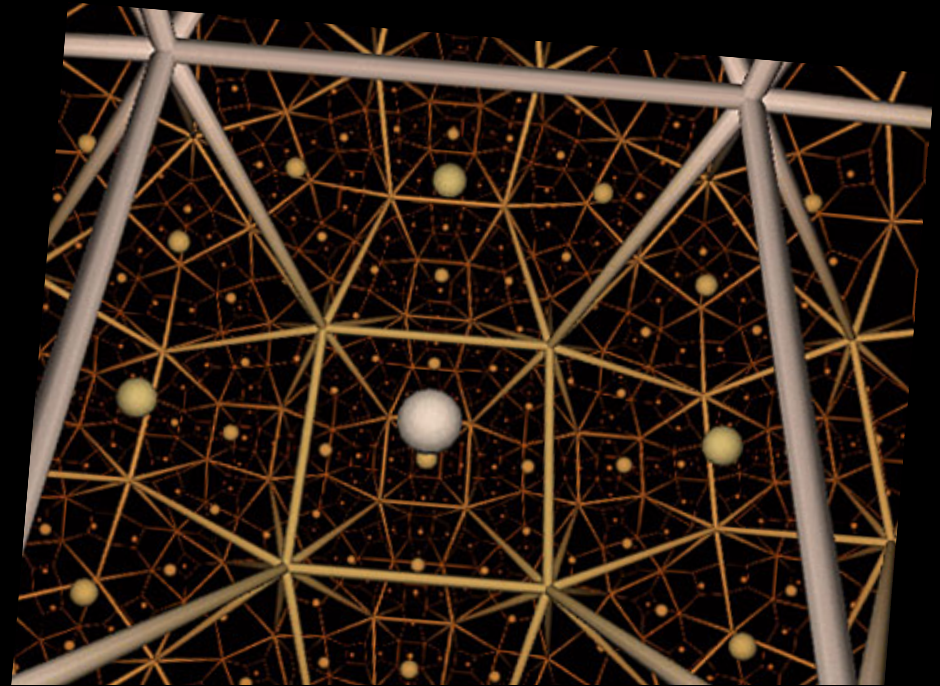
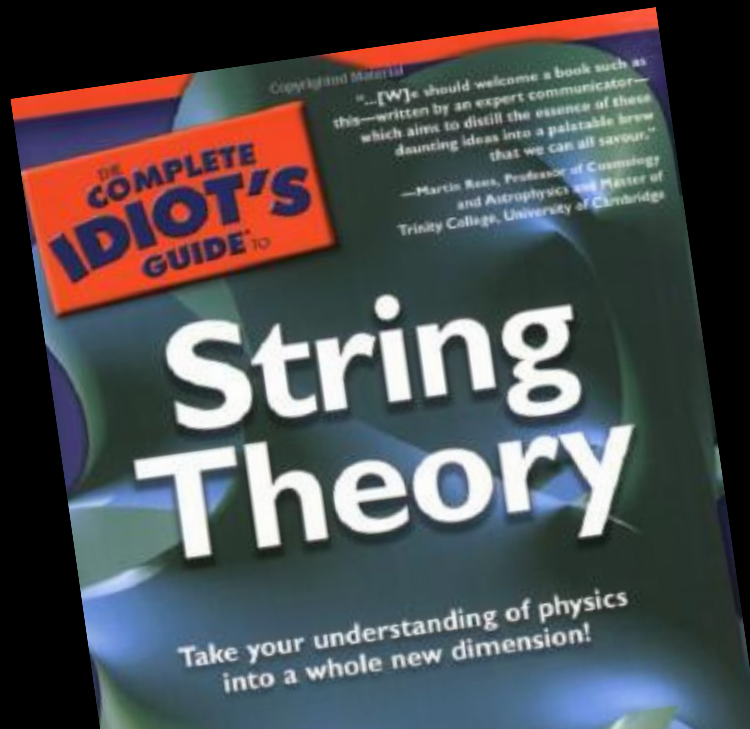


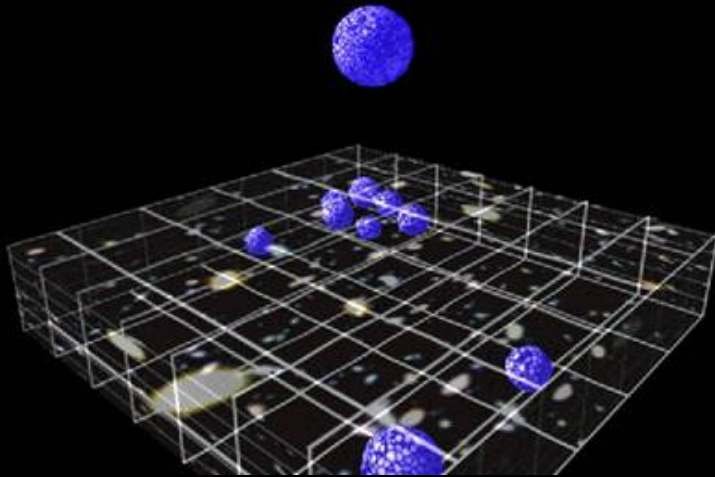
*String Theory and the Multiverse**



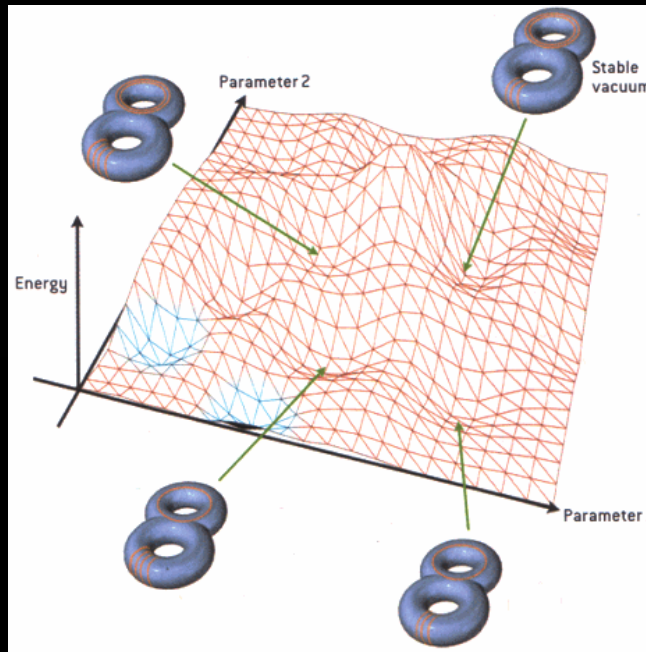
8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 9 November 2020

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1. Quantum Gravity?



2. A Messy Landscape



3. A Package Deal



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Hundred-Year Challenge

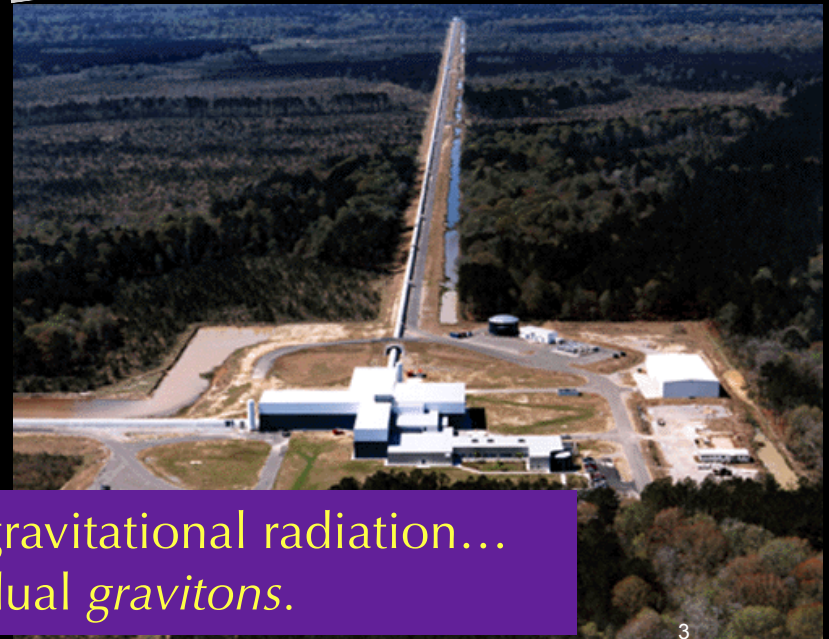
Three of the four known forces of nature are inherently quantum-mechanical; gravity has been the stubborn hold-out.

Physicists have long recognized that gravity *could* be described in terms of particle exchange, with a massless, spin-2 particle: the “**graviton**.”

M. Bronstein

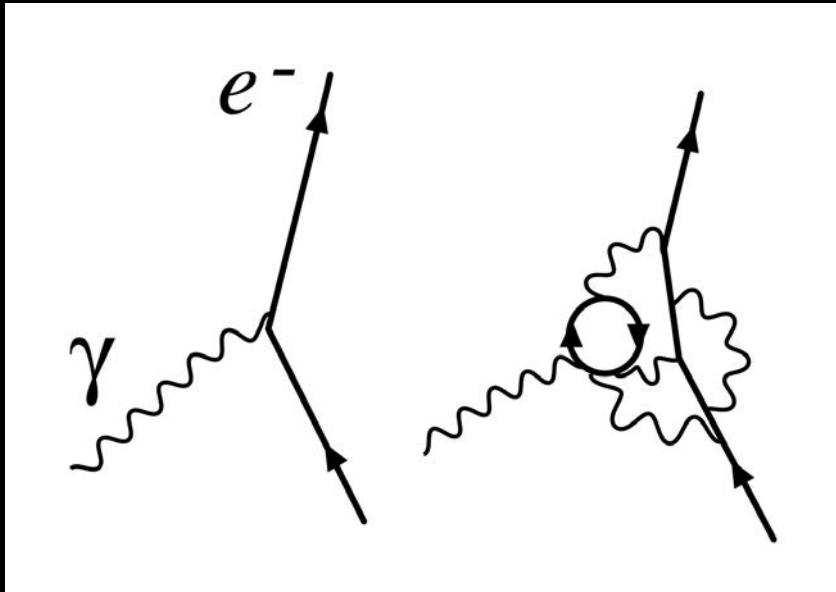


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LIGO detected *classical* gravitational radiation...
still no evidence for individual *gravitons*.

Infinites Return



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One can model graviton exchange like other quantum field theories:

$$g_{\mu\nu} = g_{\mu\nu}^0 + h_{\mu\nu}, \quad h_{\mu\nu} \rightarrow \hat{h}_{\mu\nu}$$

That leads to *infinities*. But unlike in the other cases, *no finite set of “counterterms”* can remove all of the infinities.

$$\nabla^2 \phi_{\text{electric}} = -4\pi \rho_c$$

$$[\rho_c] \sim \frac{e}{r^3} \sim |\mathbf{k}|^3$$

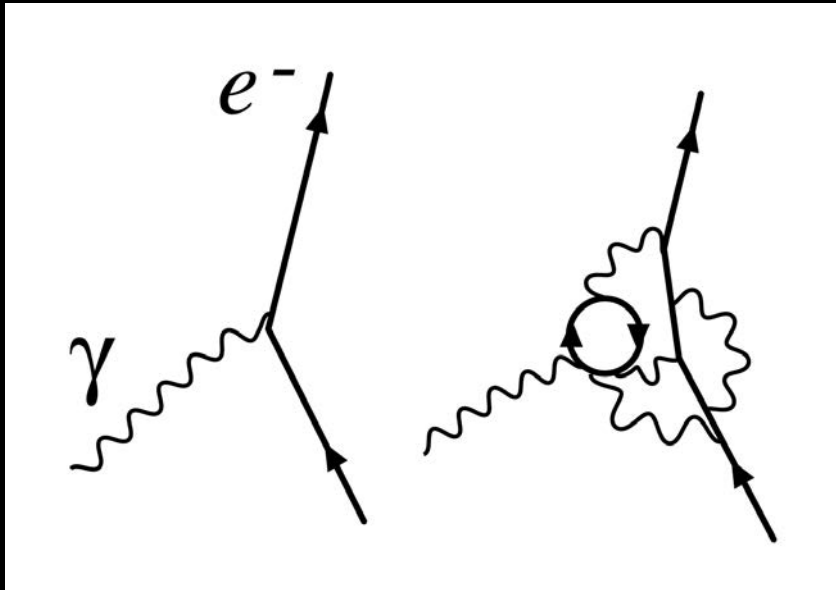
$$\nabla^2 \phi_{\text{grav}} = -4\pi \rho_m$$

$$[\rho_m] \sim \frac{m}{r^3} \sim m|\mathbf{k}|^3 \longrightarrow |\mathbf{k}|^4$$

$$E = \sqrt{m^2 c^4 + |\mathbf{p}|^2 c^2}, \quad \mathbf{p} = \hbar \mathbf{k}$$

The *source* for (quantum) gravitational effects is *mass* (rather than electric charge), so virtual processes diverge *even more strongly* with momentum \mathbf{k} .

Infinites Return



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$$e_{\text{eff}} = e_0 + e_{\text{virtual}}$$

$$m_{\text{eff}} = m_0 + m_{\text{virtual}}$$

QED

One can model graviton exchange like other quantum field theories:

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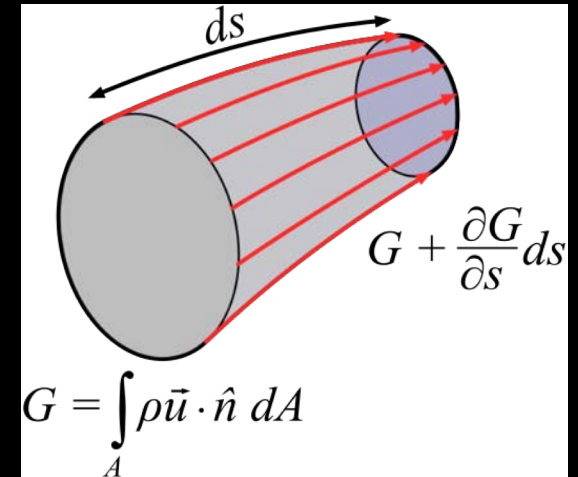
$$\beta_{\text{eff}} = \beta_0 + \beta_{\text{virtual}} + \dots$$

Quantum Gravity

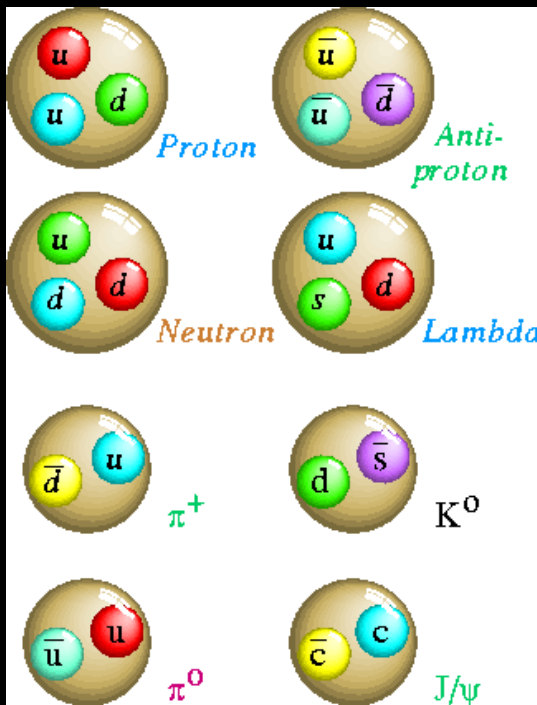
“Old School” Quantum Gravity
is not renormalizable.

Stringy Ideas

During the late 1960s, while working on Geoffrey Chew's S -matrix approach to the strong nuclear force, several theorists began playing with string-like flux tubes.

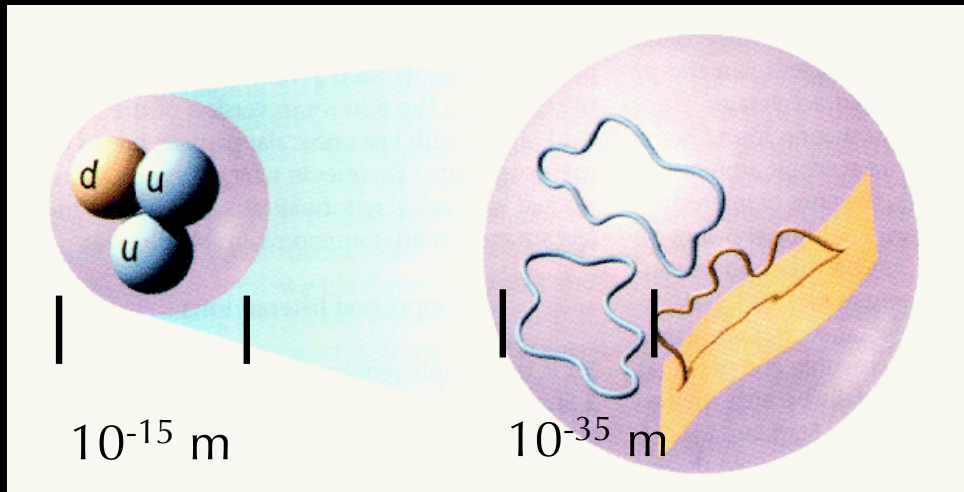


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That work was quickly overshadowed by the success of the quark model and QCD, by the mid-1970s: 'regular' quantum field theory was back, and few saw the need for a strange string-like treatment of the nuclear force.

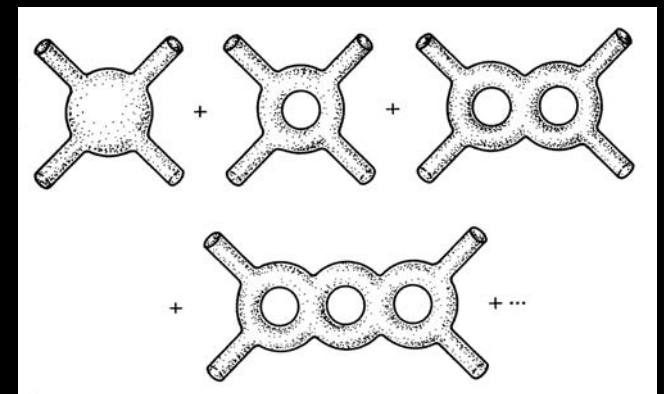
Worldsheets to the Rescue



Yet the string theorists had noticed something funny: their equations seemed to contain a massless, spin-2 particle within the low-energy spectrum.

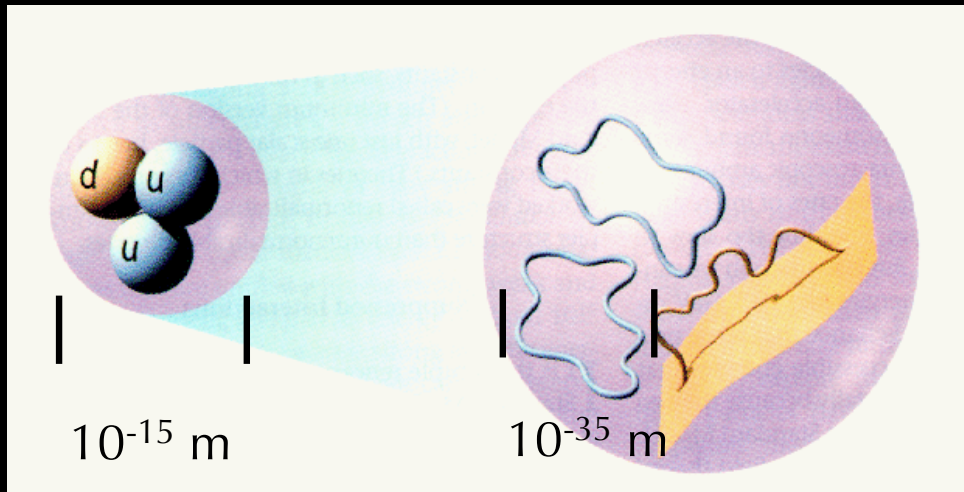
Maybe they had been looking at the *wrong scale*: string theory wasn't about nuclear forces; it might be about *gravity*.

Moreover, string theory looked *finite*. Point particles meet at point-like vertices; 1-d strings sweep out *worldsheets*, and hence vertices are *spread out* in spacetime. No infinite integrals!



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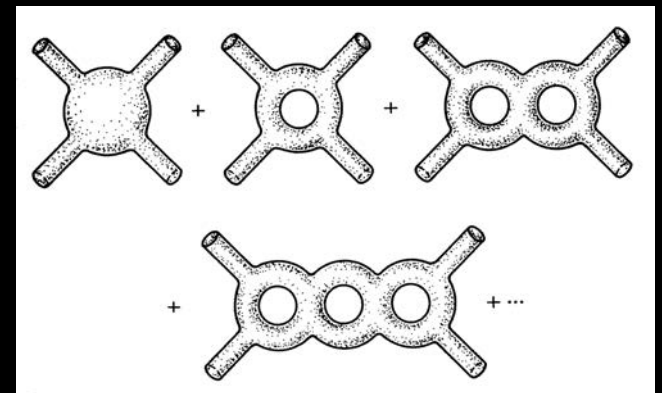
Worldsheets to the Rescue



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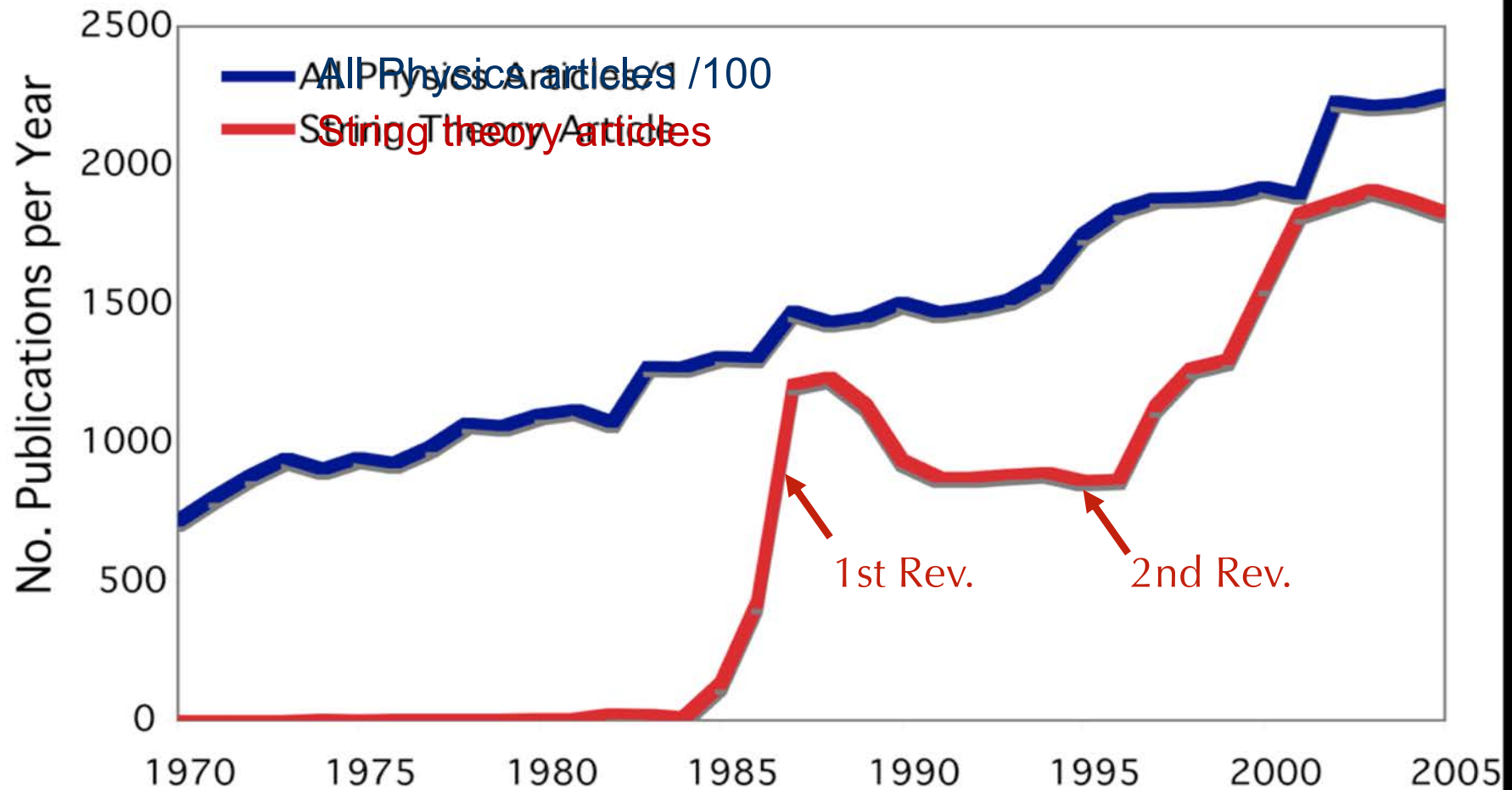
But there was a catch: the simplest model required **26 spacetime dimensions** to remain self-consistent. Models that incorporated "supersymmetry" (for every particle with half-integer spin there exists an integer-spin partner) required "only" **10 spacetime dimensions**.



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String Revolutions

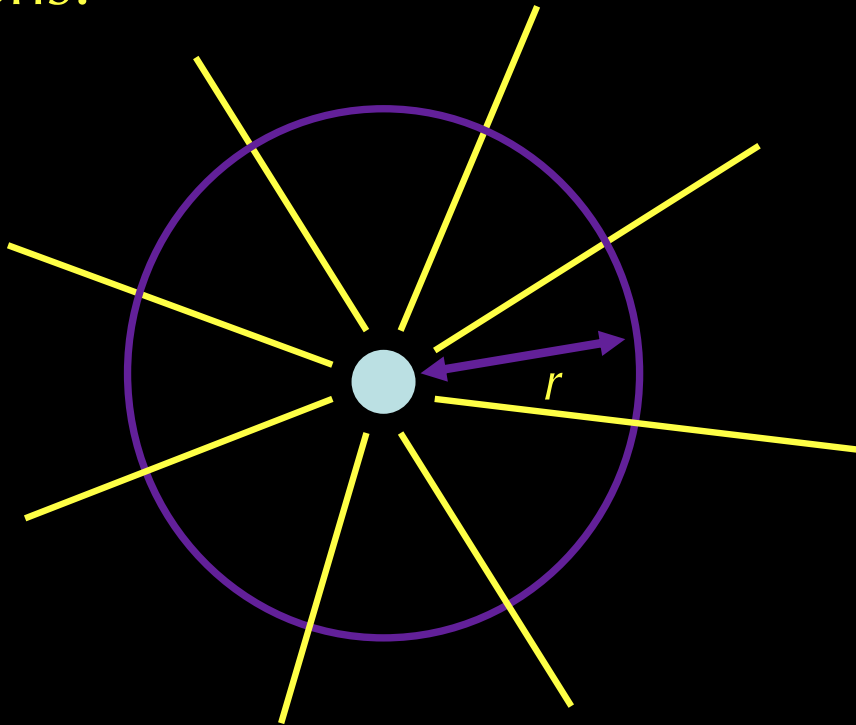
Worldwide Physics Publications, 1970-2005



Questions?

Leaky Gravity?

Usual assumption: unless something strange happens, gravity would behave *very* differently in a universe with extra dimensions.



N lines of force traverse
a $(d - 1)$ -surface:

$$\frac{N}{A} \sim \frac{1}{r^{d-1}}$$

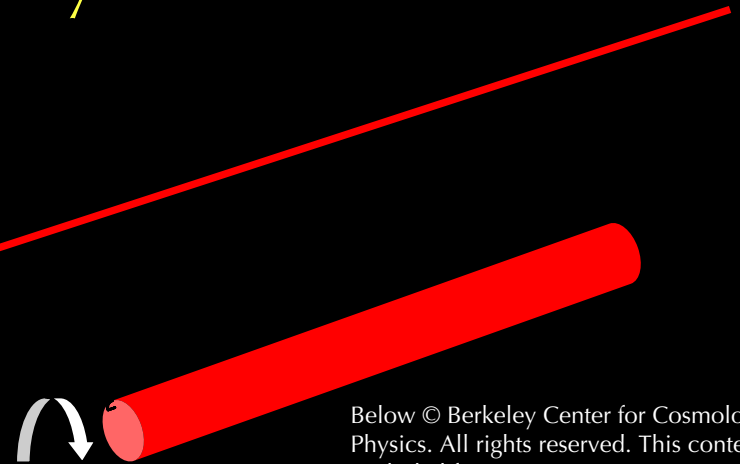
In 9 spatial dimensions, the force of gravity would fall as $1/r^8$!

Curl 'Em Up

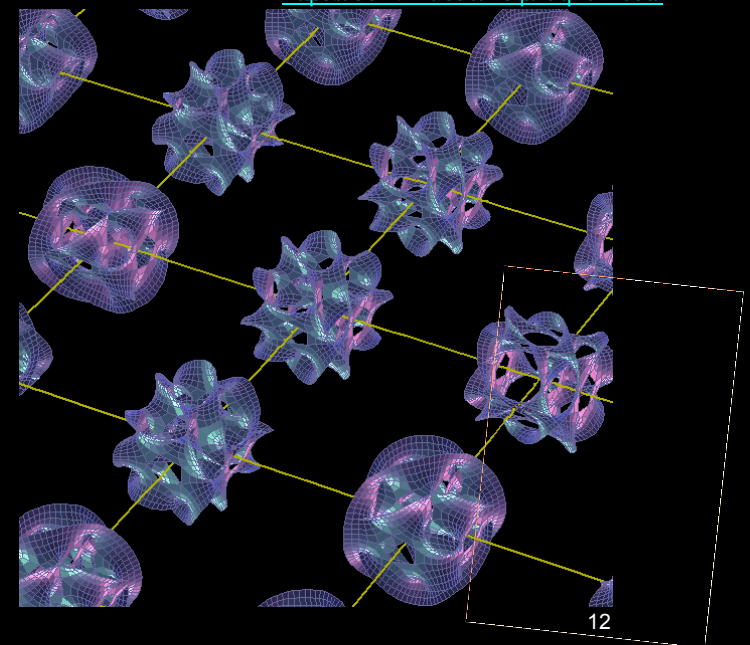
The extra dimensions could be hidden from view if they were *compactified* — curled up to very small scales.

This is straightforward to do with *one* extra dimension.

But with *six* extra dimensions, there are $\sim 10^5$ distinct possibilities. (1986)

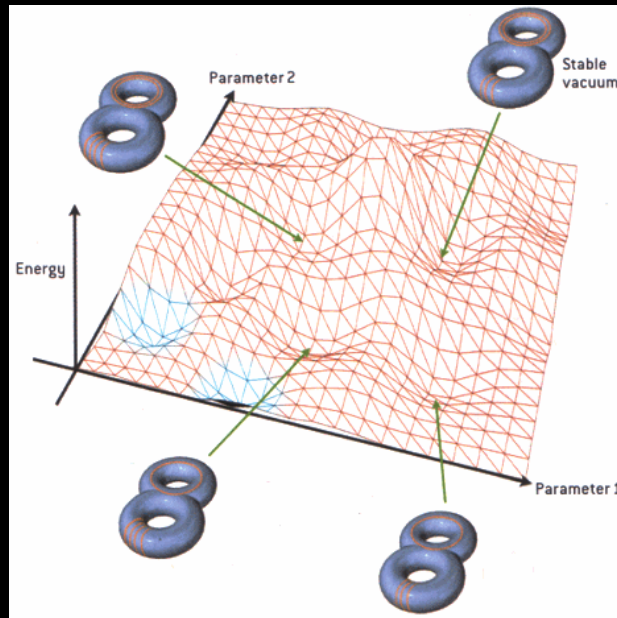
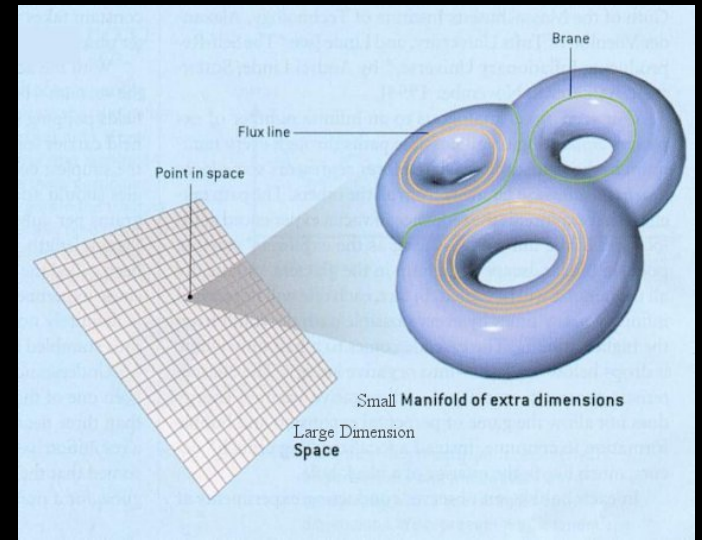


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Not a Pretty Landscape

The problem gets even worse (2003): fluxes and membranes can wrap around the shrunken dimensions, yielding at least 10^{500} distinct vacuum states.



Every observable quantity of our universe ($m_i, g_i, H, \Lambda, \dots$) would depend on precisely which of these vacua our universe “landed” in. So what picked out *ours*?

Other cosmic numbers:

$$\frac{\text{Jeff Bezos (\$)}}{\text{David Kaiser (\$)}} = 10^5$$

$$\text{age of universe} = 10^{17} \text{ s}$$

$$\frac{\text{mass of galaxy}}{\text{mass of electron}} = 10^{71}$$

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Multiverse



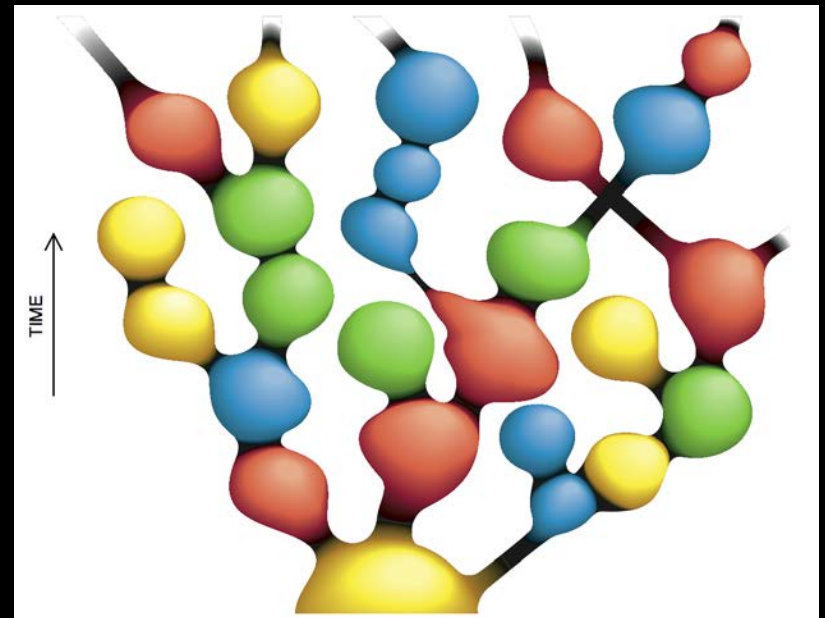
A. Guth

Eternal Inflation: $\Gamma < H$. Even as inflation ends within one region of spacetime, the volume of other regions could continue to grow exponentially.

Once inflation begins *someplace*, it could continue *forever!*

A **multiverse** could exist, populated by an *infinite set* of separate bubble universes.

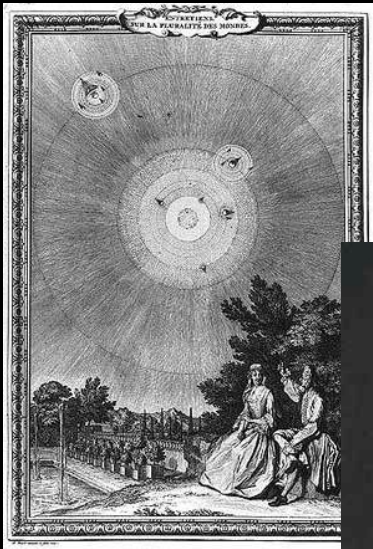
All 10^{500} distinct string vacuum states might be realized *an infinite number of times*, one each within a given bubble universe.



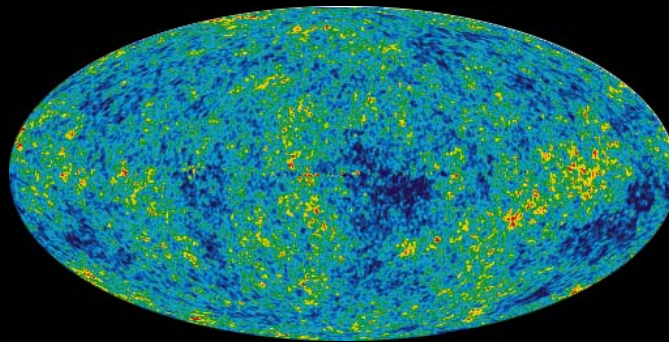
Guth © source unknown. Multiverse (above) © Andrei Linde / Stanford. All rights reserved. This content is excluded from our Creative Commons license. For more information, see <https://ocw.mit.edu/help/faq-fair-use/>

Evidence of Design?

If any of the parameters (m_i , g_i , H , Λ , ...) were even slightly different, life as we know it probably could not exist.



Bernard de Fontenelle,
*Conversations on the
Plurality of Worlds*
(1686)



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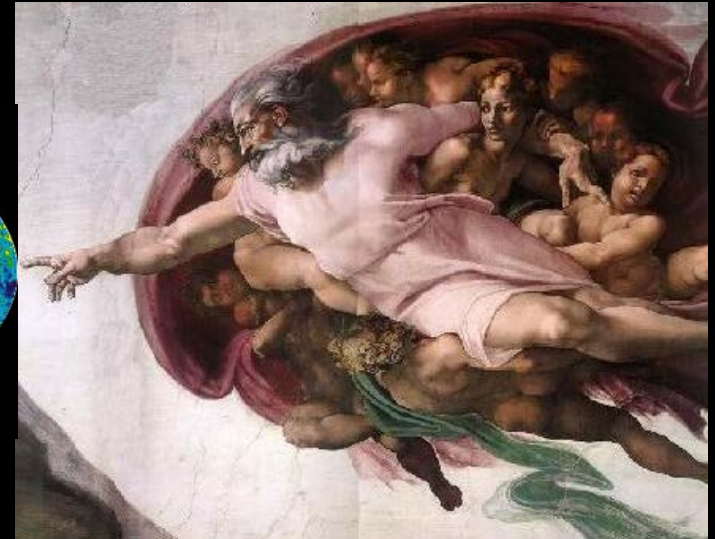
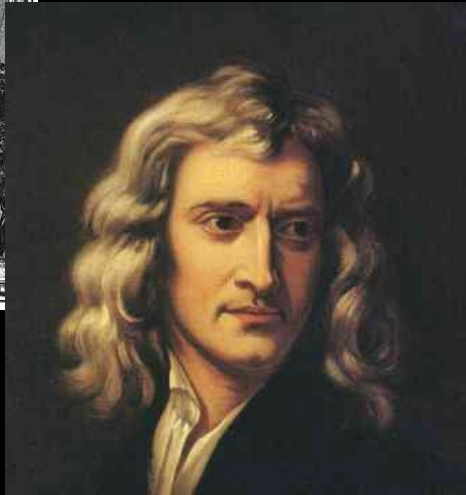


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theologian Richard Bentley,
1690s.

**A very old
argument!**

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Anthropic Response

Anthropic principle: The natural constants in our observable universe had to fall within narrow ranges; otherwise no cosmologists would be here to ask about them.

*Critics: “dangerous”;
“disappointing”; “a
virus”; “an abdication”...*

With 10^{500} distinct physical states out there, each realized an infinite number of times, ***pure random chance*** could be enough to “explain” why we happened to evolve where we did.

Susskind’s epigraph:

“Your Highness, I have no need of this hypothesis.”

Questions?

A Package Deal

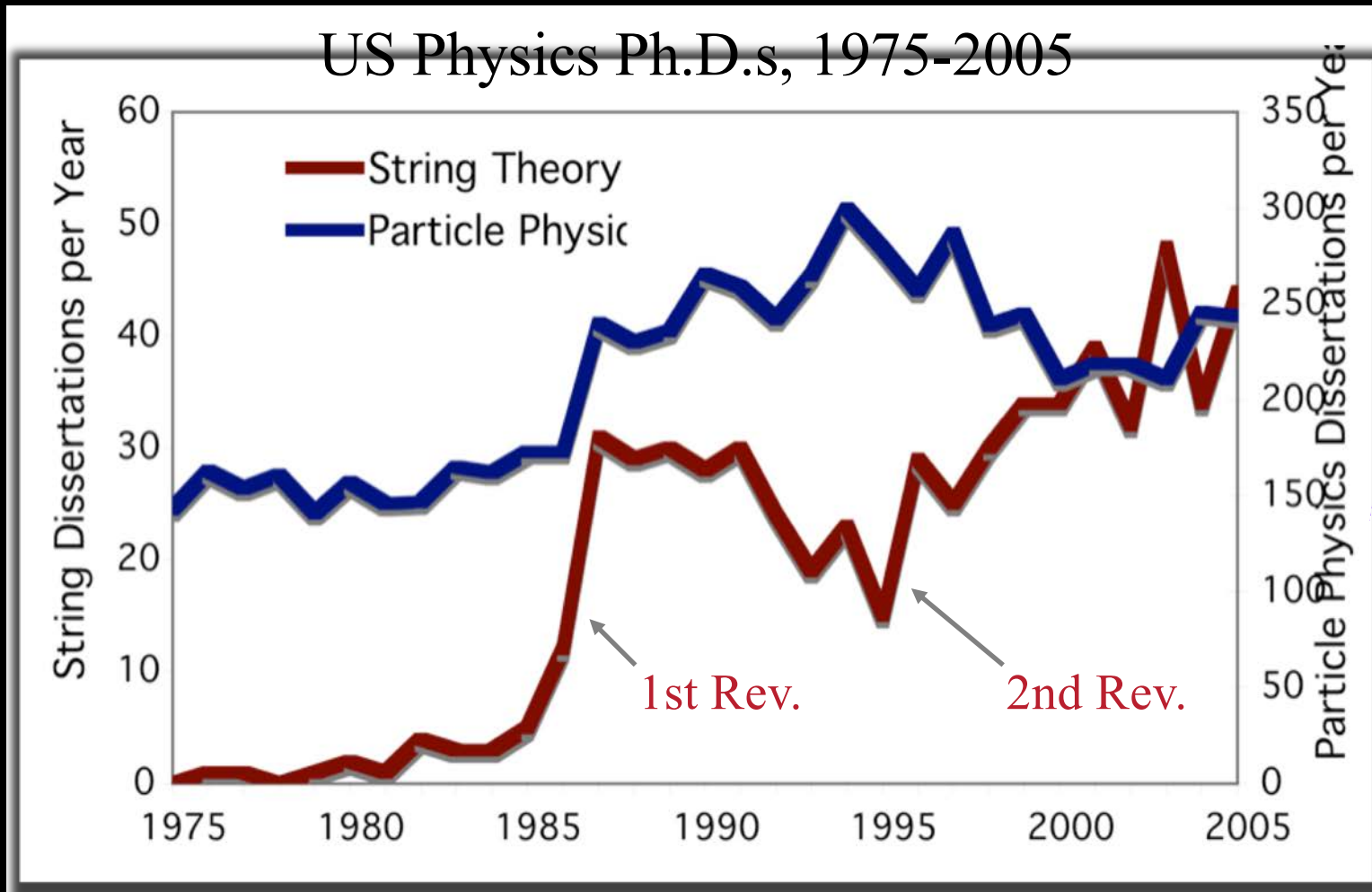
String theory has some great features. But it comes with some strange features as well:

- It requires an as-yet undetected symmetry among all the known particles (“supersymmetry”).

- It can only be formulated in $N > 4$ spacetime dimensions. The most popular variants have $N = 10$ or 11 .

- And, despite the founders’ hopes, it leads to a *huge* number of possible models, with (as yet) no way to choose between them.

Strings and the Academy



A Hole in Texas: The SSC



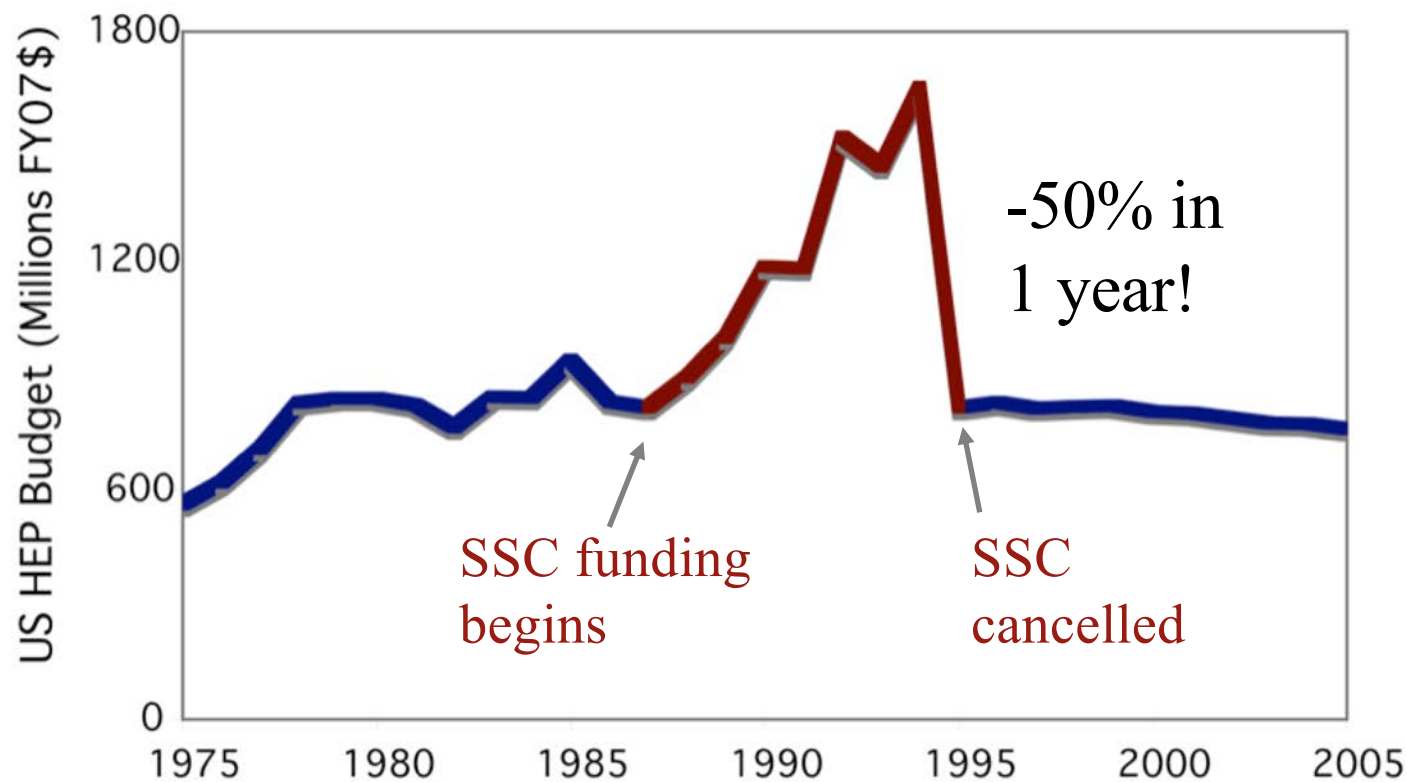
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Congress approved
funding in 1985

Projected cost:
1 Big Dig (~ \$15B)



The Rise and Fall of the SSC



Congress voted to kill the SSC in Oct 1993; \$3B had already been spent.

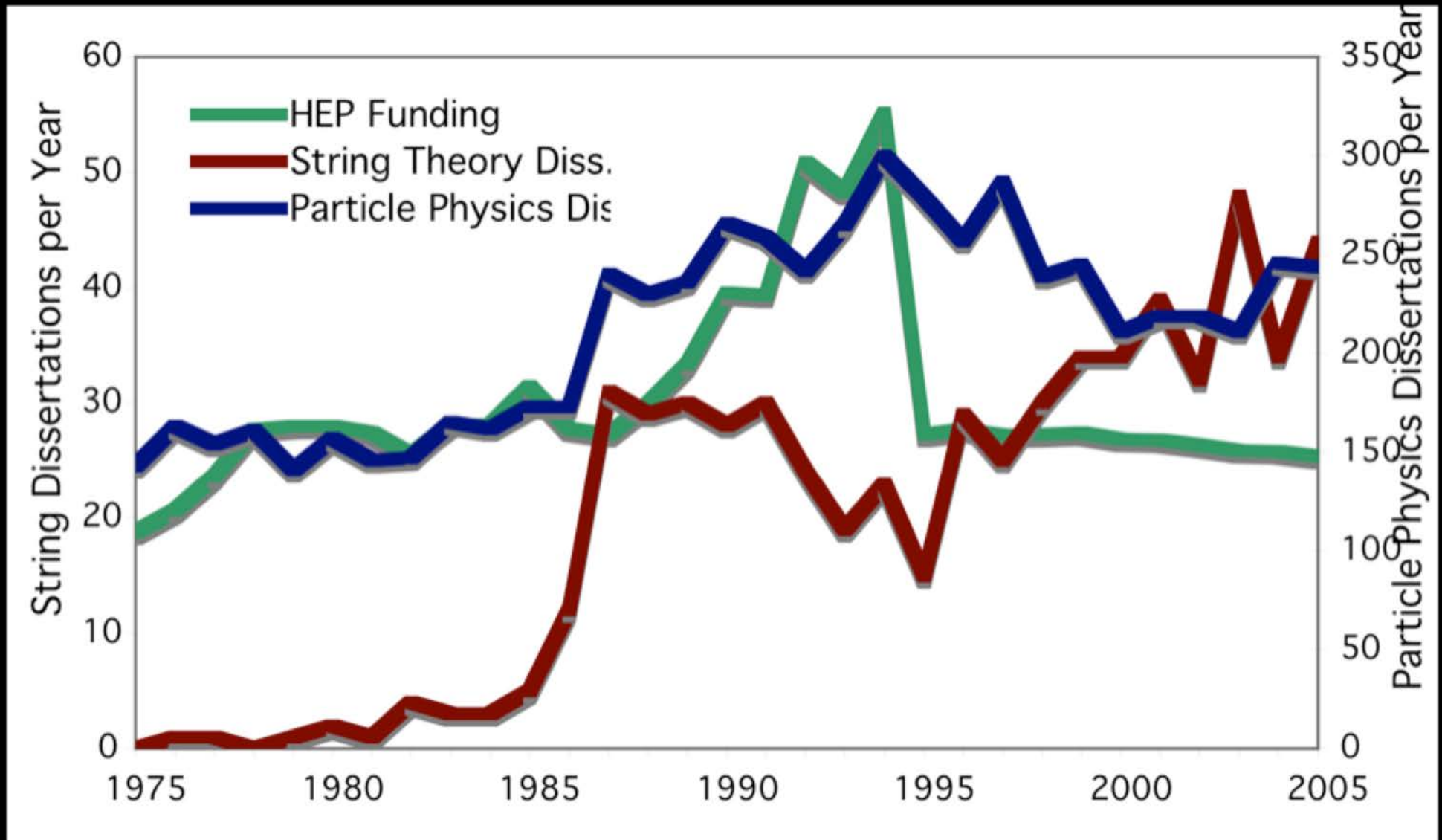
**Total US
Physics
Funding,
1993 to 1999:**

DOE: -25%

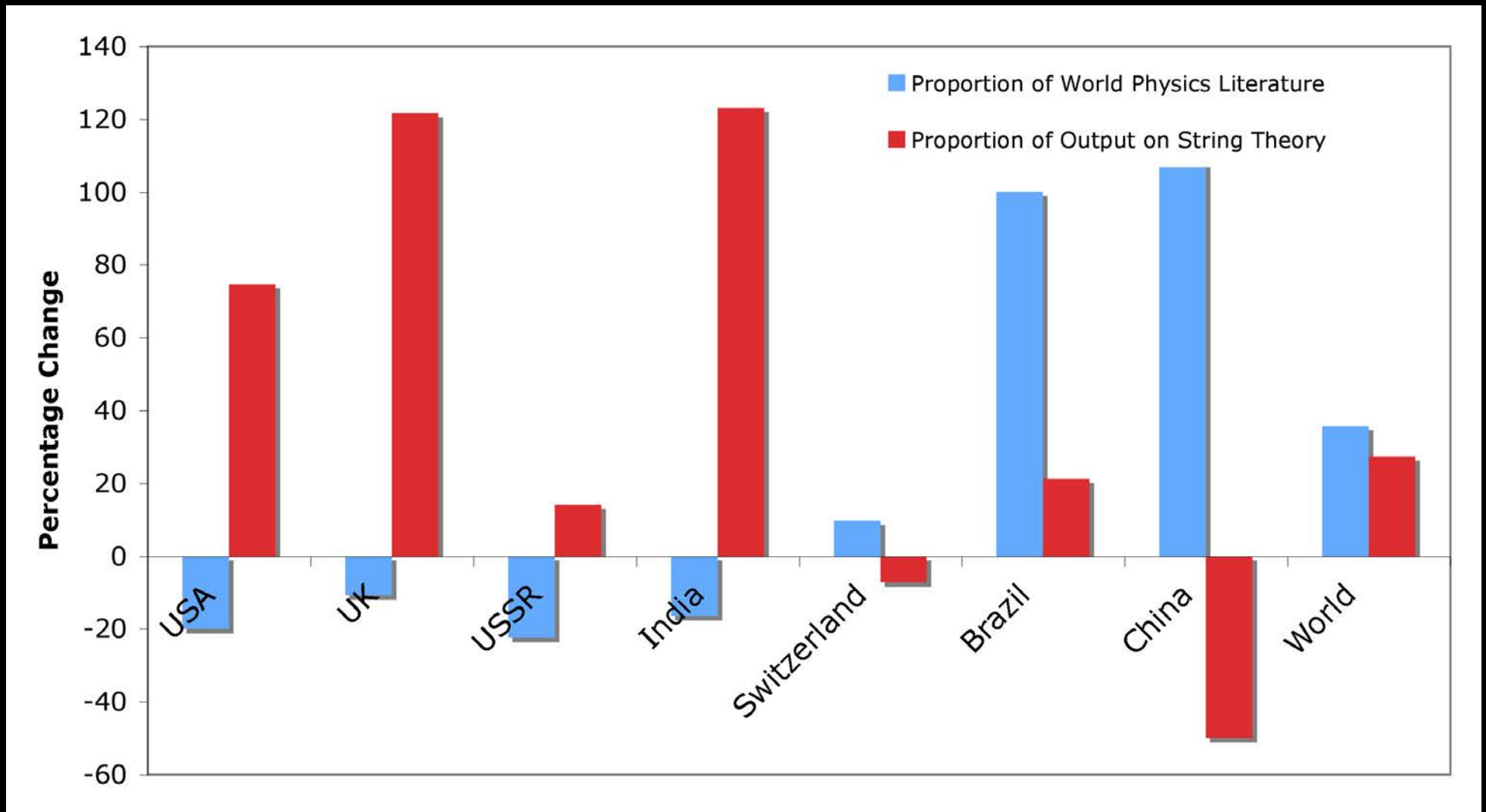
DOD: -58%

NSF: -5%

Death of SSC and Life of String Theory



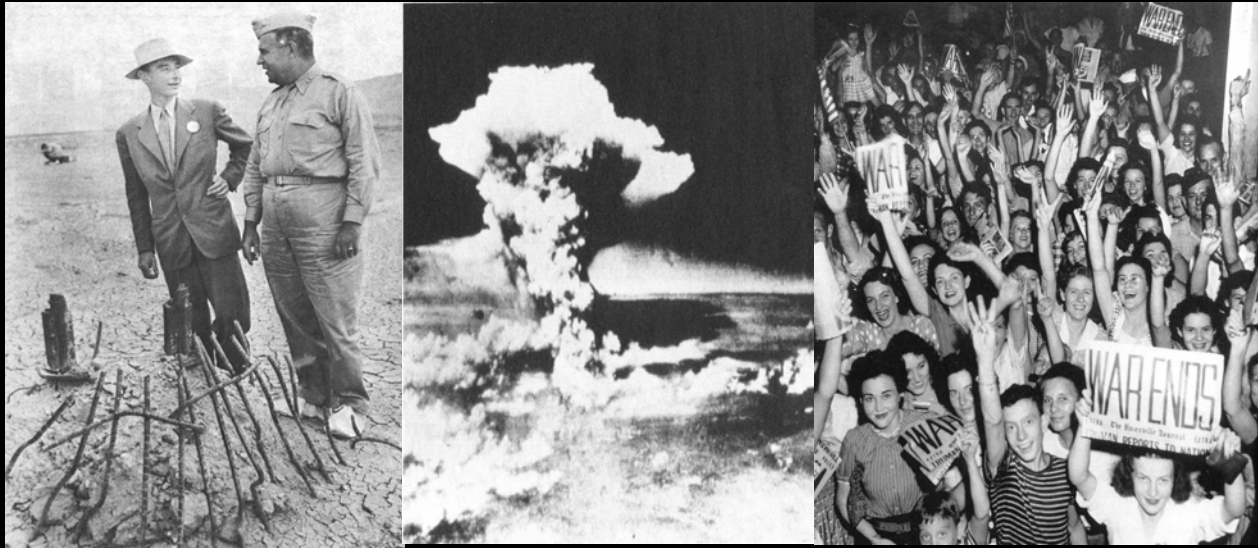
Strings Around the World



Percentage change between decade averages, 1985-94 vs. 1995-04

Millennial Physics

Early in the 21st century, physics seems just as wrapped up in the flow of culture and politics as it did throughout the 20th century.



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Physicists emerged from World War II with significant political clout. That kept the money flowing and provided cover against various critiques. After the Cold War, the political and cultural landscape has changed.

Keep on Truckin'...

Posted on creationist website one week after our article was published:

"We had to show you in their own words what these MIT eggheads are saying. ... *Guth and Kaiser need to take up truck driving.* That would get them out of their ivory towers at MIT and into the real world, where they would be forced to look at trees, mountains, weather, ecology and all the other **observable** things on our privileged planet that are inexplicable by chance: realities that proclaim *design, purpose, intention.*"

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