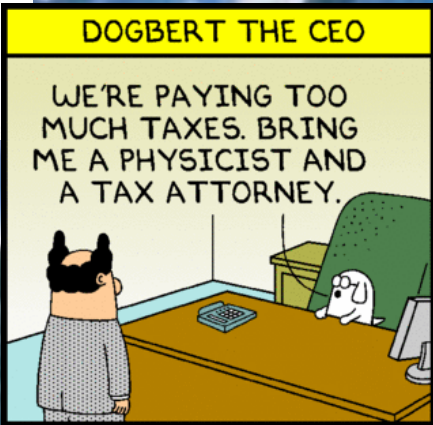
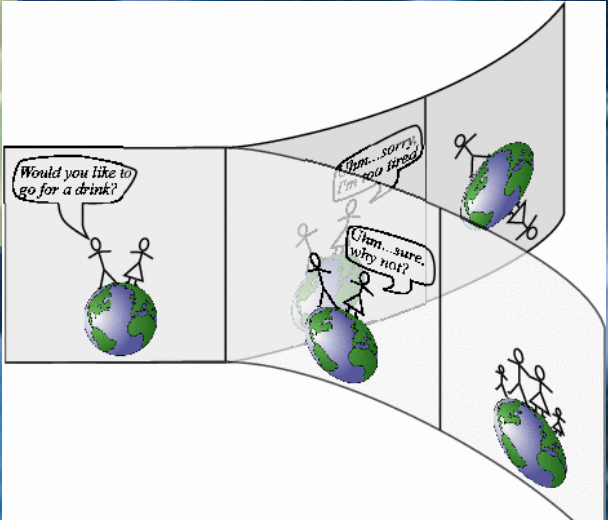
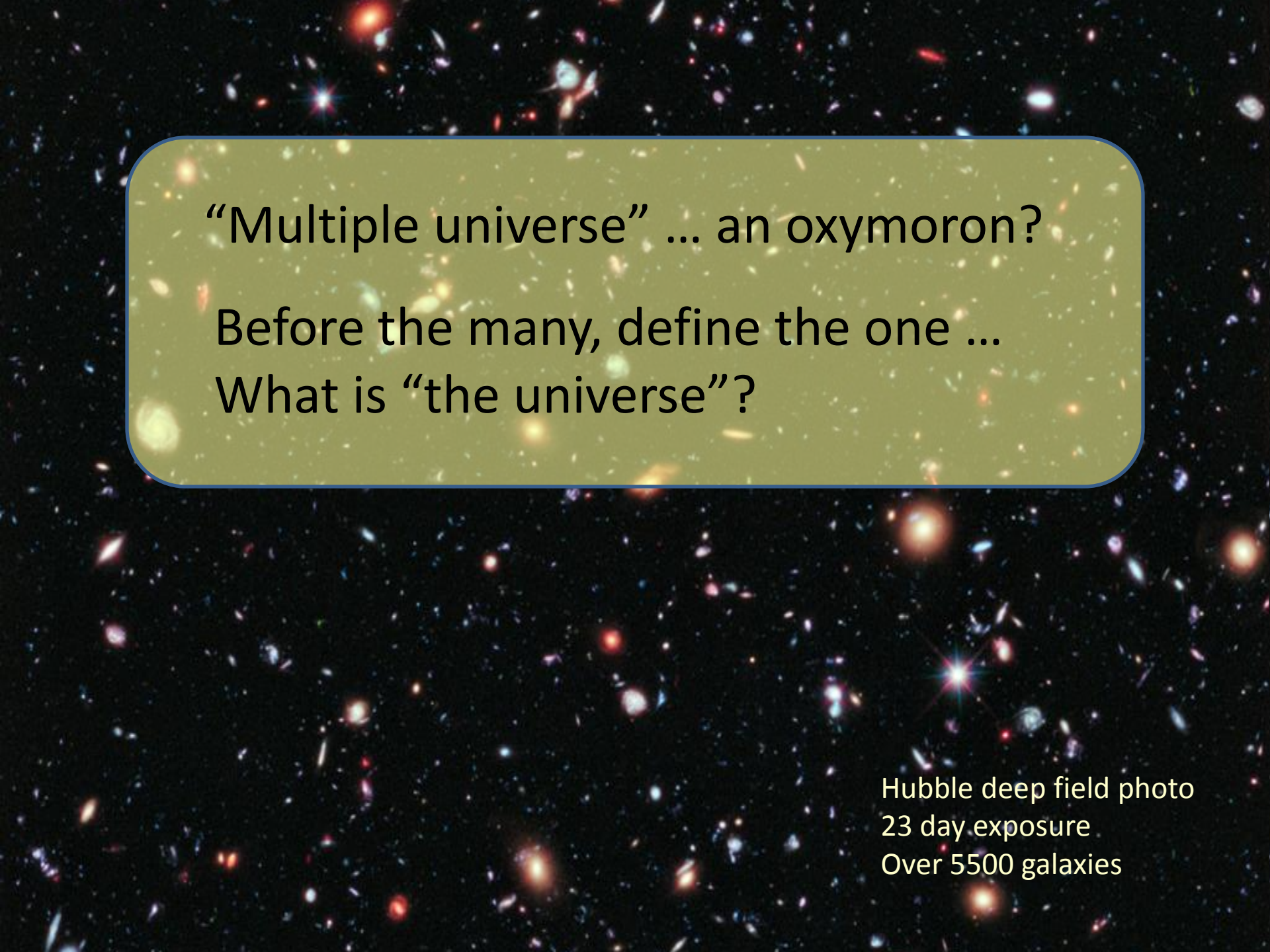


Visions of the Multiverse

S. Manly
Dept. of Physics and Astronomy
University of Rochester
P102 summary
April 23, 2014



A Hubble deep field photograph showing a vast field of galaxies in various colors and shapes, including spirals, ellipticals, and irregular forms, set against a dark cosmic background.

“Multiple universe” ... an oxymoron?

Before the many, define the one ...

What is “the universe”?

Hubble deep field photo
23 day exposure
Over 5500 galaxies

Universe



From Wikipedia, the free encyclopedia

For other uses, see [Universe \(disambiguation\)](#).

The **Universe** is commonly defined as the totality of existence,^{[1][2][3][4]} including [planets](#), [stars](#), [galaxies](#), the contents of [intergalactic space](#), and all [matter](#) and [energy](#).^{[5][6]} Similar terms include the *cosmos*, the *world* and *nature*.

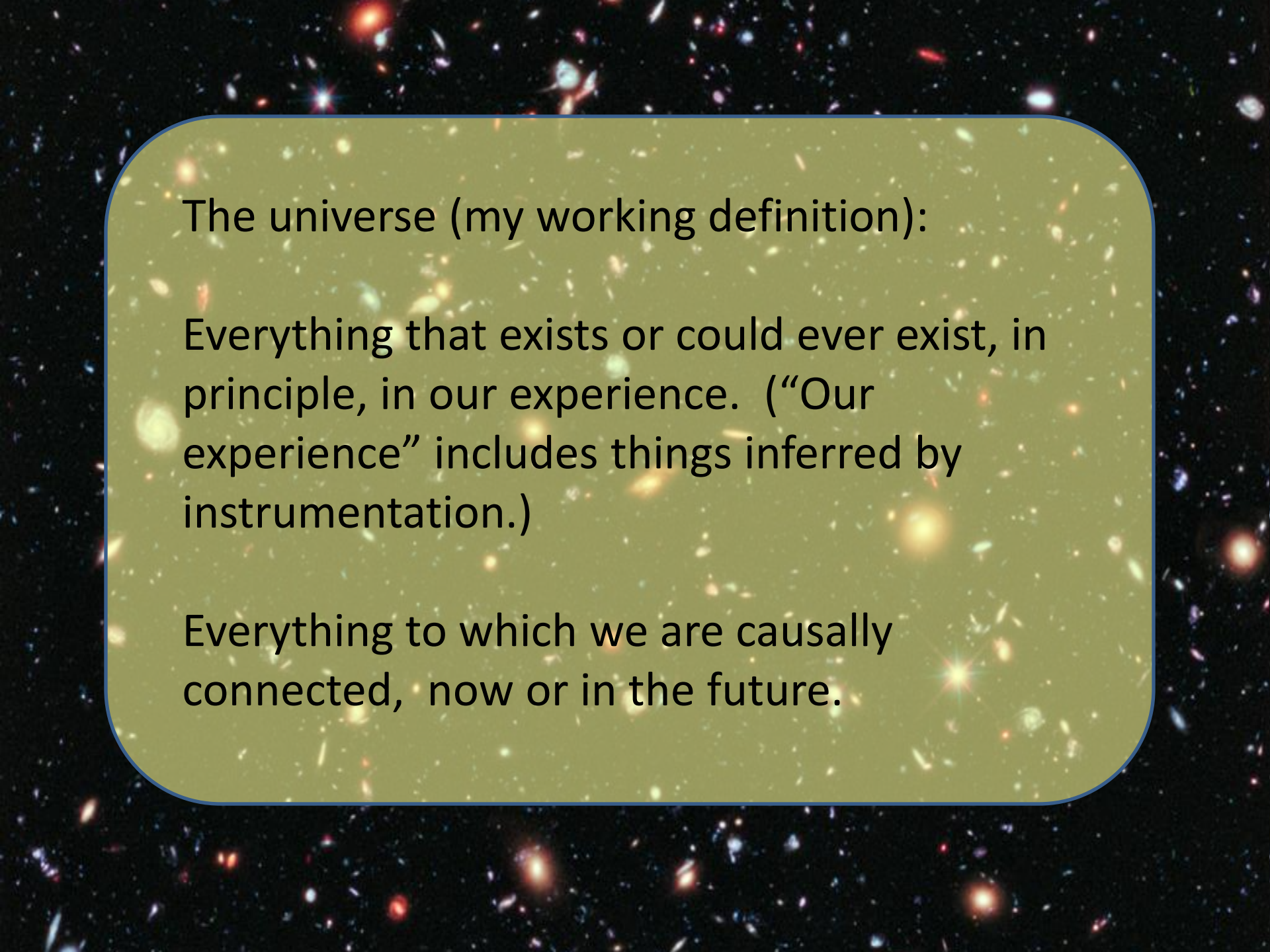
The [observable universe](#) is about 46 billion light years in radius.^[7] Scientific observation of the Universe has led to inferences of its earlier stages. These observations suggest that the Universe has been governed by the same physical laws and constants throughout most of



u·ni·verse  [yoo-nuh-vurs]  [Show IPA](#)

noun

1. the totality of known or supposed objects and phenomena throughout space; the cosmos; macrocosm.
2. the whole world, especially with reference to humanity: *a truth known throughout the universe.*
3. a world or sphere in which something exists or prevails: *his private universe.*



The universe (my working definition):

Everything that exists or could ever exist, in principle, in our experience. (“Our experience” includes things inferred by instrumentation.)

Everything to which we are causally connected, now or in the future.

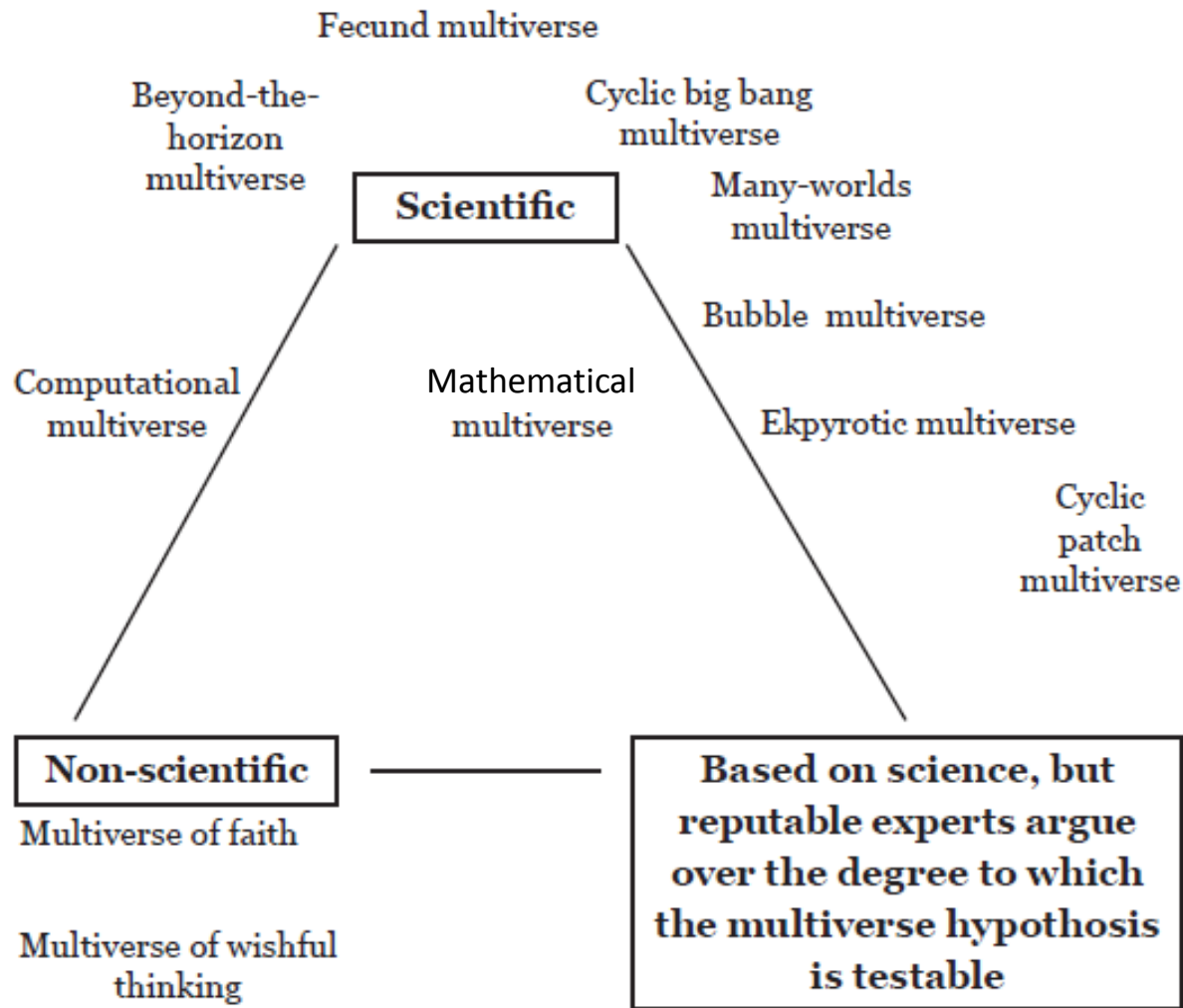


Figure 1.1: Relative degrees to which different multiverse concepts are scientific.

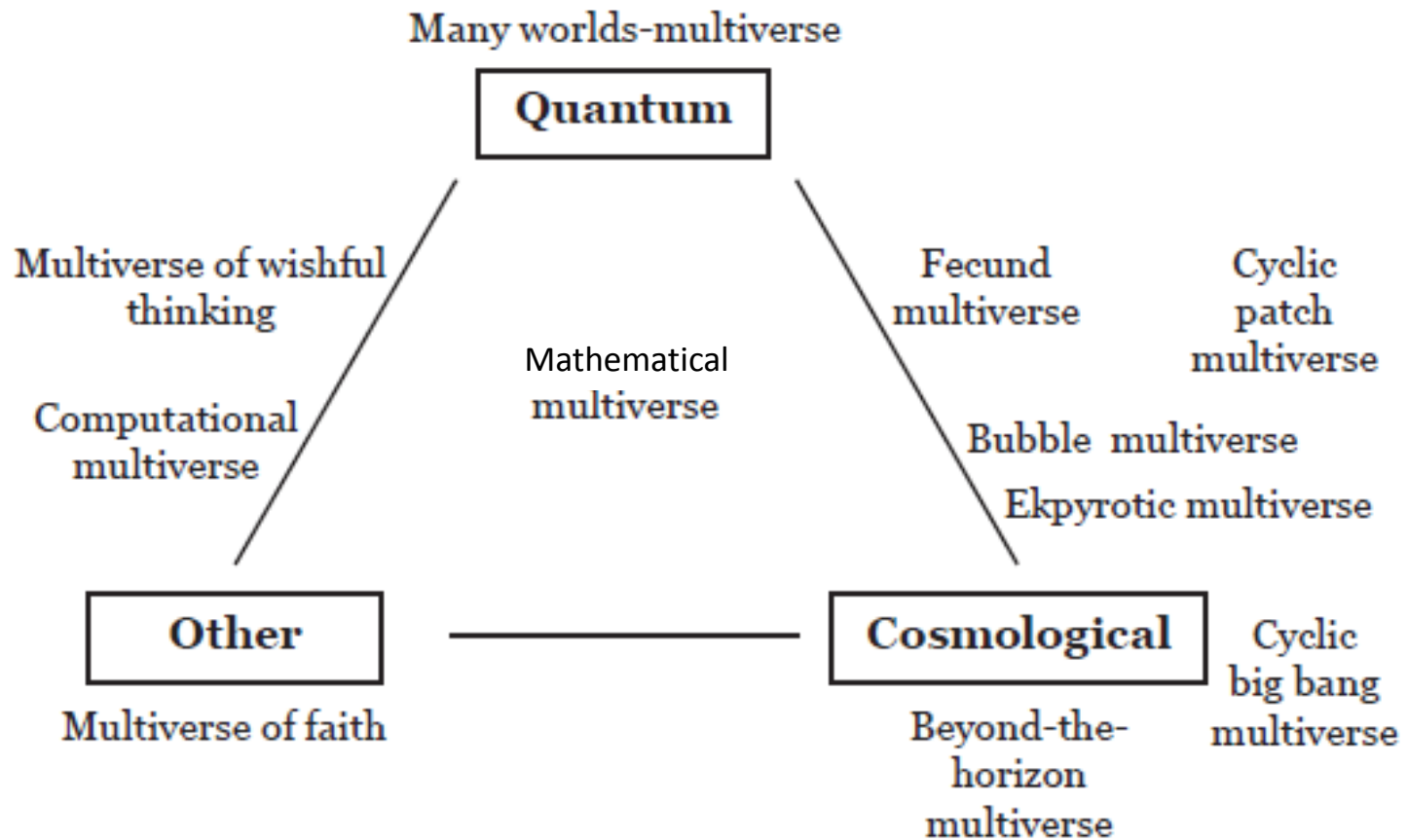
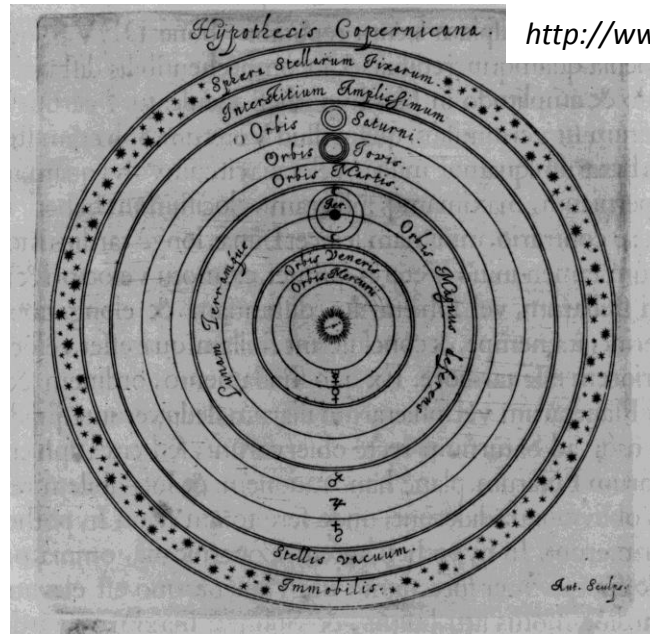


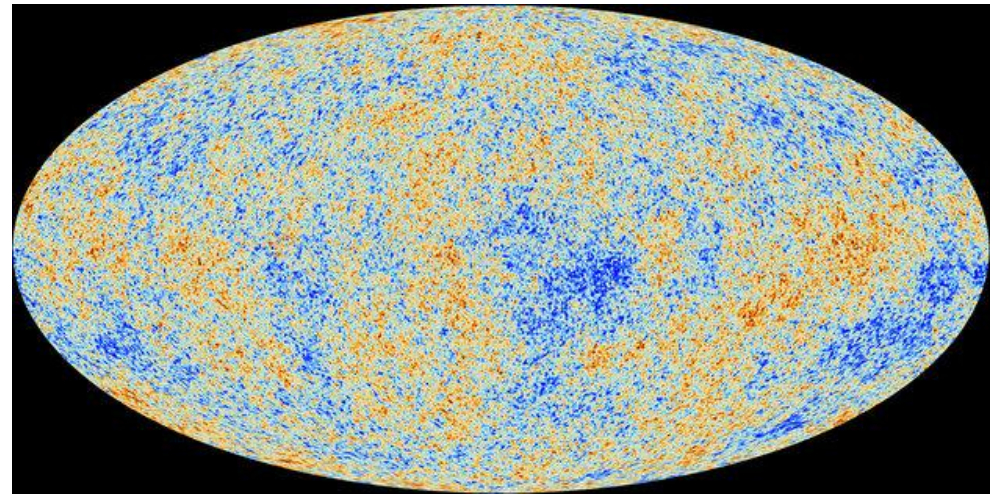
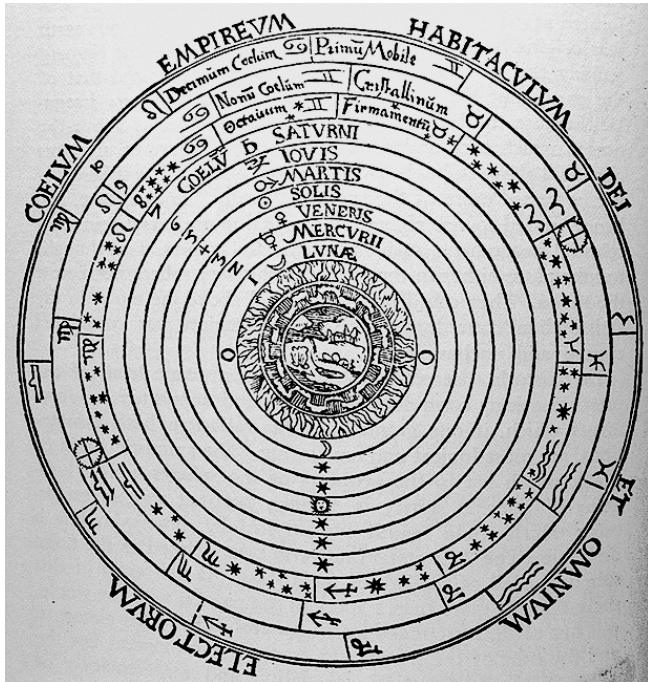
Figure 1.2: Relative degree of quantum versus cosmological character for different multiverse concepts.

Cosmology for
non-cosmologists



<http://www.hps.cam.ac.uk/starry/copercosmol.html>

Representation of Copernicus' Cosmos taken from Johannes Hevelius' *Selenographia*.



CMB, from ESA's Planck mission website

The Christian Aristotelian cosmos, engraving from Peter Apian's *Cosmographia*.



**Vesto Slipher (1875-1969) Lowell Observatory
discovers a strange thing in 1912 ...**

Most nearby galaxies are moving away from us

Made use of the Doppler shift in atomic spectra





Hubble

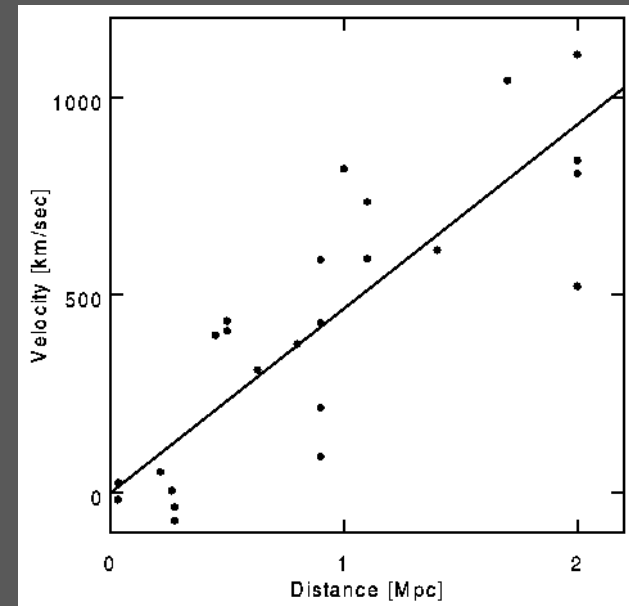
Edwin Hubble (1889-1953) and Milton Humason (1891-1972) at Mount Wilson Observatory combine Hubble's distance measurements (Cepheid variable stars) with Slipher's redshift information and discover ...

Galaxies that are further away are moving away from us faster

Hubble's Law $V=Hd$

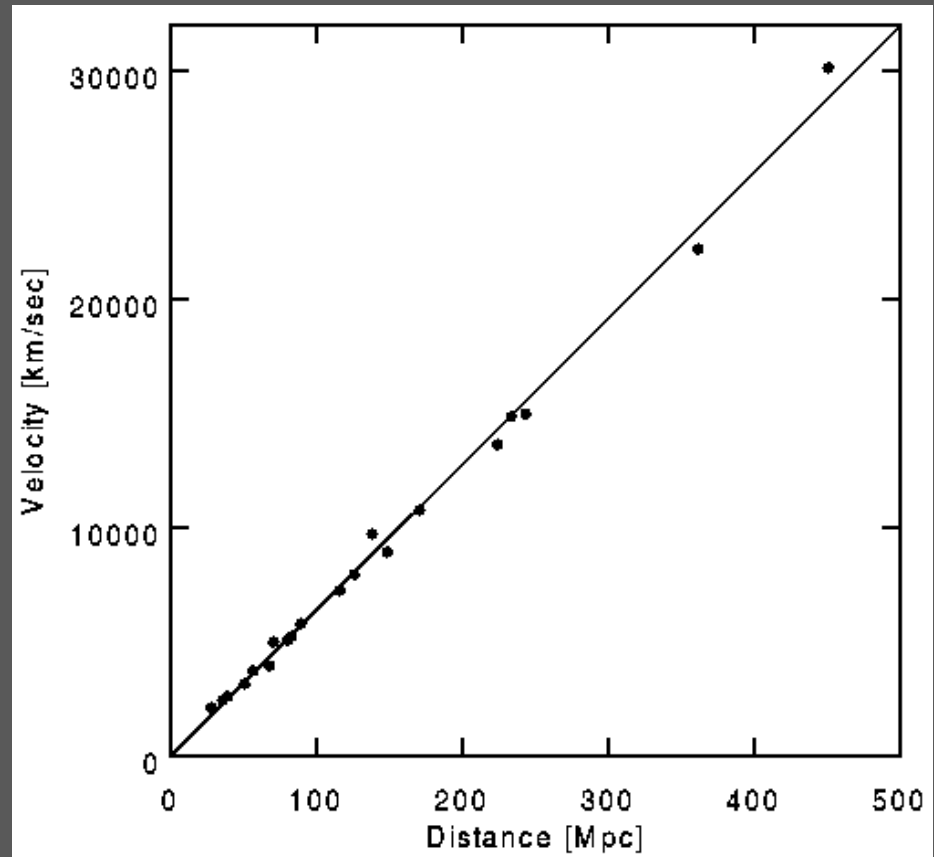


Humason (from AIP)



Welcome to the
“expanding universe”!!

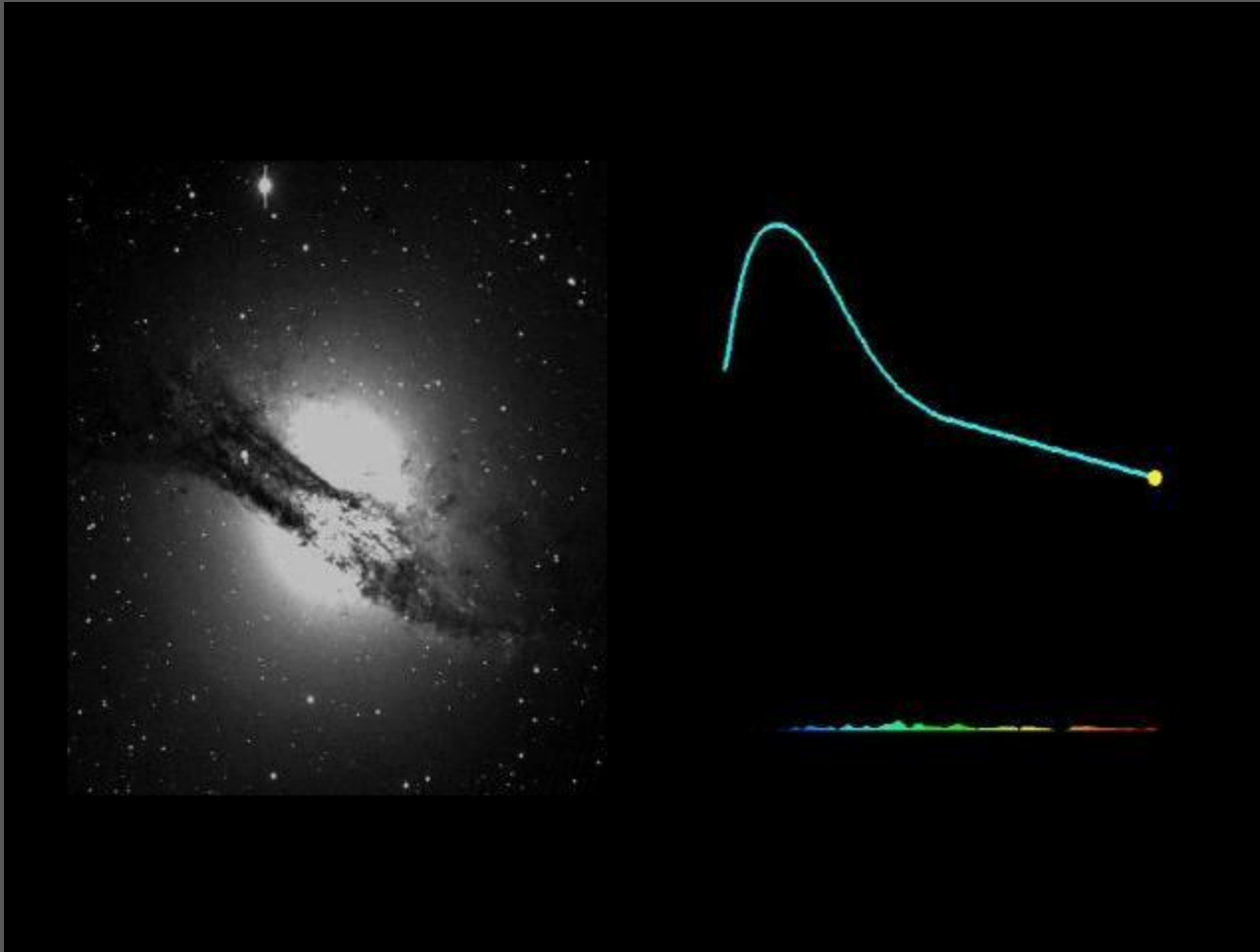
extrapolate back in time
find the age of the
universe → 13.7 billion
years.



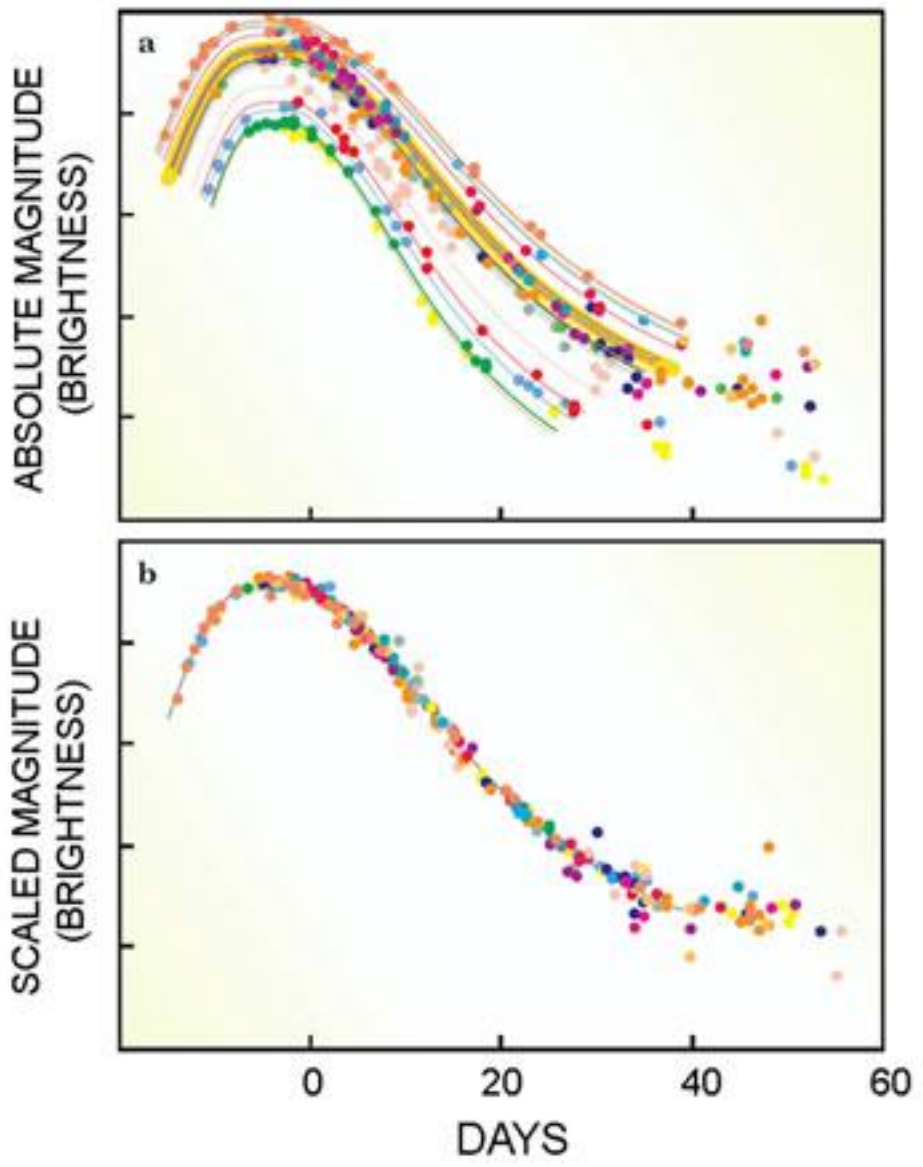
Type Ia SNe from Riess, Press and Kirshner (1996)

Light travels 1 Mpc in 3 million years

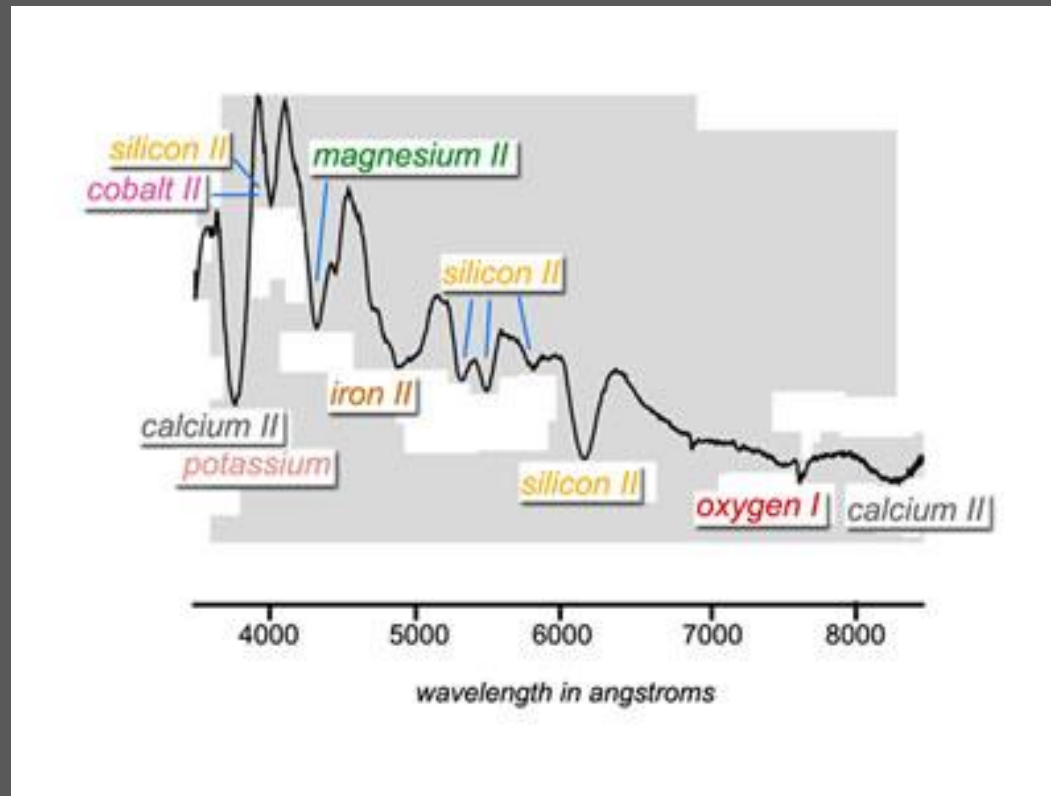
Type 1A supernovas – Use as “standard candle” to gauge distance to distant objects



Energy produced in a short period is roughly that produced by the sun (at current energy output) in about 10 billion years.

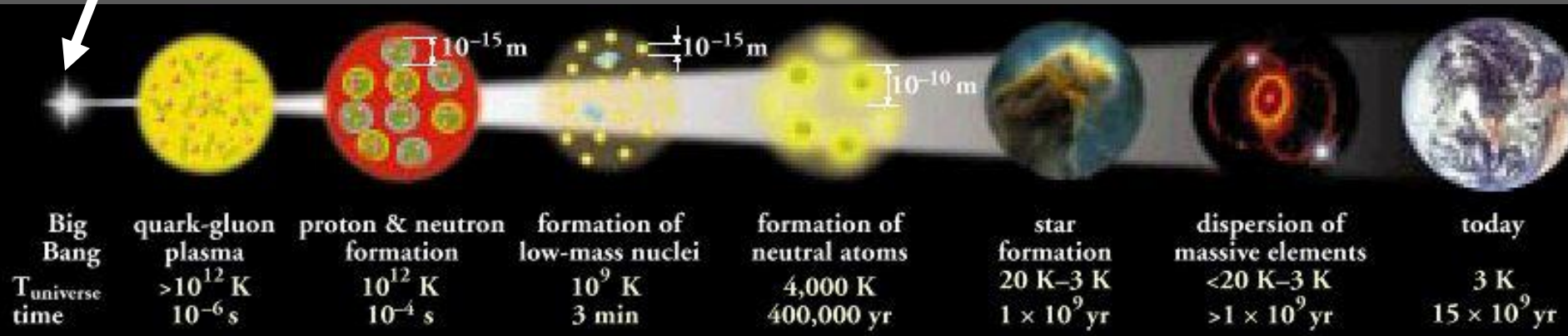
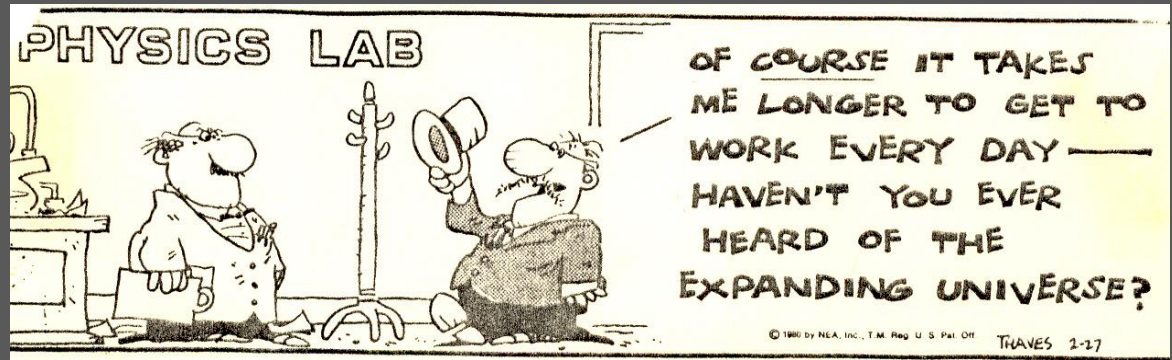


Spectral lines (atomic absorption) can provide classification information for the type of supernova and allow for recession velocity determination using the relativistic Doppler effect (frequency shift of the light)



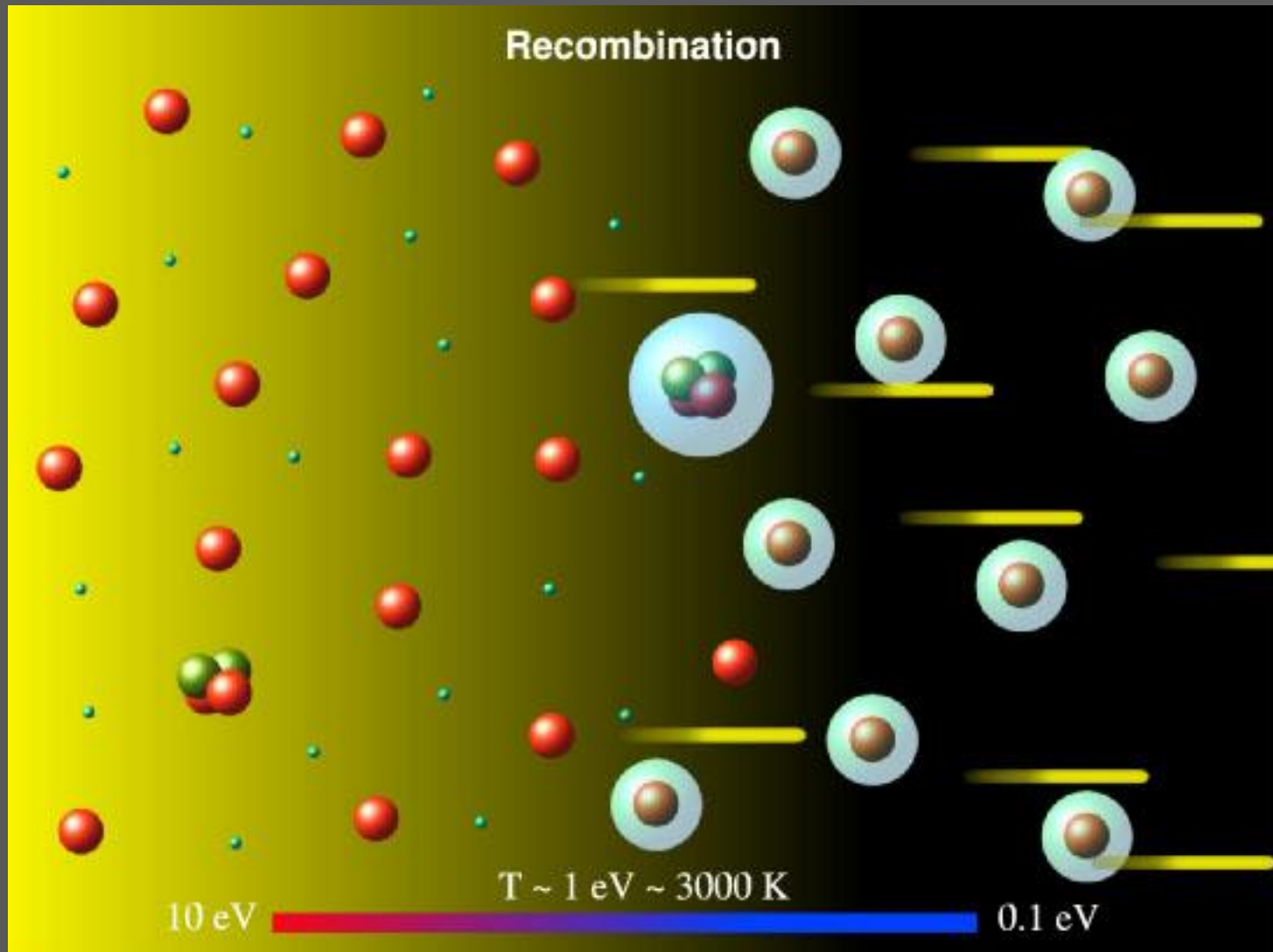


Beasts dwell here

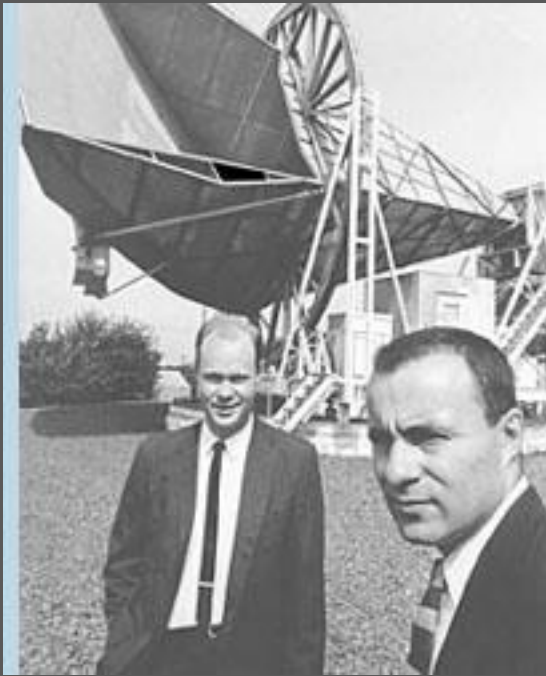


TIME



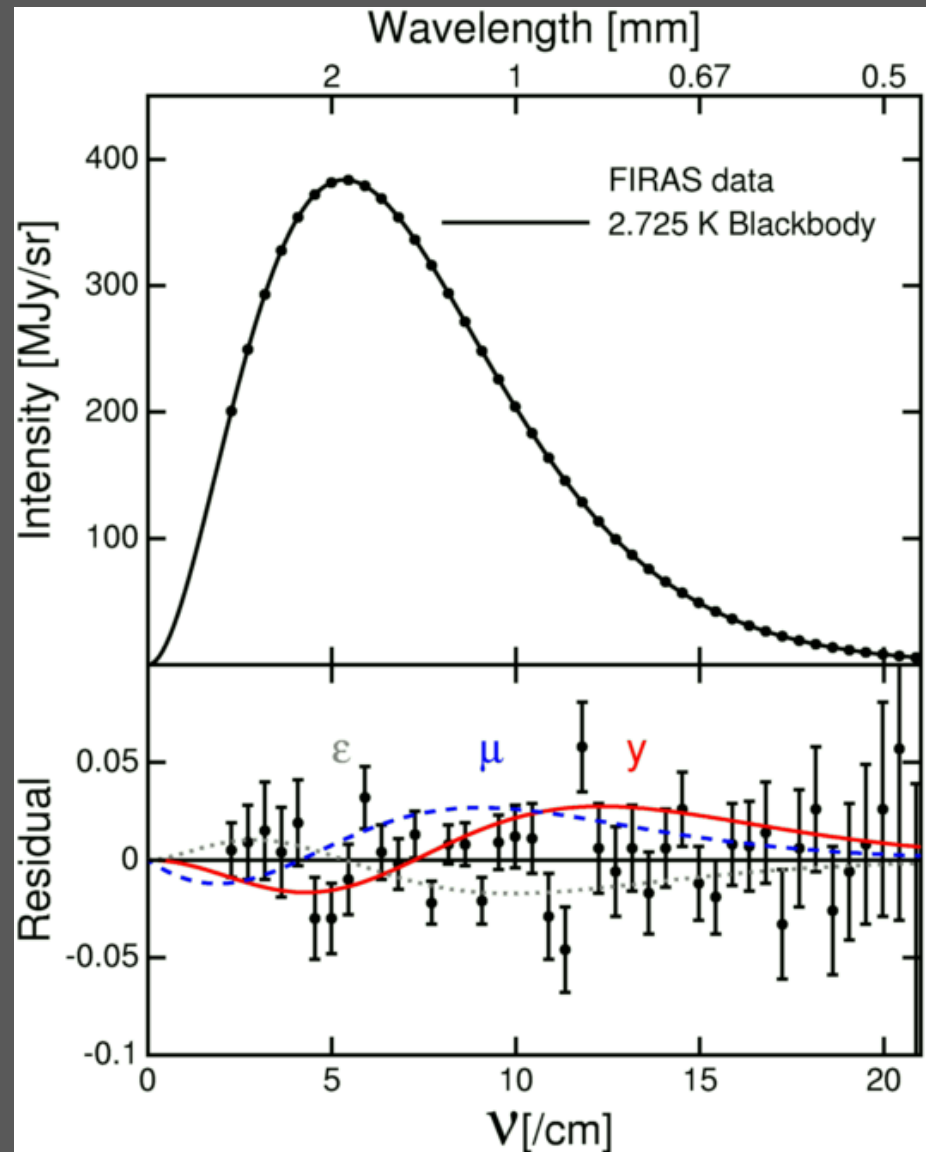


From <http://ned.ipac.caltech.edu/level5/Sept02/Kinney/Kinney3.html>

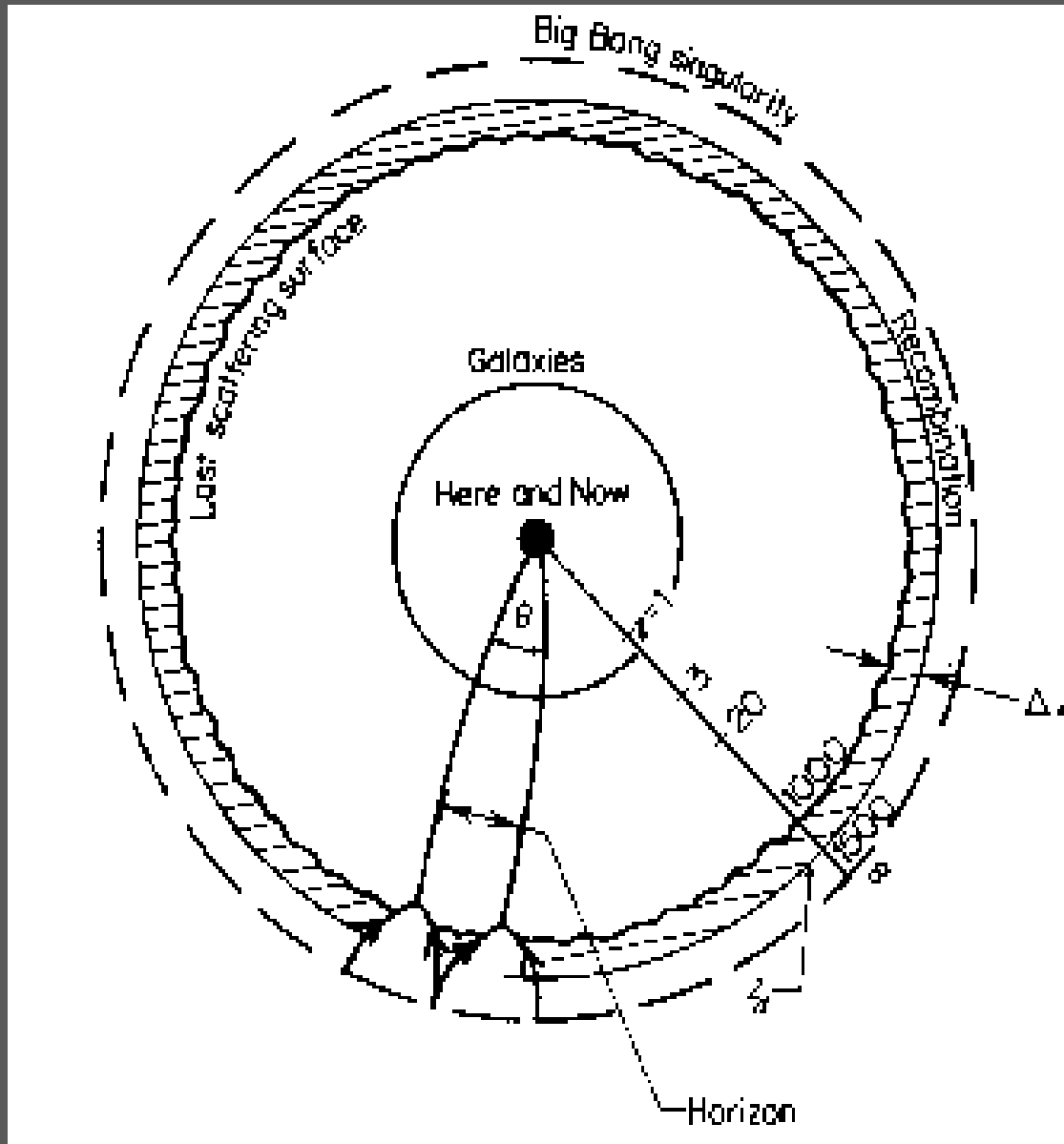


Penzias and Wilson and the antenna used to first detect the CMB

From <http://aether.lbl.gov/cmb.html>

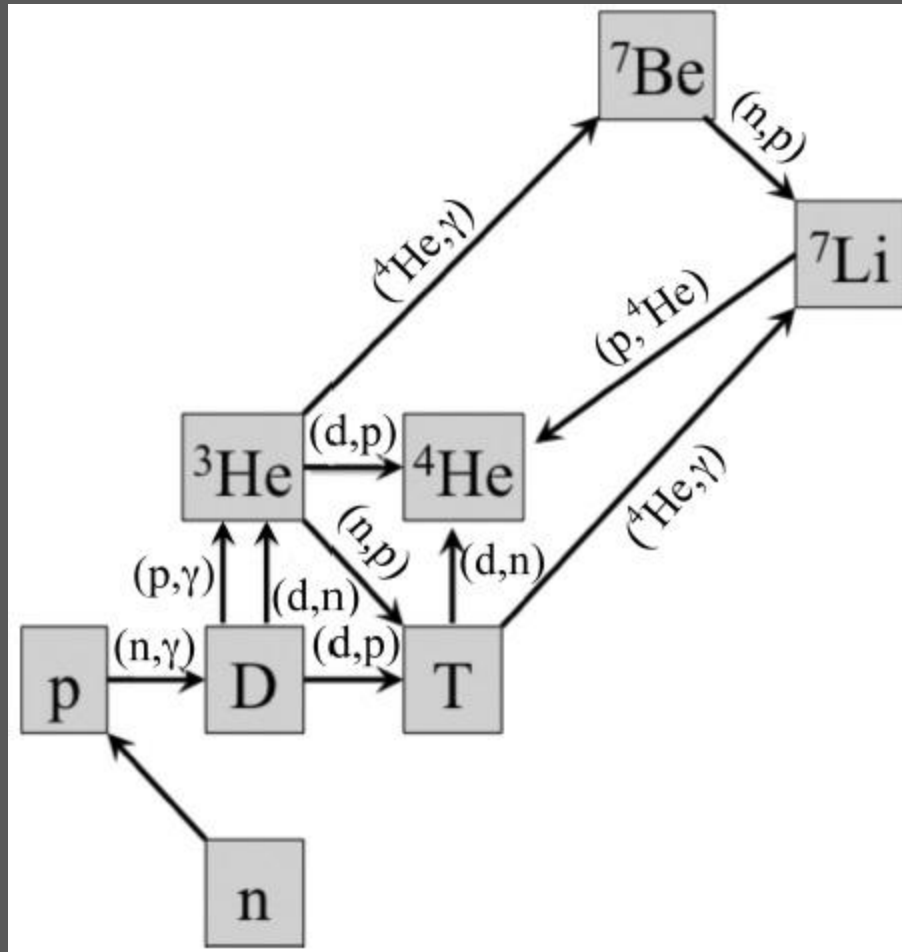


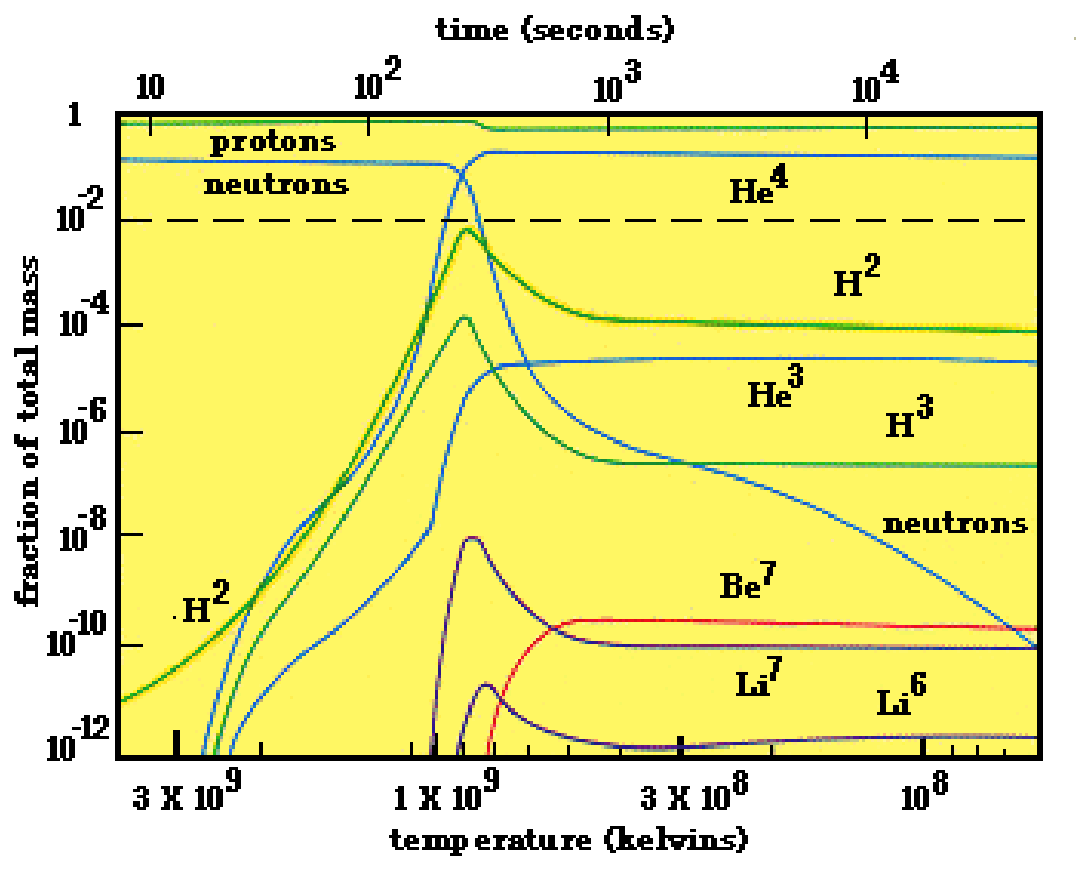
From <http://www.astro.ucla.edu/~wright/CMB.html>



From <http://aether.lbl.gov/cmb.html>

Big bang nucleosynthesis



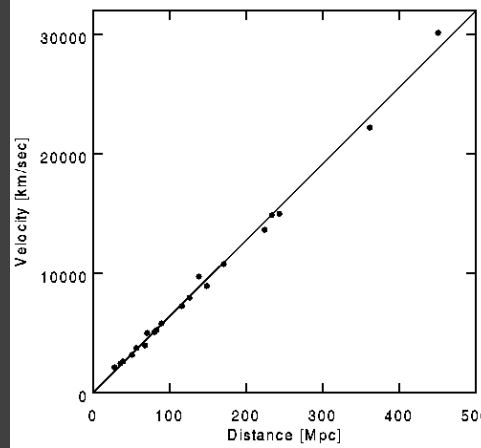


Origin of elements

B B	Big Bang	L Large stars	\$ Super-novae
c Cosmic rays	s Small stars	M Man-made	

H B																He B					
Li C	Be C															B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L															Al \$ L	Si \$ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti \$ L	V \$ L	Cr L	Mn L	Fe \$ L	Co \$	Ni \$	Cu L	Zn L	Ga \$	Ge \$	As L	Se \$	Br \$	Kr \$				
Rb \$	Sr L	Y L	Zr L	Nb L	Mo \$ L	Tc L	Ru \$ L	Rh \$	Pd \$ L	Ag \$ L	Cd \$ L	In \$ L	Sn \$ L	Sb \$	Te \$	I \$	Xe \$				
Cs \$	Ba L	Hf \$ L	Ta \$ L	W \$ L	Re \$	Os \$	Ir \$	Pt \$	Au \$	Hg \$ L	Tl \$ L	Pb \$	Bi \$	Po \$	At \$	Rn \$					
Fr \$	Ra \$	La L	Ce L	Pr \$ L	Nd \$ L	Pm \$ L	Sm \$ L	Eu \$	Gd \$	Tb \$	Dy \$	Ho \$	Er \$	Tm \$	Yb \$ L	Lu \$					
		Ac \$	Th \$	Pa \$	U \$	Np \$	Pu \$	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M					

➤ Expansion of space

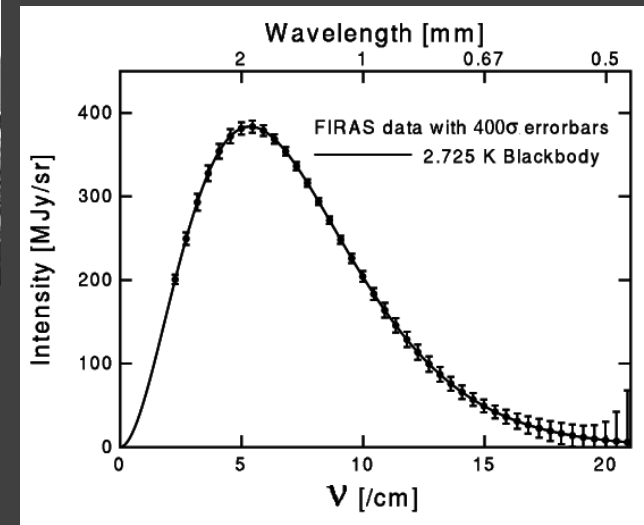
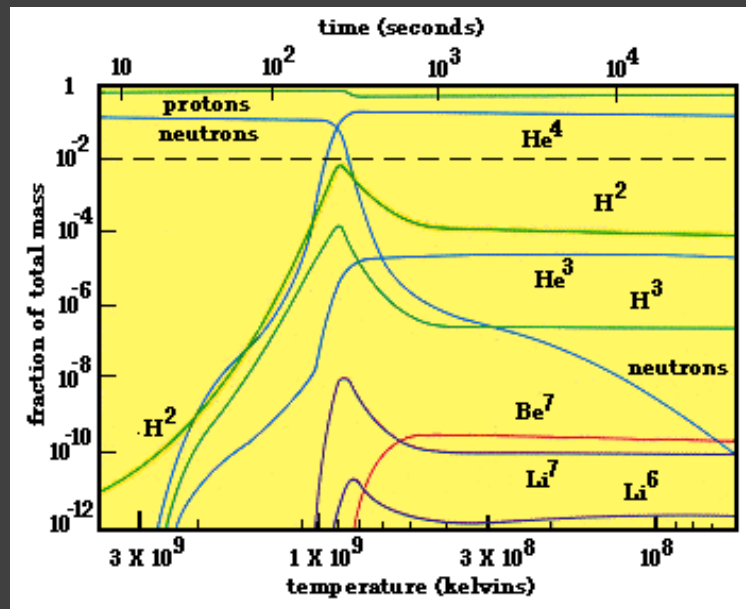


➤ Cosmic microwave background

Penzias and Wilson, 1964

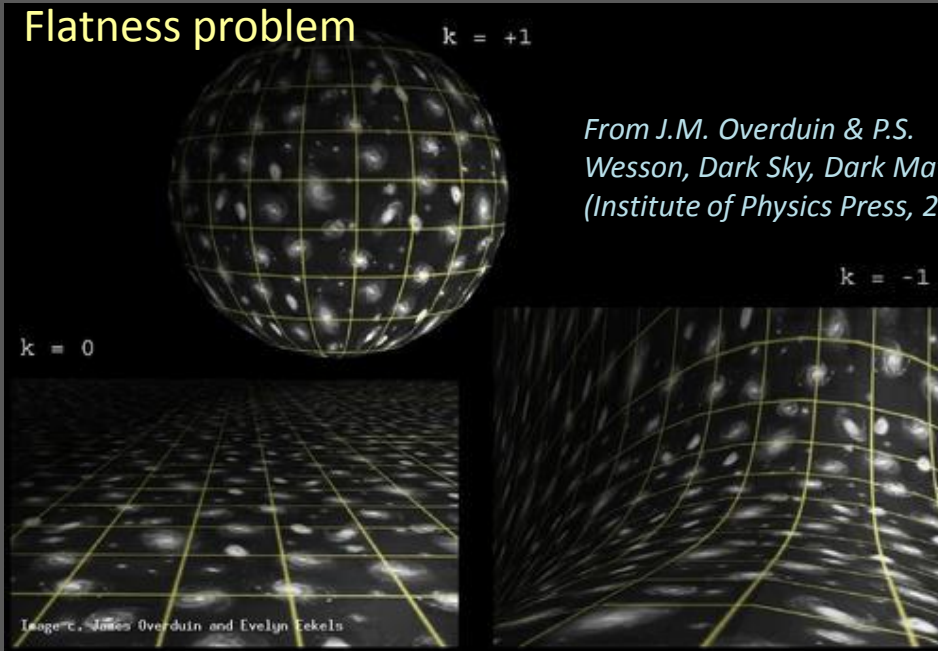


➤ Nucleosynthesis



The big bang HAD to happen

Flatness problem



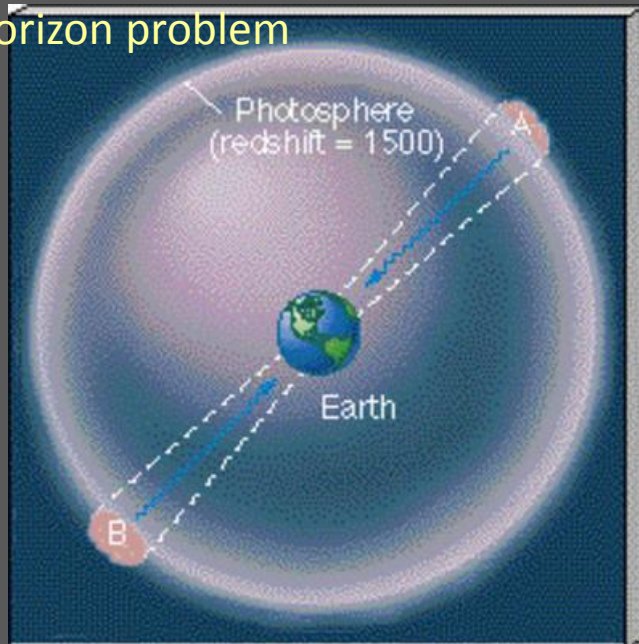
The hot big bang?
What utter nonsense!

Magnetic monopole problem

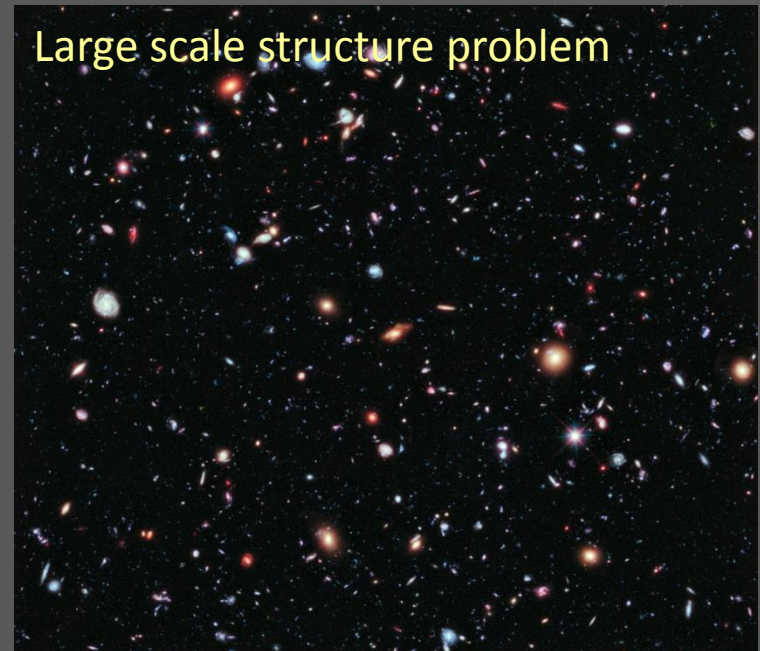


Singularity problem

Horizon problem



Large scale structure problem



Geometry of the universe is \sim flat

<http://www.youtube.com/watch?v=x8pupNMn5nl>

History of the Universe - Current Paradigm

Cosmic inflation

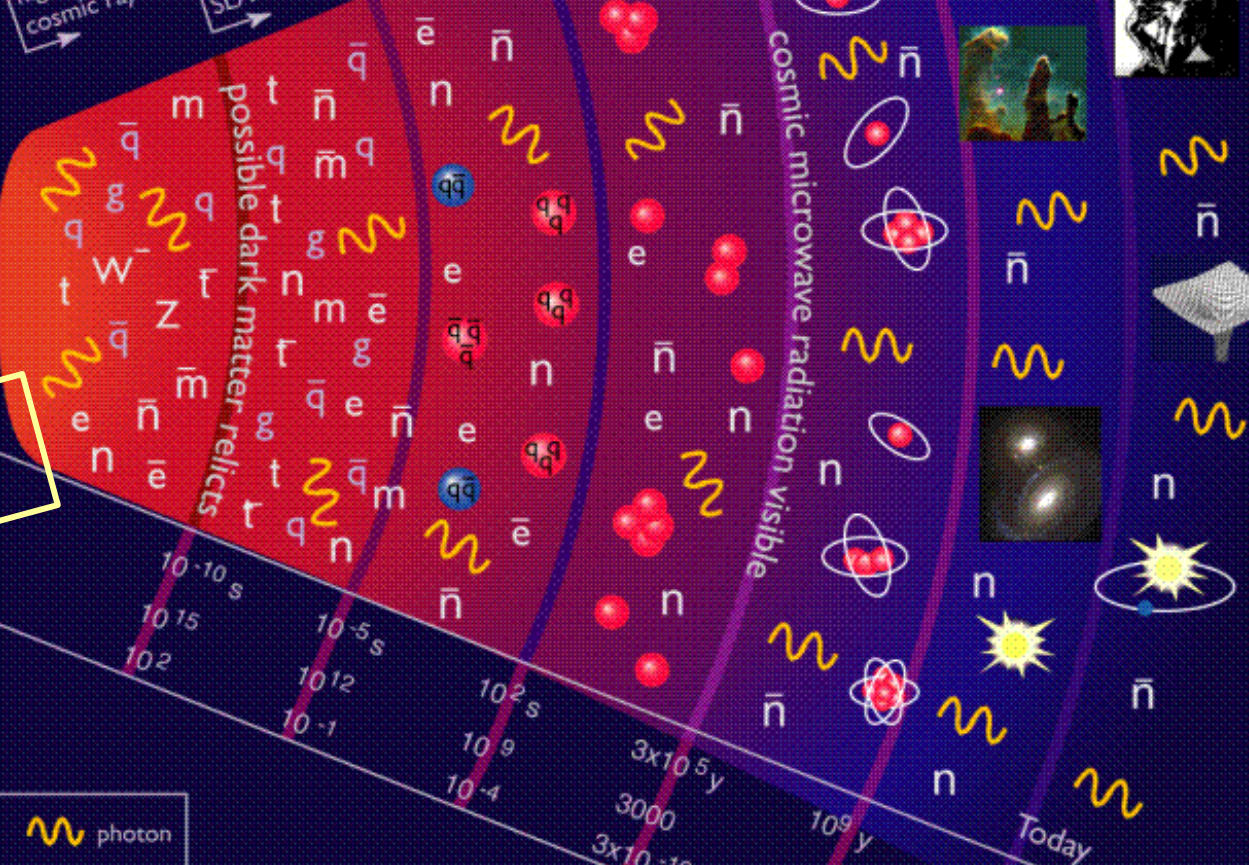
~1979
Guth
Linde
Albrecht
Steinhardt

BIG BANG

Inflation

Accelerators: CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays

Expansion by a factor of $\sim 10^{50}$ in $\sim 10^{-35}$ s



Key:

W, Z bosons	meson	photon
quark	star	galaxy
gluon	baryon	black hole
electron	ion	
muon	atom	
tau		
neutrino		

Flatness problem

$k = +1$

Start out with arbitrary curvature ... expand to very big, space will be flat

From J.M. Overduin & P.S. Wesson, *Dark Sky, Dark Matter* (Institute of Physics Press, 2003)

$k = -1$

Image © James Overduin and Evelyn Eckels



... bang?
... nonsense!

Magnetic monopole problem

Magnetic monopole density $\rightarrow 0$

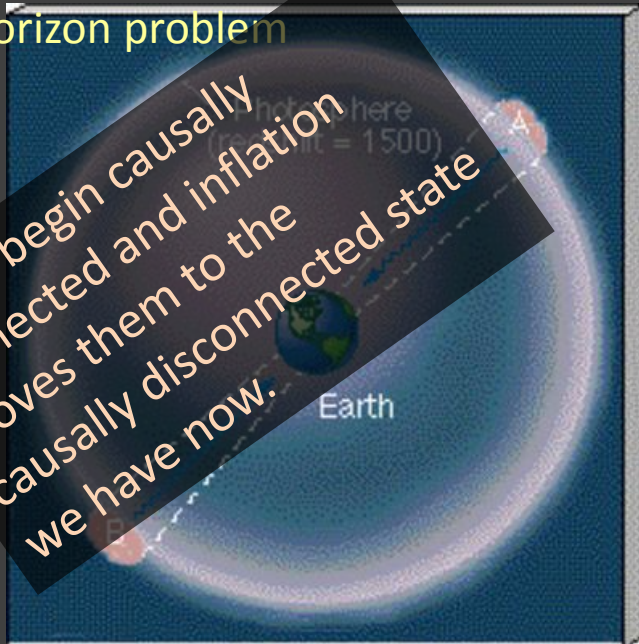


Singularity problem

Singularity not necessary.

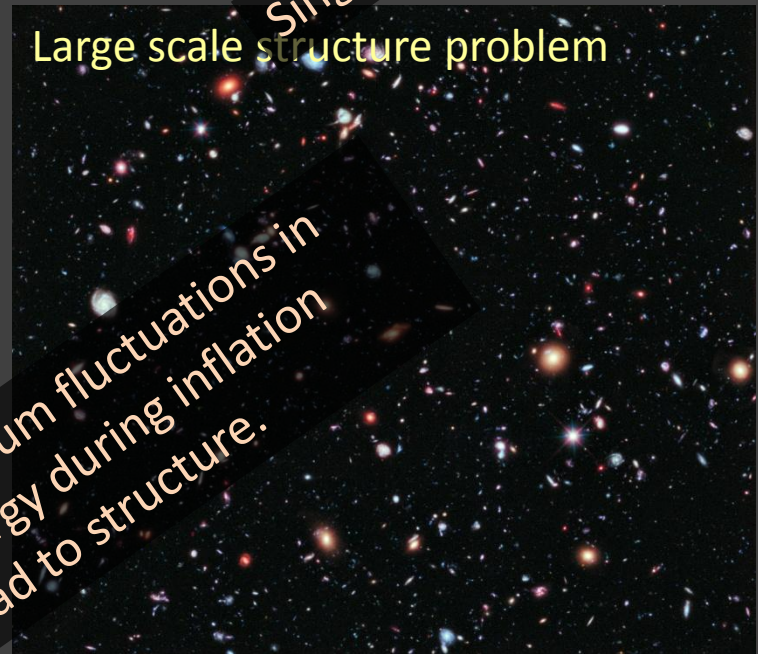
Horizon problem

Points begin causally connected and inflation moves them to the causally disconnected state we have now.

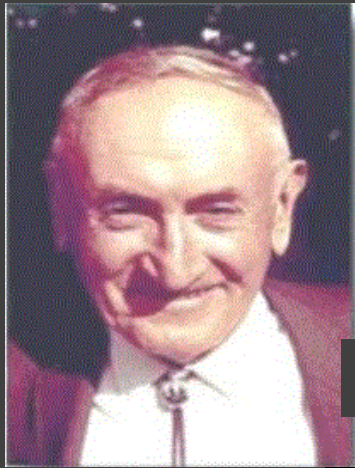


Large scale structure problem

Quantum fluctuations in energy during inflation lead to structure.



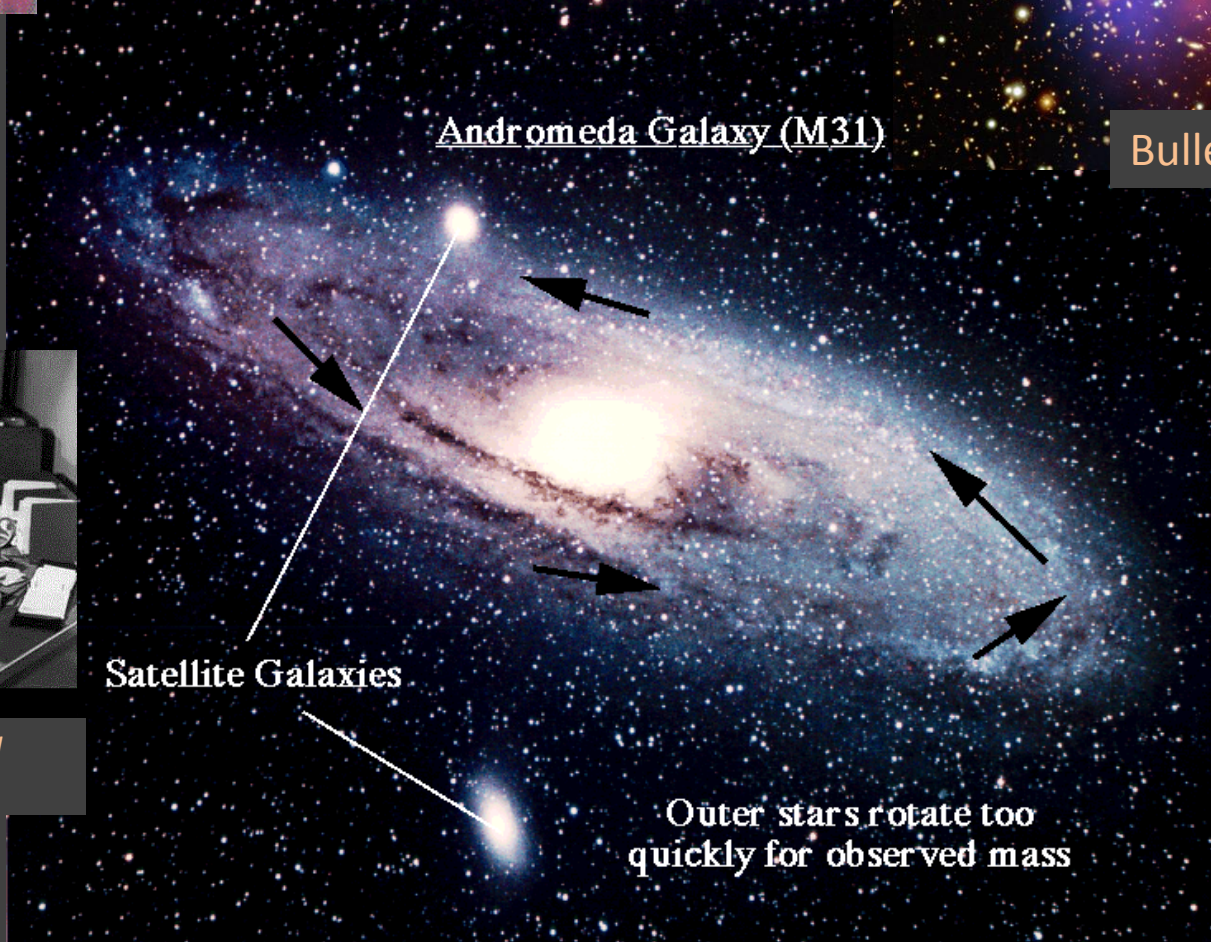
Cold dark matter



Fritz Zwicky



Bullet cluster



Andromeda Galaxy (M31)

Satellite Galaxies

Outer stars rotate too quickly for observed mass

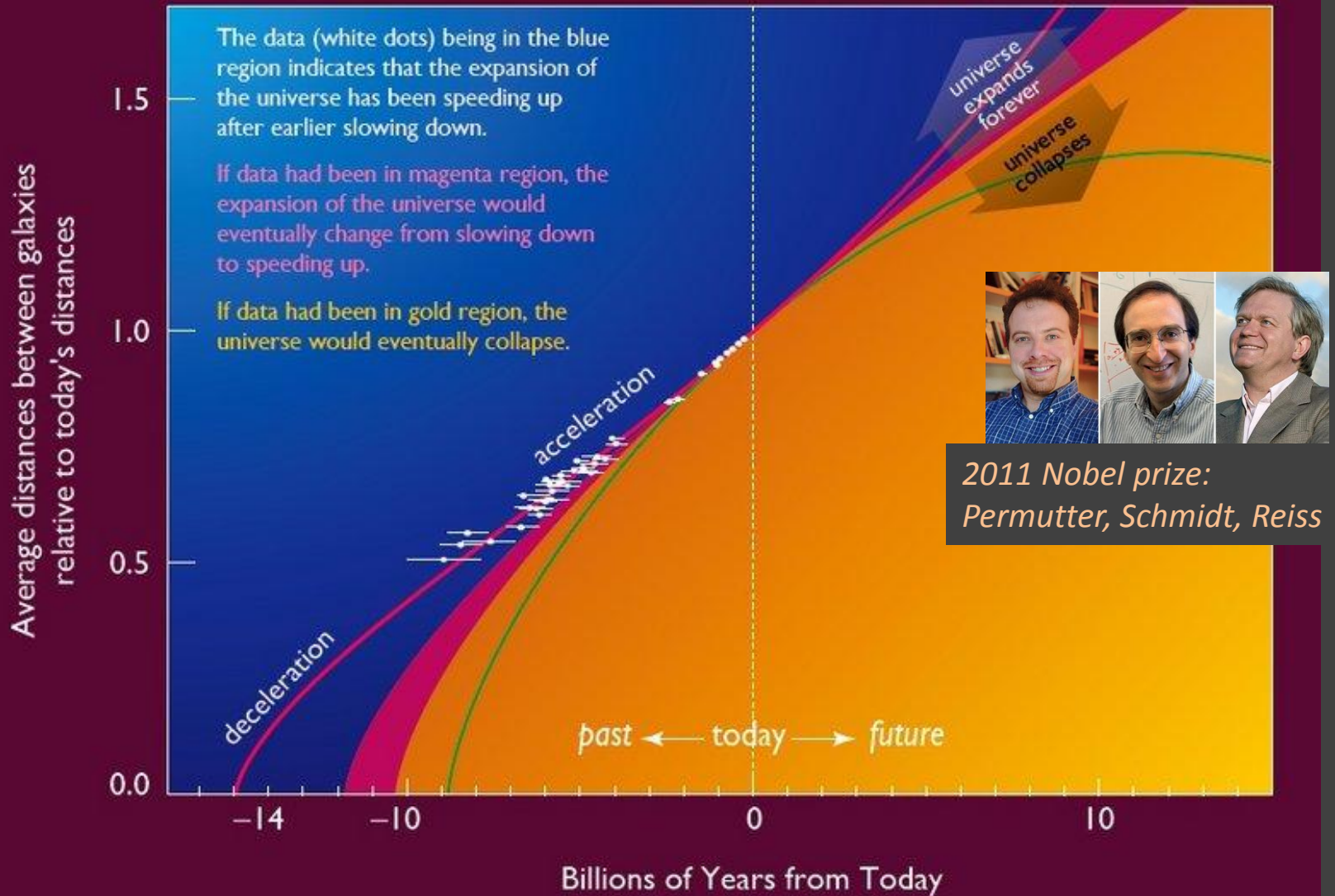


Scanned at the American Institute of Physics

Vera Rubin (published with Kent Ford)

Dark energy

Plot courtesy of the Supernova Cosmology Project at LBNL



“The total energy – matter plus gravitational – remains constant and very small, and could even be exactly zero. ... If inflation is right, everything can be created from nothing, or at least from very little. If inflation is right, the universe can properly be called the ultimate free lunch.”

- Alan Guth



EV ⑤
Dec 7, 1979

SPECTACULAR REALIZATION:

This kind of supercooling can explain why the universe today is so incredibly flat — and therefore ~~why~~ resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

Let me first rederive the Dicke paradox. He relies on the empirical fact the the deceleration parameter today q_0 is of order 1.

$$q_0 \equiv - \ddot{R} \frac{R}{\dot{R}^2}$$

Use the eqs of motion

$$3\ddot{R} = -4\pi G (\rho + 3p) R$$

$$\dot{R}^2 + k = \frac{8\pi G}{3} \rho R^2,$$

so

~~$$q_0 = \frac{\frac{1}{2} (1 + 3p/\rho)}{1 - \frac{3kM_p^2}{8\pi\rho R^2}}$$~~

$$\frac{k}{R^2} = \frac{8\pi\rho}{3M_p^2} - H^2$$

$$G = \frac{1}{M_p^2}, \quad H = \frac{\dot{R}}{R}$$

$$q_0 = \frac{4\pi}{3M_p^2} (\rho + 3p) \frac{1}{H^2}$$

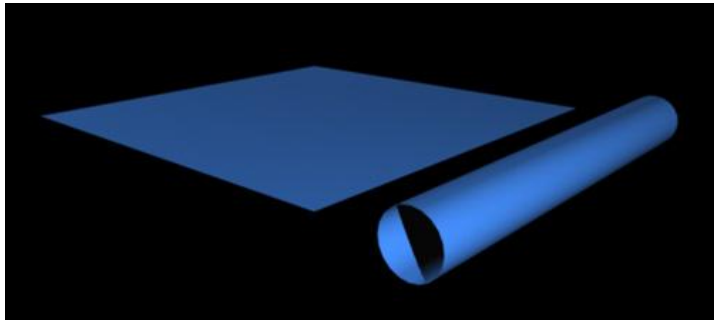
$$\frac{k}{R^2} = \frac{H^2}{(1 + \frac{3p}{\rho})} \left[2q_0 - 1 - \frac{3p}{\rho} \right]$$

Using the above eq, the fact the $\frac{3p}{\rho} \approx 0$ for today's universe, and the fact that $q_0 \sim 1$, one has

What drives inflation? What is dark energy?

A non-string theorist's view of a string theorist's view of inflation/dark energy

A viable string theory of reality (if such exists) will have to be in 10 dimensions



Compactification

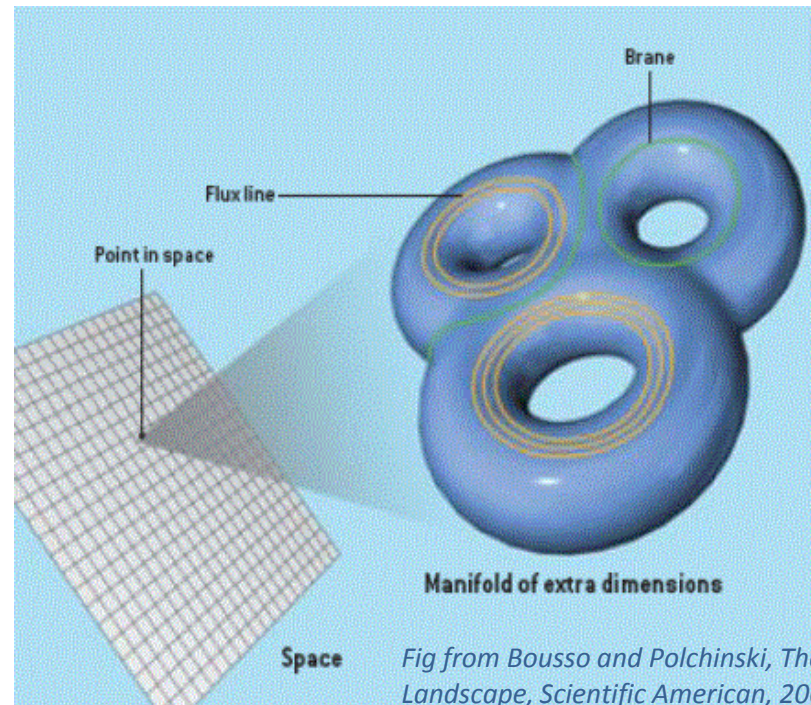
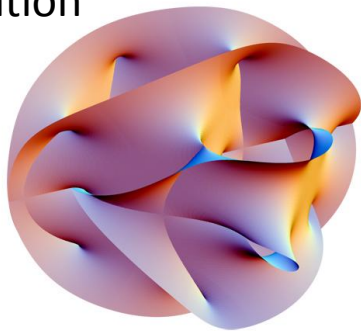
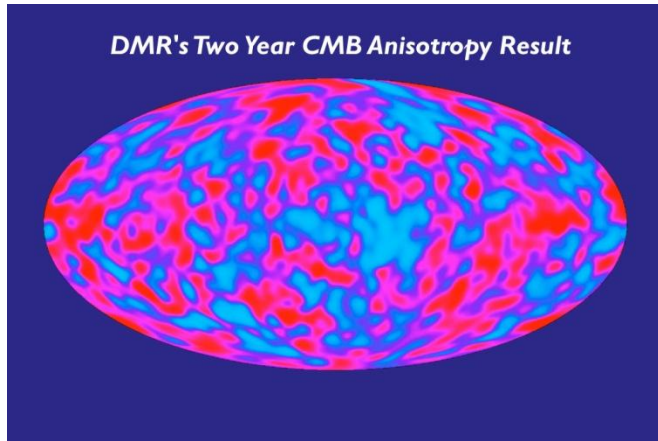


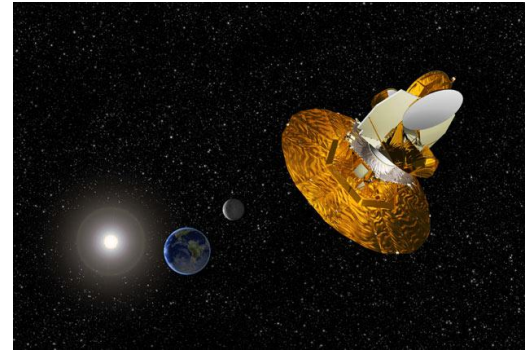
Fig from Bousso and Polchinski, The String Theory Landscape, Scientific American, 2004.

Hot big bang + CDM + DE + inflation
Is this crazy?

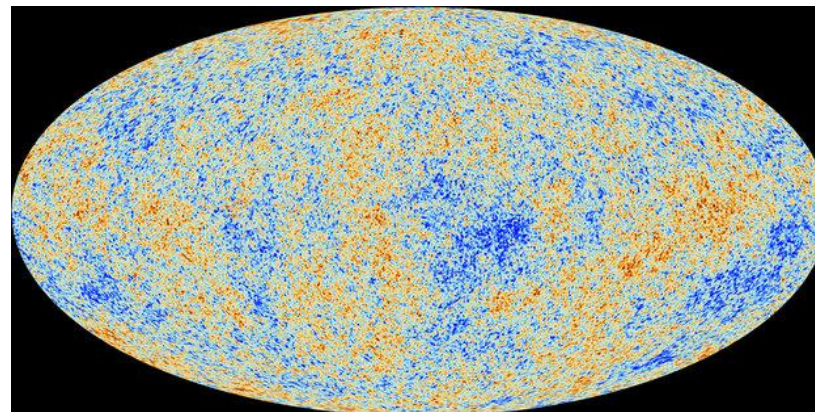
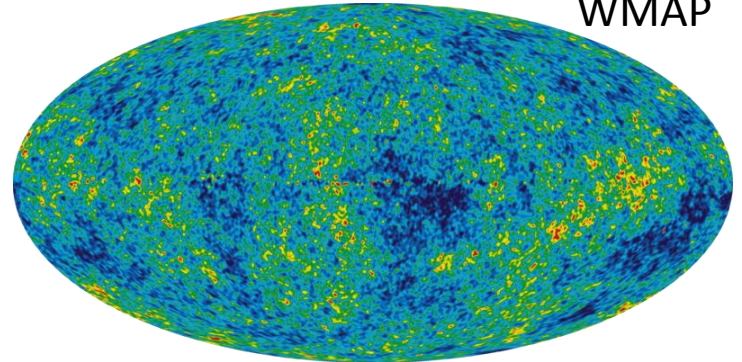
Clues from the CMB



COBE



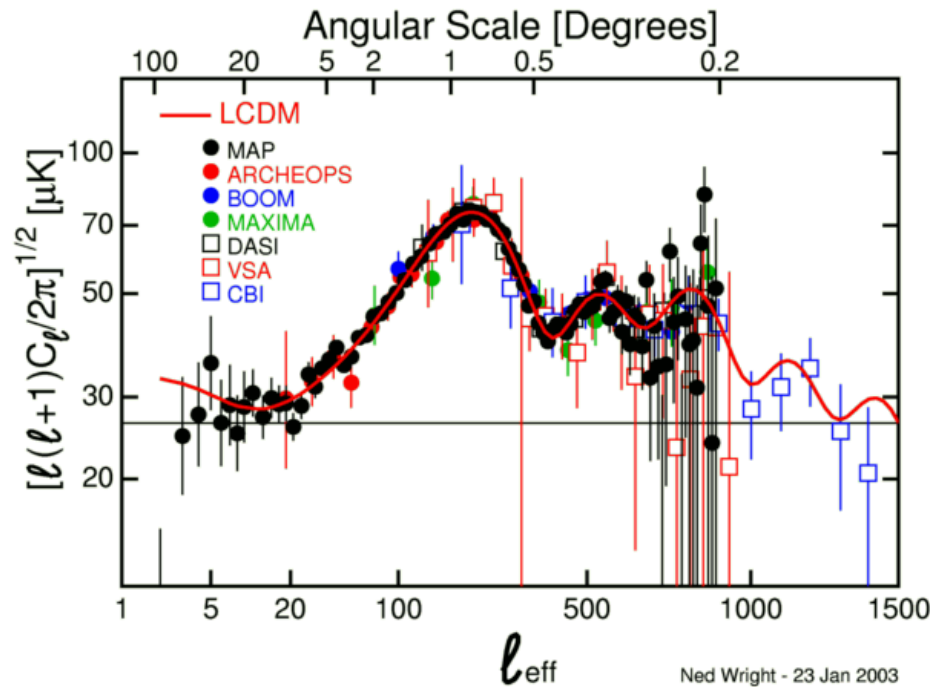
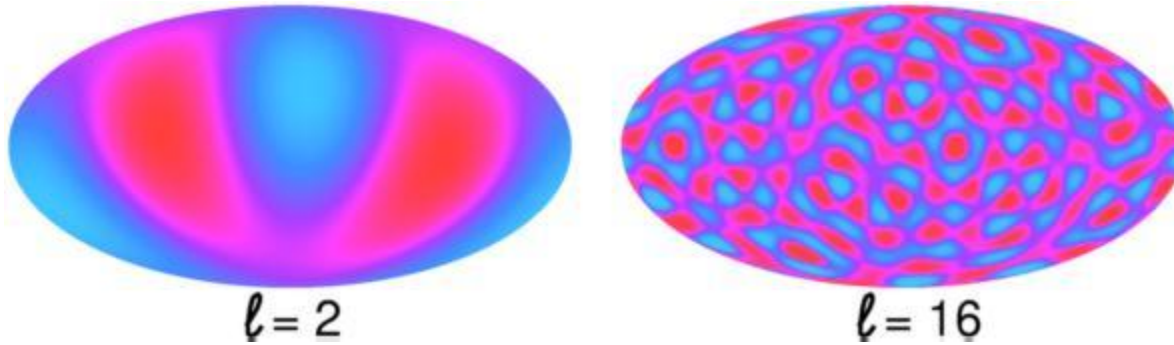
WMAP



Planck

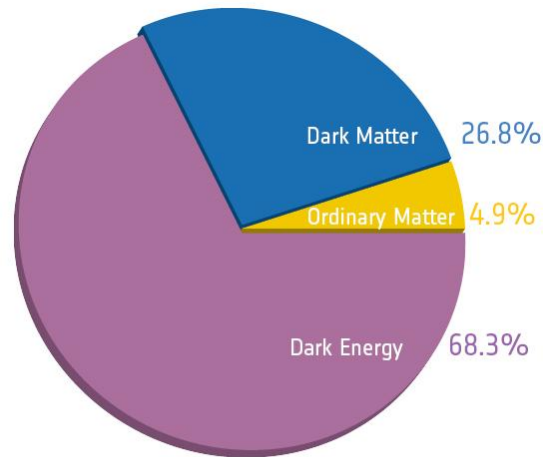
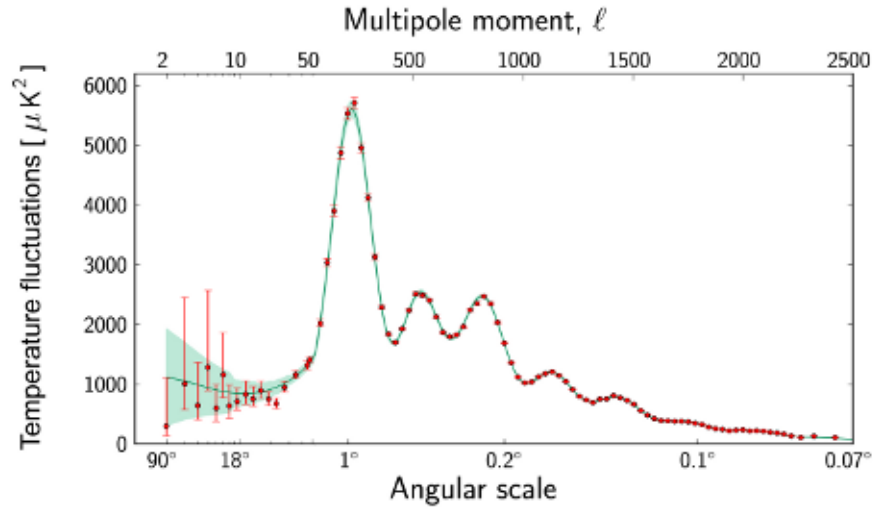
CMB, from ESA's Planck mission website

WMAP CMB angular feature size power spectrum – acoustics in the early universe!



The characteristics of sound waves depend on the medium!

This data is sensitive to amount of Normal matter, dark matter, dark energy and inflationary model of the early universe



After Planck

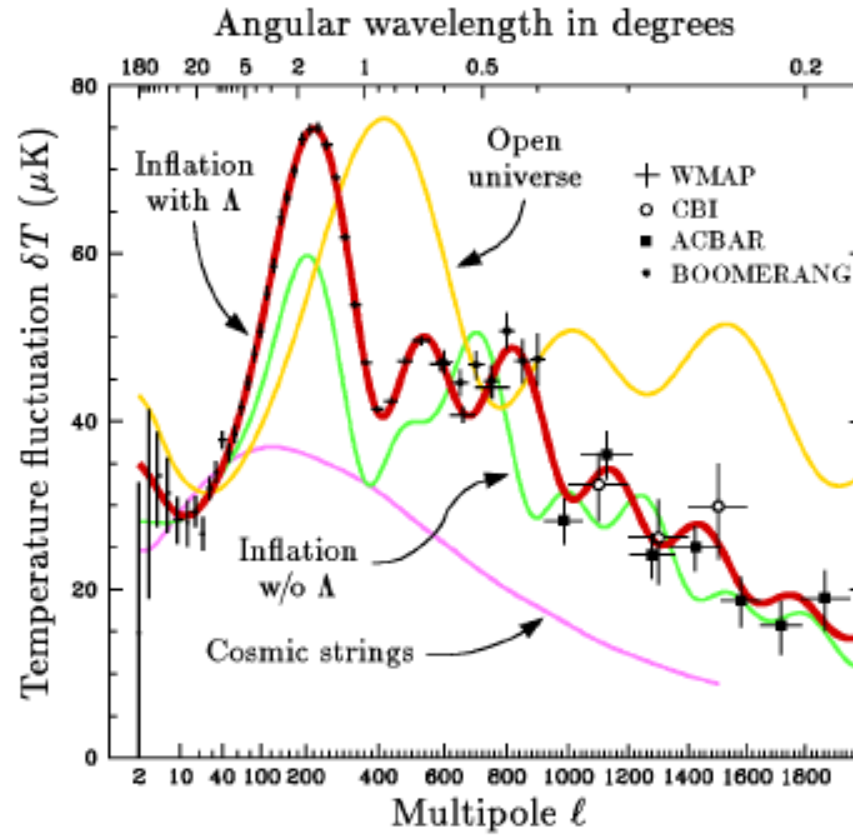
*From the Planck
collaboration*

Eternal inflation and its implications‡

Alan H. Guth

Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

2007



Planck 2013 results. XXII. Constraints on inflation

Planck Collaboration: P. A. R. Ade³⁶, N. Aghanim³⁹, C. Armitage-Caplan³², M. Arnaud⁷², M. Ashdown^{69,6}, F. Atrio-Barandela¹⁹, J. Aumont⁵⁹,
C. Baccigalupi³⁵, A. J. Banday^{35,10}, R. B. Barreiro⁶⁶, J. G. Bartlett^{1,67}, N. Bartolo³³, E. Battaner³⁶, K. Benabed^{60,94}, A. Benoît³⁷,
A. Benoit-Lévy^{26,68,94}, J.-P. Bernard¹⁰, M. Bersanelli^{36,50}, P. Bielewicz^{35,10,85}, J. Bobin⁷², J. J. Bock^{67,11}, A. Bonaldi⁶⁸, J. R. Bond⁹, J. Borrill^{14,80},
E. P. Bucher^{60,94}, M. Bradař^{63,63}, M. Brubeck⁷, C. Burigana^{63,9}, P. C. Butler⁴⁹, E. Calabrese⁸², J. E. Carlstrom^{73,1,68}, A. Castaldi^{74,71}

ABSTRACT

We analyse the implications of the *Planck* data for cosmic inflation. The *Planck* nominal mission temperature anisotropy measurements, combined with the *WMAP* large-angle polarization, constrain the scalar spectral index to $n_s = 0.9603 \pm 0.0073$, ruling out exact scale invariance at over 5σ . *Planck* establishes an upper bound on the tensor-to-scalar ratio at $r < 0.11$ (95% CL). The *Planck* data shrink the space of allowed standard inflationary models, preferring potentials with $V'' < 0$. Exponential potential models, the simplest hybrid inflationary models, and monomial potential models of degree $n > 2$ do not provide a good fit to the data. *Planck* does not find statistically significant running of the scalar spectral index.

36

Planck Collaboration: Co

$f_{\text{NL}}^{\text{local}} = -5/4$. The constraint $0.98 < r_D < 1$ then corresponds to $-1.25 < f_{\text{NL}}^{\text{local}} < -1.21$. Taking into account the *Planck* result $f_{\text{NL}}^{\text{local}} = 2.7 \pm 5.8$ (Planck Collaboration XXIV, 2013), we conclude that the *Planck* data are consistent with the scenario where the curvaton decays into CDM when it dominates the energy density of the Universe, and its fluctuations are almost entirely converted into adiabatic ones.

11. Conclusions

This paper establishes the status of cosmic inflation in the context of the first release of the *Planck* cosmological results, which includes the temperature data from the first 2.6 sky surveys. CMB polarization as measured by *Planck* will be the subject of a future release. We find that standard slow-roll single field inflation is compatible with the *Planck* data. This result is confirmed by other papers of this series. *Planck* in combination with *WMAP* 9-year large angular scale polarization (WP) yields

Recent result reported by the BICEP2 collaboration

BBC News Sport Weather Capital Future
NEWS SCIENCE & ENVIRONMENT
Home US & Canada Latin America UK Africa Asia Europe Mid-East Business Health Sci/Env

★★★★ Columbia Dividend Income Fund
Class 2, Overall rating among 1,056 Large Value funds as of 12/31/13. The Fund received a Morningstar Rating™ of 4 stars among 847 funds and 6 stars among 817 funds for the 3-, 5- and 10-year periods, respectively. Past performance does not guarantee future results.

17 March 2014 Last updated at 10:46 ET



Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News

SECTIONS HOME SEARCH The New York Times
Big Bang Space Ripples Reveal Big Bang's Smoking Gun
Q&A Squeezing the Milky Way Into a Photo Start-Ups Aim to... Space Market
DIGITAL CLASSROOM DESIGN PRO VIDEO TRAINING For Next Level Skills
SPACE & COSMOS
Space Ripples Reveal Big Bang's Smoking Gun
By DENNIS OVERBYE MARCH 17, 2014

theguardian

News US World Sports Comment Culture Business Money Environment Science
News Science Physics

Primordial gravitational wave discovery heralds 'whole new era' in physics

Gravitational waves could help unite general relativity and quantum mechanics to reveal a 'theory of everything'

Facebook Share 17251
Twitter Tweet 926
Google+ 277
Pinterest 31
LinkedIn Share 120
Email

Stuart Clark
The Guardian, Monday 17 March 2014 14.08 EDT
Jump to comments (1675)

Article history

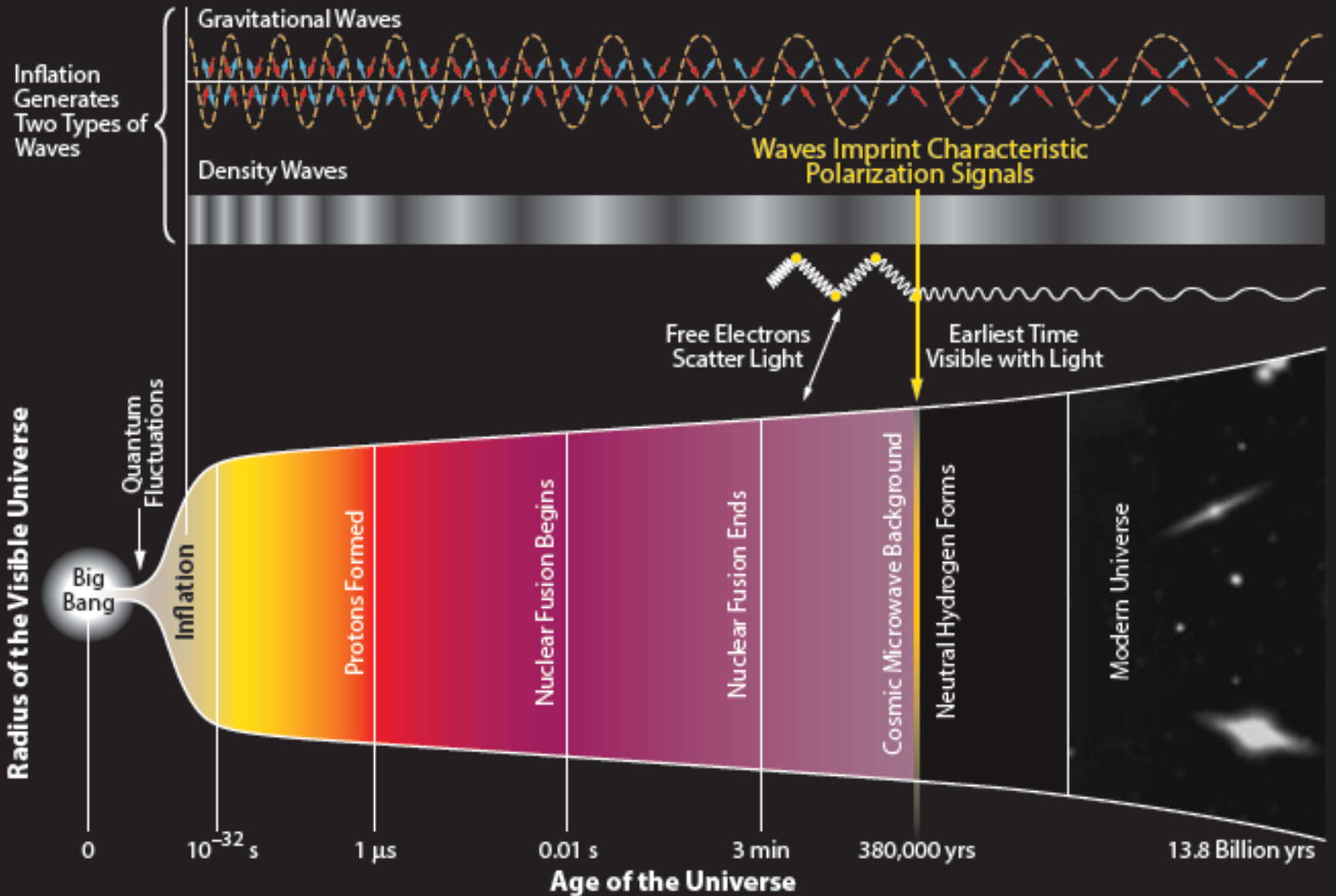


Scientists detected telltale signs of gravitational waves using the Bicep2 telescope (far left) at the South Pole. Photograph: Keith Vanderlinde/NSF

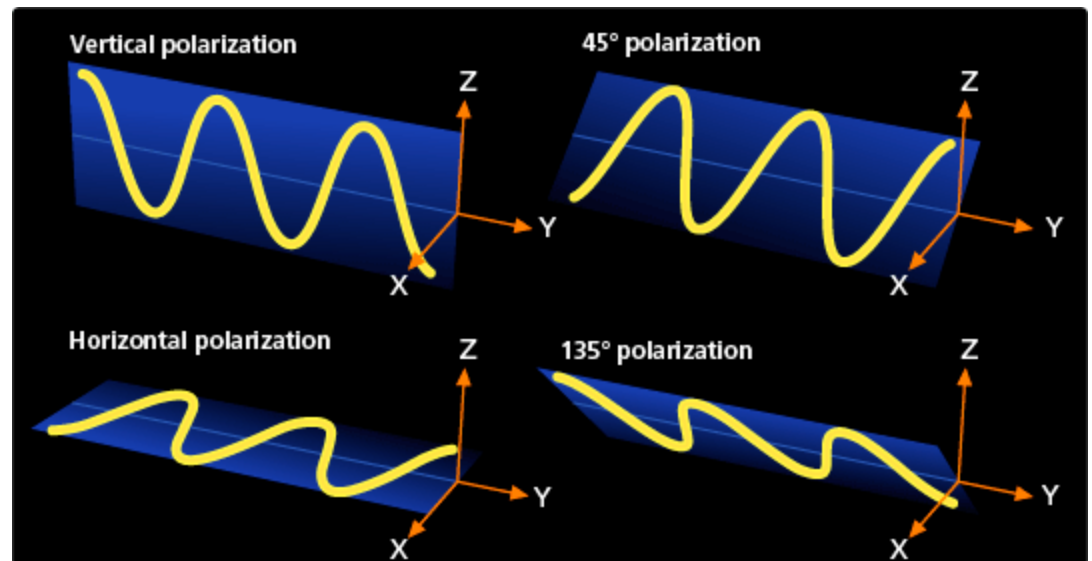
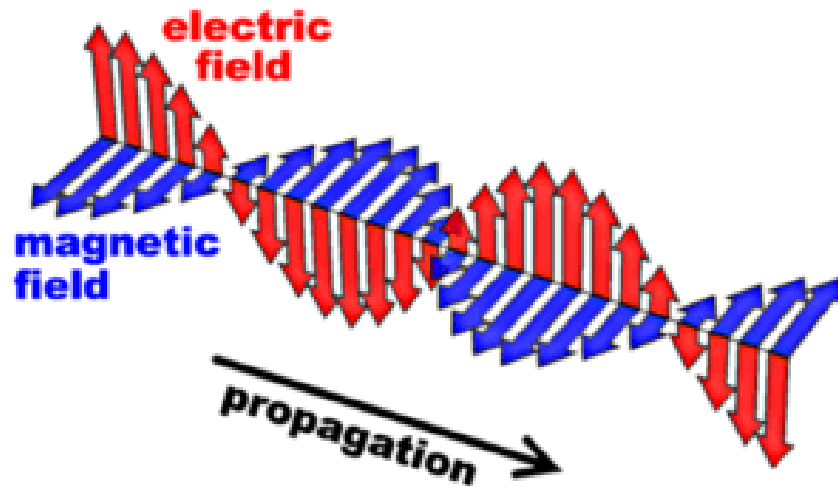
Science
Physics · Albert Einstein
World news
United States
More news

More on this story
George Smoot: 'We mapped the embryo universe'
Zoë Corbyn speaks to the Nobel-winning

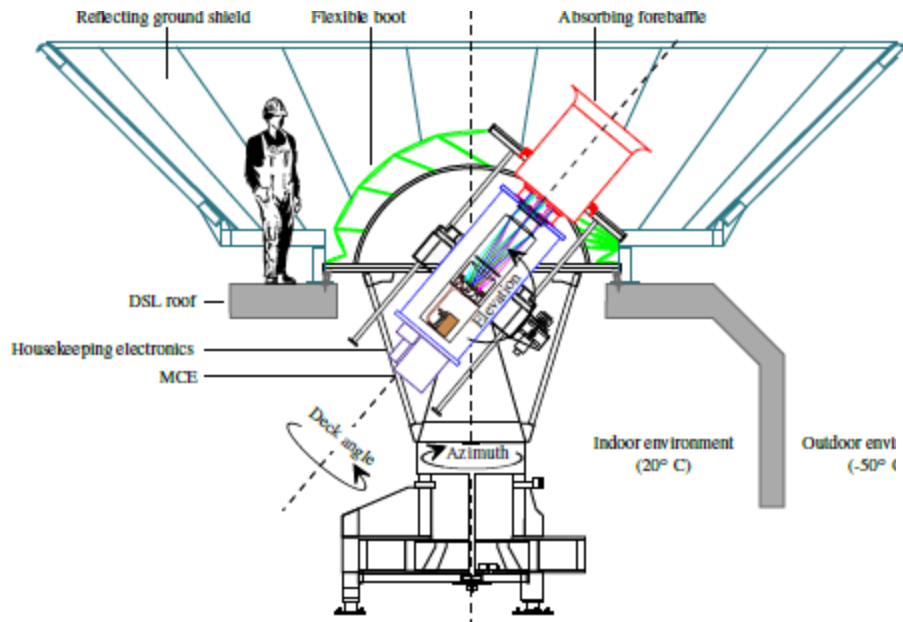
History of the Universe



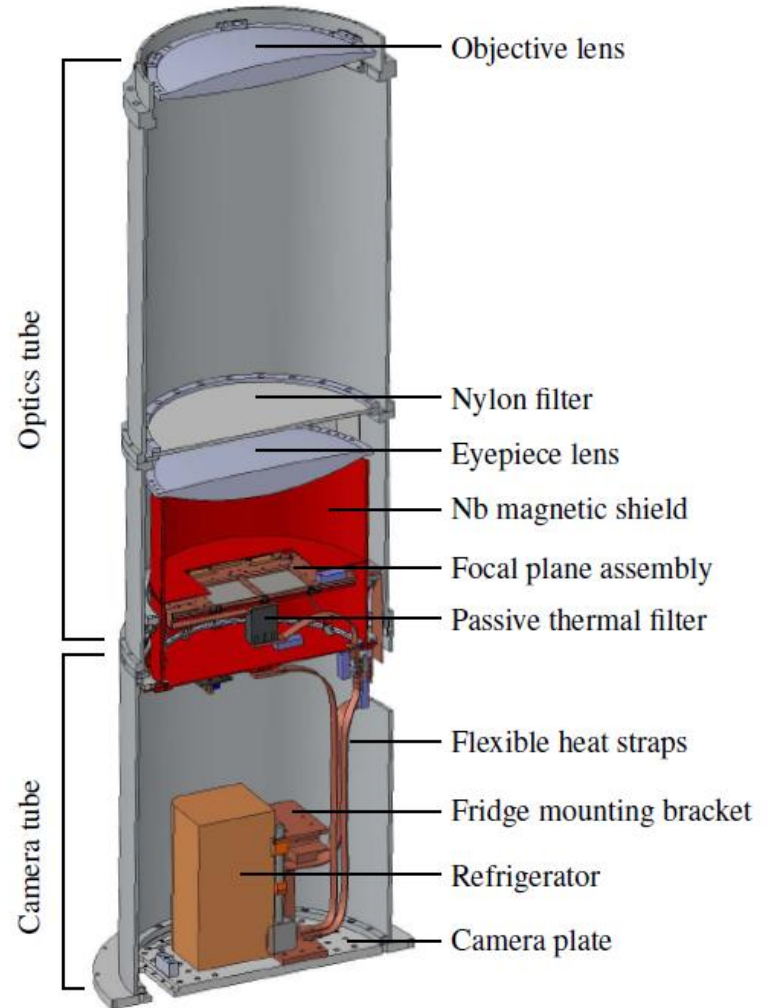
Polarization is the orientation of the electric field in an electromagnetic wave







1.2 m



BICEP2 I: DETECTION OF B -mode POLARIZATION AT DEGREE ANGULAR SCALES

BICEP2 COLLABORATION - P. A. R. ADE¹, R. W. AIKIN², D. BARKATS³, S. J. BENTON⁴, C. A. BISCHOFF⁵, J. J. BOCK^{2,6}, J. A. BREVIK², I. BUDER⁵, E. BULLOCK⁷, C. D. DOWELL⁶, L. DUBAND⁸, J. P. FILIPPINI², S. FLIESCHER⁹, S. R. GOLWALA², M. HALPERN¹⁰, M. HASSELFIELD¹⁰, S. R. HILDEBRANDT^{2,6}, G. C. HILTON¹¹, V. V. HRISTOV², K. D. IRWIN^{12,13,11}, K. S. KARKARE⁵, J. P. KAUFMAN¹⁴, B. G. KEATING¹⁴, S. A. KERNASOVSKIY¹², J. M. KOVAC^{5,17}, C. L. KUO^{12,13}, E. M. LEITCH¹⁵, M. LUEKER², P. MASON², C. B. NETTERFIELD^{4,16}, H. T. NGUYEN⁶, R. O'BRIENT⁶, R. W. OGBURN IV^{12,13}, A. ORLANDO¹⁴, C. PRYKE^{9,7,17}, C. D. REINTSEMA¹¹, S. RICHTER⁵, R. SCHWARZ⁹, C. D. SHEEHY^{9,15}, Z. K. STANISZEWSKI^{2,6}, R. V. SUDIWALA¹, G. P. TEPLY², J. E. TOLAN¹², A. D. TURNER⁶, A. G. VIAREGG^{5,15}, C. L. WONG⁵, AND K. W. YOON^{12,13}

to be submitted to a journal TBD

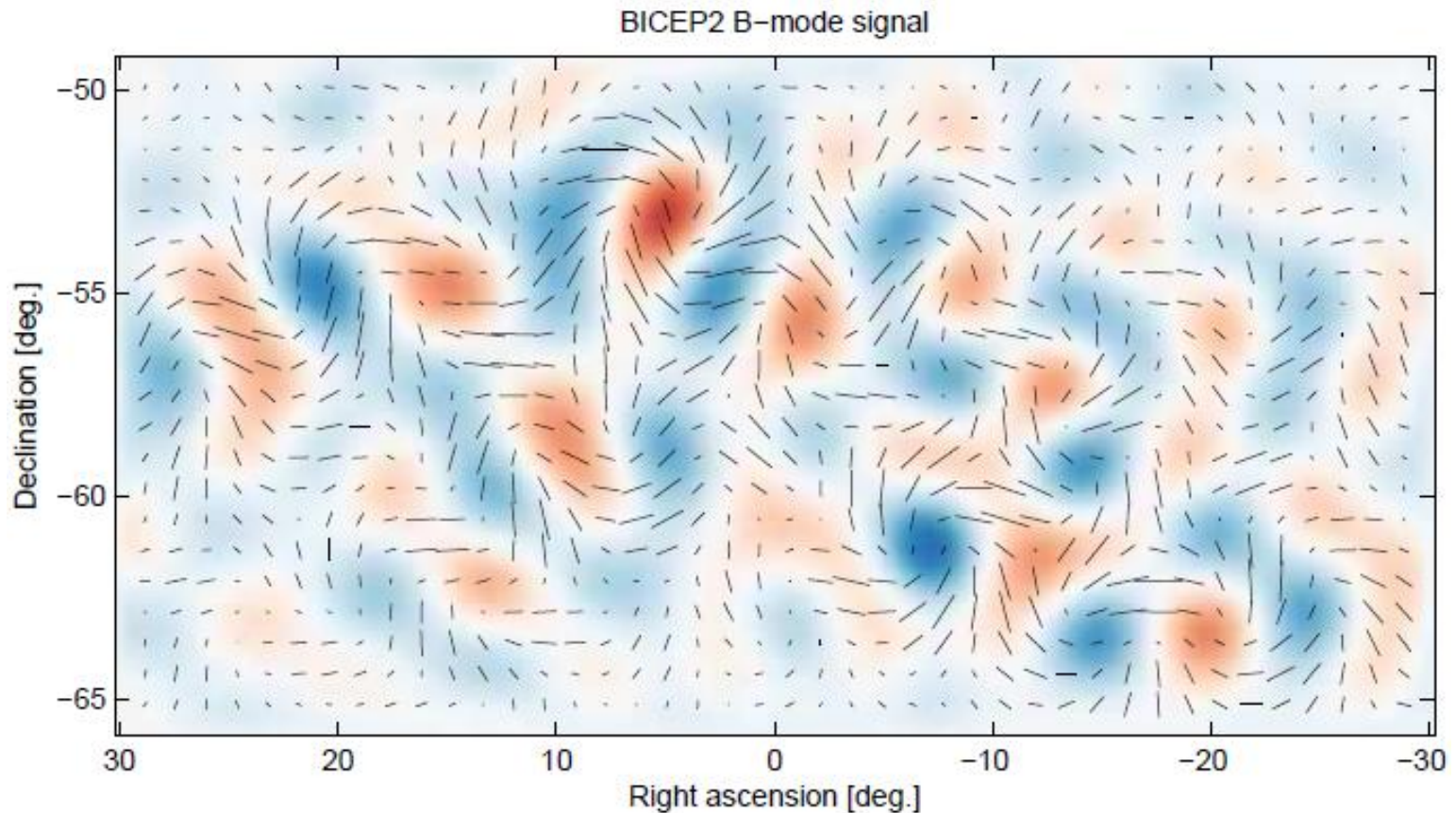
ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the B -mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300 \mu\text{K}_{\text{CMB}} \sqrt{\text{s}}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U . In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of B -mode power over the base lensed- Λ CDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ , respectively. The observed B -mode power spectrum is well-fit by a lensed- Λ CDM + tensor theoretical model with tensor/scalar ratio $r = 0.20_{-0.05}^{+0.07}$, with $r = 0$ disfavored at 7.0σ . Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ .

Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization

darriaga 1997; Peiris et al. 2003, and references above). Although highly successful, the inflationary paradigm represents a vast extrapolation from well-tested regimes in physics. It invokes quantum effects in highly curved spacetime at energies near 10^{16} GeV and timescales less than 10^{-32} s. A definitive test of this paradigm would be of fundamental importance.

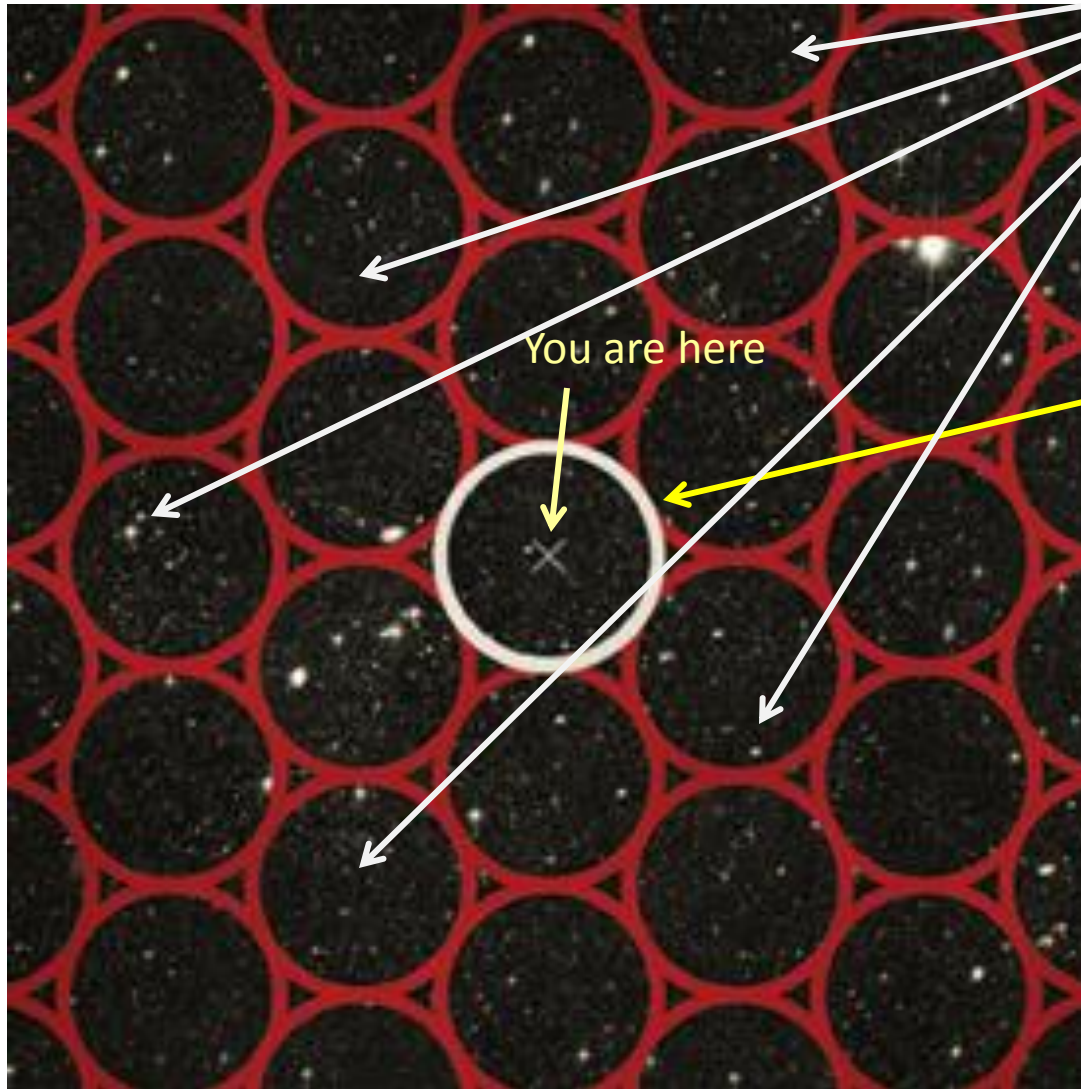
Gravitational waves generated by inflation have the potential to provide such a definitive test. Inflation predicts that the quantization of the gravitational field coupled to exponential expansion produces a primordial background of stochastic gravitational waves with a characteristic spectral shape (Grishchuk 1975; Starobinsky 1979; Rubakov et al. 1982; Fabri & Pollock 1983; Abbott & Wise 1984; also see Krauss & Wilczek 2013). Though unlikely to be directly detectable in modern instruments, these gravitational waves would have imprinted a unique signature upon the CMB. Gravitational waves induce local quadrupole anisotropies in the radiation field within the last-scattering surface, inducing polarization in the scattered light (Polnarev 1985). This polarization pattern will include a “curl” or *B*-mode component at degree angular scales that cannot be generated primordially by density perturbations. The amplitude of this signal depends upon the tensor-to-scalar ratio, *r*, which itself is a function of the energy scale of inflation. The detection of *B*-mode polarization of the CMB at large angular scales would provide a unique confirmation of inflation and a probe of its energy scale (Seljak 1997; Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997).



Degree of curl-ness in the polarization on the size scale chosen is the signal. No known way to induce that other than the effect of primordial gravity waves on the CMB.

What is seen is a large signal, even larger than expected ... perhaps an indication of a surprise to come? Other experiments working to make similar observations. Stay tuned.

If inflation ... welcome to the multiverse!



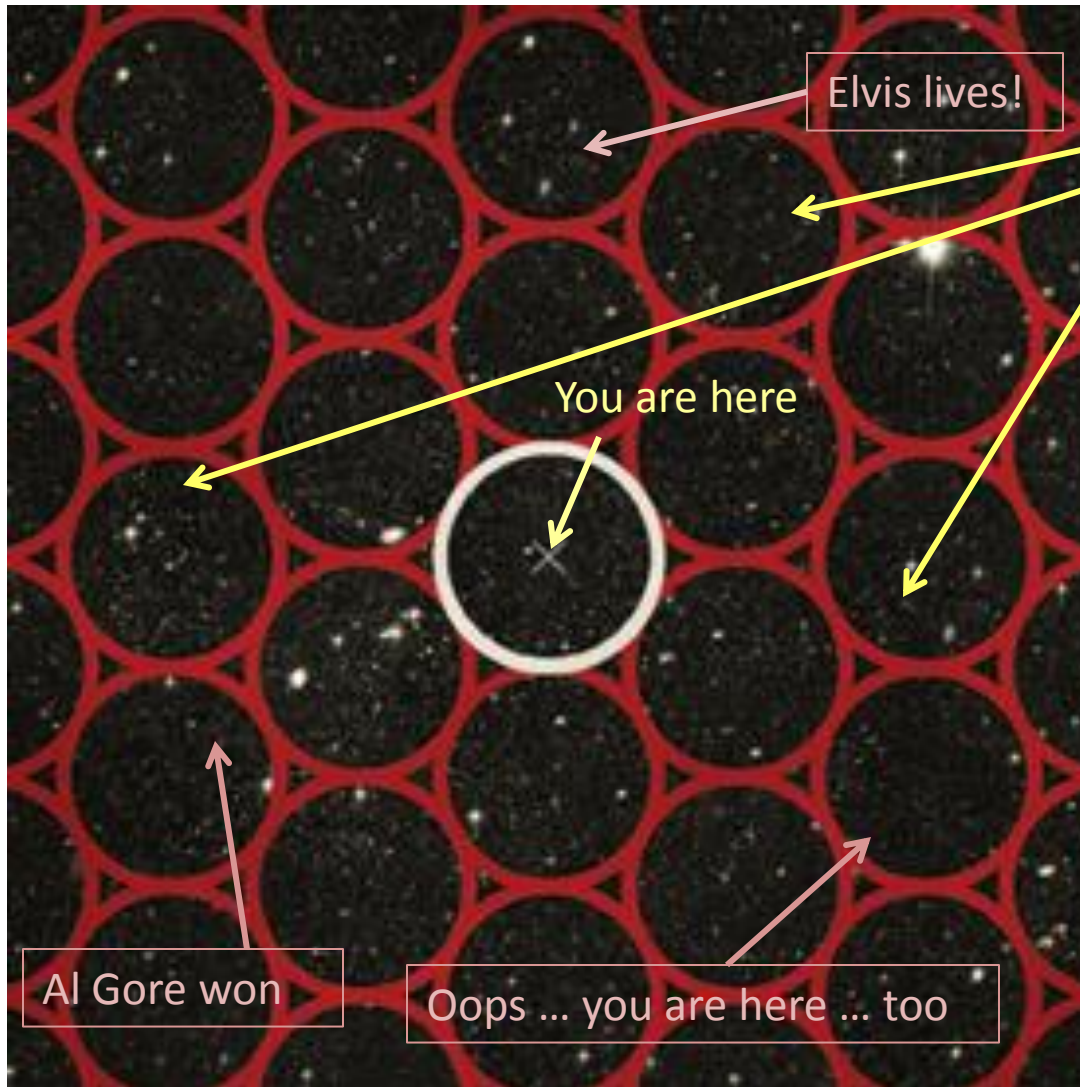
The greater reality which is outside and will always be outside our experience

Our cosmic event horizon

SM "beyond-the-horizon" multiverse

Tegmark's Type I multiverse

How big is this reality? How big does it need to be?
How long did inflation last?



These regions share our physics ... have the same spacetime characteristics.

But each has a different initial condition.

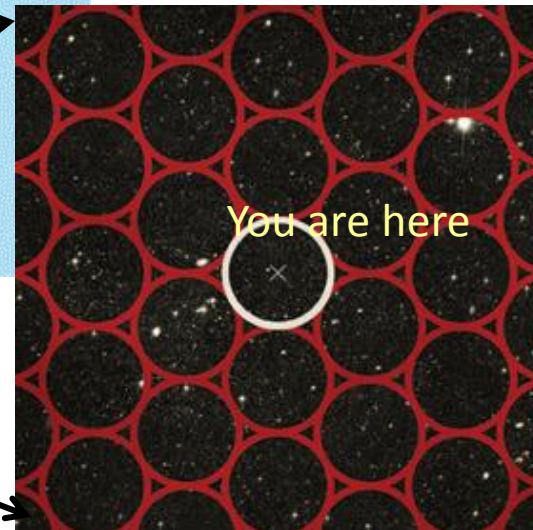
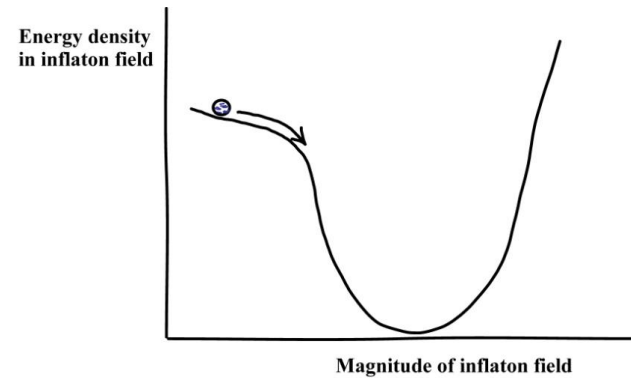
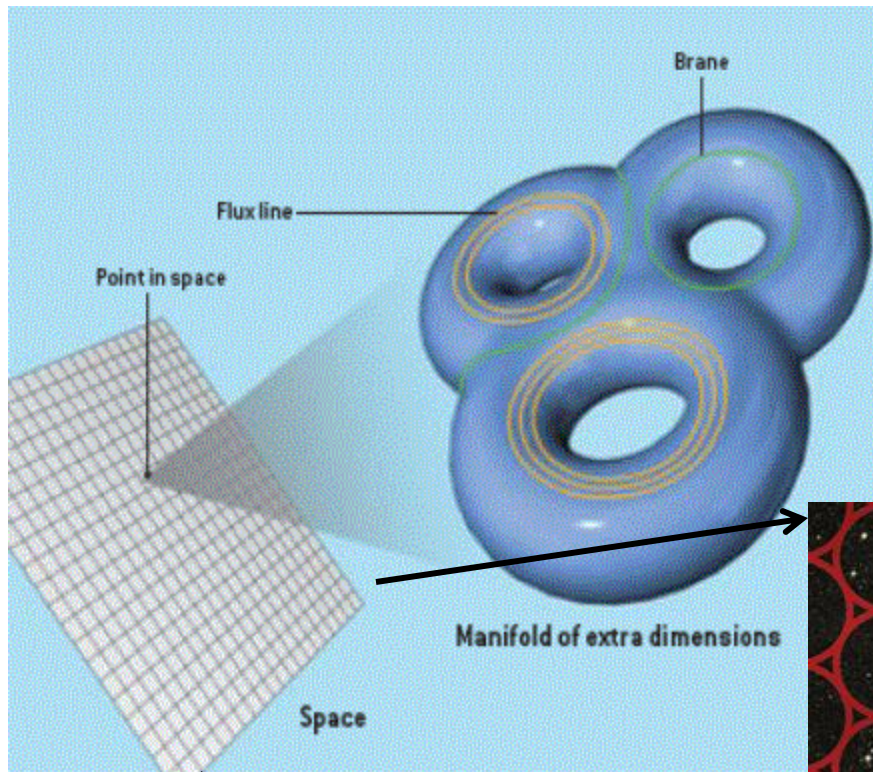
Some serious estimates say there are countless regions of "our universe" size.

All possible initial conditions explored. Anything that could happen does happen.

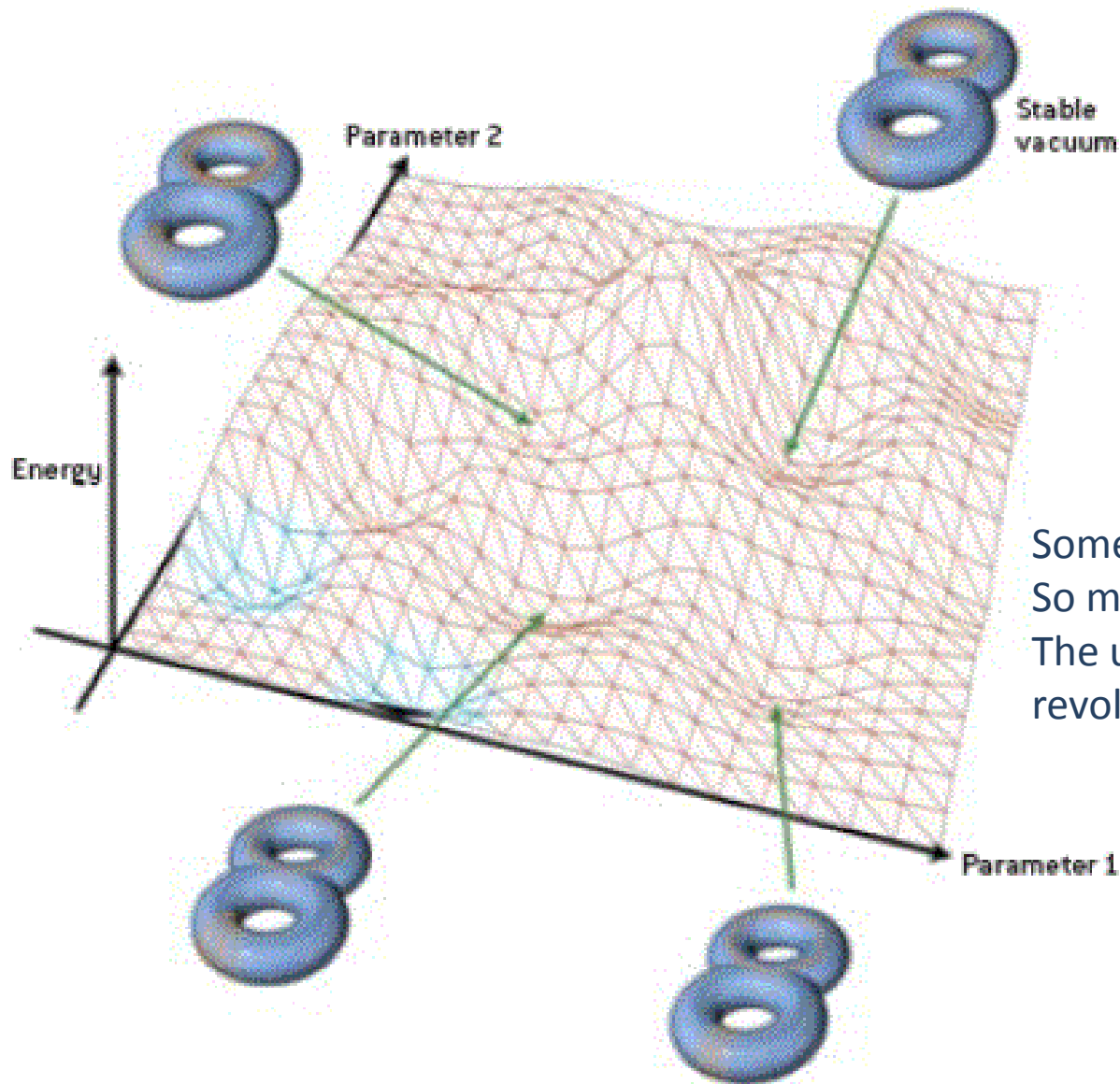
Garriga and Vilenkin, Phys. Rev. D64, 2001, 043511;

Tegmark, Parallel Universes in Science and Ultimate Reality: quantum theory, cosmology and complexity, eds. Barrow, Davies, Harmer, Cambridge Univ. Press, 2004.

Recall mechanism for inflation ...

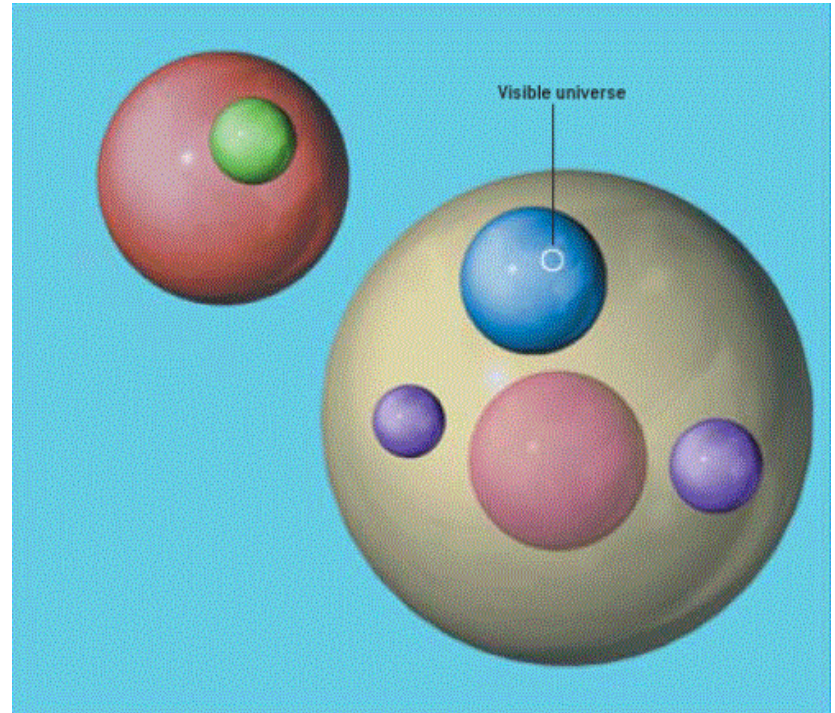
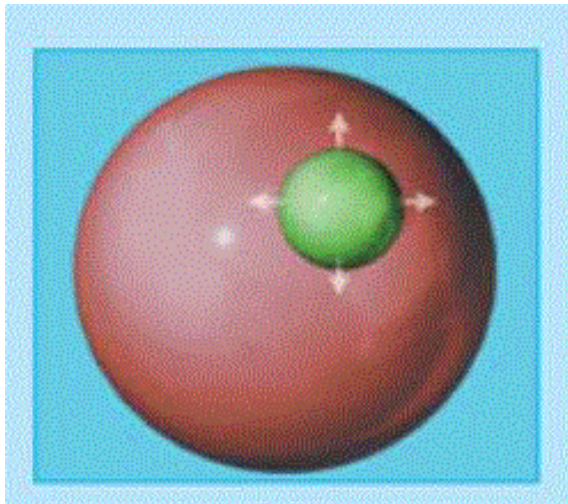
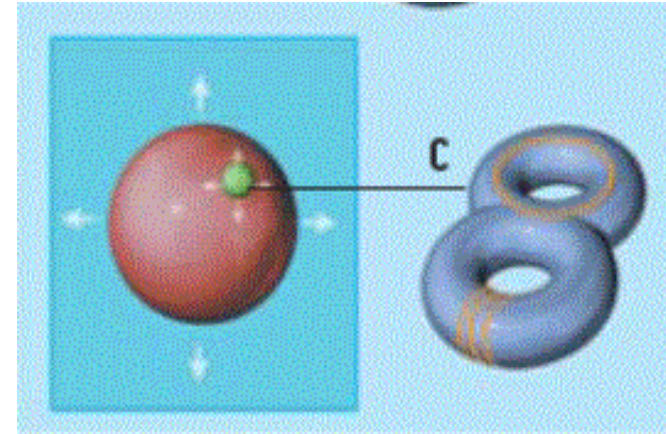
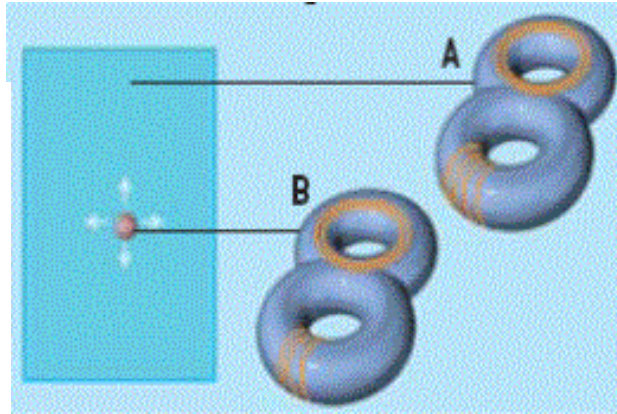
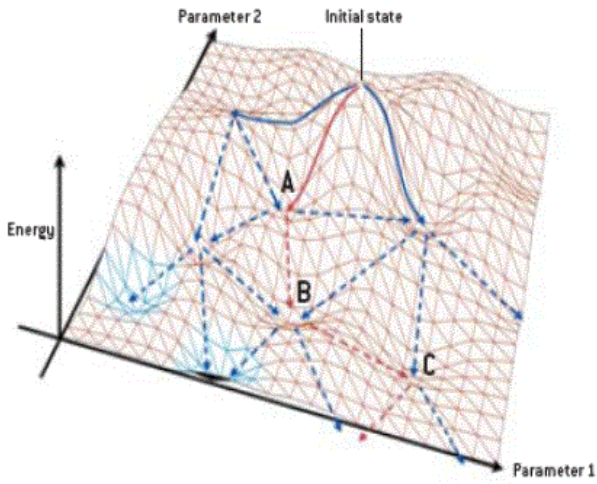


The Cosmic Landscape

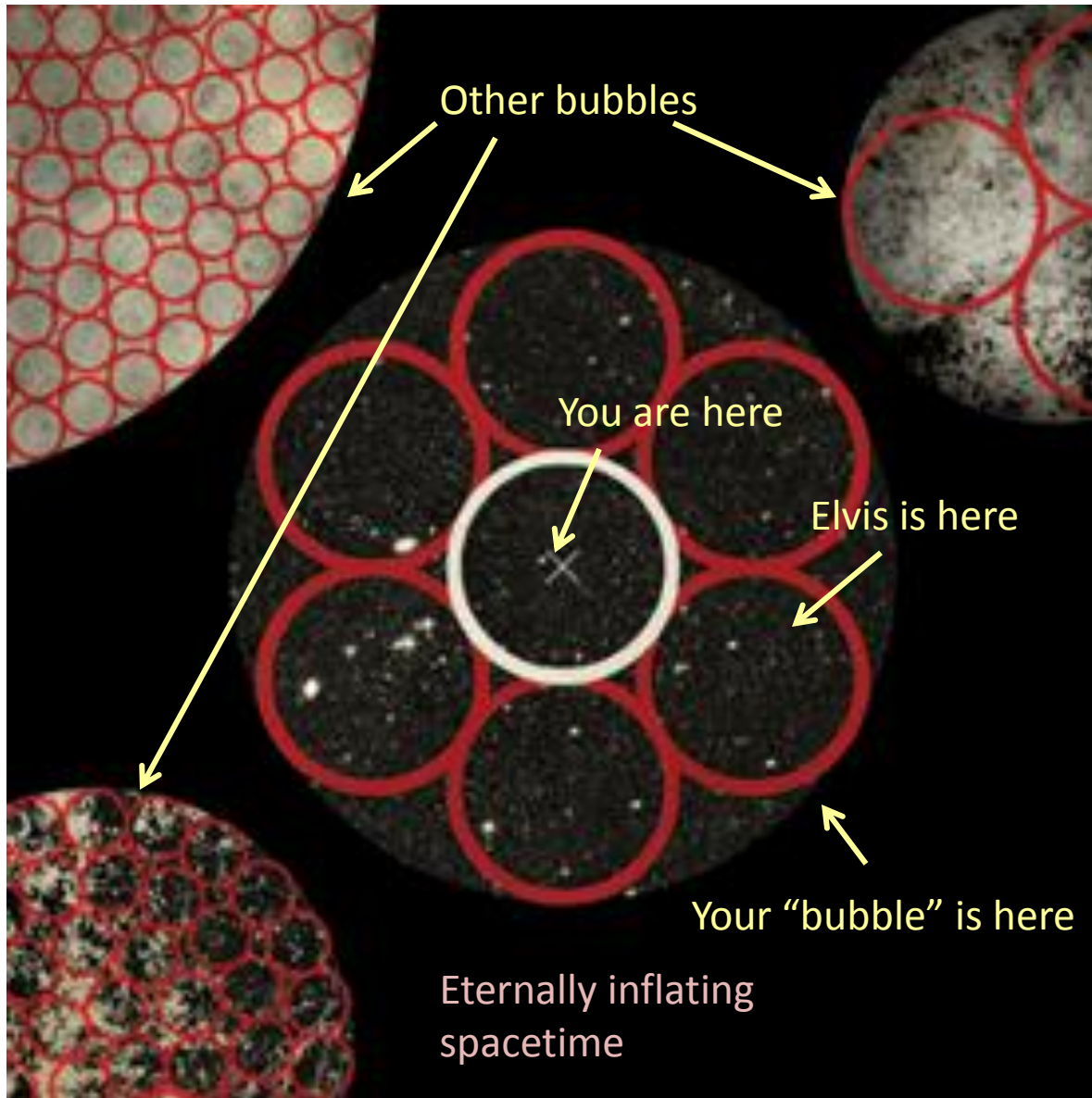


Some 10^{500} minima?
So much for the TOE.
The ultimate "Copernican
revolution"!

The Cosmic Landscape



Eternal inflation ...



There is an eternally inflating “matrix”.

Here and there a fluctuation in the structure of the spacetime causes inflation to stop/change locally and a “bubble universe” might form.

The local minima in the spacetime parameter phase space number $\sim 10^{500}$. So all parameters explored.

The physics in each bubble is different.

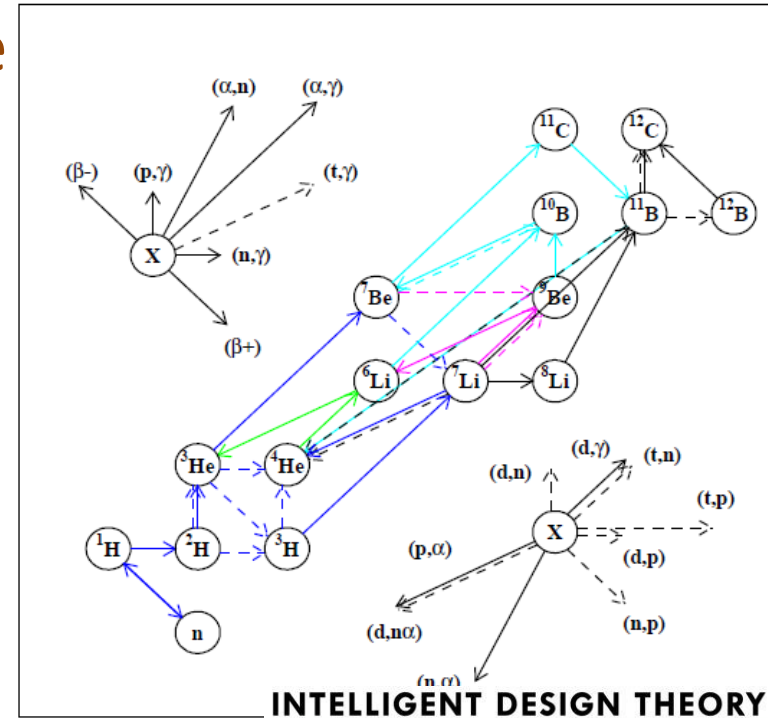
*SM “bubble”
multiverse*

*Tegmark’s Type II
multiverse*

Is our universe special? Intelligent design

➤ Our existence is possible due to the “fine-tuning” of the constants of nature

- If weak force stronger: All n decay and universe is all hydrogen
- If weak force weaker: Universe is all ${}^4\text{He}$
- If cosmological constant larger: universe expands too fast to form stars
- If cosmological constant negative: universe collapses before stars form carbon
- If gravity stronger, stars burn faster and less time for life to evolve

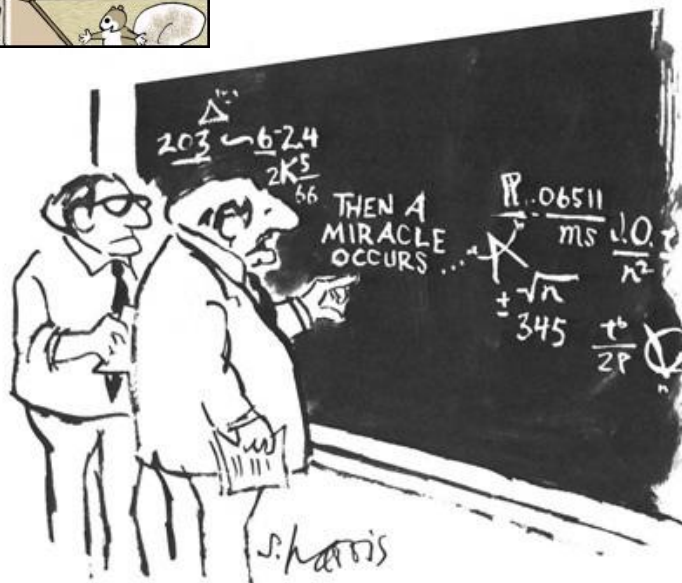
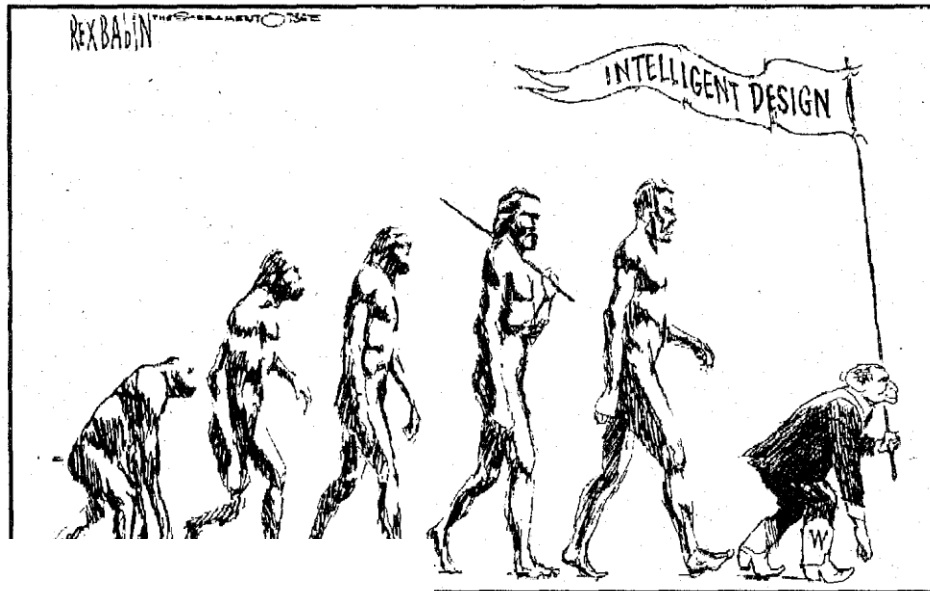


➤ The probability of this fine-tuning to be accidental is infinitesimal.

➤ It must be by design, i.e., God did it.





The study of patterns in nature that are best explained as the result of intelligence



"I think you should be more explicit here in step two."

Texas textbook review panel: Put more 'creation science based on Biblical principles' in biology books

 Like  2,772 people like this. [Sign Up](#) to see what your friends like.

By Scott Kaufman

Tuesday, September 10, 2013 11:51 EDT

This is a real and current issue.

Published on Tuesday, August 2, 2005 by [Knight Ridder Newspapers](#)

Bush Endorses Teaching 'Intelligent Design' Theory in Schools

by **Ron Hutcheson**


WASHINGTON - President Bush waded into the debate over evolution and "intelligent design" Monday, saying schools should teach both theories on the creation and complexity of life.

In a wide-ranging question-and-answer session with a small group of reporters, Bush essentially endorsed efforts by Christian conservatives to give intelligent design equal standing with the theory of evolution in the nation's schools.

“
Creationism,

46% Americans Believe In Creationism According To Latest Gallup Poll

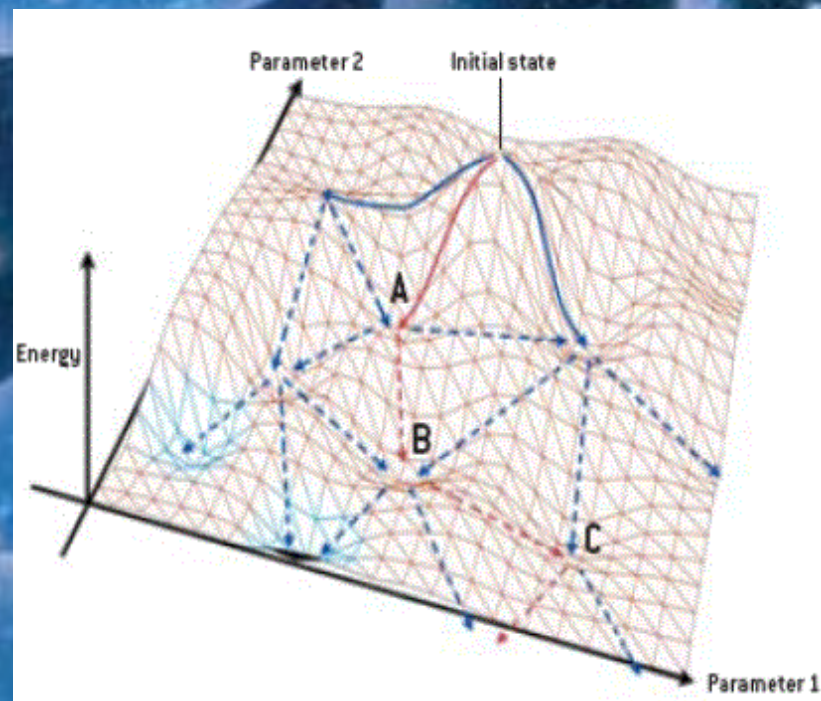
The Huffington Post | By Jahnabi Barooah  

Posted: 06/05/2012 1:10 pm Updated: 06/06/2012 2:41 pm 

Even if you are strongly against intelligent design as a scientific conclusion, science abhors accidents and our universe IS finely tuned.

With eternal inflation and the cosmic landscape, all possibilities are populated and, of course, we will find ourselves in a universe where we can exist.

Copernicus on steroids!



The Ekpyrotic universe – no inflation necessary

Cyclic (in time) multiverse

Steinhardt and Turok

Limit where particles can go

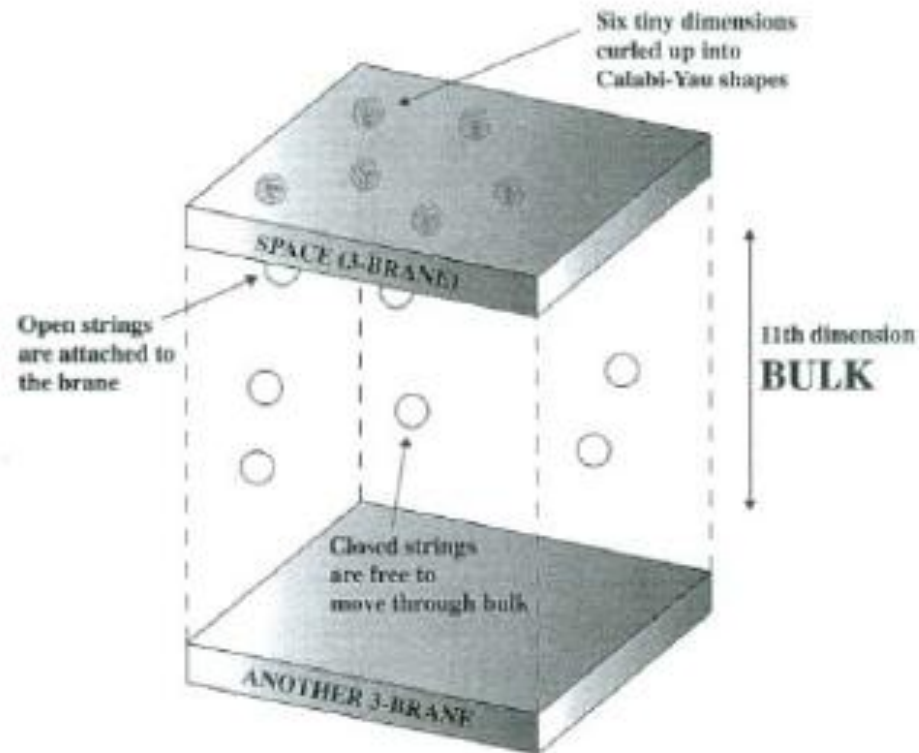
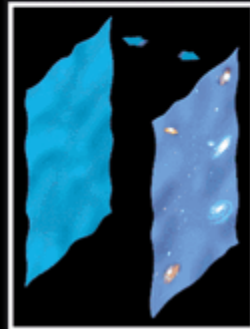
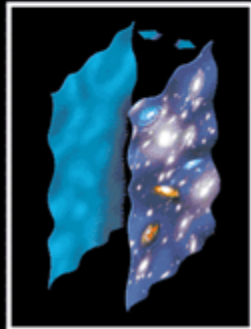
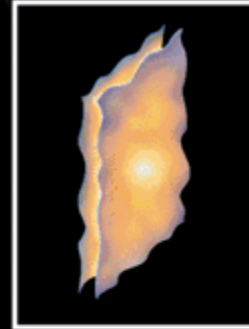
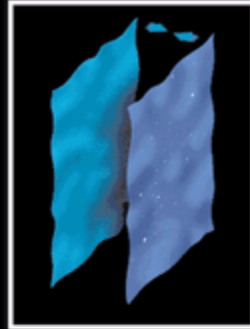
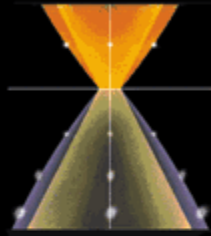


image from

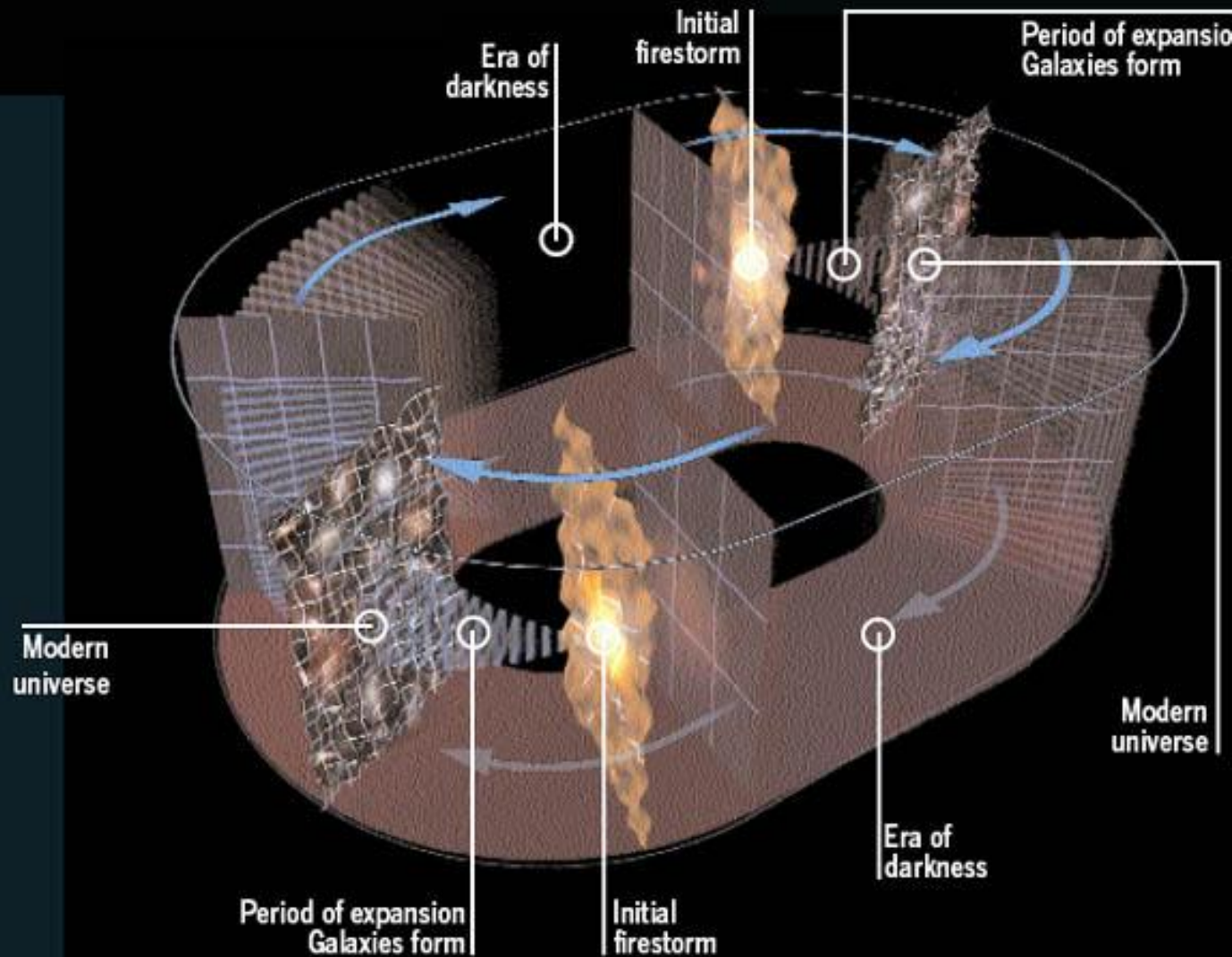
<http://abyss.uoregon.edu/~js/qc/qc.html>

EKPYROTICKÝ MODEL



Cyclic Model

To address some of the limitations and paradoxes of the Big Bang model, cosmologists Paul Steinhardt and Neil Turok have developed a new cosmology that views the visible universe as one small part of a much larger reality, most of which exists in other dimensions that we cannot perceive. Our universe exists on a three-dimensional membrane (represented by the flat panels at right) that lies right next to another membrane. Every trillion years or so, the two membranes collide, unleashing a firestorm of energy analogous to the Big Bang. As in the earlier model, the universe cools, gives rise to galaxies, and eventually expands to near emptiness. In this version, however, another collision between membranes then restarts the whole cycle of creation. Thus, time and space are both infinite.

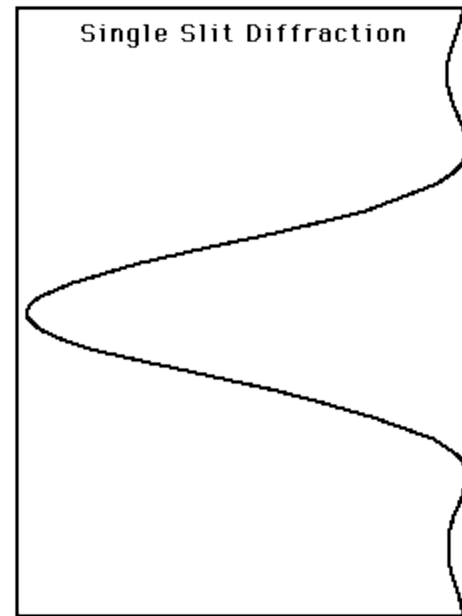
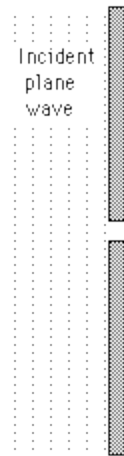


The quantum mechanical multiverse



Heisenberg and Bohr

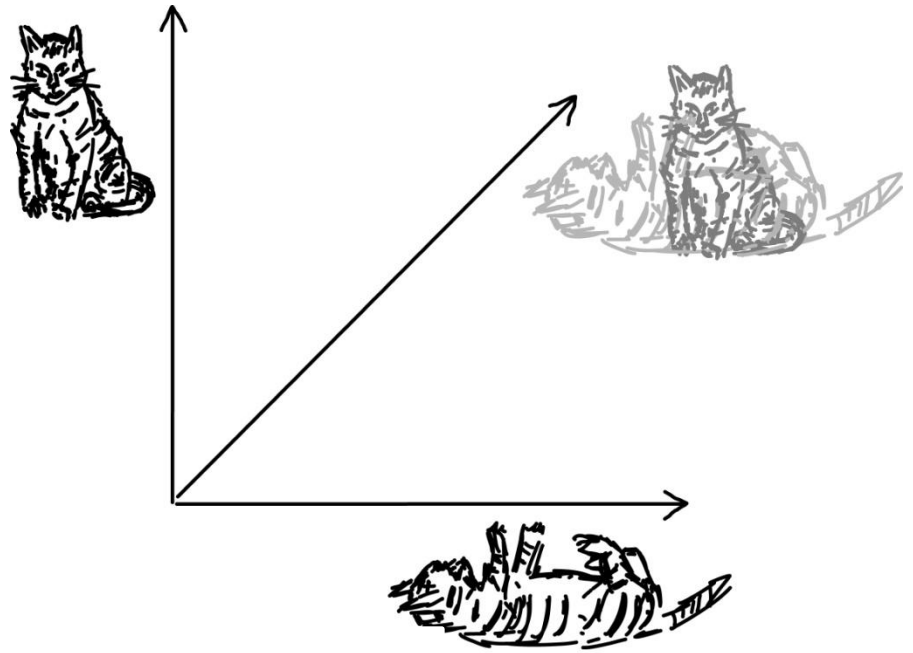
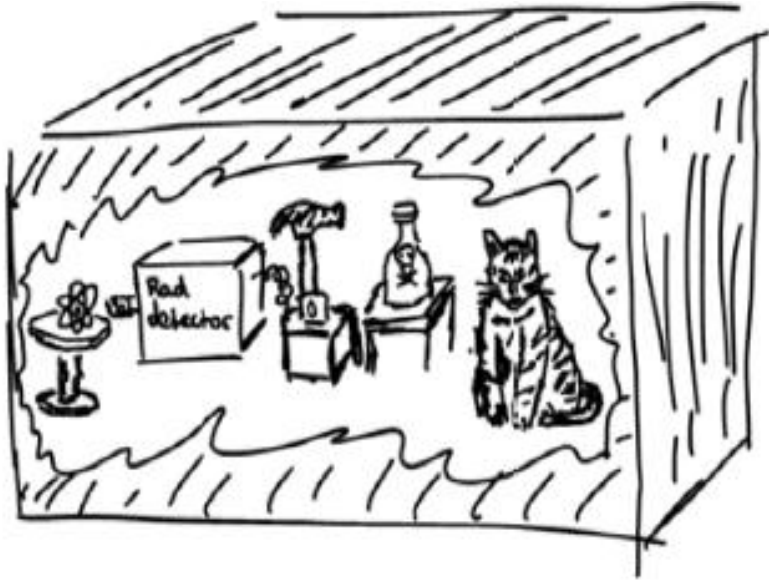
Copenhagen
Interpretation of
quantum mechanics
(1920s)



Probability $\sim \psi^2$



Max Born

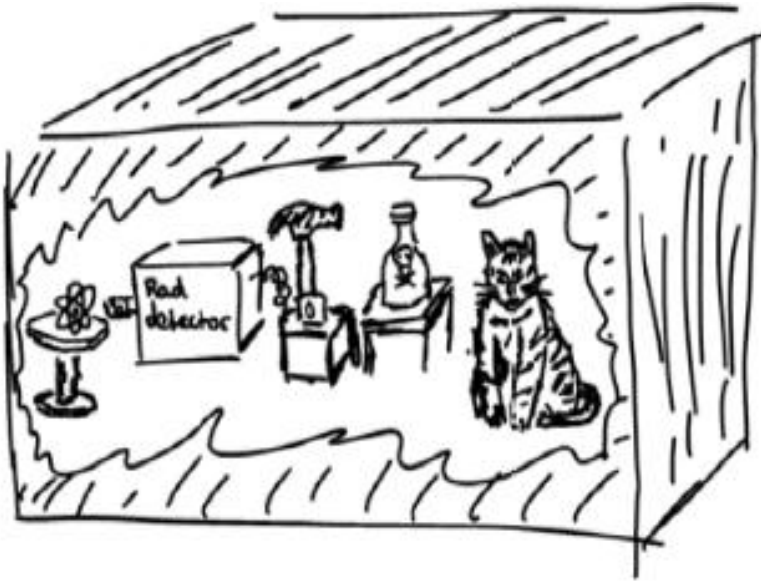


Relative state formalism (1957)

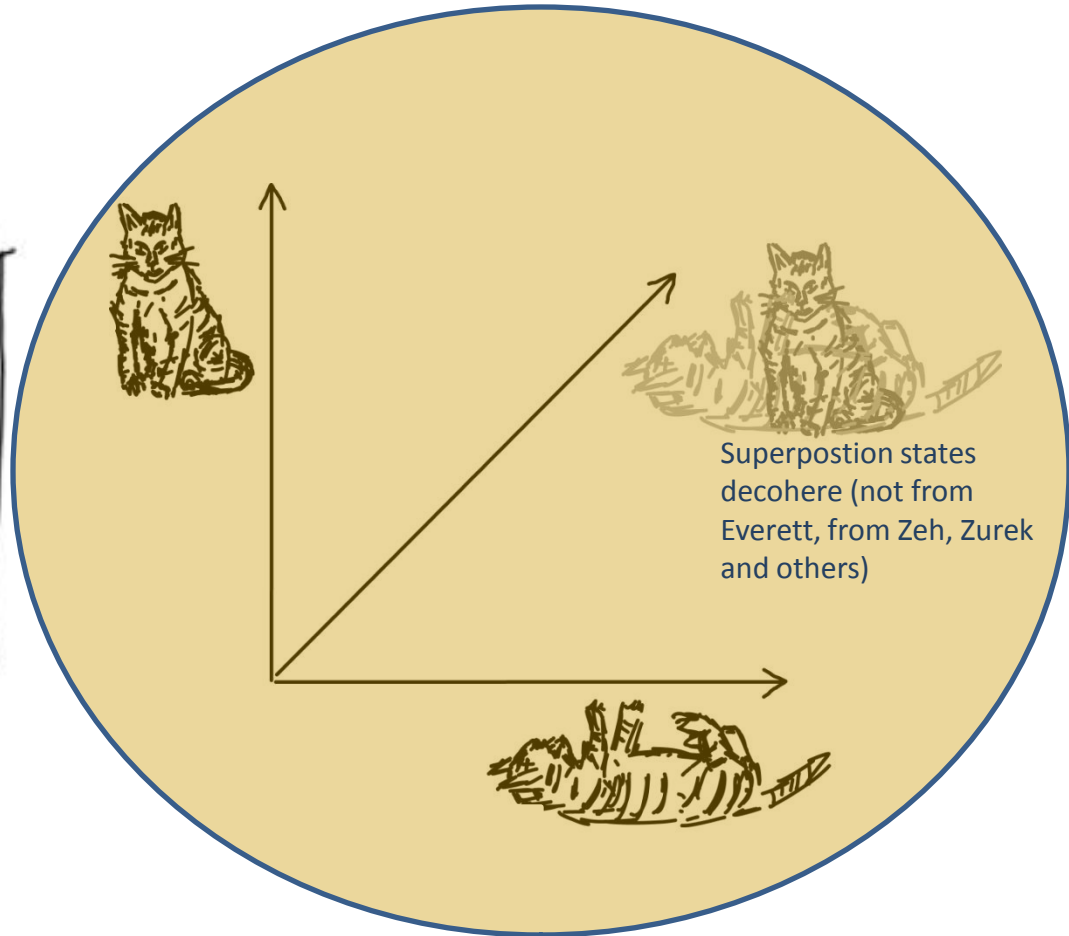
Usually called the “many worlds” interpretation of quantum mechanics (Bryce DeWitt)



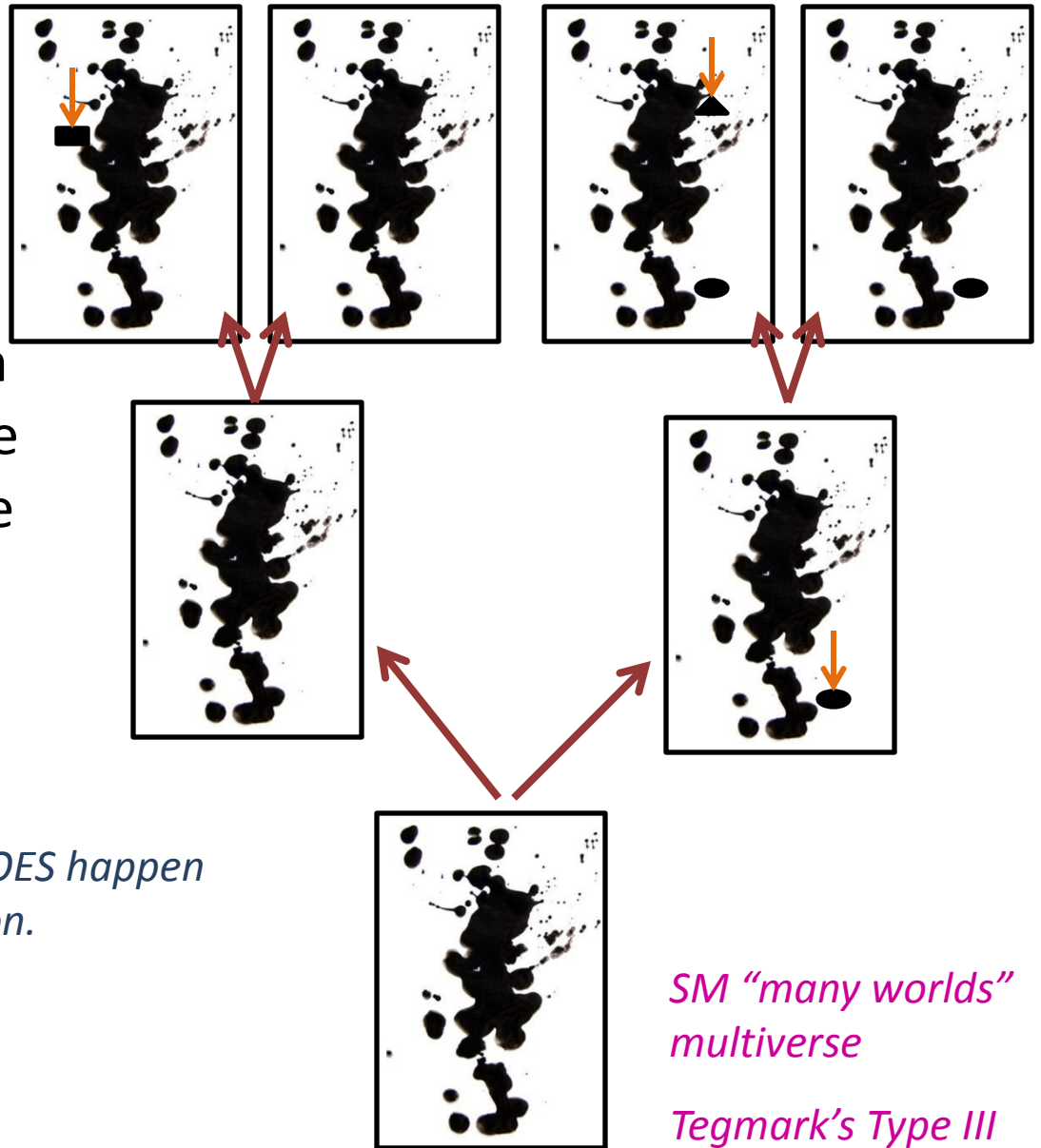
Hugh Everett III



Unitary Hilbert space



Many worlds: A continuum of realities separated by the dimensions of Hilbert space



Anything that COULD happen, DOES happen within the universal wave function.

The Fecund multiverse

– *cosmological natural selection*

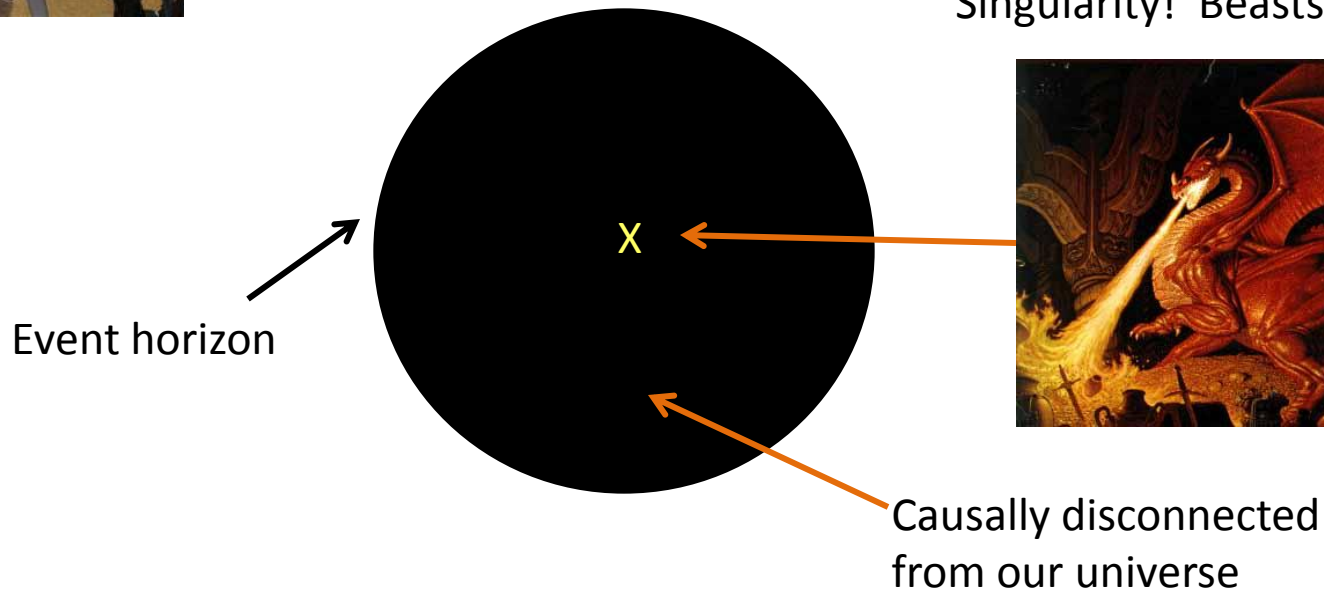


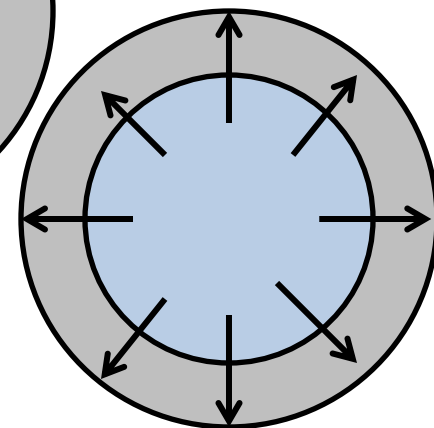
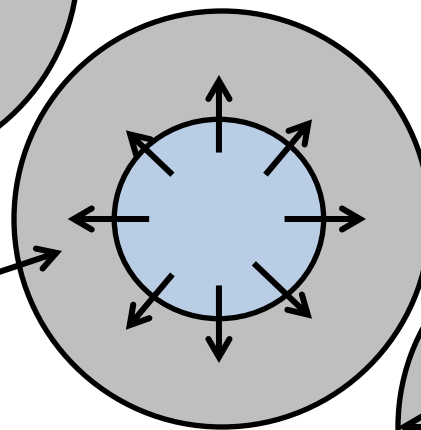
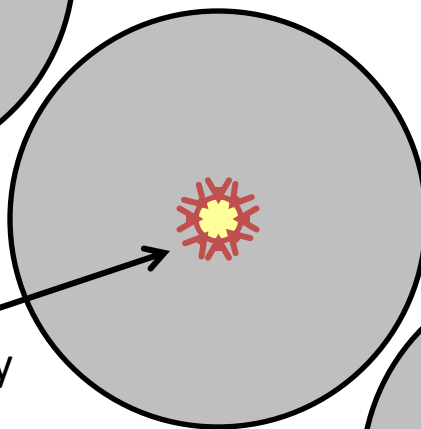
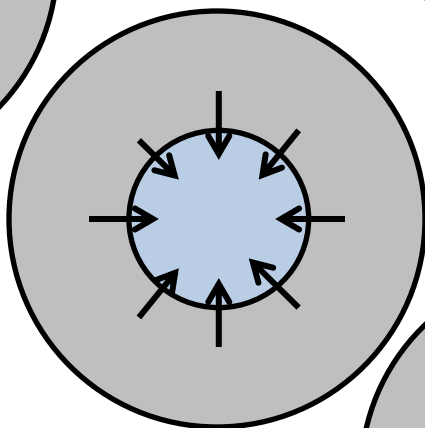
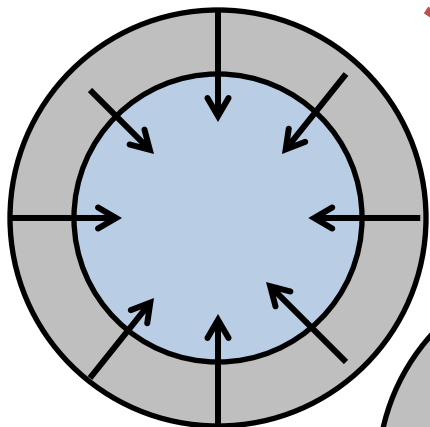
Lee Smolin, The Life of the Cosmos, Oxford Univ. Press, 1997

Fecund: fruitful in offspring

What happens inside a black hole?

Singularity! Beasts dwell here.





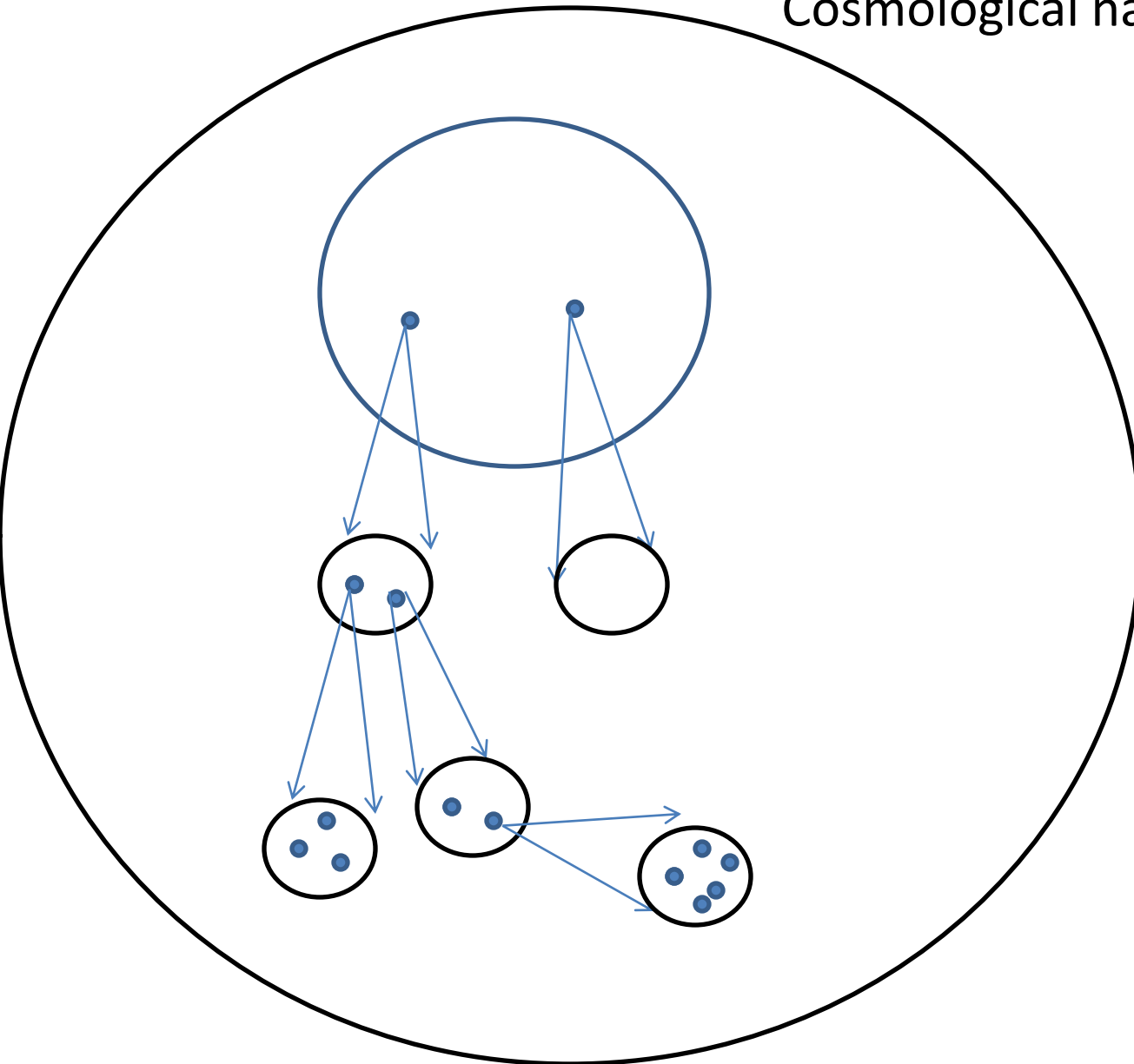
Quantum gravity
to the rescue!

Time

Some sort of
quantum gravity
"bounce"

Birth of an expanding universe within the
black hole, causally disconnected from us
Physical characteristics of the "daughter
universe" similar to but not exactly like
the "parent universe"

Cosmological natural selection



Parameters of the universes naturally gravitate toward being favorable for production of black holes

Long stellar lifetimes also favorable for development of life

Natural fine-tuning

Falsifiable: is our universe optimal for black hole production?

Computational multiverse

Nick Bostrom (Oxford philosopher) in 2003 paper:

- 1) humanity is likely to become extinct before reaching the level of technological advancement that we can simulate universes with Sims;
- 2) there is a fundamental limitation in computing that keeps advancing civilizations from simulating a universe with Sims or, for some unknown reason, a civilization that develops the capability to simulate a universe with Sims chooses not to do so;
- 3) we are almost certainly living in a computer simulation.



John Barrow (Cambridge cosmologist): Once this capability to simulate universes is achieved, fake universes will proliferate and will soon greatly outnumber the real ones.

The [University of Rochester](#) will spend \$50 million to establish itself as a leader in the evolving field of “big [data](#)” research — constructing a 50,000-square-foot home for a new Institute for Data Science and hiring at least 20 new faculty members.

“We intend for the [University](#) of Rochester to be among the world’s leaders in this new discipline,” said UR president Joel Seligman.

From the Oct 18, 2013 Democrat and Chronicle

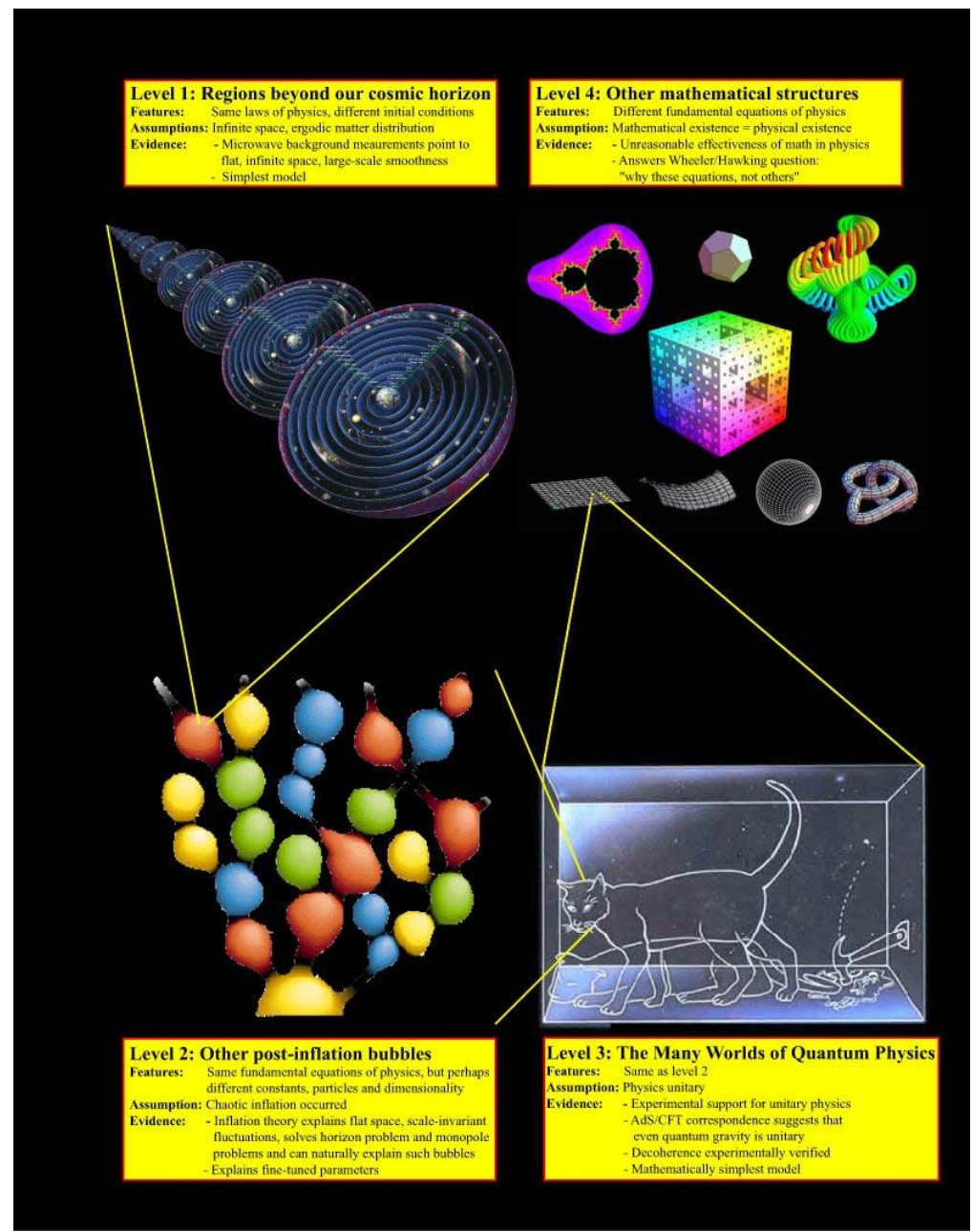


Max Tegmark's multiverse taxonomy Classified by level of abstraction/complexity

arXiv: astro-ph/0302131 (Feb. 2003)



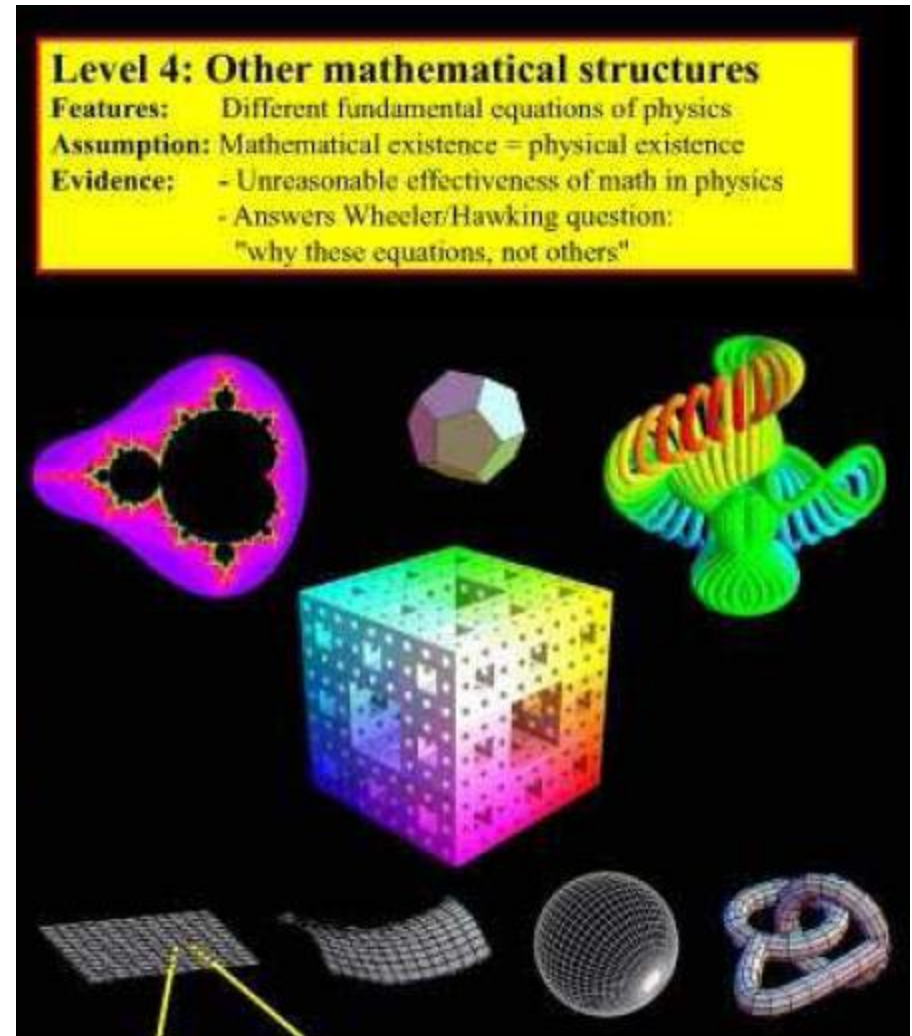
Cosmologist at MIT



The ultimate Copernican revolution – The Mathematical Universe

Tegmark's idea:

- Assume there is an external reality independent of humans
- There exists a TOE (theory of everything)
- TOE must be well-defined and unambiguous (no human language, etc.)
- TOE must be mathematics
- TOE must be a self-contained mathematical theory
- The TOE must be perfect and must have parts that correspond to every aspect of reality ... isomorphic mapping
- The TOE is reality
- If this self-contained, self-consistent mathematical framework corresponds to our reality, why not others?



SM "mathematical" multiverse

SM populist taxonomy – classified according to primary form of separation of the universes

Space-time separated

- Beyond the horizon multiverse (Tegmark's level I)
- Fecund multiverse (black holes, smolin)
- Oscillating big bang multiverse (technical and experimental problems)
- Ekpyrotic multiverse (colliding branes, Steinhardt, Turok, Ovrut, Khoury)
- Cyclic patch multiverse (dark energy gone crazy, Frampton , Baum)
- Bubble multiverse (eternal inflation, Tegmark's level II)

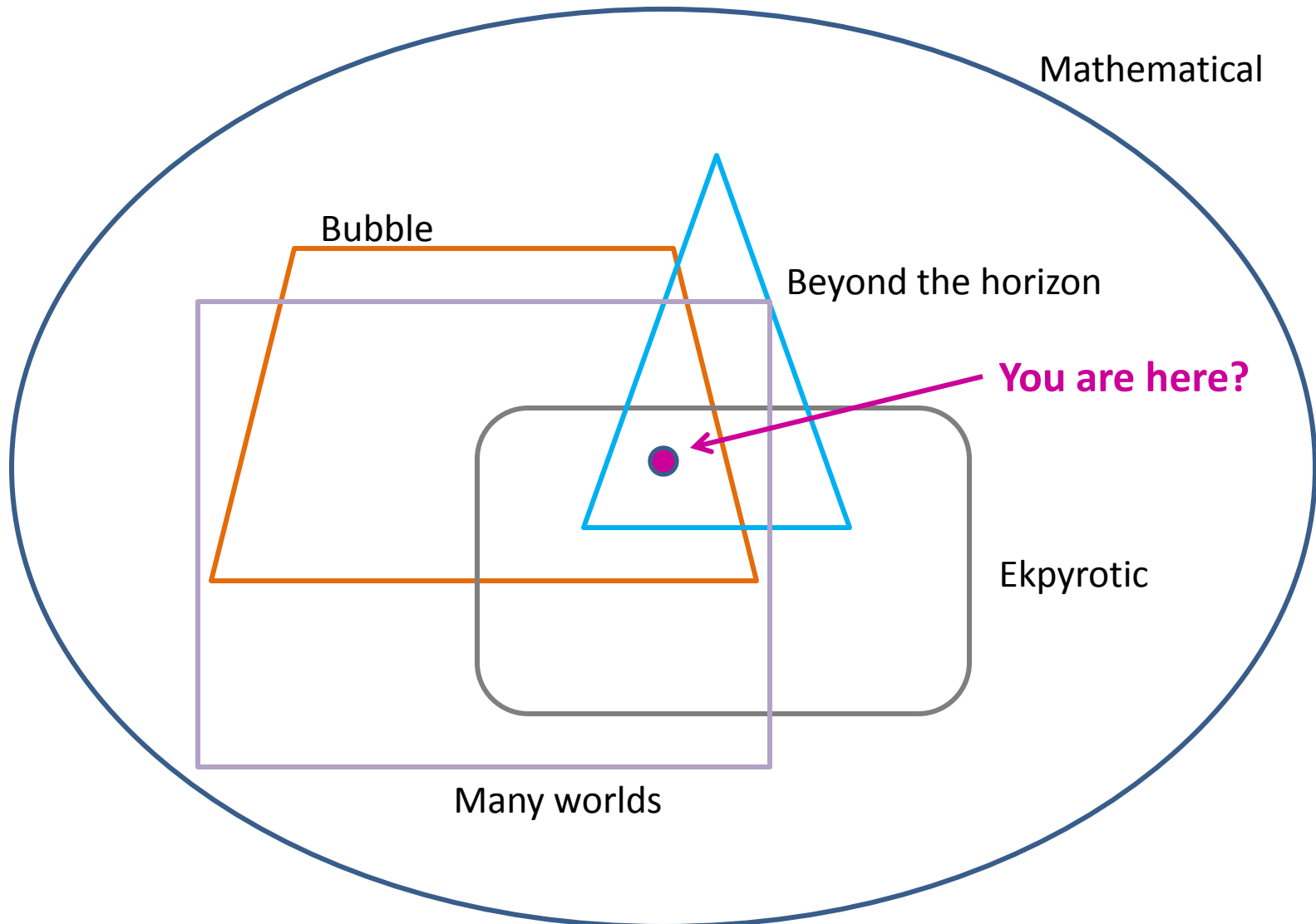
Dimensionally separated

- Many worlds multiverse (Everett, quantum mechanics, Tegmark's level III)

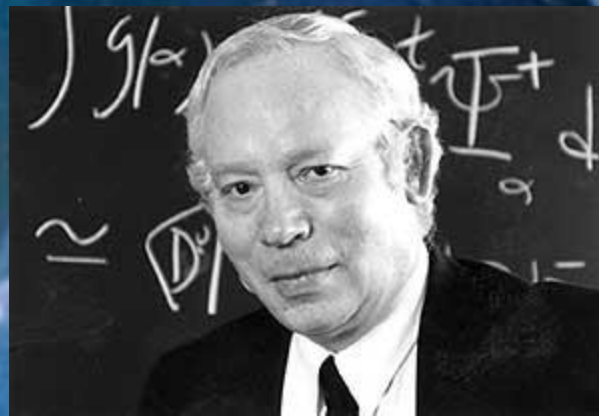
Faith separated

- Multiverse of faith (other planes of existence, heaven, hell, etc.)
- Mathematical multiverse (Tegmark's level IV)
- Computational multiverse (the matrix)
- Multiverse of wishful thinking (law of attraction, The Secret)

Perhaps the question isn't "do we live in a multiverse"
but rather "how many types of multiverses are there in
which we live?"



When asked about whether or not he believed in the multiverse, Weinberg related that he just read that Martin Rees said he had enough confidence in the multiverse to bet his dog's life on it. Andrei Linde said he had enough confidence to 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’ dog.”

-Stephen Weinberg

