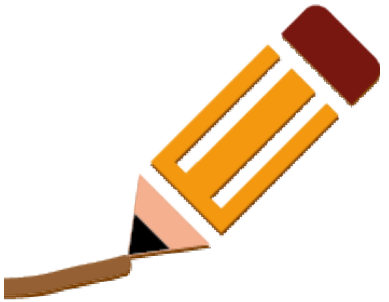
The birth of the Standard Model of Cosmology : pioneering contributions of Steven Weinberg



U A Yajnik, IIT Bombay,

TIFR colloquium 17-11-2021


degenerate
tower

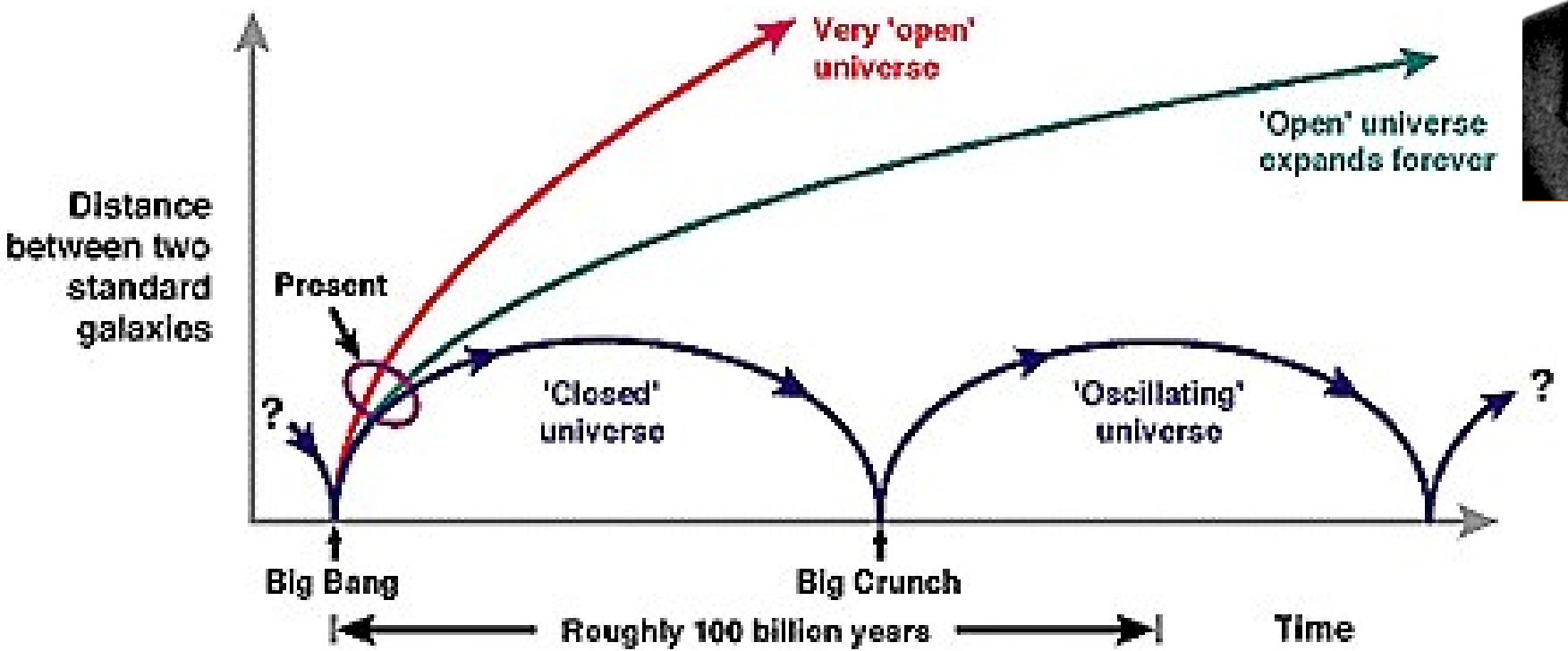
Outline

- Antecedents of Cosmology
- General Theory of Relativity “images on astronomers’ plates”
- “The first Three Minutes”
- The Big Bang <--> Grand Unification connection
  - Meltdown of spontaneous symmetry breaking
  - Baryogenesis and gravitino bound
- Cosmic Microwave Background (CMB) analysis
- Mentor Crusader ... personal glimpses

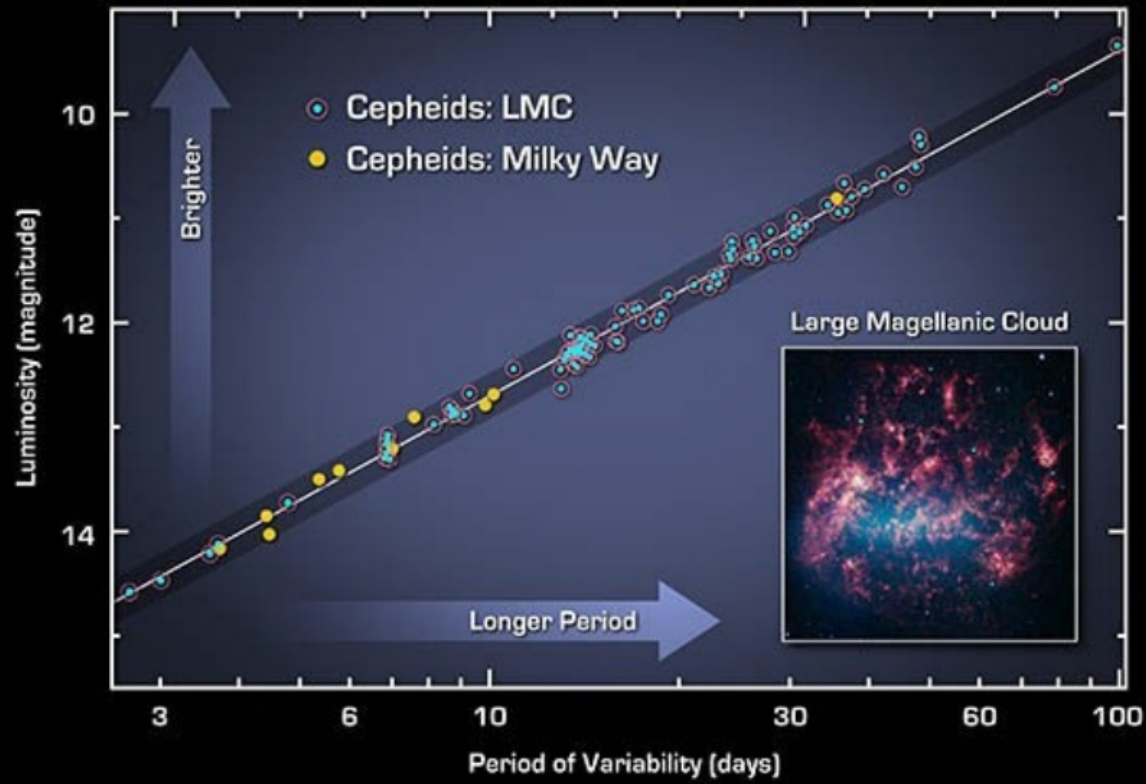
proto-Cosmology before 1964

- A. A. Friedmann's 1919-22 solutions – ever expanding or recollapsing universes
- Telescopes (Lowell, Mt Wilson) under clear skies in the USA
- Henrietta Leavitte develops a calibration of the Cepheids
- Edwin Hubble draws the line
- Rapid developments in quantum theory and nuclear physics
  - Nuclear fusion as energy source in stars
  - Primordial nucleosynthesis – formation of Helium and others

Friedmann 1919-22 discovers the truth of gravity
His papers are ignored



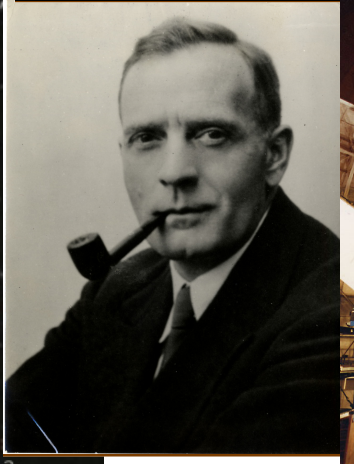
Brightness-period Relationship

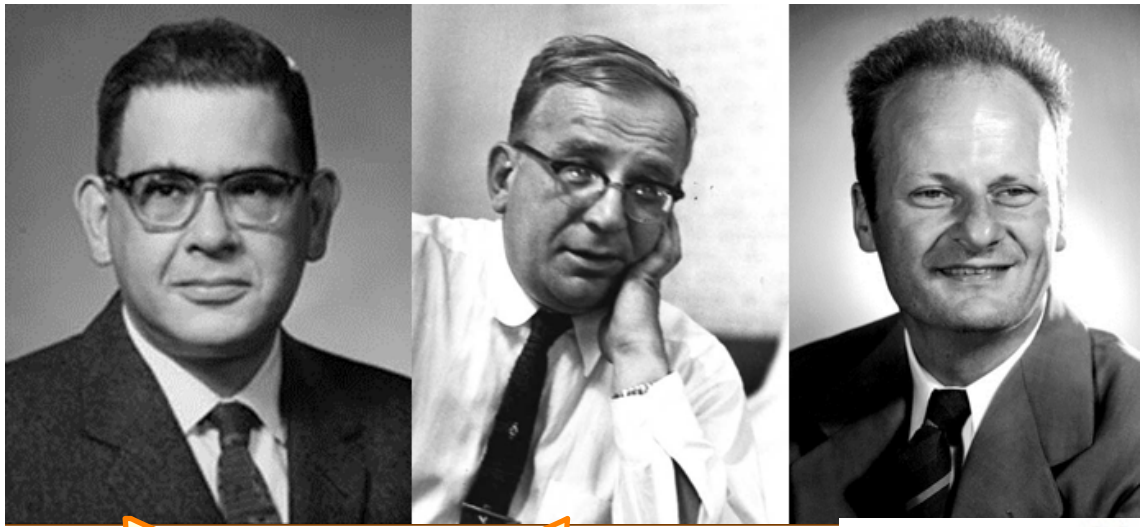


Calibrated Period-luminosity Relationship for Cepheids
NASA / JPL-Caltech / W. Freedman (Carnegie)
Spitzer Space Telescope • IRAC
ssc2012-13a

Leavitte
Hubble 1929

Scanned at the American Institute of Physics





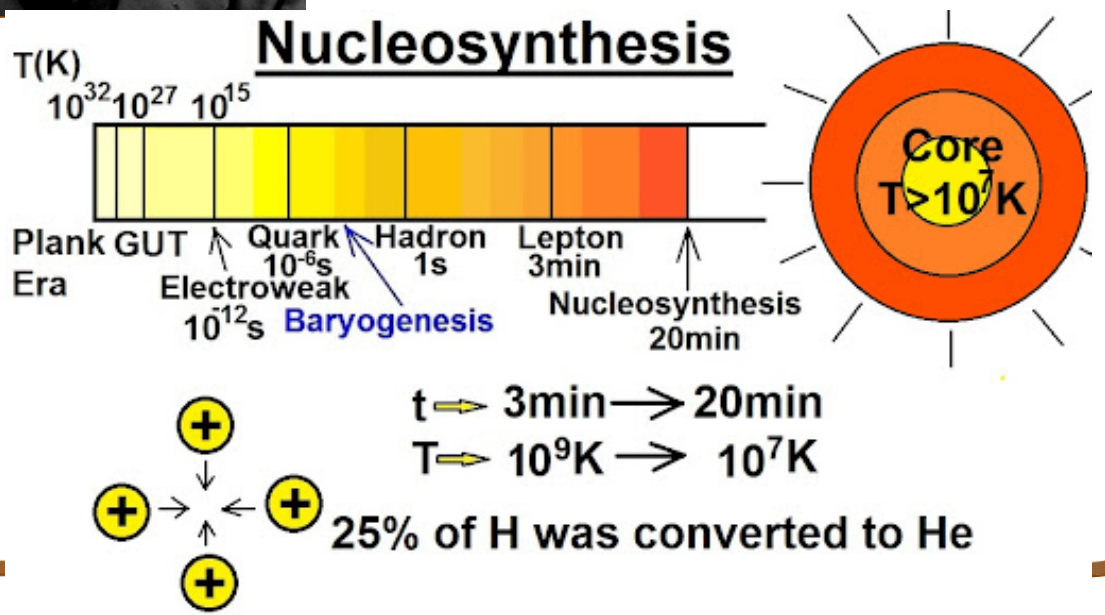
Alpher and Gamow do the first ever calculation of Primordial Nucleosynthesis 1940's

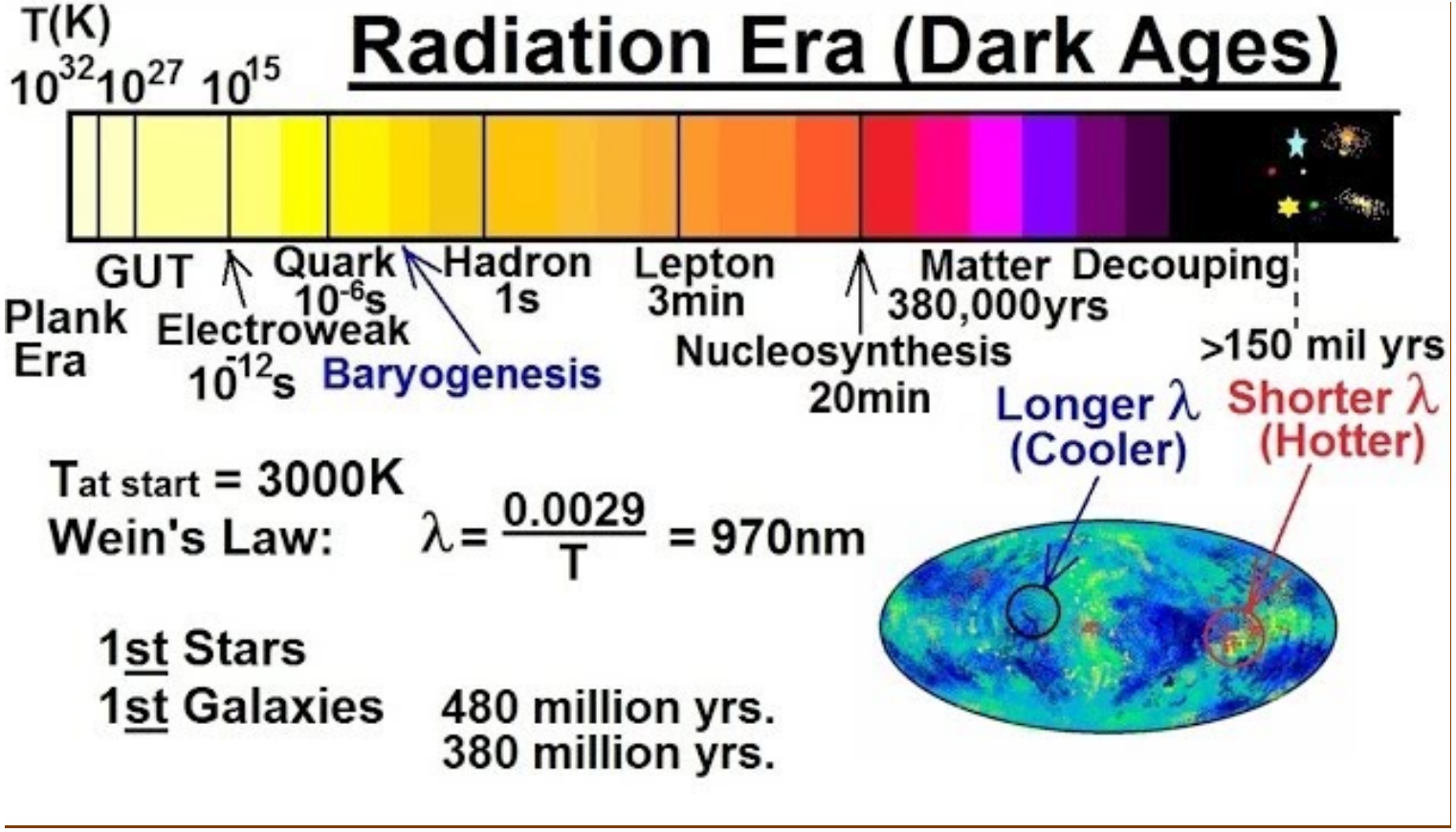
(Bethe added as second author to get Alpher Bethe Gamow)

The work is ignored

Hot compact origins are ridiculed as the

Big Bang



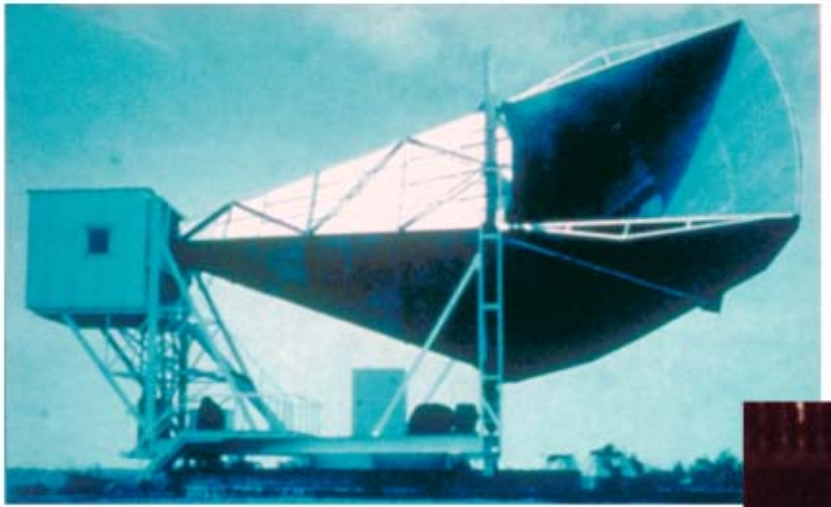


Alpher and Hermann 1948

Temperature of the residual radiation after first neutral H forms

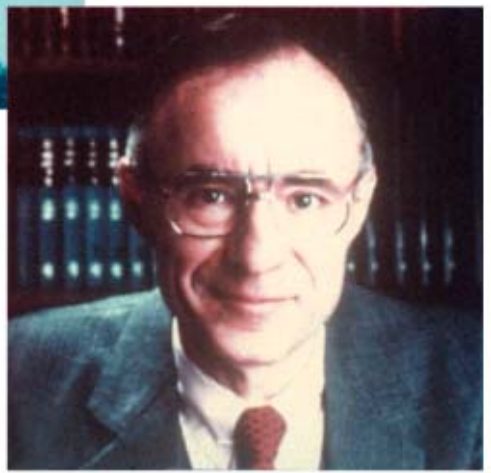
Graphic : Micheal van Biezen

Discovery of Cosmic Background



Microwave Receiver

Robert Wilson



Arno Penzias

Penzias and Wilson (Bell Labs NJ) stumble upon the

Cosmic Microwave Background

1964

Weinberg comments ...

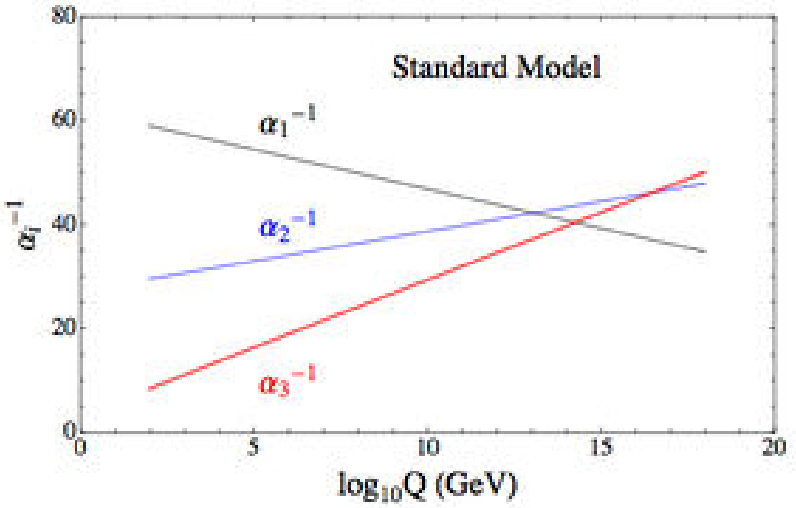
In 1964 Brandeis lectures
Weinberg remarks

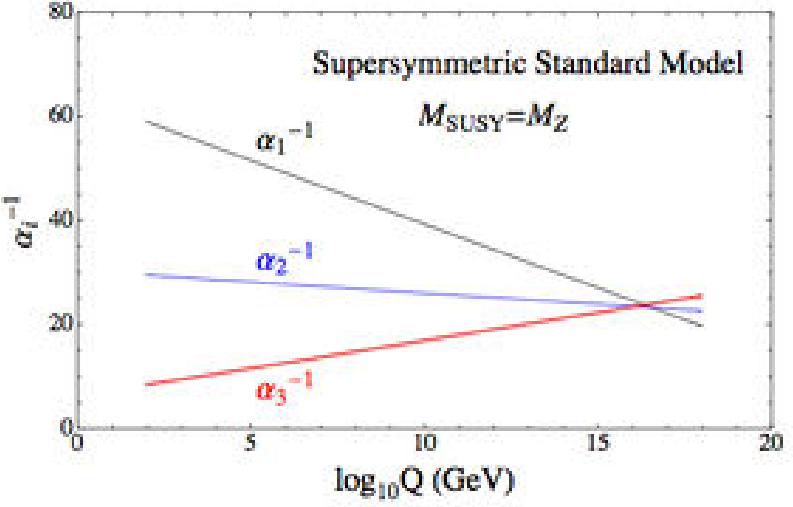
1) CP violation disovered
2) The Big Bang is established

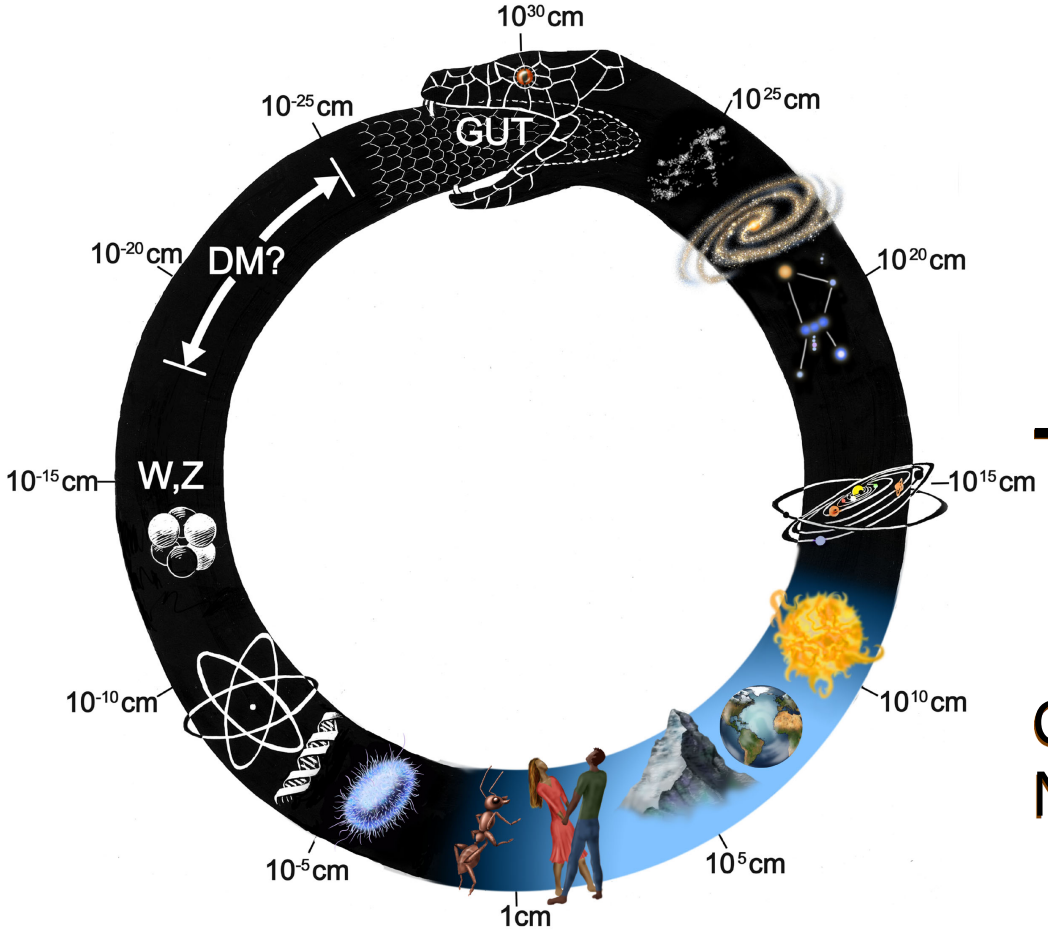
Hence the possibility of dynamical creation of Matter-anti-matter asymmetry

The Big Bang – GUT connection

- Running coupling in gauge theory 1973
- Georgi-Glashow propose SU(5) Grand Unification
- Georgi, Quinn and Weinberg argue for the high scale unification of the coupling constants
- Proton decay is a corollary – needed for generation of baryon asymmetry







The Uroboros

Glashow borrows from Norse mythology

GUT scale baryogenesis

(Sakharov 1967; Yoshimura; Weinberg 1978)

1. There should exist baryon number B violating interaction

$$X \to qq \qquad \Delta B_1 = \frac{2}{3}$$
$$\bar{q}\bar{l} \qquad \Delta B_2 = -\frac{1}{3}$$

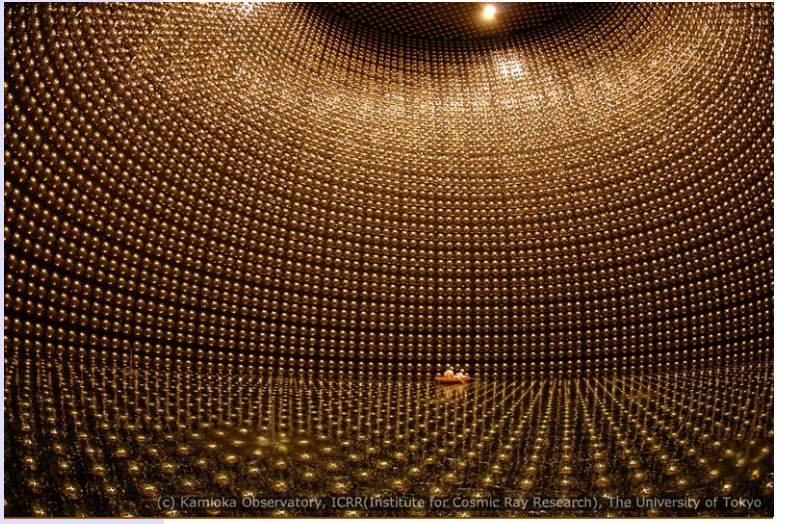
2. Charge conjugation C must be violated

$$\mathcal{M}(X \to qq) \neq \mathcal{M}(\bar{X} \to \bar{q}\bar{q})$$

3. CP violation

$$r_1 = \frac{\Gamma(X \to qq)}{\Gamma_1 + \Gamma_2} \neq \frac{\bar{\Gamma}(\bar{X} \to \bar{q}\bar{q})}{\bar{\Gamma}_1 + \bar{\Gamma}_2} = \bar{r}_1$$

4. Out of equilibrium conditions
   Reverse reactions don't get the time to reverse the products



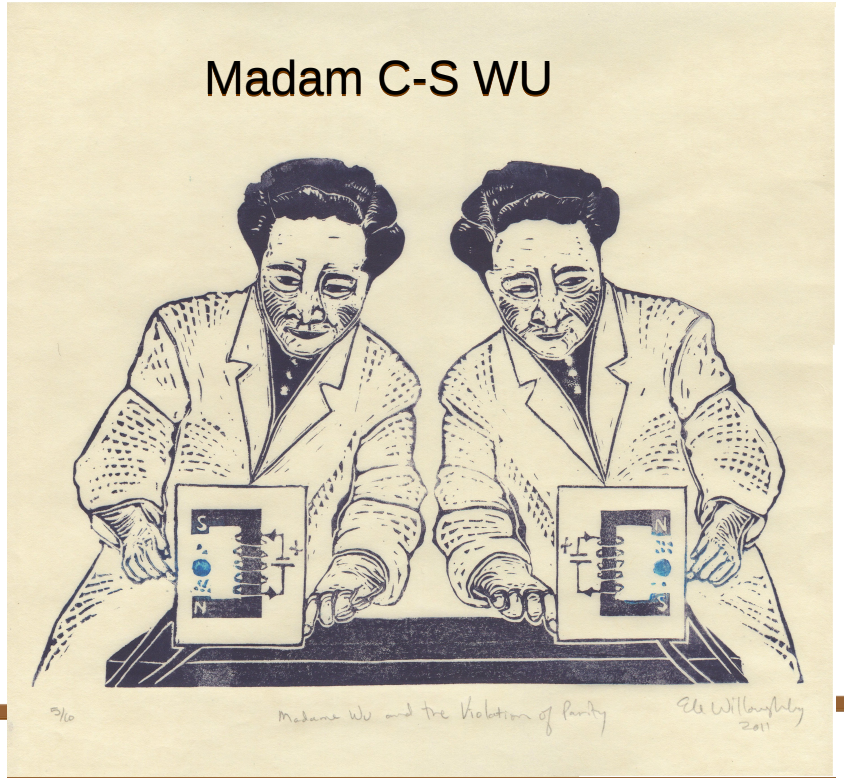
Super-Kamiokande

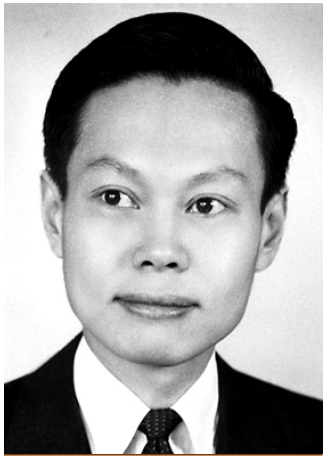
Proton decay lab also becomes neutrino lab

Electroweak unification Nobel 1979

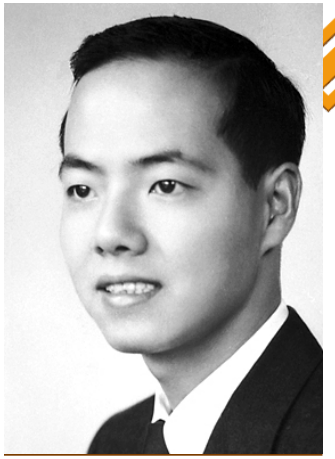
Paradigm – chirality

- Only Left “Chiral” electron and neutrino in charged Weak transitions

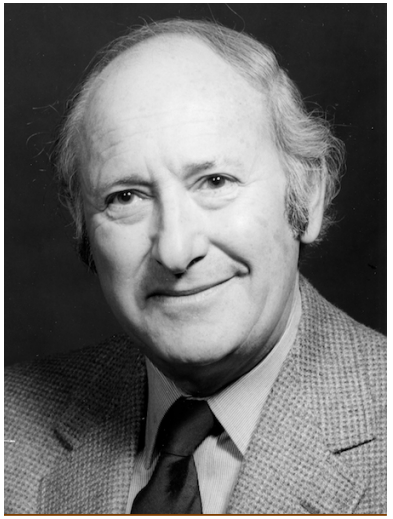




C N Yang



T D Lee



R E Marshak

E C G Sudarshan

Electroweak unification

- Maxwell 1855 put together several related laws
  - Magnetic and electric effects
  - Formulated Electromagnetism
- Weinberg-Salam 1967 leverage
  - Yang-Mills symmetry
  - Schwinger-Glashow SU(2)XU(1)
  - Marshak-Sudarshan's left chiral leptons (V – A theory)
  - Higgs ++ mechanism – Spontaneous Symmetry Breaking
  - Formulate Electroweak Theory

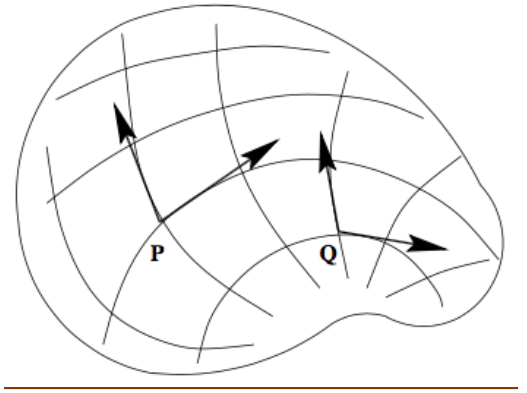
On a mission to rationalise and demystify

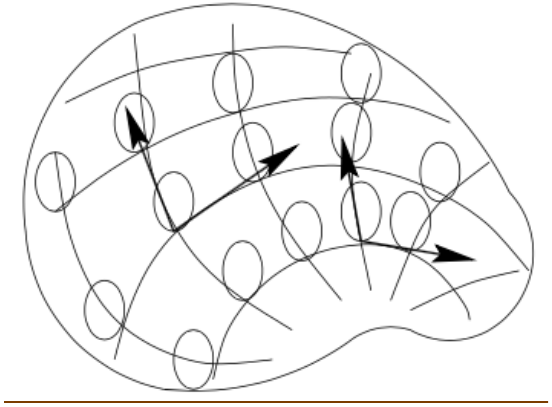
Approach to General Theory of Relativity

- Curved space-time displaces “dynamics” ...in most people’s minds
  - Kaluza-Klain : “geometrising” Electrodynamics
- Weinberg :

  General Theory of Relativity
  =

  Relativistic Theory of Gravity





- RQM = QFT
  - QFT as the one universal tool
  - Farewell to “wave equations” and current algebra
  - Upturning Landau’s pronouncement “QFT is dead”
- QFT of Massless particles implies gauge invariance
- General Relativity = Classical Field Theory with a gauge invariance
  - Geometry only as analogy

GRAVITATION AND COSMOLOGY: PRINCIPLES AND APPLICATIONS OF THE GENERAL THEORY OF RELATIVITY

1972

STEVEN WEINBERG

Massachusetts Institute of Technology

I found that in most textbooks geometric ideas were given a starring role, so that a student who asked why the gravitational field is represented by a metric tensor, or why freely falling particles move on geodesics, or why the field equations are generally covariant would come away with an impression that this had something to do with the fact that space-time is a Riemannian manifold.

Of course, this *was* Einstein's point of view, and his preeminent genius necessarily shapes our understanding of the theory he created. However, I believe

this hope has met with disappointment, and the geometric interpretation of the theory of gravitation has dwindled to a mere analogy, which lingers in our language in terms like "metric," "affine connection," and "curvature," but is not otherwise very useful. The important thing is to be able to make predictions about images on the astronomers' photographic plates, frequencies of spectral lines, and so on, and it simply doesn't matter whether we ascribe these predictions to the physical effect of gravitational fields on the motion of planets and photons or to a curvature of space and time. (The reader should be warned that these views are heterodox and would meet with objections from many general relativists.)

Table 15.1 Summary of Measurements of the Background Radiation Flux at Microwave and Far-Infrared Wavelengths.

(The temperatures listed are those for which black-body radiation would give the observed flux at the indicated wavelength.)

λ (cm)	Method	Reference	$T_\gamma(\lambda)$ (°K)
73.5	Ground-based radiometer	a	3.7 ± 1.2
49.2	Ground-based radiometer	a	3.7 ± 1.2
21.0	Ground-based radiometer	b	3.2 ± 1.0
20.7	Ground-based radiometer	c	2.8 ± 0.6
7.35	Ground-based radiometer	d	3.5 ± 1.0
3.2	Ground-based radiometer	e	3.0 ± 0.5
3.2	Ground-based radiometer	f	$2.69^{+0.16}_{-0.21}$
1.58	Ground-based radiometer	f	$2.78^{+0.12}_{-0.17}$
1.50	Ground-based radiometer	g	2.0 ± 0.8
0.924	Ground-based radiometer	h	3.16 ± 0.26
0.856	Ground-based radiometer	i	$2.56^{+0.17}_{-0.22}$
0.82	Ground-based radiometer	j	2.9 ± 0.7
0.358	Ground-based radiometer	j′	2.4 ± 0.7
0.33	Ground-based radiometer	k	$2.46^{+0.40}_{-0.44}$
0.33	Ground-based radiometer	k′	2.61 ± 0.25
0.263	CN ($J = 1/J = 0$)	l	≈ 2.3
0.263	CN ($J = 1/J = 0$)	m	3.22 ± 0.15 ζ Oph 3.0 ± 0.6 ζ Per
0.263	CN ($J = 1/J = 0$)	n	3.75 ± 0.50
0.263	CN ($J = 1/J = 0$)	o	$\leqq 2.82$
0.132	CN ($J = 2/J = 1$)	n	< 7.0
0.132	CN ($J = 2/J = 1$)	o	< 4.74
0.0559	CH	n	< 6.6
0.0559	CH	o	< 5.43
0.0359	CH^+	o	< 8.11
0.04–0.13	Rocket-borne IR telescope	p	$8.3^{+2.2}_{-1.3}$
> 0.05	Balloon-borne IR radiometer	q	$\approx 3.6, 5.5, 7.0$
0.6–0.008	Rocket-borne IR radiometer	r	$3.1^{+0.5}_{-2.0}$
0.18–1.0	Balloon-borne IR radiometer	s	$2.7^{+0.4}_{-0.2}$
0.13–1.0	Balloon-borne IR radiometer	s	2.8 ± 0.2
0.09–1.0	Balloon-borne IR radiometer	s	$\leqq 2.7$
0.054–1.0	Balloon-borne IR radiometer	s	$\leqq 3.4$

a T. F. Howell and J. R. Shakeshaft, Nature, **216**, 753 (1967).
b A. A. Penzias and R. W. Wilson, Astron. J., **72**, 315 (1967).
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j′ A. G. Kislyakov, V. I. Chernyshev, Yu. V. Lebskii, V. A. Mal'tsev, and N. V. Serov, Ast. Zh., **48**, 39 (1971) [transl. Sov. Astron.—AJ, **15**, 29 (1971)].
k P. E. Boynton, R. A. Stokes, and D. T. Wilkinson, Phys. Rev. Letters, **21**, 462 (1968).
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q D. Muehlner and R. Weiss, Phys. Rev. Letters, **24**, 742 (1970).
r A. G. Blair, J. G. Beery, F. Edeskuty, R. D. Hiebert, J. P. Shipley, and K. D. Williamson, Jr., Phys. Rev. Letters, **27**, 1154 (1971).
s D. Muehlner and R. Weiss, to be published (1972).

COSMOLOGY

2008

and radiation) these conservation equations are satisfied *separately* by each fluid, information that could not be derived from the field equations.

The results obtained so far are repulsively complicated. Fortunately, the spatial isotropy and homogeneity of the unperturbed metric and energy-momentum tensor allow us to simplify these results by decomposing the perturbations into scalars, divergenceless vectors, and divergenceless traceless symmetric tensors, which are not coupled to each other by the field equa-

Lectures on Quantum Field Theory

Physics 389M
Fall 1982
University of Texas at Austin

To do z integrals, note that

$$V(z,p) = z^{-n} V(1,p) z^{n}$$

where $\quad n \equiv \sum_n n\, a_n^{\mu *} a_{n\mu}$

$$A_N(p_1 \cdots p_N) = \int_{0 \le z_2 \le \cdots z_{N-2} \le 1} z_2^{2\alpha' K_1 \cdot p_2} dz_2 \cdots z_{N-2}^{2\alpha' K_{N-3} \cdot p_{N-2}} dz_{N-2}$$

$$\times \langle 0 | V(1,p_2) \left(\frac{z_2}{z_3}\right)^{n} V(1,p_3) \left(\frac{z_3}{z_4}\right)^{n} \cdots \left(\frac{z_{N-2}}{z_{N-1}}\right)^{n} V(1,p_{N-1}) | 0 \rangle$$

$z_{N-1} = 1$

Define $\quad u_2 = z_2/z_3 \quad \cdots \quad u_{N-3} = \dfrac{z_{N-3}}{z_{N-2}} \quad u_{N-2} = z_{N-2}$

$$\det\left(\frac{\partial u_i}{\partial z_j}\right) = \begin{vmatrix} \frac{1}{z_3} & -\frac{z_2}{z_3^2} & 0 & 0 & \cdots & & 0 \\ 0 & \frac{1}{z_4} & -\frac{z_3}{z_4^2} & 0 & \cdots & & 0 \\ 0 & 0 & \frac{1}{z_5} & -\frac{z_4}{z_5^2} & 0 & \cdots & 0 \\ & & & \cdots & & & \\ 0 & 0 & - & - & - & \frac{1}{z_{N-2}} & -\frac{z_{N-3}}{z_{N-2}^2} \\ 0 & 0 & - & - & - & 0 & 1 \end{vmatrix}$$

$$= \frac{1}{z_3 z_4 \cdots z_{N-2}}$$

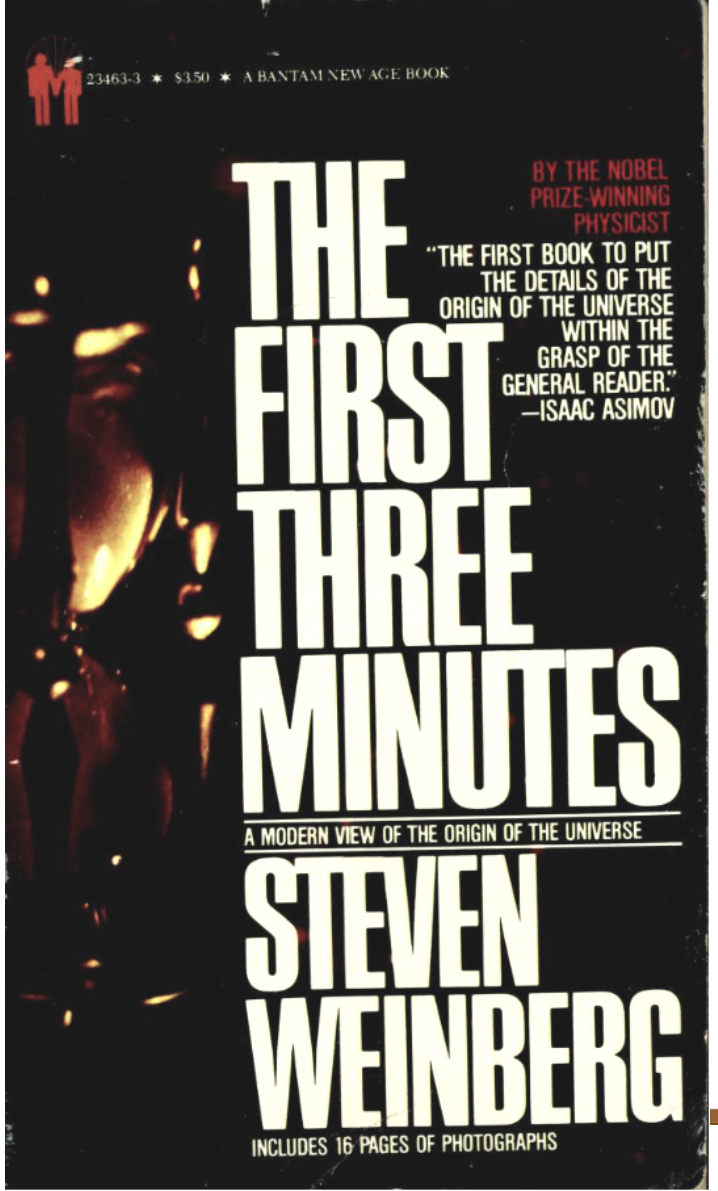
$$z_2^{2\alpha' K_1 \cdot p_2} z_3^{2\alpha' K_2 \cdot p_3} \cdots z_{N-2}^{2\alpha' K_{N-3} \cdot p_{N-2}} \cdot \det\left(\frac{\partial z}{\partial u}\right)$$

$$= u_{N-2}^{2\alpha' K_{N-3} \cdot p_{N-2} + 1} \left(u_{N-3} u_{N-2}\right)^{2\alpha' K_{N-4} \cdot p_{N-3} + 1} \cdots \left(u_3 \cdots u_{N-2}\right)^{2\alpha' K_2 \cdot p_3 + 1}$$

$$\times \left(u_2 u_3 \cdots u_{N-2}\right)^{2\alpha' \sum_{i=2}^{j} K_{i-1} \cdot p_i + j - 2}$$

$$= \prod_{j=2}^{N-2} (u_j)^{2\alpha' \sum_{i=2}^{j} K_{i-1} \cdot p_i + j - 2}$$

Science outreach and opinions

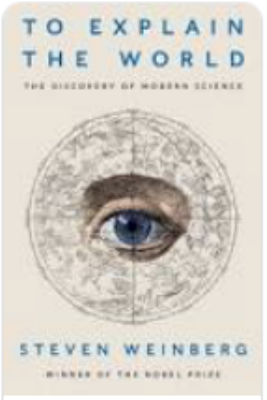


- Primoridal soup cooled down to neutrons and protons
- Nuclei began to form by fusion
- A crucial input Baryon/photon ratio
  - Miniscule value 10^{-10}
  - Thus the Universe remained largely Hydrogen and Helium

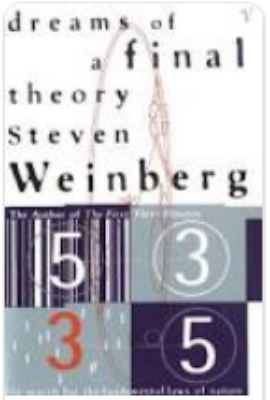
of endless cold or intolerable heat. The more the universe seems comprehensible, the more it also seems pointless.

But if there is no solace in the fruits of our research, there is at least some consolation in the research itself. Men and women are not content to comfort themselves with tales of gods and giants, or to confine their thoughts to the daily affairs of life; they also build telescopes and satellites and accelerators, and sit at their desks for endless hours working out the meaning of the data they gather. The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy.

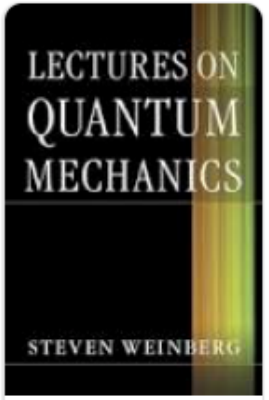
The First Three Minu…
Steven Wei…



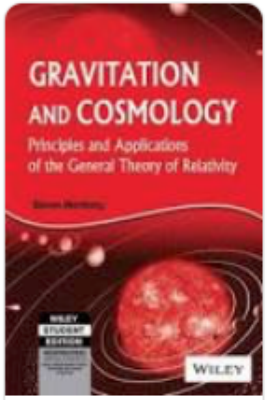
To Explain the World: The …
Steven Wei…



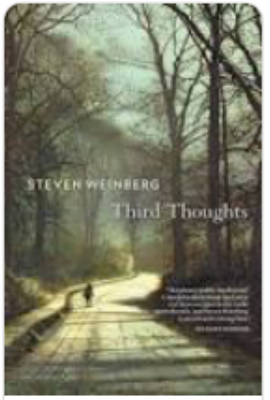
Dreams of a Final Theory
Steven Wei…



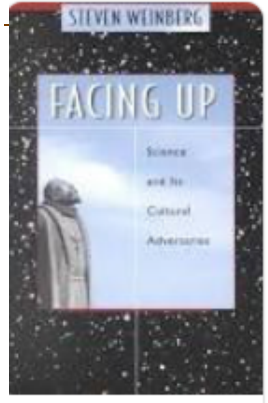
Lectures on Quantum M…
Steven Wei…



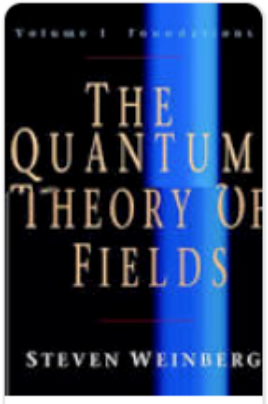
Gravitation and cosmol…
Steven Wei…



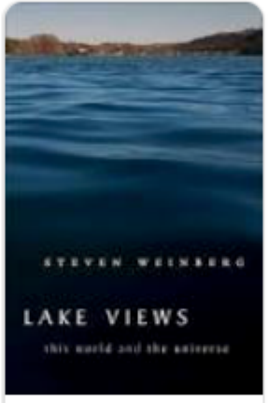
Third Thoughts
Steven Wei…



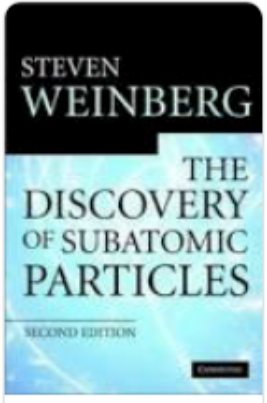
Facing Up
Steven Wei…



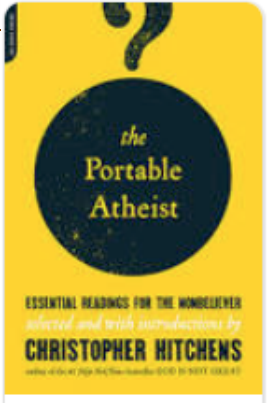
The Quantum Theory of F…
Steven Wei…



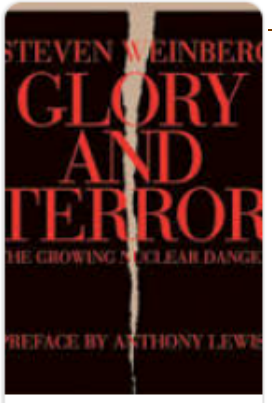
Lake Views: This World …
Steven Wei…



The discovery of subatomi…
Steven Wei…



The Portable Atheist
Christopher…



Glory and Terror: The …
Steven Wei…

Scientific speculation

- String Theory
  - Super-Gravity and extra dimensions – N=8 d=11
  - Healthy rivalry with Salam
  - Lectures course 1986

- Multiverse
  - String Theory landscape ~ 10^{500} possibilities for universes
  - If math deems it right the unseeable worlds “must be there”

Scientific speculation

- Cosmological constant – “Anthropic” argument
  - Rephrased anthropic principle
  - “Prediction” of Dark Energy 1987; 1993 – confirmed 1998

NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1987

Anthropic Bound on the Cosmological Constant

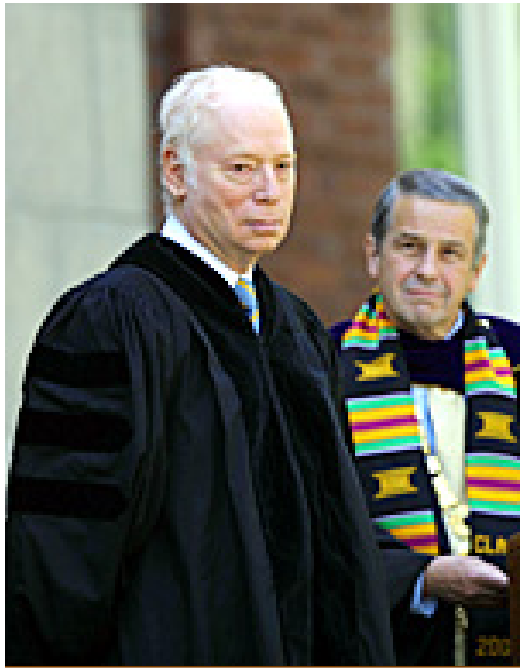
Steven Weinberg
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712
(Received 5 August 1987)

In recent cosmological models, there is an “anthropic” upper bound on the cosmological constant Λ. It is argued here that in universes that do not recollapse, the only such bound on Λ is that it should not be so large as to prevent the formation of gravitationally bound states. It turns out that the bound is quite large. A cosmological constant that is within 1 or 2 orders of magnitude of its upper bound would help with the missing-mass and age problems, but may be ruled out by galaxy number counts. If so, we may conclude that anthropic considerations do not explain the smallness of the cosmological constant.

Dreams of a Final Theory

- We are essentially within the Newtonian paradigm
- It is likely that key observations will nail down which string theory
- All the phenomena may come under complete control and the paradigm of Newton's "Mathematical Philosophy of Nature" may reach completion
  - But unlikely to happen in this century !

Crusader for the ethos of Enlightenment



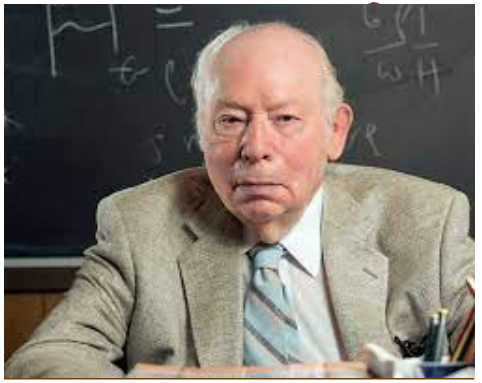
Nobel laureate Steven Weinberg asked Bates College's graduating class [2002] to join him as "allies in a movement that is about 300 years old – the movement known as the Enlightenment."

The Enlightenment has made the world "a freer and gentler place" he said, through its emphasis on the power of reason and its skepticism about many traditional social, political and religious ideas.

Personal reminiscences

Subject: Re: invitation
From: WEINBERG@physics.utexas.edu
Date: 28/04/06, 9:53 PM
To: Urjit A Yajnik <yajnik@iitb.ac.in>
Cc: WEINBERG@UTAPHY.PH.UTEXAS.EDU

Dear Urjit,
I should have been more open in my previous message. As time passes, I like air travel less and less, and although I do go abroad occasionally, I try to limit myself to a minimum of overseas travel. So I am not able to commit myself to visit India in the forseeable future. But I am very grateful to you for raising this possibility. Best, Steve



Subject: Re: HAPP lecture and the observer in quantum mechanics
From: Weinberg, Steven <weinberg@physics.utexas.edu>
Date: 01/09/20, 6:10 PM
To: yajnik@iitb.ac.in <yajnik@iitb.ac.in>

Dear Urjit,
Thanks for your interesting note. I certainly feel as many do that the emphasis on the observer presents a problem for quantum mecanics. Only I fear that if the wave function of every detail of Schrodingers cat was precisely known, we would still need interpretive postulates to give it meaning, and I don't know how to frame these postulates without mentioning observers.
Best,
Steve

From: yajnik@iitb.ac.in <yajnik@iitb.ac.in>
Sent: Monday, August 31, 2020 9:48 PM
To: Weinberg, Steven <weinberg@physics.utexas.edu>
Subject: HAPP lecture and the observer in quantum mechanics

Dear Steve
It was a pleasure to hear you on the HAPP lectures by Nobel Laureates at Oxford. The recording came to my notice recently. There were many insightful comments including the analogy of superposed states to musical notes and their perception, and the comment in Q&A about the

Texas *Gharana*

John Archibald Wheeler E C G Sudarshan Joe Polchinski

- Quantum Gravity : Bryce & Cécile de Witt and Teitelboim (Bunster)

- Texan friendliness
- QFT lectures
  - Q&A
  - Americanism
- “Brown Bag” seminars
  - After the talk
- Thesis and Associateship
- “ ... with my students”


Organic
WE HAVE 144
VARIETIES
32
Peanuts

Thank you very much for your interest and attention

Perdon si quando quiero contar mi vida
Es tierra lo que cuento