

# HOW DO WE KNOW MULTIVERSES EXIST?

Bernard Carr

What do we mean by

**KNOW**

Observe directly  
Observe indirectly  
Infer theoretically

**MULTIVERSE**

Levels I

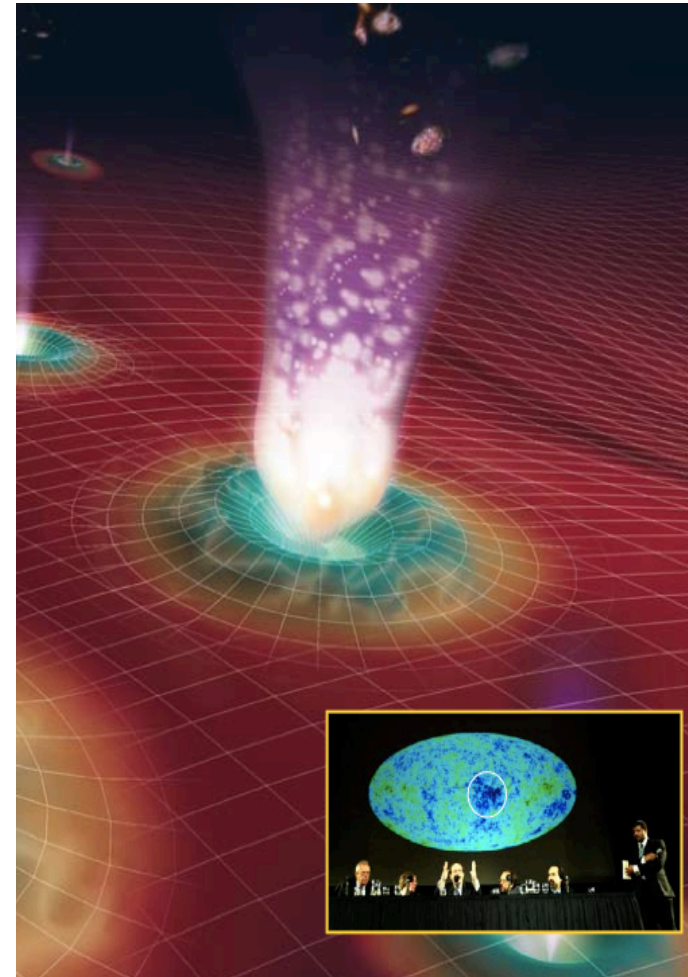
Level II

Level III

Level IV

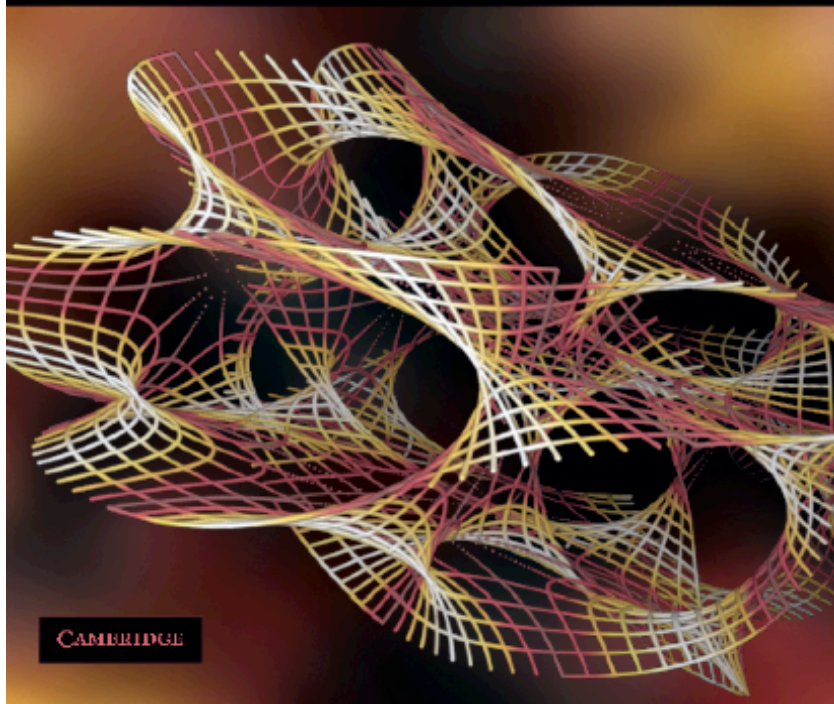
**EXIST**

Mathematically  
Physically



# Universe or Multiverse?

Edited by **Bernard Carr**



CAMBRIDGE

Recent developments in cosmology and particle physics suggest that our universe - rather than being unique - could be just one of many universes. Since the physical constants can be different in other universes, the fine-tunings which appear necessary for the emergence of life may be explained.

# CAMBRIDGE 2001

George Ellis      John Barrow  
Martin Rees      Bill Stoeger      Alex Vilenkin  
Jeremy Butterfield      Andrei Linde  
Max Tegmark



# CHANGE IN ATTITUDE TO MULTIVERSE

Frank Wilczek

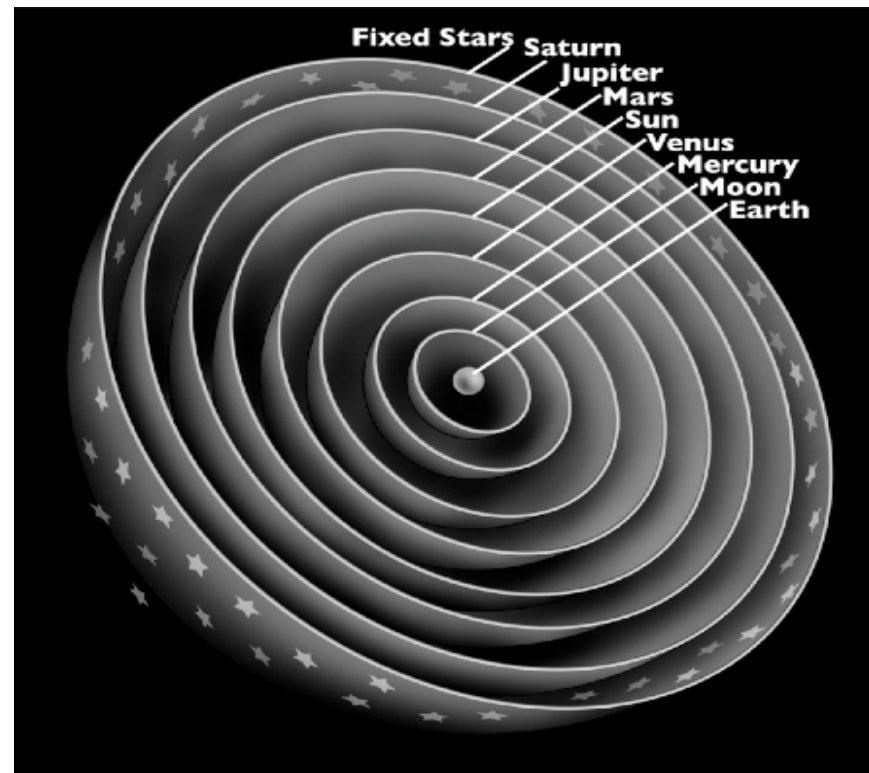
“The previous gathering [2001] had a defensive air. It prominently featured a number of physicists who subsisted on the fringes, voices in the wilderness who had for many years promoted strange arguments about conspiracies among fundamental constants and alternative universes. Their concerns and approaches seemed totally alien to the consensus vanguard of theoretical physics, which was busy successfully constructing a unique and mathematically perfect Universe. Now [2005] the vanguard has marched off to join the prophets in the wilderness.”

Critics gone from “It makes no sense and I hate it” to “I hate it”.

# LESSONS OF HISTORY

## GEOCENTRIC VIEW

Aristotle





## Supernova in Cassiopeia 1572

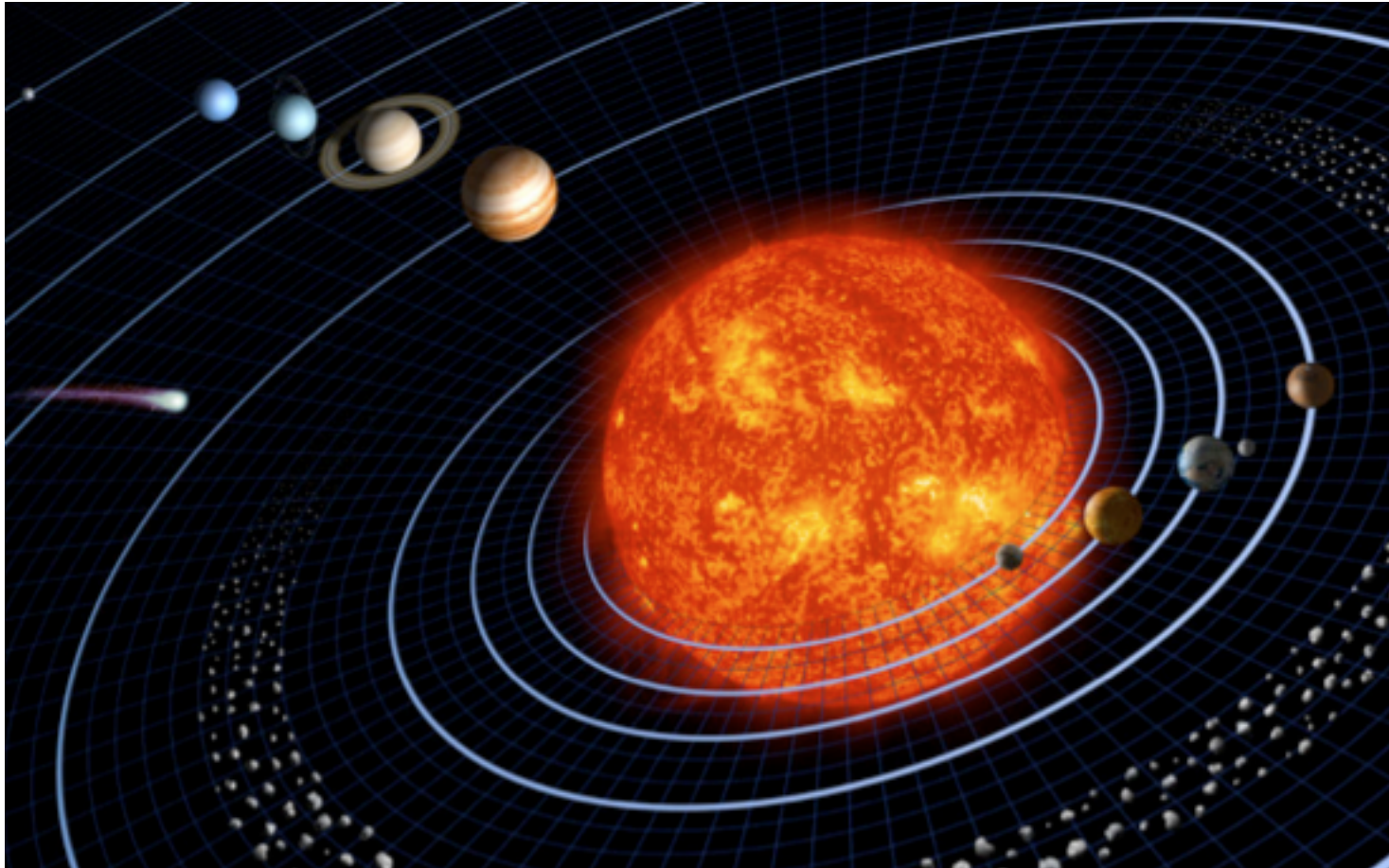
“Crassa ingenia. O coecos coeli spectores”  
(Oh thick wits. Oh blind watchers of the sky)

Preface of *De Nova Stella*

Tycho Brahe

Lesson 1: theoretical prejudice should not blind one to evidence

# HELIOCENTRIC VIEW



1542



August Comte (1859)

“Never, by any means, will we be able to study their chemical compositions [stars]. The field of positive philosophy lies entirely within the Solar System, the study of the Universe being inaccessible in any possible science.”

**Lesson 2:** New observational developments are hard to anticipate



# GALACTOCENTRIC VIEW



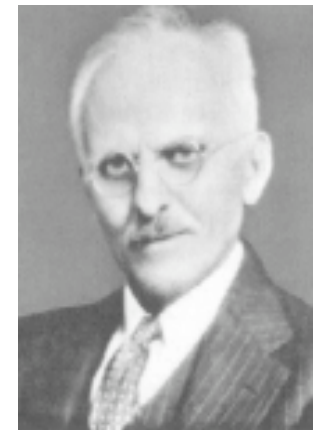


*Don't let me hear anyone use  
the word 'Universe' in my  
Department!*

Attributed to Ernest Rutherford,  
Nobel Prize in Chemistry 1908

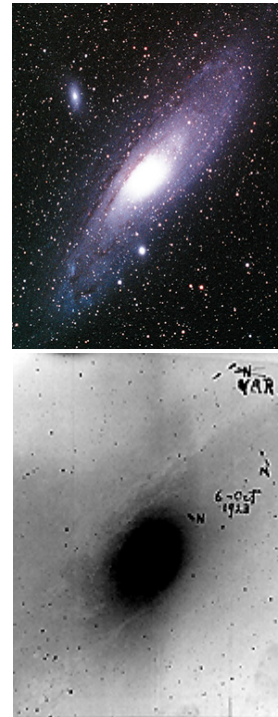
# The Great Debate (1921)

- Harlow Shapley (1885-1972)
  - believed it unlikely that nebulae could be outside the Galaxy
- Heber Curtis (1872-1942)
  - led group supporting “island universe” idea



# Resolution of Debate

- Edwin Hubble (1889-1953)
  - measured distance to M31 (Andromeda) in 1925
  - using *Cepheid variable* stars
  - 500 kpc – outside Galaxy (10s kpc in size)



Hubble, H P,  
Proc.Am.Astr.Soc.  
48 139-142 (1925)

# The recession of the Galaxies

## The Red-Shift Distance Relation



**Hubble's  
Law  
1920's**

# Hubble's original 1929 plot

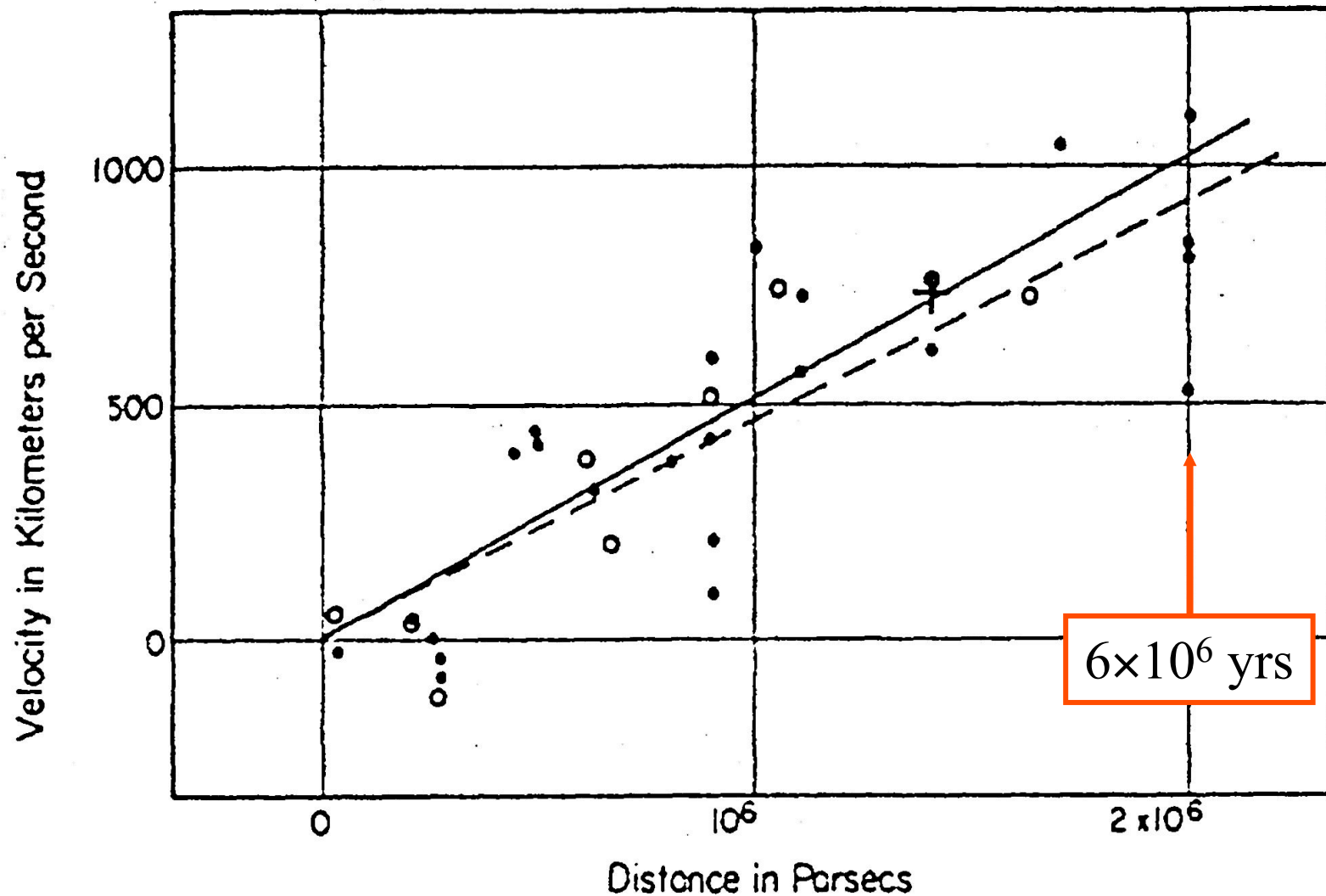
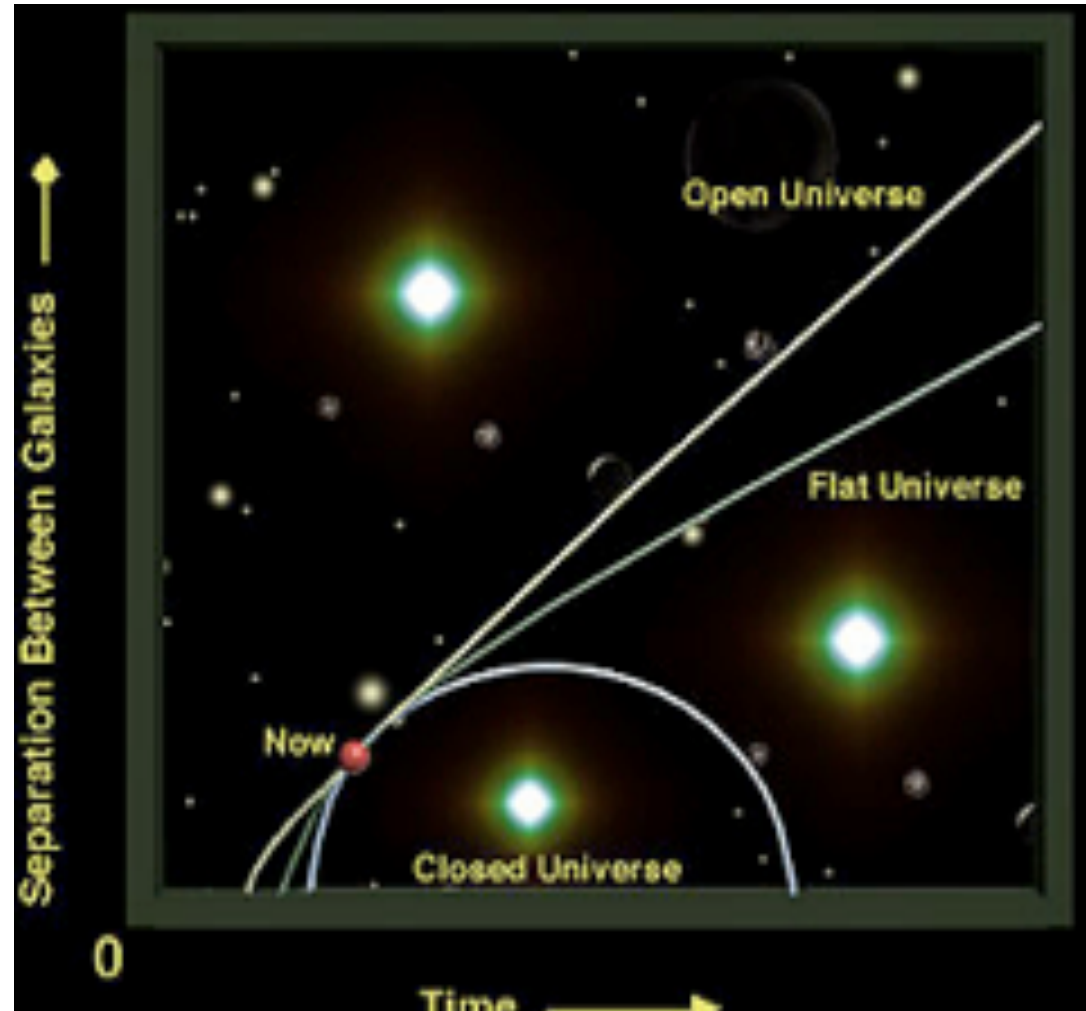


Fig. 106.1 The velocity-distance relation for extragalactic nebulae. Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and

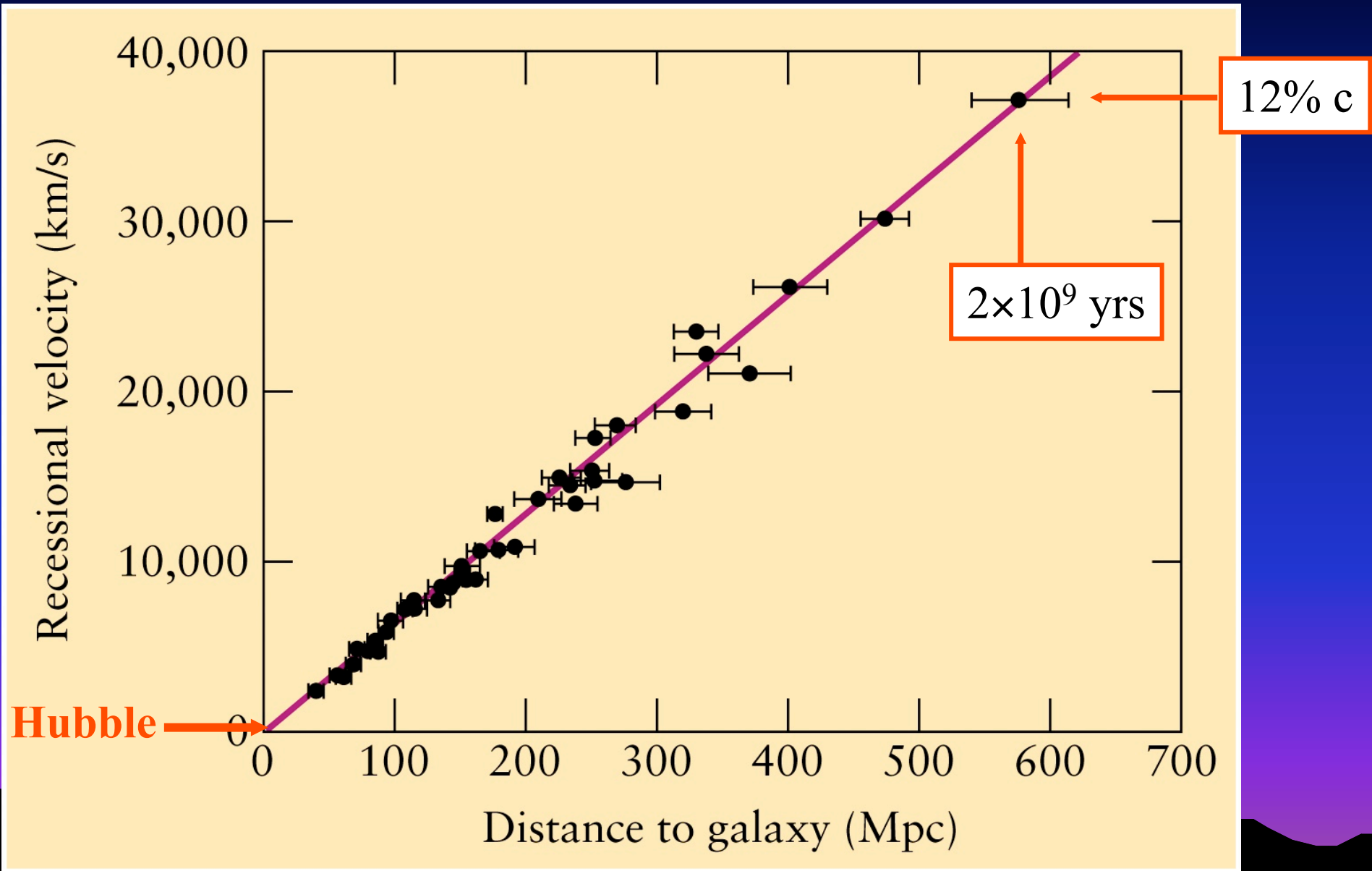


Alexander  
Friedmann



Lesson 3: Don't reject theory because no observational support

# Modern Hubble Plot going out to larger distances





# Hubble's Law $v \propto d$

- Recession Speed of source is  $v$
- Distance of source is  $d$

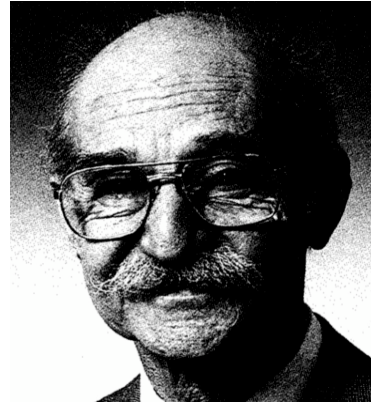
$$v = H_0 d$$

the 'Hubble Time' is

$$H_0^{-1} = (13.7 \pm 0.2) \times 10^9 \text{ y}$$

Compare ages of oldest known stars in  
Globular clusters  $(13 \pm 2) \times 10^9 \text{ yrs}$

( Confirmed by HST  $(71 \pm 2)$  & WMAP analysis, 2003)



## Ralph Alpha & Robert Herman (1946)

“Cosmology was then a sceptically regarded discipline, not worked in by sensible scientists.”



*the weight of space*

**Cosmological**

**constant**

**(dark energy)**

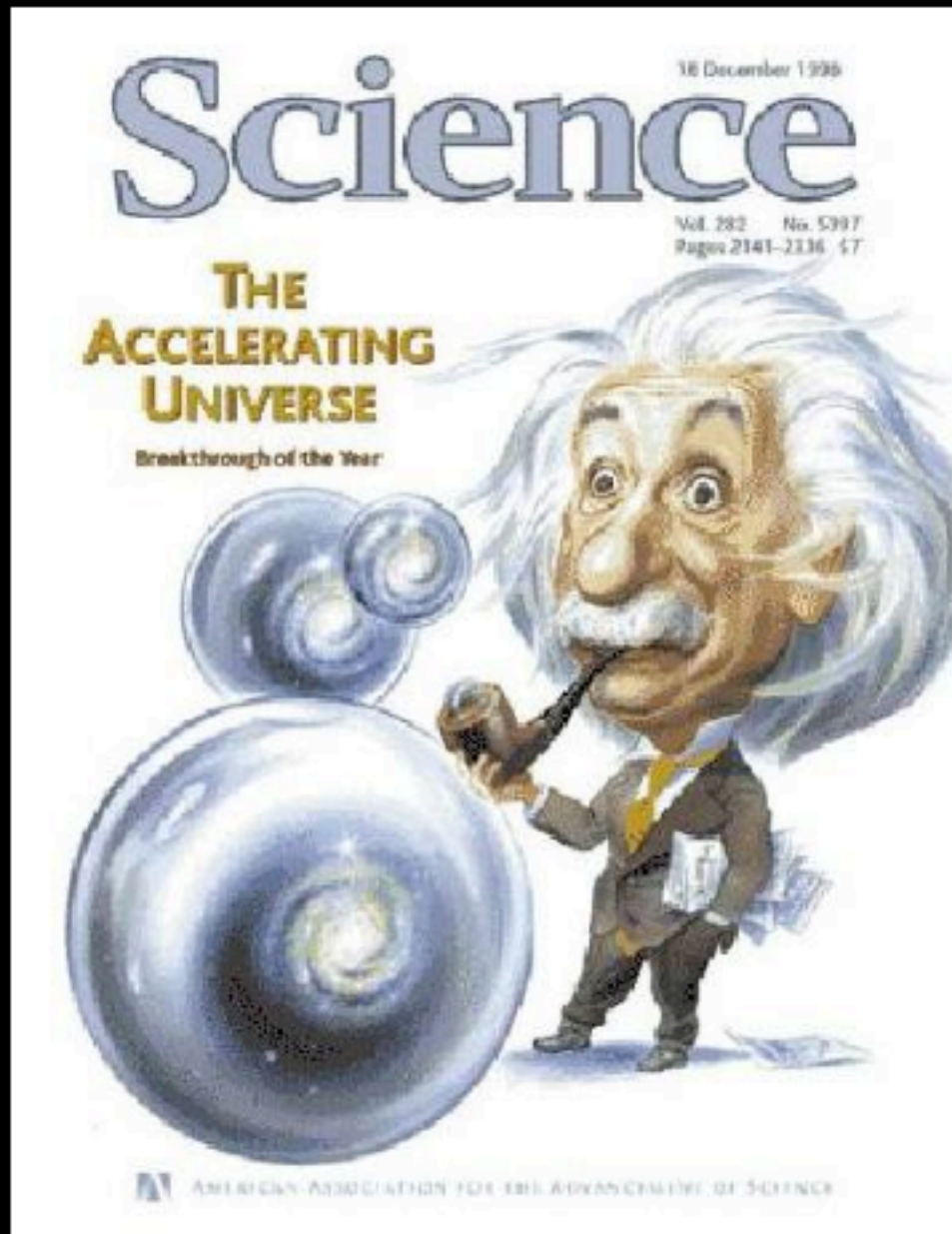
**1917 Einstein proposes  
cosmological constant**

**1929 Hubble discovers  
Expansion of the universe**

**1934 Einstein calls it  
“my biggest blunder”**

**1998 Astronomers find  
evidence for it**

1998 **BREAKTHROUGH OF THE YEAR** 2003



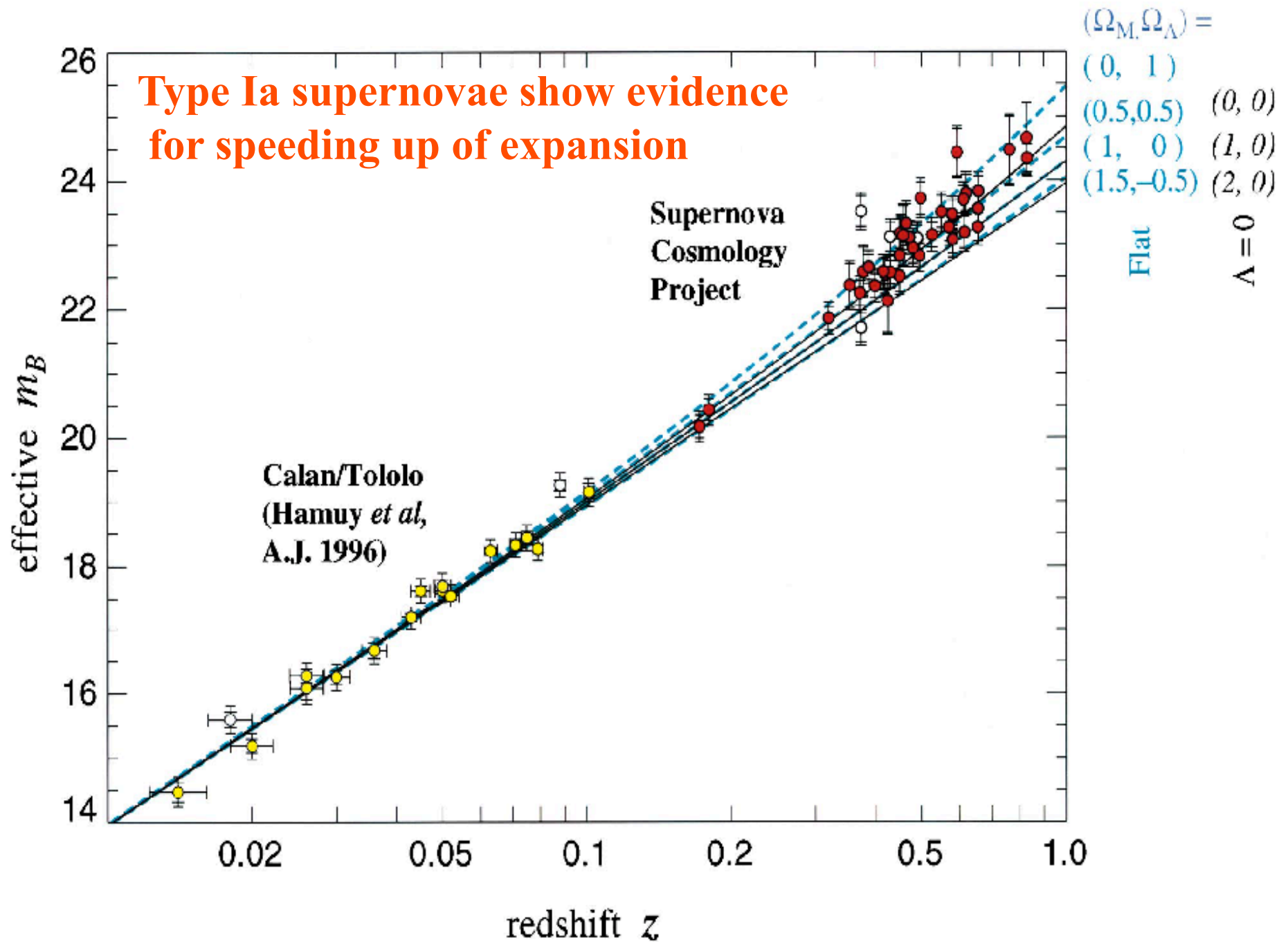
19 December 2003

# Science

Vol. 302 No. 5653  
Pages 2017-2172 \$10

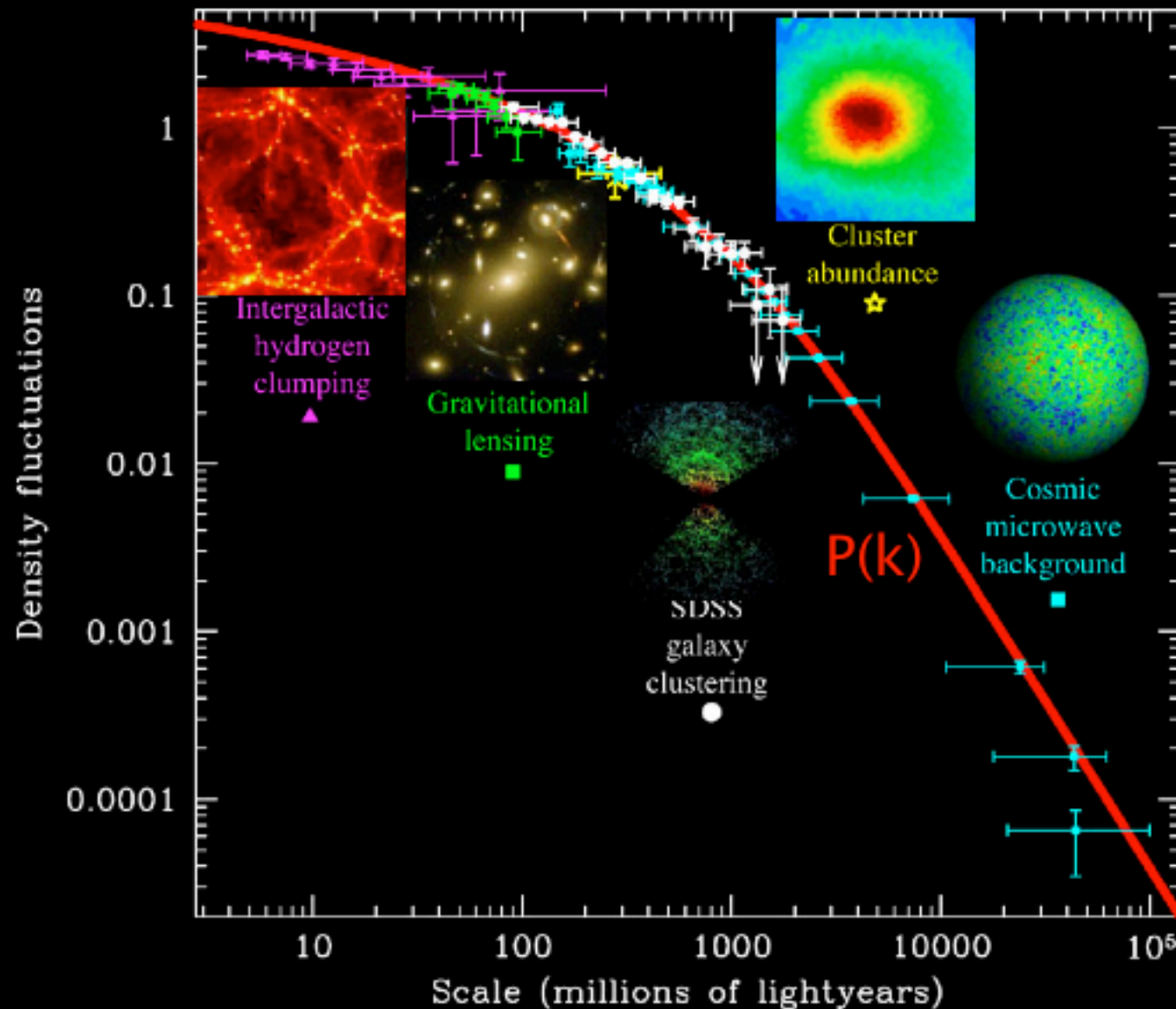
Breakthrough of the Year  
**Cosmic Convergence**

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE



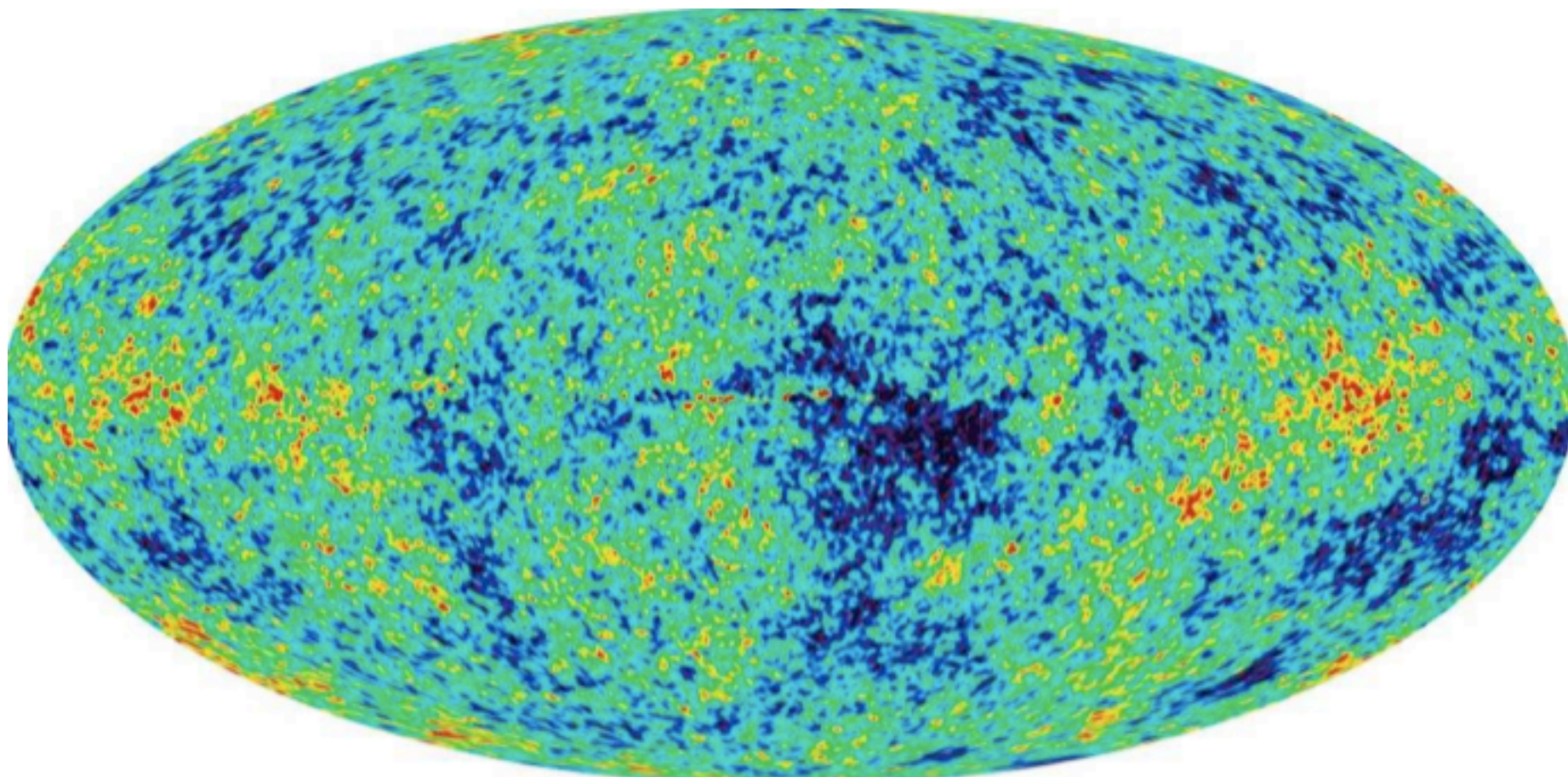
# Distribution of Matter

Also Agrees with Double Dark Theory!

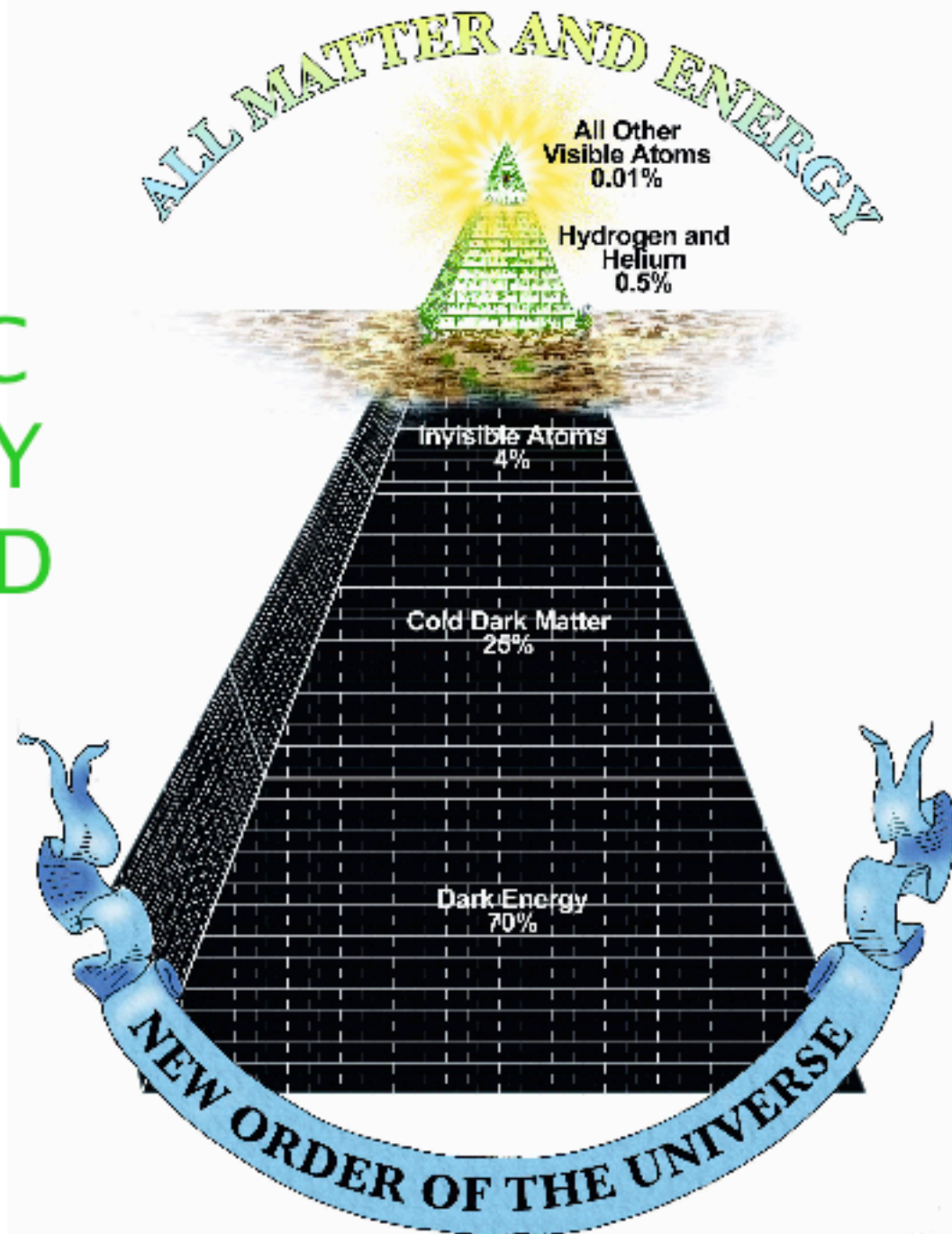


Max Tegmark

# Cosmic Background Radiation

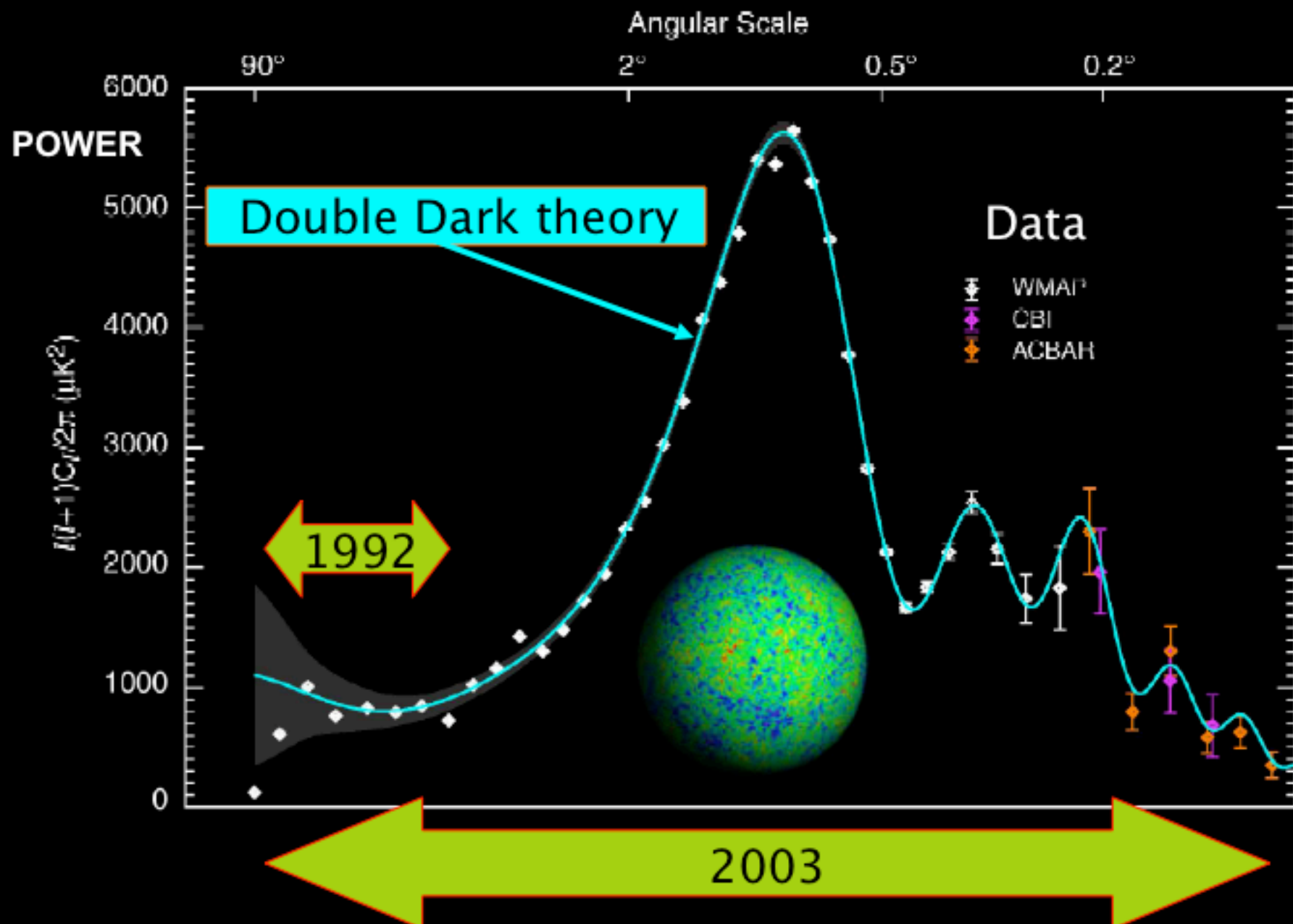


# COSMIC DENSITY PYRAMID





# Big Bang Data Agrees with Double Dark Theory!



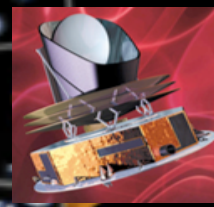
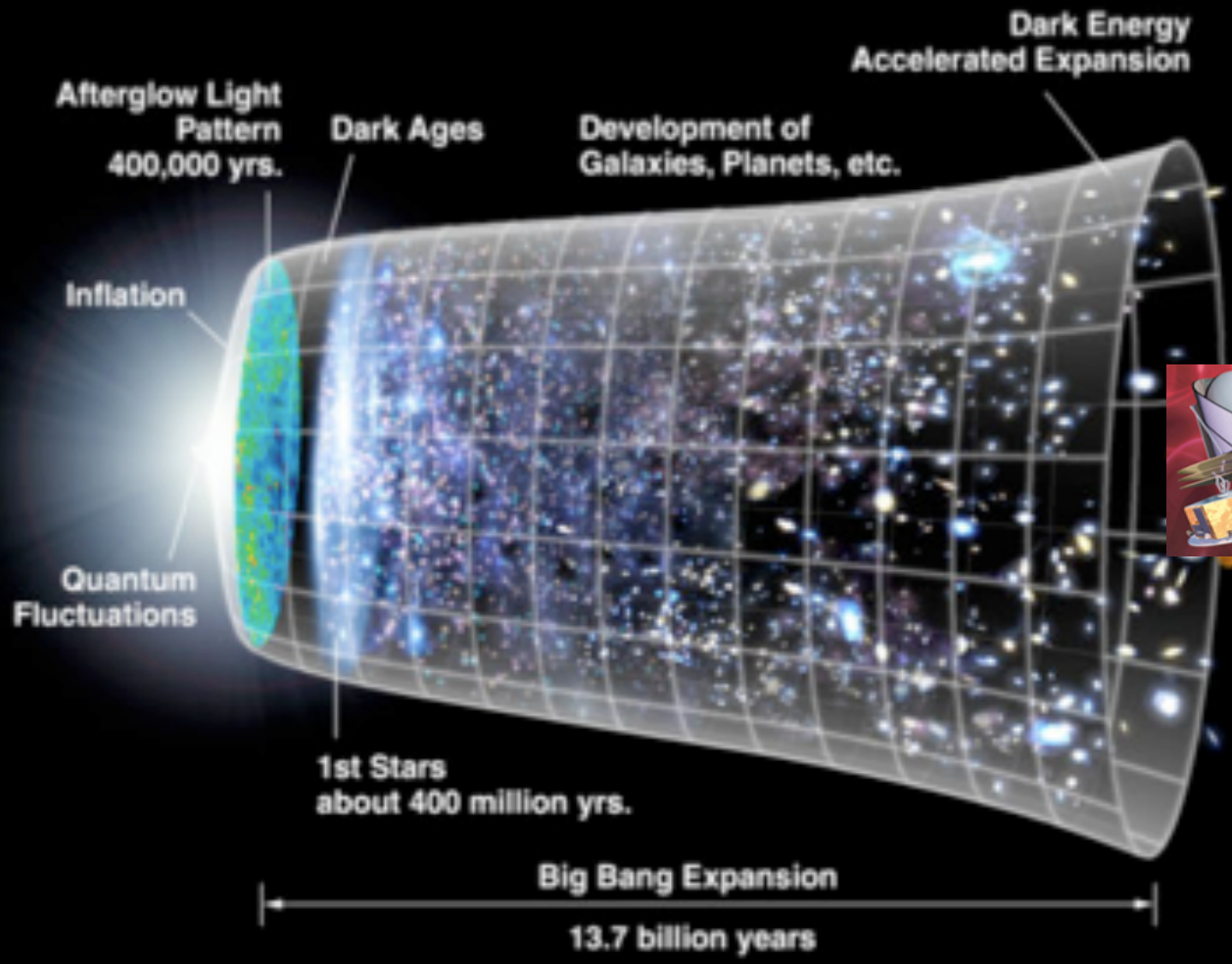
# ***Cosmological constant (dark energy)***

**Mass density of space:**

$$10^{-30} \text{ g cm}^{-3}$$

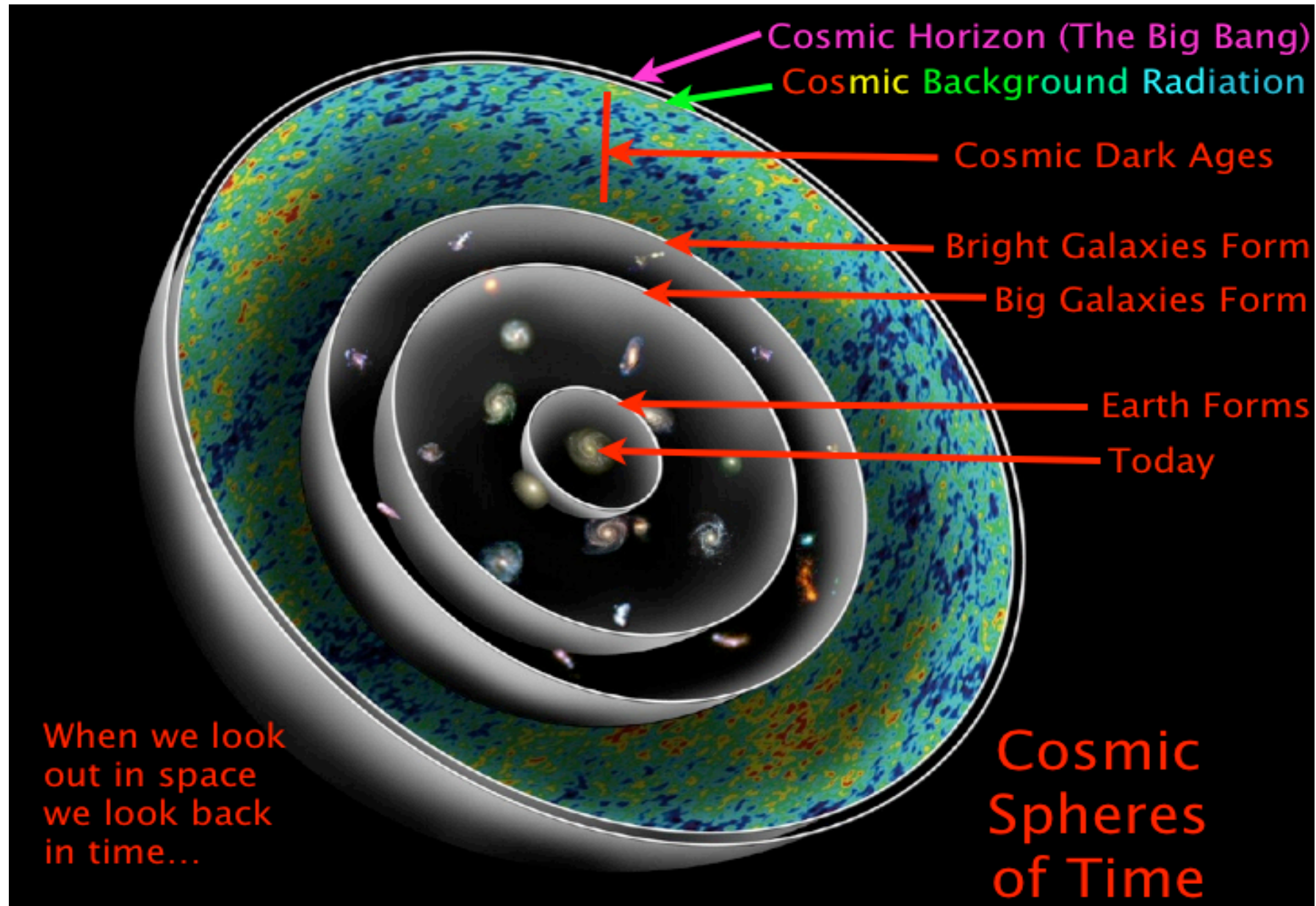
**The unbearable lightness of nothing!**

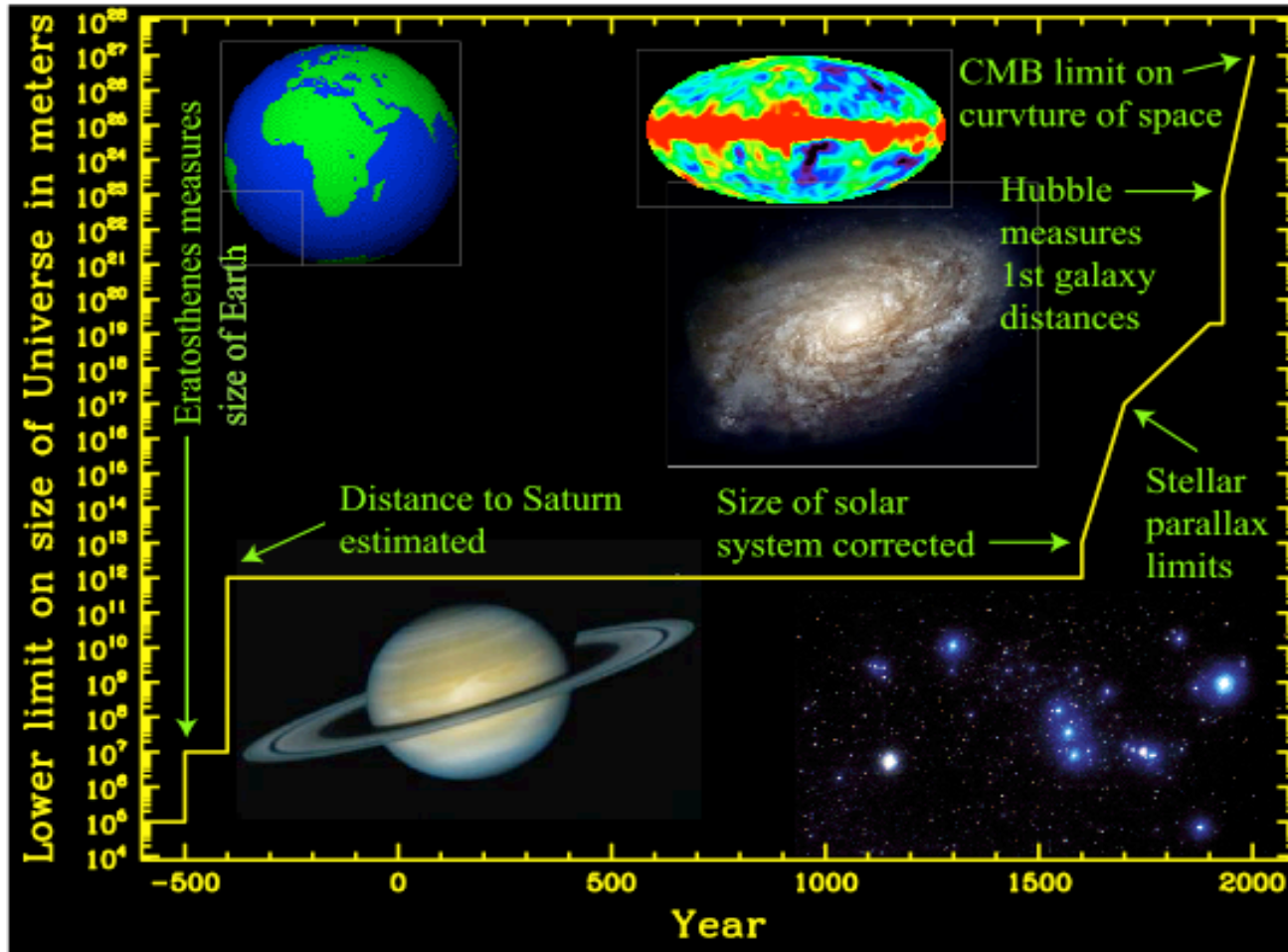
Inflation theory invokes this in early universe  
but we also need it at the present epoch



Planck

# COSMOCENTRIC VIEW



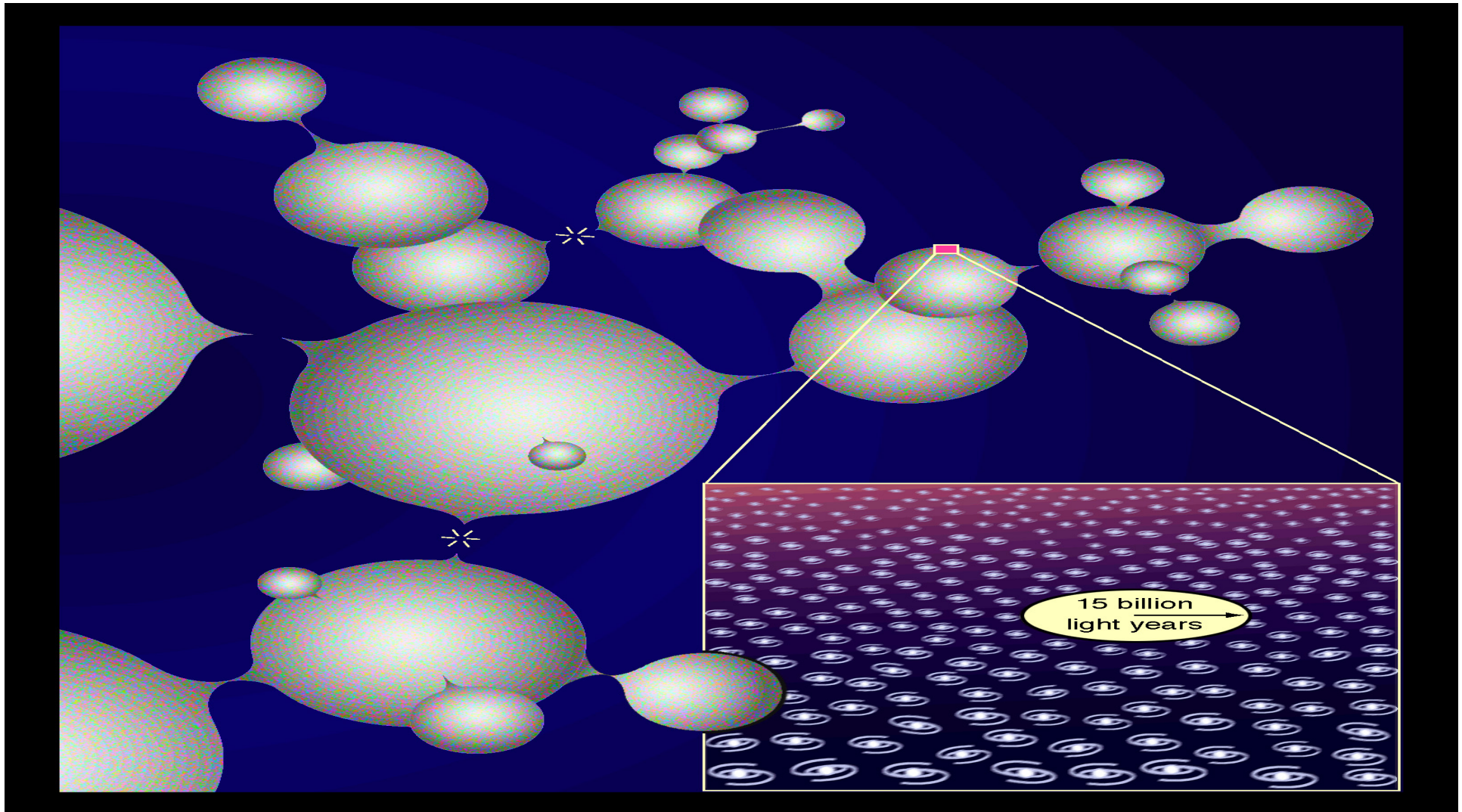


Lesson 4: Tide of history is against cosmocentric view

What we call the “universe” is always growing and as it does so nature of legitimate science changes



The observable universe is a miniscule part of larger physical reality. What lies beyond horizon?





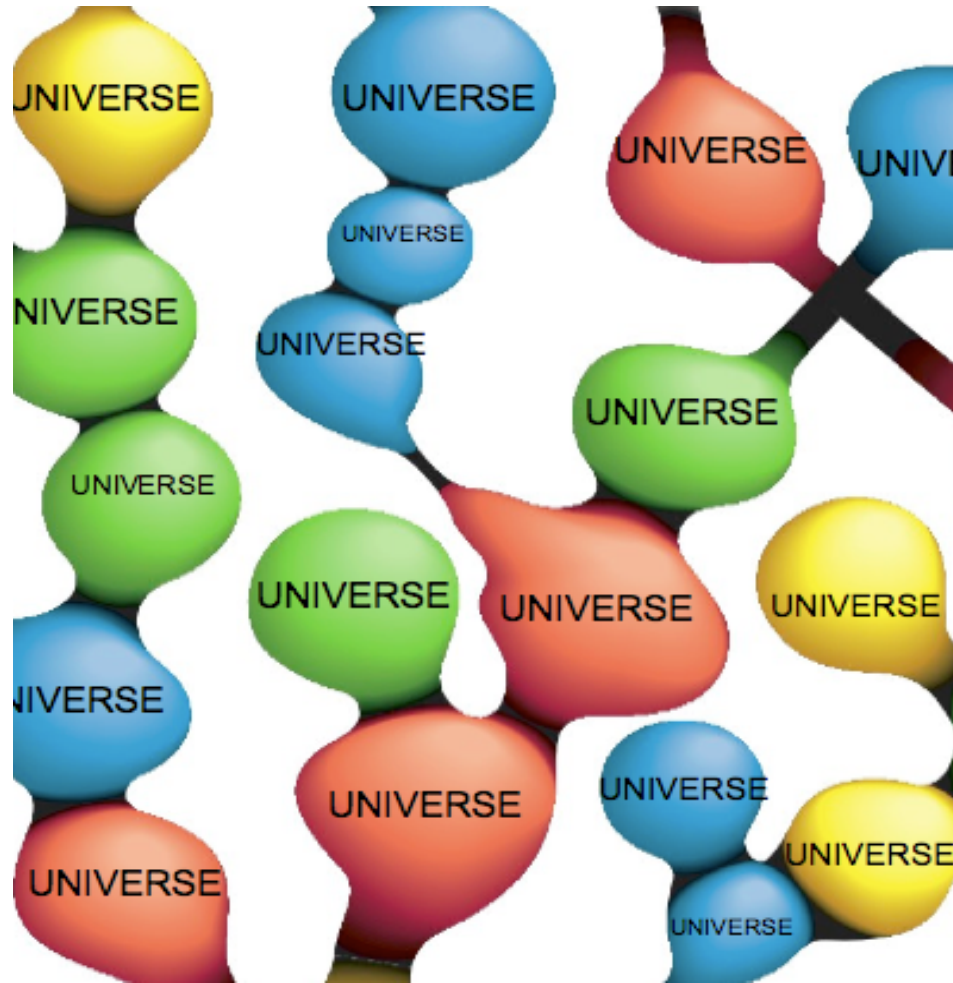
Scientific American  
May 2003 issue  
**COSMOLOGY**

“Parallel Universes:  
a direct implication  
of cosmological  
observations”

**Max Tegmark**



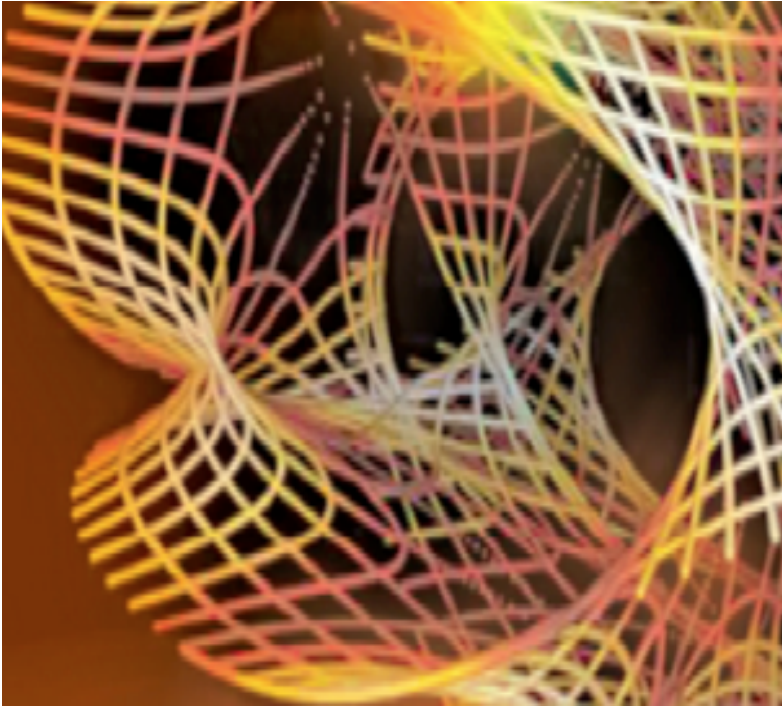
# Eternal inflation



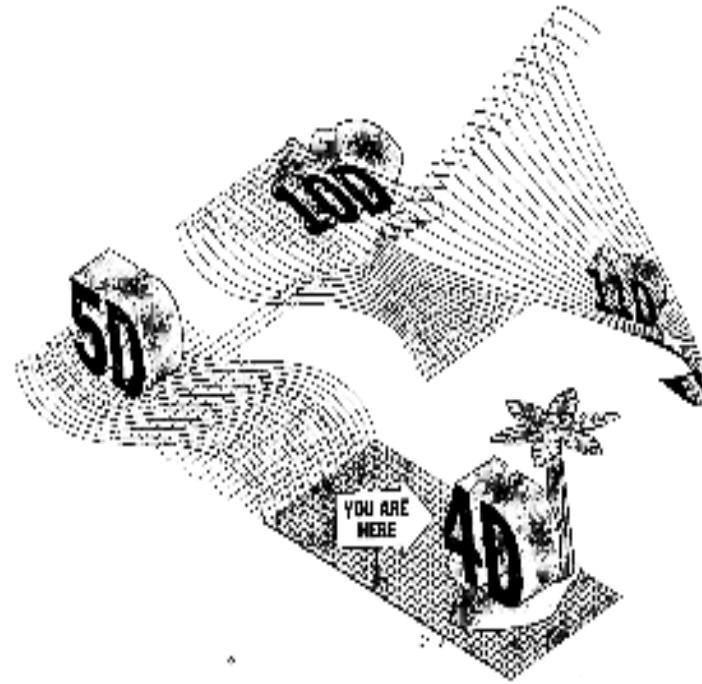
## Many pictures of eternal inflation



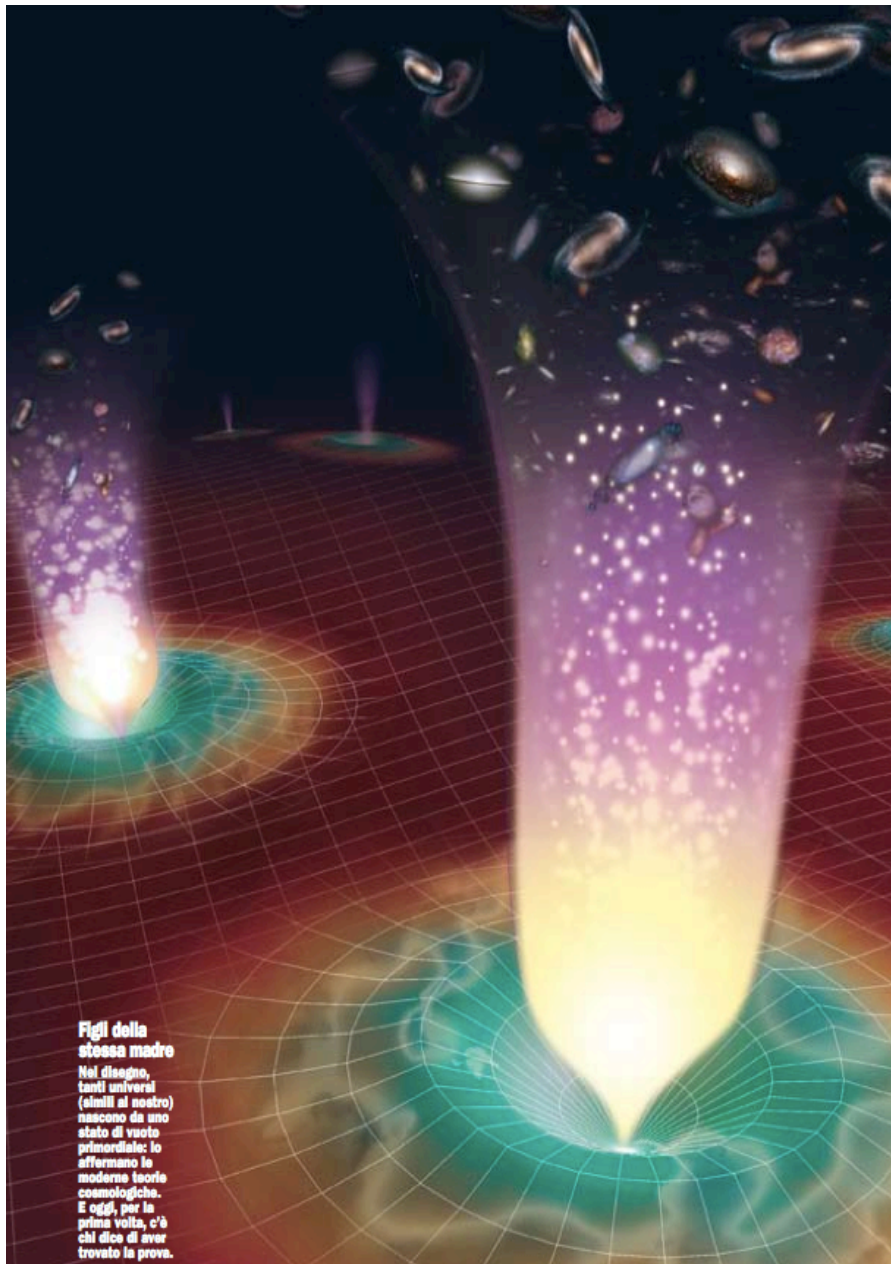
# M-THEORY



Calabi-Yau space



String Landscape

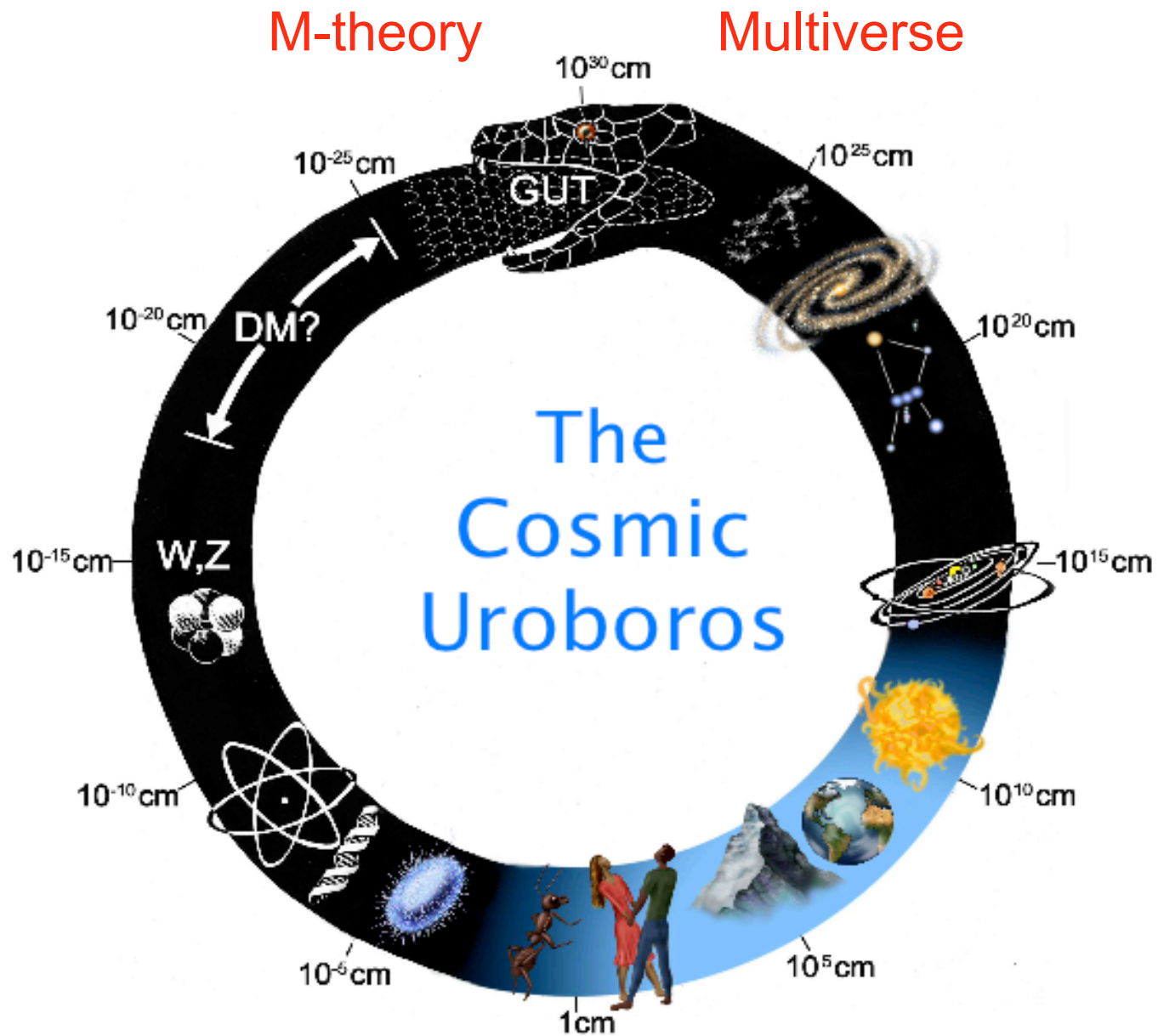


## String Landscape

# POPULAR ARGUMENT FOR MULTIVERSE

- Cosmology => inflation, acceleration
- Particle physics => string landscape

Crucial link is vacuum energy



Multiverse is culmination of macro-micro connection

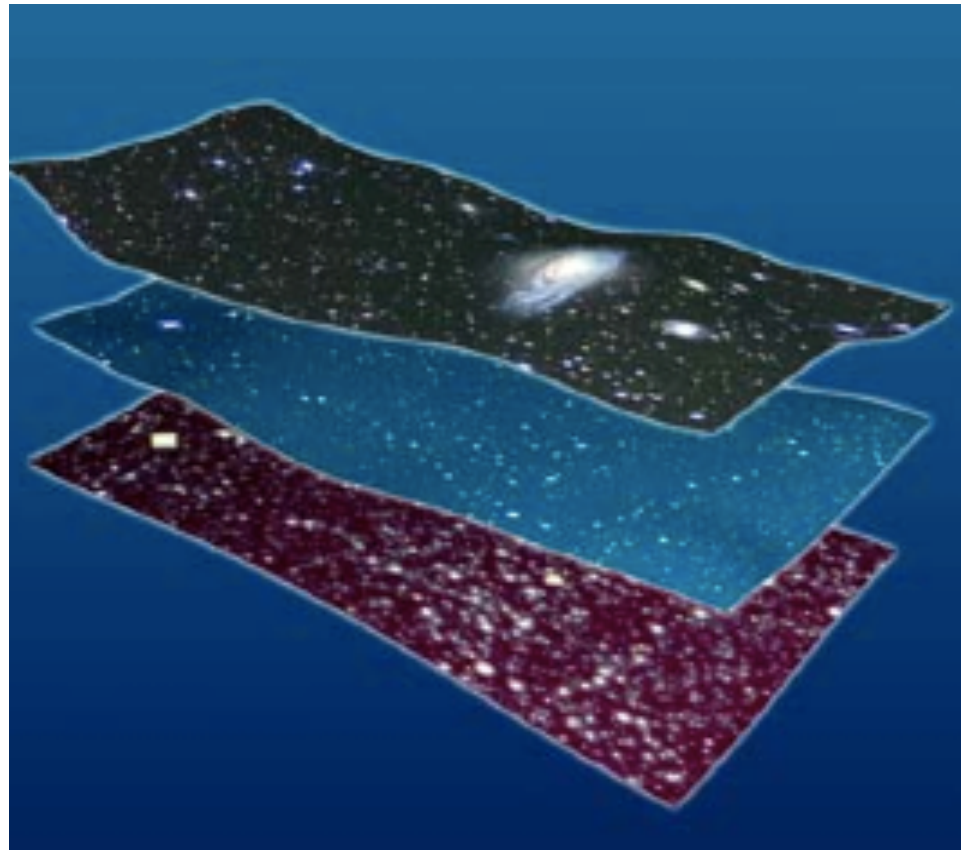
# OTHER MULTIVERSE PROPOSALS

## Cyclic Universe



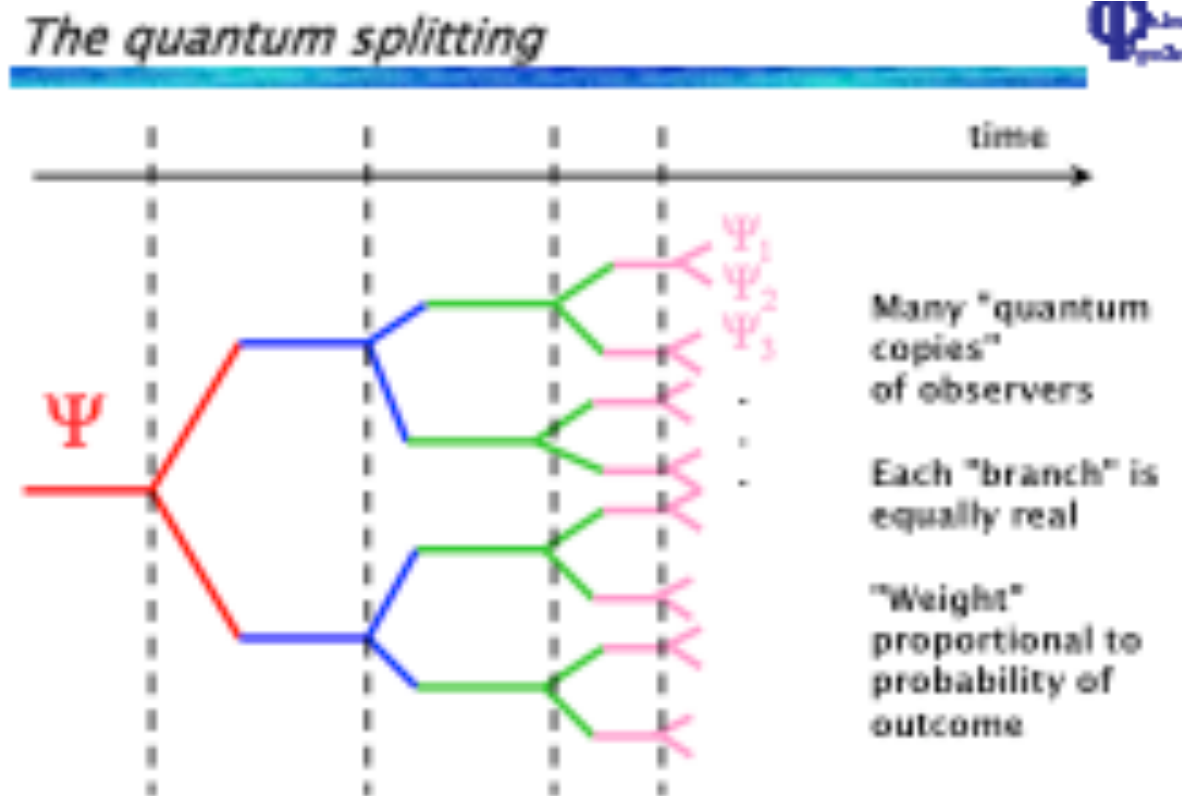
Many universes in time

# Braneworlds





# “Many worlds” interpretation of quantum mechanics



COSMOLOGY



Cyclic model  
Eternal Inflation  
Colliding branes

PARTICLE PHYSICS



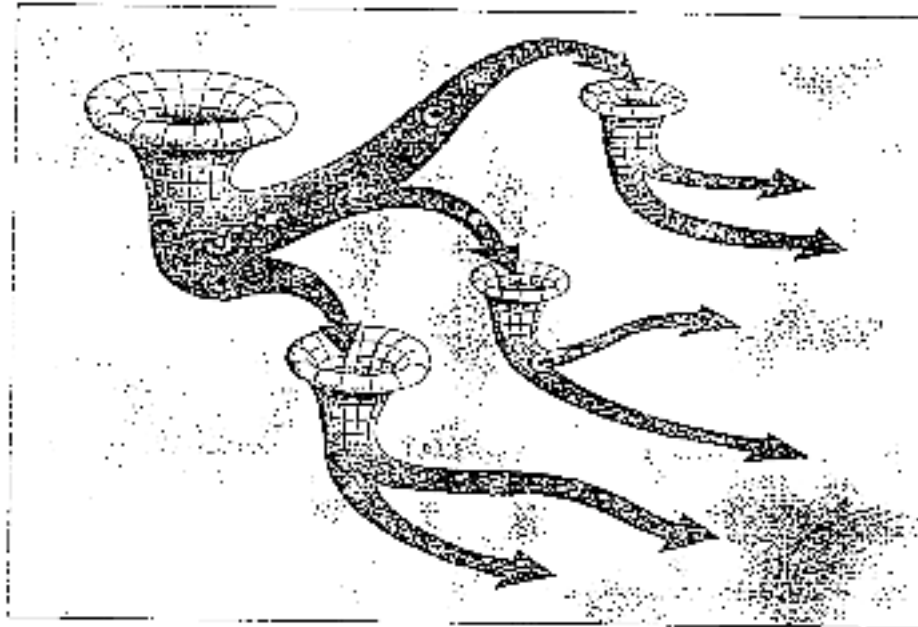
Quantum many worlds  
String landscape  
Quantum cosmology

## Message 3

Cosmology and particle physics suggest  
that there could be many other universes

# Cosmological Natural Selection

Quantum Theory + Relativity Theory + Darwinian Evolution

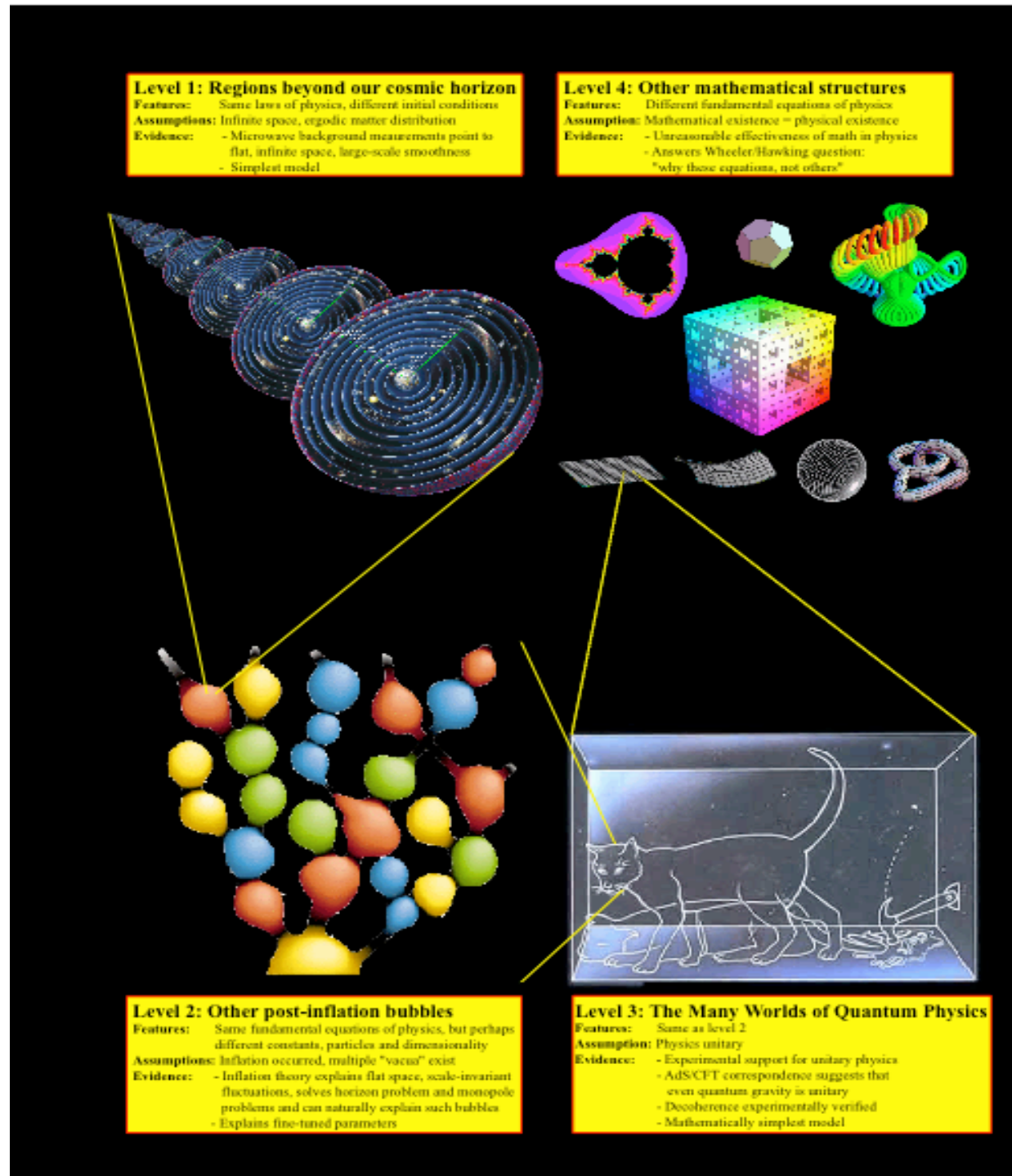


Smolin

Black hole formation => baby universe the small variation of constants

Most likely to be in universe which maximizes black hole formation!

# Tegmark

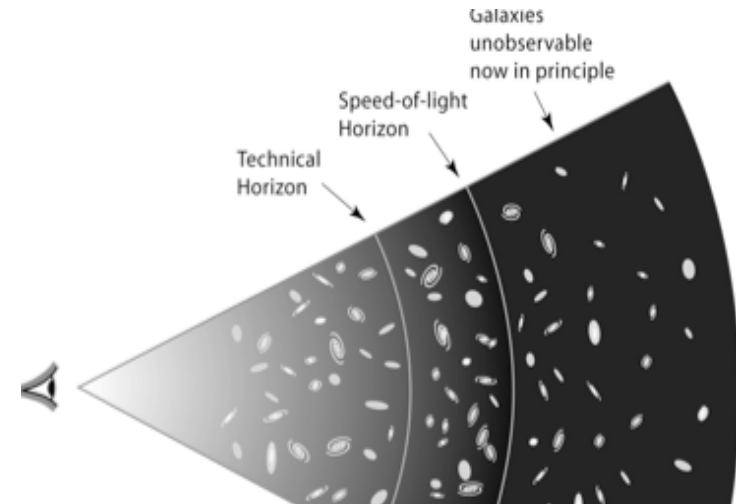


# HOW DO WE KNOW LEVEL I MULTIVERSES EXIST?

Rees's slippery slope argument

Accelerate at 1 g for 100 years

Wormholes



# HOW DO WE KNOW LEVEL II MULTIVERSES EXIST?

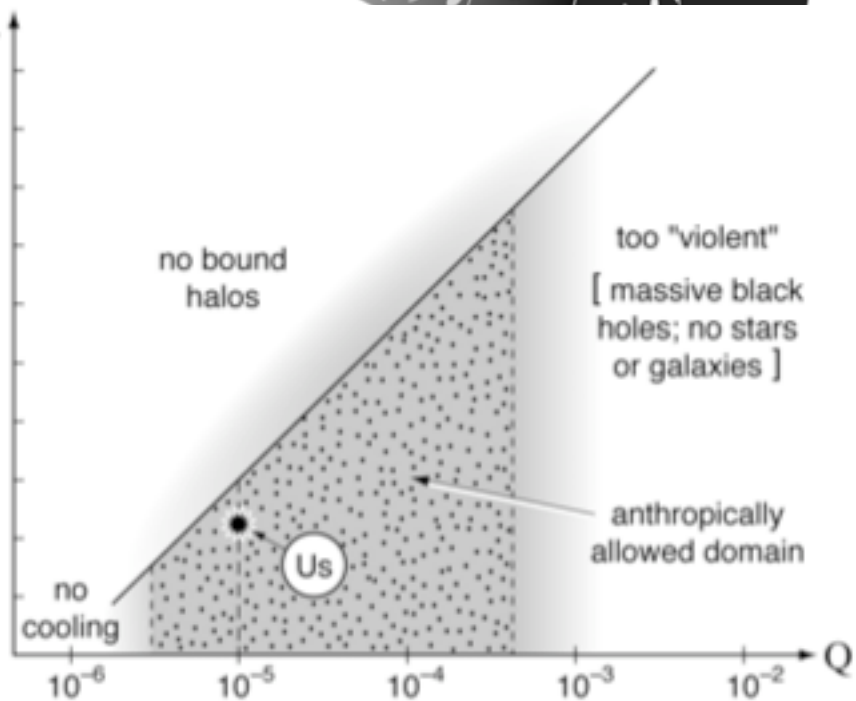
CMB  $\Rightarrow \Delta T/T \sim 1$  for  $10^{100} R_h$

Probability distributions

Bubble collisions

Giant voids

Extra dimensions



# COLLISIONS WITH OTHER UNIVERSES

Garriga, Guth & Vilenkin (2006)

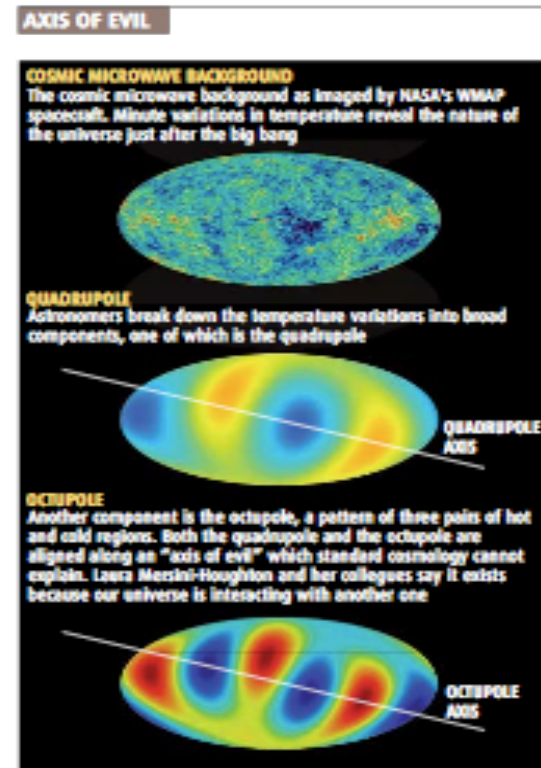
Bubbles will experience collisions with infinite number of bubbles, violating isotropy and homogeneity. Observer not at centre sees anisotropic collision rate peaking in outward direction but memory of onset of inflation persists.

Aguire, Johnson & Shommer (2007)

Benign bubble collision could give scar in CMB and explain axis of evil.

Chang, Kleban & Levi (2008, 2009)

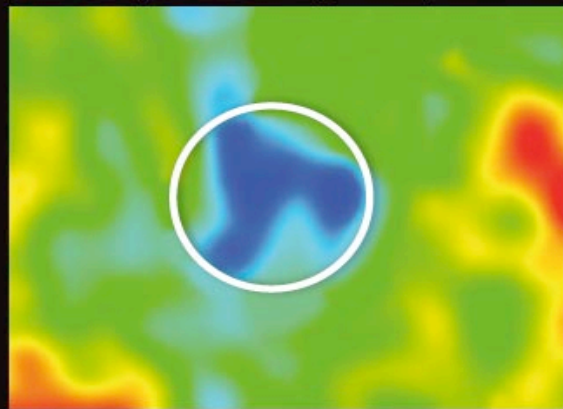
Benign collision if our  $\Lambda$  less than  $\Lambda$  for neighbour. Otherwise form wall between universes which sweeps. Can produce hot or cold spot in CMB.



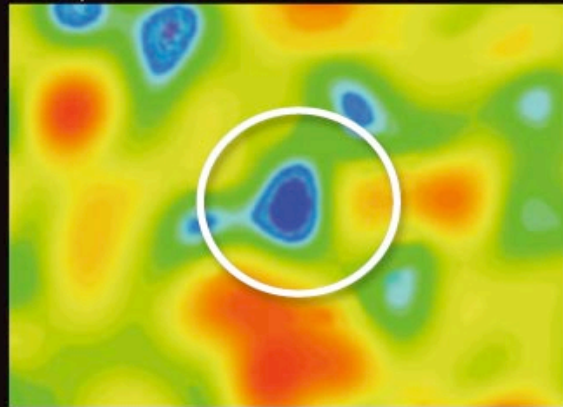
# GIANT VOIDS AS EVIDENCE OF OTHER UNIVERSES

## SENSING THE VOID

The WMAP picture of the cosmic microwave background shows a cold spot that is much larger than expected



The Very Large Array, which measures radio emissions from galaxies, shows that the cold spot also has far fewer galaxies than expected



Holman, Mersini-Haughton & Takahashi (2006).

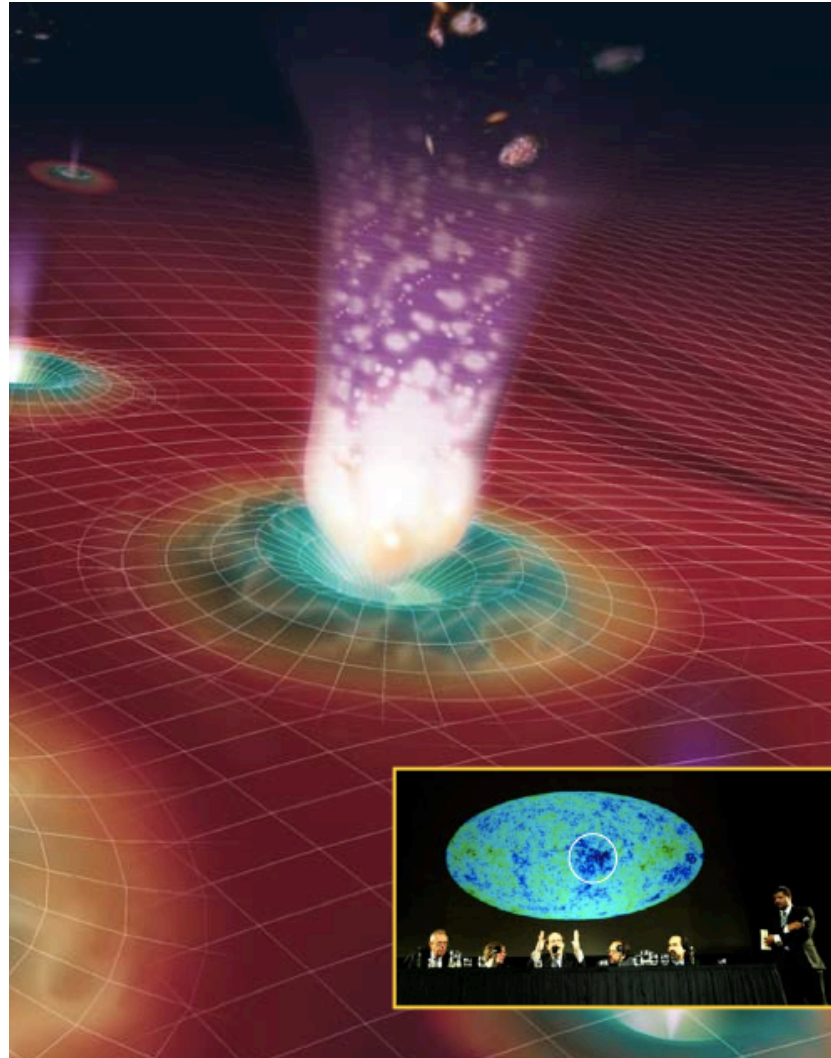
Neighbouring universes affect each other through entanglement. Predicts giant voids in north and south.

Giant void discovered in north by Rudnick et al. (2007). Very unlikely in standard big bang (cf. Peiris).

Mersini-Haughton & Holman (2008)

Also predict inexplicable dark flow, later detected by Kashlinsky et al.

Only current observational evidence for multiverse





HOW DO WE KNOW LEVEL III MULTIVERSES EXIST?

Quantum computers ?

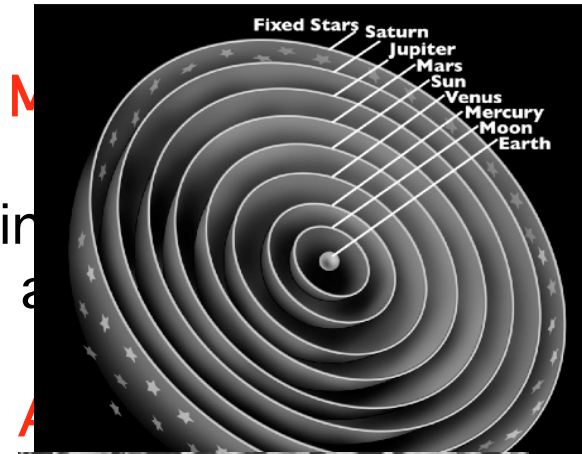
HOW DO WE KNOW LEVEL IV MULTIVERSES EXIST?

Final Theory is typical of life-supporting ones ?

BEST EVIDENCE FOR MULTIVERSE IS FINE-TUNING

# ANTHROPOCENTRIC VIEW

Man is “central” to the Universe



Universe exists in  
Man a

areness of it.  
t

Some features  
by requiremen

“explained”  
should arise

## EVOLV

## IEW

Big Bang s  
and complexity, commanding in mind



# FINE-TUNING OF COUPLING CONSTANTS

Strong force

$$\alpha_S \sim 10$$

Electric force

$$\alpha_e \sim 10^{-2}$$

Weak force

$$\alpha_W \sim 10^{-10}$$

Gravitational force

$$\alpha_G \sim 10^{-40}$$

Will the Final Theory of Everything explain these values?

Planets



$$\alpha_G \sim \alpha_e^{20}$$

Supernovae



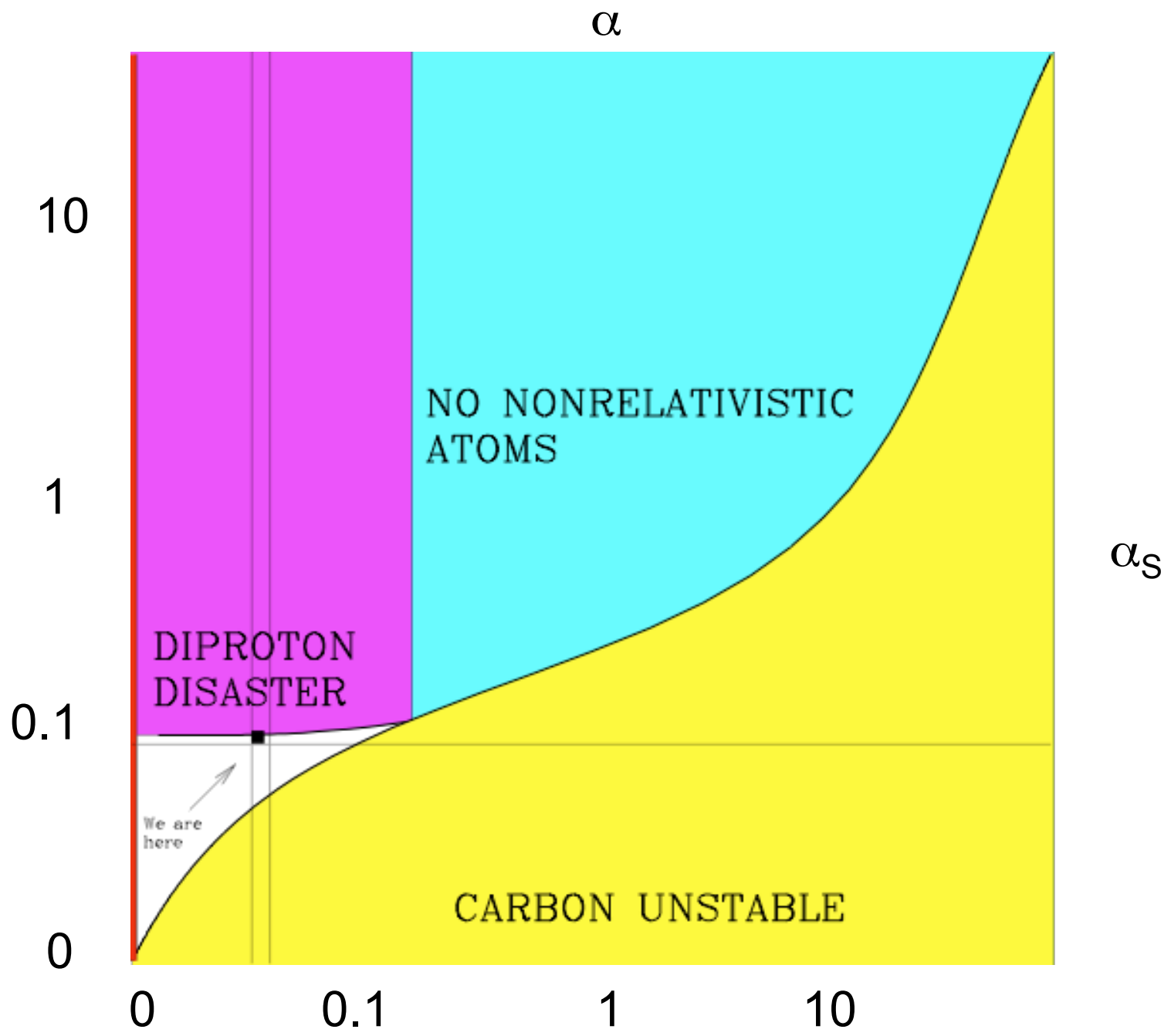
$$\alpha_G \sim \alpha_W^4$$

These relationships required for life but u

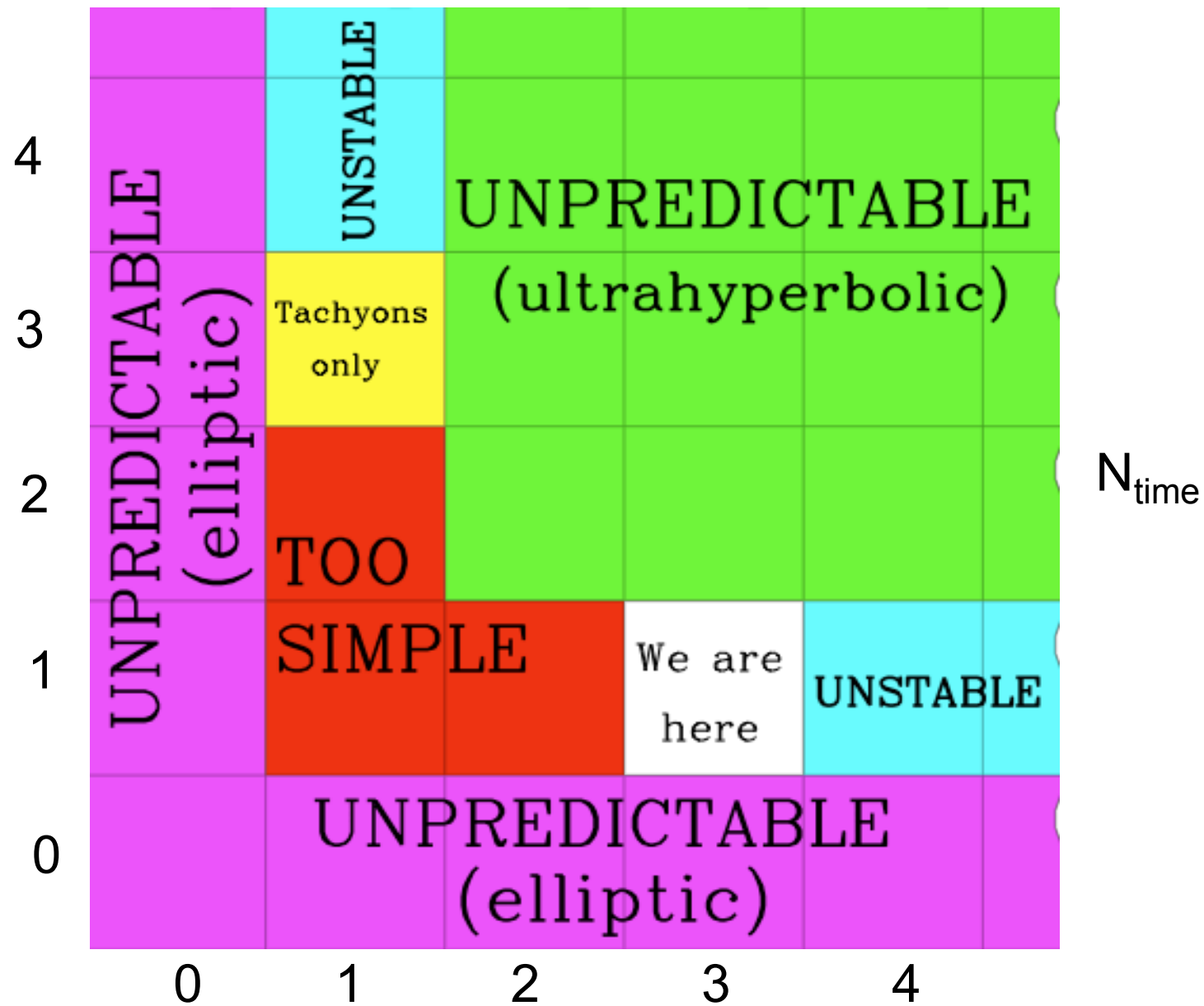


## *Just Six Numbers (Martin Rees)*

- 1.  $N$  = electrical force/gravitational force =  $10^{36}$*
- 2.  $E$  = strength of nuclear binding = 0.007*
- 3.  $\Omega$  = normalized amount of matter in universe = 0.3*
- 4.  $\Lambda$  = normalised cosmological constant = 0.7*
- 5.  $Q$  = seeds for cosmic structures = 1/100,000*
- 6.  $D$  = number of spatial dimensions = 3*

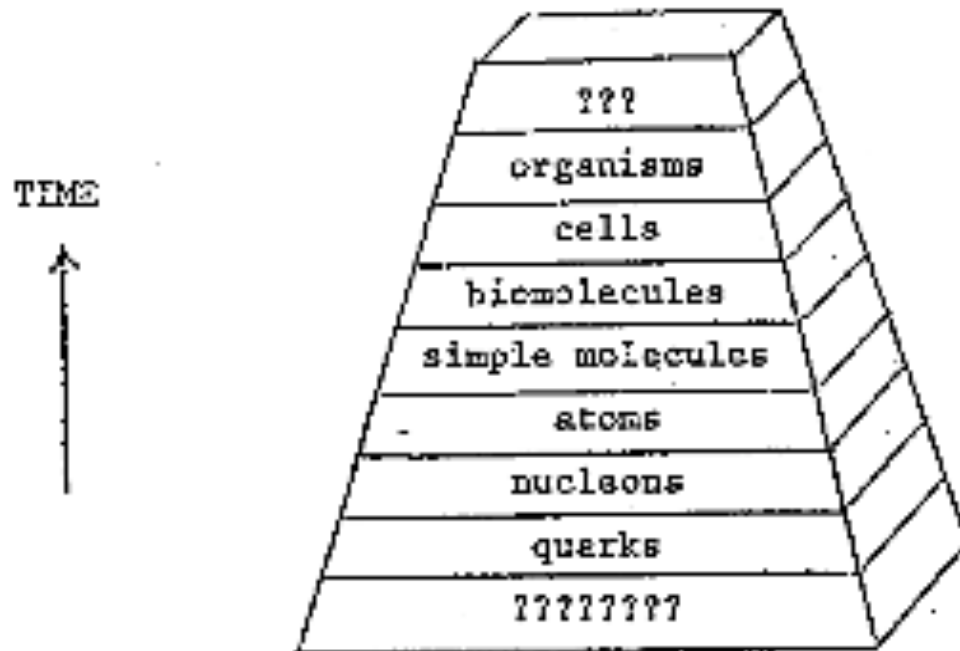


$N_{\text{space}}$



## Message 4

The multiverse naturally explains fine-tunings required for development of complexity



Pyramid of Complexity

# Wilczek's classification of fundamental parameters

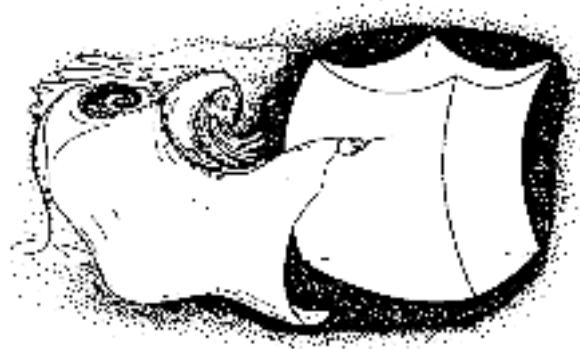
		Selected?	
		Yes	No
Good Design Ideas?	Yes	Enlightenment	Knowledge
	No	Temptation	Ignorance

		Selected?	
		Yes	No
Good Design Ideas?	Yes	$m_p \ll M_{Pl}$	$\theta_{QCD} \ll 1$ unified couplings $\tau_p \gg H^{-1}$
	No	$\rho_\lambda / (\xi^4 Q^3) \sim 10^2$ $m_e, m_u, m_d, \Lambda_{QCD} \rightarrow$ nuclear physics $m_e \ll m_W$	most M, CKM parameters most BSM parameters



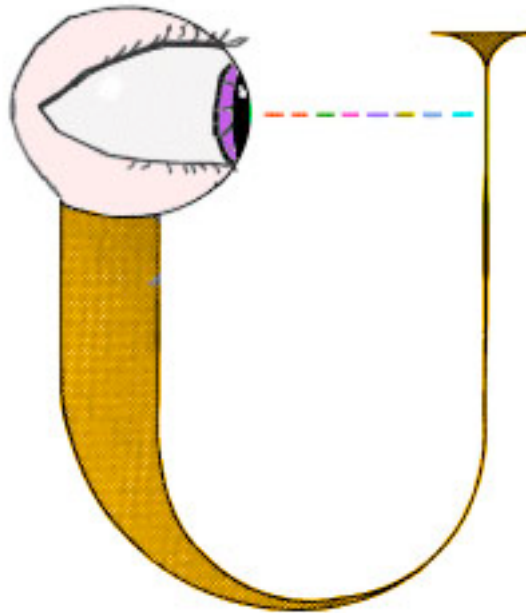
# INTERPRETATIONS OF ANTHROPIC PRINCIPLE

God created universe?



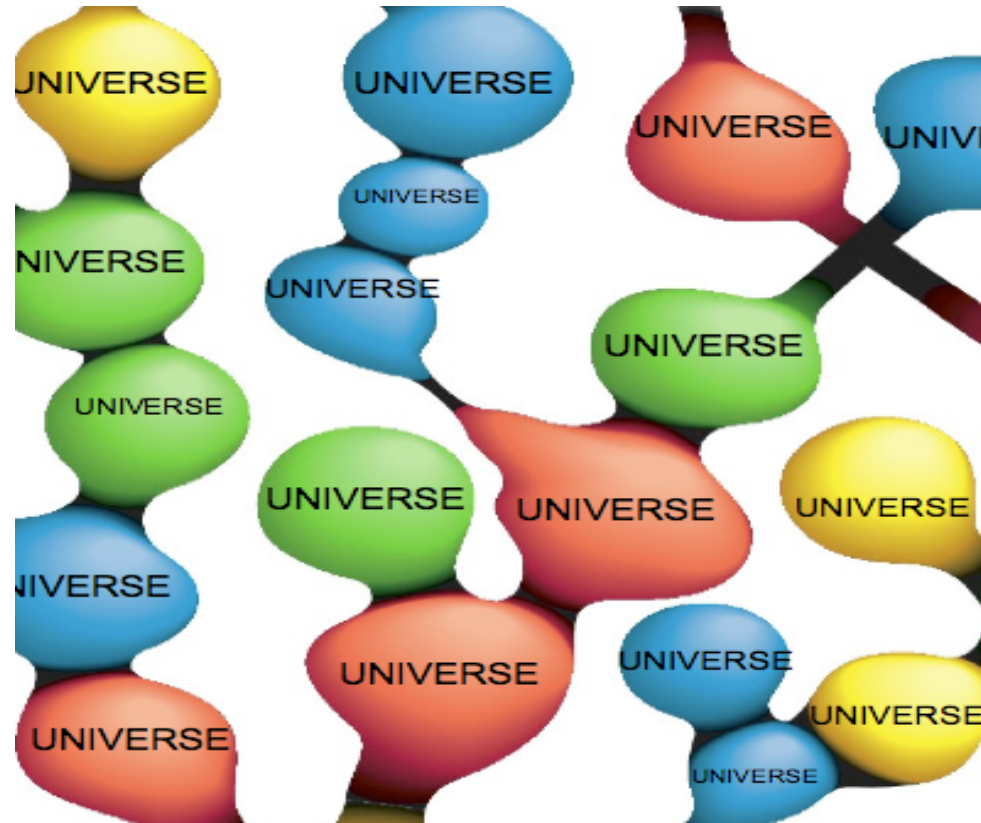
Most physicists don't favour this, which made AP unpopular

## Consciousness creates the Universe

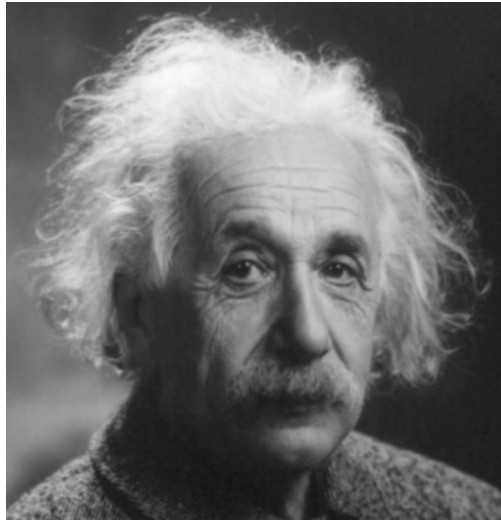


Depends on minority interpretation of quantum theory

# Fine-tunings result from selection effect in multiverse?



Some physicists like this because it removes need for God, others regard it as equally metaphysical.



## Albert Einstein

“What really interests me is whether God had any choice in the creation of the world”

“I would like to state a theorem which at present cannot be based upon anything more than upon a faith in the simplicity, i.e., intelligibility, of nature: there are no arbitrary constants ... that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory).”

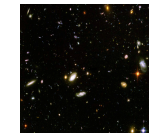
GRAND UNIIFICATION

SCALE WORLDVIEW FORCE



$10^{-25}$  cm

WIMPS



COSMIC EXPANSION



DARK MATTER

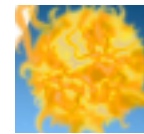
$10^{25}$  cm

Galactocentric



$10^{15}$  cm

Heliocentric



$10^{10}$  cm

Geocentric

GRAVITY

ELECTROWEAK



$10^{-15}$  cm

WEAK STRONG



$10^{-10}$  cm

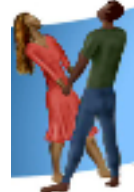
ELECTRICITY



$10^{-6}$  cm

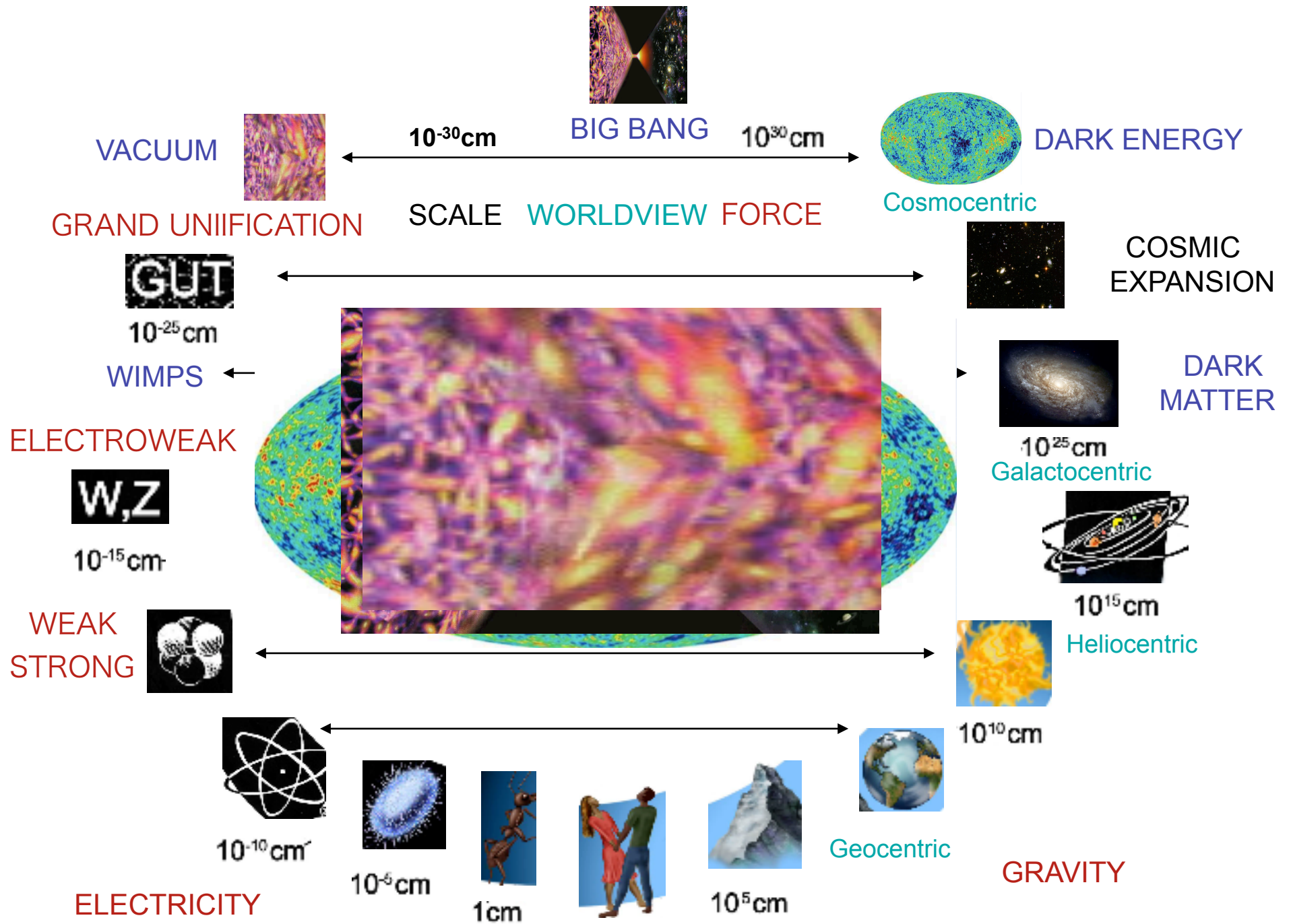


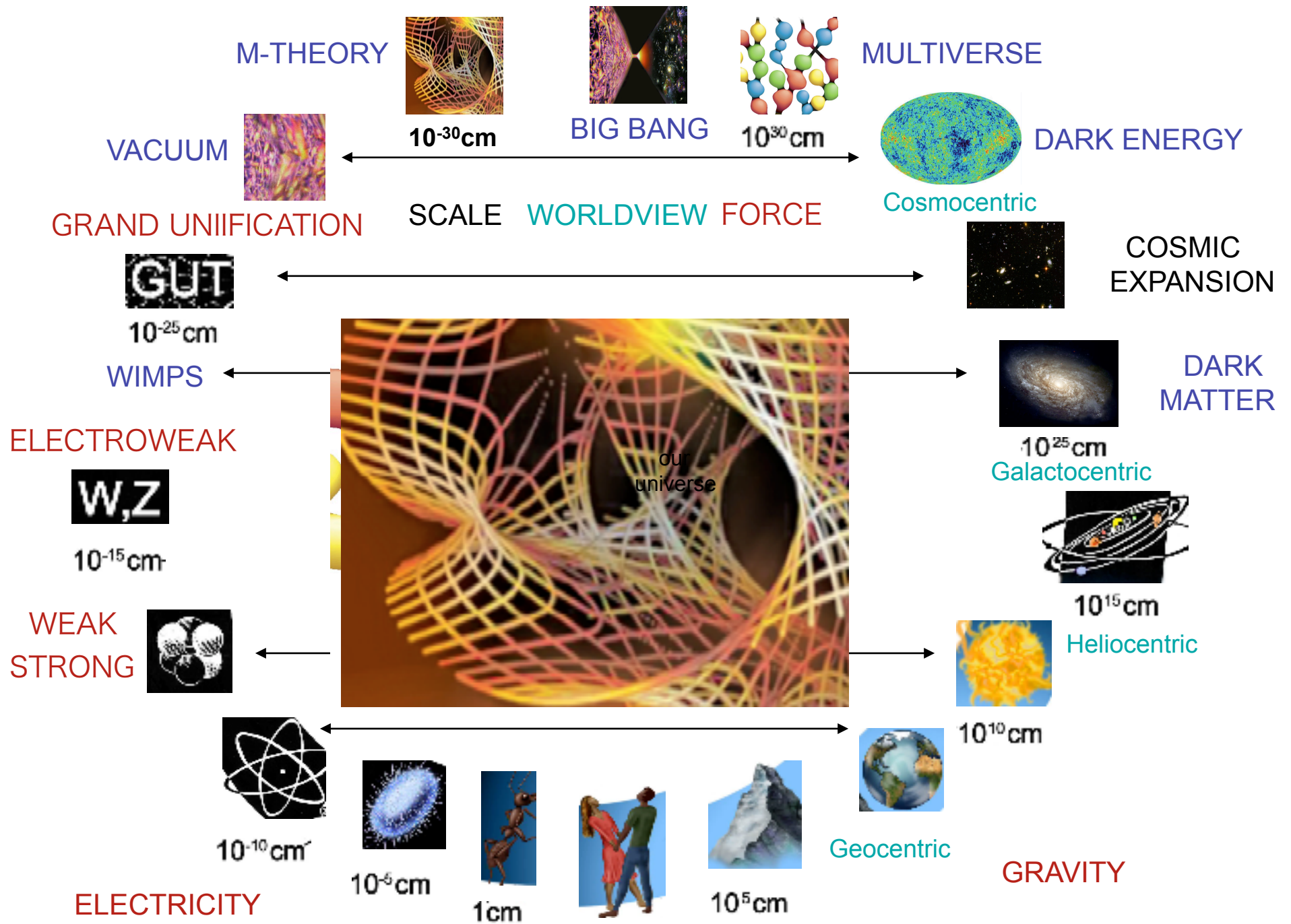
1cm



$10^5$  cm





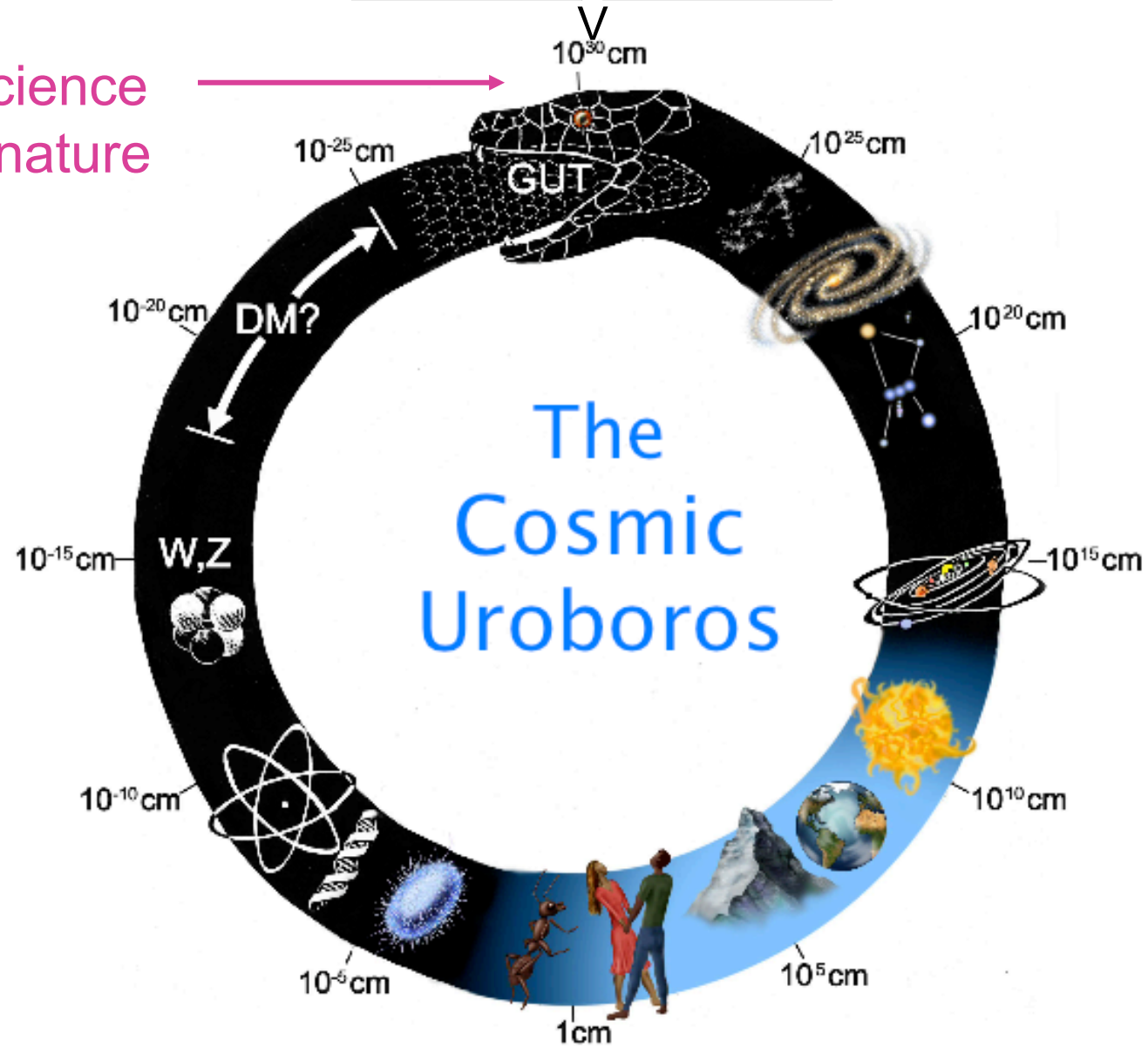


Multiverse

Higher dimensions

M-theory

The limit of science  
or change in nature  
of science?





# DOES BIG BANG NEED A CREATOR?

- How did Universe originate?
- It started as state of compressed matter 13 Gyr ago
- But where did the matter come from?
- From radiation and GUT processes at microsecond
- But where did the radiation come from?
- Generated from vacuum phase transition at  $10^{-35}$ sec
- But where did space come from?
- Ex nihilo as result of quantum gravity at  $10^{-43}$ sec
- But where did laws of quantum gravity come from?
- The laws are logical mathematical necessities

What are the limits of legitimate science?

Where does it hand over to philosophy and theology?

# PARADIGM SHIFTS - CHANGING DIMENSIONALITY OF PHYSICS

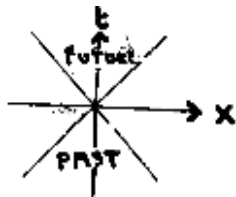
## NEWTONIAN PICTURE



Absolute space and time

3D

## SPECIAL RELATIVITY



Space + time = spacetime

4D

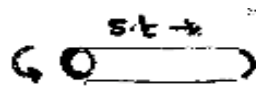
## GENERAL RELATIVITY



Gravity = curved spacetime

>4D

## KALUZA-KLEIN PICTURE



Electromagnetism = 5th dimension

5D

## M-THEORY

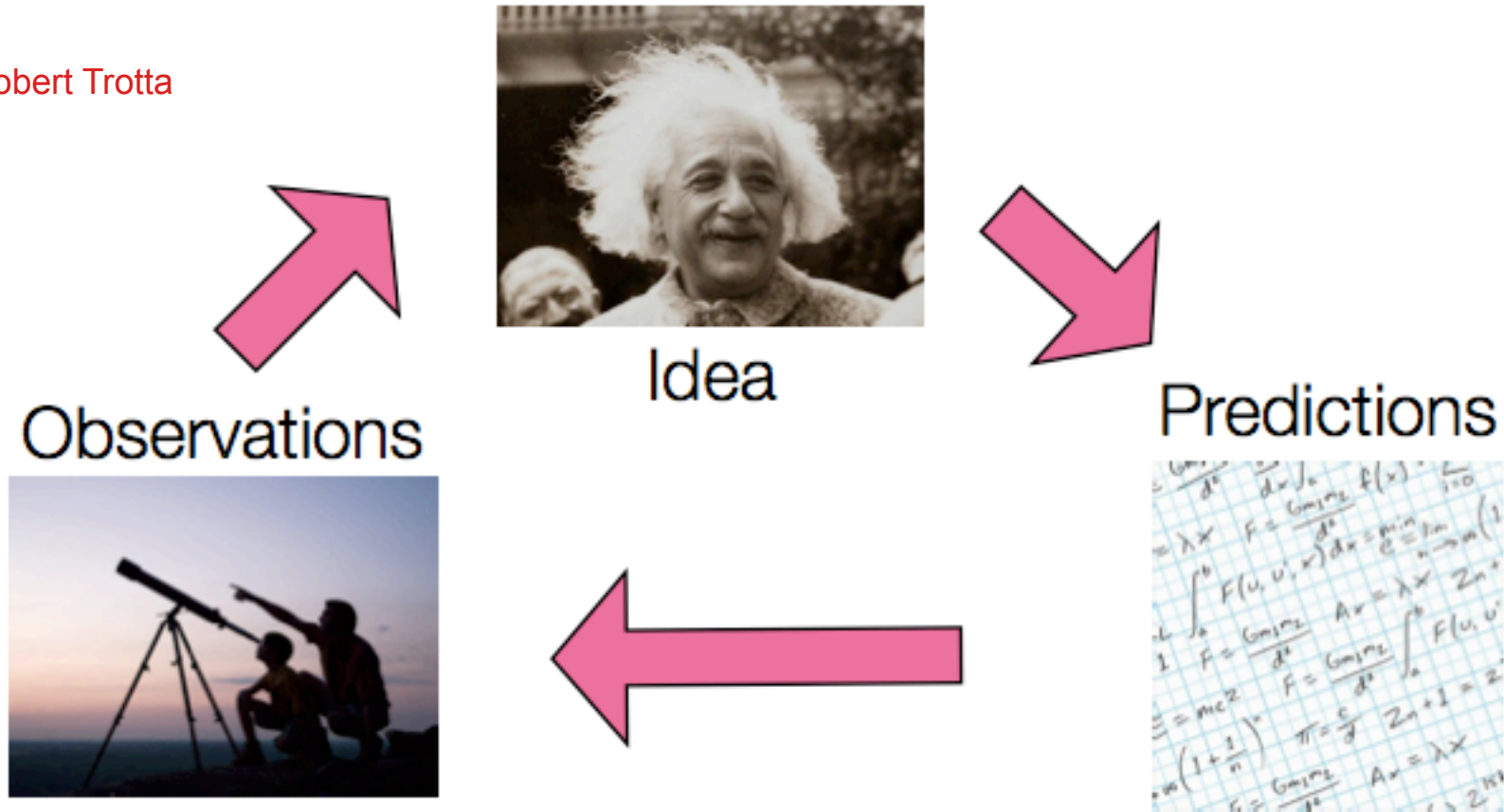


Other forces = other dimensions

11D

# THE NATURE OF LEGITIMATE SCIENCE

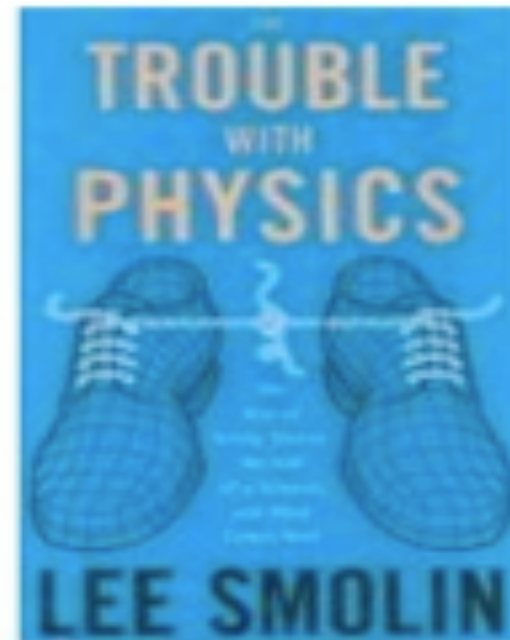
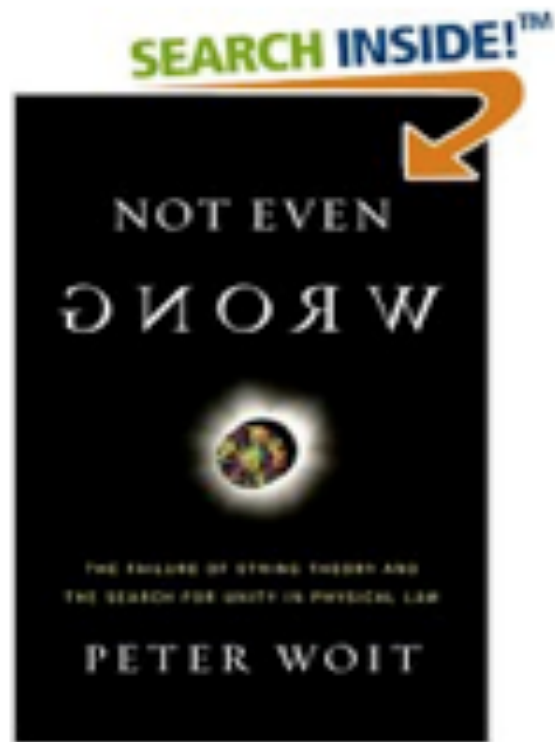
Robert Trotta



What is the timescale of each of these steps?

One needs a degree of falsifiability but how much and how soon?

The multiverse is part of science if it is predicted by a physical theory which is testable (M-theory). But what if theory is itself untestable?



# Conclusion

## The nature of legitimate science changes



Steven Weinberg

We usually mark advances in the history of science by what we learn about nature, but at certain critical moments the most important thing is what we discover about science itself. These discoveries lead to changes in how we score our work, in what we consider to be an acceptable theory.

I found a report of a discussion at a conference at Stanford, at which Martin Rees said that he was sufficiently confident about the multiverse to bet his dog's life on it, while Andrei Linde said he would bet his own life. As for me, I have just enough confidence about the multiverse to bet the lives of both Andrei Linde *and* Martin Rees's dog.



**Lesson 5:** Don't necessarily reject theoretical prediction because no observational support

## Message 5

What we call the “universe” is always growing and as it does so nature of legitimate science changes



Freivogel, Horowitz & Shenker (2007)

$\Lambda=0$  bubble colliding with  $\Lambda < 0$  bubble

Chang, Kleban & Levi (2008, 2009)

Generalize work of Freivogel et al. to non-zero  $\Lambda$  and finds can produce axis of evil. Benign collision if our  $\Lambda$  less than neighbour. Otherwise form wall between universes which sweeps through at  $c$ . Can produce hot or cold spot in CMB which can survival arbitrarily long.

Freivogel, Kleban, Nicolis & Sigurdson (2009)

Calculate probability distribution for bubble collisions and allow for dynamics of domain walls that form between them. Now predict isotropic distribution.

Dahlen (2009)

Extend Freivogel et al. to case with identical bubbles.



- The well known principle that “entities must not be multiplied beyond necessity”

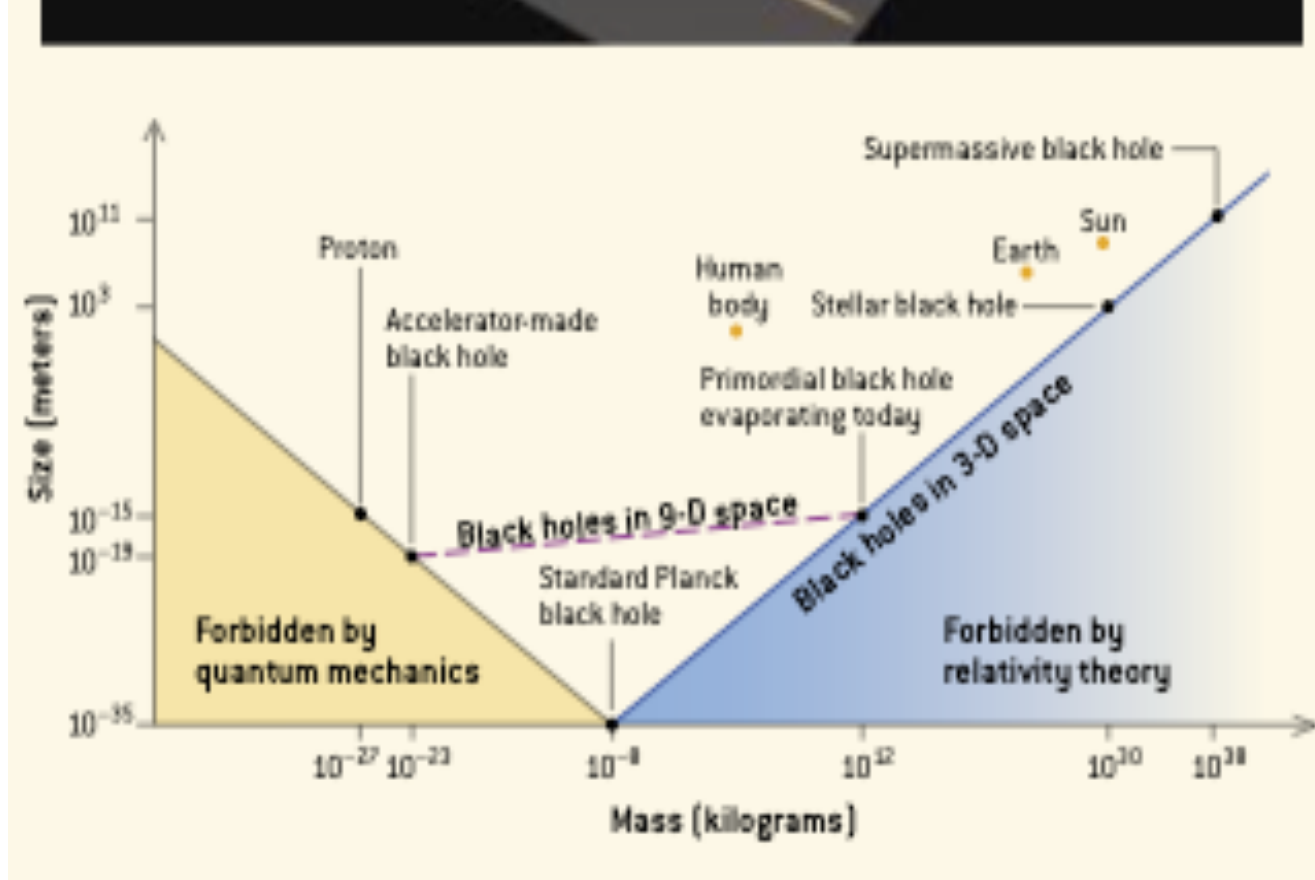
## OCCAM'S RAZOR

*A Parsimonious  
Shave Every  
Time!*



“We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. Therefore, to the same natural effects we must, so far as possible, assign the same causes.”

Isaac Newton



## Black holes as a probe of higher dimensions

Increasing  $E \rightarrow$  evol'n of dimensionality of early Universe

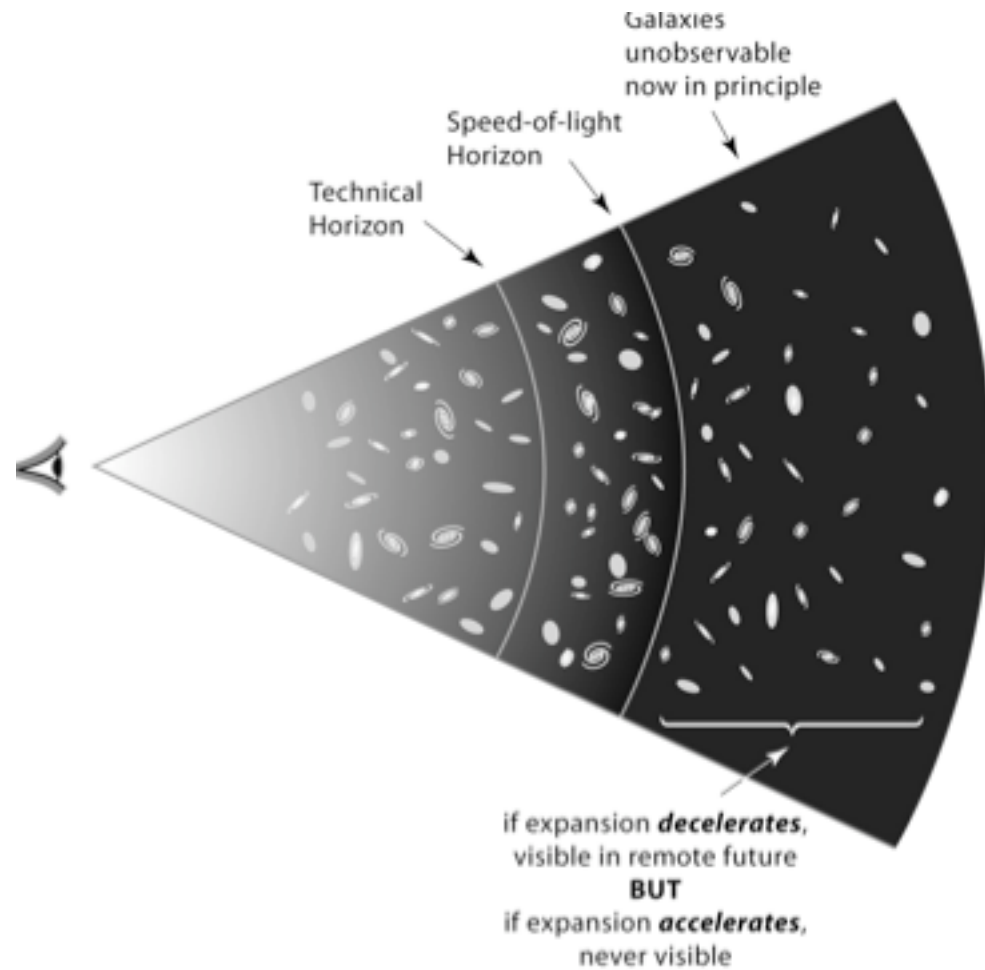
# *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design* Leonard Susskind



Why is a certain constant of nature one number rather than another? Susskind concludes that "somewhere in the megaverse the constant equals this number, somewhere else it is that number. We live in one tiny pocket where the value of the constant is consistent with our kind of life. That's it! That's all. There is no other answer to the question. The anthropic principle is thus rendered respectable and intelligent design is just an illusion"

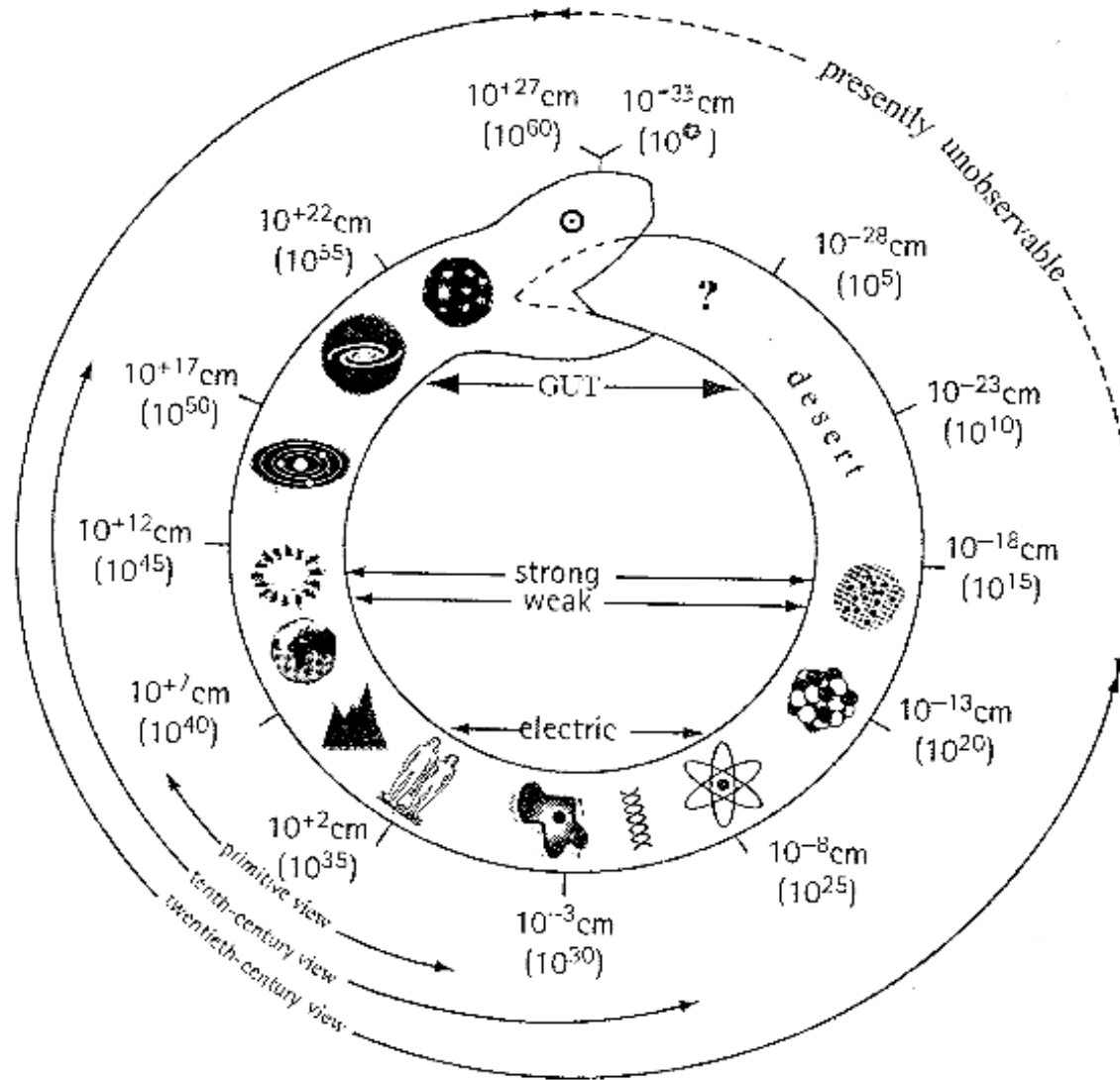
Observable universe is tiny part of physical reality

But is the unobservable universe part of science?

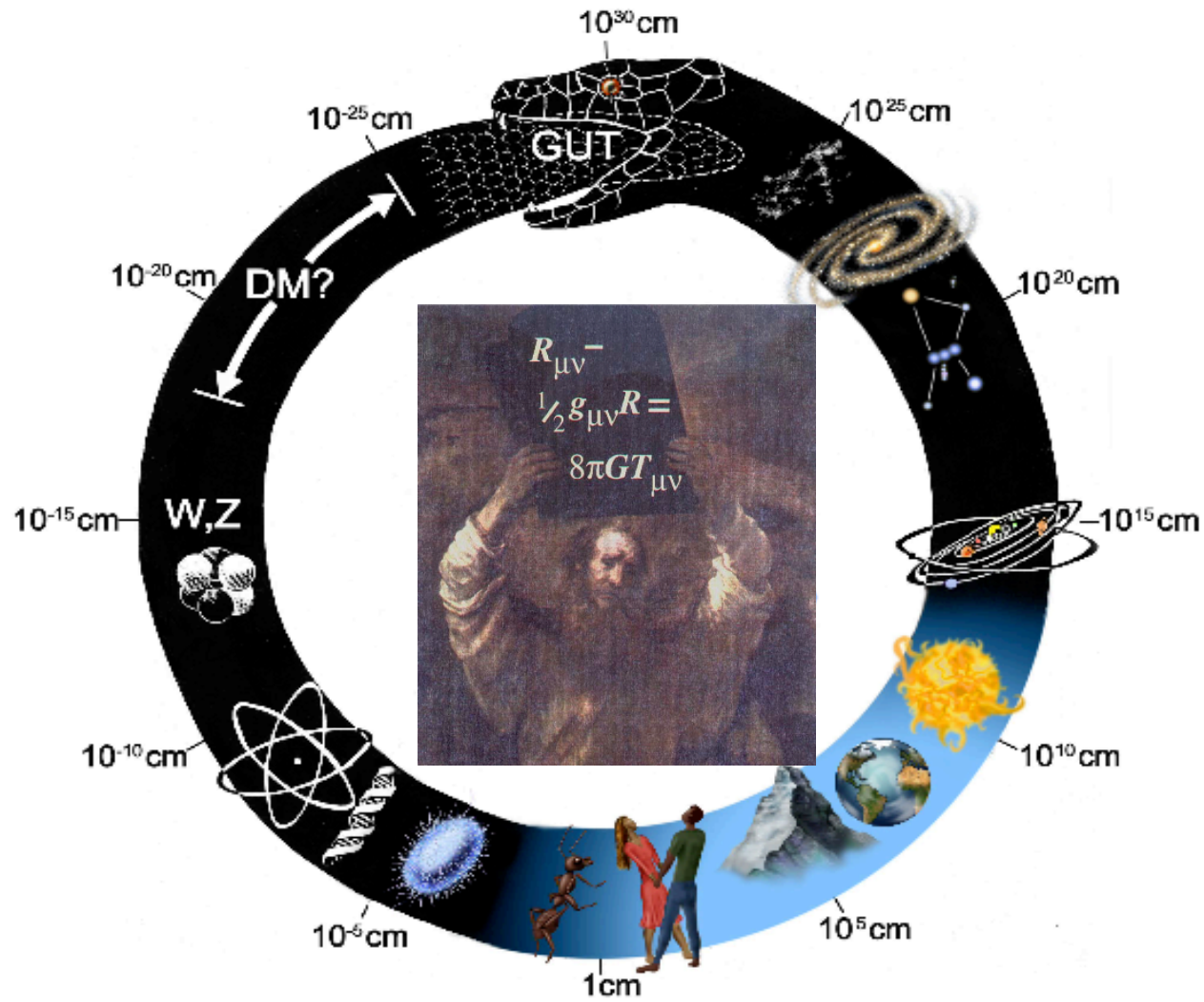


Martin Rees' slippery slope

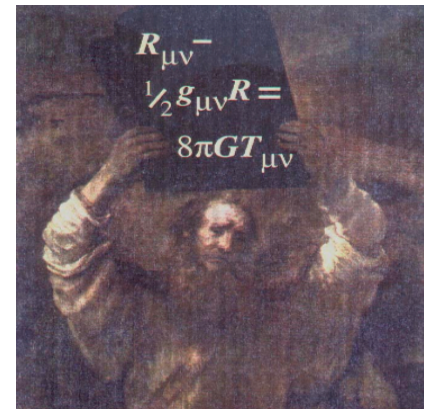
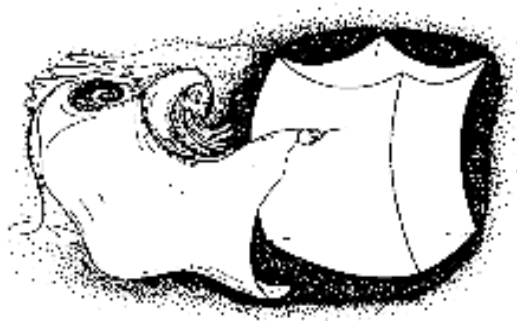
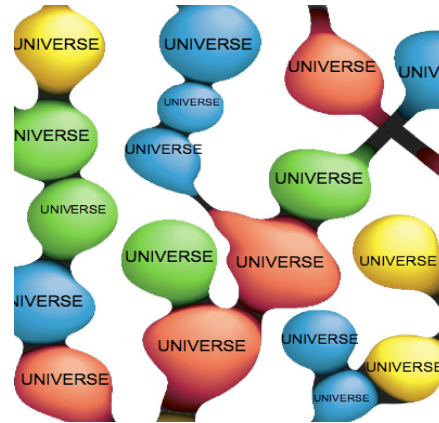
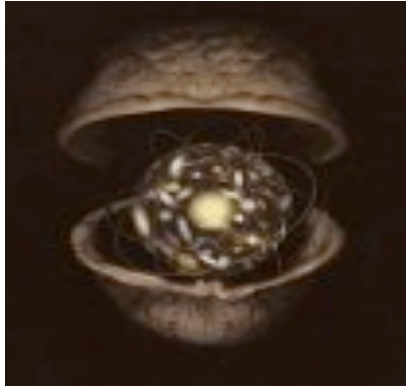
# COSMIC UROBORUS



# Is there room for God?



# FOUR VIEWS



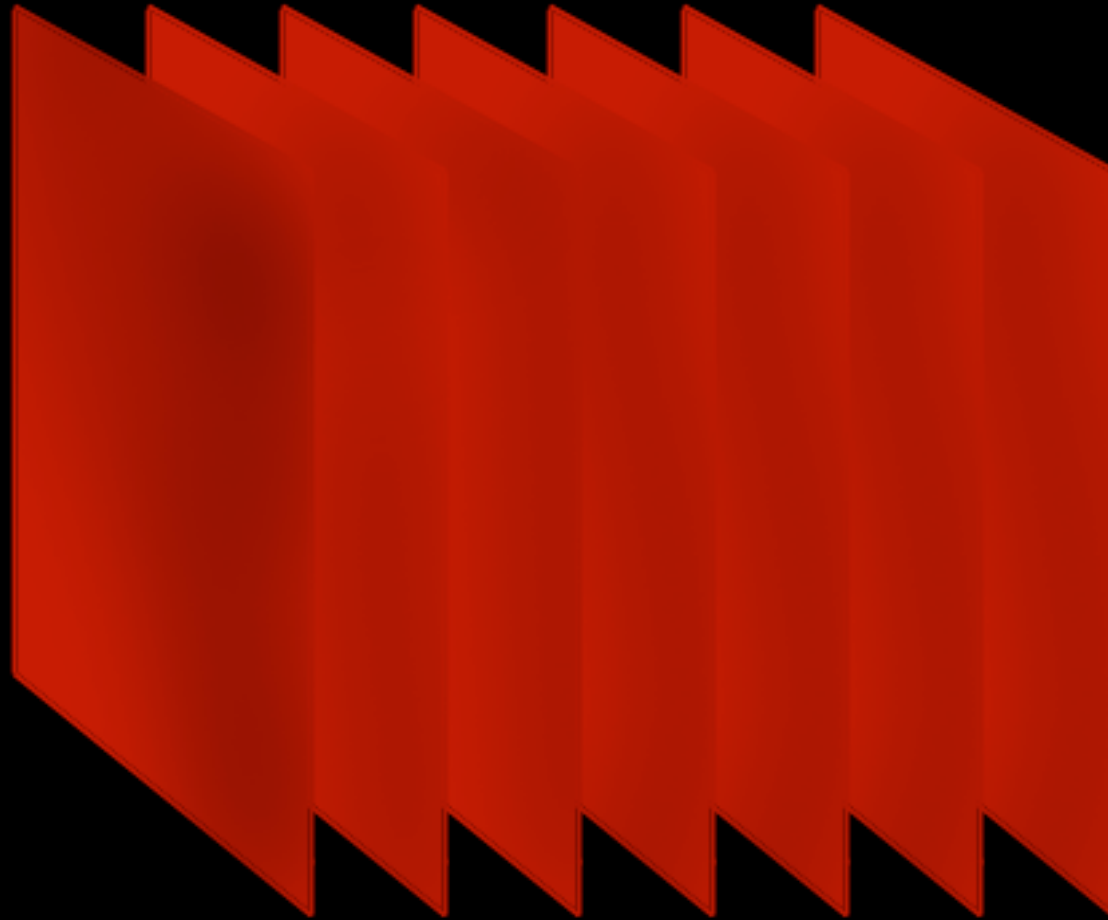
## BONES OF CONTENTION

(Carr v Ellis, A & G, April 2008)

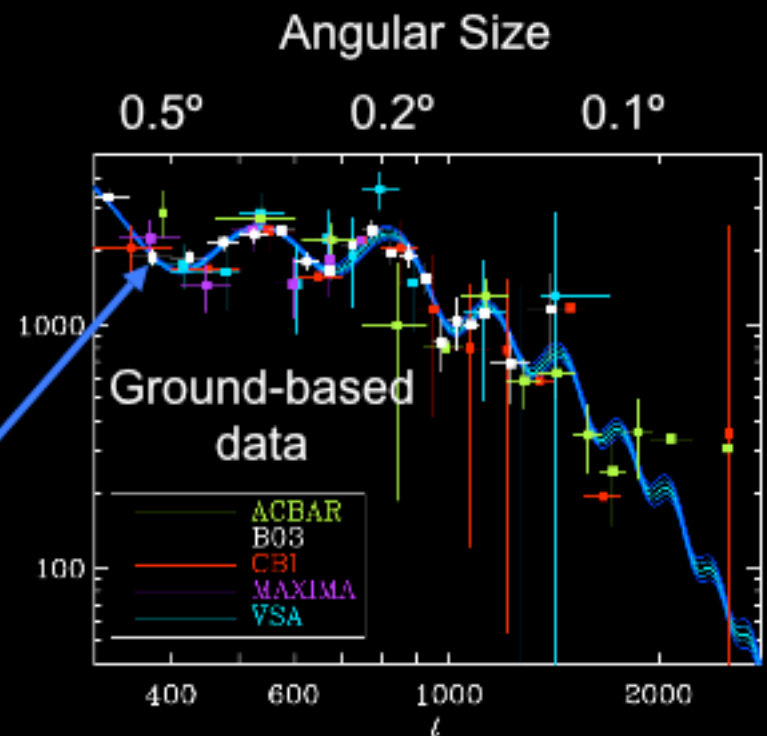
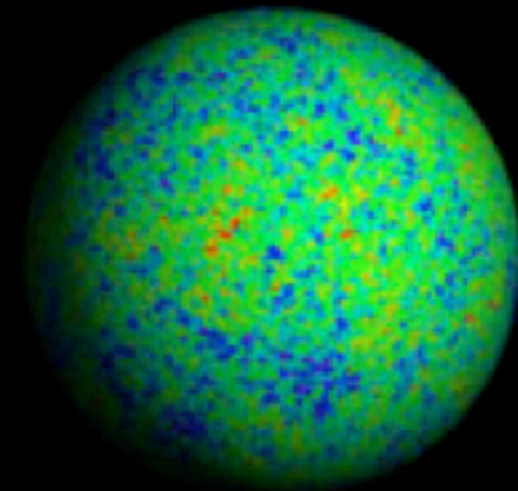
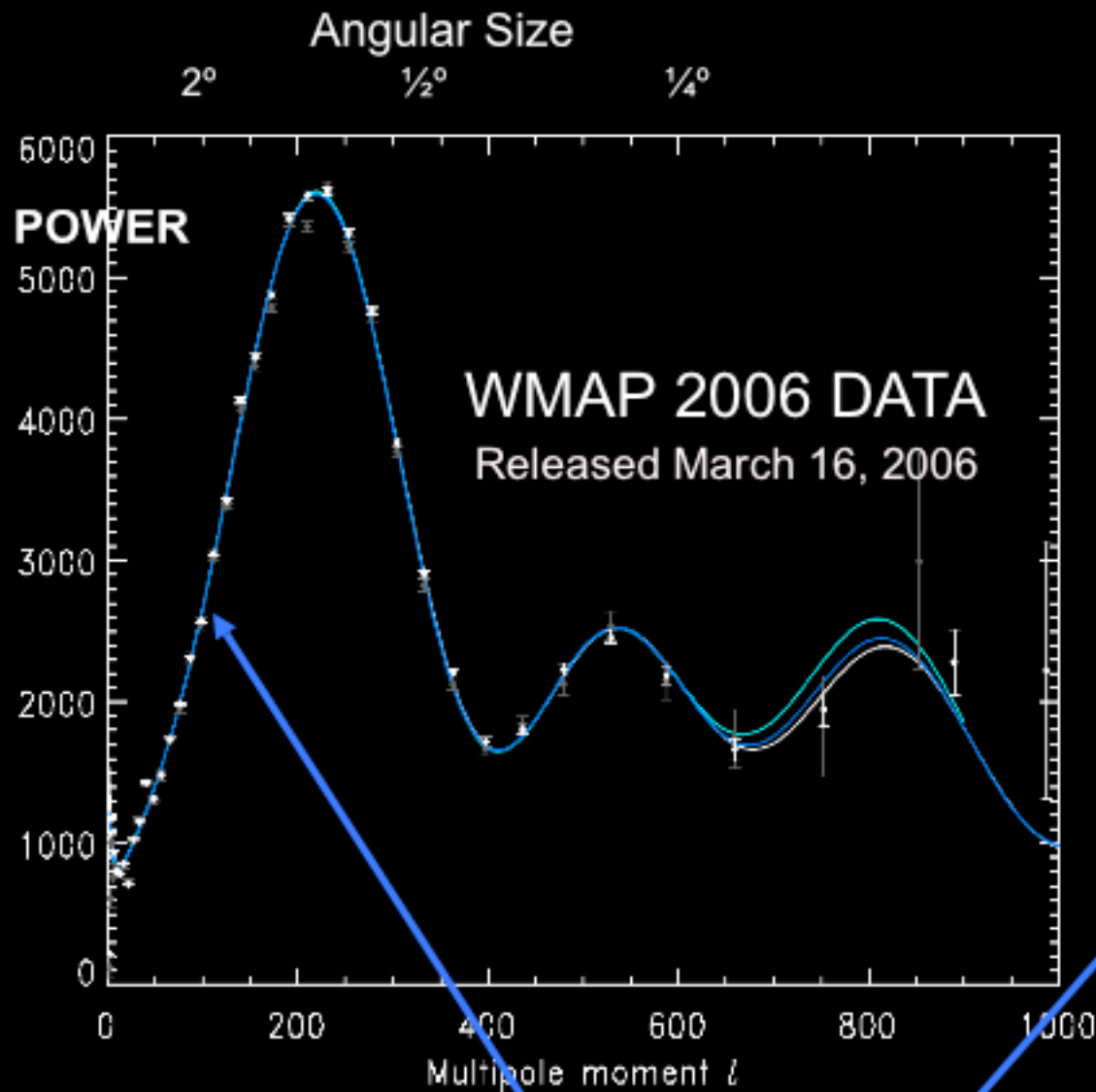
1. There are plausibly galaxies just beyond the visual horizon, where we cannot see them, so we can extend this argument, step by step, to way beyond the horizon and infer there are many different universes which we cannot see.
2. The existence of a multiverse is implied by inflation, which is verified by the CMB anisotropy observations. In particular, known physics leads to chaotic inflation and this implies a multiverse.
3. The existence of a multiverse is the only physical explanation for the fine-tuning of parameters that leads to our existence.
4. The existence of a multiverse is implied by a probability argument: the universe is no more special than it need be to create life. In particular the small value of the cosmological constant shows that other universes exist.
5. Even if one does not accept inflation, multiverses are predicted by many theories of particle physics.
6. The nature of science changes, so what is illegitimate science today may be legitimate tomorrow.



# Braneworlds...



# Latest Big Bang Data Strengthens the Agreement!



**Double Dark theory**