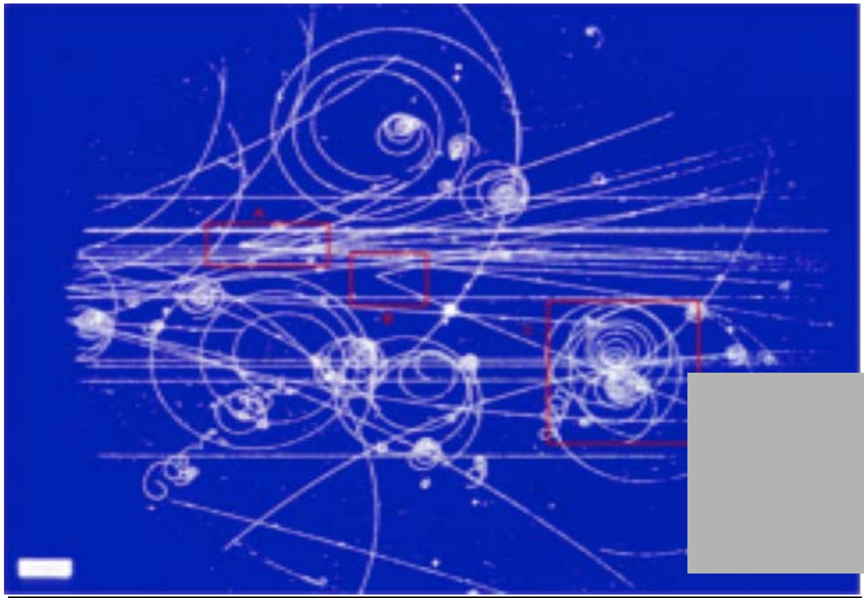


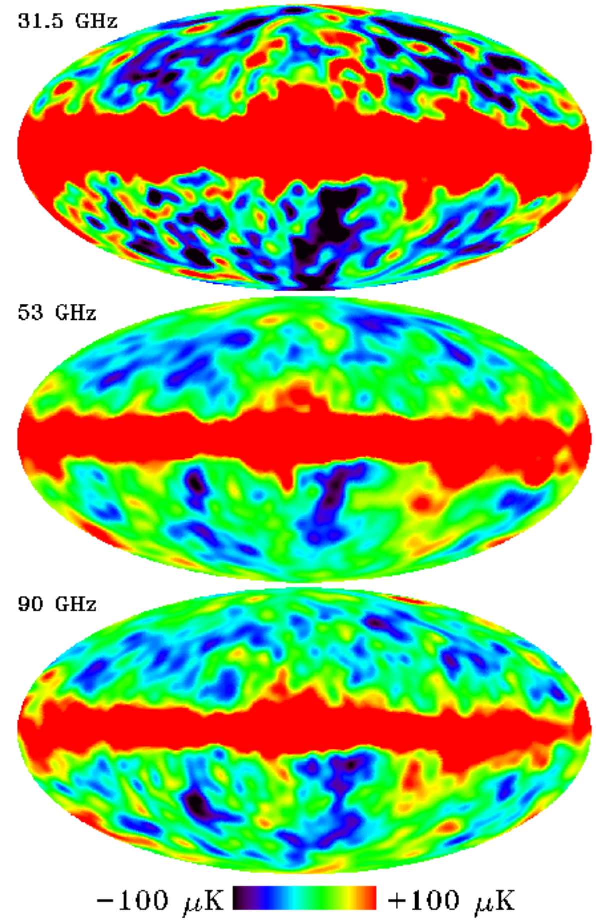
The Birth of Particle Cosmology

8.225 / STS.042, Physics in the 20th Century

Professor David Kaiser, 2 December 2020

Particle Cosmology Today

Studies smallest units of matter and their role in determining the shape and fate of the entire universe.



- 2019: $1b from NSF, DOE, and NASA
- 2 new preprints *every hour* of every day

Not bad for a field that didn't even *exist* 45 years ago!

How do new fields emerge?

Common origins story: new ideas in mid-1970s made it "natural" for particle theorists to study the early universe, and—presto chango—the new subfield was born.

The whole story?

Institutions and ***training*** proved critical. Follow two sets of ideas—one from gravitation and the other from particle theory—from the 1960s through the 1980s. Just like radioactive dyes, they serve as tracers, illuminating larger processes.

1. The Problem of Mass: A Tale of Two φ's

2. Institutions and Ideas

3. Training and New Habits

The Problem of Mass

Important question during the early 1960s: *why do objects have mass?*

Gravitation and Cosmology. Mach's principle: Are local inertial effects the result of distant gravitational interactions?

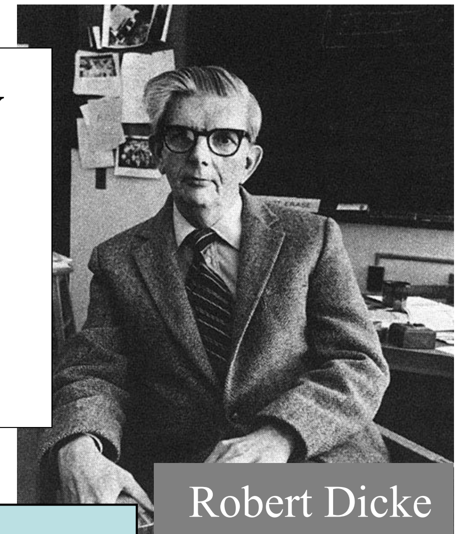
Particle Physics. Masses of force-carrying particles: How can the nuclear force have a finite range without violating gauge symmetries?

Scalar Solutions, 1

Around the same time, physicists in both fields proposed answers to explain the origin of mass.

Carl Brans

Brans-Dicke, 1961: Introduce new scalar field, φ, so that Newton's gravitational constant varies over space and time: $G \sim 1/\varphi(x)$.



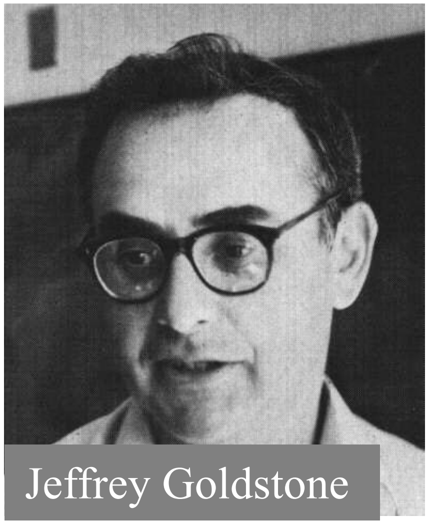
Robert Dicke

Einstein: $[(1/G)\, R]$

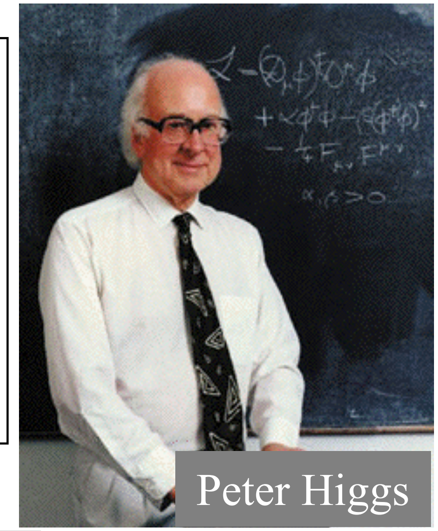
Brans-Dicke: $[\varphi\, R - \omega\, (\varphi_{,i}\, \varphi^{,i}) / \varphi\,]$

All matter interacts with φ, which leads to the observed inertial behavior.

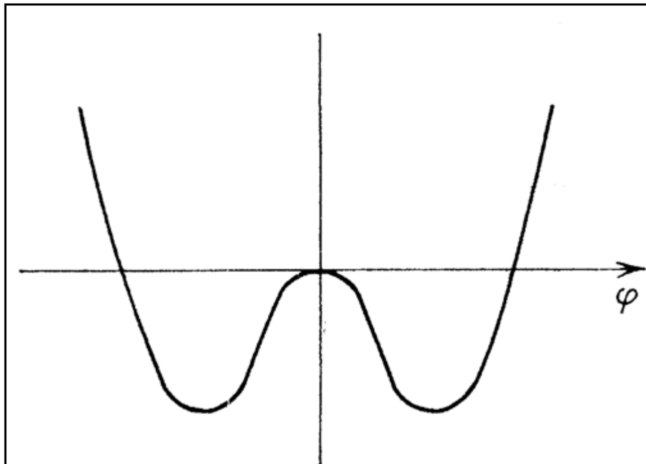
Scalar Solutions, 2



Goldstone, Higgs, et al., 1961-64:
Introduce new scalar field, φ, whose potential, $V(\varphi)$, leads to *spontaneous symmetry breaking*.



Although the governing *equations* are L-R symmetric, any given *solution* breaks this symmetry.



All matter interacts with φ, which leads to the observed particle masses.

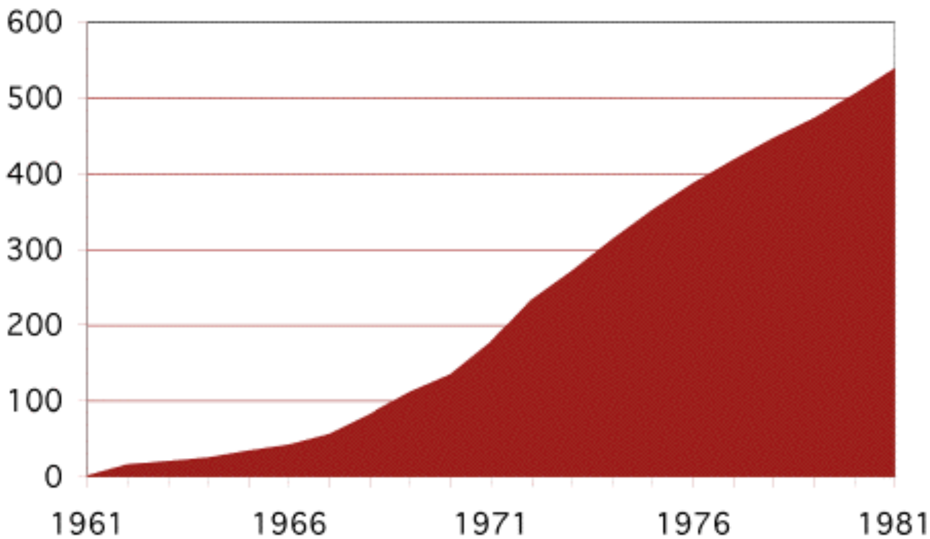
Communities and their Objects

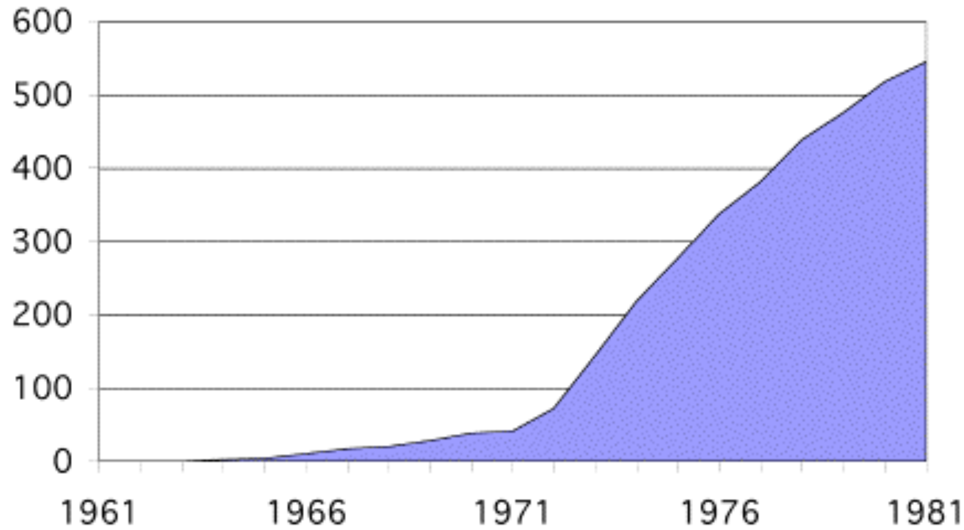
The two communities saw different things in their respective φ's:

To gravitation/cosmologists, φ_{BD} was exciting because it offered an alternative to Einstein's general relativity, spurring high-precision tests of gravitation.	To particle theorists, φ_H was exciting because it offered hope that gauge field theories might be able to explain (finite-range) nuclear forces.

No one suggested that φ_{BD} and φ_H might be similar, or even worth considering side by side, before the late 1970s.

Both Papers Became "Renowned"…





… Yet Almost No Overlap

Only 6 papers out of 1083 cited *both* **Brans-Dicke** *and* **Higgs** between 1961-81; earliest in 1972, most after 1975.

Only 21 authors out of 990 cited *both* **Brans-Dicke** *and* **Higgs** – usually in separate papers – between 1961-81.

Historical Objects

Why no overlap? Were the scalar fields fundamentally different from each other?

No: in 1979, ***Anthony Zee*** and ***Lee Smolin*** each suggested that $\boldsymbol{\varphi}_{\mathrm{BD}}$ and $\boldsymbol{\varphi}_{\mathrm{H}}$ might be *physically identical*.

So the objects' changing status can't be a function only of the things in themselves. The objects' status and identity were *historical*.

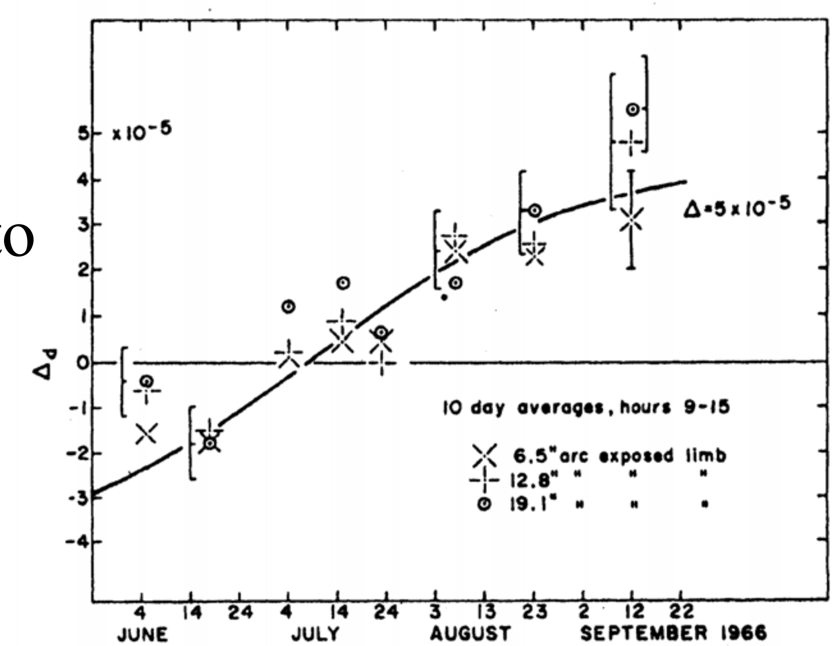
What had changed?

Questions?

Changes in Data?

The Einstein and Brans-Dicke gravitational theories were subjected to a series of high-precision tests during the 1960s and 1970s:

solar oblateness (1966, 1974)
radio ranging to the Viking Mars spacecraft (1979).

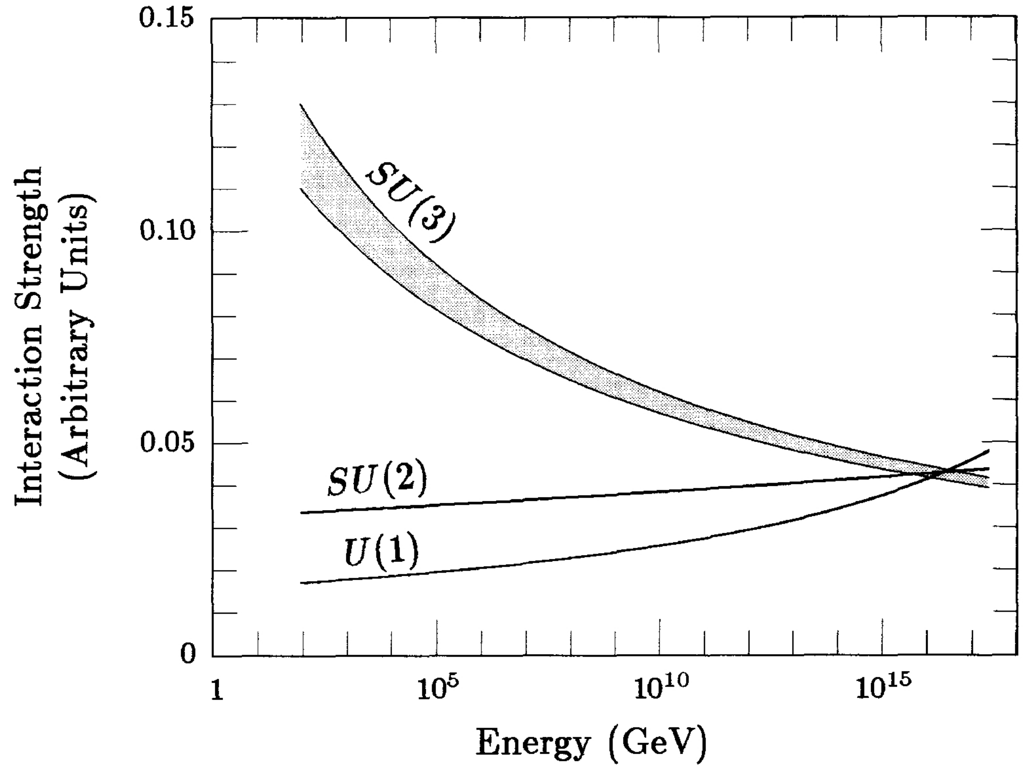


Limited $\omega \geq 500$. Einstein's version seemed favored – just at the time that many particle theorists became interested in φ_{BD}.

Meanwhile, after several decades of intense searching, the first experimental evidence for φ_{H} only came together in *2012!*

Changes in Particle Theory

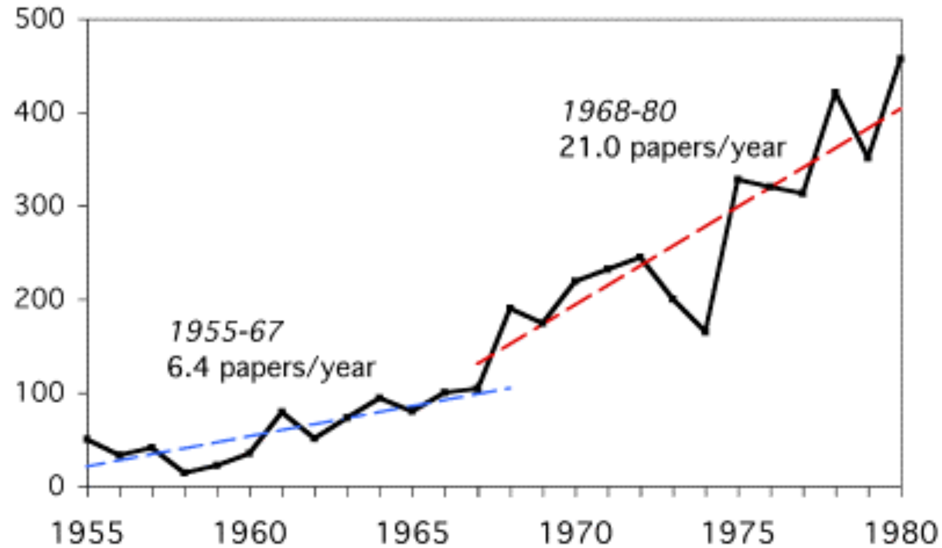
Asymptotic freedom (1973), GUTs (1974). It became "natural" for particle theorists to begin asking about the high-energy early universe. Cosmology would provide the "poor man's accelerator."



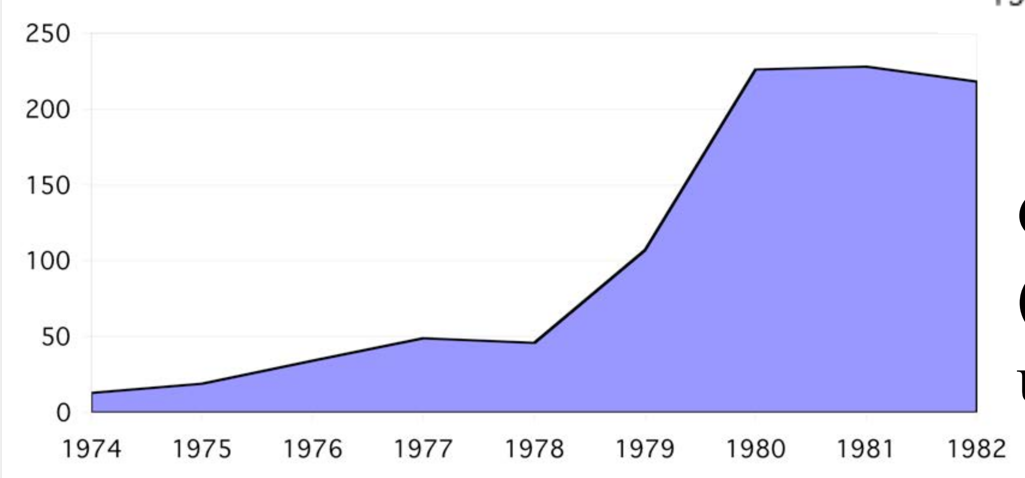
Standard, oft-repeated refrain among physicists, historians, and philosophers: this is *the* reason for the birth of "particle cosmology."

The Whole Story?

Although certainly important, these ideas are insufficient to explain the creation of the new field. The timing is a bit off.

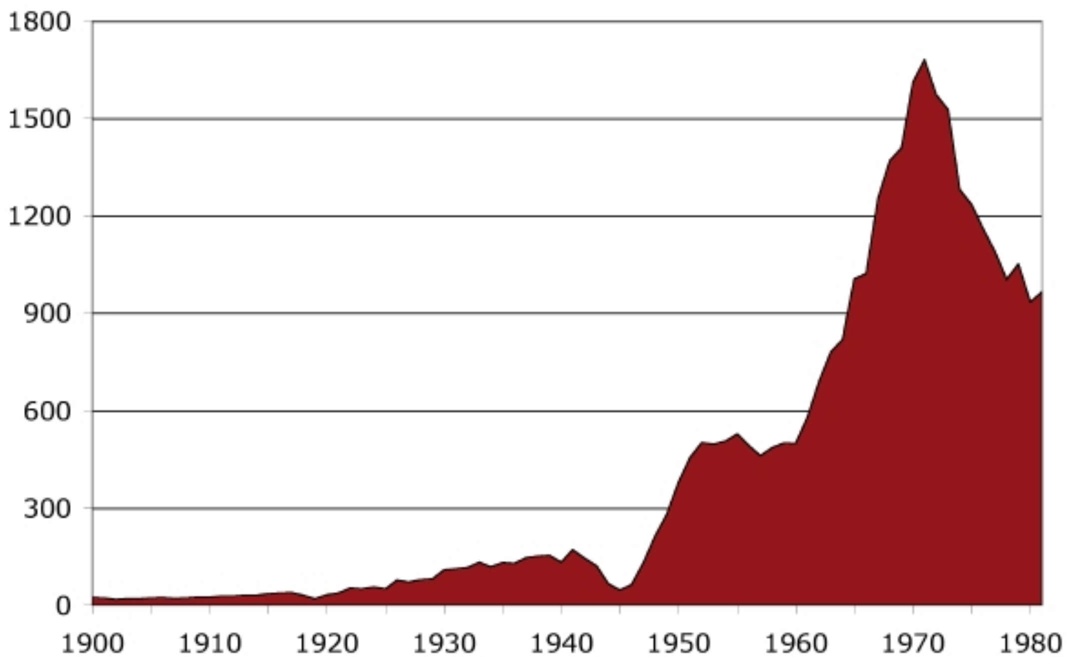


Publications on cosmology began a steep rise *before* 1973-74, and the rate of increase was unaffected by the particle theory papers.



Though introduced in 1974, GUTs did not get much attention (even from particle theorists) until the early 1980s.

Institutions and Infrastructure



Détente, anti-Vietnam War protests, Mansfield Amendment: the first Cold War bubble burst ca. 1968-72. Physicists in US saw their discipline in crisis.

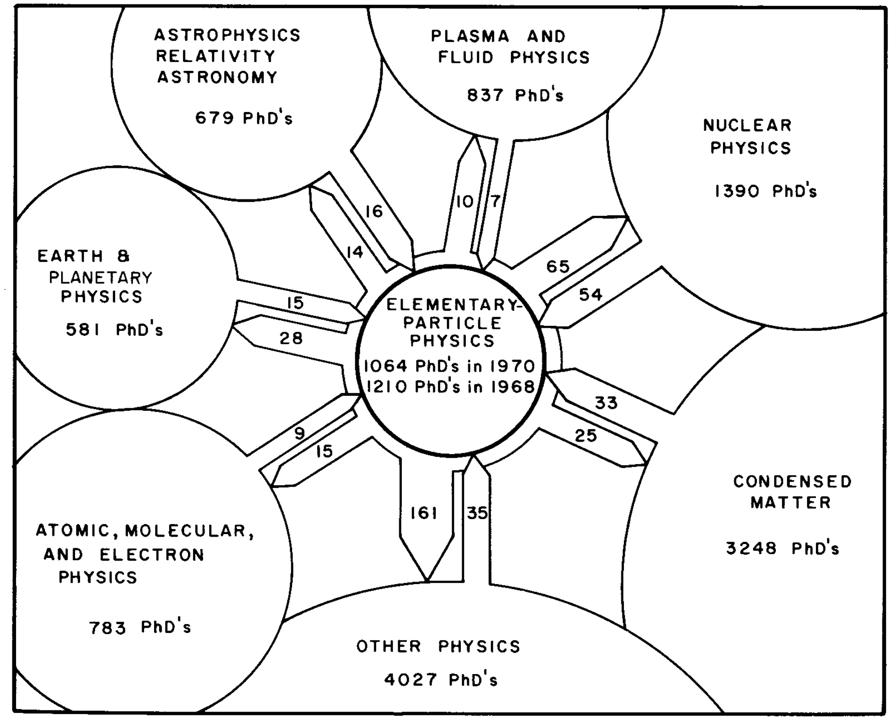
Hardest hit: particle physicists. US budget for high-energy physics cut by 50% between 1970-74, combined with sudden drop in government demand for high-energy physicists.

AIP Job Placement Registries

	Students registered	*Jobs on offer*
1963	449	514
1968	989	253
1970	1010	63
1971	1053	53

Greener Pastures

Rapid out-flow of US particle physicists to other fields, within and beyond physics. Between 1968-1970, *twice* as many people *left* particle physics as entered it.



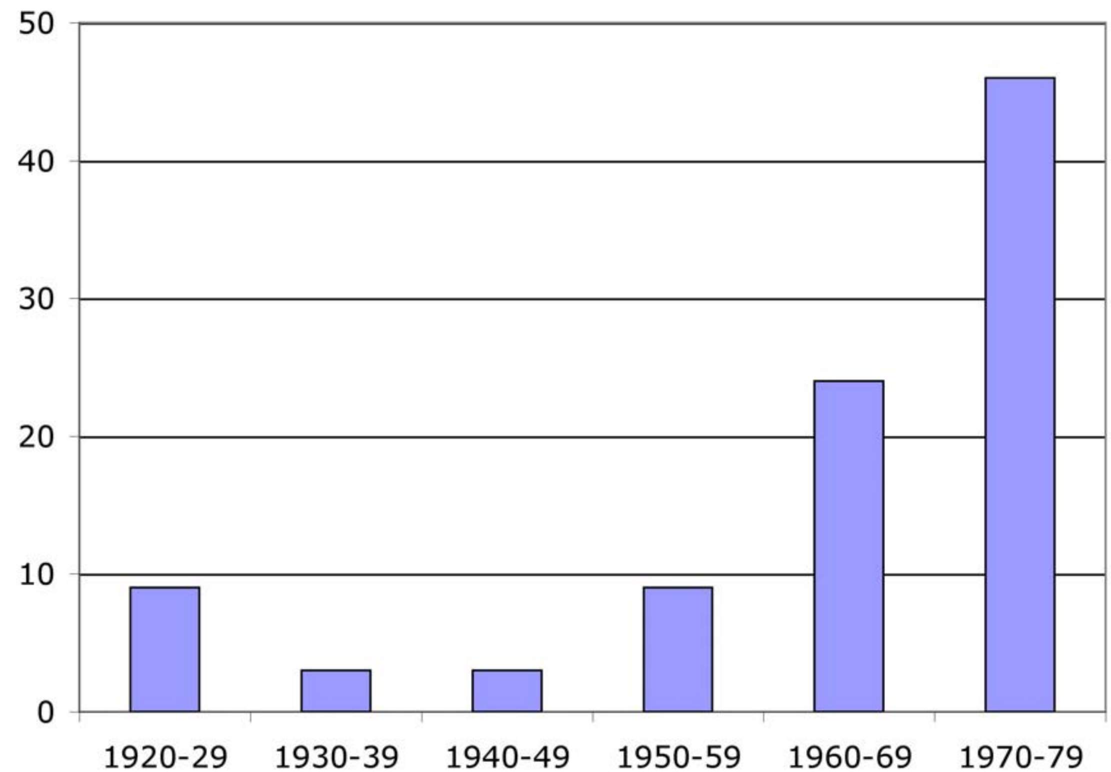
1972 NAS report: Particle theorists fared so poorly when the crunch came because their training was too specialized. Need to revamp how particle theorists are trained. (Only subfield singled out for such criticism in the 2500-page report.)

Pedagogical Hybrids

In the wake of the crunch, after the initial wave of outward migration from particle theory, came more formalized curricular changes in the subfield, including more focus on gravitation.

New graduate courses; gravitation and cosmology began to appear more often on graduate students' general examinations.

Flood of new GR textbooks: 46 published during 1970s (*twice* rate for 1960s) – two-thirds between 1975-79 alone.



Questions?

Broken-Symmetric Gravity

In 1979, **Anthony Zee** and **Lee Smolin** independently introduced a new model, uniting φ_{BD} and φ_{H}.

$$[\ \varphi^2 R - \omega\,(\varphi_{,i}\ \varphi^{,i}) + V(\varphi)]$$

Now the local strength of gravity varies as $G \sim 1/\varphi^2$. Its present-day value only emerges after φ settles into the minimum of its symmetry-breaking potential, V.

Why is gravity so weak (compared to other forces)? Because once $\varphi = \pm\, v$, it pushes $G \sim 1/v^2 << 1$.

The Generations of φ

Anthony Zee wandered into cosmology from particle theory. He finished his Ph.D. in 1970; Paris sabbatical in 1974 sparked his interest in cosmology. His first papers identifying φ_{BD} and φ_{H} appeared in 1979.

Lee Smolin entered graduate school in 1975; formally studied particle theory *and* GR/cosmology from the start. Studied with **Deser**, **Weinberg**, **Coleman**, **Georgi**, **'t Hooft**. Identified φ_{BD} and φ_{H} in his 1979 dissertation.

Smolin's experiences became routine: **Michael Turner**, **Rocky Kolb**, and **Paul Steinhardt** (all 1978 Ph.D.s) trained in similar ways; all soon led groups identifying φ_{BD} and φ_{H}.

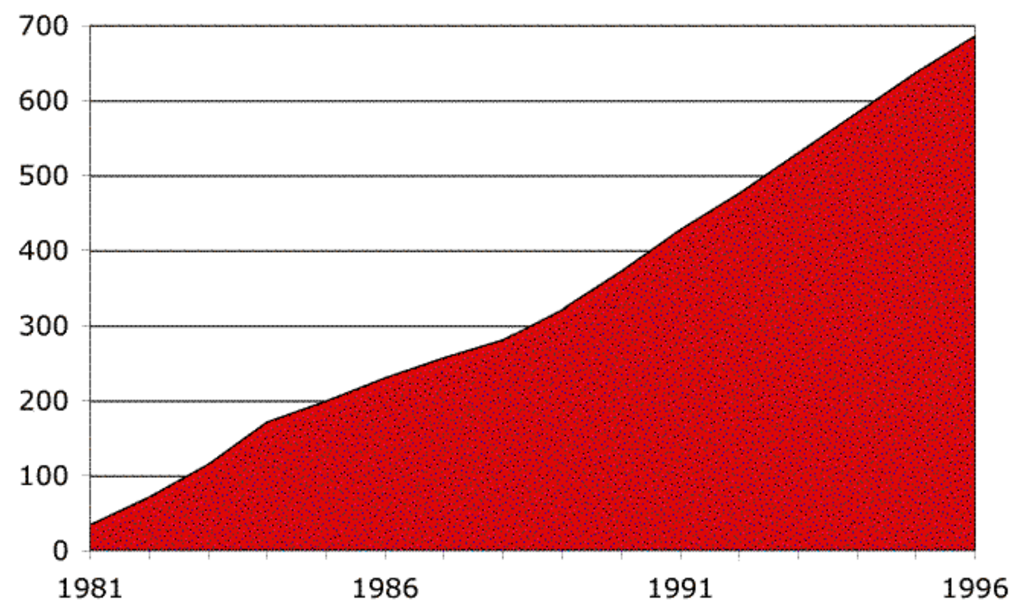
Objects vs. Theories

Though few think that the Brans-Dicke *theory* describes gravity today, the *object* φ_{BD} was hardly killed off by the 1970s experiments.

The new generation of theorists, trained to work in particle cosmology, found new uses for φ_{BD}, far beyond the original motivations of Brans and Dicke:

- Generic correction terms from renormalization;
- Phenomenology of superstring theories;
- Early-universe alterations to gravity, e.g. during inflation.

Citations actually *increased* during the 1980s and 1990s, *after* the experiments that favored $\omega > 500$.



Object Lessons

Neither ***data*** nor ***theories*** forced **Smolin**, **Turner**, **Kolb**, and **Steinhardt** to unite φ_{BD} and φ_{H}. Rather, concrete changes in ***training*** led to a generational shift in what seemed "natural" to do with these theoretical objects.

In turn, these new recruits became institution-builders themselves, solidifying the growth of particle cosmology.

Turner & Kolb: directors of first "Center for Particle Astrophysics" at Fermilab (1983); later wrote first textbook, ***The Early Universe*** (1990).

The Power of Pedagogy

Soon after these changes, ***inflationary cosmology*** was introduced, with its own special scalar field, ***φ***. Nowadays it is routine to study scalar fields like φ_{BD}, φ_{H}, and their ilk as part of a common project.

This seeming naturalness—the banality of combining these fields today, or the bizareness of holding them at arm's length—illustrates the power of pedagogy.

Vast institutional changes and curricular reforms re-shaped what young physicists would find natural, compelling, or worth pursuing.