THE COSMOLOGICAL CONSTANT

$$\underbrace{R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda}_{\text{STRUCTURE OF SPACE-TIME}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{MATTER + ENERGY}}$$

ATTRACTIVE

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} \underbrace{- g_{\mu\nu}\Lambda}_{\text{REPULSIVE}}$$

WITHOUT Λ THE UNIVERSE CONTRACTS

EINSTEIN PUT Λ IN, TO MAKE IT STATIC

$$\Lambda = 8\pi\left(\frac{G}{c^4}\right)\rho_{VAC} = K\rho_{VAC}$$

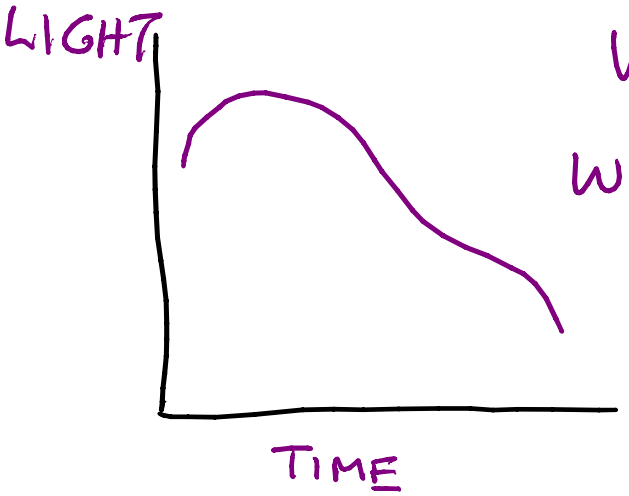
ENERGY DENSITY OF VACUUM

UNTIL 1998 MOST COSMOLOGISTS WOULD HAVE SAID $\Lambda = 0$

PERLMUTTER *et al* STUDIED TYPE 1A SUPERNOVAE → WHITE DWARF PULLS IN MATERIAL FROM COMPANION

LIGHT GENERATED ~ 10^{11} STARS

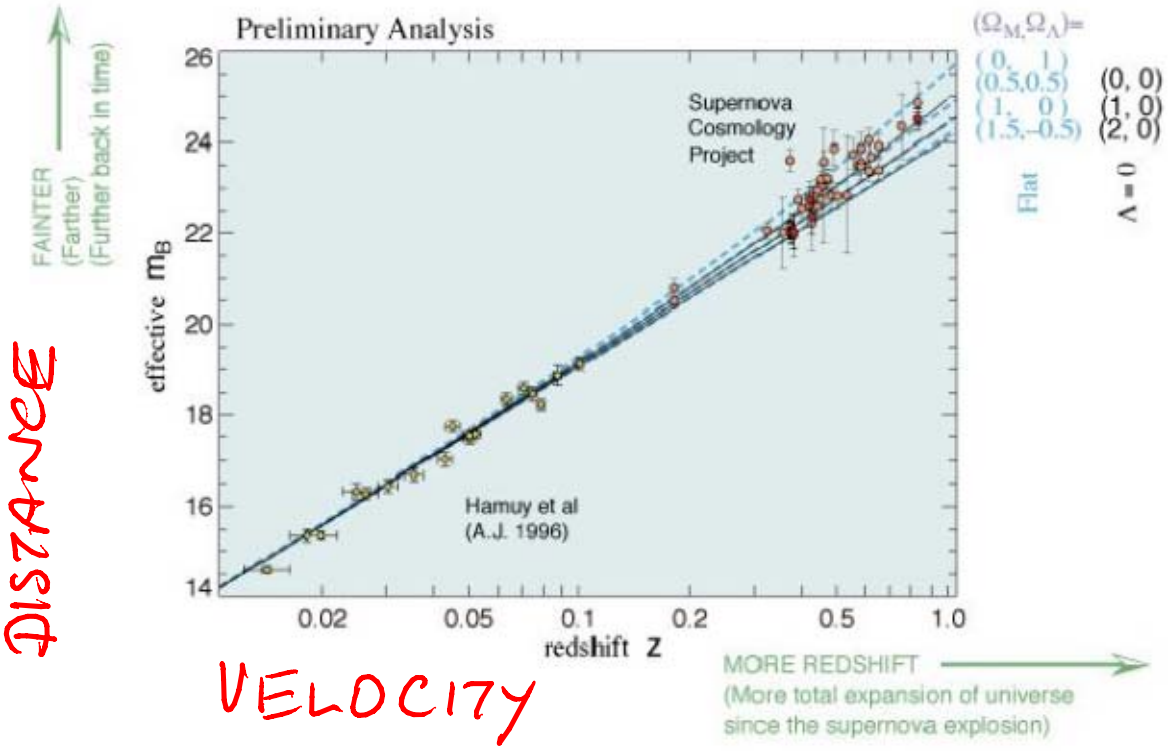
THEY OCCUR EVERY FEW HUNDRED YEARS IN A TYPICAL GALAXY



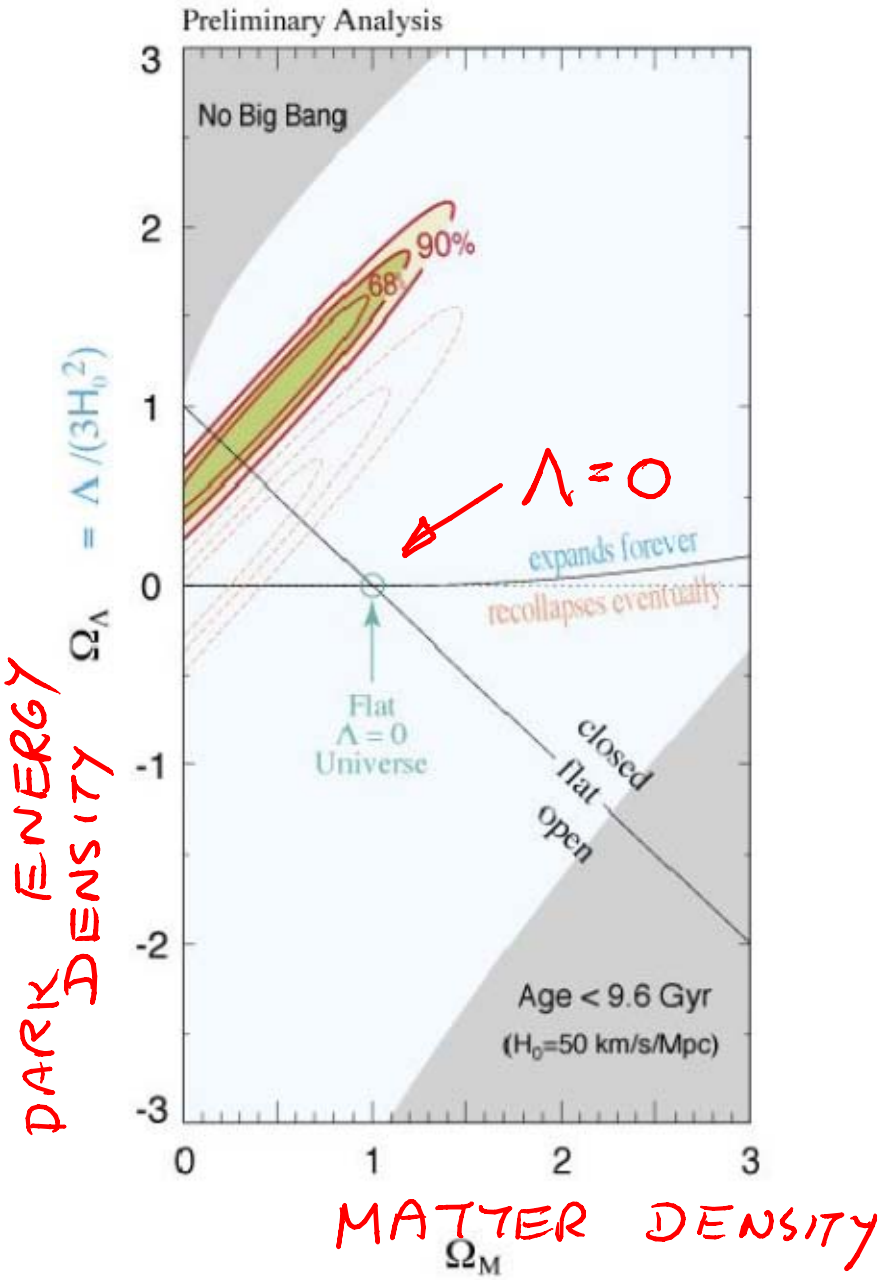
VARIATIONS OF LIGHT OUTPUT WITH TIME → ABSOLUTE BRIGHTNESS

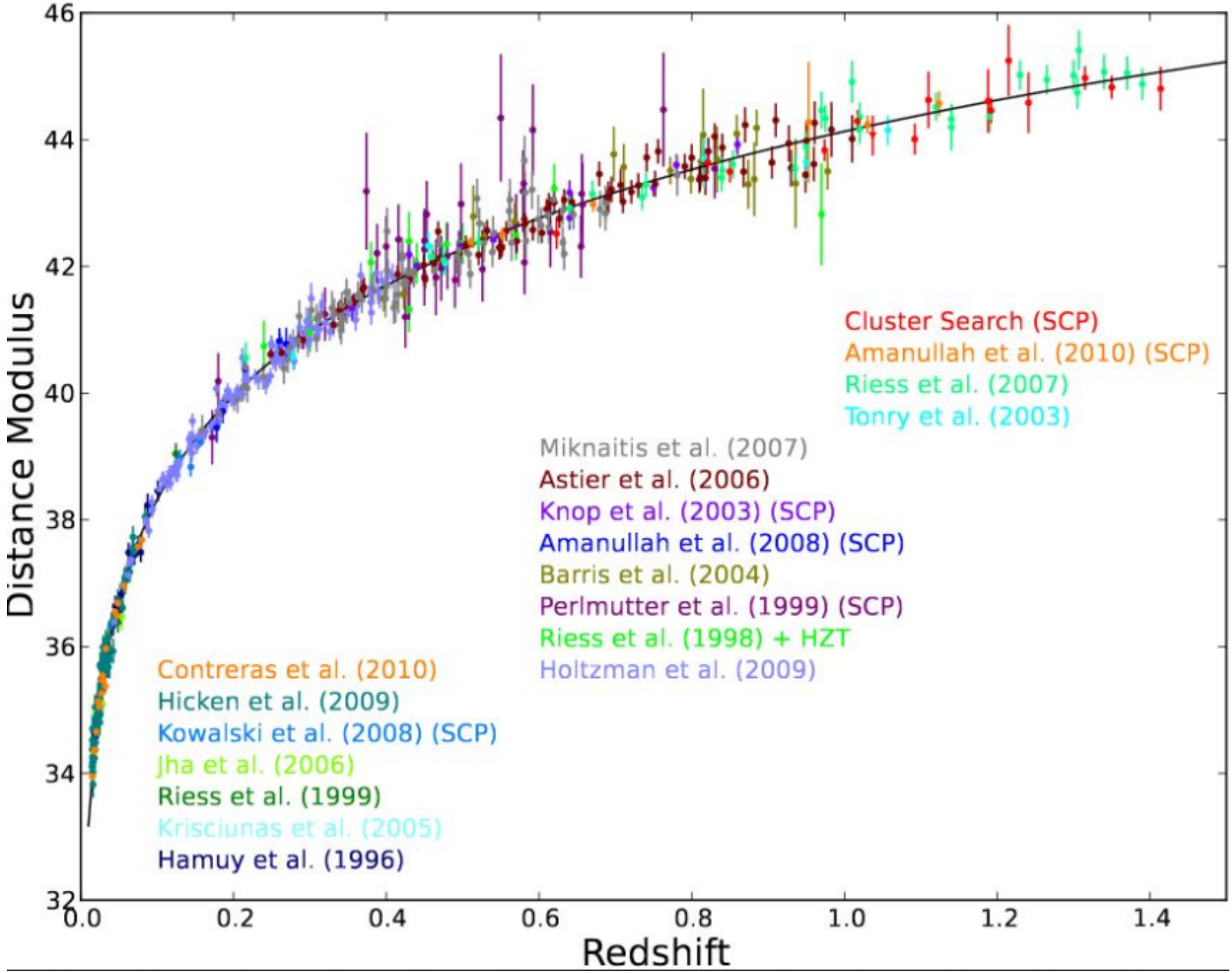
STANDARD CANDEL

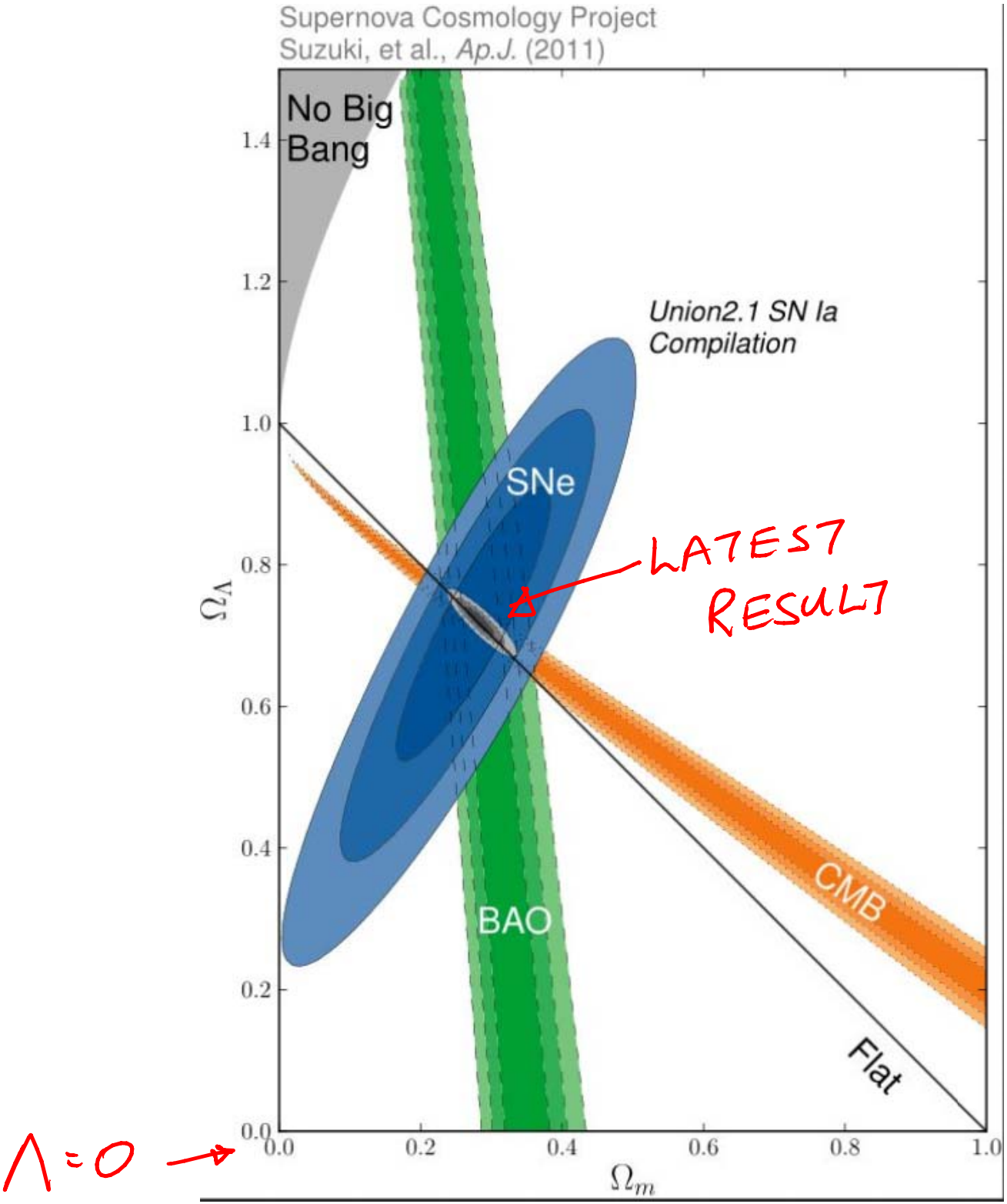
DISTANCE SCALE



$$\Omega = \frac{\rho}{\rho_c}$$




Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)


Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)
No Big Bang
Union2.1 SN Ia Compilation
SNe
BAO
CMB
Flat
LATEST RESULT
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

$\Lambda = 0$ →

THE BRIGHTNESS (MAGNITUDE) MEASURES HOW FAR AWAY THE SUPERNOVA IS

BUT THE LIGHT SET OUT AEONS AGO.

IS THIS DISTANCE

1) BETWEEN OUR POSITION AEONS AGO, AND GALAXY'S POSITION AEONS AGO?

2) BETWEEN OUR CURRENT POSITION, AND GALAXY'S POSITION AEONS AGO?

3) BETWEEN OUR CURRENT POSITION AND CURRENT POSITION OF GALAXY

THINK OF A MAP WITH A DISTANCE SCALE

1 cm = 100 MILES

IF THE EARTH'S SURFACE SWELLS UNIFORMLY

→ IT IS JUST A SCALE CHAGE 1cm = 200 MILES

GALAXIES DO NOT MOVE UNDER THEIR OWN POWER!

THEY ARE JUST CARRIED APART BY THE EXPASION OF SPACE → SCALE CHANGE

WE MEASURE DISTANCE BETWEEN CURRENT LOCATIONS

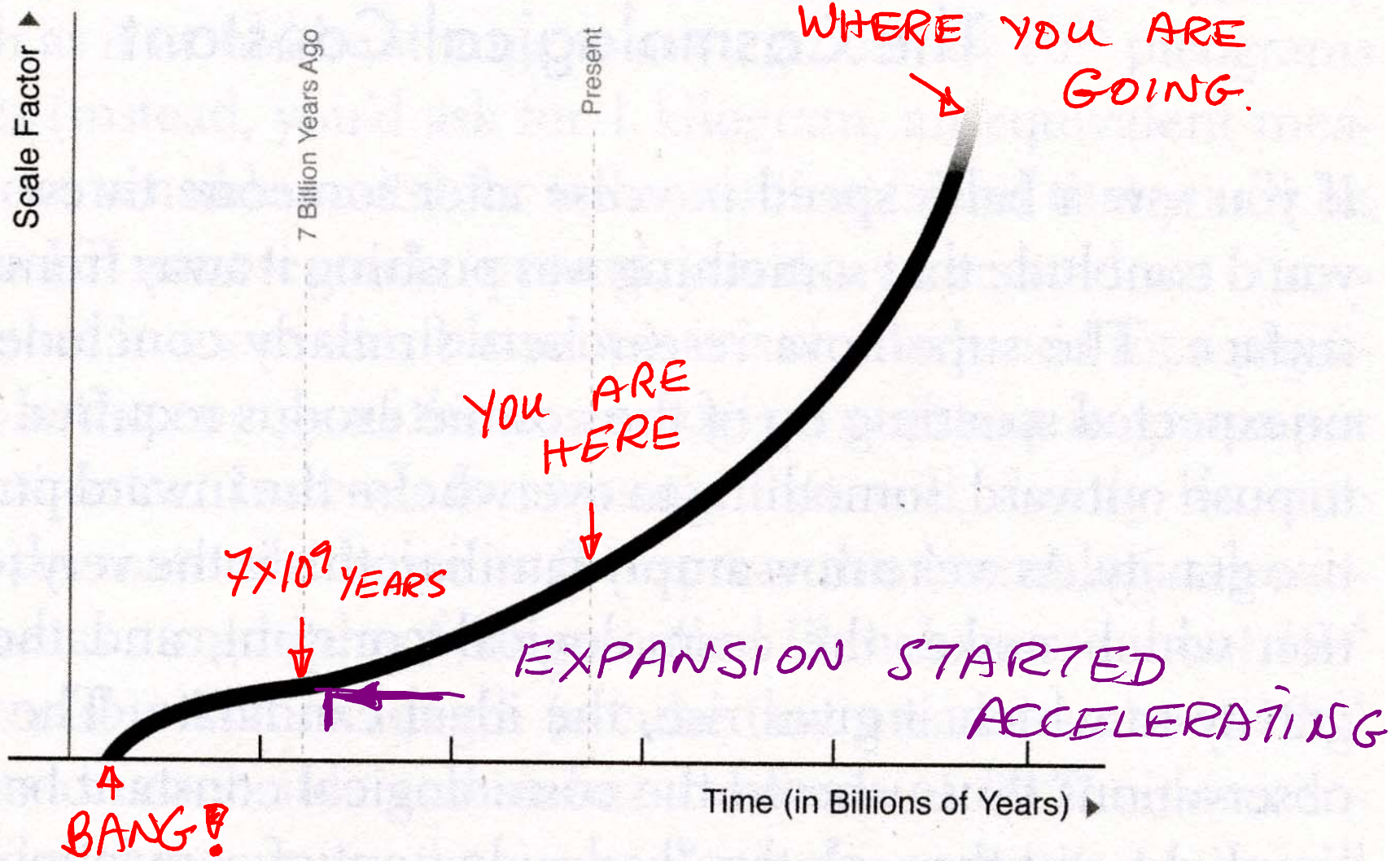


Figure 6.2 *The scale factor of the universe over time, showing that cosmic expansion slowed down until about 7 billion years ago, when it began to speed up.*

THE UNIVERSE'S EXPANSION STARTED ACCELERATING WHEN THE PRESSURE OF Λ OVERCAME THE RETARDATION FROM THE RETARDING FORCE CAUSED BY GRAVITATIONAL ATTRACTION OF MATTER IN THE UNIVERSE

PERLMUTTER et al DETERMINED THAT THE ENERGY DENSITY (DARK ENERGY) CAUSING THE ACCELERATION IS 10^{-29} grams/cc

PLANK MASS = 10^{-5} g

PLANK LENGTH = 10^{-33} cm

1 PLANK MASS / 1 PLANK VOLUME = 1

IN THESE UNITS

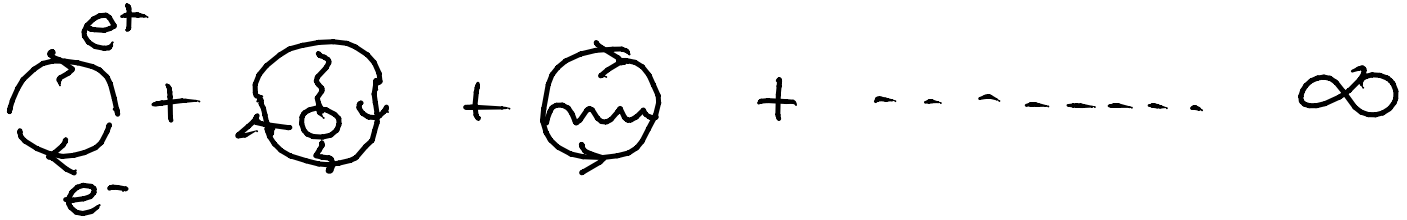
$\Lambda = 10^{-123}$

IS THAT ZERO?

NO!

10^{-123} IS A SMALL NUMBER, WE EXPECT EITHER EXACTLY ZERO, OR ENORMOUS

QUANTUM FIELD THEORY SAYS VACUUM HAS ENERGY DUE TO FLUCTUATIONS



QUANTUM FIELD THEORY SAYS WE HAVE ∞ ENERGY IN ANY VOLUME

IF CUT THIS CALCULATION OFF AT PLANK LENGTH

→ I.E. QUANTUM GRAVITY COMES INTO PLAY

→ STILL HAVE 10^{94} gms / cc

QUANTUM FIELD THEORY → 10^{94} gms/cc

→ ALL STARS IN ALL GALAXIES IN 1 cc

→ THIS IS 1 $M_P/L_P^3 = 1$ cf 10^{-123} EXP

QFT IS OUT BY A FACTOR OF 10^{123}

IN PHYSICS A VALUE OF ≡ ZERO CAN ONLY BE DUE TO SOME SYMMETRY

FOR EXAMPLE GAUGE SYMMETRY REQUIRES PHOTON MASS EXACTLY ZERO → WHICH IT IS.

SO PHYSICISTS EXPECTED $\Lambda = 0$ DUE TO SOME SYMMETRY.

BUT IT IS NOT ZERO, 10^{-123} → WHY??

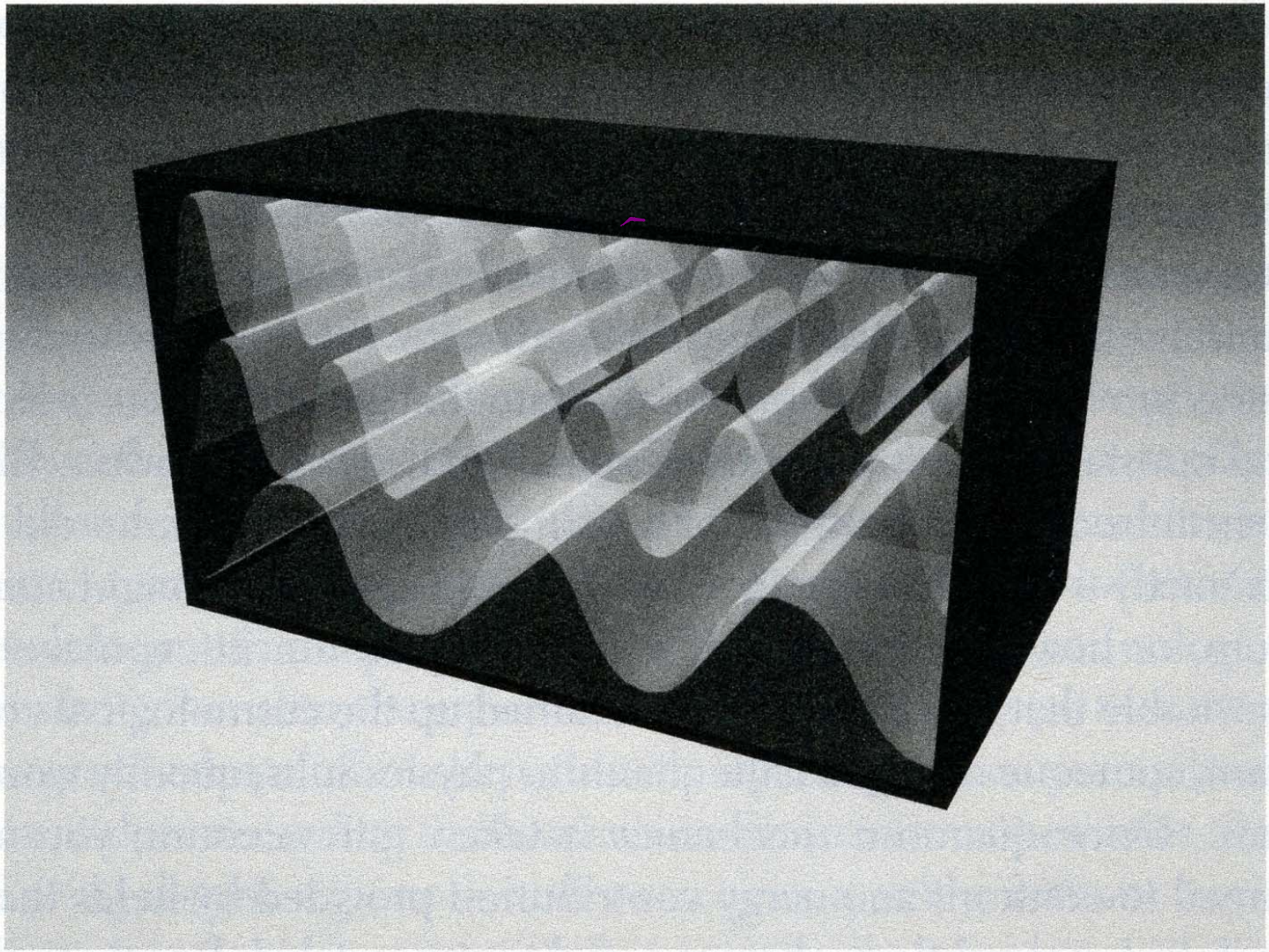
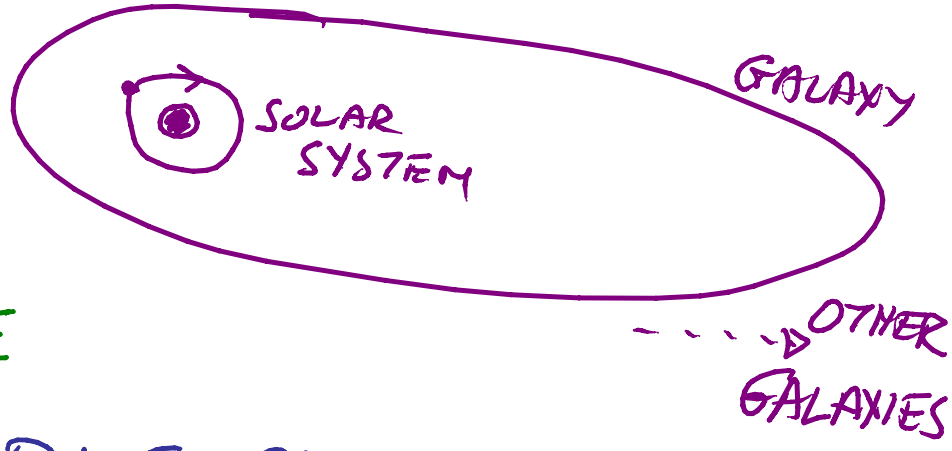


Figure 6.3 *There are infinitely many wave shapes in any volume and hence infinitely many distinct quantum jitters. This yields the problematic result of an infinite energy contribution.*

ANTHROPIC PRINCIPLE

SINCE THE TIME OF COPERNICUS WE HAVE REPEATEDLY LEARNED THAT WE ARE NO WHERE SPECIAL



BUT WE DO PLAY SOME KIND OF SPECIAL ROLE

WE ARE OBSERVERS. AND WE CAN ONLY EXIST UNDER SPECIAL CONDITIONS

GREEN → IF YOU ONLY LOOK FOR FISH IN THE SAHARAH, YOU MIGHT TRY TO UNDERSTAND WHY FISH HAVE BECOME EXTINCT.

IF WE DON'T THINK ABOUT OBSERVER BIAS
WE CAN BECOME HOPELESSLY CONFUSED

EG. → WHY IS THE EARTH 93×10^6 MILES FROM THE SUN? NO REASON!

NEWTON'S LAWS ALLOWS PLANETS TO BE ANY DISTANCE FROM THE SUN.

WE JUST HAPPEN TO LIVE HERE

IF THERE WERE NO OTHER PLANETS WE MIGHT PUZZLE OVER 93×10^6

BUT THERE ARE OTHER PLANETS

→ NO PUZZLE

MAYBE THIS PRINCIPLE ALSO WORKS FOR THE UNIVERSE

MAYBE THERE IS NO FUNDAMENTAL REASON FOR $m_e = 0.00056\, m_p$ ---- $\Lambda = 1.38 \times 10^{-123}$

EXCEPT THAT THEY HOLD IN A UNIVERSE WHERE WE CAN EVOLVE. NO FUNDAMENTAL LAW DETERMINES VALUES OF FUNDAMENTAL CONSTANTS.

THIS REASONING IS DEVOID OF LOGIC IF ONLY ONE UNIVERSE

CAN STILL DISCUSS

— DEEPER EXPLANATION

— LUCKY COINCIDENCE.

THIS ANTHROPIC ARGUMENT IS MUCH MORE POTENT IF THERE ARE MANY UNIVERSES Of .... MANY PLANETS AT ARBITRARY DISTANCES

DEPENDS ON!

1) OUR UNIVERSE IS PART OF A MULIVERSE
   → VERY LARGE ENSEMBLE

2) AMONG THESE MANY UNIVERSES, THE FUNDEMENTAL CONSTANTS CAN HAVE WIDELY VARYING VALUES.

3) FOR MOST OF THE VARIATIONS IN THE VALUES OF FUNDEMENTAL CONSTANTS LIFE AS WE KNOW IT, COULD NOT EVOLVE.

STEVEN WEINBERG'S CALCULATION OF Λ (1987)

SEEMS FRUITLESS TO ATTEMPT TO CALCULATE HOW Λ DETERMINES OUR EXISTENCE

→ TOO COMPLEX

HOWEVER STRUCTURE FORMATION (GALAXIES.....) DETERMINE OUR EXISTENCE

STRUCTURE FORMATION DEPENDS ON GRAVITATIONAL ATTRACTION Λ ACTS AGAINST THIS.

WEINBER — $\Lambda >$ A FEW 100 TIMES CURRENT VALUE WOULD STOP STRUCTURE FORMATION

$$\Lambda_{WEINBERG} \sim 10^{-121}$$

ANTHROPIC ARGUMENT → NEEDS A LARGE NUMBER OF UNIVERSES, SO THAT ONE HAS TO CONTAIN OUR VALUE OF Λ.

HOW LARGE?

ASSUME THAT IN PLANK MASS UNITS $0 < \Lambda < 1$

THE TICKS ON THE SCALE OF Λ MUST BE AT LEAST AS SMALL AS WHAT WE OBSERVE

IE $10^{-121} \rightarrow 10^{121}$ UNIVERSES FO $0 < \Lambda < 1$

NUMBER OF CELLS IN YOUR BODY 10^{13}

NUMBER OF SECONDS SINCE BIG BANG 10^{18}

NUMBER OF PHOTONS IN UNIVERSE 10^{88}

10^{121} IS A BIG NUMBER

GO BACK TO STRING THEORY

→ MANY POSSIBLE CALABI-YAU MANIFOLDS

→ THE "HOLES" IN THEM FILL WITH ENERGY

↳ I.E. THE EXTRA DIMENSIONS ARE FULL OF ENERGY

→ THIS ENERGY IS THE VALUE OF Λ

→ WE HAVE 10^{500} UNIVERSES EACH WITH DIFFERNT VALUE OF Λ

→ WHEN INFLATION "STOPS" ENERGY DENSITY IN UNIVERSE $\equiv$ Λ

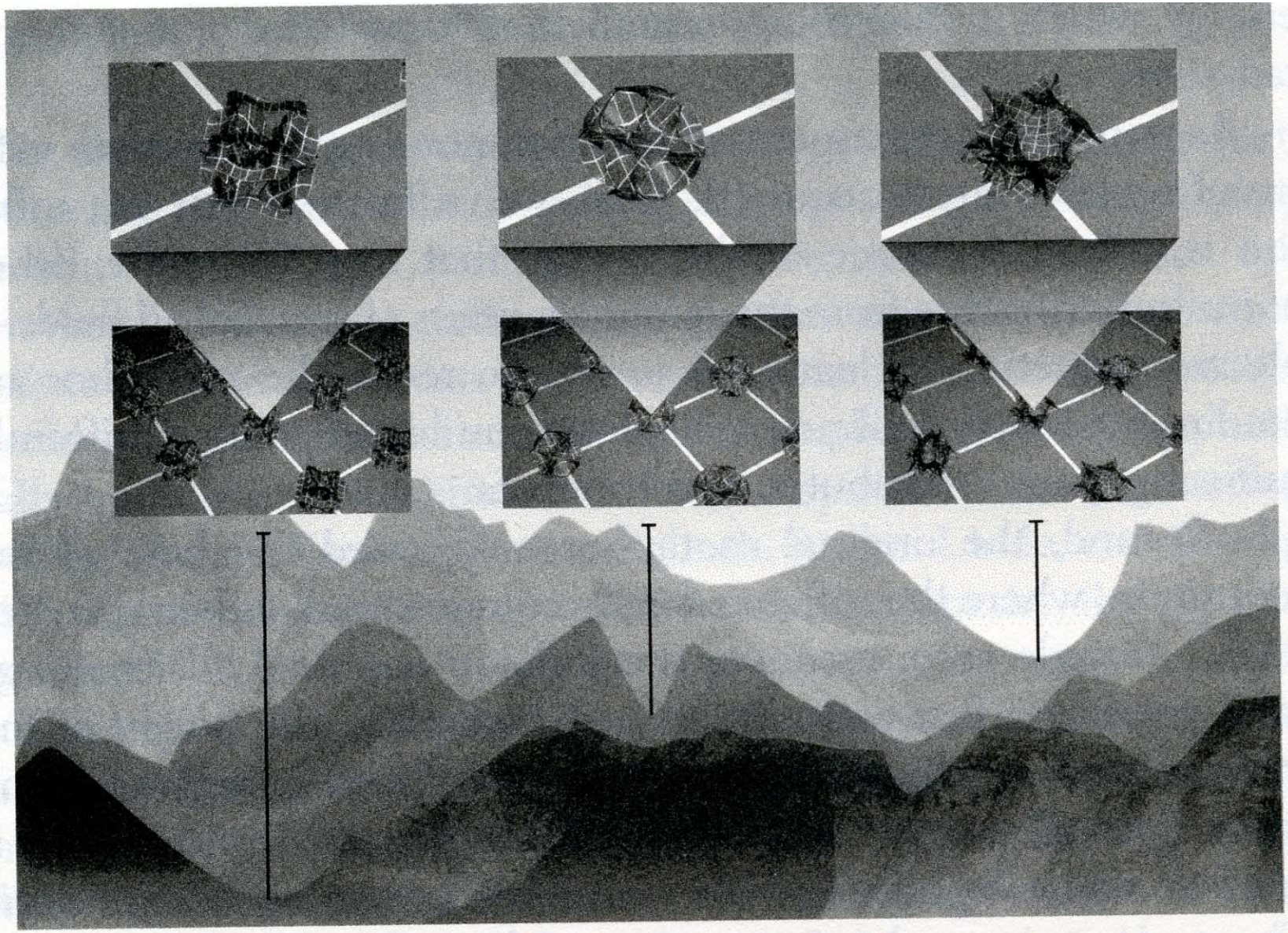
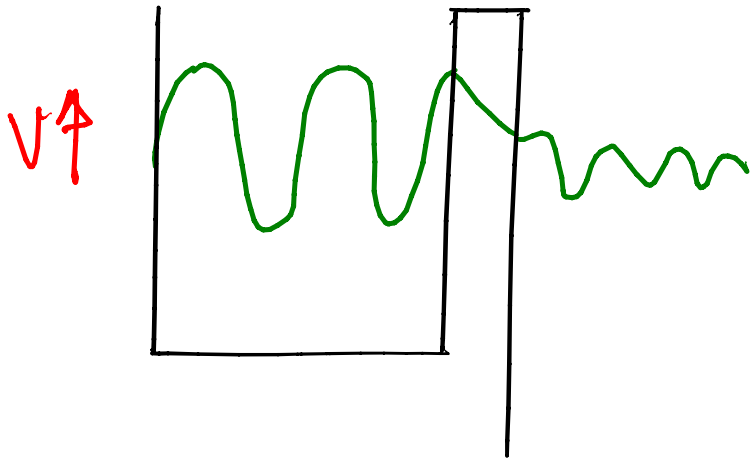


Figure 6.4 *The string landscape can be visualized schematically as a mountainous terrain in which different valleys represent different forms for the extra dimensions, and altitude represents the cosmological constant's value.*

EVERY POSSIBLE VALUE OF Λ ?

ELEMENTARY QUANTUM MECHANICS



PARTICLES CAN "TUNNEL" THROUGH POTENTIAL BARRIER

SAME THING CAN HAPPEN FOR UNIVERSES

V ABOVE IS ANALOG OF Λ

UNIVERSE WITH GIVEN Λ CAN QUANTUM MECHANICALLY TUNNEL TO LOWER Λ

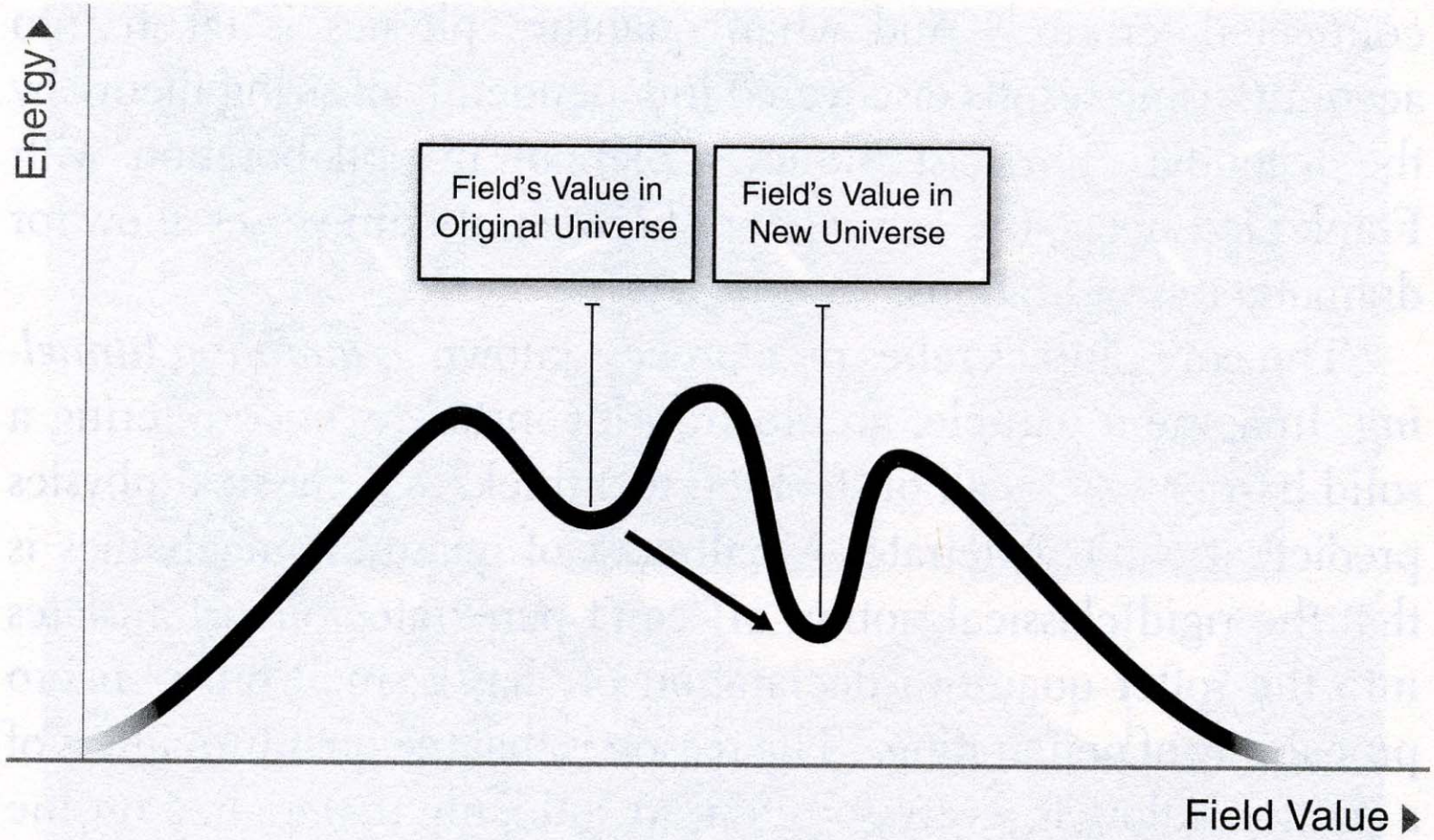
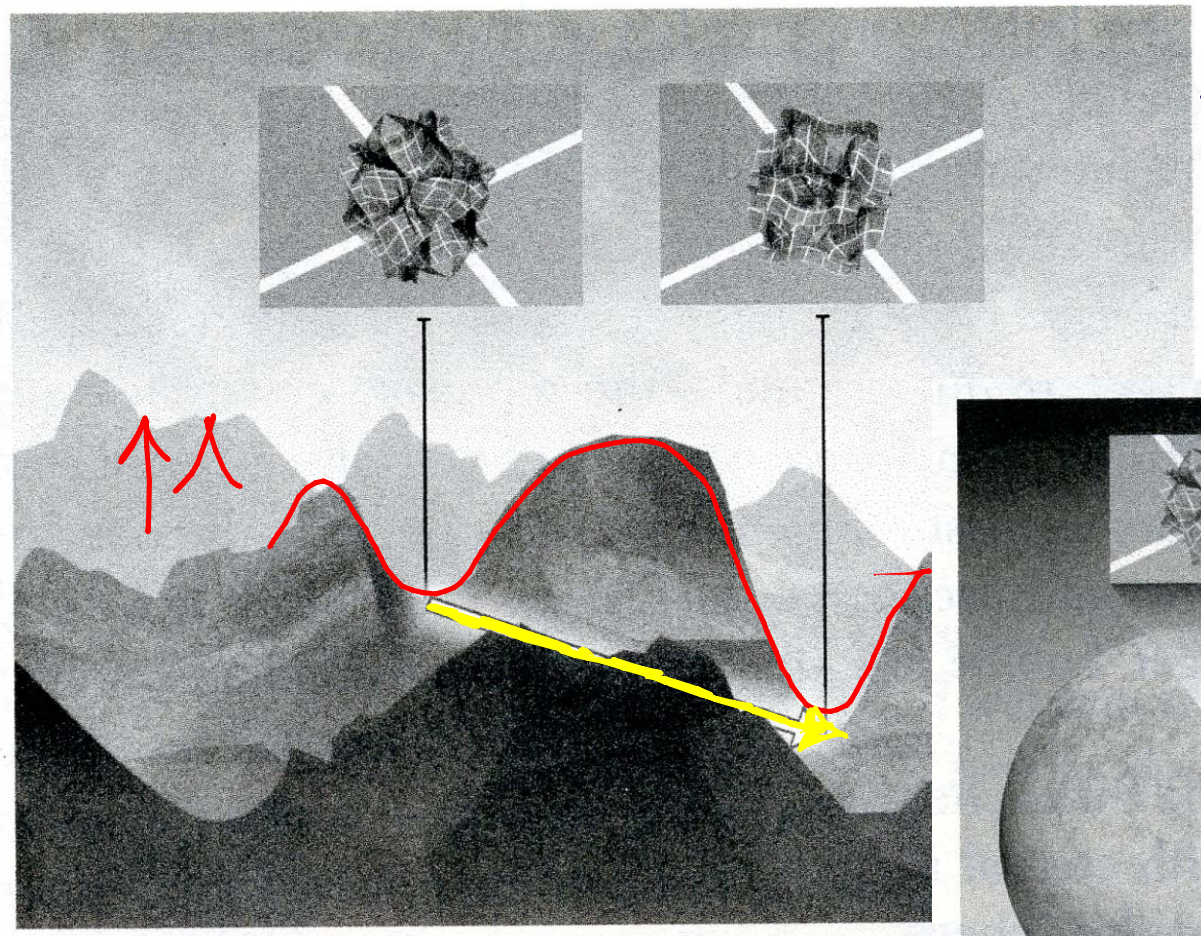


Figure 6.5 *An example of a field's energy curve that has two values—two troughs or valleys—where the field naturally comes to rest. A universe suffused with the higher-energy field value can quantum tunnel to the lower value. The process involves a small randomly located region of space in the original universe acquiring the lower field value; the region then expands, converting an ever-wider domain from the higher to the lower energy.*



← DIFFERENT KINDS OF EXTRA DIMENSIONS

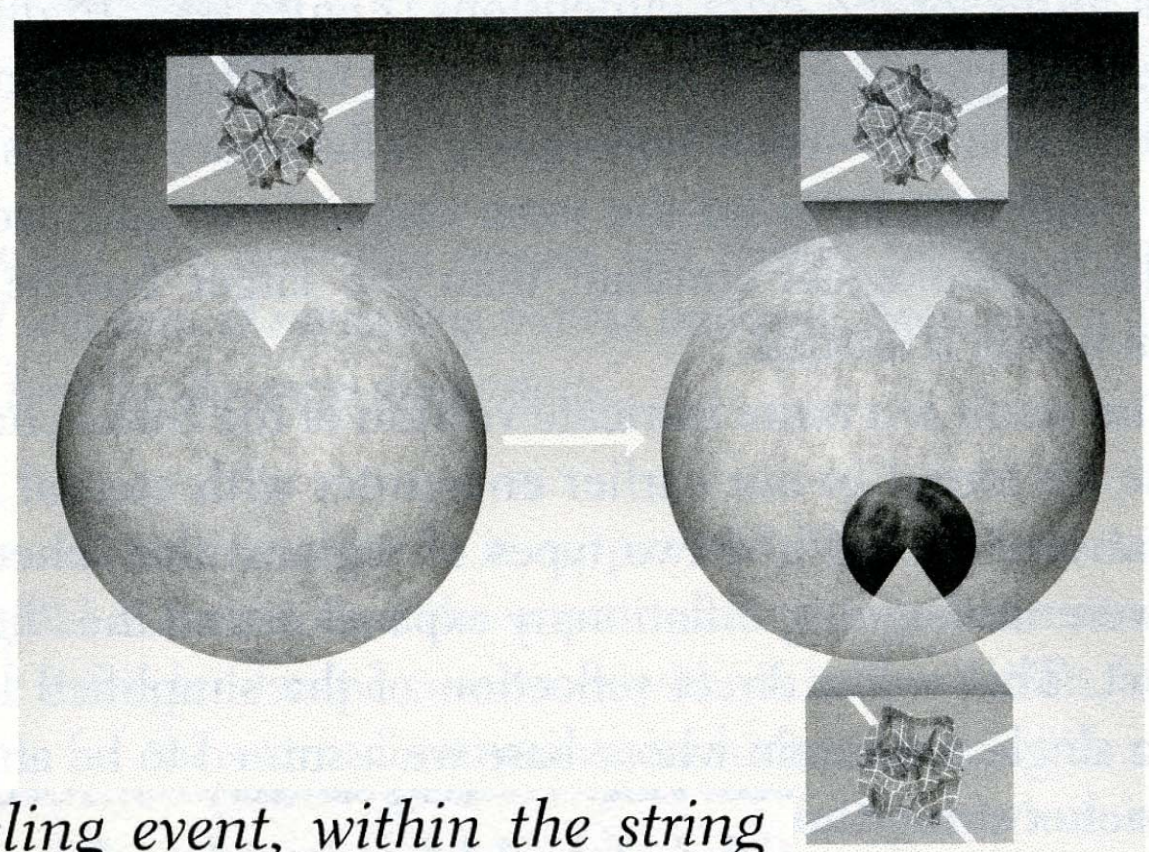


Figure 6.6 (a) A *quantum tunneling event, within the string landscape.* (b) *The tunneling creates a small region of space—represented by the smaller and darker bubble—within which the form of the extra dimensions has changed.*

TUNNELING DOES NOT OCCUR SIMULTANEOUSLY AT ALL POINTS IN THE UNIVERSE

HAPPENS IN RANDOMLY DISTRIBUTED BUBBLES WHICH THEN START TO EXPAND

IN NEW BUBBLE Λ IS SMALLER → SLOWER EXPANSION

BUBBLES INSIDE BUBBLES INSIDE BUBBLES ----

EVENTUALLY GET EVERY POSSIBLE KIND OF EXTRA DIMENSIONS

IN OUR BUBBLE Λ SHOULD BE SMALL ENOUGH FOR STRUCTURE FORMATION

→ BUT NOT MUCH SMALLER → WHICH IT IS.

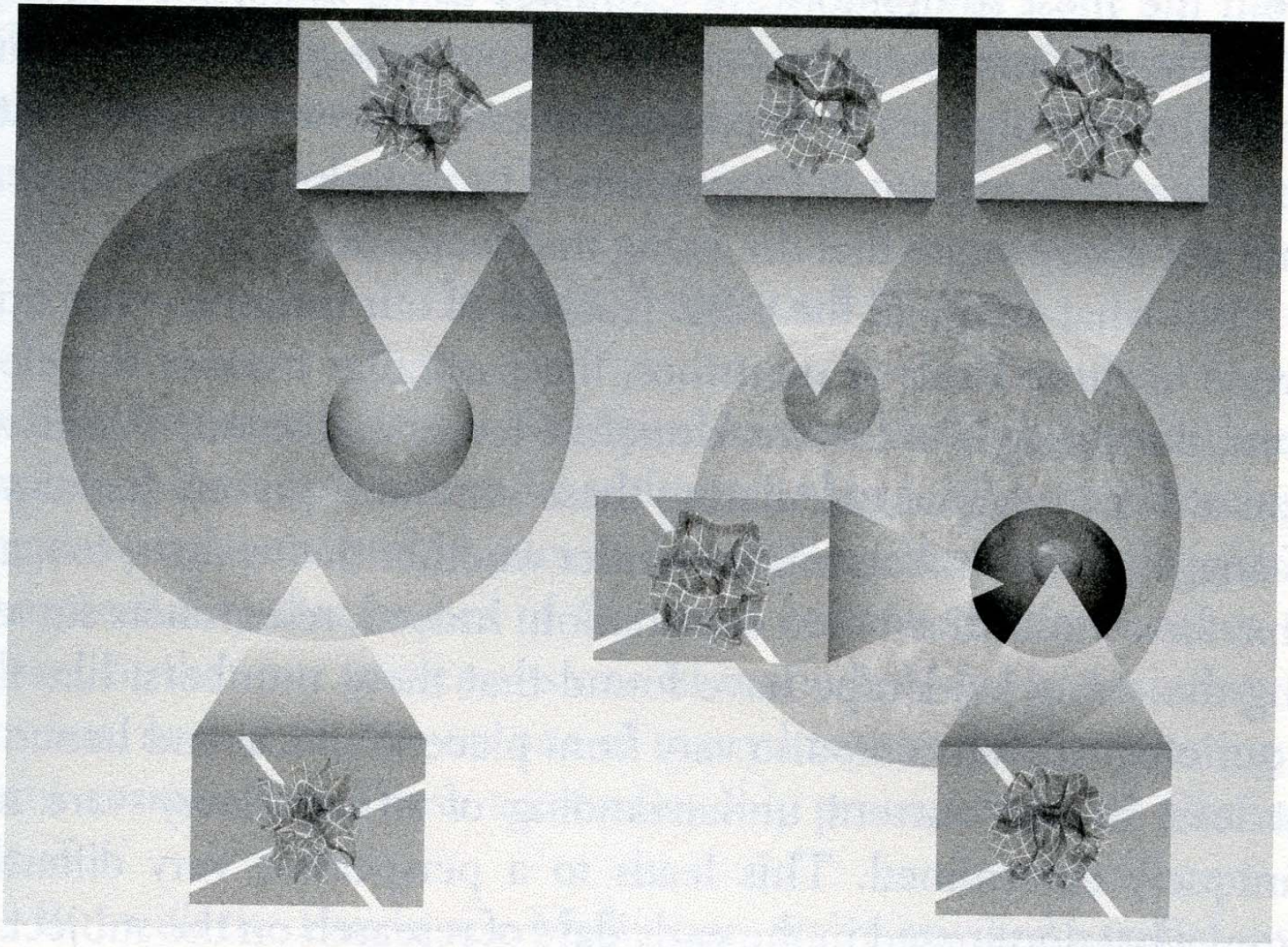


Figure 6.7 *The tunneling process can repeat, yielding a vast nested sequence of expanding bubble universes, each with a different form for the extra dimensions.*

IN EACH OF THIS INFINITUDE OF BUBBLES ALL THE THINGS WE THOUGHT FUNAMENTAL ARE DIFFERENT

- # OF QUARK LEPTON GENERATIONS
- MASS OF ELECTRON
- α_{EM}
- α_{STRONG}
- G_N
- ⋮

CAN WE EVER KNOW IF OUR UNIVERSE IS ACTUALLY FOUND IN STRING LANDSCAPE ?

GREENE SAYS PEOPLE SEARCH " WITH BEST COMBINATION OF RIGOROUS SCIENCE AND ARTISTIC SENSIBILITY "

OR MAYBE YOU COULD SAY THAT ALL THIS COMPLICATED MATHEMATICS HAS LED NO WHERE AT ALL.

Is This Science?

In this chapter we've turned a logical corner. Until now, we've been exploring the implications for reality, writ large, of various developments in fundamental physics and cosmology research. I delight in the possibility that copies of the earth exist in the far reaches of space, or that our universe is one of many bubbles in an inflating cosmos, or that we live on one of many braneworlds constituting a giant cosmic loaf. These are undeniably provocative and alluring ideas.

But with the Landscape Multiverse, we've invoked parallel universes in a different way. In the approach we've just followed, the Landscape Multiverse is not merely broadening our view of what might be out there. Instead, an array of parallel universes, worlds that may be beyond our ability to visit or see or test or influence, now and perhaps always, are directly invoked to provide insight into observations we make here, in this universe.

Which raises an essential question: Is this science?