowed

2) Any two equations then give $n_F = 4n_A$ and $n_{s,0} = 3n_A$

3) For gauge group $SU3 \times SU2 \times U1$, *predict* n_F =48, *i.e.*, 3 fermion generations (each with a RH ν)

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

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

Projector onto spin 2 component
- gauge invariant

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

SM corrections to the graviton propagator:

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, resummed $D(k)$ (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, positivity and microcausality (at one loop in SM gauge+fermion fields: we are now examining higher orders)

A Minimal Explanation of the Primordial Cosmological Perturbations

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

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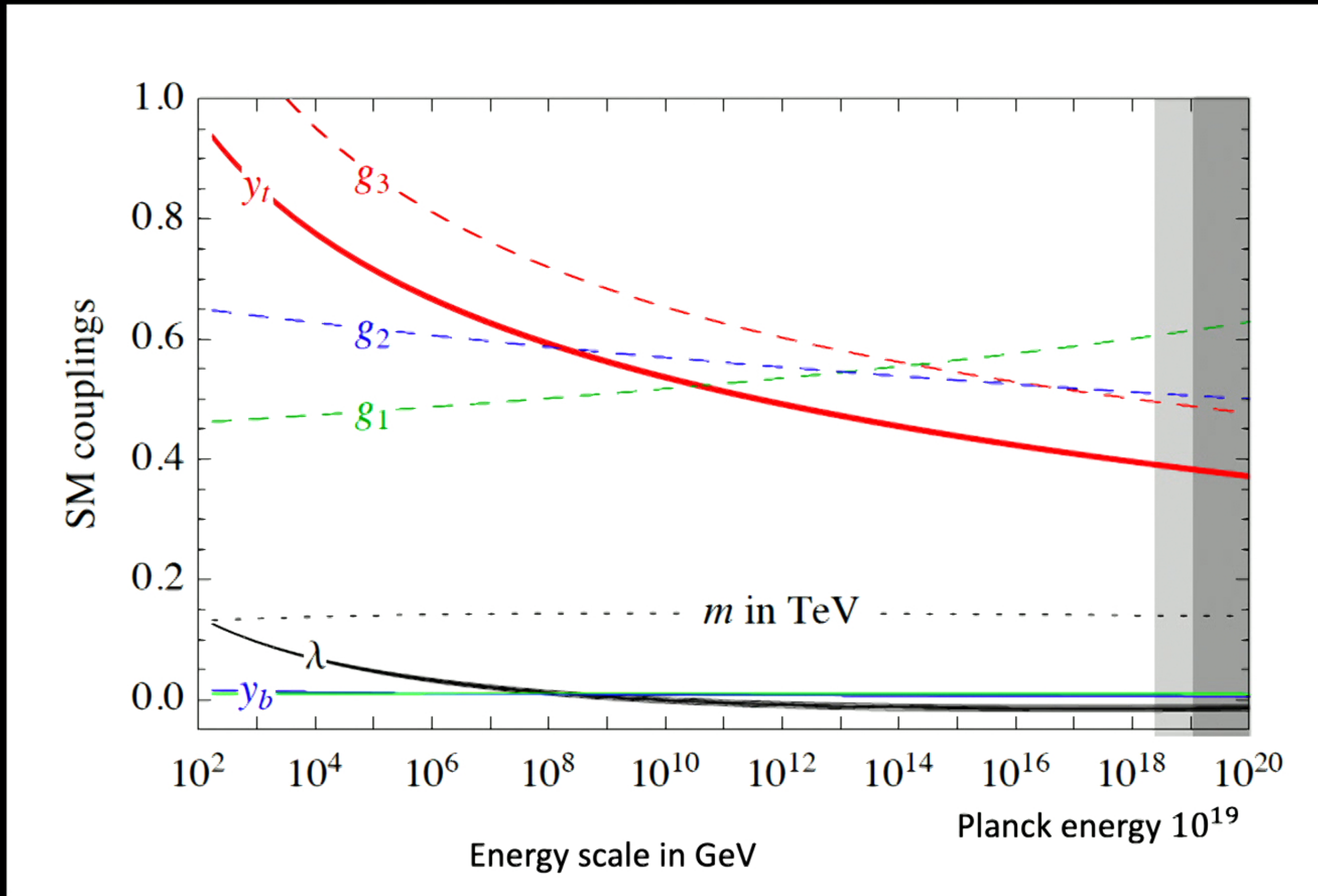
[2] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5*

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]

Buttazzo et al
1307.3536
[hep-ph]



Spectral tilt

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

We argue that, at small k, $\mathcal{P}_{\mathcal{R}}(k)$ scales with k as α^2

This leads to the prediction $n_s - 1 \equiv \frac{d \ln \mathcal{P}_{\mathcal{R}}(k)}{\mathrm{d} \ln k} = 2\frac{\beta_\alpha}{\alpha} = -\frac{7}{\pi}\alpha_{QCD}(M_P)$

Since this is a critical exponent (*i.e.*, the result of an anomalous dimension) we can extrapolate (over 30 orders of magnitude!) from the Planck length to today's (comoving) Hubble radius at the Planck time.

Amazingly, the amplitude and tilt agree with observation (so far!)

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Prediction for primordial perturbations

$\mathcal{P}_{\mathcal{R}}(k) = \frac{3^2 5^2}{7(2\pi)^4}\left(\frac{c_\beta^{SM}}{\mathcal{N}_{eff}}\right)^2 \left(\frac{k}{k_P}\right)^{-\frac{7\alpha_3}{\pi}}$; 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 $\mathcal{N}_{eff} = 106\frac{1}{4}$

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

Thank you for listening!

Boyle, Finn, NT Phys. Rev. Lett. 121 (2018) 251301; Annals of Physics 438 (2022) 168767
arXiv: 2109.06204, 2110.06258, 2201.07279, 2208.10396, 2210.01142, 2302.00344