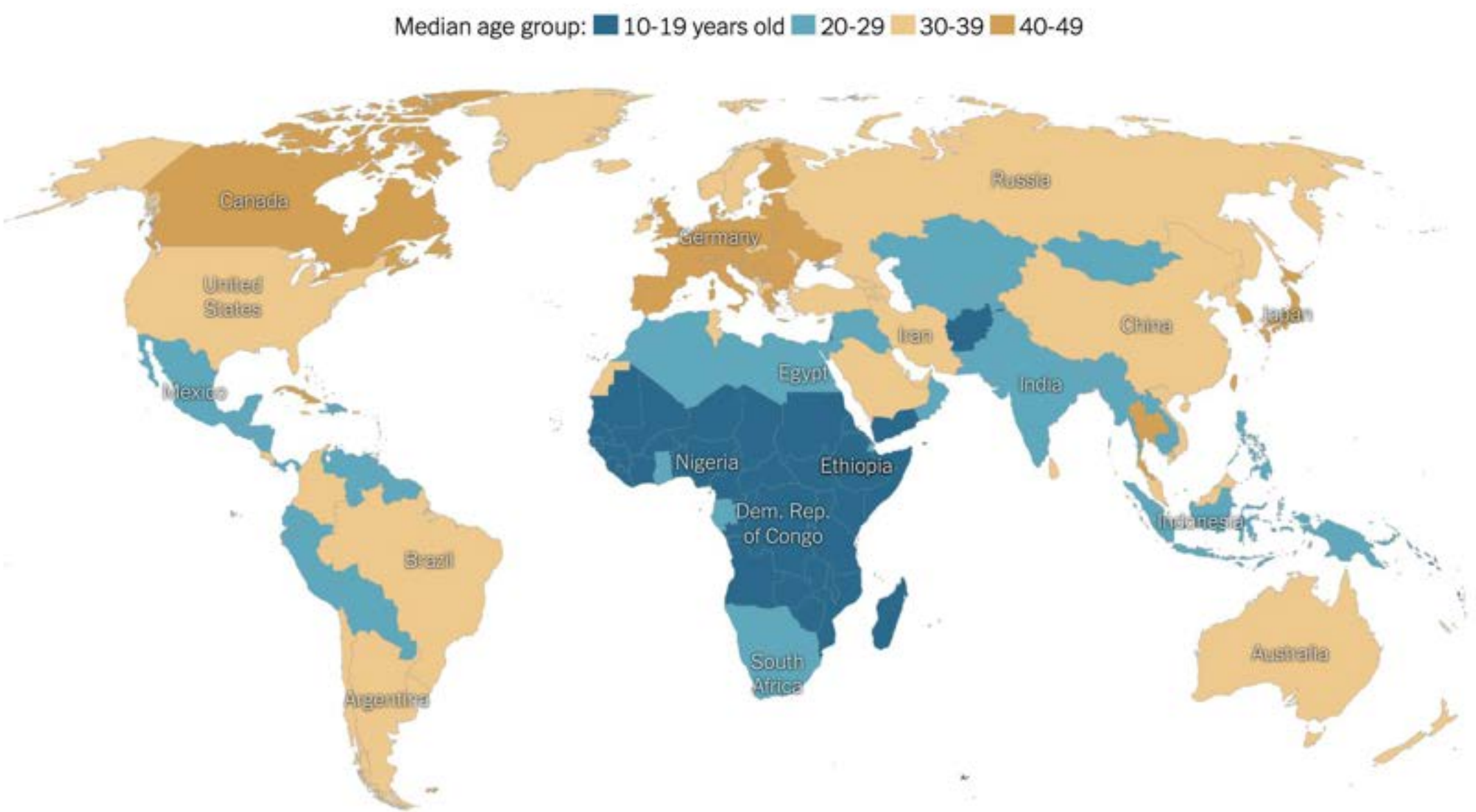
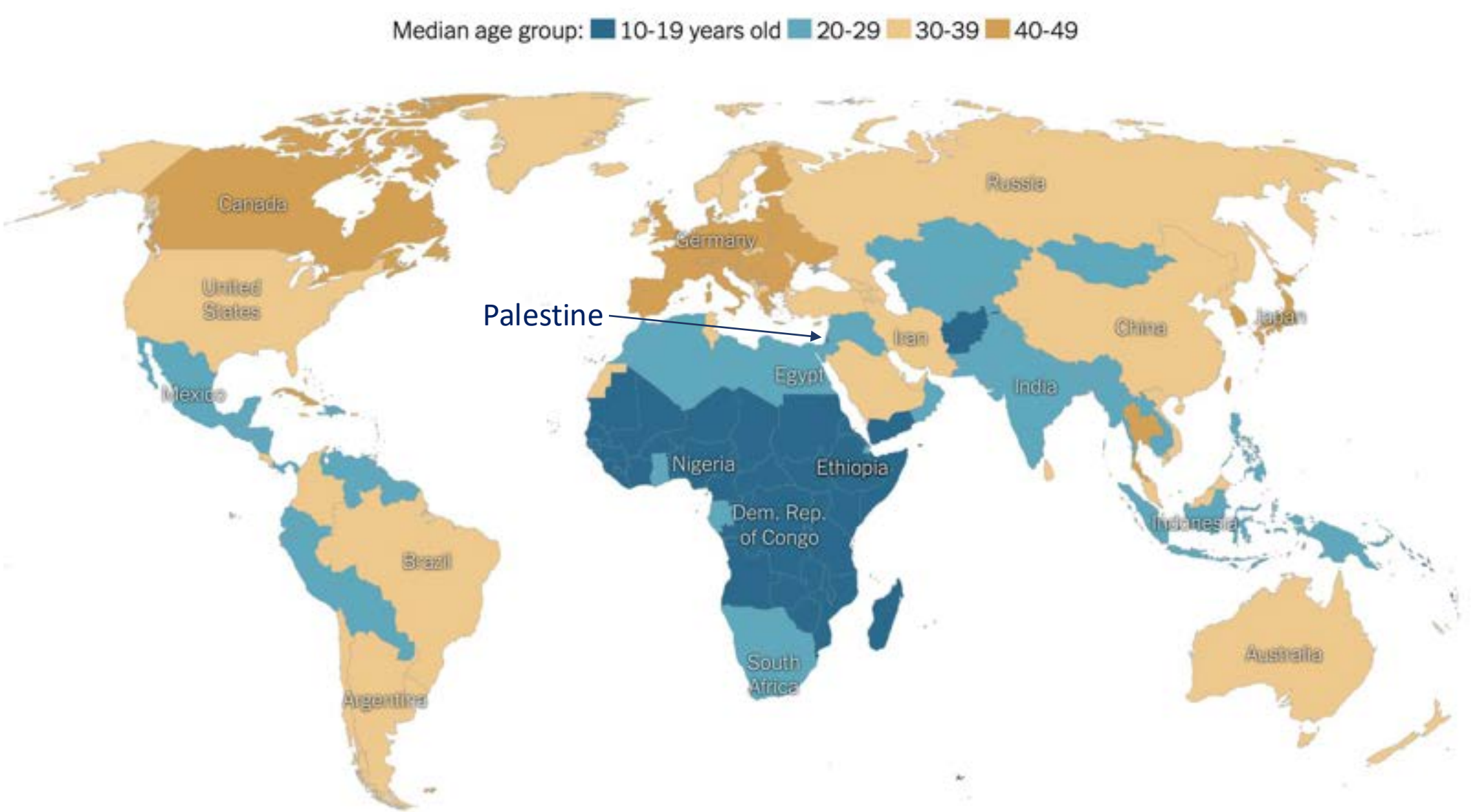
origin of mathematics and astronomy

+ Ibn Al-Haytham 965-1040 (*Book of Optics*)



Source: U.N. World Population Prospects 2022


Median age group: 10-19 years old 20-29 30-39 40-49
Canada
United States
Mexico
Brazil
Argentina
Germany
Russia
Palestine
Iran
Egypt
Nigeria
Ethiopia
Dem. Rep. of Congo
South Africa
India
China
Japan
Indonesia
Australia
Source: U.N. World Population Prospects 2022

A simple cosmology

Neil Turok

University of Edinburgh, UK and Perimeter Institute, Canada

with Latham Boyle

and Maegan Andersen, Sam Bateman, Kostas Tsanavaris

the large-scale universe is stunningly simple
It is well-modelled with just five numbers:

energy

Λ (70%)

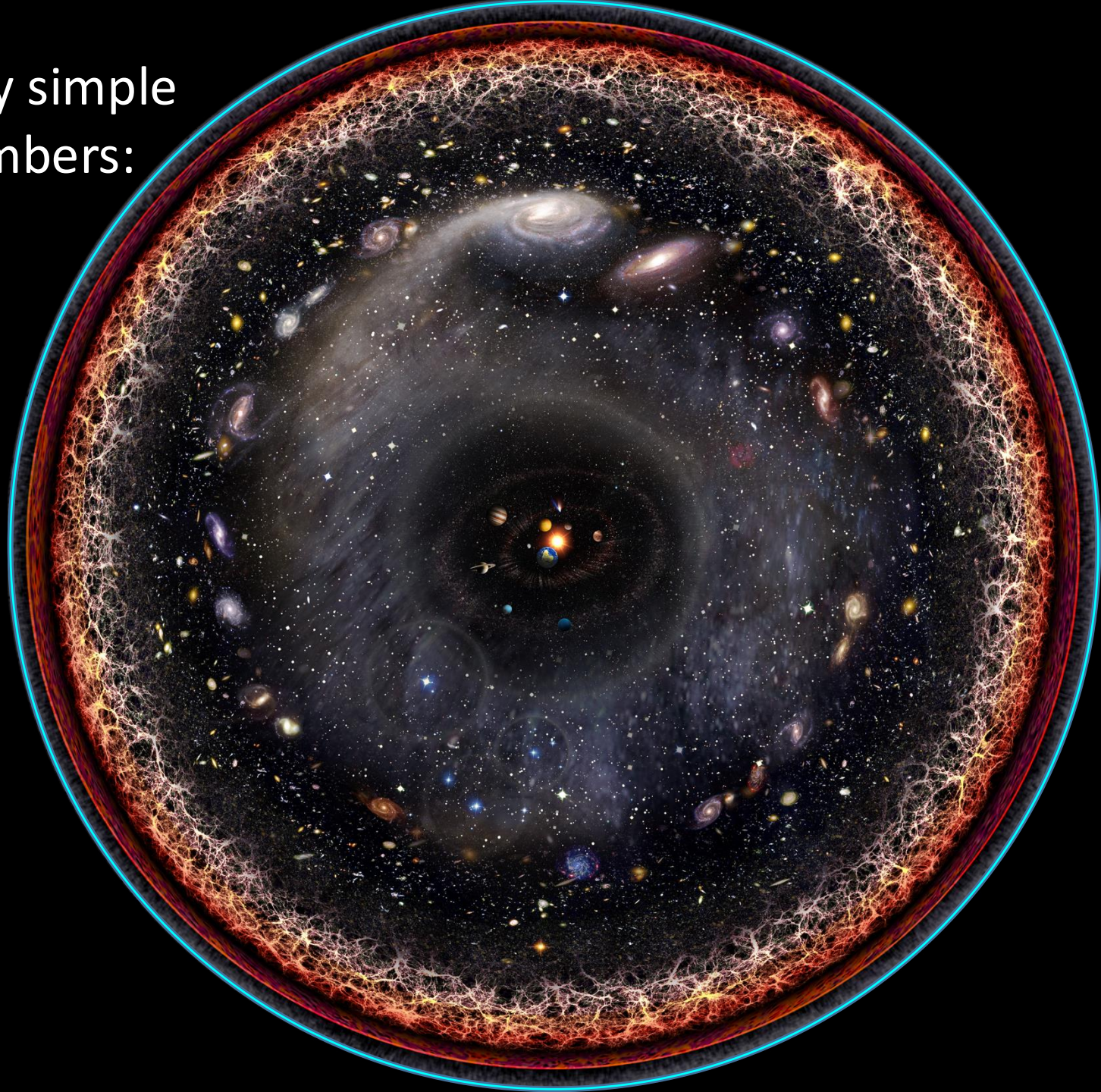
Dark matter (25%)

Nuclear matter (5%)

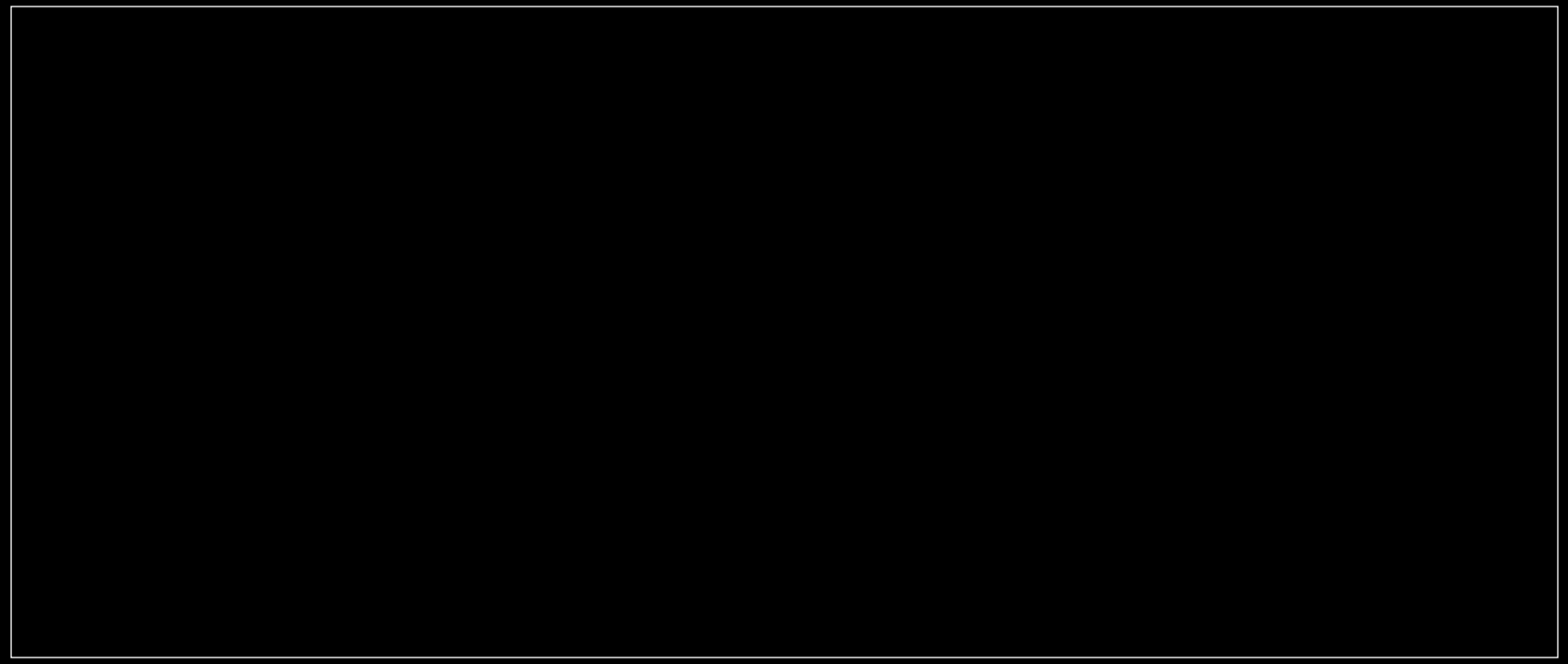
perturbations

amplitude $\approx 10^{-4} \left(\frac{\lambda}{\lambda_0}\right)^{0.02}$

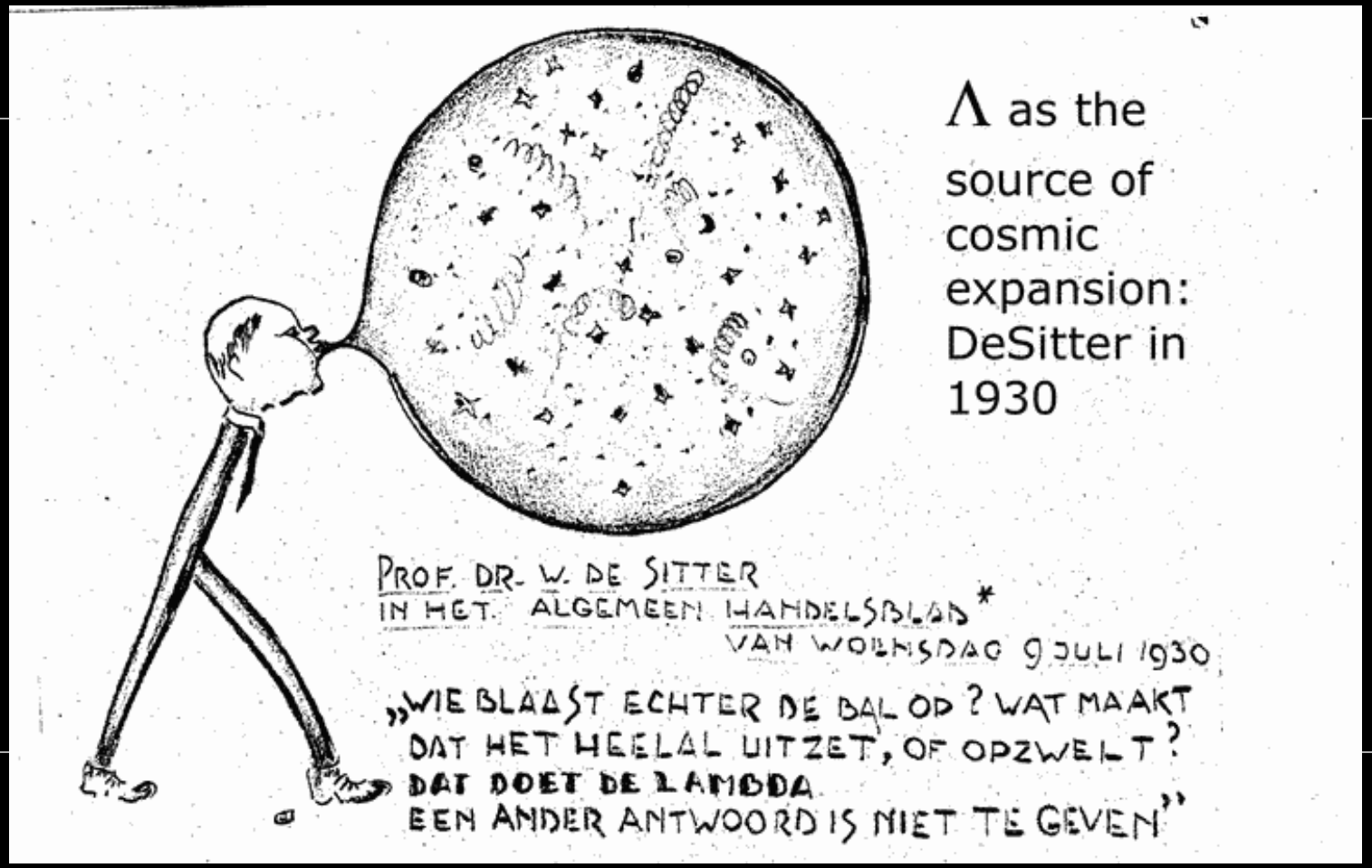
red “tilt”



Λ and gravity



Λ and gravity



gravity sets the smallest and largest observable scales

Planck length

$l_{Pl} \sim 10^{-35} m$

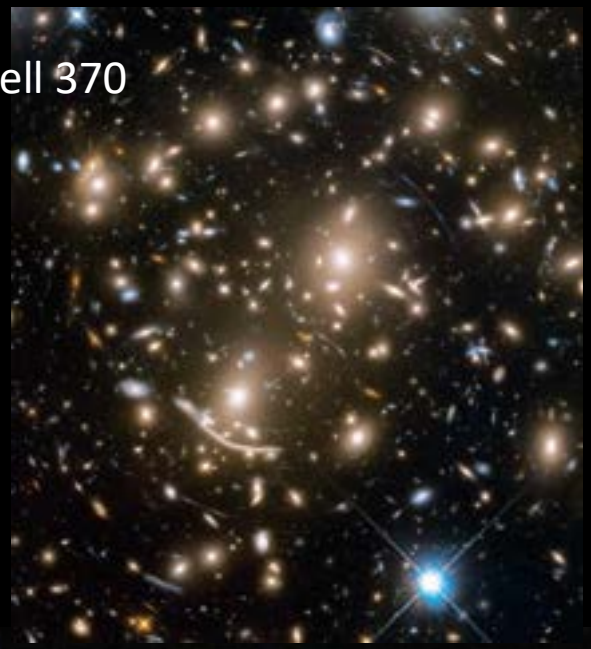
$\sqrt{l_{Pl}\ l_H} \sim 10^{-4} m$

de Sitter length

$l_H \sim 10^{+27} m$

seeing cold dark matter with gravitational lensing

Abell 370

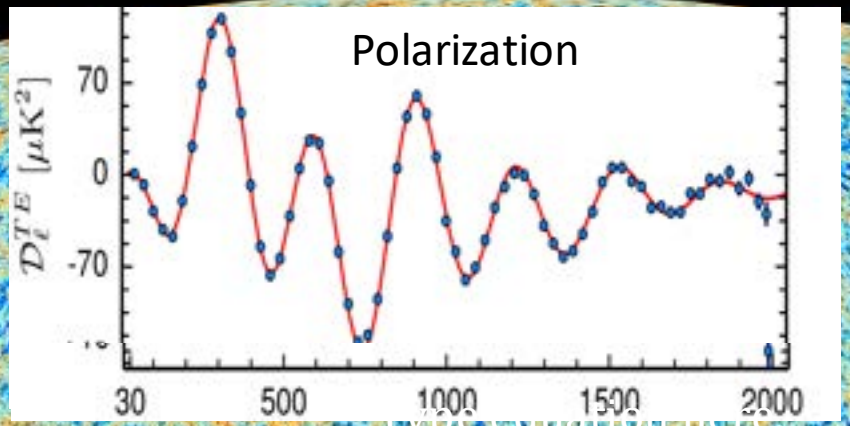


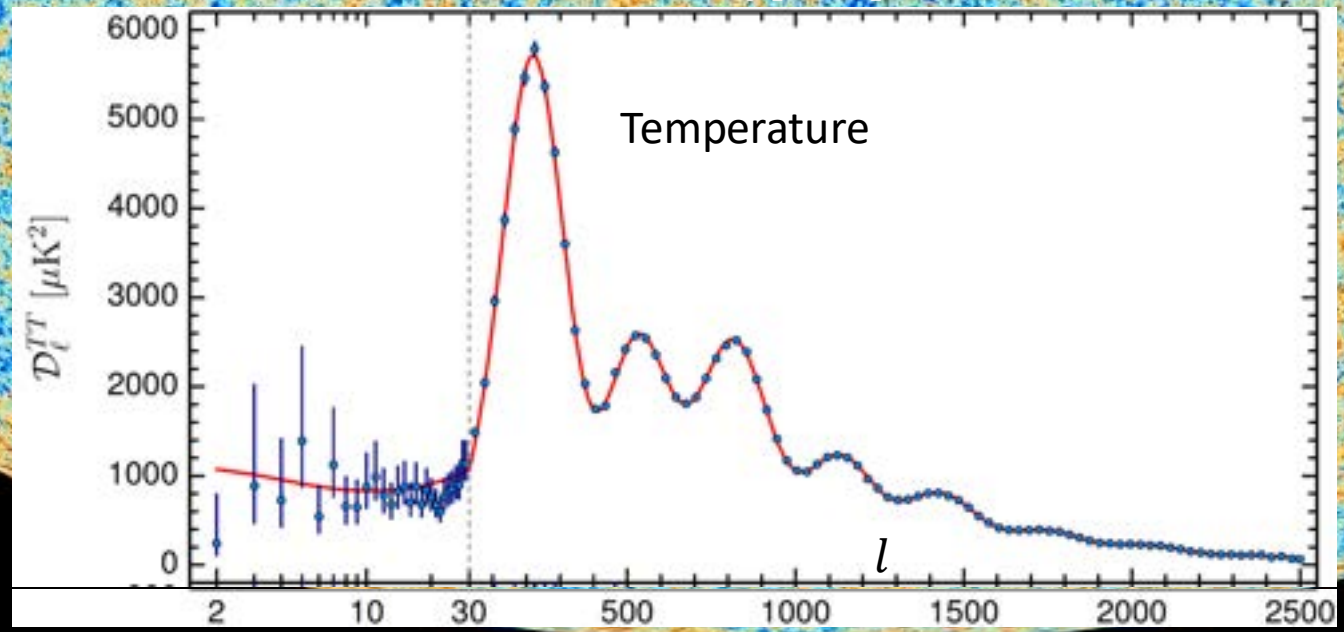
Horseshoe Einstein Ring

1E 0657-558
"bullet cluster"

ΛCDM is an amazingly successful fit

Coulson, Crittenden, NT (1994)
no free parameters!





acoustic peaks (sound waves in plasma)

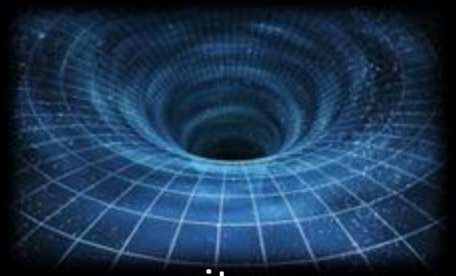
ESA Planck satellite

all known physics respects relativity and quantum mechanics

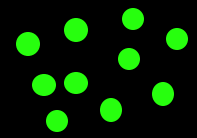
gauge fields

Higgs

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



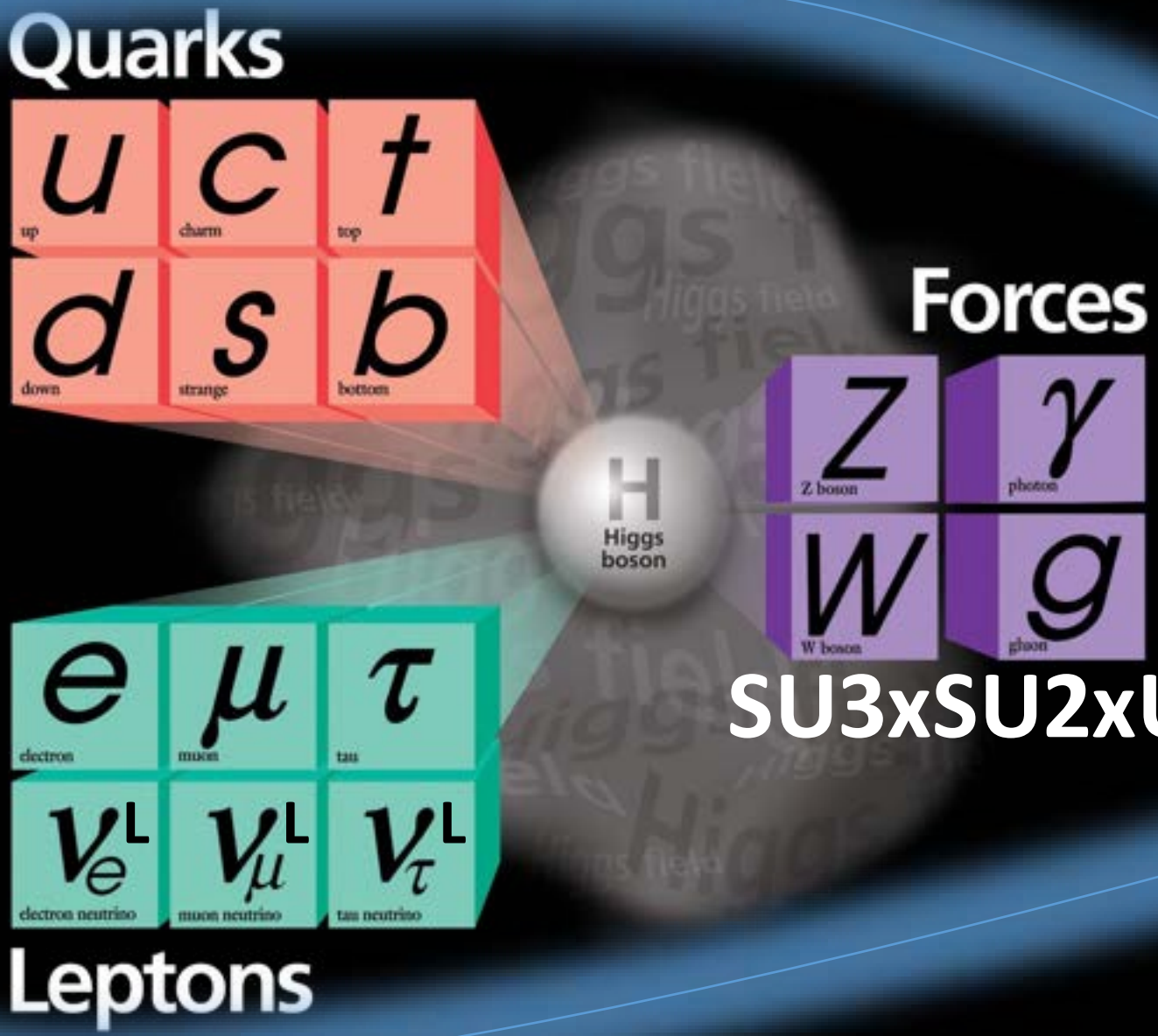
gravity



particles

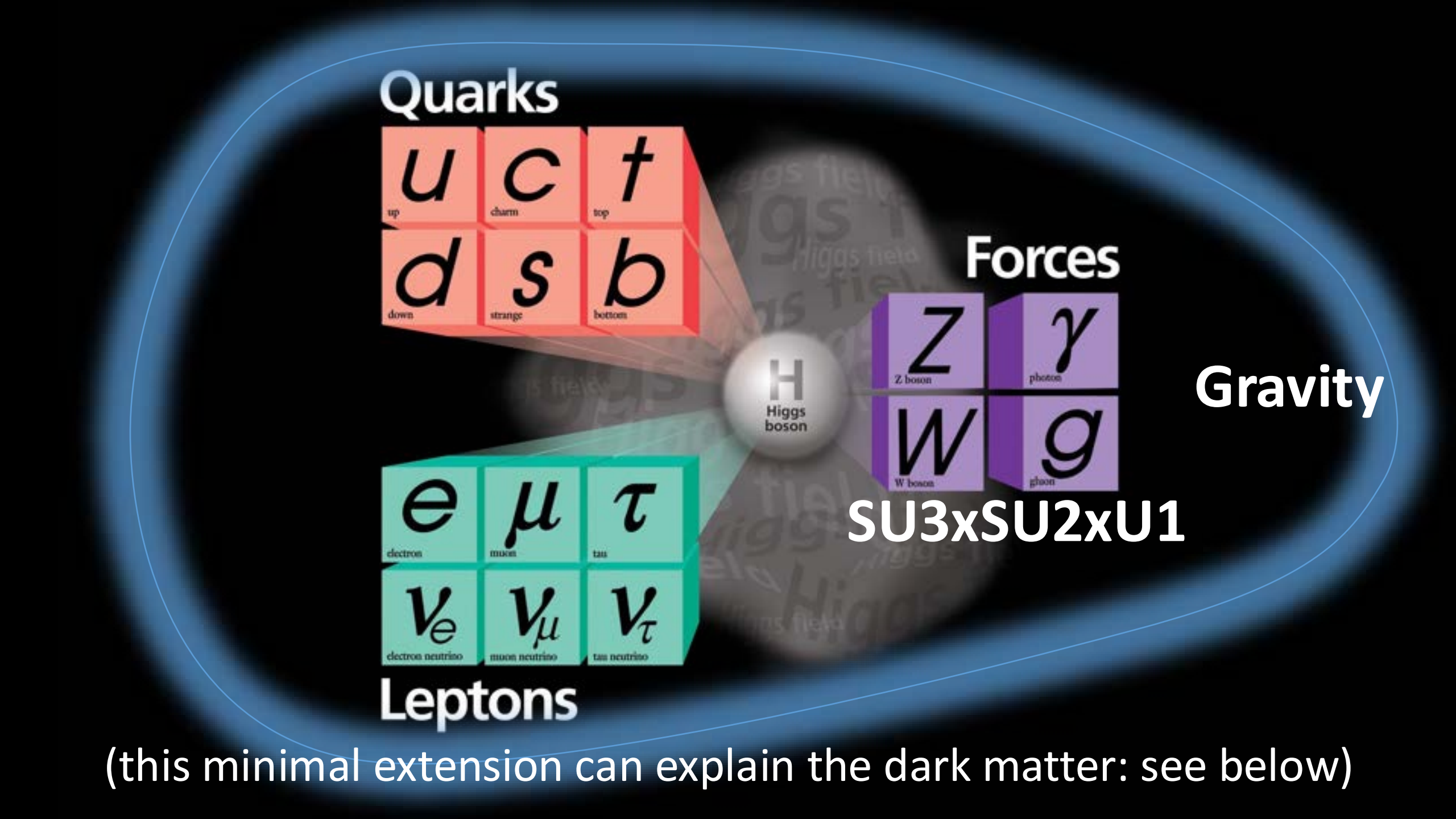
its mysteries are connected with gravity,
e.g., infinities and the big bang singularity

all known Particles And Forces: “The Standard Model”

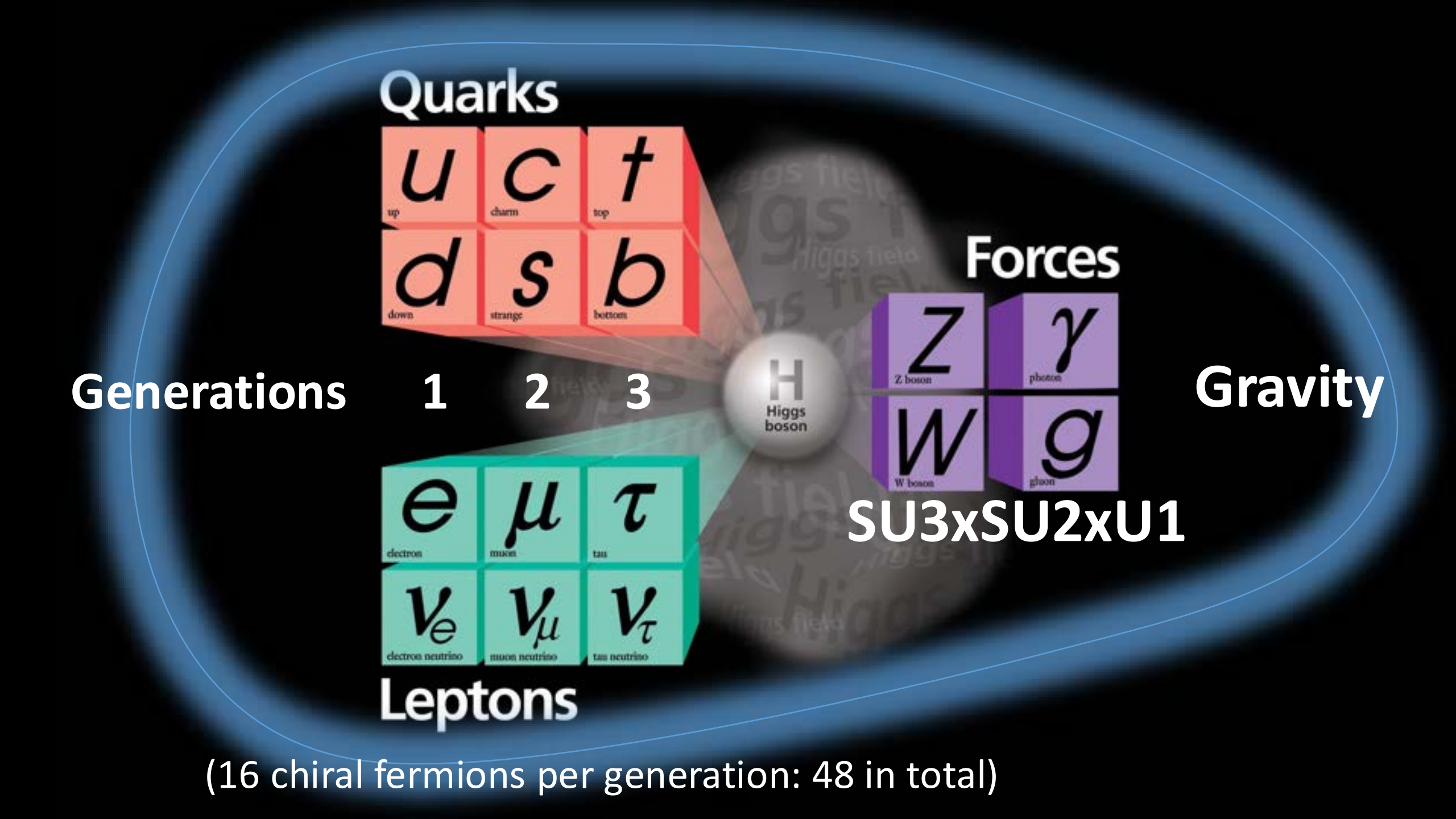


Gravity

SU3xSU2xU1



(this minimal extension can explain the dark matter: see below)



(16 chiral fermions per generation: 48 in total)

An analogy:

$e^+ e^-$

"pair creation"
in an electric field

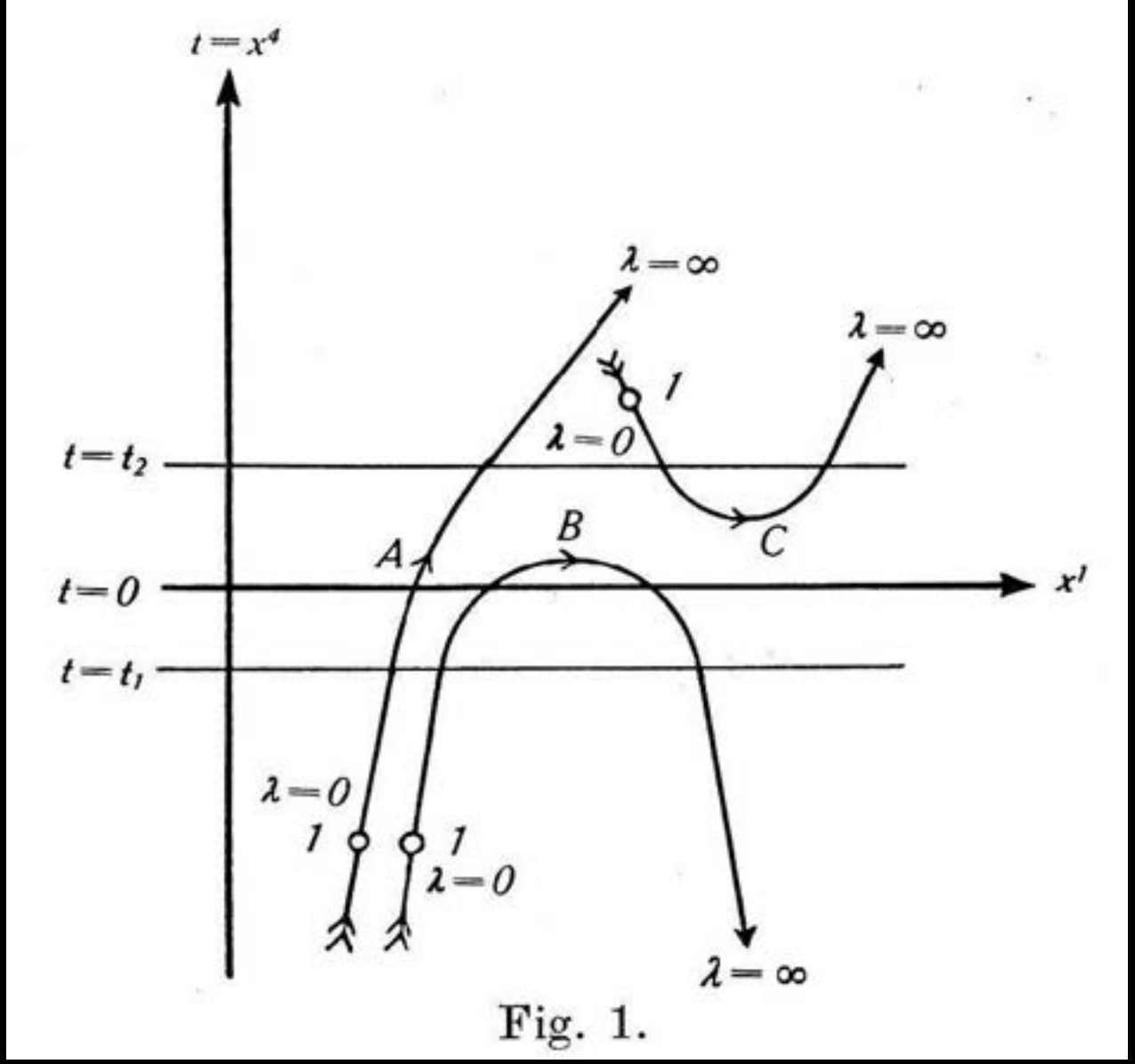


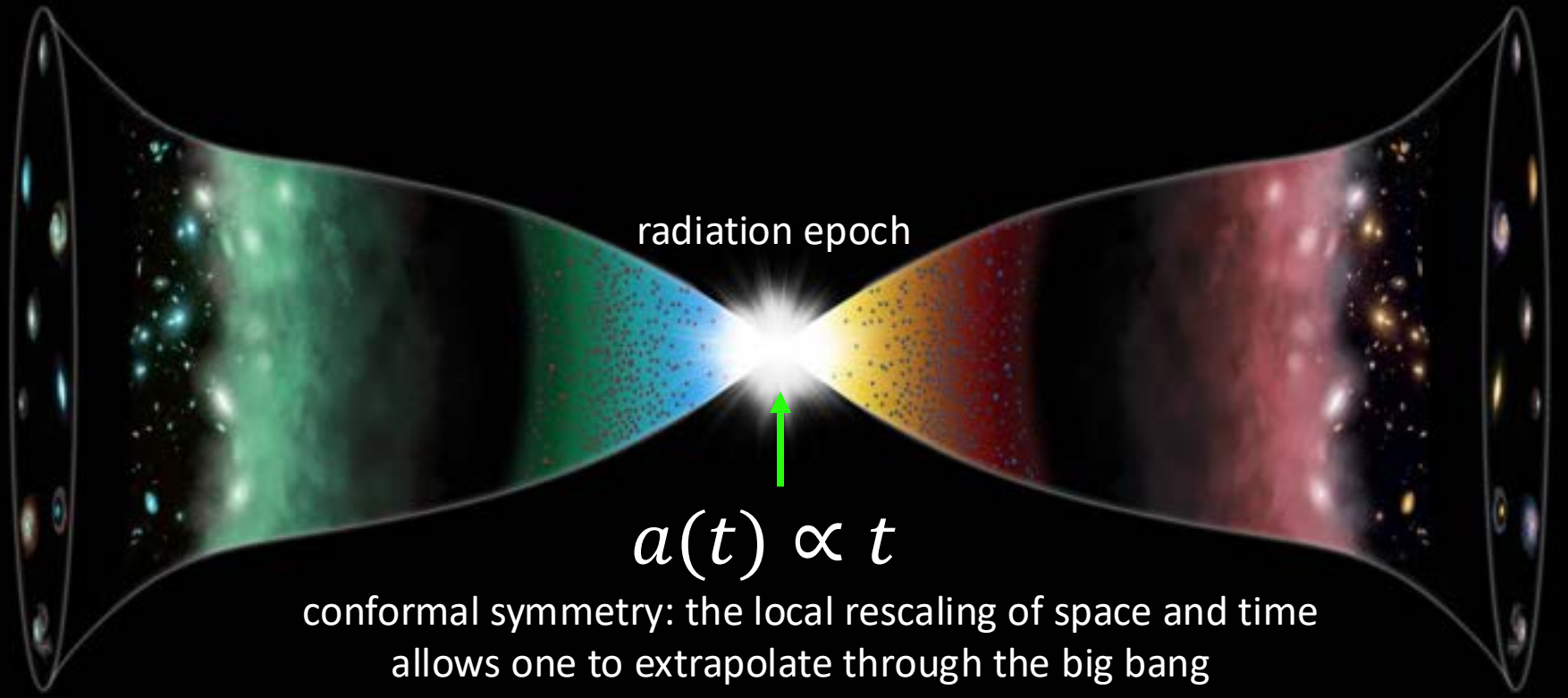
Fig. 1.

Ernst Stueckelberg 1941

All physical processes respect Charge, Parity and Time reversal symmetry

Boyle, Finn, NT (2018)

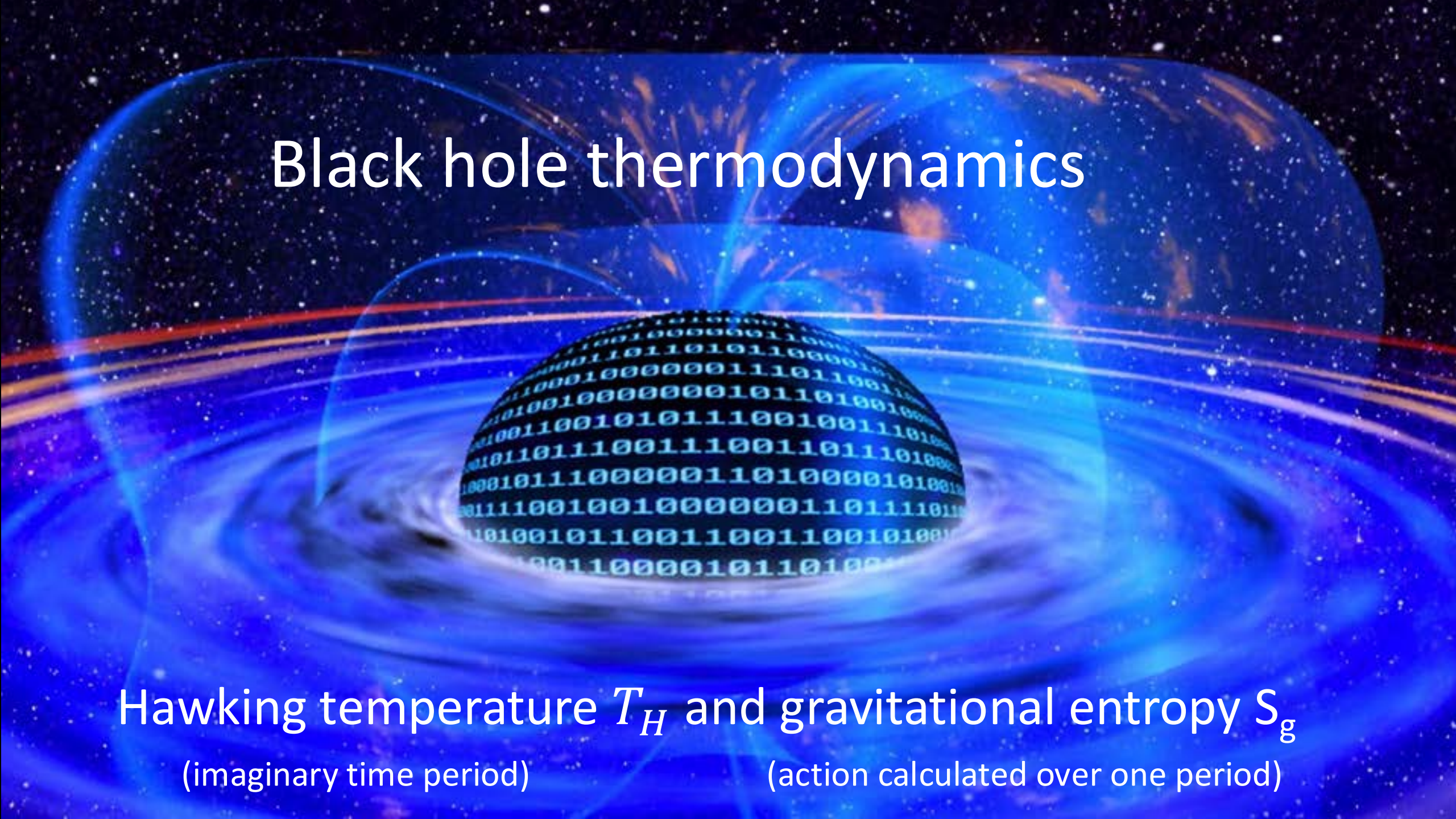
radical new hypothesis: the universe is CPT symmetric



conformal symmetry: the local rescaling of space and time
allows one to extrapolate through the big bang

CPT-symmetric bc's imposed via the method of images – the big bang is a mirror!

Black hole thermodynamics



Hawking temperature T_H and gravitational entropy S_g

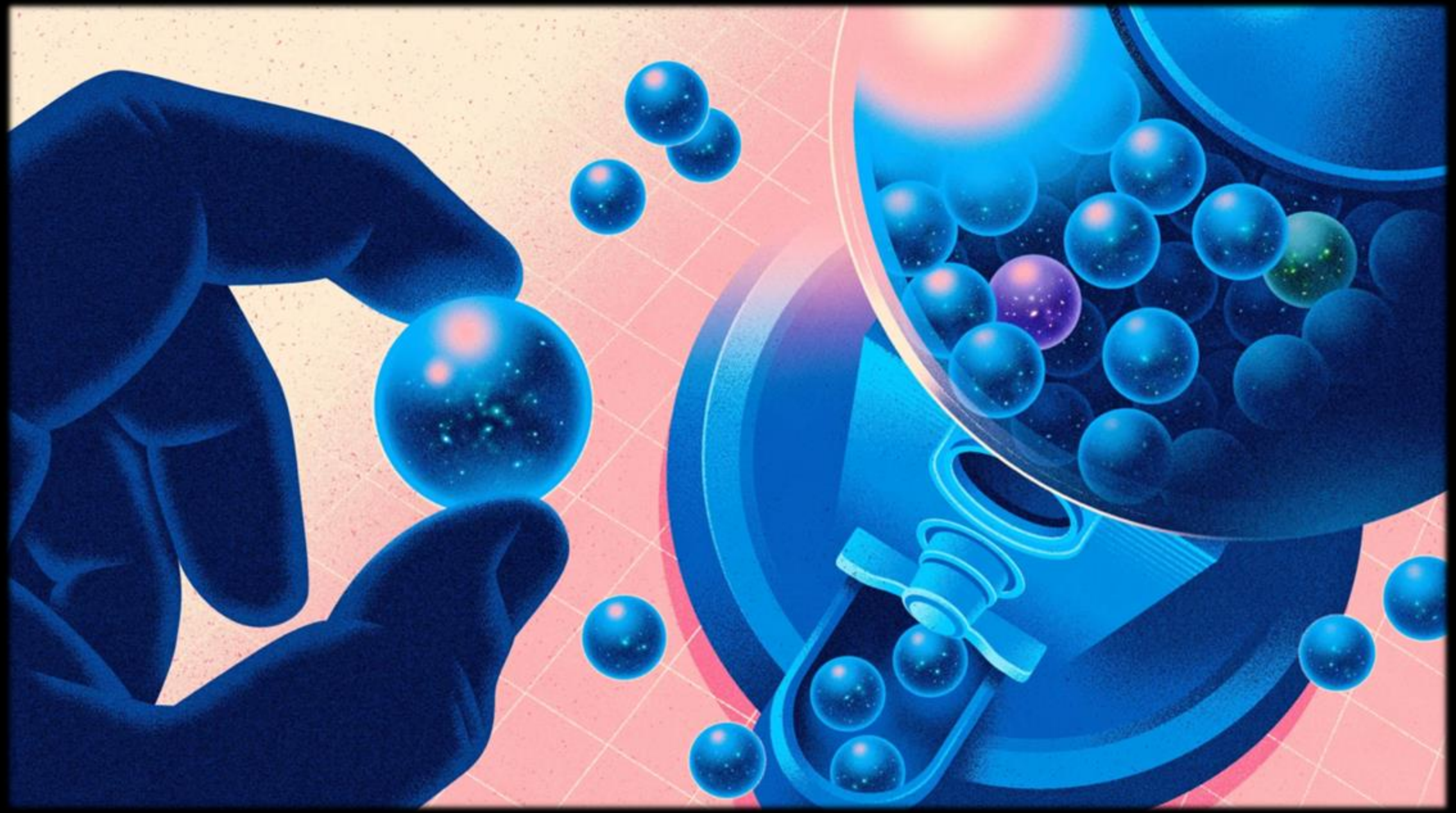
(imaginary time period) (action calculated over one period)

We recently calculated the gravitational entropy for realistic cosmologies with CPT-symmetric bc's, providing a quantitative "measure" on cosmologies.

It turns out to be greatest for

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

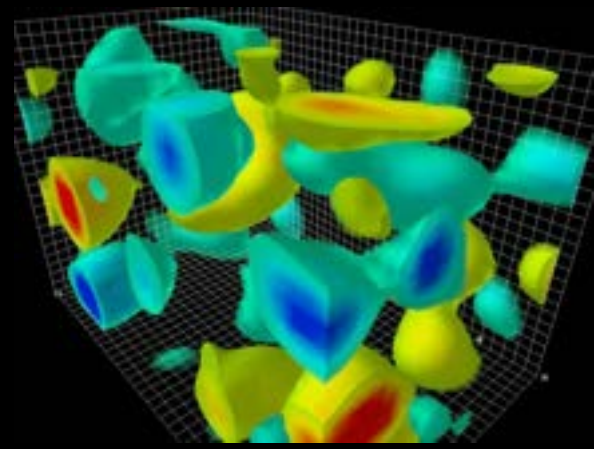
A thermodynamic explanation of the basic features of the large-scale cosmos.



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

What about the density fluctuations?

Quantum fields in curved spacetime



QCD vacuum

Vacuum “zero point” energy density and pressure are a puzzle

Gravity “sees” their infinite gravity: can subtract some but not all of these effects via “renormalization”

The infinities spoil a basic symmetry of Maxwell and massless Dirac fields, Invariance under a local rescaling of space and time

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

The “trace anomalies” *cannot* be renormalized away.

dimension zero scalars

A *four*-derivative, locally scale-invariant action Boyle+NT

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

Such fields have scale-invariant fluctuations in their vacuum

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

Just like the gravitational potential fluctuations observed in cosmology

Dimension zero fields cancel the anomalies in SM!

L. Boyle+NT
2110.06258 [hep-th]

number of dim one scalars | chiral fermions | gauge bosons | dim zero 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 (Weyl^2) $\propto n_{s,1} + 3\, n_F + 12\, n_A - 8\, n_{s,0}$

1) Vanishing of all three implies $n_{s,1} = 0$
the Higgs must be composite: opportunity to explain the gauge-gravity hierarchy
2) Any two equations then give $n_F = 4n_A$; for $SU3 \times SU2 \times U1$, $n_A = 12$
Hence, *we predict* n_F =48, *i.e., 3 fermion generations each including a RH* ν
3) $n_{s,0} = 3n_A = 36$ suggests a new symmetry linking gravity and particle physics

Density perturbations

density perturbations

Under some technical assumptions, we find a power spectrum

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

(SM gauge couplings extrapolated to the Planck scale)

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

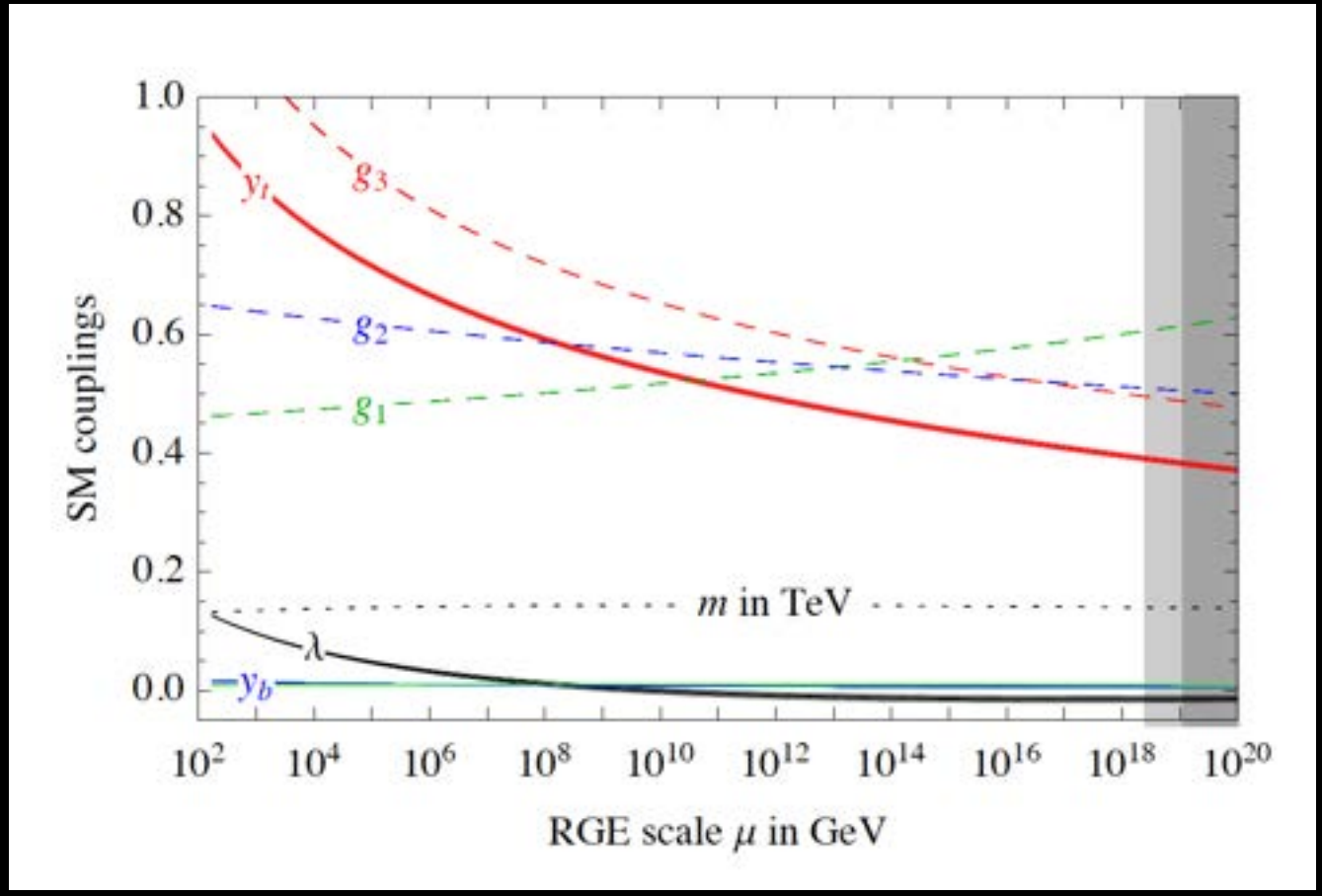
Thus, we predict $\mathcal{P}_{\mathcal{R}} = A\left(\frac{k}{k_*}\right)^{n_s-1}$, $A = (13 \pm 5) \times 10^{-10}$; $n_s = 0.958$

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

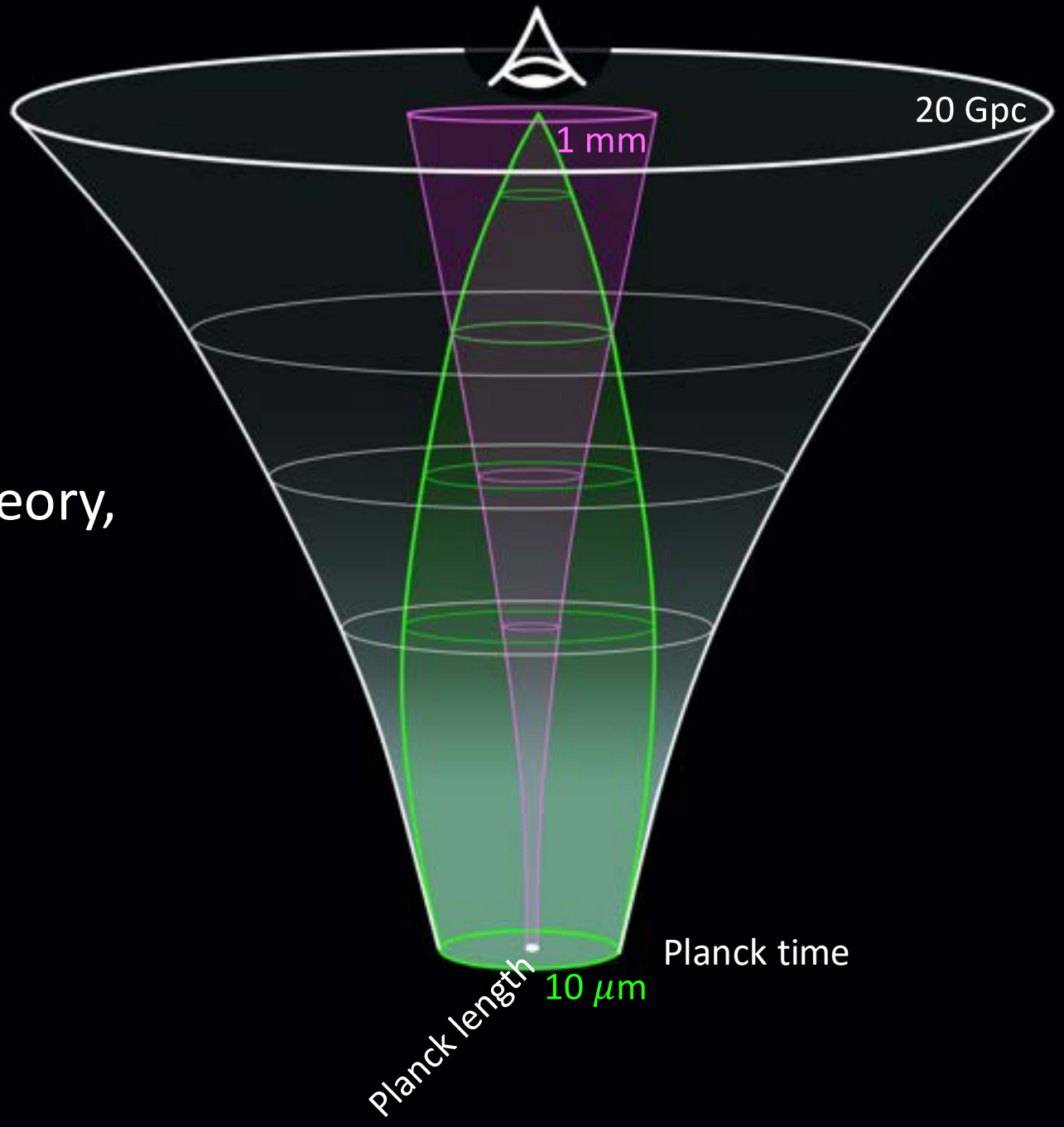
Red tilt

Dominated by QCD: asymptotic freedom/infrared slavery

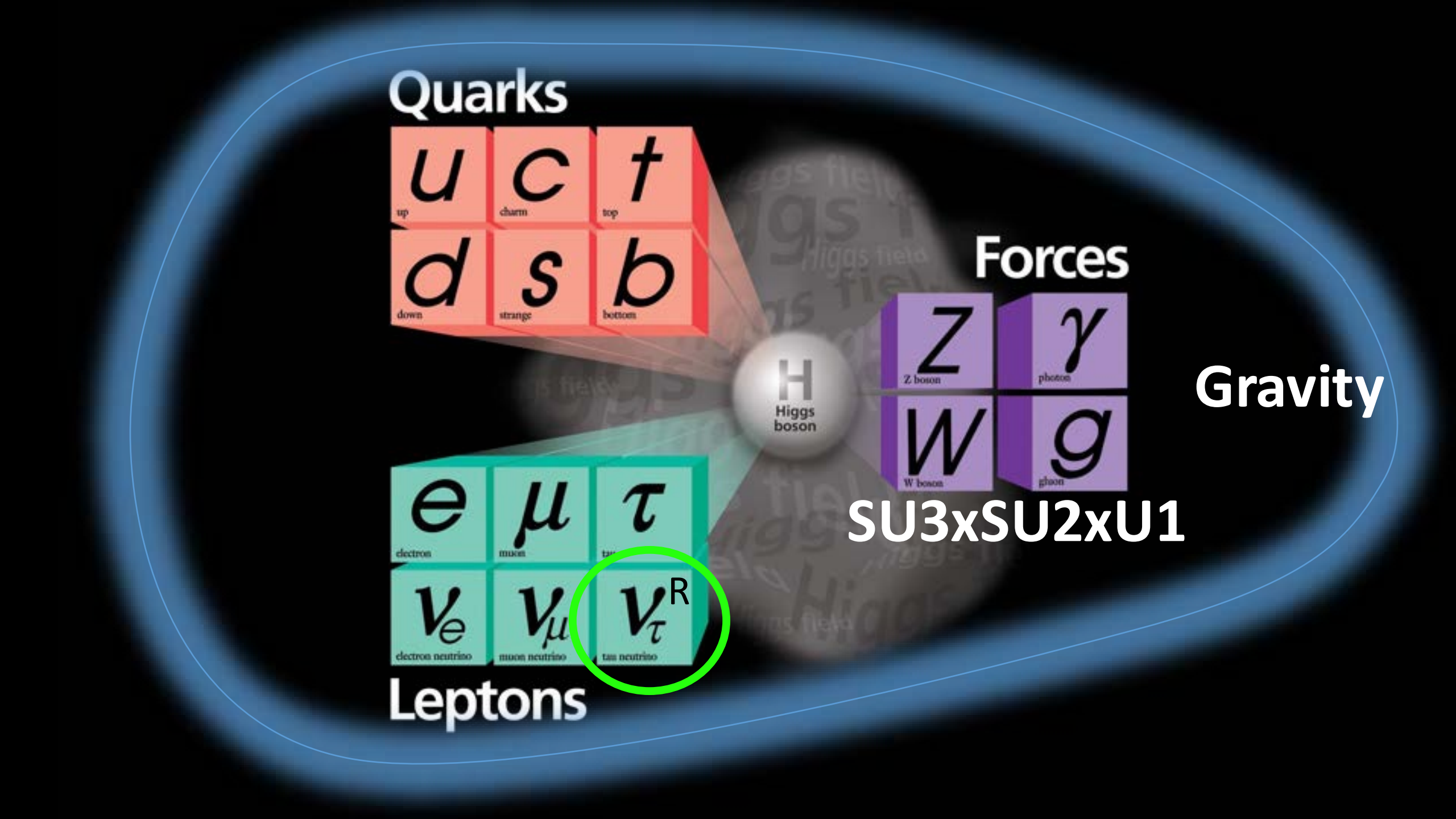
Buttazzo et al
1307.3536
[hep-ph]



Potentially an extremely predictive theory, connecting the smallest and largest observable scales in the universe.

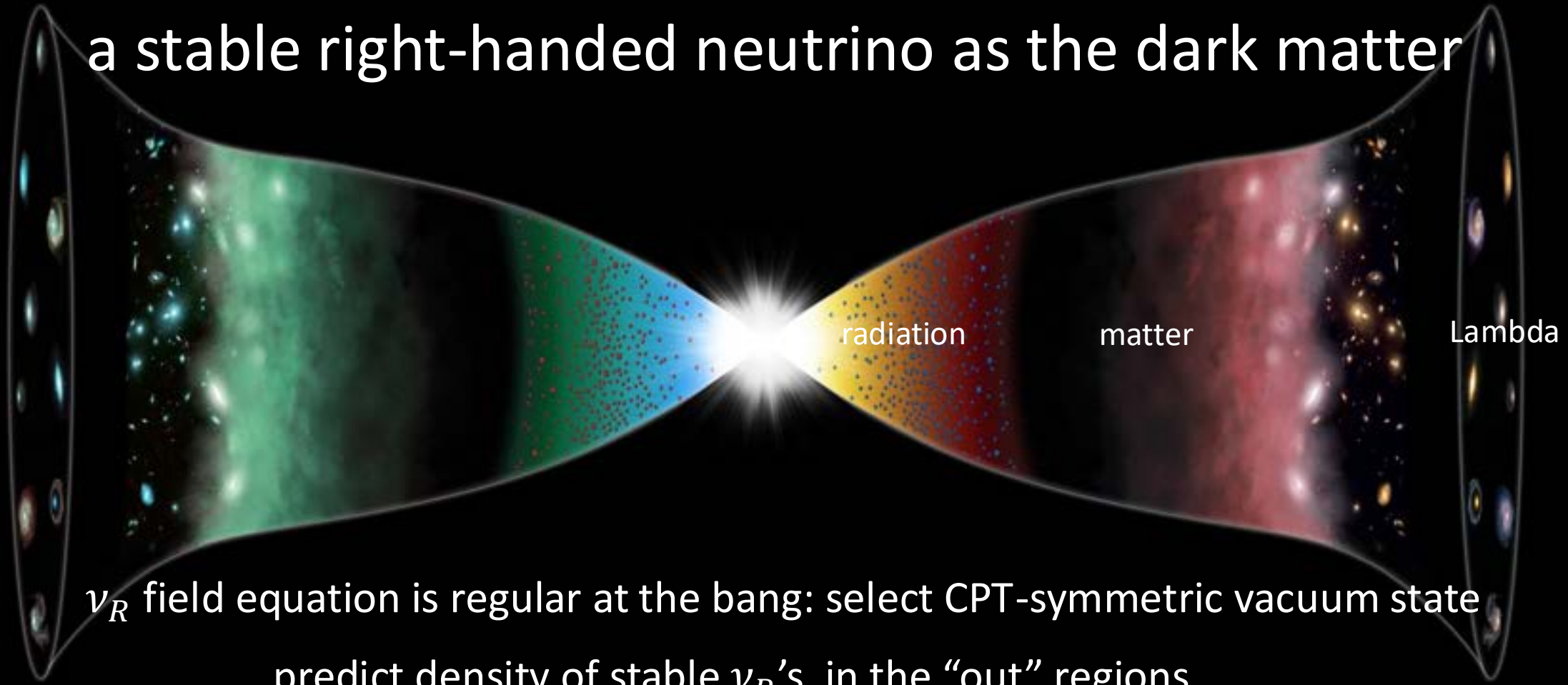


Dark matter


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

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

a stable right-handed neutrino as the dark matter

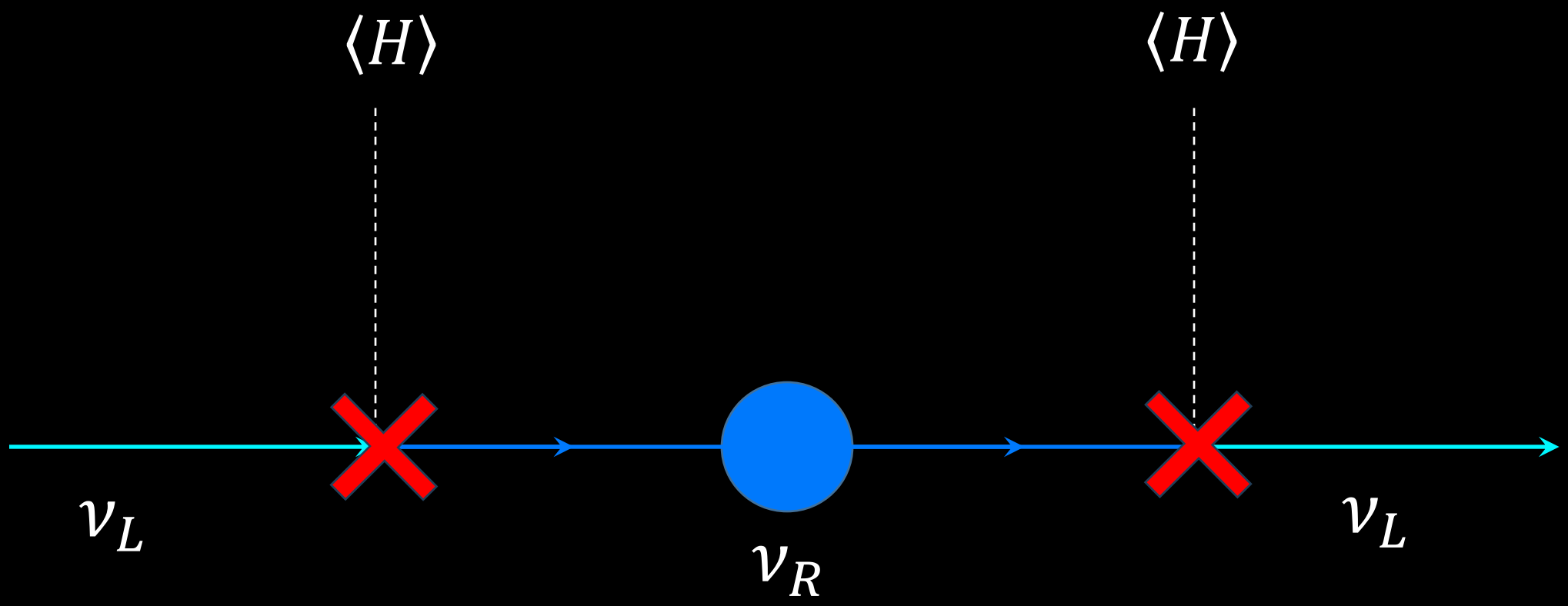


ν_R field equation is regular at the bang: select CPT-symmetric vacuum state

predict density of stable ν_R's in the "out" regions

if one ν_R is stable, its density matches Ω_{DM} if its mass $M \approx 5 \times 10^8 GeV$

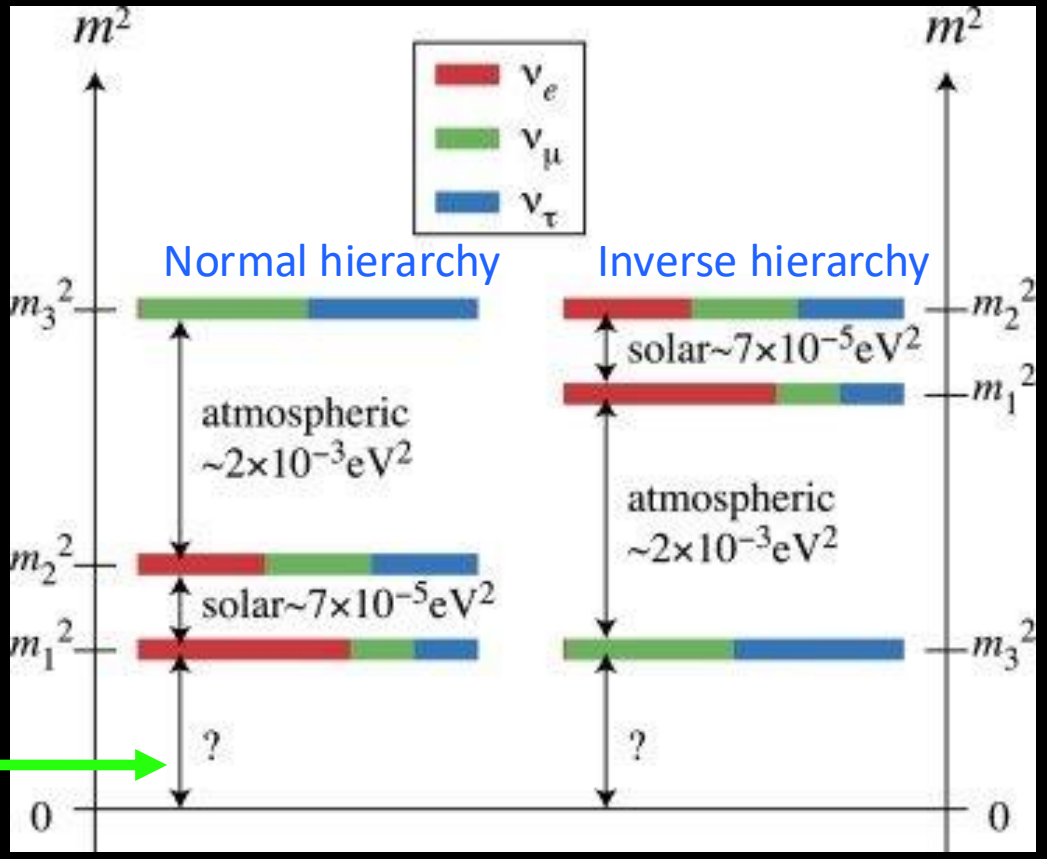
$\mathbb{Z}_2$ symm $\Rightarrow$ one RH neutrino stable $\Rightarrow$ lightest ν massless



about to be tested using EUCLID, LSST and S4

Light neutrinos: observations

we predict zero



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

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

current data

eBOSS 2007.08991

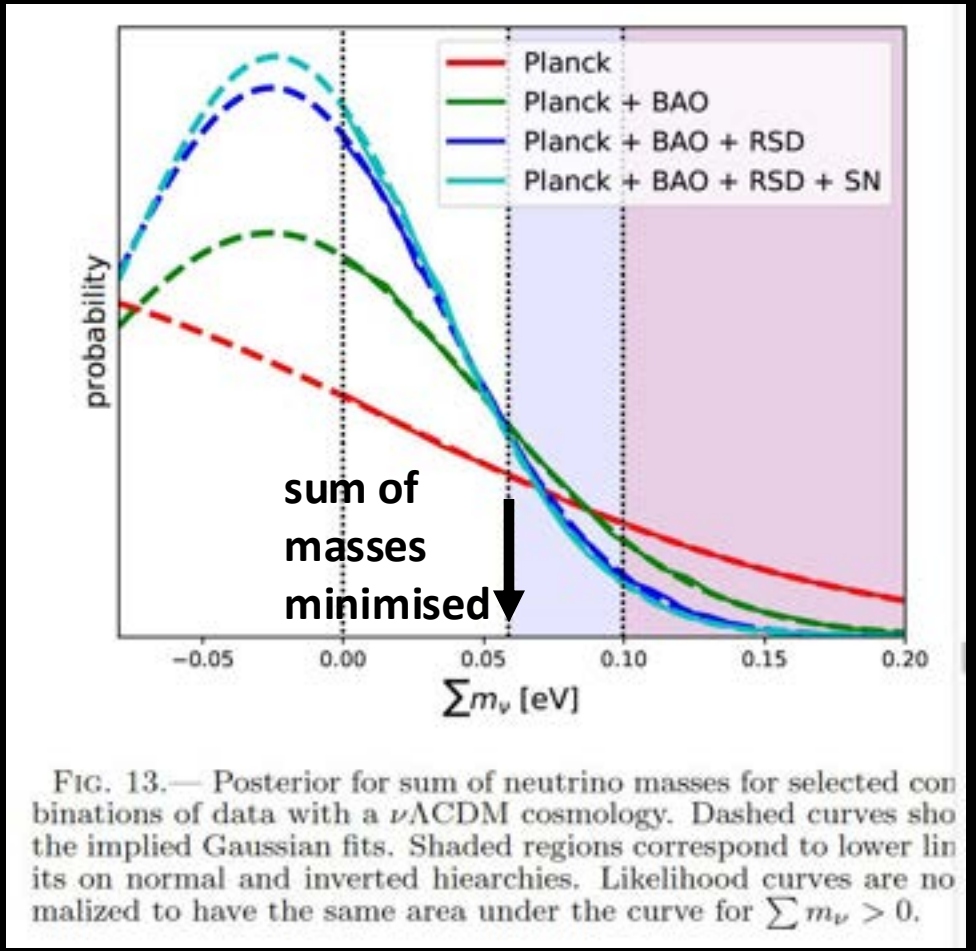


FIG. 13.— Posterior for sum of neutrino masses for selected combinations of data with a $\nu\Lambda$CDM cosmology. Dashed curves show the implied Gaussian fits. Shaded regions correspond to lower limits on normal and inverted hiearchies. Likelihood curves are normalized to have the same area under the curve for $\sum m_\nu > 0$.

Exciting cross-checks coming from terrestrial experiments: JUNO, DUNE, Hyper K etc.

Longer term: ν-less double β decay rate predicted exactly

Summary

- thermodynamic explanation for the observed large scale cosmos
- a new way to cancel the SM's vacuum energy and trace anomalies
- predicts large scale density perturbations consistent with what we see
- predicts 3 generations of fermions, each with a RH neutrino
- the simplest-yet explanation for the cosmic dark matter, testable soon!
- the matter-antimatter asymmetry also explained

this is only the beginning … much remains to be done

“Therefore, the seeker after the truth is not one who studies the writings of the ancients and, following his natural disposition, puts his trust in them, but rather the one who suspects his faith in them and questions what he gathers from them, the one who submits to argument and demonstration, and not to the sayings of a human being whose nature is fraught with all kinds of imperfection and deficiency.

The duty of the man who investigates the writings of scientists, if learning the truth is his goal, is to make himself an enemy of all that he reads, and ... attack it from every side. He should also suspect himself as he performs his critical examination of it, so that he may avoid falling into either prejudice or leniency.”

Ibn Al-Haytham

Thank you: with prayers for the future