

# Parallel Universes

The background of the slide is a dark, almost black space filled with numerous glowing, translucent spheres of various sizes and colors. The colors range from deep purples and blues to vibrant greens and pinks. Some spheres are larger and more prominent, while others are smaller and more numerous, creating a sense of depth and a vast field of potential universes. The spheres have a soft, ethereal glow and some internal patterns, suggesting they might represent different universes or states of matter.

**Max Tegmark**  
**MIT**

HEARING COLORS, TASTING SHAPES • ICEMAN REVISITED

# SCIENTIFIC AMERICAN

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Infinite Earths in

## PARALLEL UNIVERSES

Really Exist

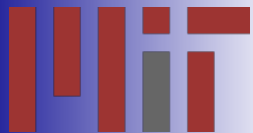
Orphan Drugs:  
Too Successful?

Keys to Robust Networks

Smallpox Defense  
Readiness

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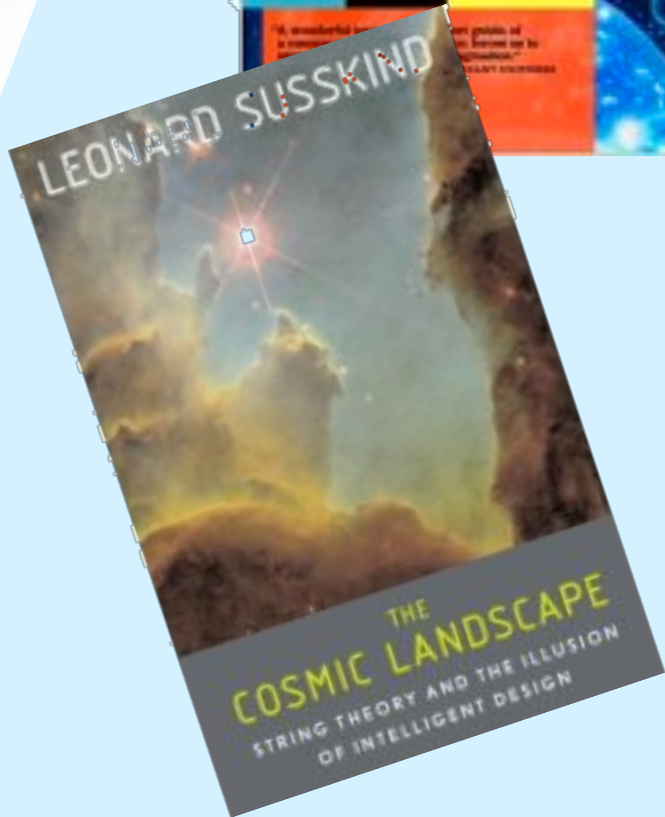
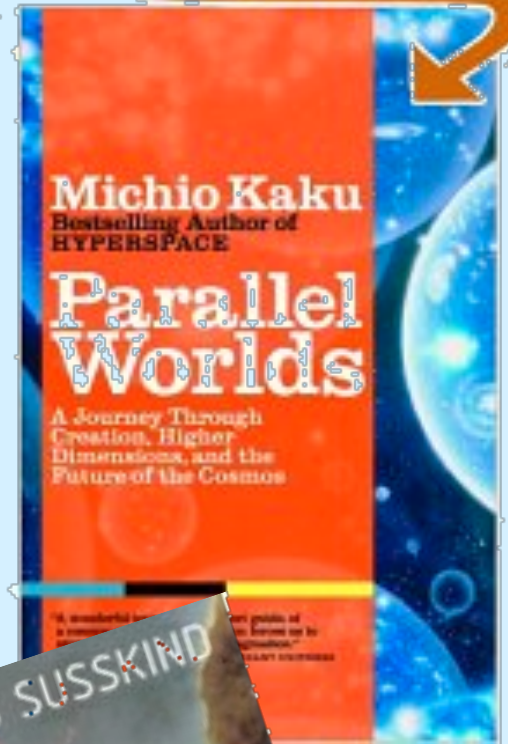
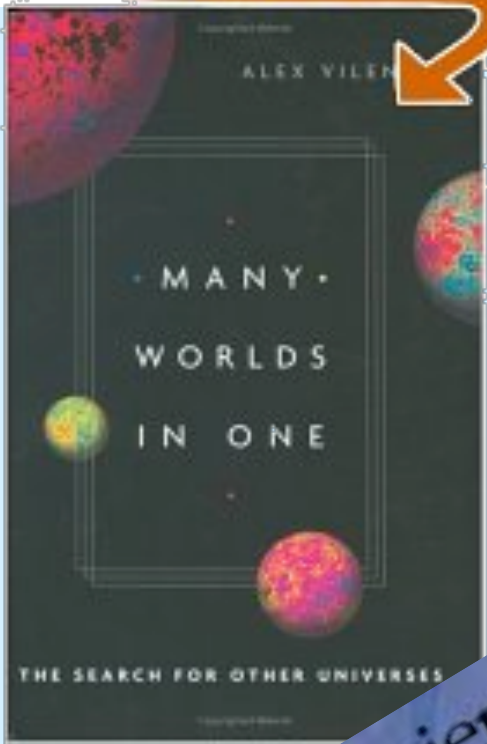
\$4.95 U.S./\$6.50 CAN



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May 31, 2010

SEARCH INSIDE!™

SEARCH INSIDE!™



A large conference room with rows of chairs and a speaker at a table. The room has a patterned carpet and a large chandelier. A speaker is standing at a table with a laptop, and several people are seated in the audience. A thought bubble is overlaid on the image.

**This isn't science!**

A close-up portrait of a man with grey hair, wearing a dark jacket over a light blue shirt. He has a serious expression. A thought bubble is overlaid on the image.

**It's inevitable**



**Makes sense!**

**Why not?**

**I hate it!**

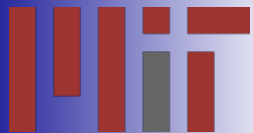
**Party on!**



Q: Is there more that exists than we can see?



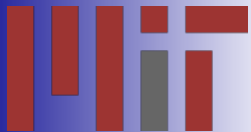
Cosmology suggests yes!



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## Outline:

- The most interesting question isn't whether parallel universes exist, but whether the multiverse has 1, 2, 3 or 4 levels
- Evidence for parallel universes
- Reasons to like/dislike multiverses

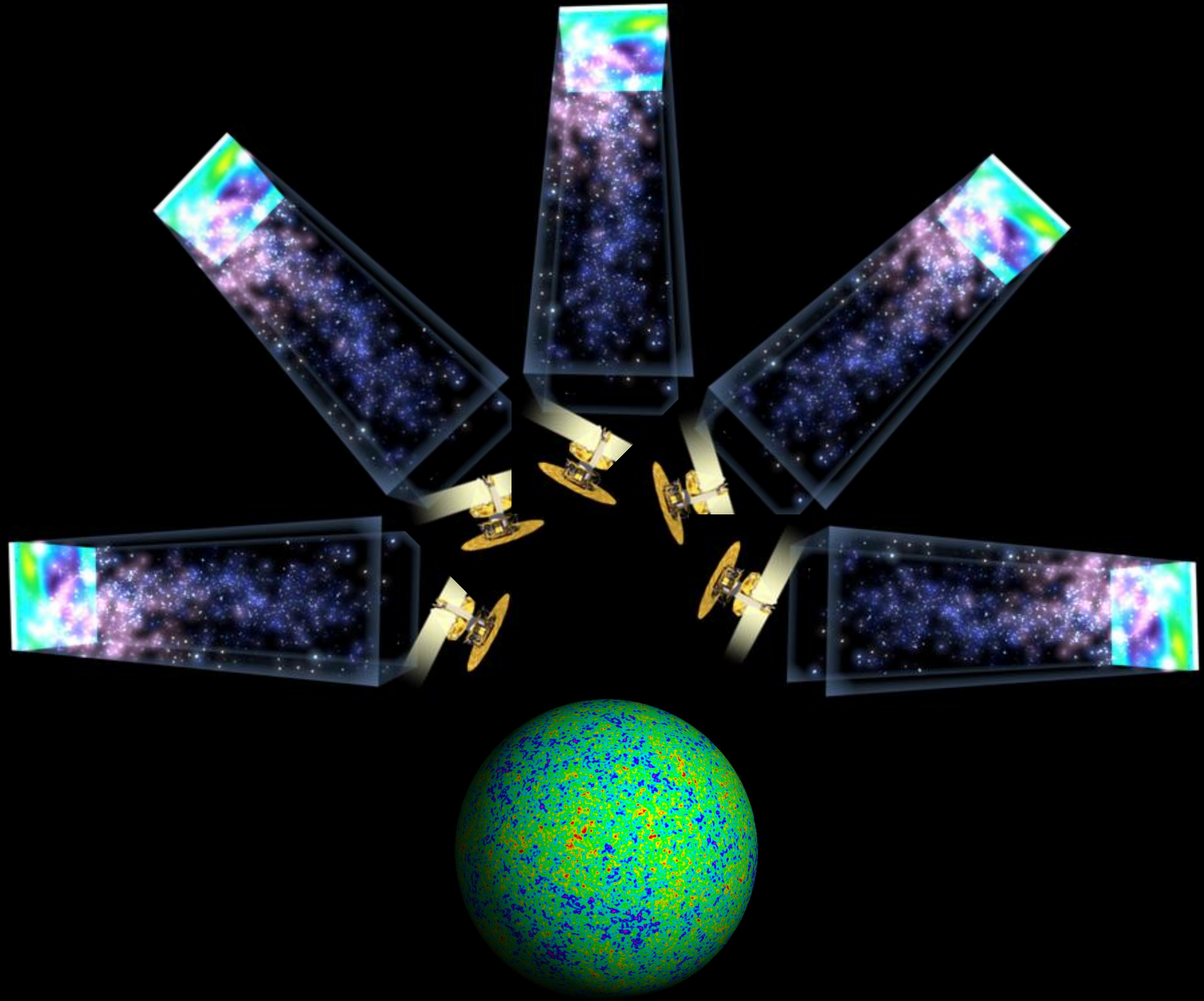


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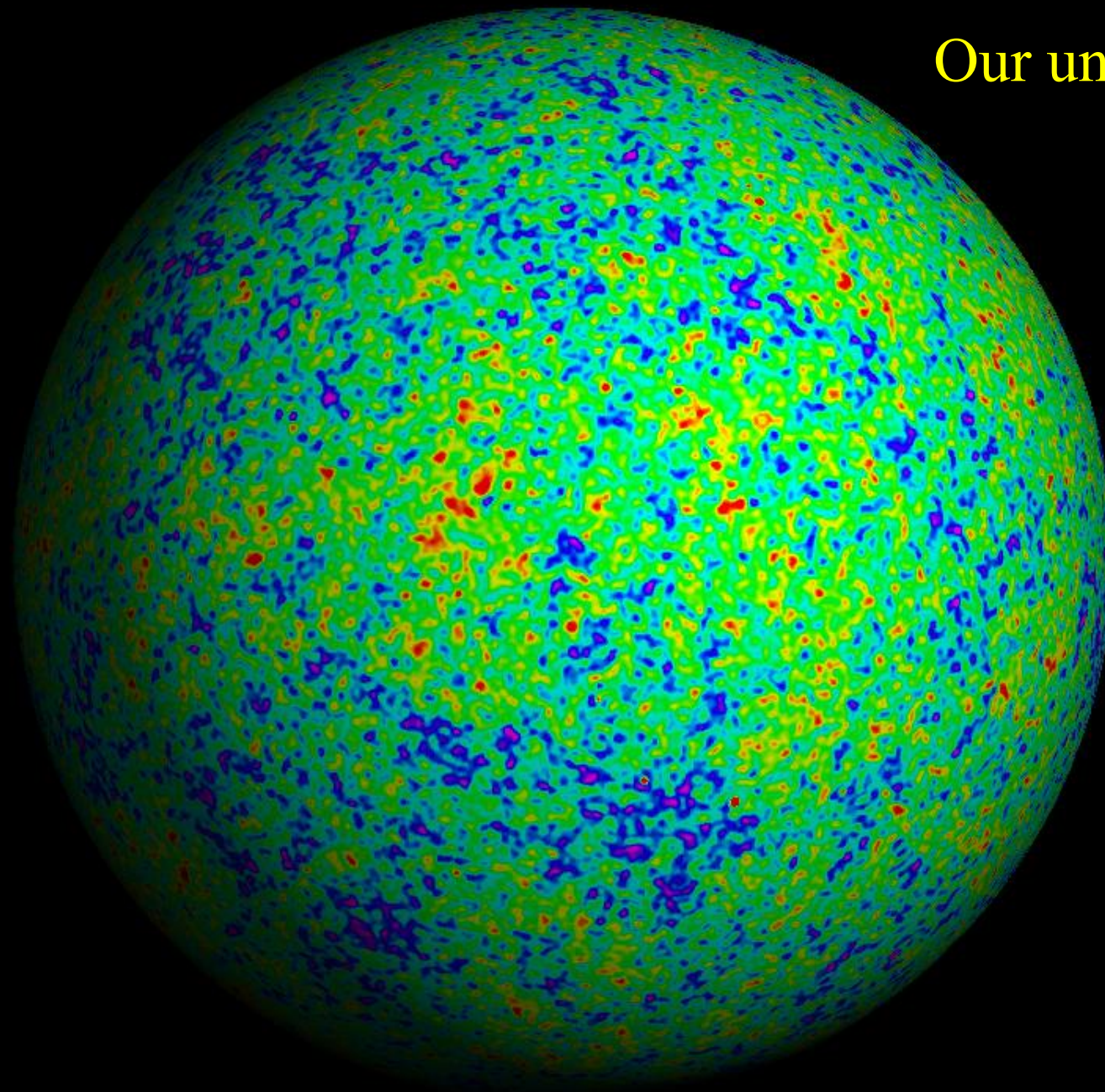
What do we mean  
by *our* universe?

ry



y

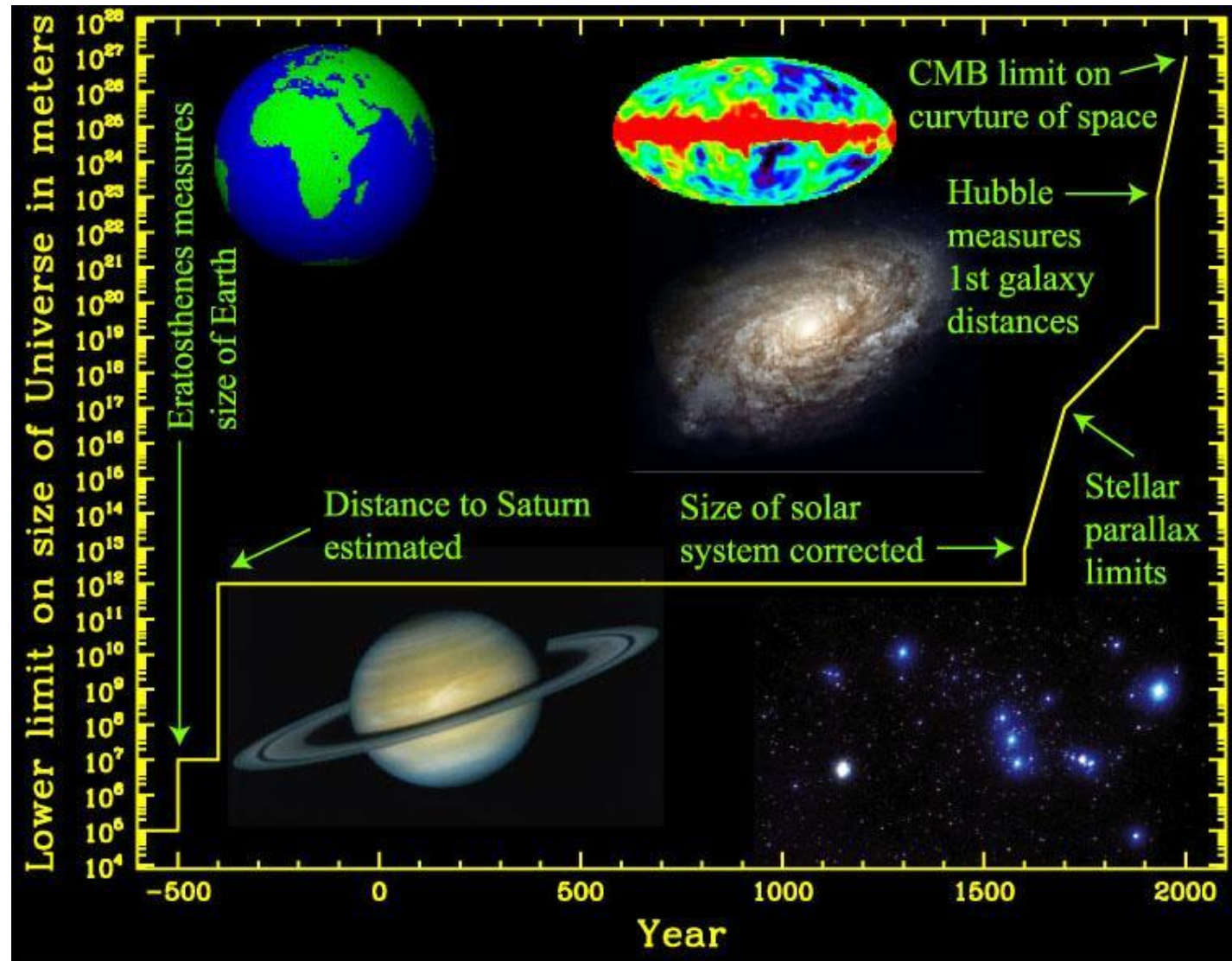
Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496



Our universe

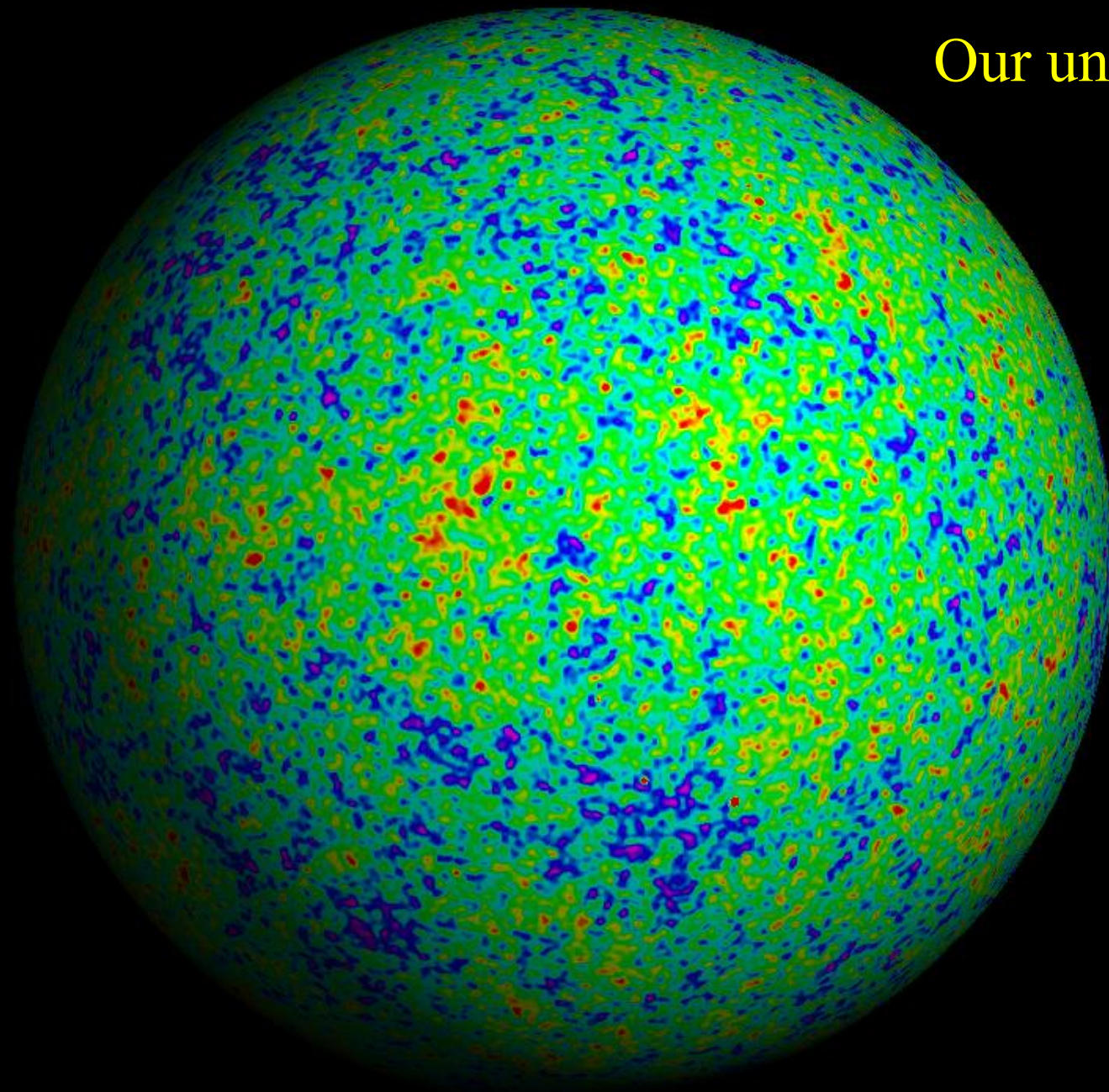
Level I

# How big is our space?



y

Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

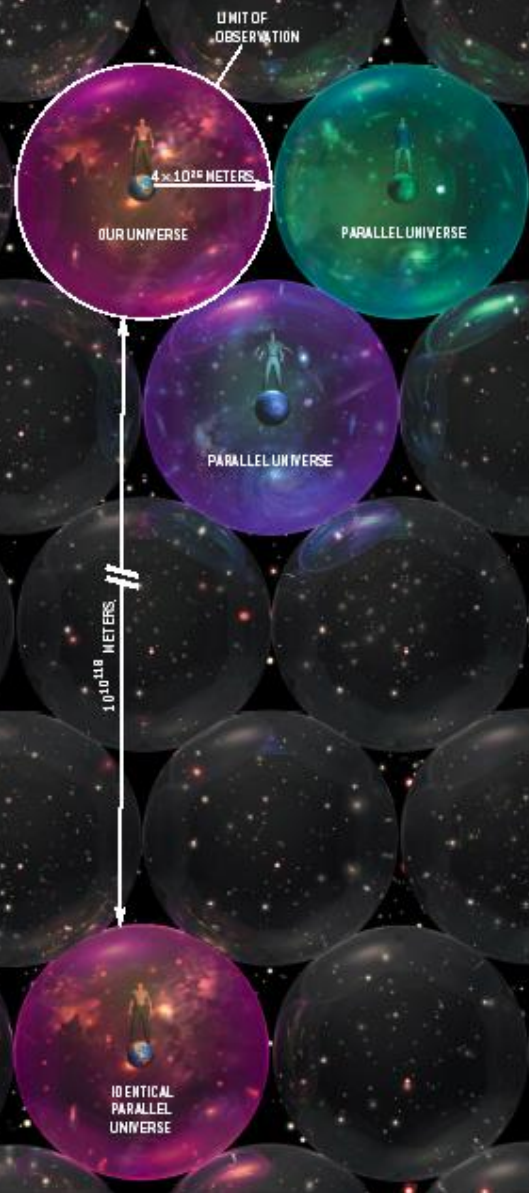


Our universe

# LEVEL I MULTIVERSE

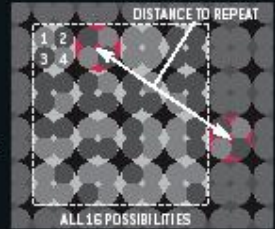
THE SIMPLEST TYPE of parallel universe is simply a region of space that is too far away for us to have seen yet. The farthest that we can observe is currently about  $4 \times 10^{26}$  meters, or 42 billion light-years—the distance that light has been able to travel since the big

bang began. (The distance is greater than 14 billion light-years because cosmic expansion has lengthened distances.) Each of the Level I parallel universes is basically the same as ours. All the differences stem from variations in the initial arrangement of matter.



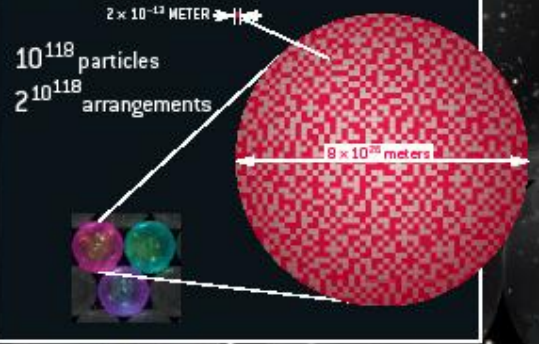
## How Far Away is a Duplicate Universe?

**EXAMPLE UNIVERSE**  
Imagine a two-dimensional universe with space for four particles. Such a universe has  $2^4$ , or 16, possible arrangements of matter. If more than 16 of these universes exist, they must begin to repeat. In this example, the distance to the nearest duplicate is roughly four times the diameter of each universe.



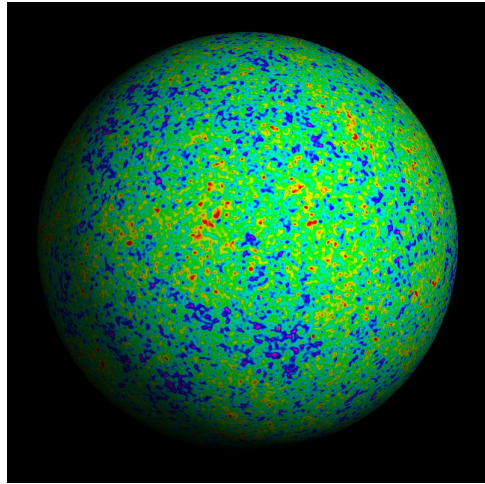
4 particles  
 $2^4$  arrangements

**OUR UNIVERSE**  
The same argument applies to our universe, which has space for about  $10^{118}$  subatomic particles. The number of possible arrangements is therefore 2 to the  $10^{118}$ , or approximately 10 to the  $10^{118}$ . Multiplying by the diameter of the universe gives an average distance to the nearest duplicate of 10 to the  $10^{118}$  meters.



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# Multiverse level I: other Hubble volumes beyond our cosmic horizon



Giordano Bruno (executed 1600)  
Ellis & Brundrit 1979, Q.J.R. Astr. Soc. 20, 37  
Garriga & Vilenkin 2001, Phys.Rev. D64, 043511

## Features:

- Same (effective) laws of physics
- Different initial conditions

## For our flat “concordance” cosmological model:

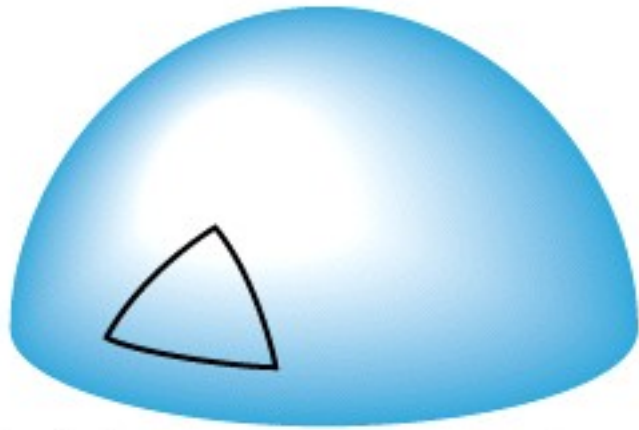
- Size of our Hubble volume  $\sim 10^{26}$ m,
- Closest copy of you  $\sim 10^{10^{29}}$ m
- Closest 100 lightyear bubble like ours  $\sim 10^{10^{91}}$ m
- Closest Hubble volume like ours  $\sim 10^{10^{118}}$ m



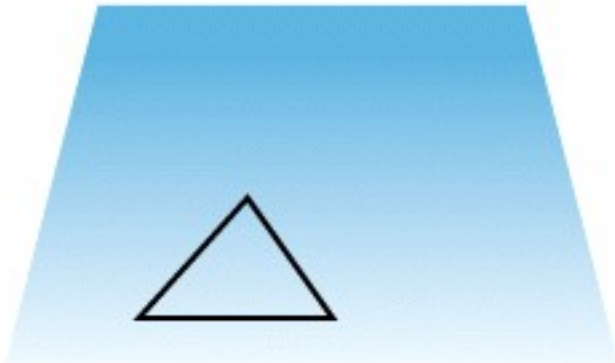
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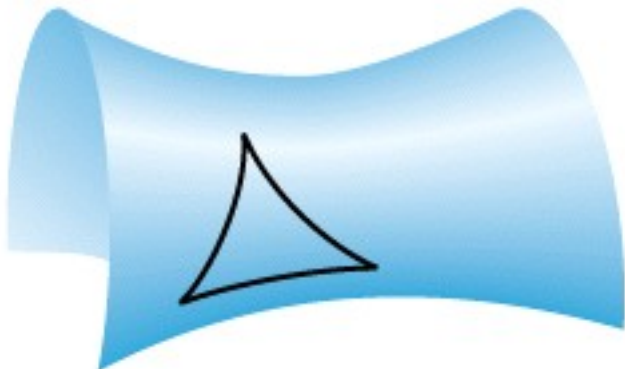
Evidence



a Spherical space  $\rho > \rho_c$



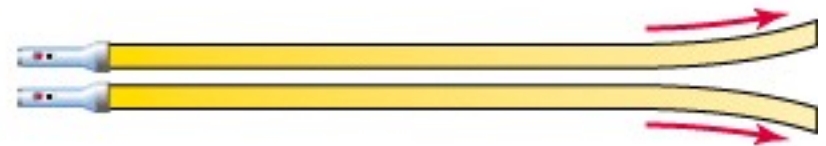
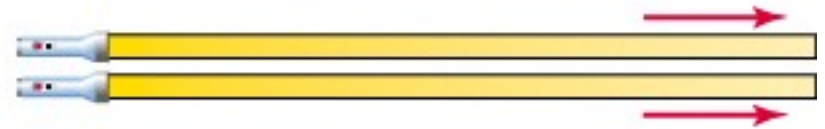
b Flat space  $\rho = \rho_c$



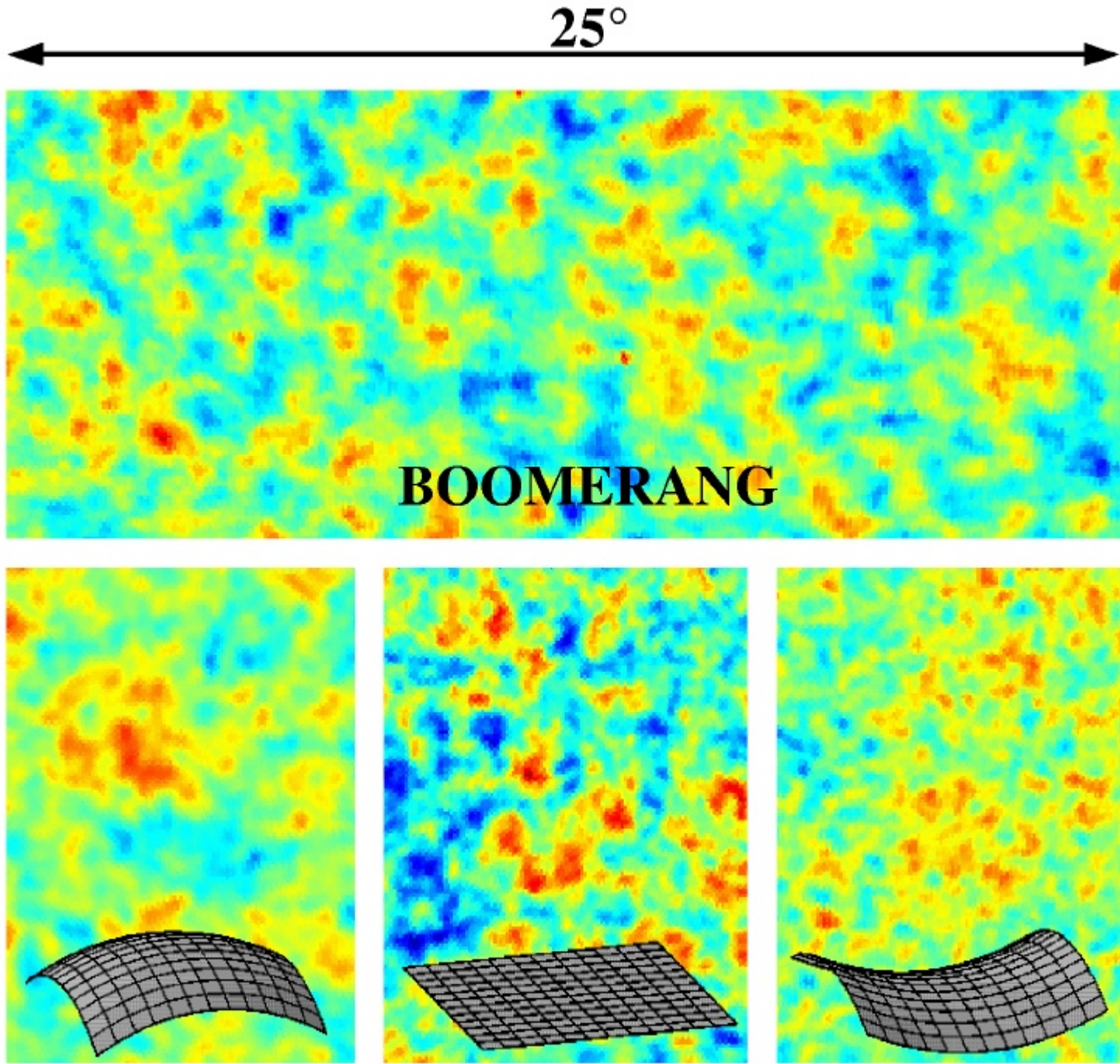
c Hyperbolical space  $\rho < \rho_c$

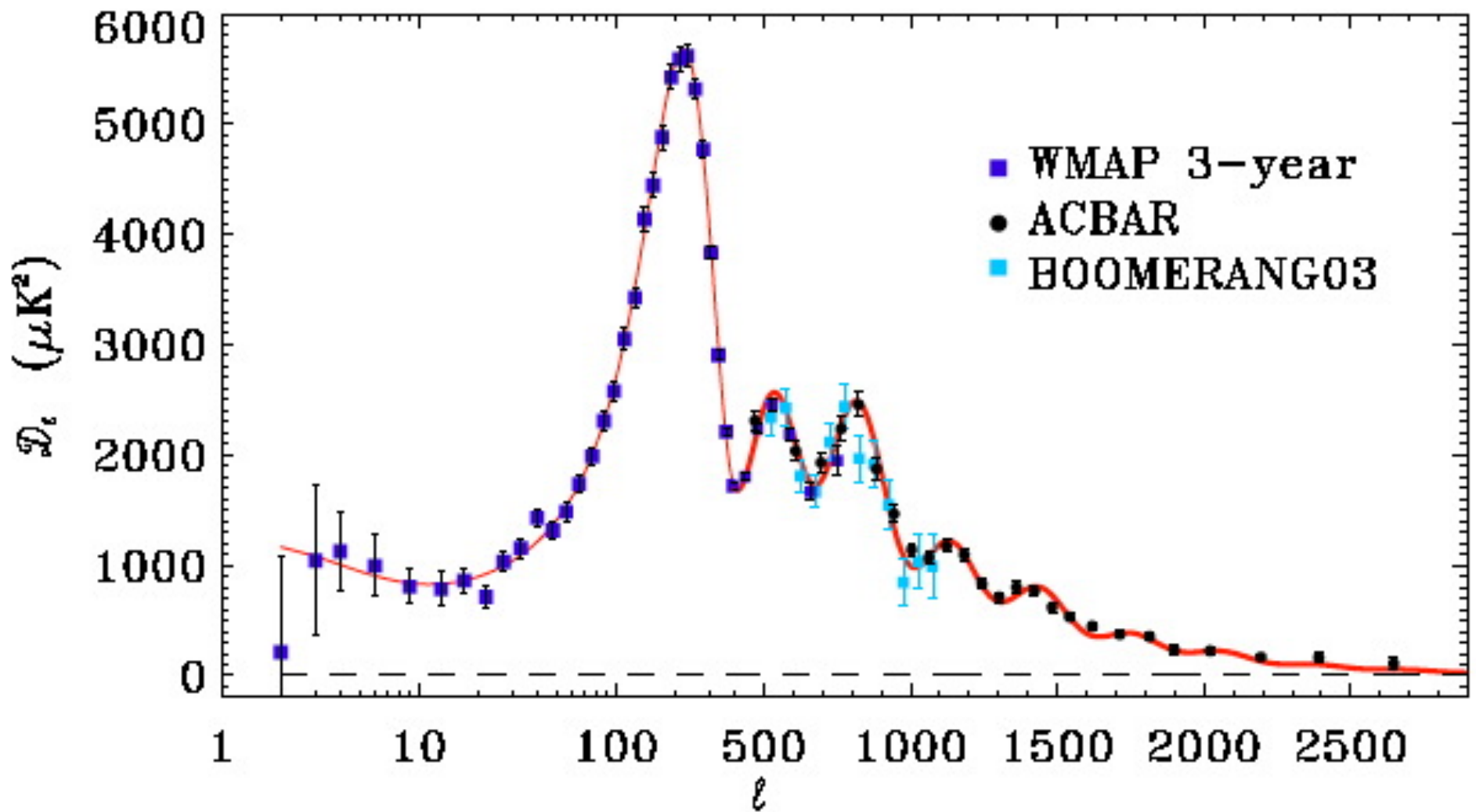


Alan Guth

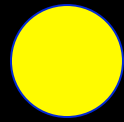


(Figure from Boomerang team)



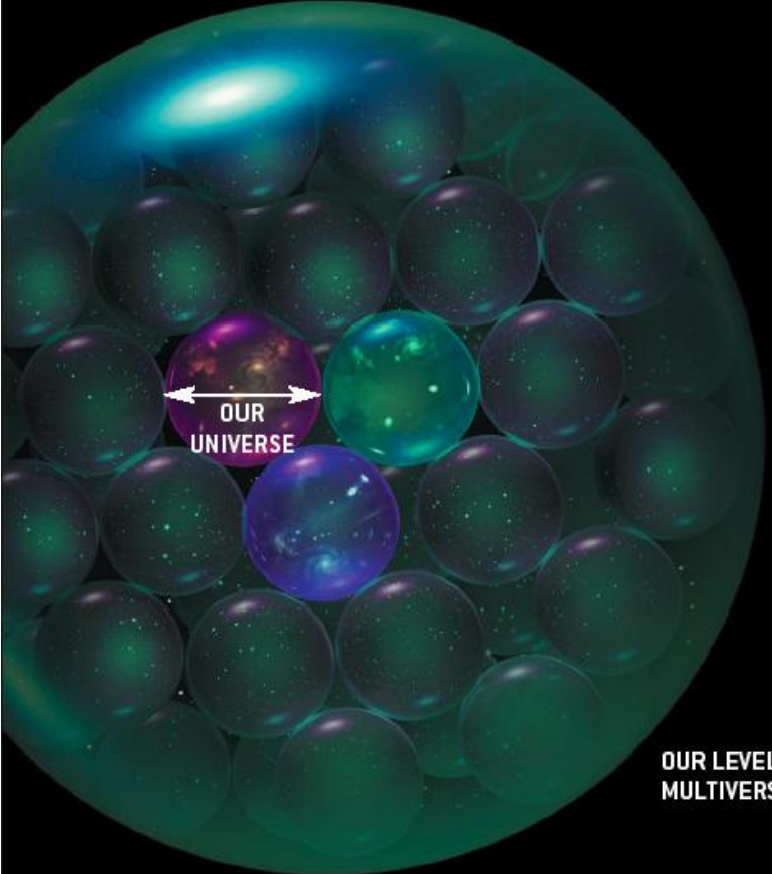


Reichardt et al 2008, arXiv:0801.1491



$\Omega_k$  movie

Level III

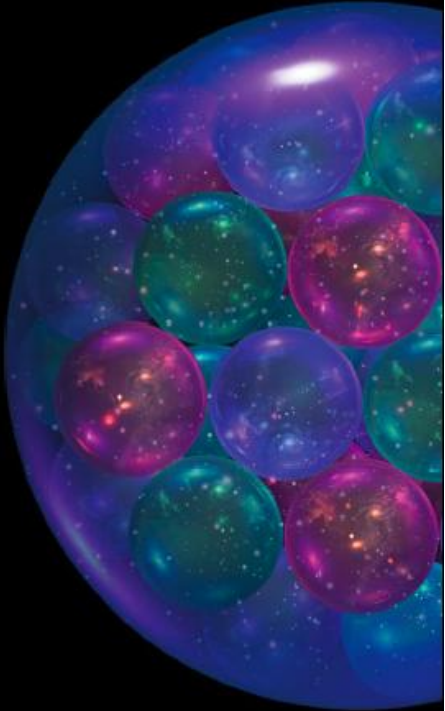


OUR LEVEL I  
MULTIVERSE



PARALLEL  
LEVEL I  
MULTIVERSE

EMPTY  
SPACE  
(INFLATING)



PARALLEL  
LEVEL I  
MULTIVERSE

Why these values?

# Standard model parameters:

Particle physics

Cosmology

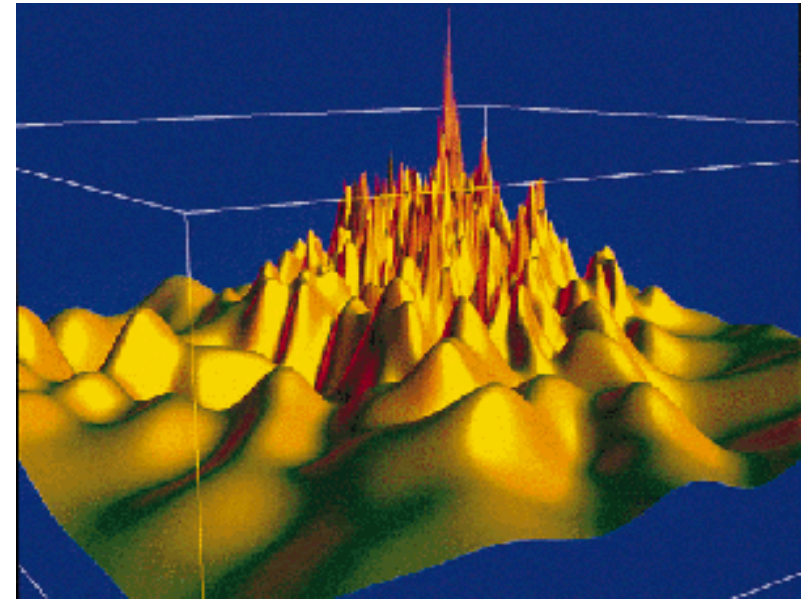
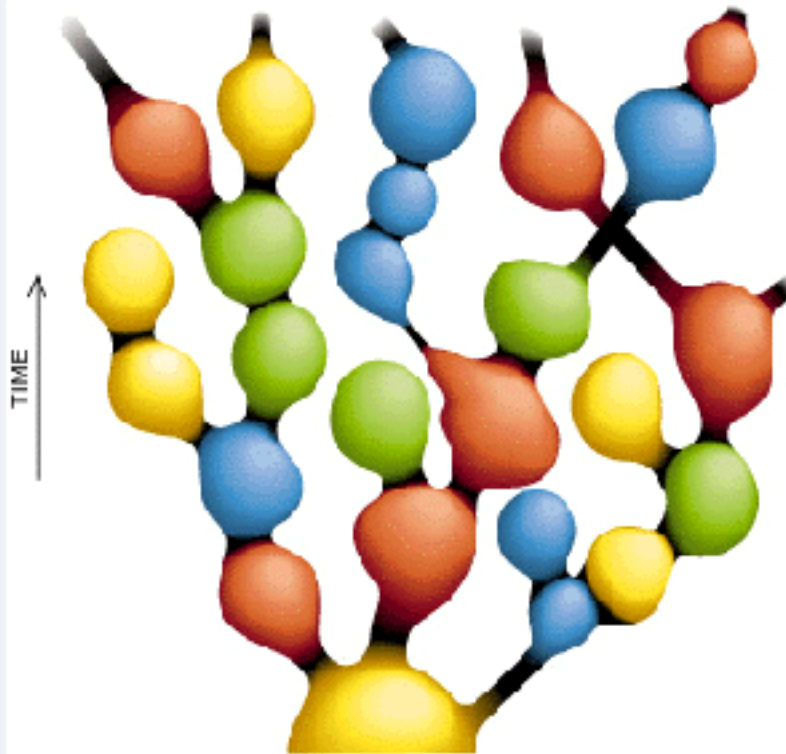
Parameter	Meaning	Measured value
$g$	Weak coupling constant at $m_Z$	$0.6520 \pm 0.0001$
$\theta_W$	Weinberg angle	$0.48290 \pm 0.00005$
$g_s$	Strong coupling constant at $m_Z$	$1.221 \pm 0.022$
$\mu^2$	Quadratic Higgs coefficient	$\sim -10^{-33}$
$\lambda$	Quartic Higgs coefficient	$\sim 1?$
$G_e$	Electron Yukawa coupling	$2.94 \times 10^{-6}$
$G_\mu$	Muon Yukawa coupling	0.000607
$G_\tau$	Tauon Yukawa coupling	0.0102156233
$G_u$	Up quark Yukawa coupling	$0.000016 \pm 0.000007$
$G_d$	Down quark Yukawa coupling	$0.00003 \pm 0.00002$
$G_c$	Charm quark Yukawa coupling	$0.0072 \pm 0.0006$
$G_s$	Strange quark Yukawa coupling	$0.0006 \pm 0.0002$
$G_t$	Top quark Yukawa coupling	$1.002 \pm 0.029$
$G_b$	Bottom quark Yukawa coupling	$0.026 \pm 0.003$
$\sin \theta_{12}$	Quark CKM matrix angle	$0.2243 \pm 0.0016$
$\sin \theta_{23}$	Quark CKM matrix angle	$0.0413 \pm 0.0015$
$\sin \theta_{13}$	Quark CKM matrix angle	$0.0037 \pm 0.0005$
$\delta_{13}$	Quark CKM matrix phase	$1.05 \pm 0.24$
$\theta_{\text{qcd}}$	CP-violating QCD vacuum phase	$< 10^{-9}$
$G_{\nu_e}$	Electron neutrino Yukawa coupling	$< 1.7 \times 10^{-11}$
$G_{\nu_\mu}$	Muon neutrino Yukawa coupling	$< 1.1 \times 10^{-6}$
$G_{\nu_\tau}$	Tau neutrino Yukawa coupling	$< 0.10$
$\sin \theta'_{12}$	Neutrino MNS matrix angle	$0.55 \pm 0.06$
$\sin 2\theta'_{23}$	Neutrino MNS matrix angle	$\geq 0.94$
$\sin \theta'_{13}$	Neutrino MNS matrix angle	$\leq 0.22$
$\delta'_{13}$	Neutrino MNS matrix phase	?
$\rho_\Lambda$	Dark energy density	$(1.25 \pm 0.25) \times 10^{-123}$
$\xi_b$	Baryon mass per photon $\rho_b/n_\gamma$	$(0.50 \pm 0.03) \times 10^{-28}$
$\xi_c$	Cold dark matter mass per photon $\rho_c/n_\gamma$	$(2.5 \pm 0.2) \times 10^{-28}$
$\xi_\nu$	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11} \sum m_{\nu_i}$	$< 0.9 \times 10^{-28}$
$Q$	Scalar fluctuation amplitude $\delta_H$ on horizon	$(2.0 \pm 0.2) \times 10^{-5}$
$n_s$	Scalar spectral index	$0.98 \pm 0.02$
$\alpha_n$	Running of spectral index $dn_s/d \ln k$	$ \alpha  \lesssim 0.01$
$r$	Tensor-to-scalar ratio $(Q_t/Q)^2$	$\lesssim 0.36$

$$C = h = G = k_b = q_e = 1$$

MT,  
 Aguirre,  
 Rees &  
 Wilczek  
 2005



## Multiverse level 2: other post-inflationary regions



(Pics from Andrei Linde)

### Features:

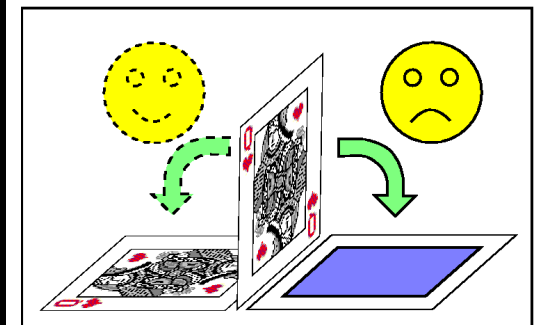
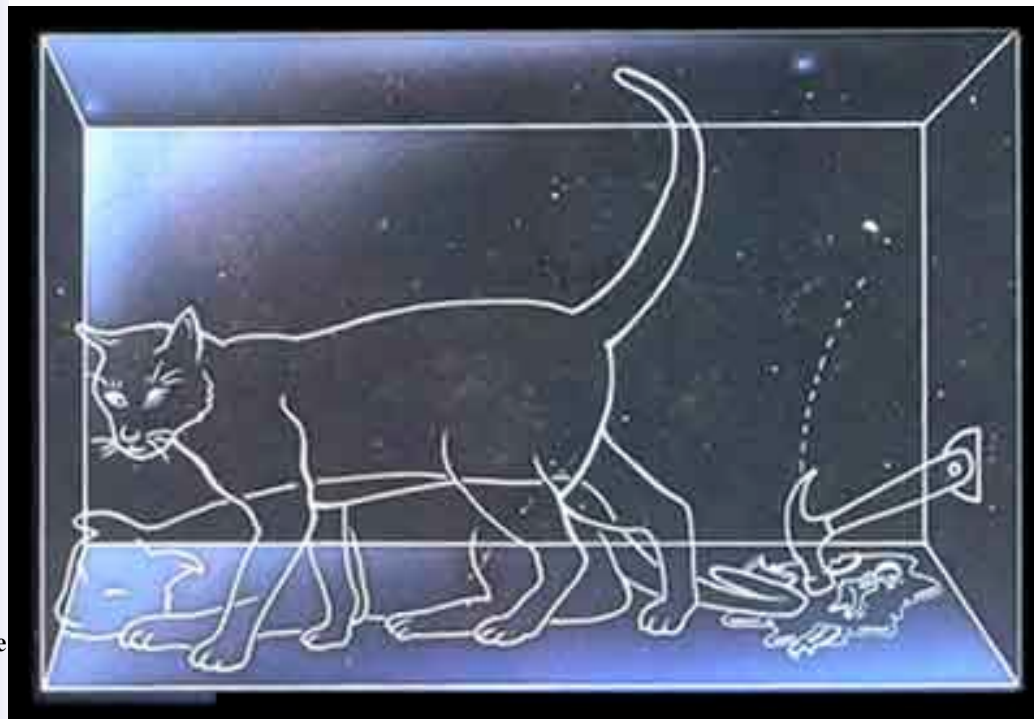
- Perhaps different *effective* laws of physics (physical constants, particles, symmetries, dimensionality)
- Perhaps even uncountably infinite  
(Compare a literally parallel Universe; living on another brane)



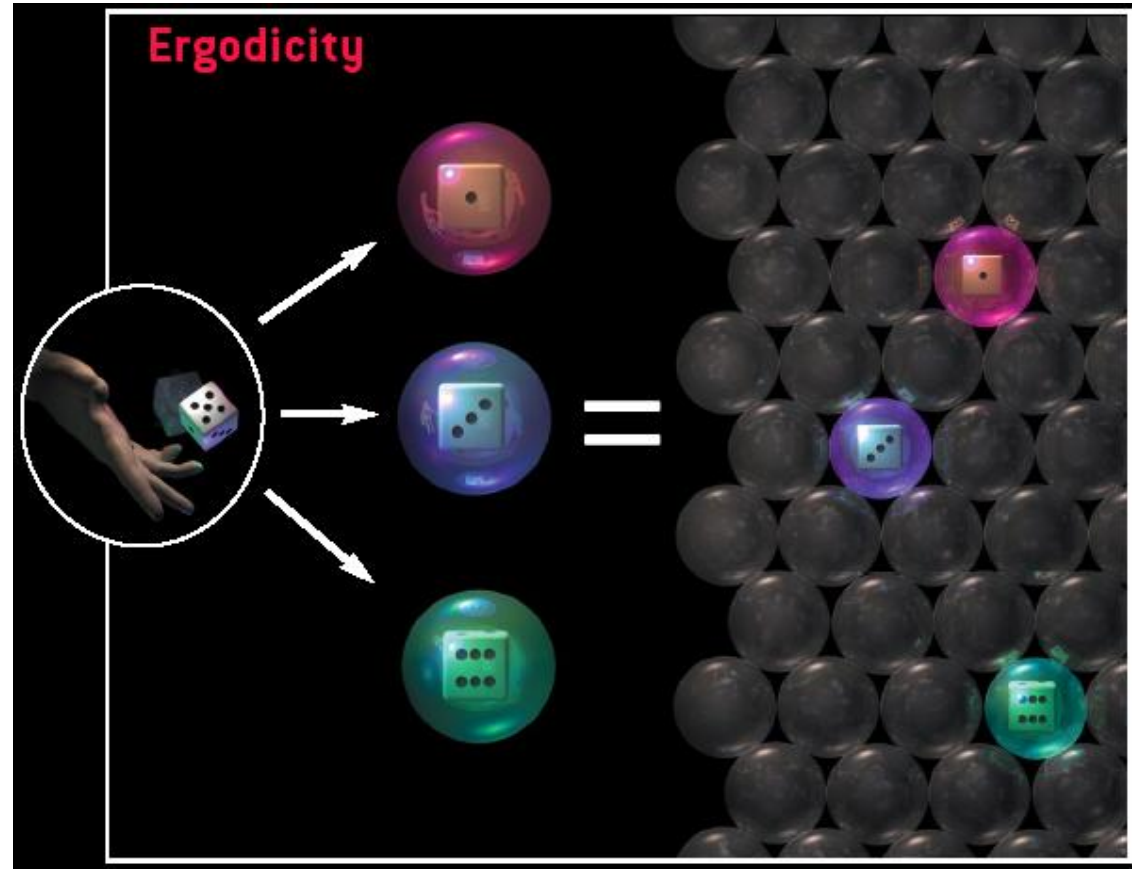
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Level III

# Multiverse level 3: Everett's many worlds

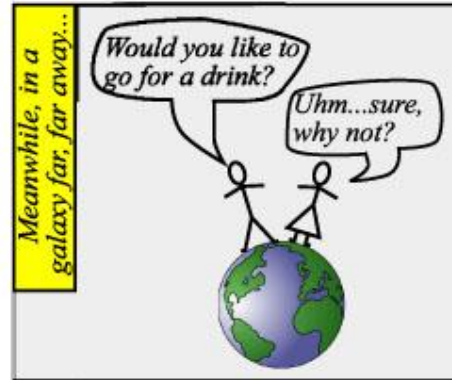
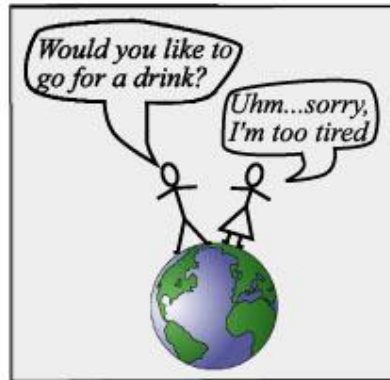


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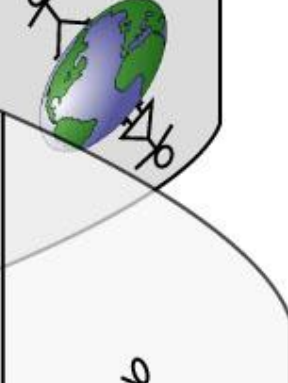
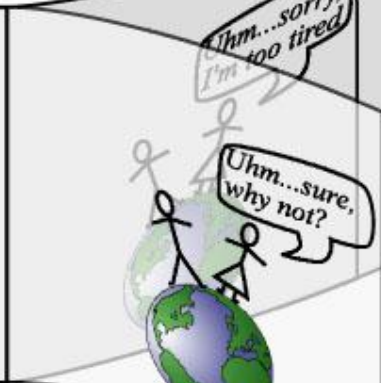
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# LEVEL 1



Meanwhile, in a galaxy far, far away...

# LEVEL 3

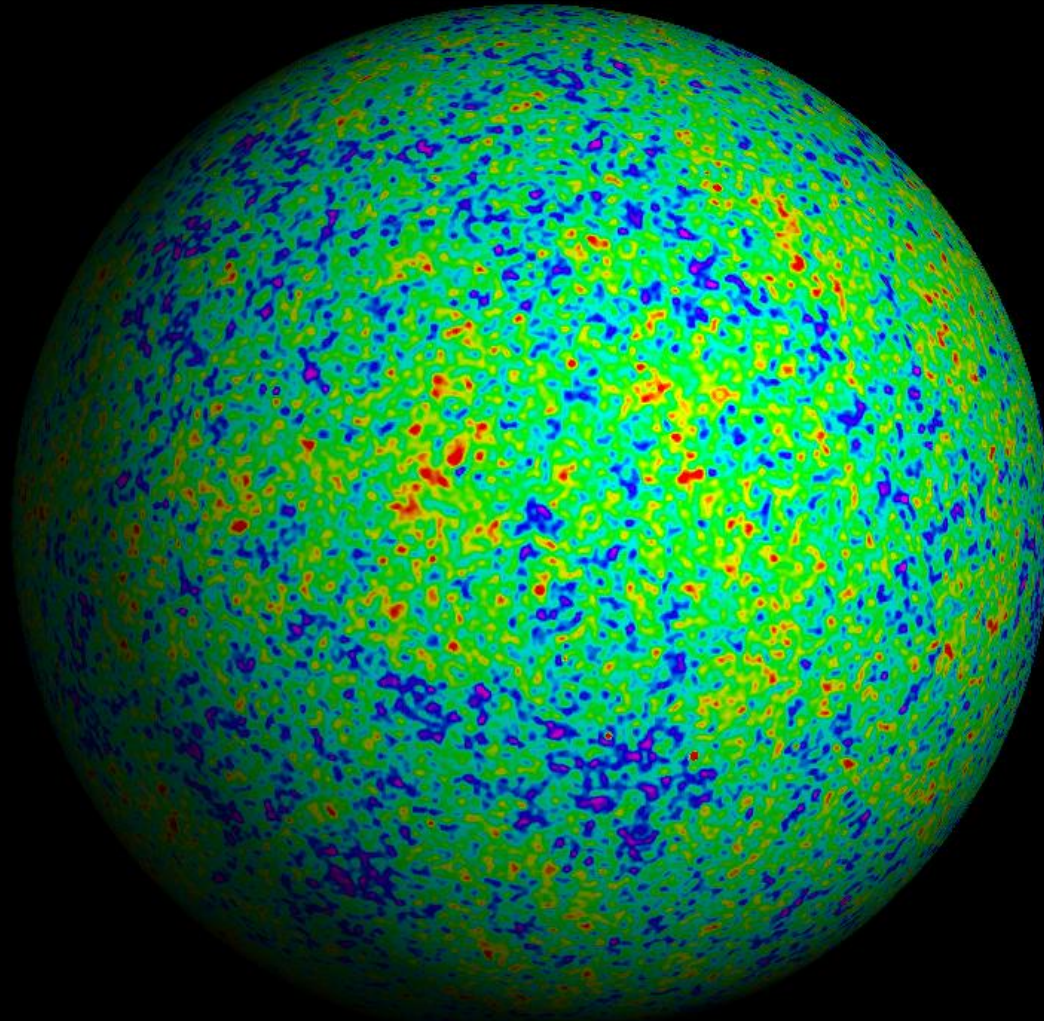


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Level IV

Q: What's the entropy of our universe?

A: About  $10^{89}$  bits



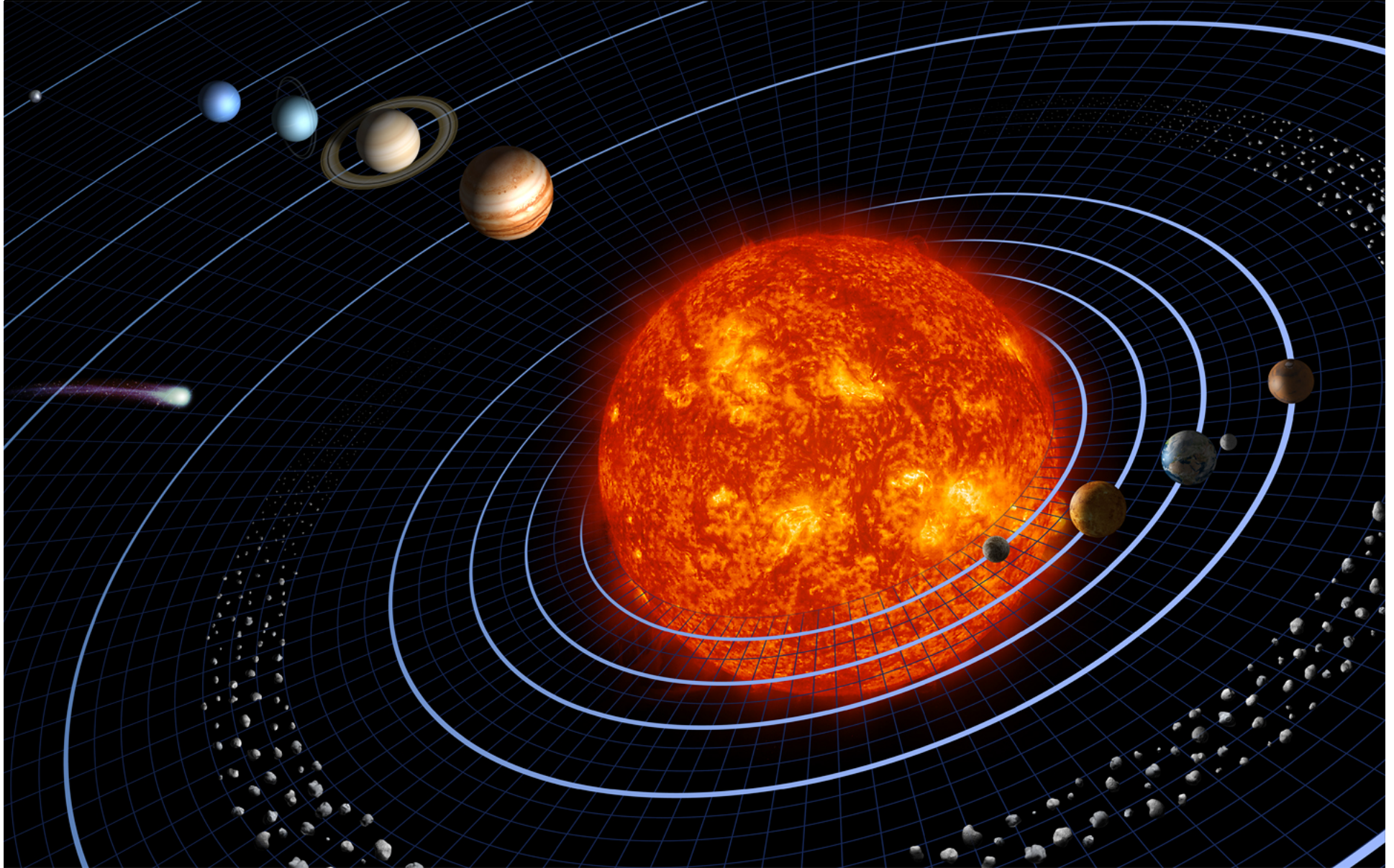
What does all that information really tell us?



$10^3$  bits

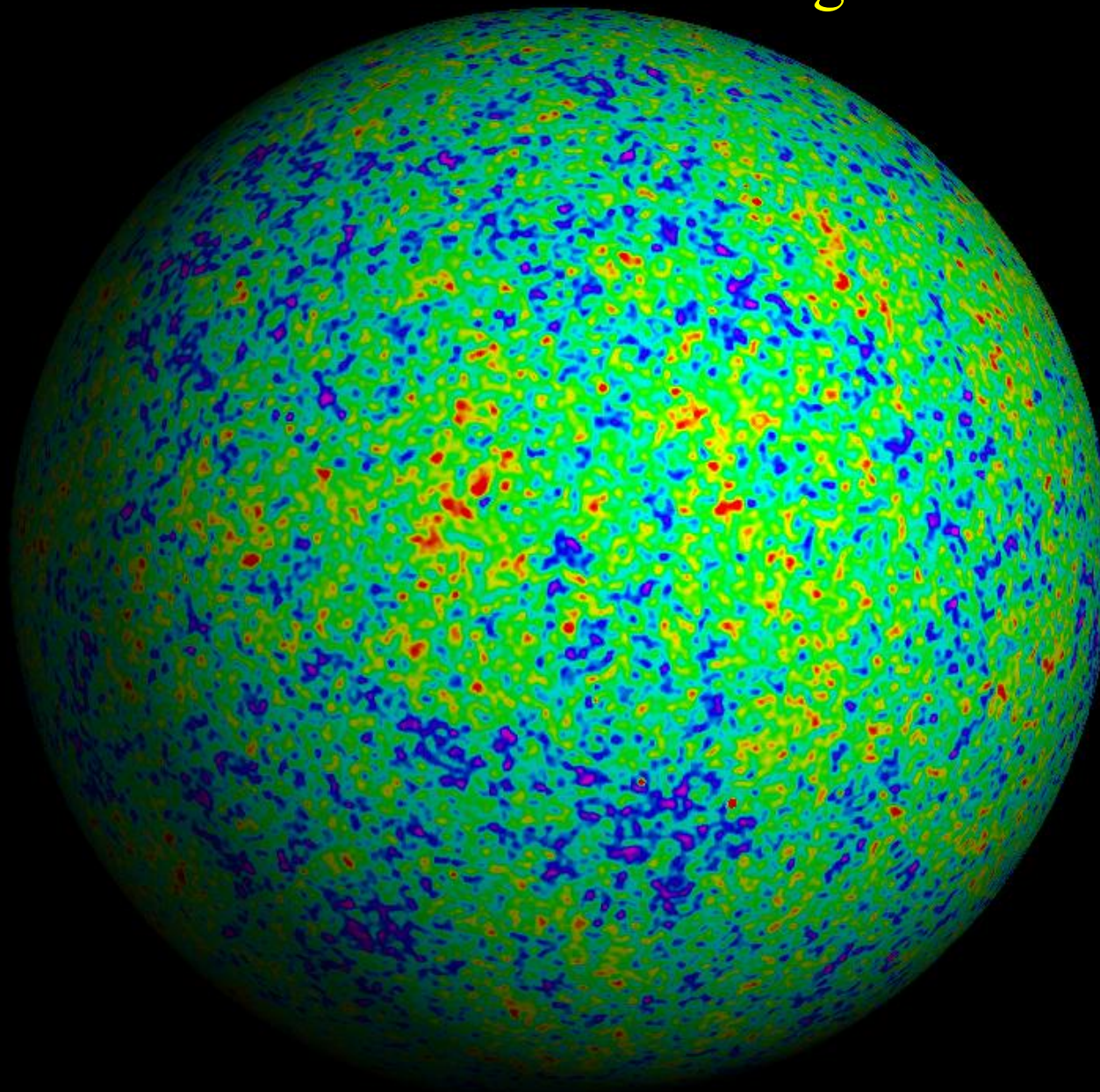


How much of this information needs to go on the T-shirt?



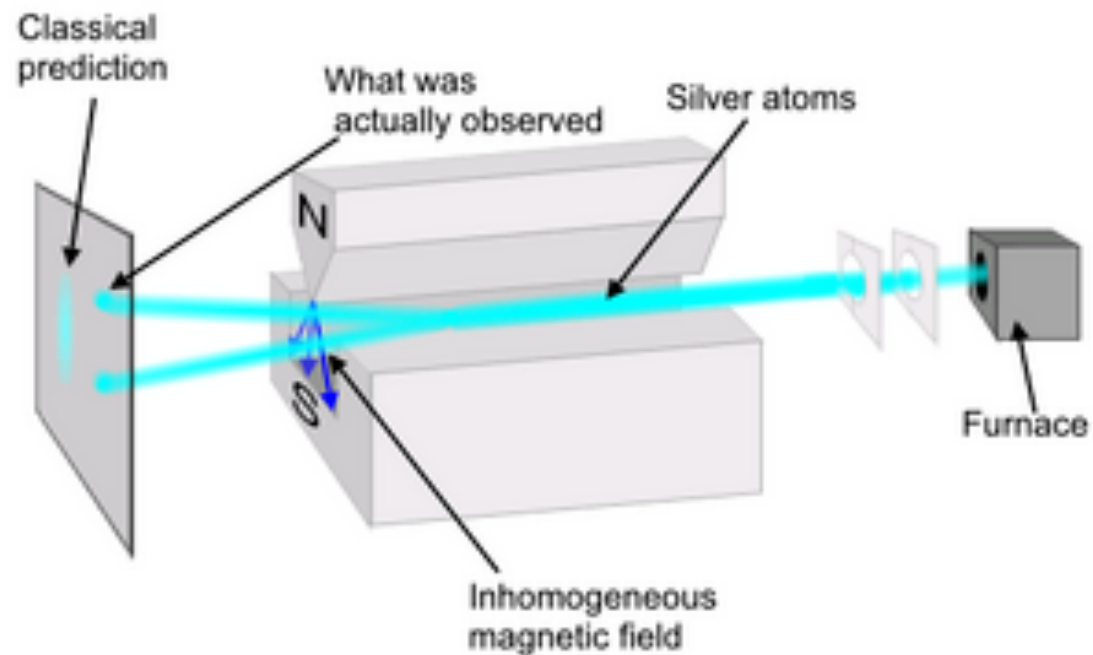
Very little

How much of this information needs to go on the T-shirt?



Very little

# Quantum random number generator based on Stern-Gerlach apparatus:



Generic outcome: 101100100011001001110...  
(Just our address in Hilbert space - not specified on T-shirt)



So what *does* go on the T-shirt?

# Standard model parameters:

Particle physics

Cosmology

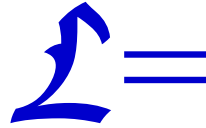
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MT,  
Aguirre,  
Rees &  
Wilczek  
2005

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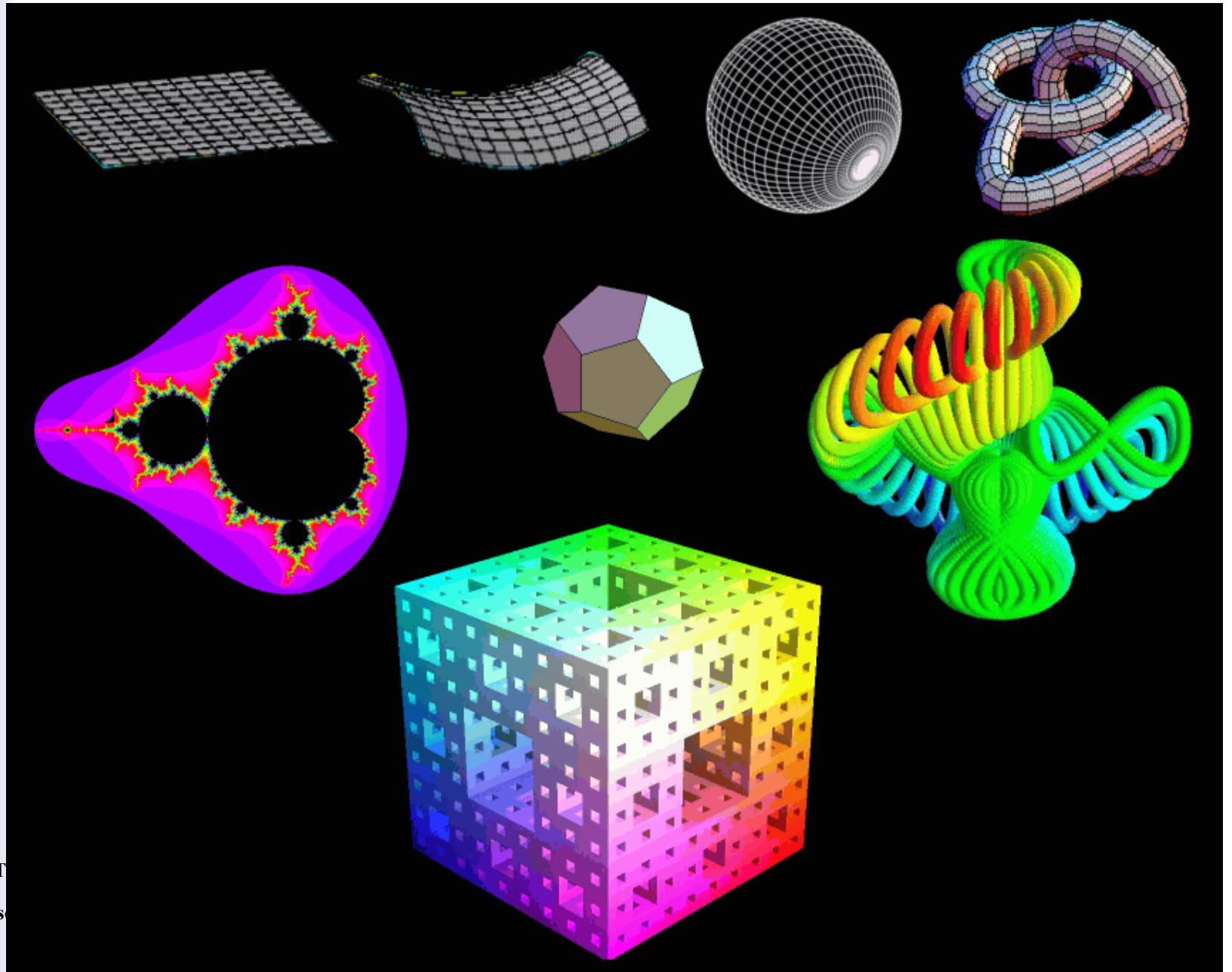
The Standard Model Lagrangian



$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\nu^b g_\nu^c g_\mu^d g_\mu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w} M \phi^0 \phi^0 - \beta_h \left[ \frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
 & m_d^\lambda) d_j^\lambda + ig s_w A_\mu [ -(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma d_j^\lambda) ] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + \\
 & (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda) ] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
 & \gamma^5) C_{\lambda\nu} d_j^\nu) ] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\nu C_{\lambda\nu}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda) ] + \\
 & \frac{ig}{2\sqrt{2}} \frac{m_h^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda) ] - \frac{g}{2} \frac{m_h^2}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) ] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\lambda (\bar{u}_j^\lambda C_{\lambda\nu} (1 - \gamma^5) d_j^\nu) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\nu} (1 + \\
 & \gamma^5) d_j^\nu) ] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\nu C_{\lambda\nu}^\dagger (1 + \gamma^5) u_j^\lambda) - m_u^\lambda (\bar{d}_j^\nu C_{\lambda\nu}^\dagger (1 - \gamma^5) u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_h^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
 & igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
 & igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
 & igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
 & \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \\
 & \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

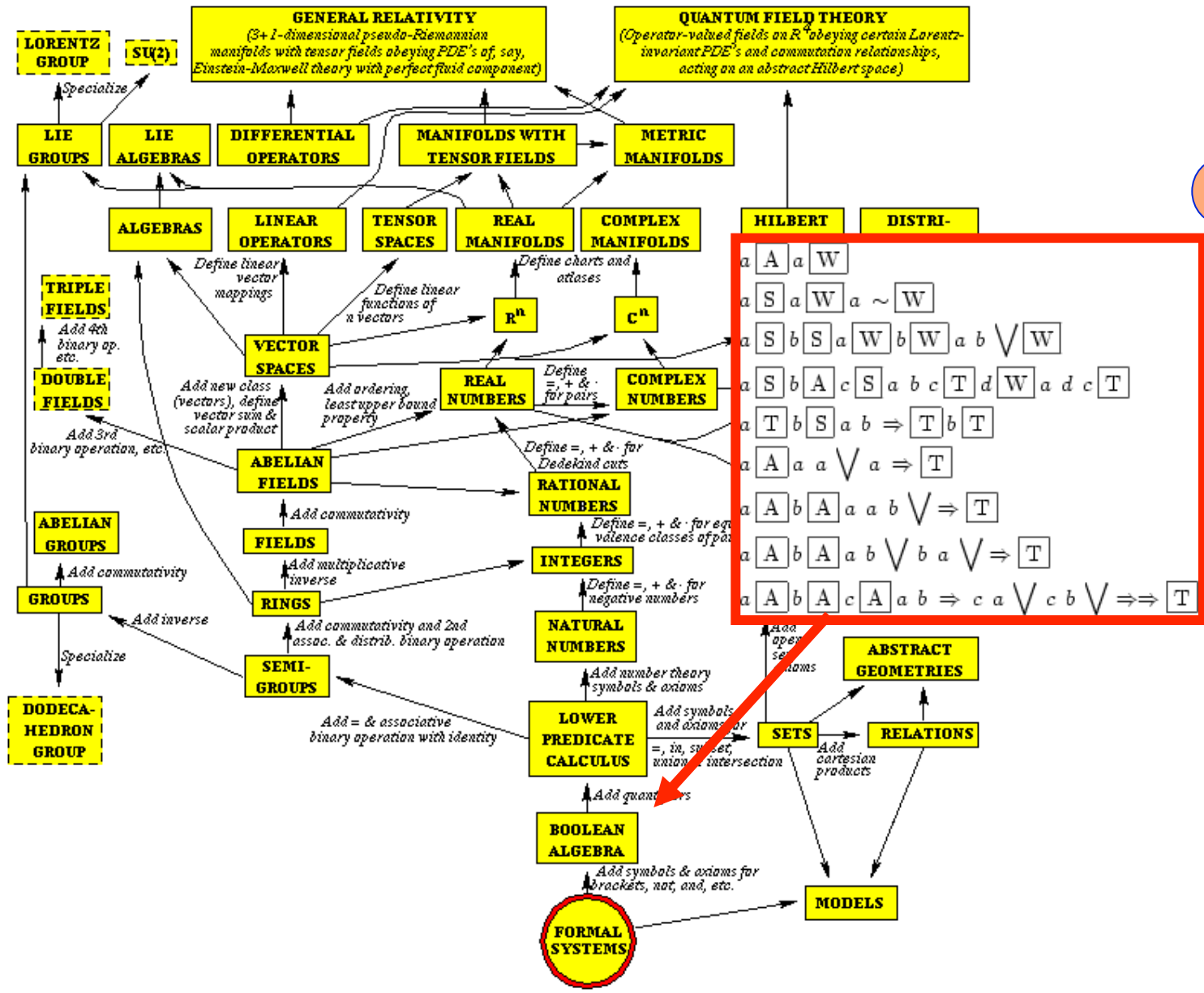
(From T.D. Gutierrez)

# Multiverse level 4: other mathematical structures



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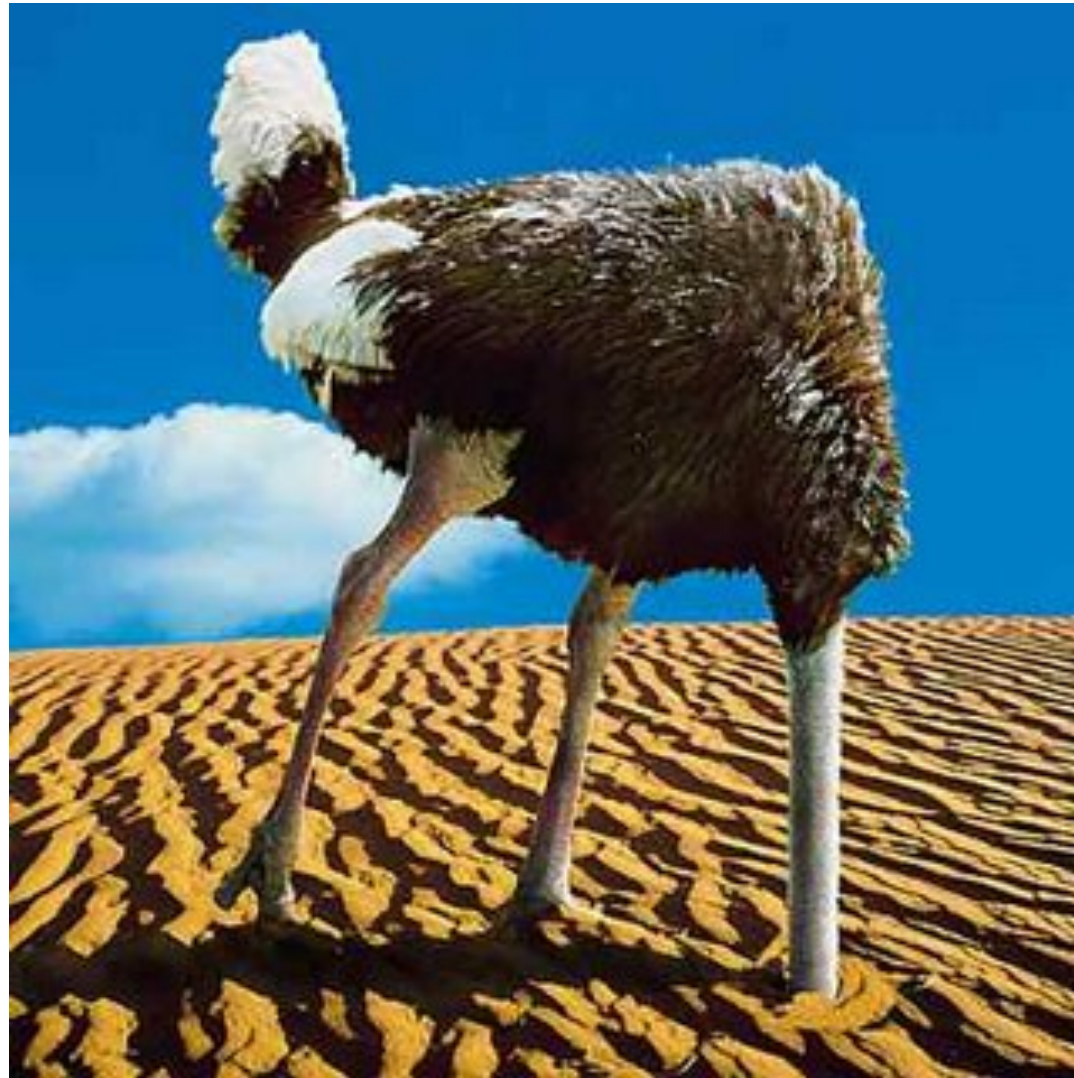




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Q: Is all we observe all there is?

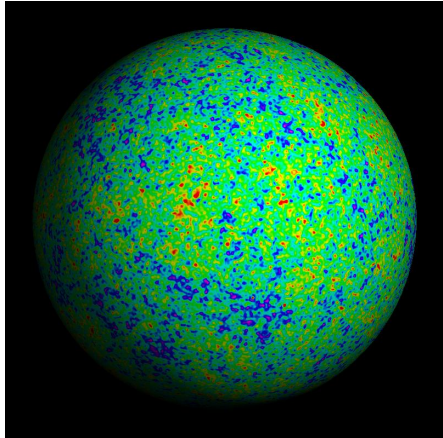


Our high entropy suggests *no!*



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*If what we observe...*



$10^{89}$   
bits?

*...requires more bits to describe than...*

$10^3$   
bits?

*...a complete mathematical description of the world...*



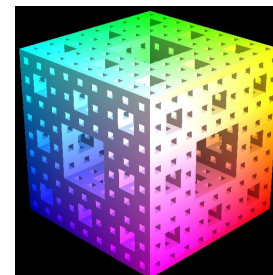
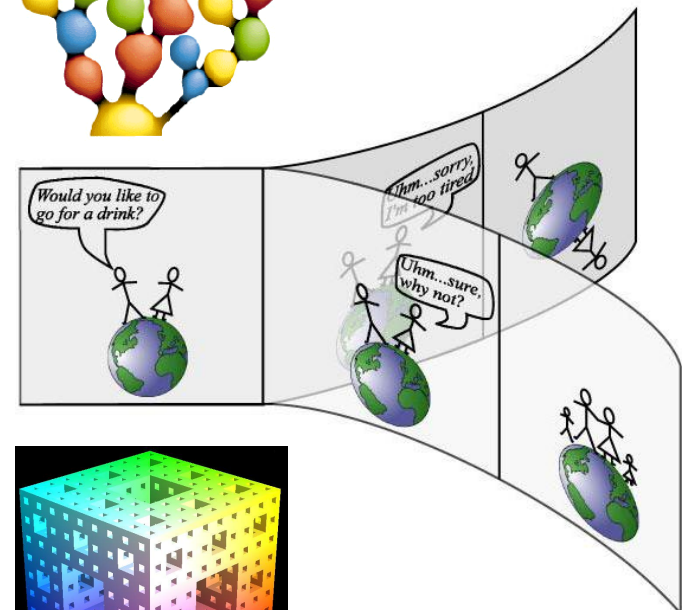
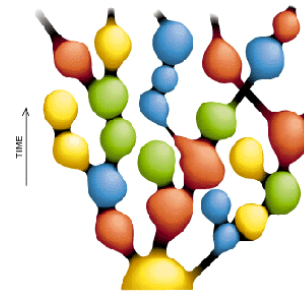
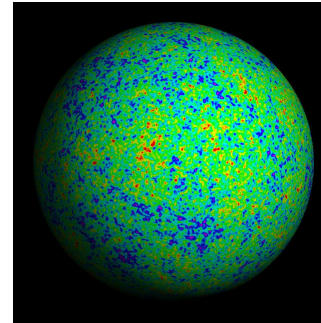
*...then we're in a multiverse!*



*So if you're looking for a simple mathematical TOE, you're looking for a multiverse theory.*

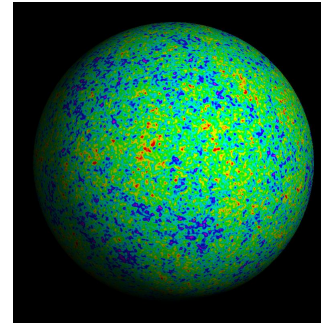
# Which are the 4 multiverse levels?

- 1) Different Hubble volumes
- 2) Different post-inflationary regions
- 3) Different decohered branches of the quantum wavefunction
- 4) Different mathematical structures

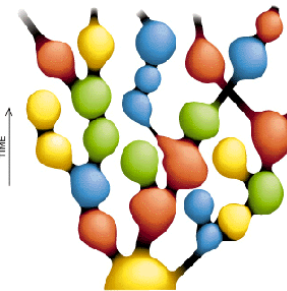


# Where are the parallel universes?

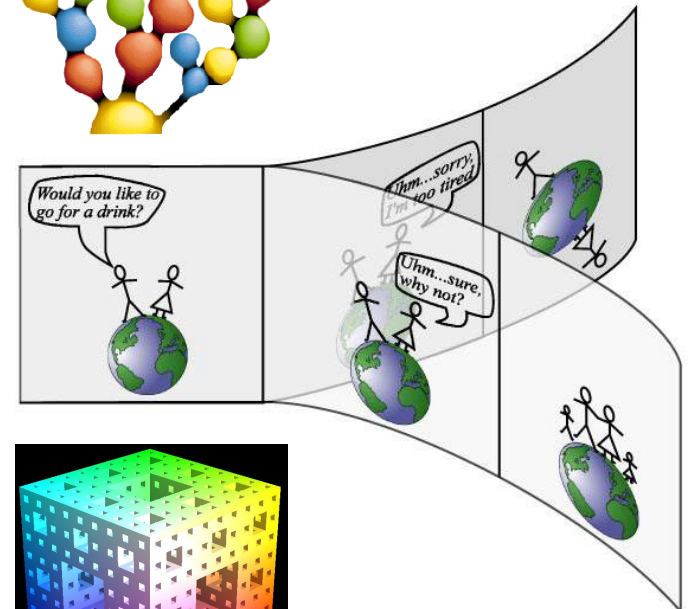
1) Far away in space



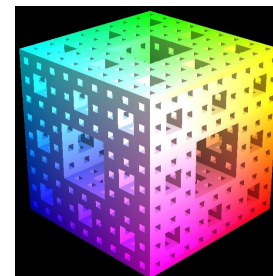
2) Infinitely far away in space



3) Elsewhere in Hilbert space

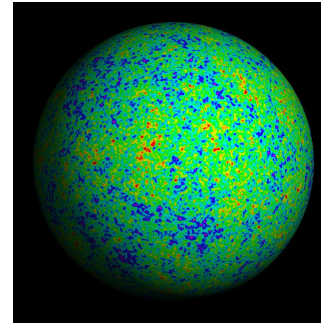


4) Elsewhere in “math space”

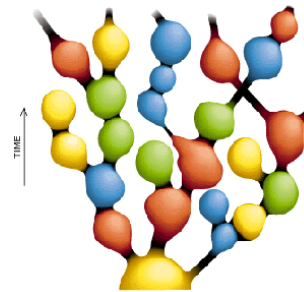


# What are the 4 multiverse levels like?

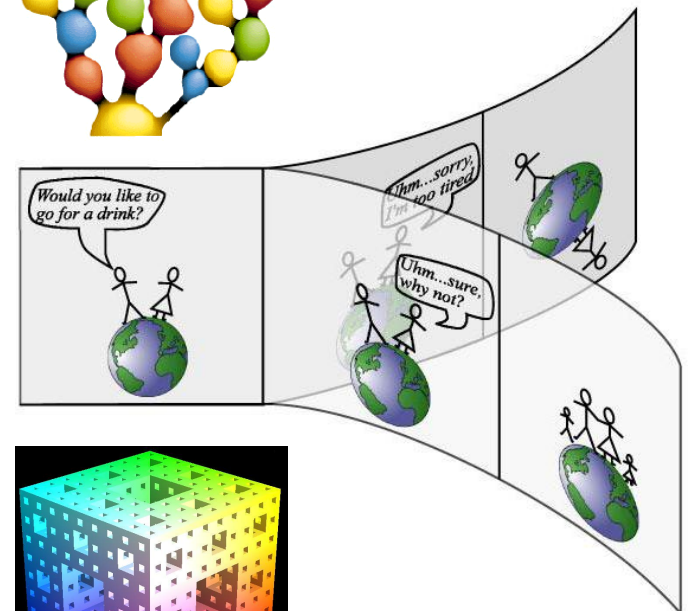
1) Same effective laws of physics, different initial conditions



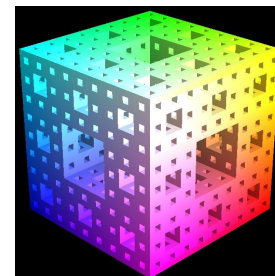
2) Same fundamental laws of physics, different effective laws (“bylaws”)



3) Nothing qualitatively new



4) Different fundamental laws of physics



Evidence

# PHYSICS OR PHILOSOPHY?

**Q: Are theories which predict the existence of unobservable parallel universes untestable?**



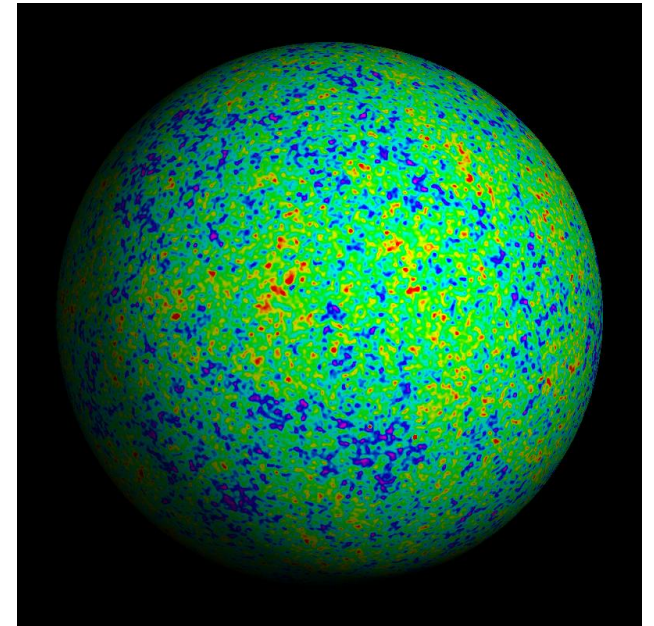
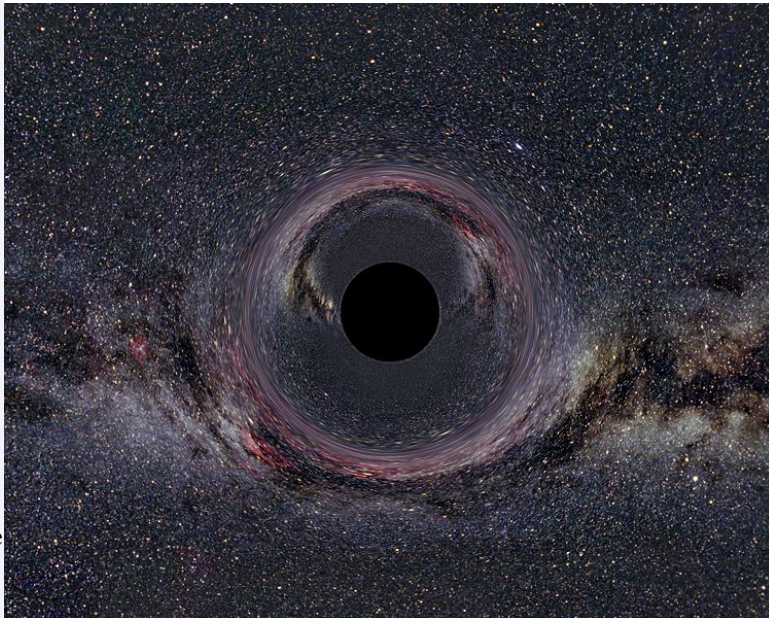
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# PHYSICS OR PHILOSOPHY?

**Q: Are theories which predict the existence of unobservable parallel universes untestable?**

**A: No, as long as they also make predictions for things we *can* observe.**

**Parallel universes are not a theory, but the prediction of certain theories.**



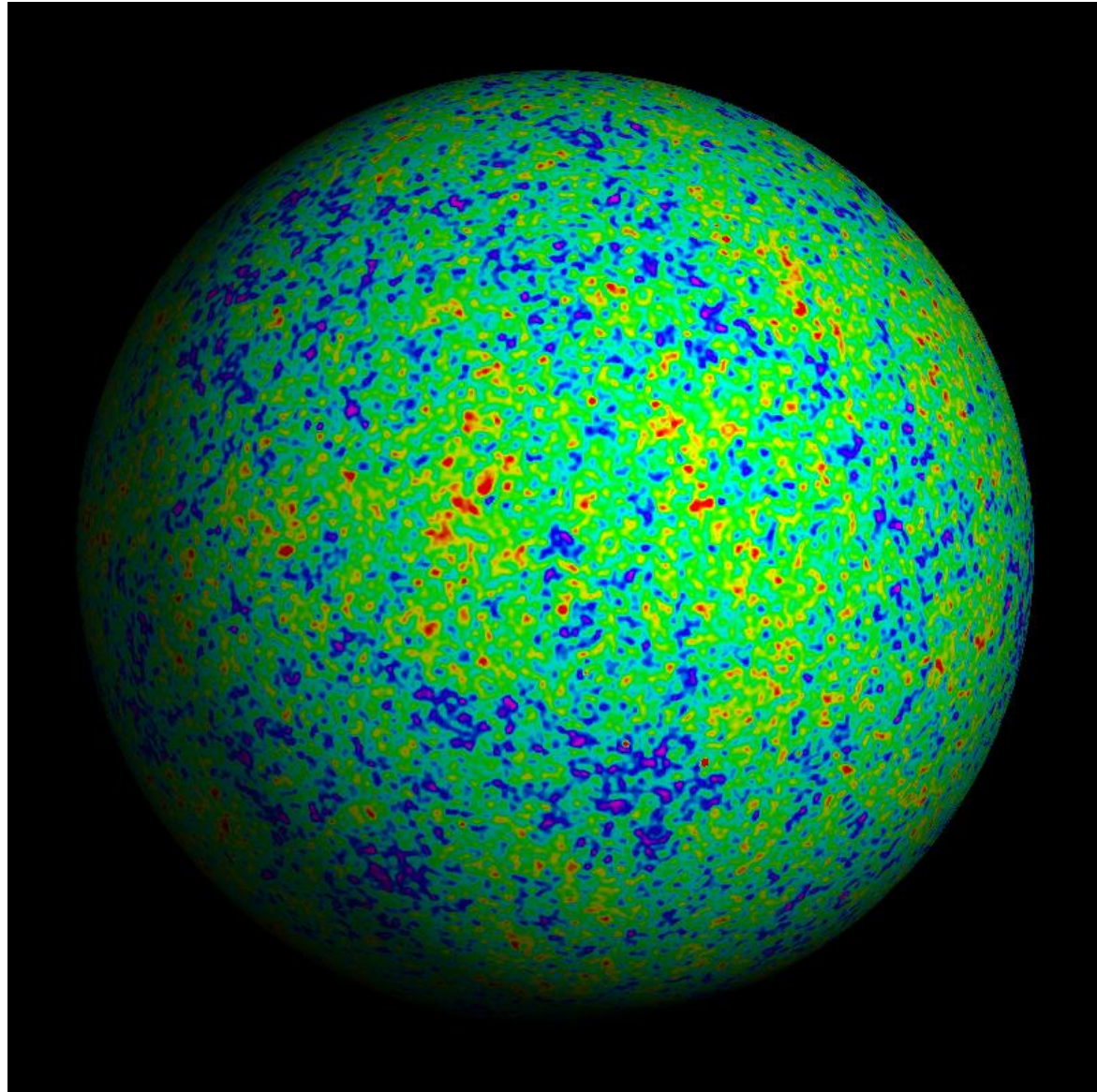
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## How to test/falsify a multiverse theory:

**Not** necessary that rest of ensemble be observable

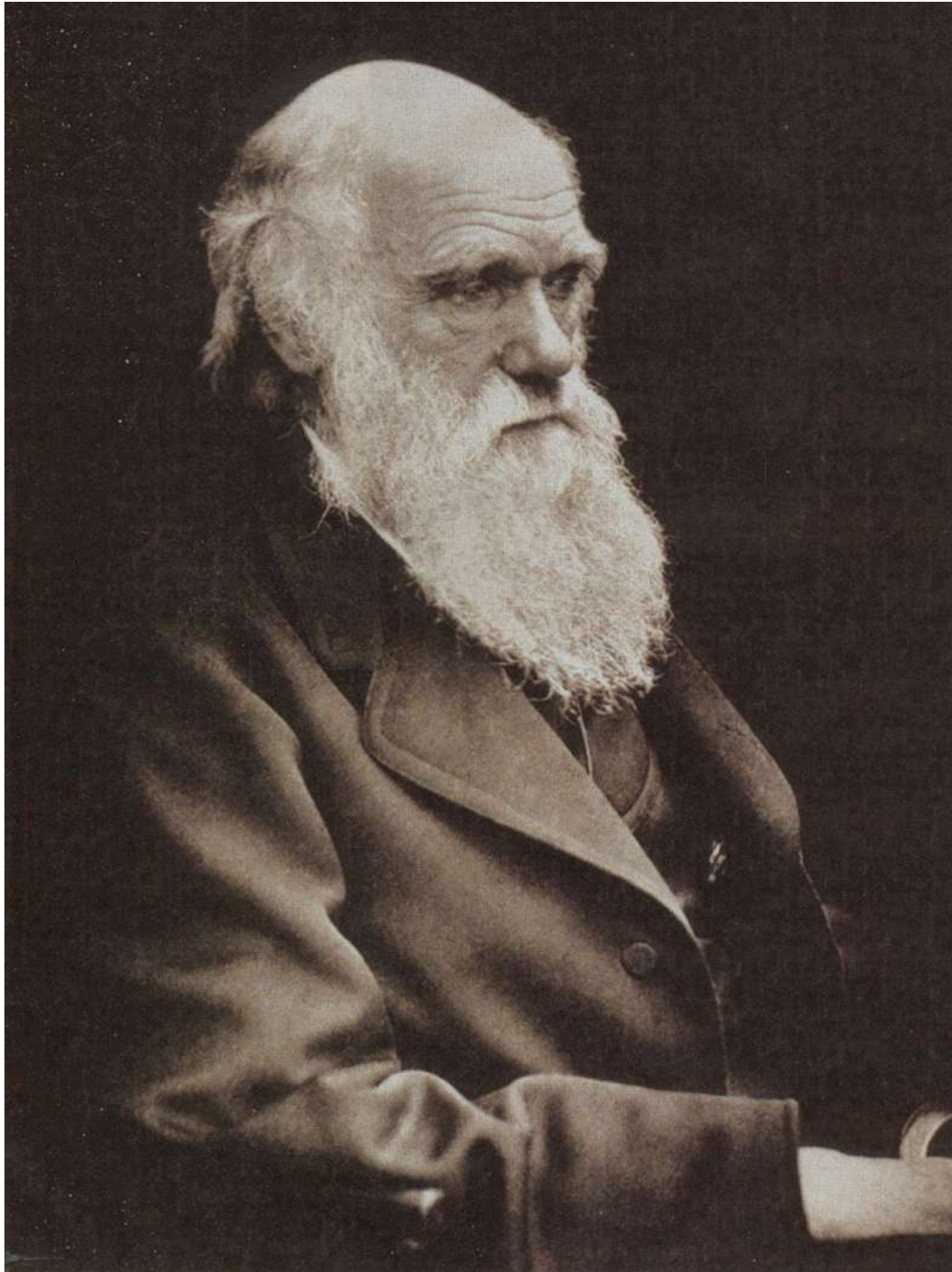
*Example: the theory that there's no dark matter*



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Sound too  
crazy?

We're  
not  
taking  
this guy  
seriously  
enough



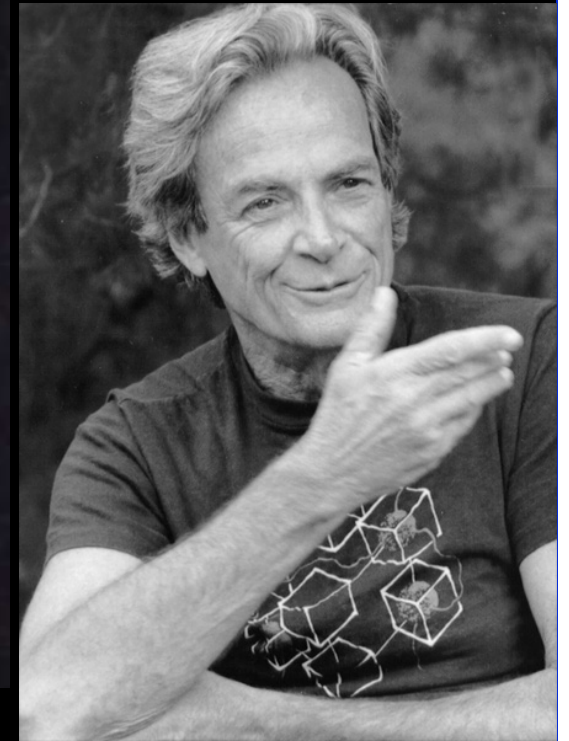
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The strongest form of the anthropic principle:



*“The Universe must be such that we like it.”*

The strongest form of the anthropic principle:



*“The Universe must be such that we like it.”*