a new theory of the universe

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University of Edinburgh + Perimeter Institute (PI) + AIMS

with Latham Boyle (PI), 2109.06204, 2110.06258, 2201.07279, 2208.10396, 2210.01142

Boyle, Finn, NT Phys. Rev. Lett. 121 (2018) 251301; Annals of Physics 438 (2022) 168767

Large Scale Universe

remarkably simple:

just 5 basic parameters

matter/energy content

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

gravity $\Phi_{k,rms} = A(\frac{k_s}{k})^\varepsilon$ (primordial)

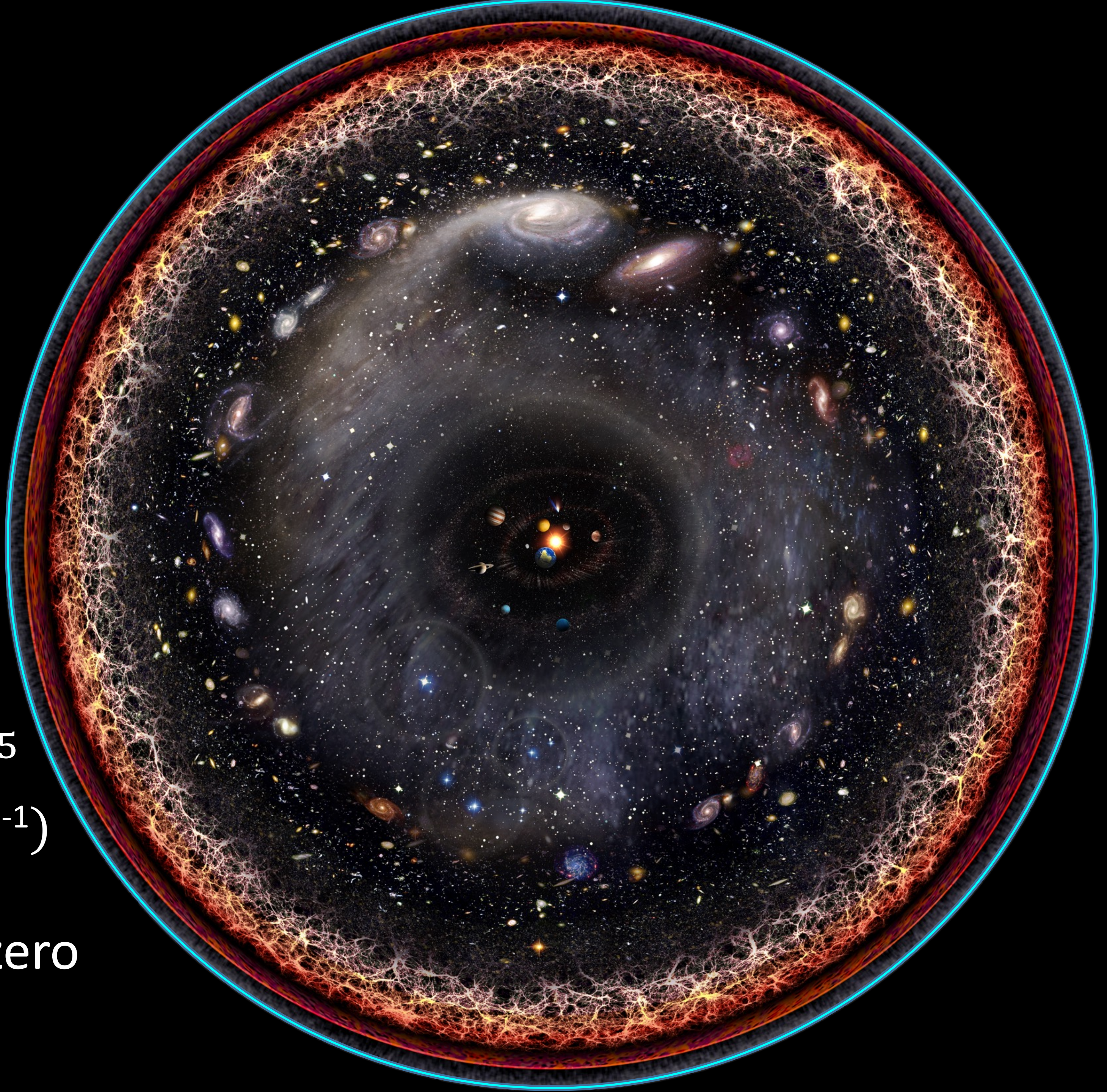
4. $A = 3\times10^{-5}$

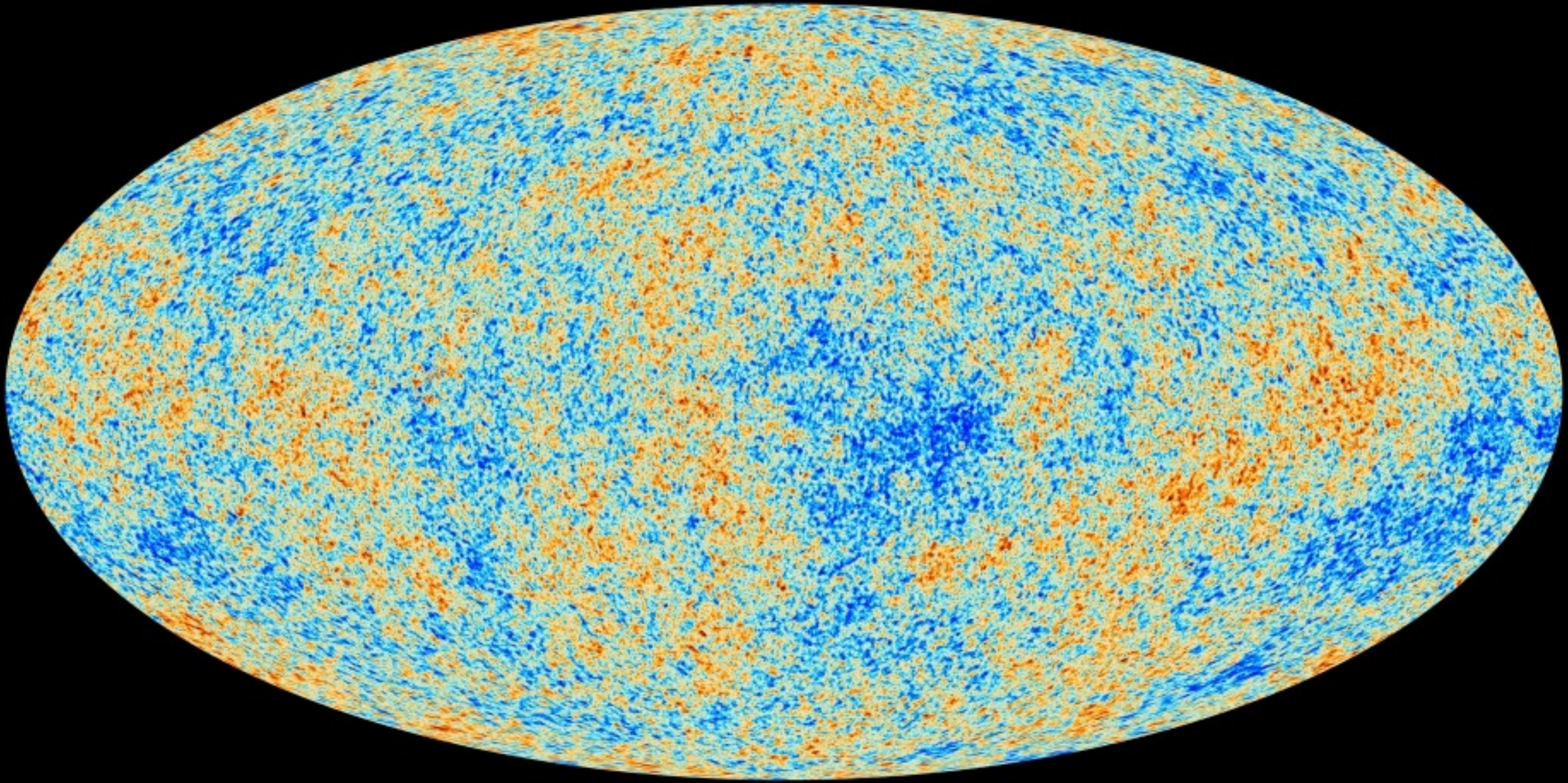
Sachs-Wolfe

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

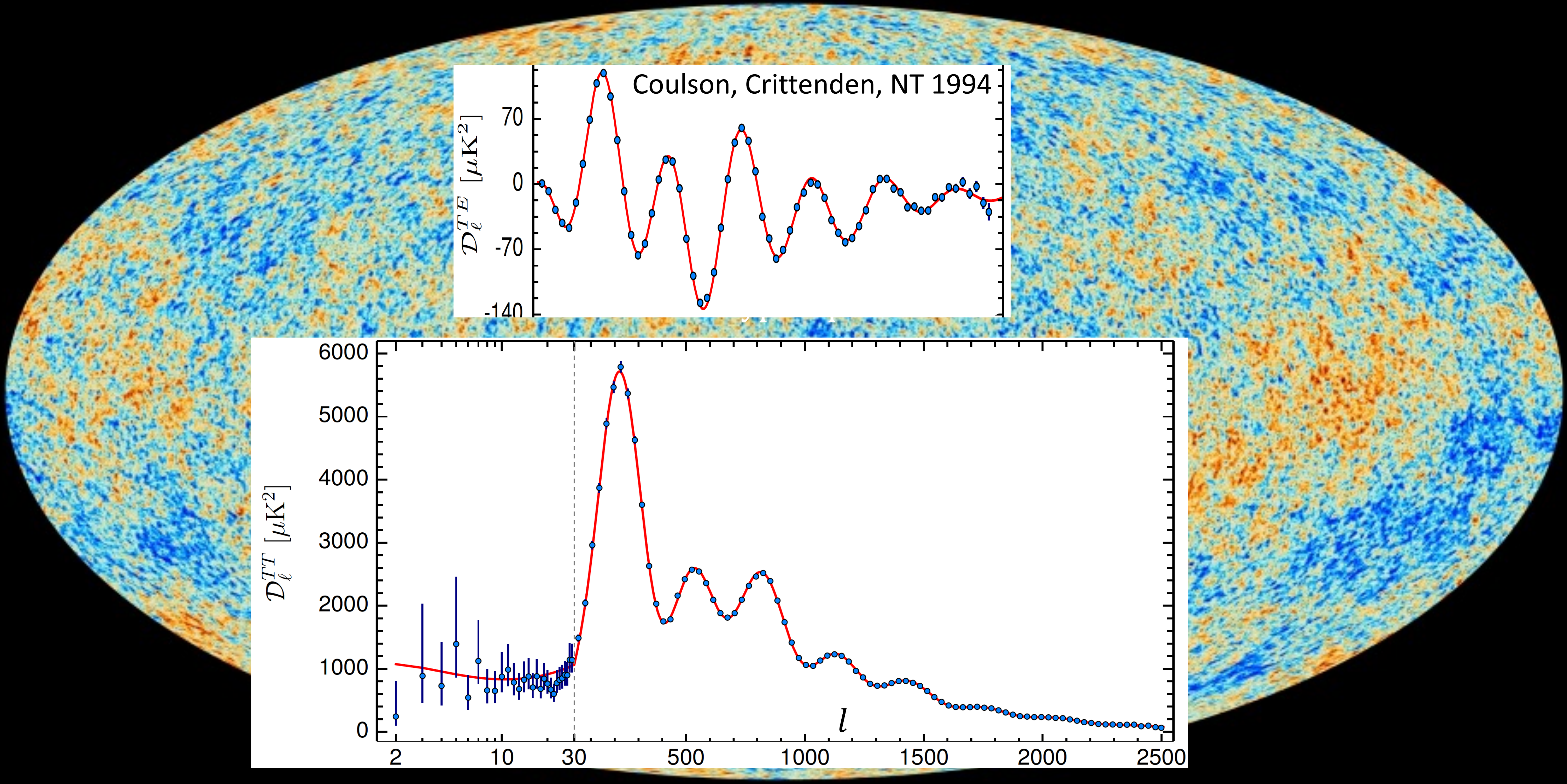
5. $\varepsilon = 0.02$ red tilt ($k_s \equiv 0.05\text{Mpc}^{-1}$)

many quantities consistent with zero

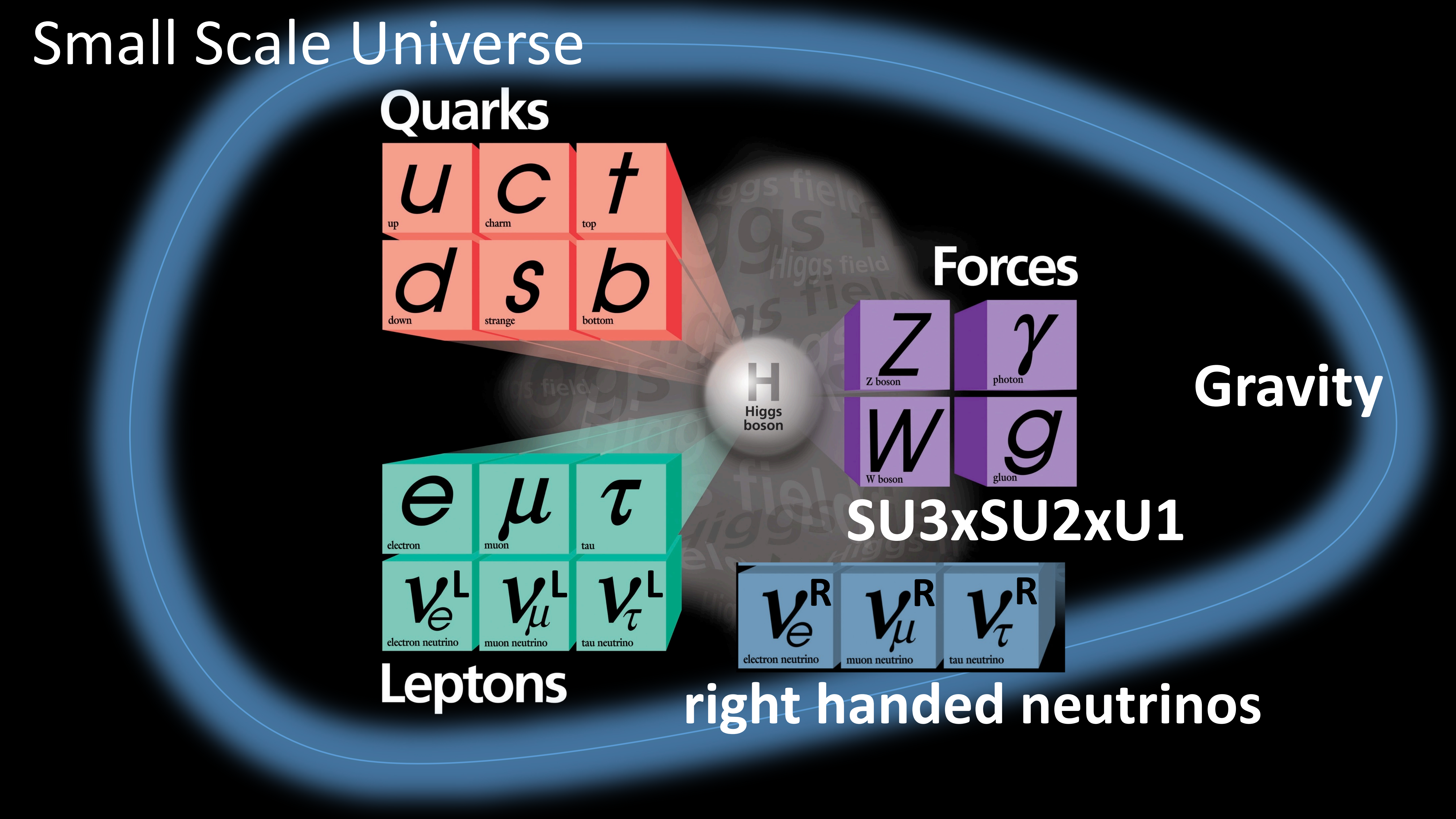




ESA Planck satellite



ESA Planck satellite


Small Scale Universe
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Higgs field
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
Gravity
SU3xSU2xU1
e
electron
μ
muon
τ
tau
ν_e^L
electron neutrino
ν_μ^L
muon neutrino
ν_τ^L
tau neutrino
Leptons
ν_e^R
electron neutrino
ν_μ^R
muon neutrino
ν_τ^R
tau neutrino
right handed neutrinos

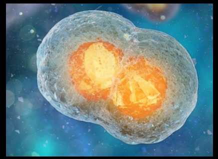
predictable at the extremes

Planck length

10^{-35}m

SIMPLE
& PREDICTABLE

living cell



10^{-4}m

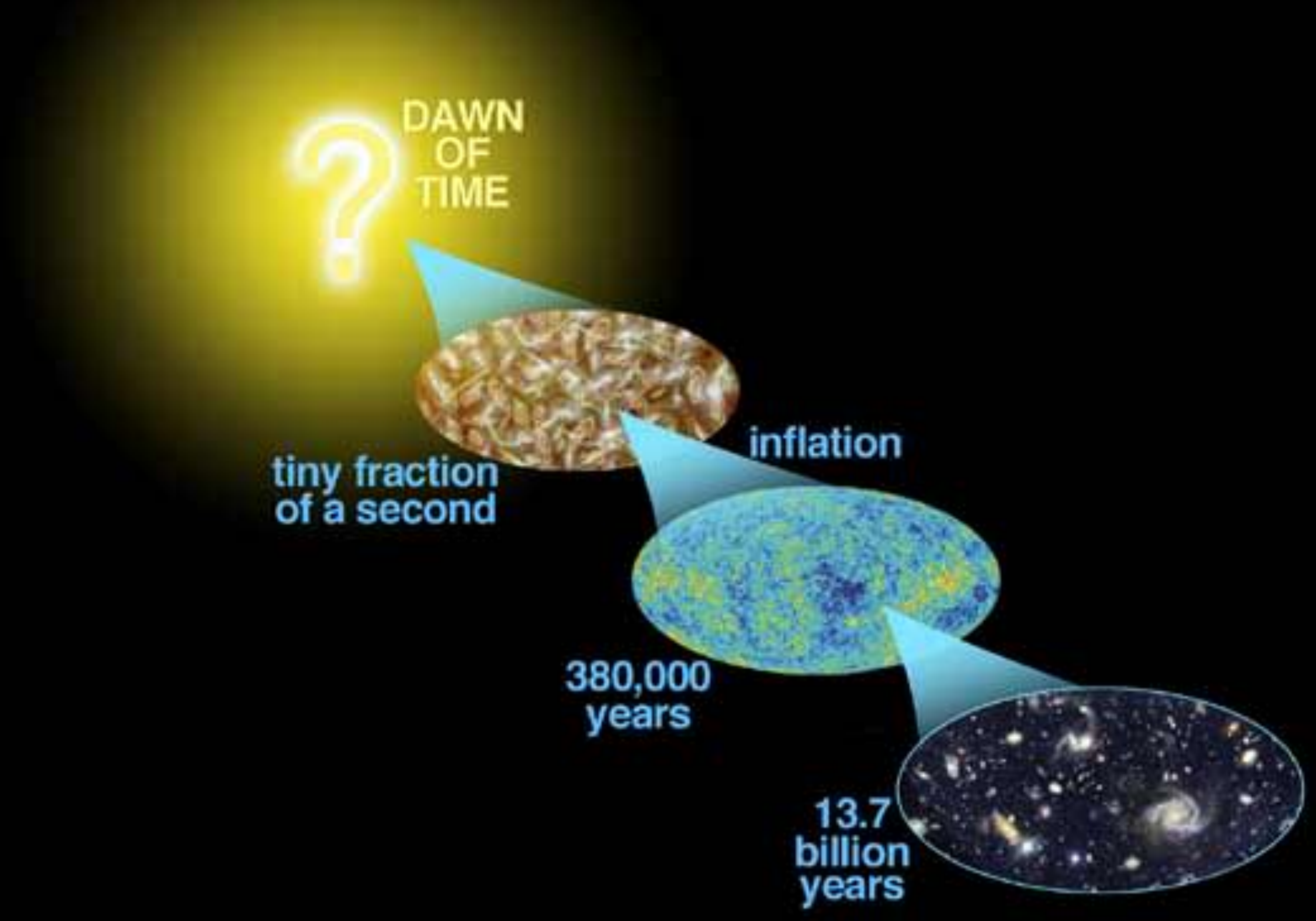
(geometric mean)

de Sitter horizon

10^{27}m

SIMPLE
& PREDICTABLE

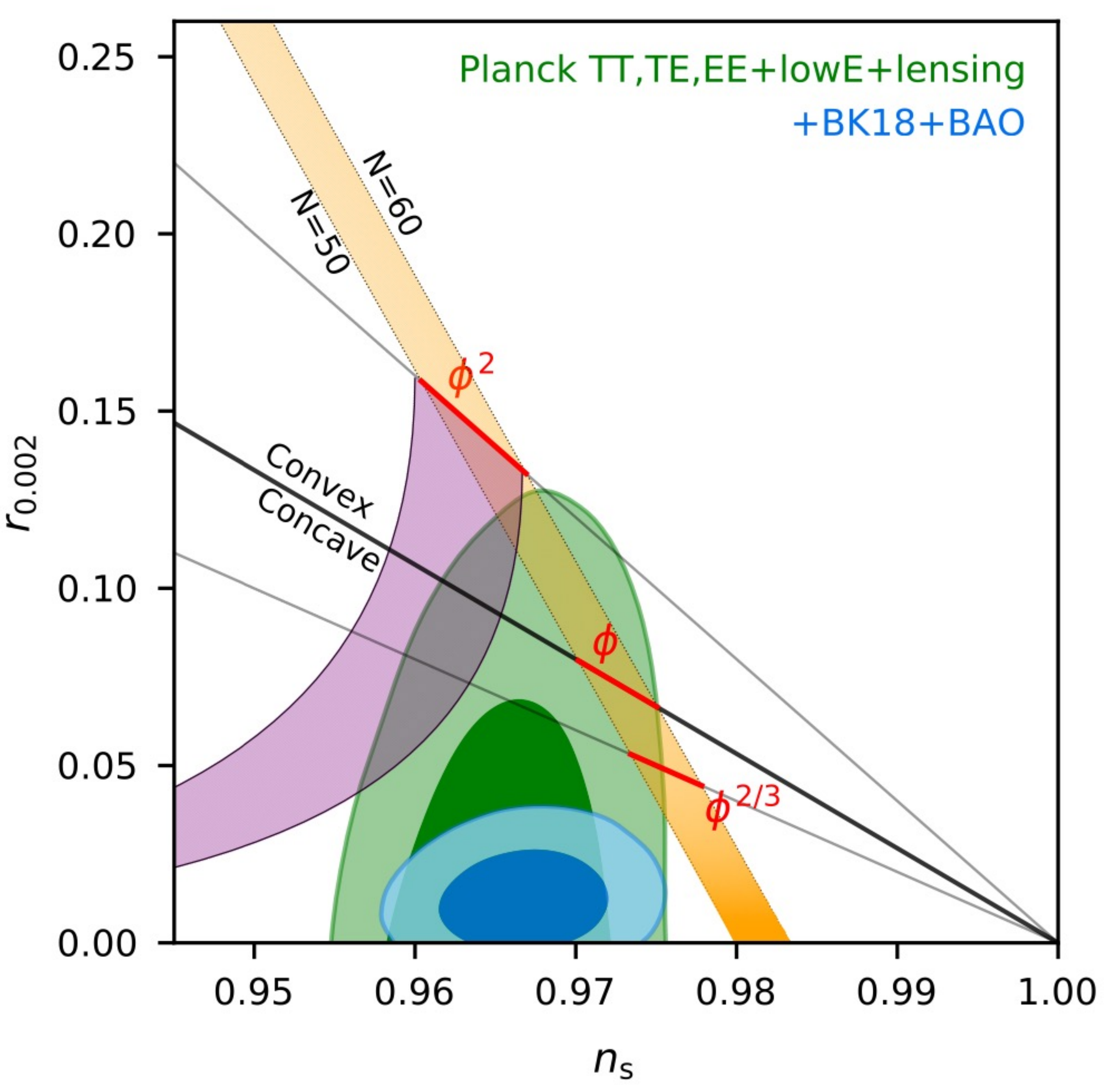
why do we need a new theory?
current consensus



no sign of
inflationary
tensor modes

BICEP/Keck
Collaboration
2203.16556
[astro-ph]
March 2022

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

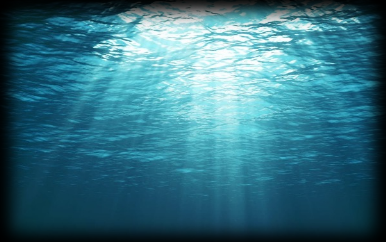



(imho)
inflationary
multiverse

our philosophy: start from known physics

gauge fields

Higgs



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

particles

gravity

look deeper, for simpler explanations

the most basic puzzles are our best clues

big bang singularity

resolution: conformal symmetry and analyticity

large scale geometry – why so symmetrical and flat?

resolution: a measure on 4-geometries - gravitational entropy

gravity and quantum fields – the vacuum energy

resolution: a new cancellation mechanism

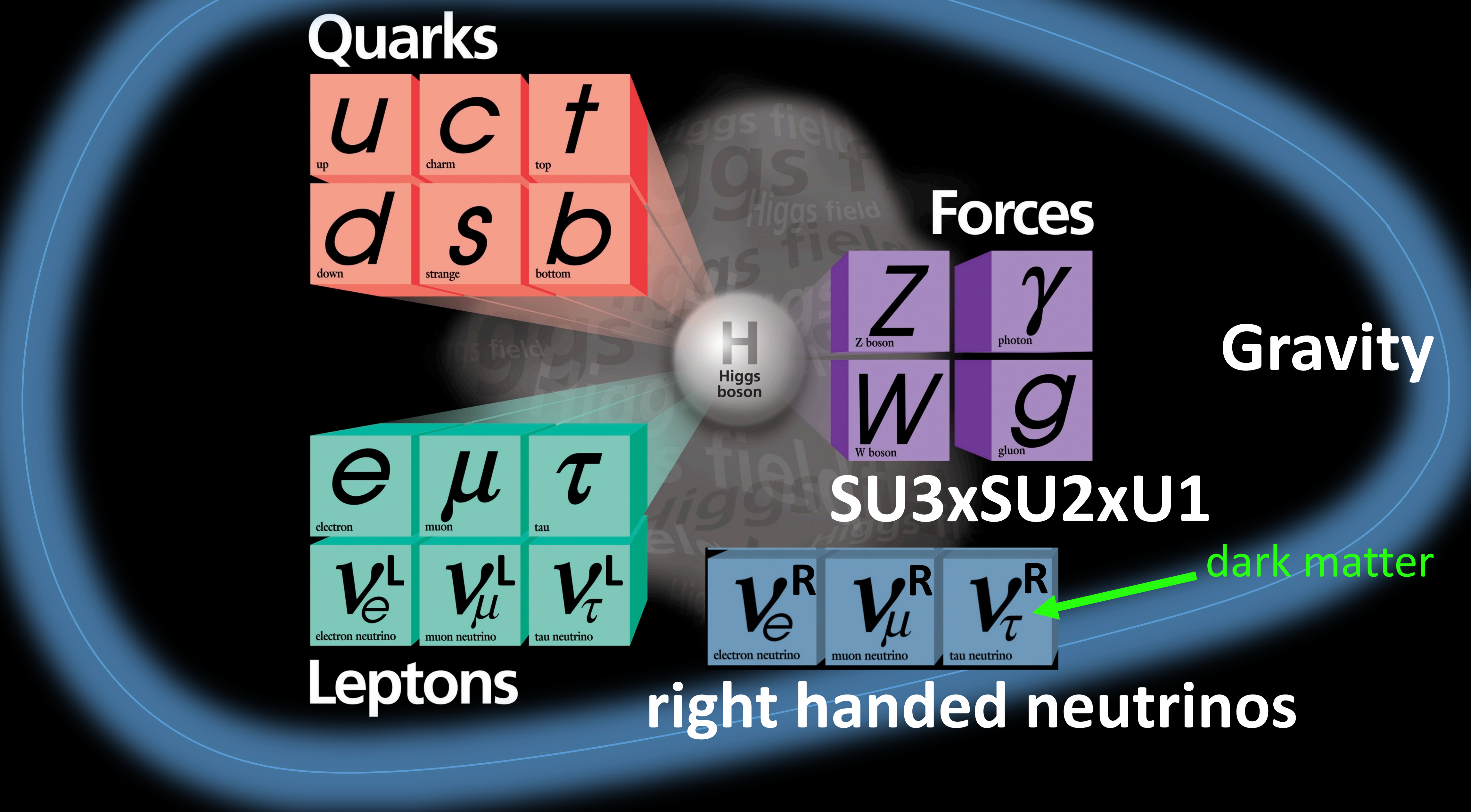
CPT symmetry: why does the universe seem to break it

resolution: it doesn’t! extended universe is CPT symmetric

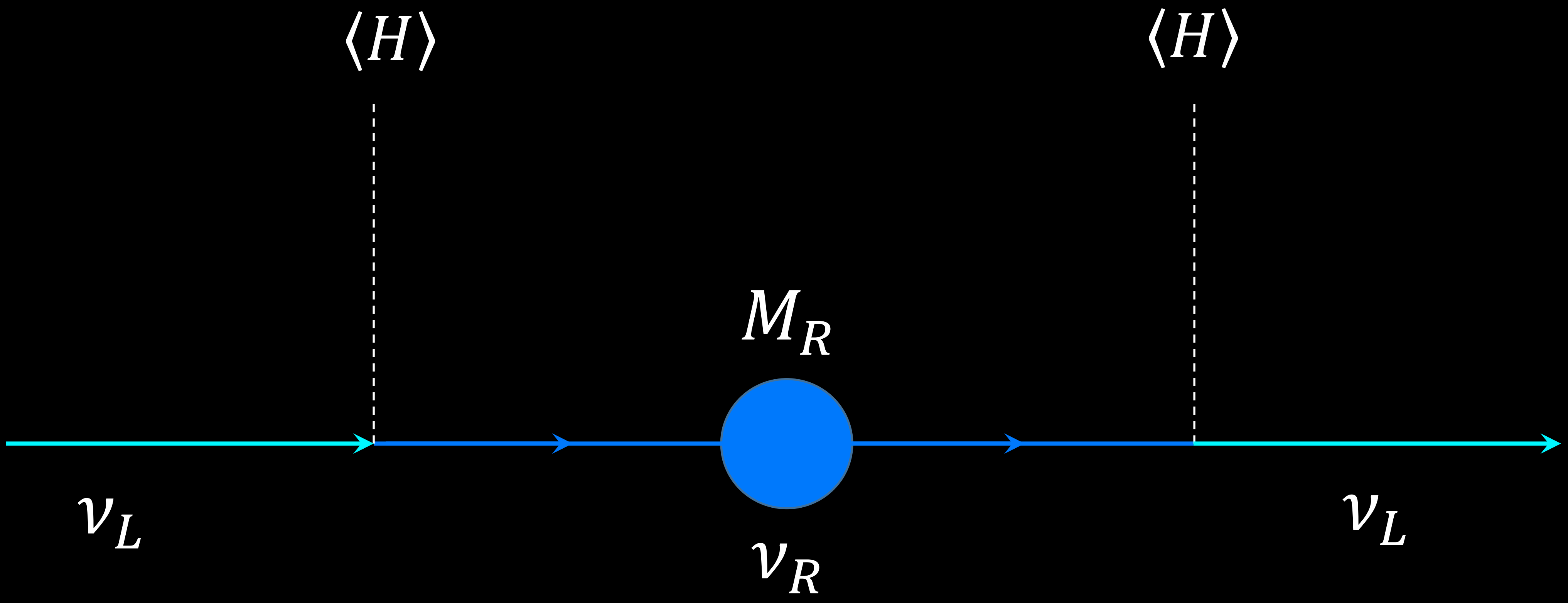
dark matter: solution has been staring us in the face since the 70’s

New: primordial density variations are calculable from standard model physics

Small Scale Universe

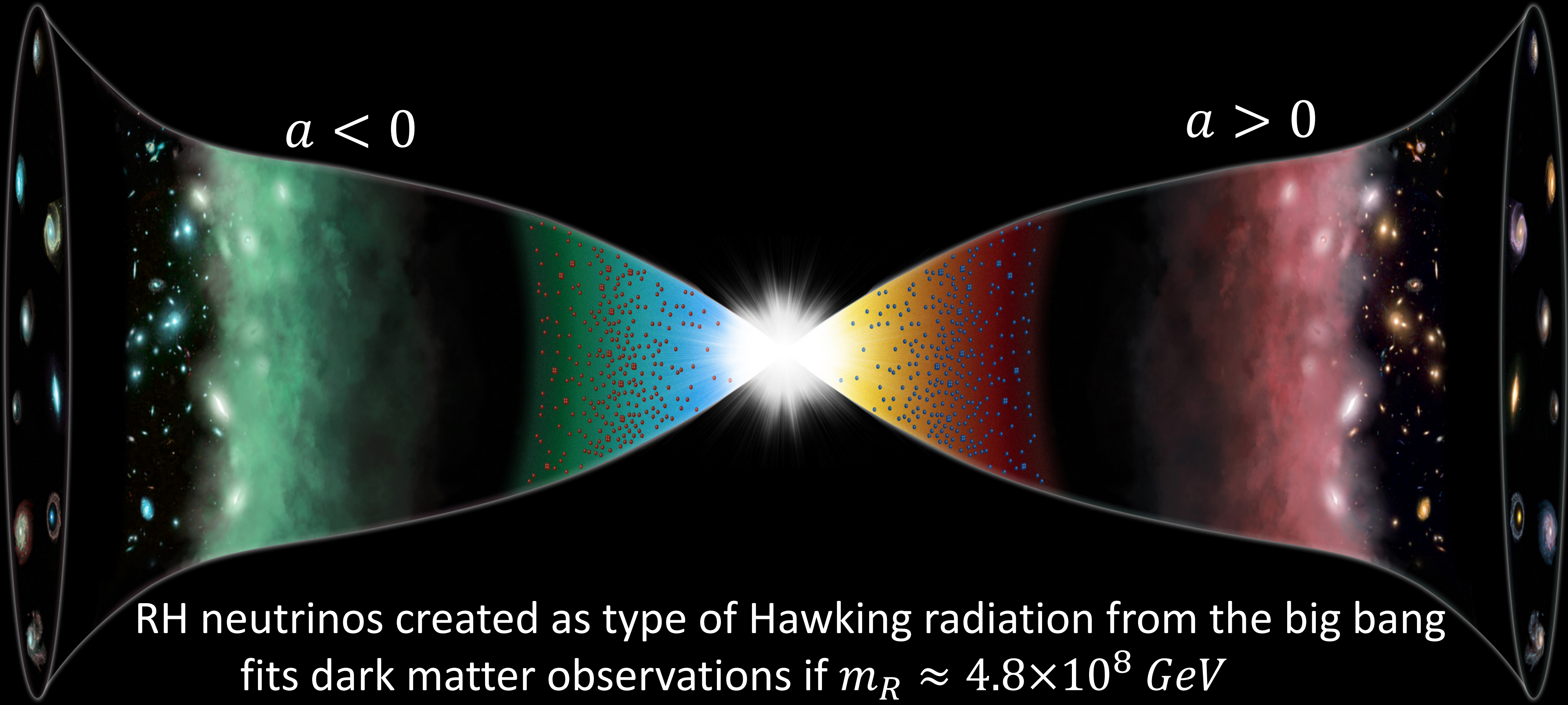


seesaw mechanism and neutrino masses



Boyle, Finn, NT *Phys. Rev. Lett.* 121 (2018) 251301
Annals of Physics 438 (2022) 168767

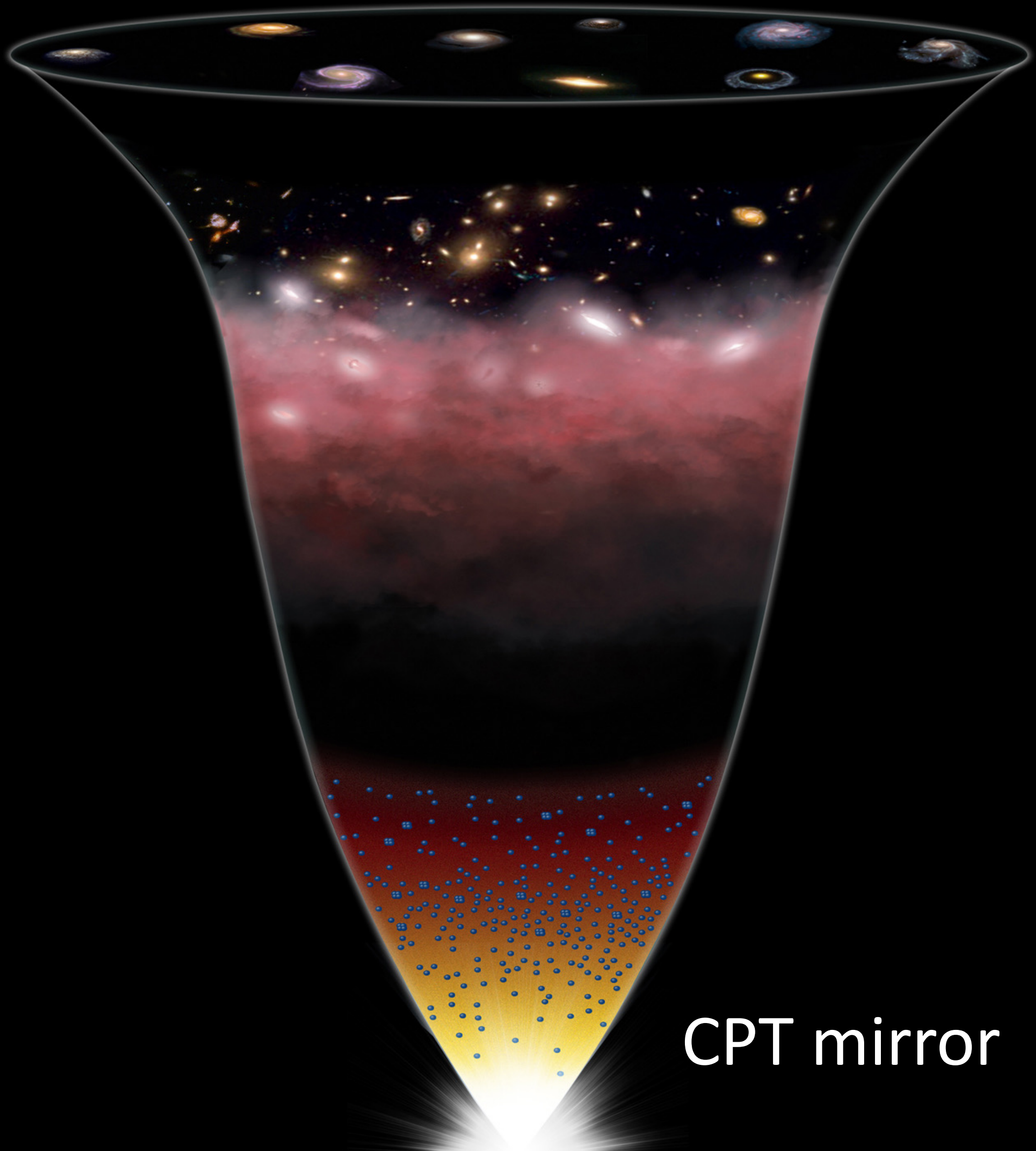
CPT symmetric universe

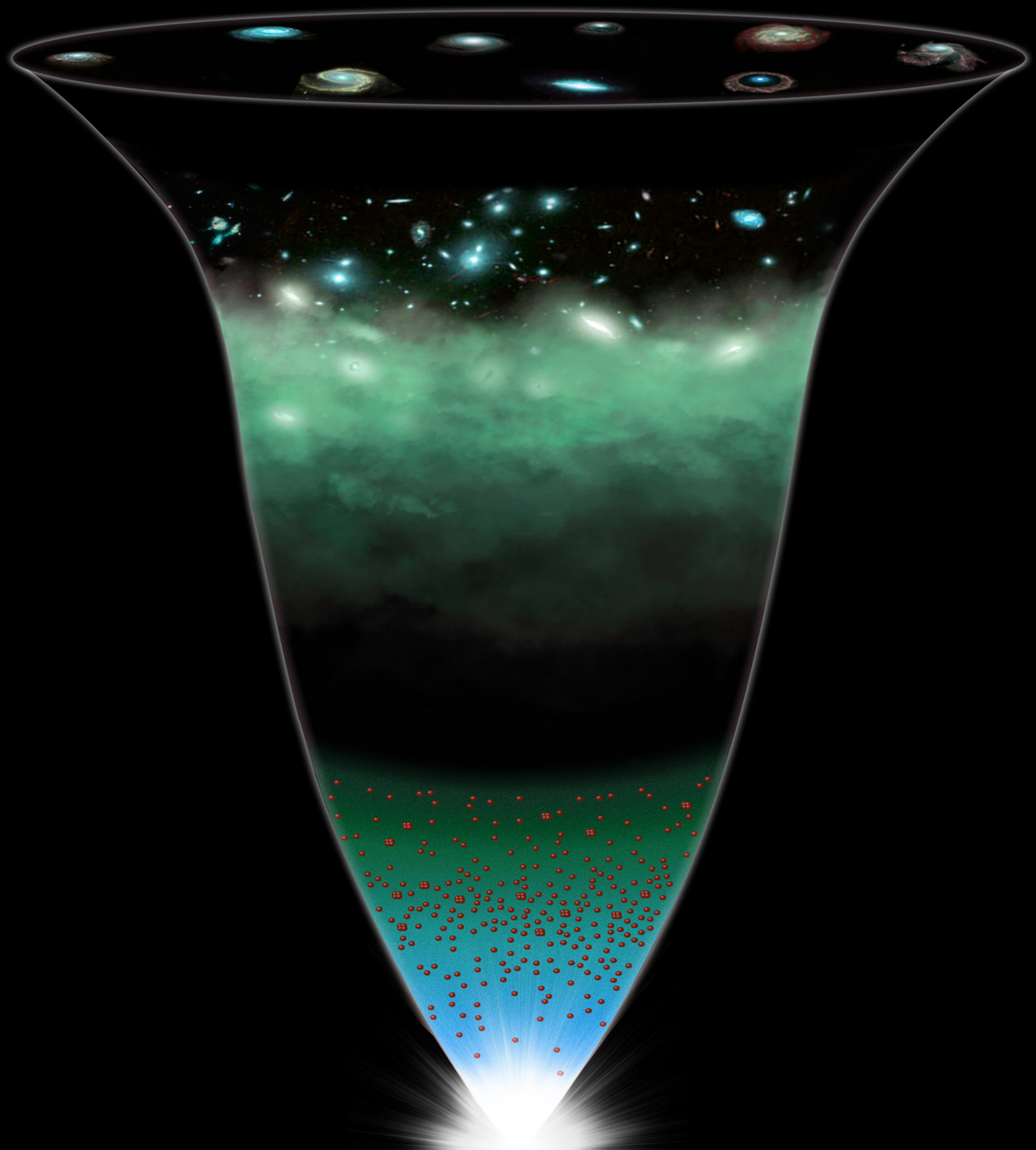


RH neutrinos created as type of Hawking radiation from the big bang fits dark matter observations if $m_R \approx 4.8 \times 10^8\ GeV$

Prediction: stability of the dark matter neutrino implies the lightest neutrino is massless will be tested using galaxy surveys in the next 3-5 years

the big bang as a CPT mirror





“Conformal zero”

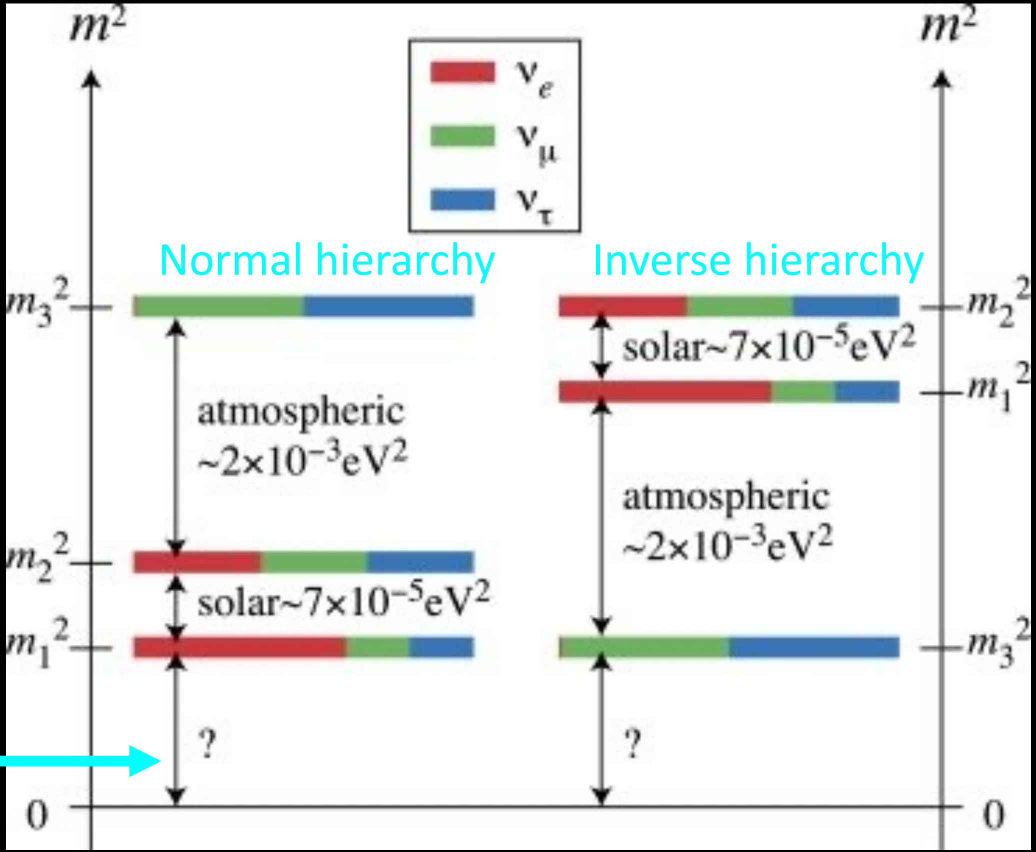
R. Newman (1993):

for GR+conformal fluid, conformal 3-metric provides complete Cauchy data at the bang

Light neutrinos: observations

current data

eBOSS 2007.08991



we predict zero

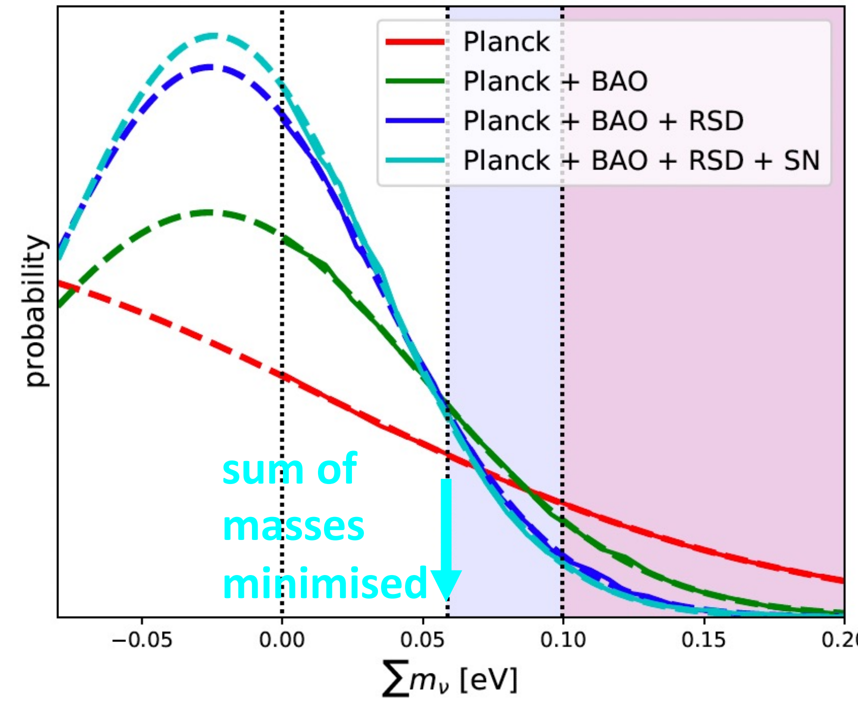


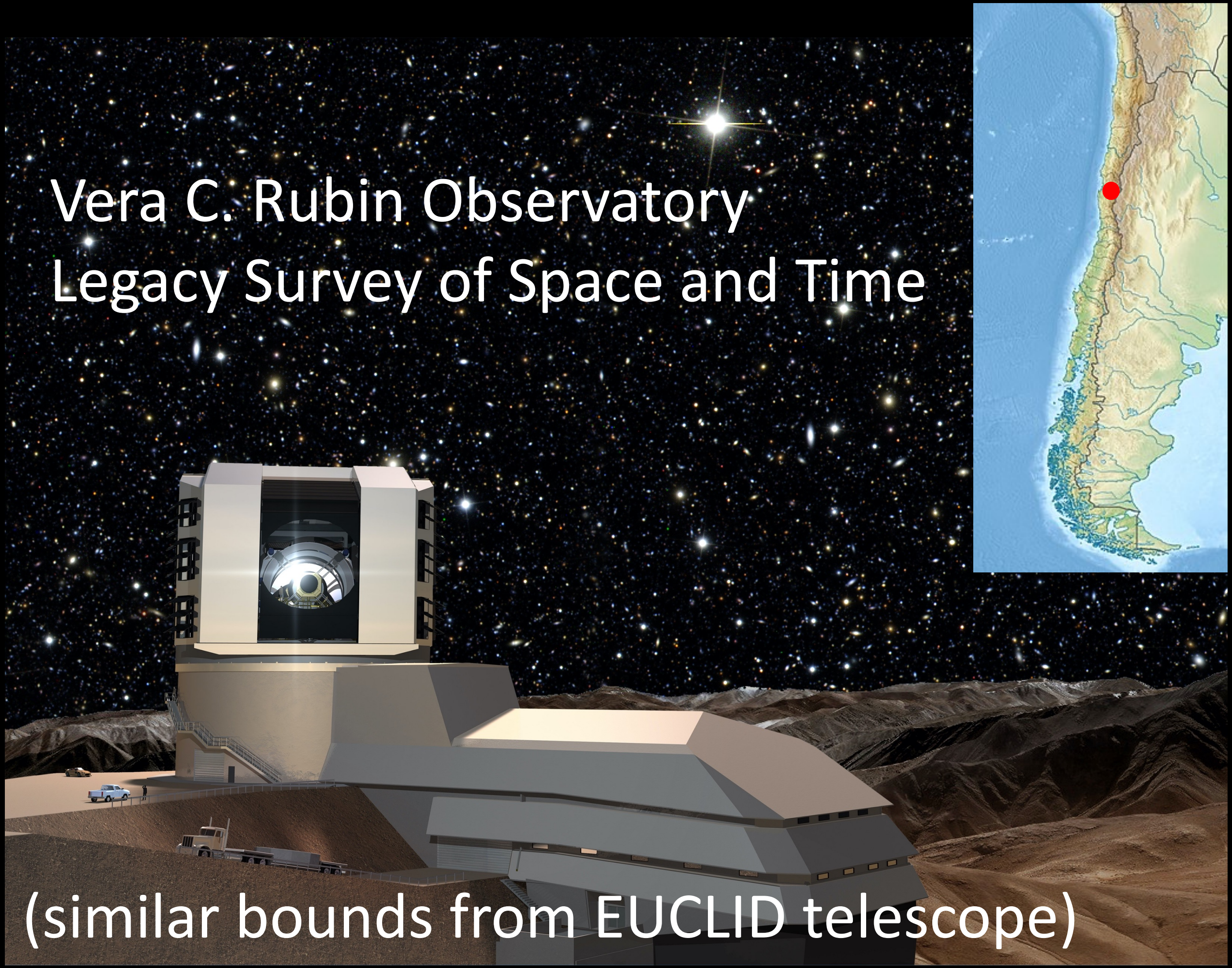
FIG. 13.— Posterior for sum of neutrino masses for selected con binations of data with a $\nu\Lambda$CDM cosmology. Dashed curves sho the implied Gaussian fits. Shaded regions correspond to lower lin its on normal and inverted hiearchies. Likelihood curves are no malized to have the same area under the curve for $\sum m_\nu > 0$.

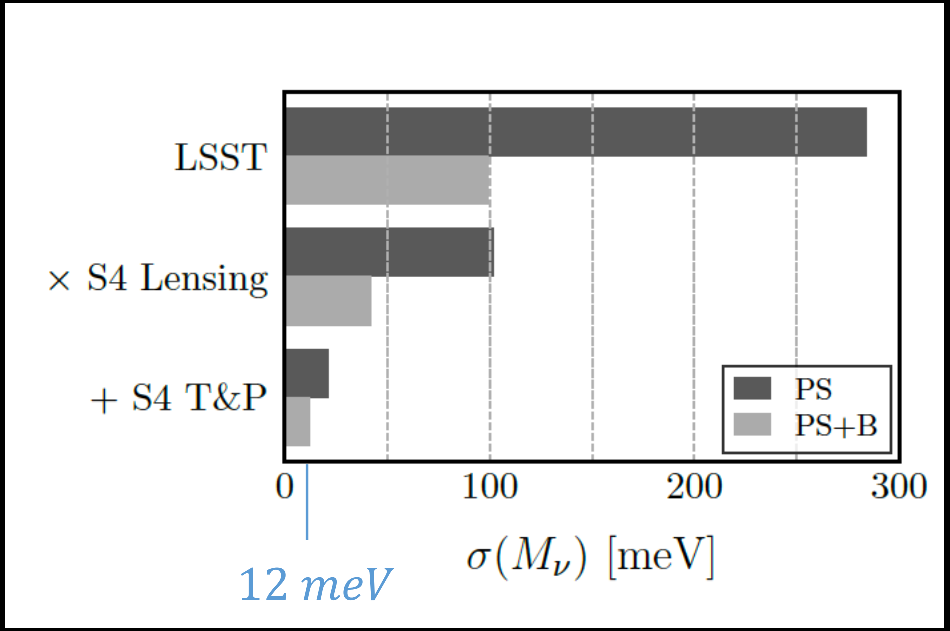
Normal hierarchy: $M_\nu \equiv \sum m_\nu \approx 0.06\ eV$

Inverted hierarchy: $M_\nu \approx 0.1\ eV$

Chen et al. 2103.01229

Vera C. Rubin Observatory
Legacy Survey of Space and Time





(similar bounds from EUCLID telescope)

the puzzling large-scale geometry of the cosmos

Penrose

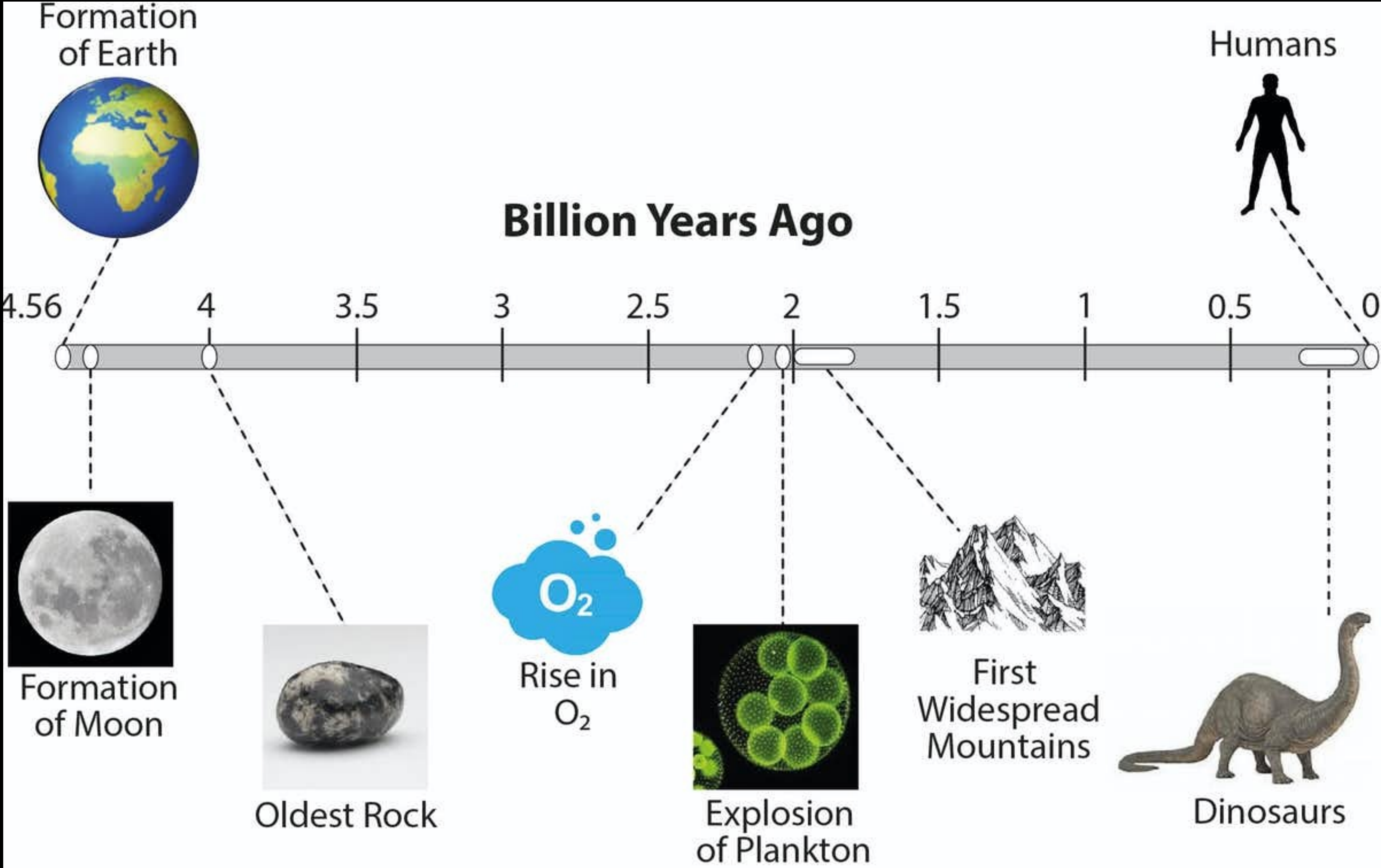
flatness closer to home...

one explanation

a better explanation

- the earth is large
  ($\sim 10^{50}$ atoms)
- gravity, dissipation, thermodynamics
  (entropy)

recent supporting evidence



Parnell and Brolly
Nature Comms Earth and Envirnt (2021) 2:238

Key: Conformal Symmetry and Analyticity

scale factor

symmetric space

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

conformal time

Einstein

comoving space (assume compact)

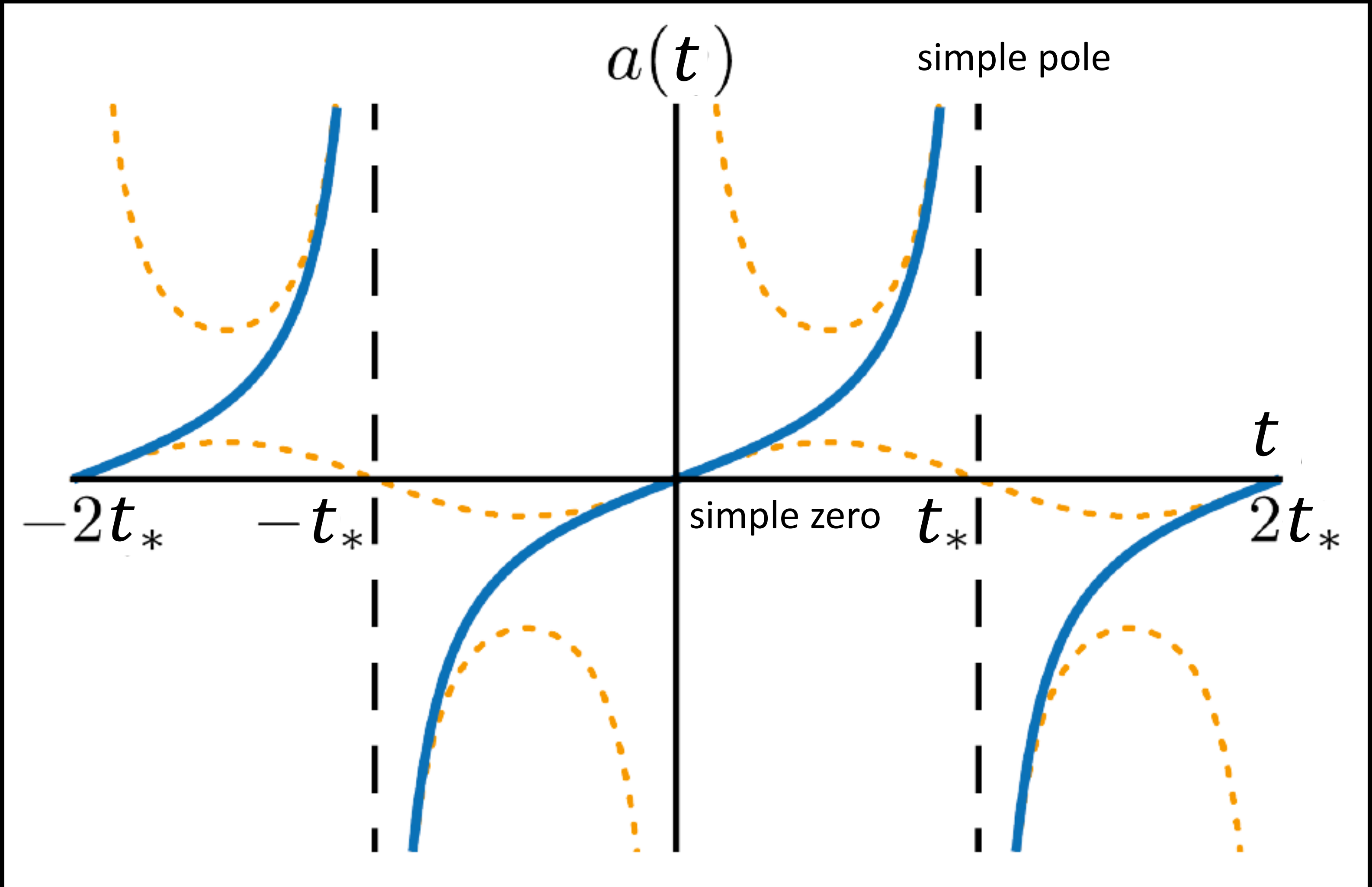
conformal symmetry at t=0 $\Longrightarrow$ $T^{\mu}{}_{\mu} = 0$ $\Longrightarrow R = 0 \Longrightarrow a(t)$ analytic

radiation matter space curvature dark energy

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

(ignoring numerical factors)

solution has remarkable analytical properties



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

its only singularities are simple poles; doubly-periodic in complex t-plane

periodicity in imaginary time implies a Hawking temperature

L. Boyle and NT

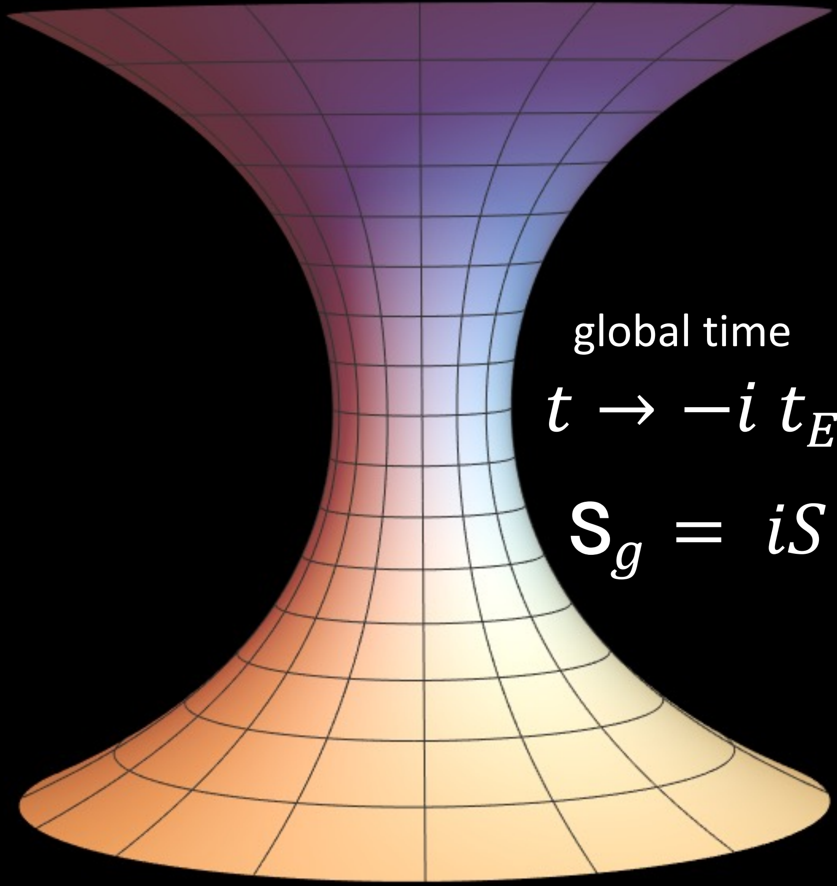
gravitational entropy:
black hole thermodynamics

Hawking
Bekenstein
Bardeen
Geroch
Gibbons
Hartle
Unruh
Wald

$$T_H = \frac{M_P^2}{M}; \quad S = \frac{A_{hor}}{4G} = \frac{M^2}{2M_P^2}; \; M_P^2 \equiv \frac{1}{8\,\pi G}; L_P^2 = 8\pi G$$

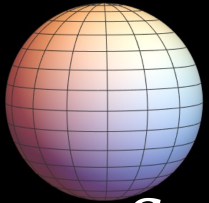
(in units where $c = \hbar = k_B = 1$)

de Sitter



gravitational entropy calculated from the Euclidean path integral

S^4



global time

$t \to -i\, t_E$

trace of Einstein

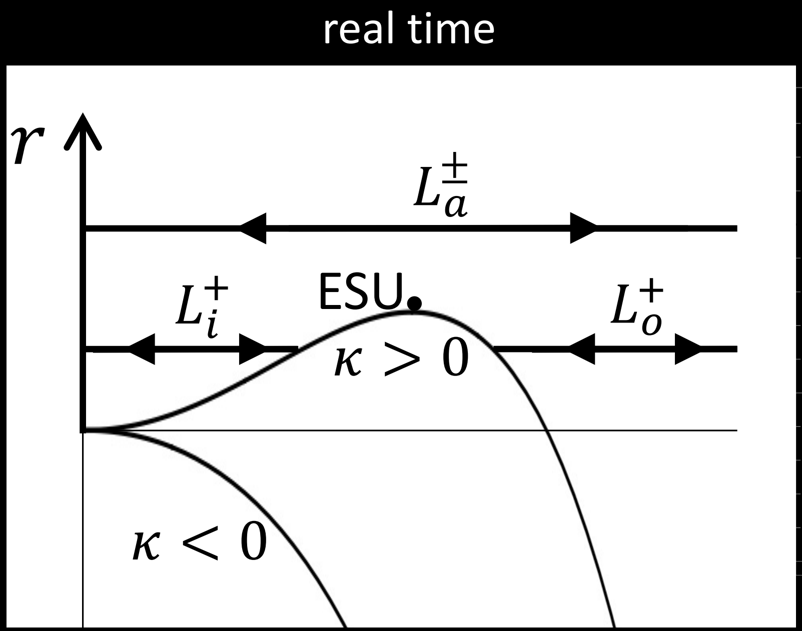
$$R = \frac{4\rho_\Lambda}{M_P^2}$$

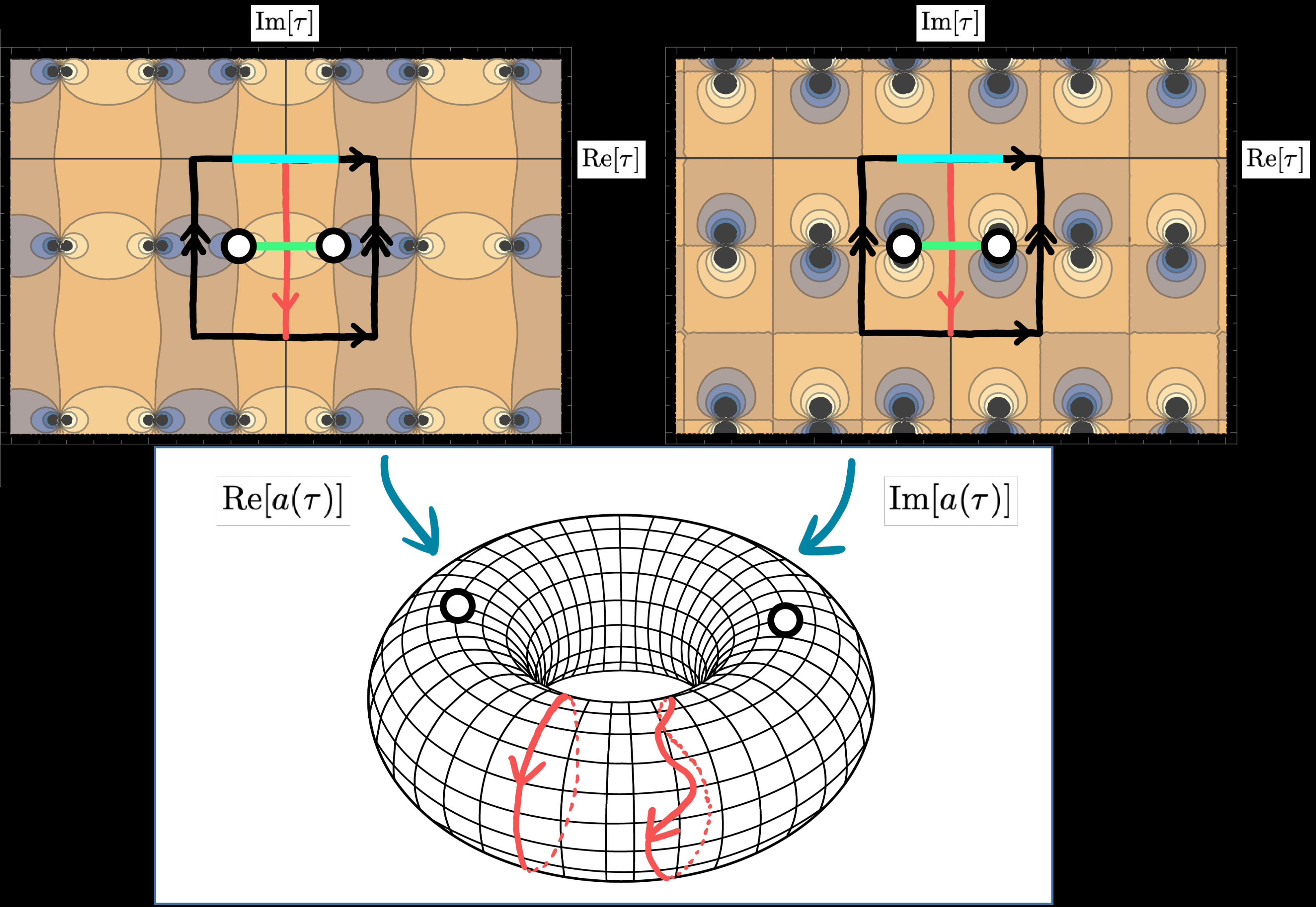
$$\mathbf{S}_g = iS = -S_E = \int\left(\tfrac{1}{2}M_P^2 R - \rho_\Lambda\right) = \rho_\Lambda \,\mathrm{Vol} = \frac{24\pi^2 M_P^4}{\rho_\Lambda}$$

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

de Sitter Entropy

Cosmological solutions wind around a torus in complex time (topology $S^1 \times \Sigma$)





with these analytical solutions, Gibbons-Perry-Hawking trick allows us to calculate the gravitational entropy

This provides a **probability measure** on cosmological spacetimes

According to this measure, the most likely universes are flat, homogeneous and isotropic on large scales. No flattening or smoothing mechanism is required.

The cosmological constant may be interpreted as a Lagrange multiplier, or chemical potential, for the Euclidean 4-volume. Large 4-volume requires small Λ. The larger the 4-volume, the larger the gravitational entropy.

Coupling the standard model to gravity

- The vacuum energy and pressure are divergent

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

A nice physical regularization is point splitting. This introduces a direction in spacetime. Taking the separation to be timelike, as the two points come together one accesses higher and higher energies. For electromagnetic fields in flat spacetime

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

which violates Lorentz invariance. Some regularizations set these divergences to zero but their physical meaning is less clear.

- Conformal invariance (traceless stress tensor) important to getting consistent physical answers (see DeWitt for Casimir effect).

- Conformal invariance is our best hope of describing the big bang. In the SM, both gauge fields and chiral fermions are classically conformal invariant. Ignoring the Higgs field, no mass terms are allowed.
  However, conformal symmetry is spoiled by quantum field theory divergences.

Natural possibility: the Higgs is a composite field, whose mass scale arises from quantum effects (just as the QCD mass scale)

Scalar fields

Dimension-one scalars have a two-derivative Weyl-invariant action

$$S_2 = \frac{1}{2} \int d^4x \sqrt{-g}\, g^{\mu\nu} \partial_\mu H \partial_\nu H + \cdots \qquad H(x) \longrightarrow \Omega(x)^{-1} H(x)$$

Dimension-zero scalars have a four-derivative Weyl-invariant action

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

A very interesting theory

Bogoliubov et al (1987); Rivelles (2003)
(dates back to Thirring, Heisenberg …)

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

The only physical state is the vacuum: no excited states (see this most clearly in BRST)

The vacuum fluctuations are scale-invariant

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

Vacuum energy and conformal anomalies

dim-one scalars, chiral fermions, gauge fields, dim-zero scalars

$$E_{\boldsymbol{k}} = \tfrac{1}{2}\hbar k(n_0 - 2\,n_{1/2} + 2n_1 + 2n_{0'})$$

$$C^2 = C^{\alpha\beta\gamma\delta}C^{\alpha\beta\gamma\delta};$$
$$E = R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta} - 4R_{\alpha\beta}R^{\alpha\beta} + R^2$$

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

$$a = \frac{1}{360(4\,\pi)^2}\left[n_0 + \frac{11}{2}n_{1/2} + 62\,n_1 - 28\,n_{0'}\right]$$

$$c = \frac{1}{120(4\,\pi)^2}\left[n_0 + 3\,n_{1/2} + 12\,n_1 - 8\,n_{0'}\right]$$

Given the SM gauge group $SU3{\times}SU2{\times}U1$, the solution is unique:

$$n_{1/2} = 4n_1 = 48;\ \ n_{0'} = 3n_1 = 36;\ \ n_0 = 0.$$

Requires precisely three generations, each with one RH neutrino

Also requires that Higgs is not fundamental (cf condensed matter)

primordial perturbations from φ's using standard model physics

Running couplings violate conformal or scale symmetry at order $\hbar$

At high temperature, running of the abelian gauge coupling α_1 dominates:

$T^{\mu}_{Q\mu} = \rho - 3P = -\frac{5}{108}(\alpha_1 N_Y)^2 T^4$: $N_Y = \frac{N\,gen}{2}\Sigma Y^2 = \frac{3}{2}(\frac{2}{4}+1+\frac{3\times 2}{36}+\frac{3\times(4+1)}{9})$ Callan+Thorlacius 1989

Generalizing 2d string sigma model, this violation is cancelled with a classical term

$-\frac{1}{2}\int d^4x\sqrt{-g}\, T^{\mu}_{Q\mu}\sum d_j\varphi_j$, with $\sum d_j = -1$

This term corrects the Einstein-fluid equations, converting quantum correlations in the 36 fields φ_j into large scale curvature fluctuations: Friedmann equation becomes

$$\dot{a}^2 = \frac{8\pi G}{3}\rho_r a^4(1+c\varphi) \text{ with } \varphi = \sum d_j\varphi_j,\ c = \frac{5}{108}(\alpha_1 N_Y)^2/\left(\frac{\pi^2}{30}N_{eff}\right), N_{eff}=108$$

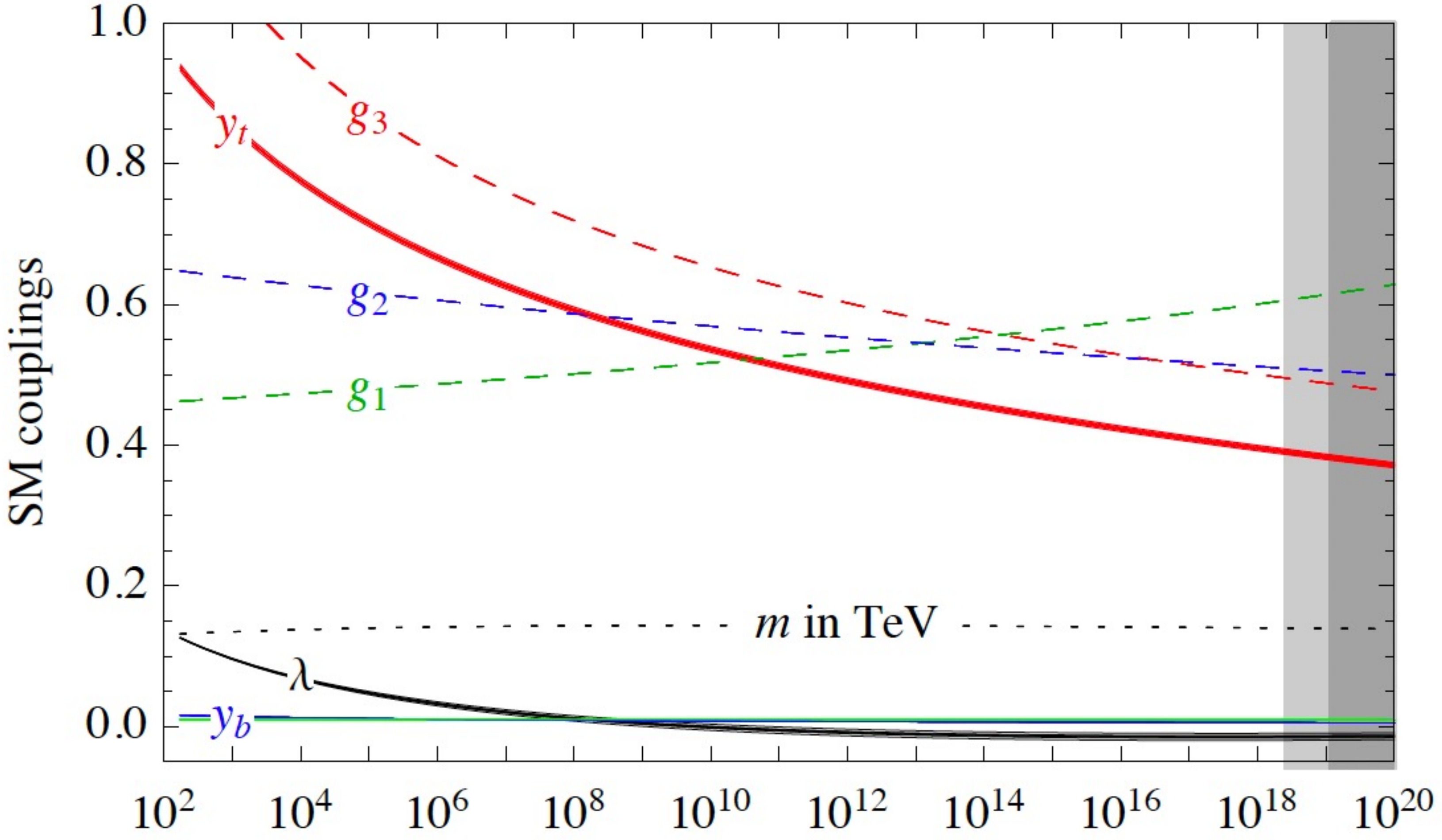
Conformal factor translates directly into curvature perturbation $\mathcal{R} = \frac{1}{4}c\varphi$

Predict $\mathcal{R}_{rms} \approx 3.07\times 10^{-5}\sqrt{36(\bar{d}^2+\sigma^2)}$ where $\bar{d} = -\frac{1}{36}$ is the mean and σ the rms of the d_j

Fits the Planck-measured amplitude 4.57×10^{-5} if $\sigma = 0.25$

(adiabatic, Gaussian, scalar: no primordial tensors)

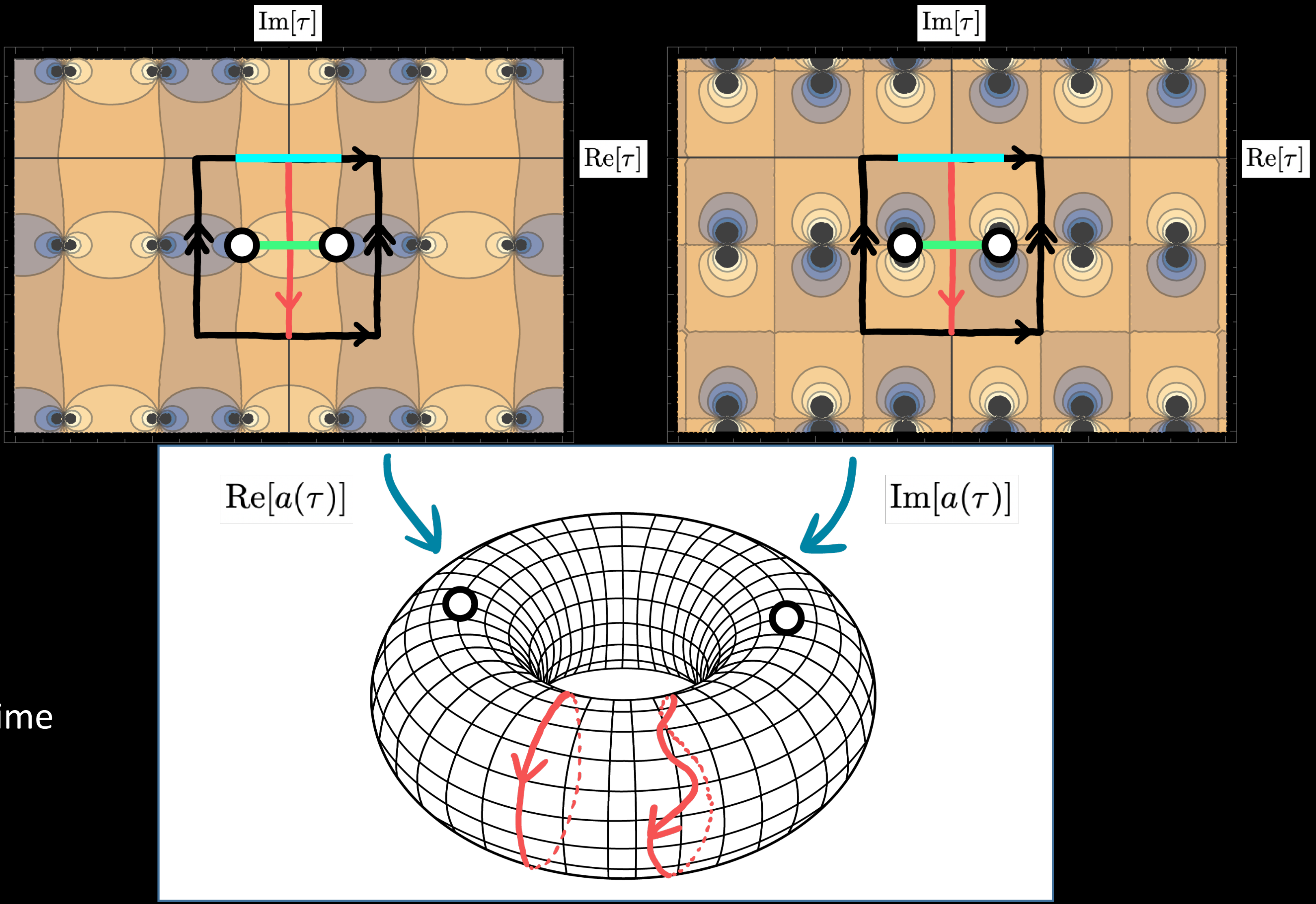
Buttazzo et al
1307.3536
[hep-ph]



Planck energy 10^{19}

Energy scale in GeV

Cosmological solutions wind around a torus in complex time (topology $S^1 \times \Sigma$)



period in imaginary time
$\approx \pi \, R_{dS}$

Power spectra

Newtonian potential

$$\langle|\delta\Phi_k|^2\rangle \propto k^{-3}, \quad k \gtrsim R_{dS}^{-1}: \quad \text{“Minkowski”}$$

$$\langle|\delta\Phi_k|^2\rangle \propto k^{-4}, \quad k \lesssim R_{dS}^{-1} \quad \text{“de Sitter”}$$

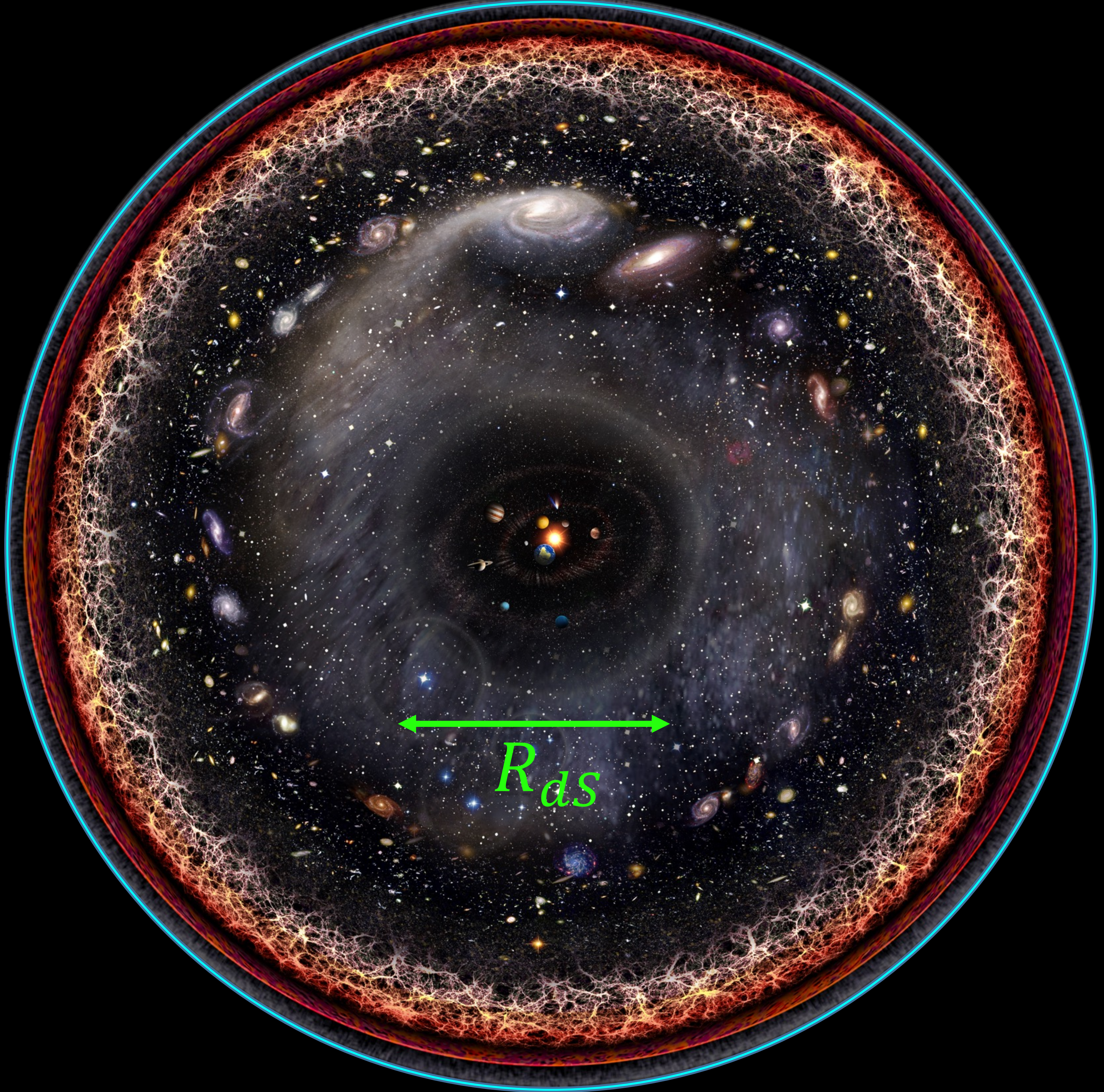
matter overdensity

$$\left\langle\left|\frac{\delta\rho_k}{\rho}\right|^2\right\rangle \propto k^4 \langle|\delta\Phi_k|^2\rangle \propto k^1 \quad \text{HPZ}$$

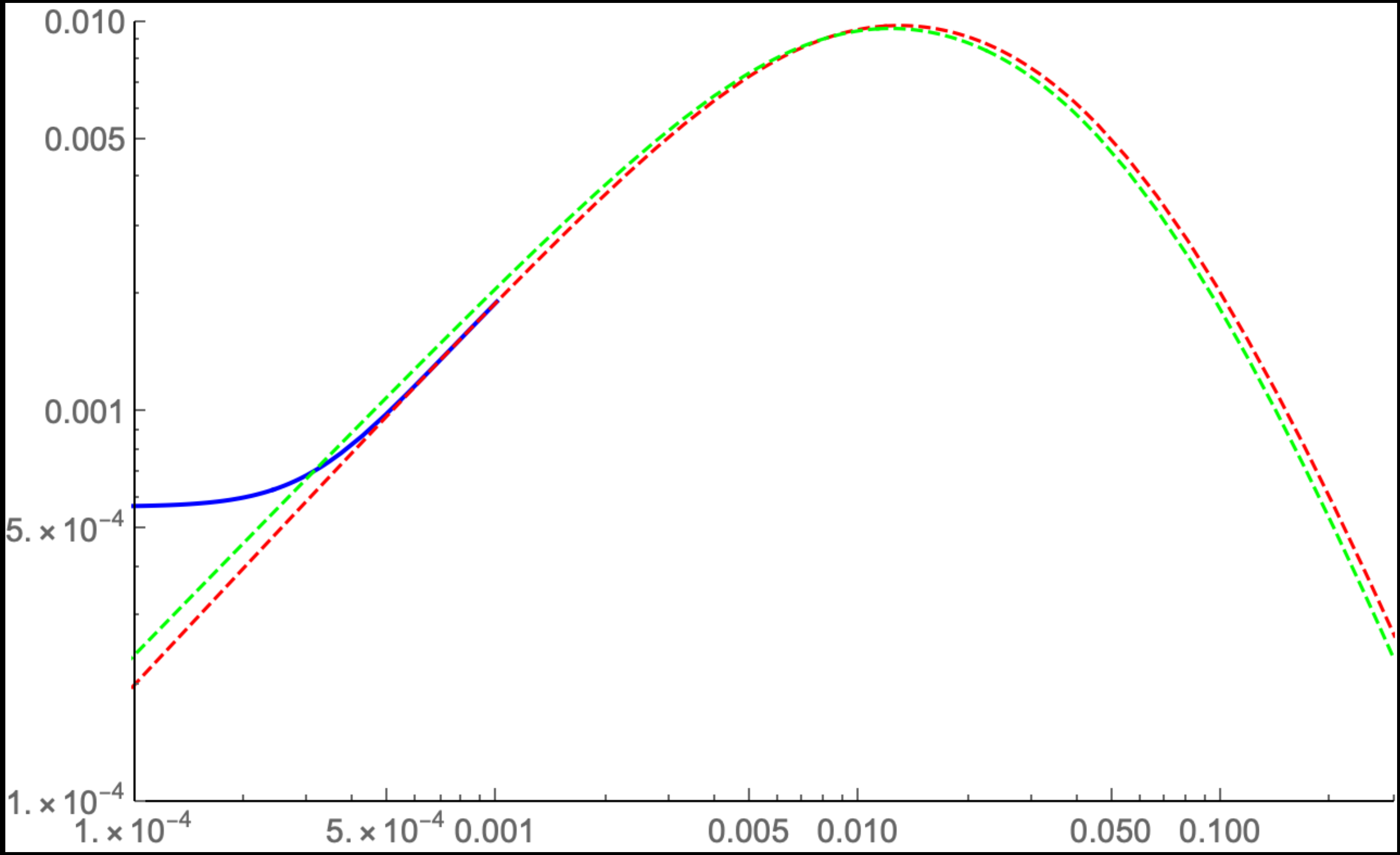
$$\propto k^0 \quad k \lesssim R_{dS}^{-1}$$

we predict additional power on very large scales

(for a recent review of large scale observations see, *e.g.*, Aluri *et al.* 2207.05765 [astro-ph])



new model for red tilt



It will be interesting to compare this in detail with the observations

summary

analytic extension of cosmological solutions of the Einstein equations lead to

- a new picture of the big bang as a CPT mirror
- a formula for the gravitational entropy

these provide new explanations and predictions for

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

In addition, curing the anomalies in the standard model's coupling to gravity with 36 dim zero scalars

- cancels the vacuum energy and Weyl anomalies at free field order
- explains why there are 3 generations
- yields perturbations of the right character and amplitude with no need for inflation

- without adding any new particles, forces or propagating degrees of freedom

these are encouraging signs, but much remains to be understood

Thank You!