Limiting science

Particle Physics, cosmology and beyond Popper

Talk at the Center for Contemporary Studies, IISc Bangalore
13th August 2009

Outline

- When did cosmology become a science?
- Cosmology and the Standard Model of particle physics
- Unification, grand unification and TOE
- Strings and loops
- The Landscape
- Falsifiability and a case study from theoretical physics

Before 1915

- Fixed static infinite universe (Newton)
- One galaxy
- Very little known about distant stars except a little about spectral composition
- Cosmology strongly within the purview of theology:

Newton: I do not hypothesize

Einstein's general relativity

- Spacetime dynamical

  curvature of space-time is gravitation

  $R = -8\pi G\, T$

- Capability for space-time to be curved even in the absence of matter (de Sitter solutions)
- Spacetime as a whole can expand!

  This is truly revolutionary!

Expanding universe

- Expanding universe is a big problem for Einstein since (1) there is no observational evidence to support this and (2) an expanding universe is too bizarre an idea.
- Einstein modifies his equation

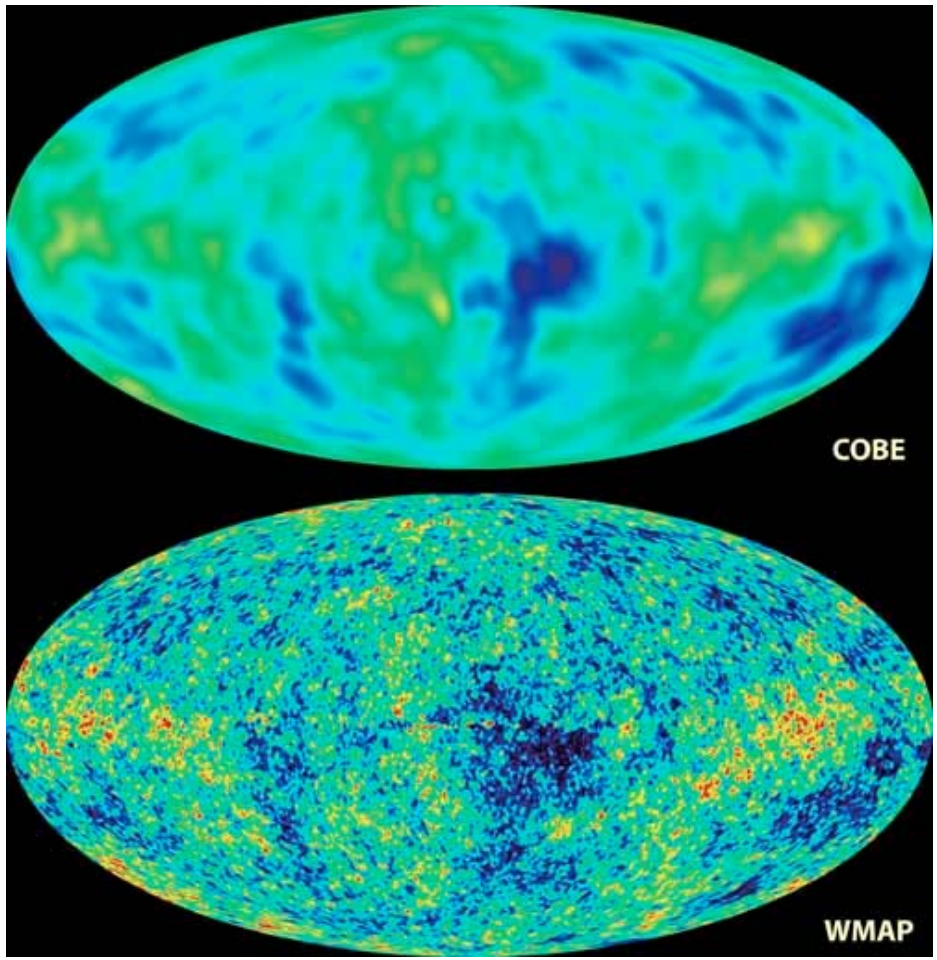
$$R - \Lambda = -8\pi G\, T$$

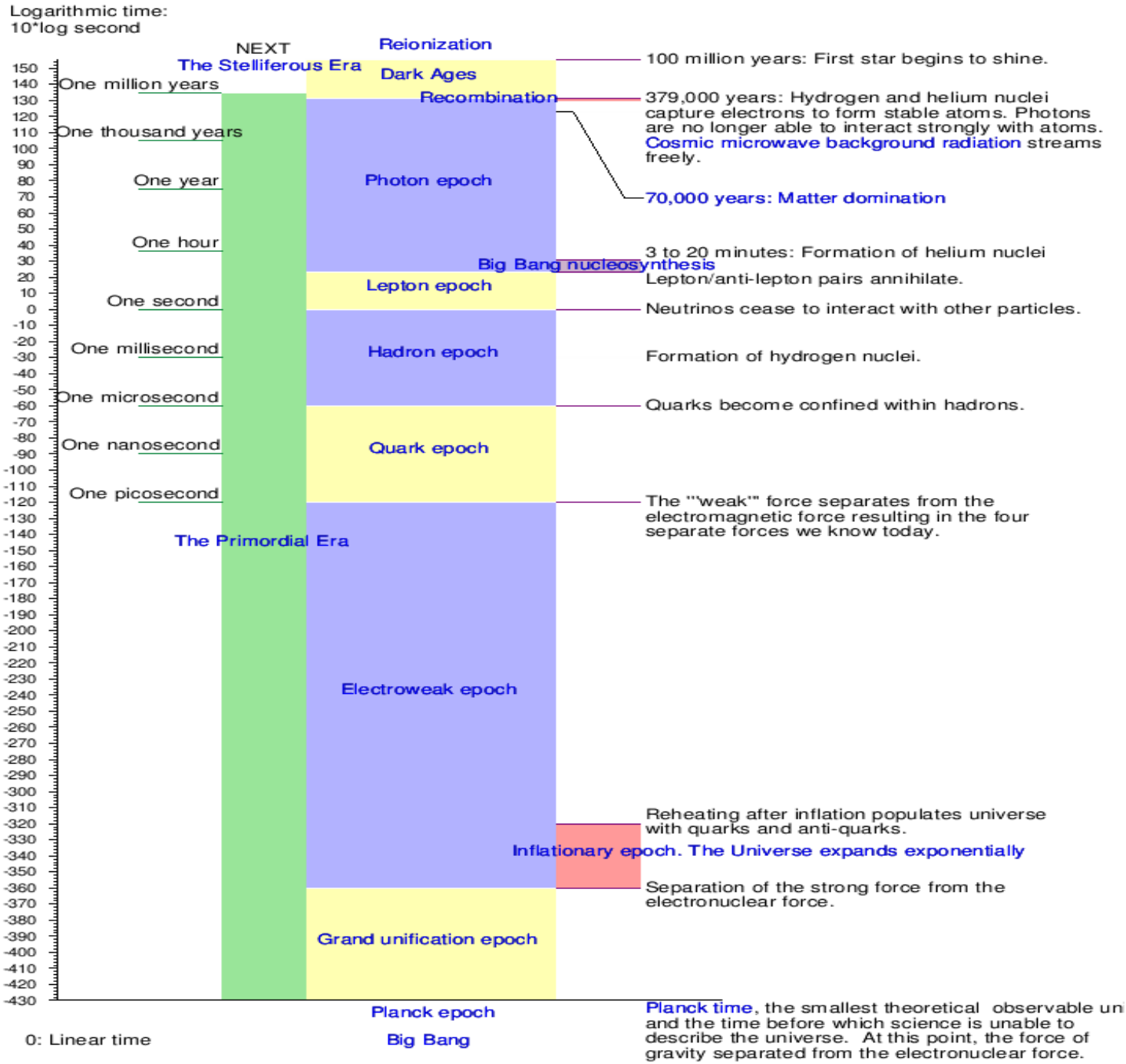
- Einstein: “Biggest blunder of my life”
- Hubble: the universe is expanding redshift of the spectra of light from distant galaxies

Hot early universe

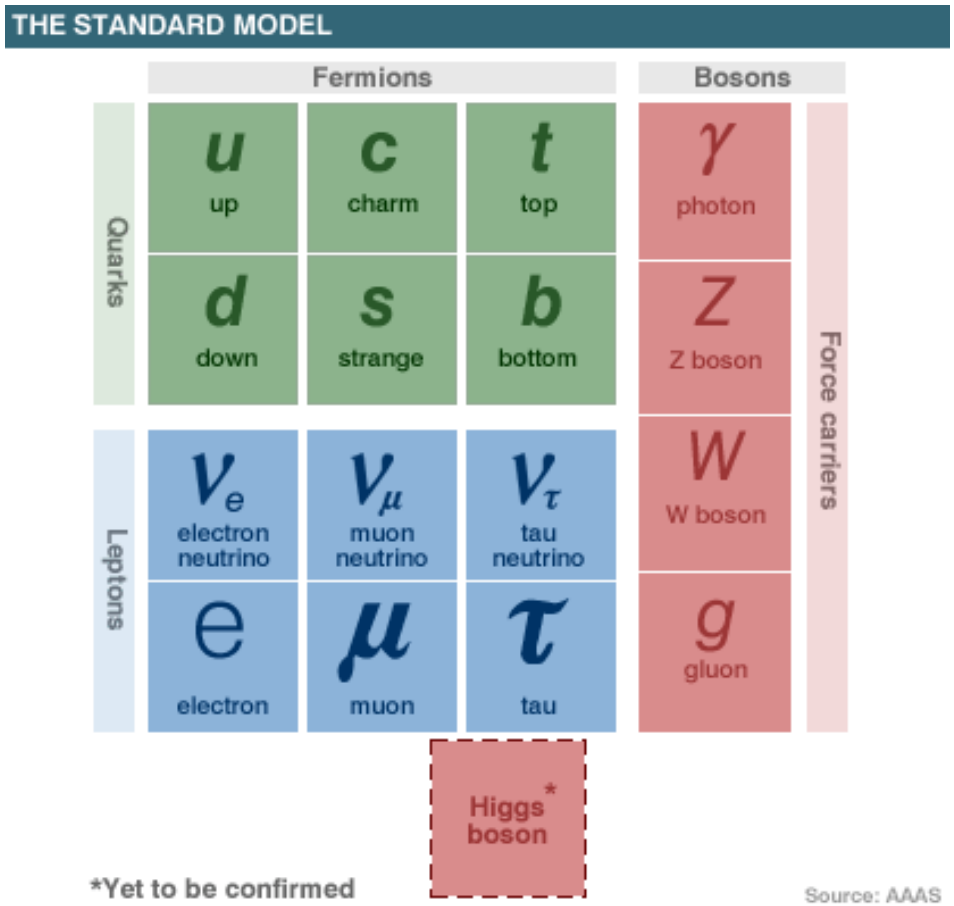
- If the universe is expanding (+ some other observations) then there should be a constant microwave static of about 3 Kelvin!
- Verified in the Bell Labs at 2.73 Kelvin.
- Over the years, refined estimates about homogeneity and isotropy of background radiation verified!

COBE/WMAP




Logarithmic time:
10*log second
NEXT
Reionization
The Stelliferous Era
Dark Ages
One million years
Recombination
One thousand years
Photon epoch
One year
One hour
Big Bang nucleosynthesis
Lepton epoch
One second
Hadron epoch
One millisecond
One microsecond
Quark epoch
One nanosecond
One picosecond
The Primordial Era
Electroweak epoch
Inflationary epoch. The Universe expands exponentially
Grand unification epoch
Planck epoch
0: Linear time
Big Bang
100 million years: First star begins to shine.
379,000 years: Hydrogen and helium nuclei capture electrons to form stable atoms. Photons are no longer able to interact strongly with atoms. Cosmic microwave background radiation streams freely.
70,000 years: Matter domination
3 to 20 minutes: Formation of helium nuclei
Lepton/anti-lepton pairs annihilate.
Neutrinos cease to interact with other particles.
Formation of hydrogen nuclei.
Quarks become confined within hadrons.
The "'weak'" force separates from the electromagnetic force resulting in the four separate forces we know today.
Reheating after inflation populates universe with quarks and anti-quarks.
Separation of the strong force from the electronuclear force.
Planck time, the smallest theoretical observable un
and the time before which science is unable to describe the universe. At this point, the force of gravity separated from the electronuclear force.

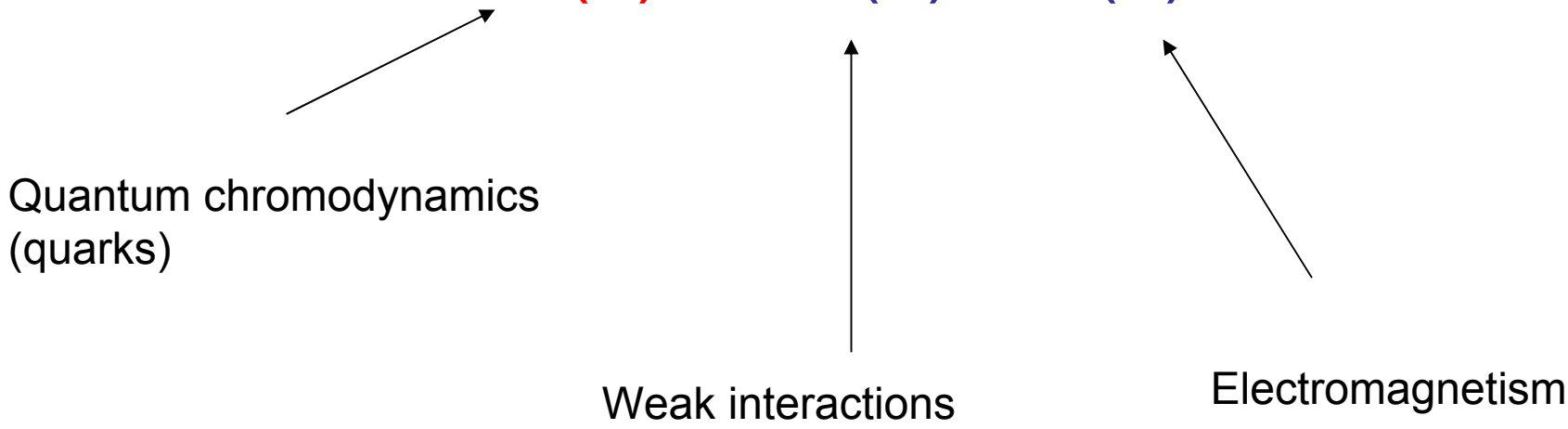
Standard Model of Particle Physics



The Standard Model

Gauge group of symmetries

$$SU(3) \times SU(2) \times U(1)$$



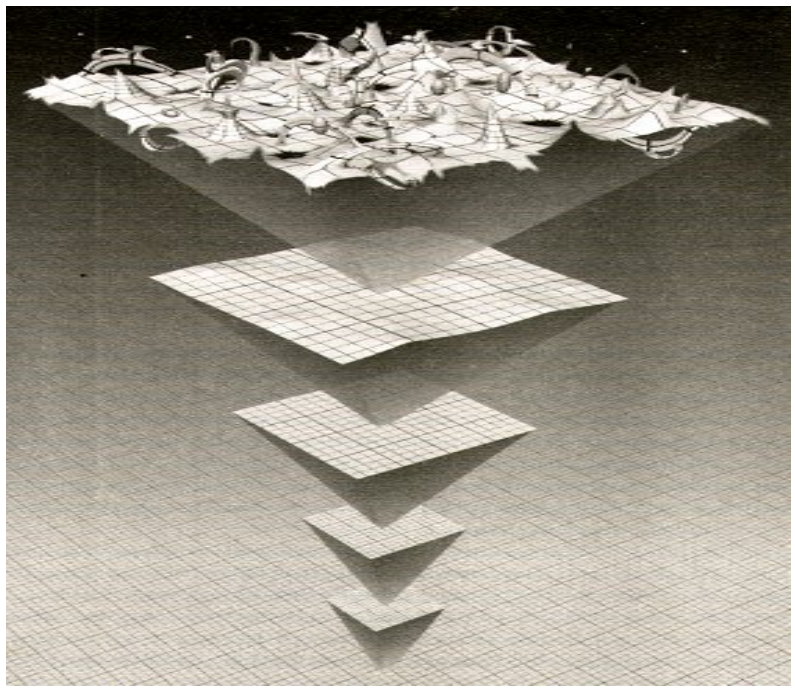
Planck scale

- Once we try to have a quantum theory of gravitation we run into big trouble
- Why? Quantum theory pertains to very small lengths and (consequently!) large energies. Usual notion of space and time breaks down

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616252(81) \times 10^{-35} \text{ meters}$$

Physics at Planck scale

- “Wild West”
- Conventional notions break down!



Most importantly …

Planck energy

$$E_p = \sqrt{\frac{\hbar c^5}{G}} \approx$$ 1000000000000000000 Gev!

At this energy scale, the three forces of the Standard Model should unify with gravity in a quantum theory of everything!

Except this energy is completely out of reach of any experimental regime in particle accelerators!

Actually, even at “smaller energies”…

We have a problem! Electroweak unification (80 Gev, Salam-Weinberg model) predicts a Higgs boson which we are yet to see…

Implicit credo of “effective theory”

- QCD: 0.8 Gev
- Weinberg-Salam SU(2) x U(1): 80 Gev
- GUT: 10^16 Gev
- With gravity: 10^19 Gev

We have experimental verification of QCD, almost all of Weinberg-Salams (sans higgs). A consequence of SU(5) GUT is proton decay (in Kollar!)- Not there!

Effective theory

Simple idea: to study fluid mechanics, we need not worry about atomic structure!

Extrapolation: we should not worry about what happens at 10^19 Gev to get “low-energy physics”

[Technical note: problems with the running of coupling constanst, renormalization group flow]

Effective theory works!

- Almost all of contemporary physics is based on that!
- We can worry about electricity without understanding the detailed structure of leptons.

We do not know why this effective description of the universe holds so well up to the Planck scale and breaks down there!

There is something special about gravity!

- Trying to get a quantum theory naively breaks down! The numbers are infinite!
- Gravity may fundamentally be a classical theory: no gravitational waves seen so far, for example!
- The theory gets very subtle at energy close to GUT 10^16 Gev range! Technical: renormalization group!

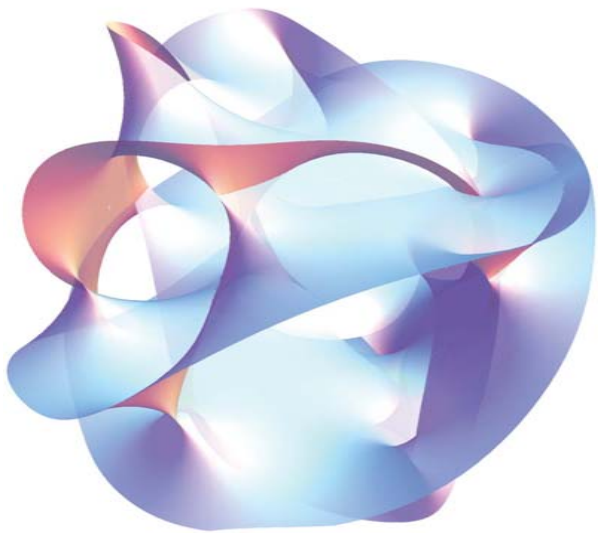
Dilemma

- Should we then, in absence of direct experimental evidence for a quantum theory of gravity, declare physics > 10^19 Gev not science?
- Falsifiability gets out of the window but in a more subtle way.

This is where philosophy steps in!

Strings

- TOE: all matter closed loops on Planck length, vibrations of these loops give all forces and interactions.
- Works only in 10 dimensions! 6 compactified into Calabi-Yau spaces, not directly accessible.



Supersymmetry

For any superstring approach to work, we need an additional kind of symmetry

Supersymmetry!

SUSY posits very particle should have a superpartner

Squarks, selectrons, swhatever [Smolin ☺]

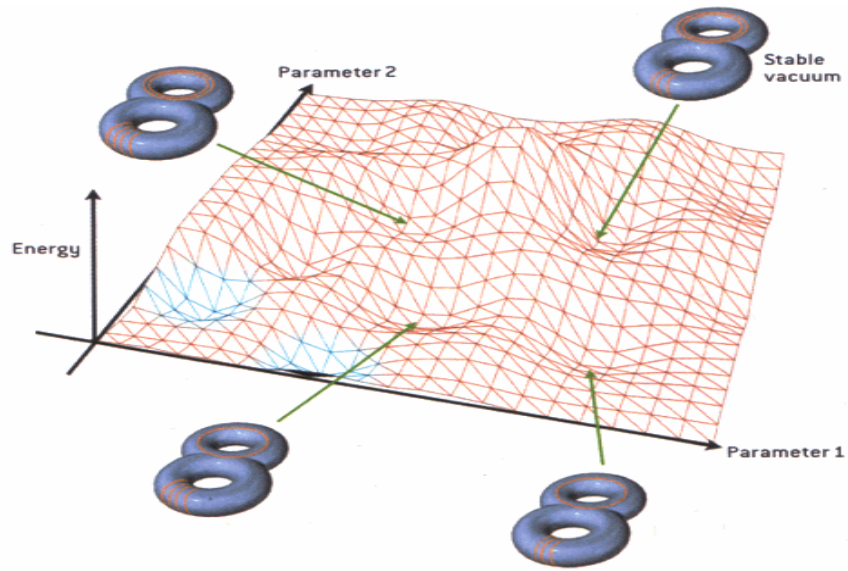
Unfortunately …

- No evidence for that as well!
- On the other hand, very beautiful mathematics unexpectedly connecting to very very deep problems in pure math.

Not clear what do believe in !

Strings Landscape

- Now we know there are almost infinitely many solutions to superstring theory
- Landscape of theories (like Evolutionary Biology)



"The Landscape" (Picture from *Scientific American*)

Where are we on the landscape?

- Anthropic principle! Choose those values of the parameter which makes complex life possible.
- Surprisingly, this really isolates parts of the landscape out (Polchinski, Susskind, Bousso, Douglas)
- But is it science?

More on the anthropic principle

- Need to account for the values of fundamental constants in any final theory of physics
- 17 free constants in the Standard model
- ~100 in a supersymmetric version
- Values of G or c or Planck's constant have to be very fine-tuned to get life as we know it!

Why these values and not others? Problem becomes more acute in string theory! Fundamental theoretical reasons?

One argument

- Our living in a landscape confirms the very “specialness” of life
- Final proof from string landscape of no God!

"...may explain how the constants of nature that we observe can take values suitable for life without being fine-tuned by a benevolent creator." Weinberg

No falsifiability!

- Pseudoscience or just a bad hiatus?
- Lots of press to the issue, people fairly emotional about it.
- Should we radically rethink what science is, or just get rid of string theory?

Pros and cons

- There is no evidence for any physics (stringy or otherwise) at Planck length.
- On the other hand, there is something called the Planck length, it would be too ad-hoc to imagine the universe just starting at 10^16 Gev length scales ☺
- String theory relates very deeply to almost all problems in pure math independently. This can not be an accident!

Alternatives (technical)

- It may just be that gravity is not a quantum theory and just have a standard model minimally coupled to the GR action!
- Beautiful recent results of Dixon-Zvi Bern on N=8 SUGRA finiteness

Devil's advocate

We may have finally reached what can be known about the universe!

Let's hope not!