The Going Gets Weird

Creation of the Universe

Relying on Theory Now

- We have a consistent picture of history of the universe back to the start of inflation
  - Assumed to occur around $k_B T = 10^{16}$ GeV, $t \sim 10^{-39}$ s
- This is also the scale at which grand unified theories (GUTs) become relevant
- We have unified three of the forces: Strong, Electromagnetic, and Weak
- Any signature of times before this gets wiped out due to inflation
  - All particle densities get reduced to near zero
  - Any curvature gets inflated away
  - Any inhomogeneities disappear due to inflation
- We are relying completely on theory

Outline of History of Universe

Time	T or $k_B T$	Events
10^{-43} s	10^{18} GeV	Planck Era; time becomes meaningless?
10^{-39} s	10^{16} GeV	Inflation begins; forces unified
10^{-35} s	10^{15} GeV	Inflation ends; reheating; forces separate; baryosynthesis (?)
10^{-13} s	1500 GeV	Supersymmetry breaking, LSP (dark matter)
10^{-11} s	160 GeV	Electroweak symmetry breaking
14 μs	150 MeV	Quark Confinement
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.7 MeV	Neutron/Proton freezeout
20 s	170 keV	Electron/Positron annihilation
200 s	80 keV	Nucleosynthesis
57 ky	0.76 eV	Matter-Radiation equality
370 ky	0.26 eV	Recombination
600 My	30 K	First Structure/First Stars
13.8 Gy	2.725 K	Today

Quantum Gravity

- Straightforward attempts to include gravity in with the other theories are largely unsuccessful
  - Standard approaches are perturbative
  - Gravity appears to be inherently non-perturbative

- At low energies, gravitational forces between objects are completely irrelevant compared to other forces
  - Upcoming homework problem
- But as the energies get very large, gravity becomes stronger
  - Same homework problem

- Around 10^{18} GeV, the gravitational coupling becomes "strong"
- At this point, if not before, we need a quantum theory of gravity
  - The Planck Era

- A quantum theory of gravity would have quantum effects that influence the particles in spacetime, but also the very structure of spacetime itself
- Sometimes, our words to describe things start to break down

Some Ideas for Quantum Gravity

- We have two theories that seem to incorporate quantum mechanics and gravity consistently

- *String theory*, now sometimes called *M theory*, says that all particles are actually tiny loops of a single fundamental string
  - Different particles correspond to different vibration modes on the strings
- Only works in ten spacetime dimensions
  - Not necessarily a problem, in that extra dimensions could be “compactified,” curled up into a tiny ball

- *Loop quantum gravity* is a theory where there is no space or time, just “events” with no definite separation
- Time steps shorter than the Planck scale are meaningless
- The dimensionality of spacetime must somehow arise spontaneously from these fundamental interactions

- At present, neither theory has produced <u>any</u> predictions that can be checked against experiment

The Planck Era

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}}\left(\frac{\text{MeV}}{k_B T}\right)^2$$

- Assume the universe is still radiation dominated
- Substituting the energy 10^{18} GeV, this would be at $t \approx 10^{-43}$ s
- This is only about a factor of 100 in energy above the start of inflation
  - Given the sloppiness of our estimates, there may be little or no gap between the Planck era and inflation
- Some complicated possibilities:
- Whole universe might be inflating, with only little pockets escaping to make universe
- Entire universe might quantum tunnel from nothing
- Time might become meaningless
- Universe may have had a “bounce” at the Big Bang

Chaotic Inflation/Eternal Inflation

- Universe may have begun in inflationary era, everywhere
  - Everything is expanding, very fast, everywhere

- A small pocket manages to escape and start forming a universe
  - We'll have to get slow roll, or something, to make it continue inflating enough
- This pocket grows to make observable universe

- There will be other bubble universes that form
- Different bubbles will not collide – the universe is expanding too fast
- It is quite possible that there is more than one way to escape from inflation
- Different "universes" could have different fundamental constants

- Only a few of them may have intelligence
- The vast majority of the universe is always inflating

The String Landscape:

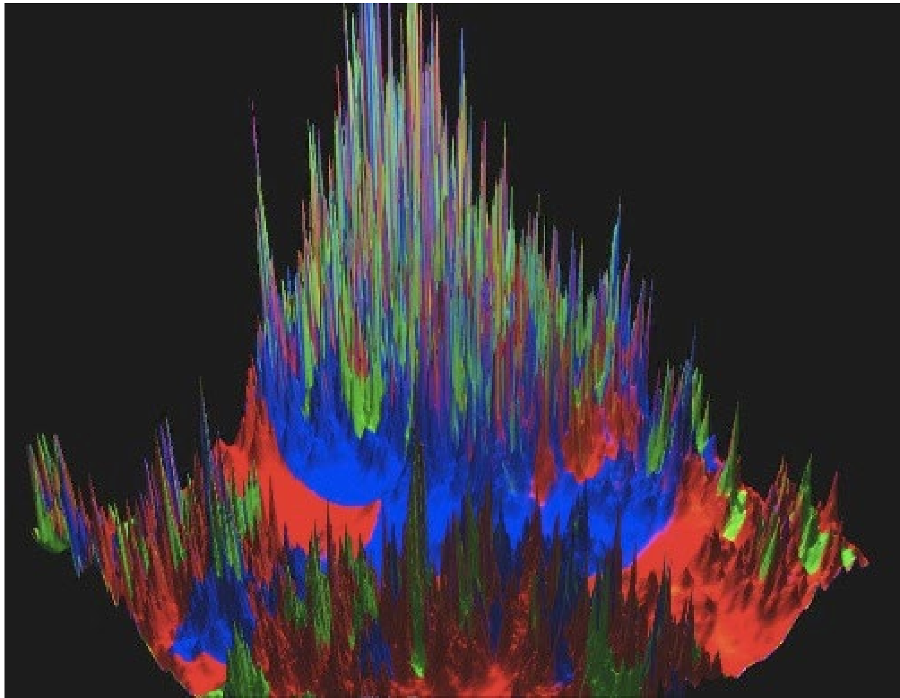
- String theory is *incredibly* complex
    - No one understands it

- Just like in the electroweak theory, the minimum (the vacuum) can be non-trivial

- However, the potentials (which determine those minima) are effectively infinite dimensional

- The number of minima – which determines the apparent laws of physics – is very, very large
    - The “String Landscape”

- There may be many, many minima
    - Many possible universes with apparently different laws of physics
    - Some estimates give ~ 10^{100} to 10^{1000} possibilities



The Ultimate Free Lunch

- Around the time of the Planck Era, particles have energies around $E = 3k_B T = 3\times 10^{18}\ \text{GeV}$
- The age of the universe is 10^{-43} s
- Multiplying these numbers, we have $Et = \left(3\times 10^{18}\ \text{GeV}\right)\left(10^{-43}\ \text{s}\right) \approx 0.46\hbar$
- According to quantum mechanics, you can violate conservation of energy, provided $\left(\Delta E\right)\left(\Delta t\right) < \frac{1}{2}\hbar$
- You can create these particles out of nothing!
- It is quite possible that we can create the whole universe out of nothing!
- Even spacetime itself is created
- There isn't even spacetime before the big bang; there's no space or time

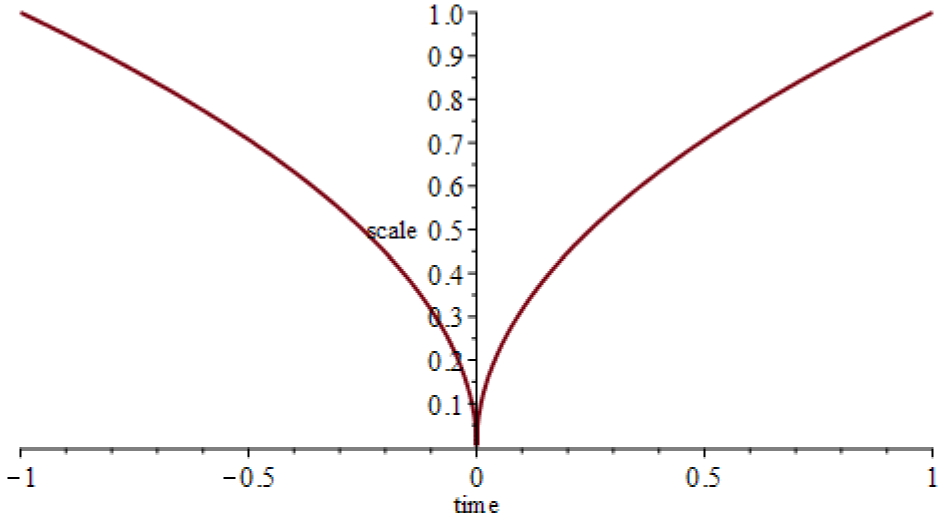
Quantum Uncertainty in Time?

- Under ordinary circumstances, events in time are pretty clearly ordered
  - Big Bang BEFORE Revolutionary War BEFORE Civil War BEFORE now

- In a quantum theory of gravity, spacetime should itself have random fluctuations on the Planck scale
  - Quantum foam structure of spacetime
  - Which events happen ambiguous on scale of 10^{-43} s

- It therefore becomes meaningless on this scale to say which event caused which event
  - The universe could cause itself to come into existence

Big Bang or Big Bounce?



- One possibility that has been discussed extensively is that there was another era of the universe where it was collapsing before the big bang.
- This theory is called the Big Bounce
- As demonstrated by Hawking, this is inconsistent with Einstein's General Theory of Relativity
- But not necessarily inconsistent with quantum gravity
- In particular, this seems to be the current prediction of Loop Quantum Gravity
- I don't know (and not sure if anyone does) if the previous half of the universe represents a time-reversed universe, where entropy increase backwards, or a more conventional universe where entropy increases forwards

For This May We Be Truly Thankful. . .

Is the Universe Fine Tuned for Intelligence?

- The universe we see around us *should* be explainable in terms of just a few things
- The standard model of particle physics predicts how particles interact with each other
- These include 18 apparently arbitrary parameters
  - Lepton masses, quark masses, fundamental couplings, mixings
- In addition, there are some things in particle physics we don't know
  - Neutrino masses and mixings
- There also various cosmological inputs that we don't understand
  - Initial density, cosmological constant, etc.
- Some of these surprisingly favorable to life
  - Luck? Design?

Some Spurious Issues …

- Many authors have pointed out how fortunate the Earth is that it allows life to exist

- Low mass stars produce deadly flares that could destroy life
- High mass stars live too short a time for life to evolve
- The Sun is just the right size

- Stars near the center of galaxies have too many unhealthy supernovae nearby
- Stars near the edge have too few "metals" to make life – probably
- The Sun is in just the right zone

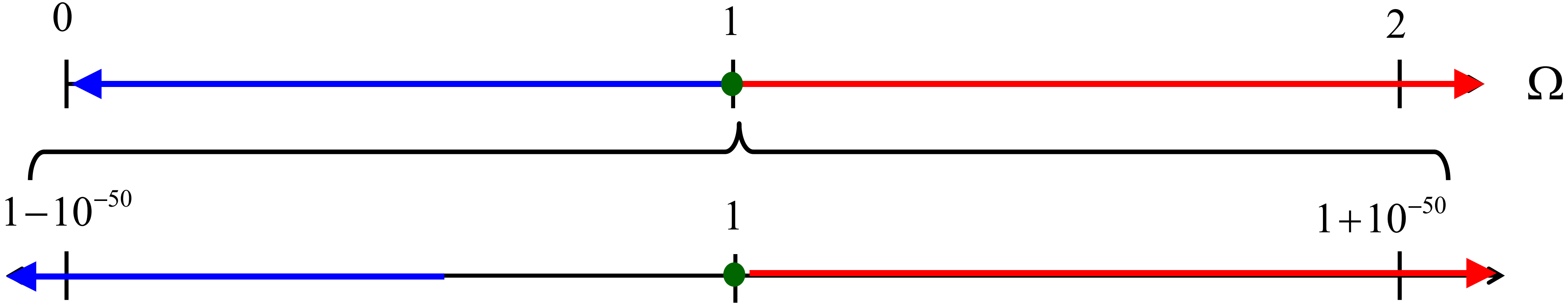
- Many stars have planets in eccentric orbits
    - Alternately cold and hot
- We got lucky – fairly stable circular orbits

- With 10^{12} stars in each of 10^{15} galaxies in the known universe, it is not surprising we occasionally get lucky
    - The chance that you win the lottery is small
    - The chance that *someone* wins the lottery is large
- Only those that win the intelligent life lottery question how they got so lucky

The Value of Ω

- We previously found that the value of Ω at the time of the GUT scale is close to 1
- What would have happened if this were not the case?
- If $\Omega_{GUT} > 1 + 10^{-52}$, universe would reach peak size and then recollapse to a point
- If $\Omega_{GUT} < 1 - 5\times10^{-51}$, then universe would grow too diffuse for structure to form
- But our value is just right

$$\Omega_{GUT} = 1 + \left(-3 \pm 18\right)\times 10^{-56}$$



Should We Take This Coincidence Seriously?

- We need: $-5\times10^{-51} < \Omega_{\text{GUT}} - 1 < 10^{-52}$
- We have: $\Omega_{\text{GUT}} - 1 = \left(-3 \pm 18\right)\times10^{-55}$

- This is far better tuned than we need to produce intelligent life
  - Suggests that *something* caused this to happen
  - I am *not* suggesting that this agent is necessarily intentional

- Indeed, we have a theory that naturally *predicts* this result
  - Inflation
  - And other theories I don't know as much about

- Odds are the flatness of the universe is *not* a lucky coincidence

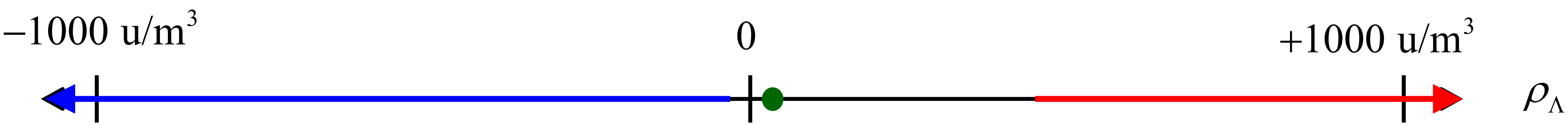
The Value of ρ_Λ

- The mass density of empty space ρ_Λ is technically a subject for particle physics
- This number could be any number between $-\infty$ and $+\infty$

- If $\rho_\Lambda > +500$ u/m^3, the universe would begin exponential growth before structure formation

- If $\rho_\Lambda < -2$ u/m^3, universe reaches maximum size and then collapses before now

- Actual value is $\rho_\Lambda = 3.4$ u/m^3



- We have no idea what the value of ρ_Λ "should be"

- Therefore it's hard to tell how "lucky" this is

What Can Particle Physics Predict for ρ_Λ? (1)

- Recall, for example, the formula for the energy density of the electromagnetic radiation

$$u = 2\int_0^\infty \frac{4\pi k^2 dk}{(2\pi)^3}\hbar\omega n_k$$

- The factor $n_{\mathbf{k}}$ is the number of photons in the state with wave number **k**

- Though it's not obvious, each photon state is really a harmonic oscillator
- The states for the harmonic oscillator have energy

$$E = \hbar\omega\left(n + \tfrac{1}{2}\right)$$

- We have missed the ½ term
  - Normally ignored, since the zero of energy is irrelevant
  - But not irrelevant when considering gravity

- There is a contribution to the energy that exists even for empty space
  - Zero point energy

$$u = 2\int_0^\infty \frac{4\pi k^2 dk}{8\pi^3}\tfrac{1}{2}\hbar\omega$$

- This leads to a contribution to the mass density in empty space

$$\rho_{\Lambda\gamma} = \frac{1}{c^2}\int_0^\infty \frac{k^2 dk}{2\pi^2}\hbar\omega = \frac{\hbar}{2\pi^2 c}\int_0^\infty k^3 dk$$

What Can Particle Physics Predict for ρ_Λ? (2)

- This integral diverges, yielding infinity $$\rho_{\Lambda\gamma} = \frac{\hbar}{2\pi^2 c}\int_0^\infty k^3\,dk$$
- However, this assumes that the physics we understand works up to $E = \infty$
- We expect, at most, this to work up to the scale where we expect quantum gravity to cut in, the *Planck Energy*: $$E_P \approx 10^{19}\ \text{GeV}$$ $$k_P = \frac{E_P}{\hbar c}$$
- So let's put in a corresponding cutoff in the scale:

$$\rho_{\Lambda\gamma} = \frac{\hbar}{2\pi^2 c}\int_0^{E_P/\hbar c} k^3\,dk = \frac{\hbar}{8\pi^2 c}k^4\Big|_0^{E_P/\hbar c} = \frac{E_P^4}{8\pi^2\hbar^3 c^5} = 3.93\times 10^{121}\ \text{u/m}^3$$

- There are also contributions from other particles, and, in principle, an arbitrary constant $$\rho_\Lambda = \rho_{\Lambda\gamma} + \rho_{\Lambda x} + \rho_{\Lambda 0}$$
- These other terms are in most cases unknown and may be of either sign

How Lucky Are We on ρ_Λ?

$$\rho_\Lambda = \left(3.93\times 10^{121}\ \mathrm{u/m^3}\right) + \rho_{\Lambda x} + \rho_{\Lambda 0}$$

- Actual value is: $\rho_\Lambda = 3.4\ \mathrm{u/m^3}$
- To make things work, we need $-2\ \mathrm{u/m^3} < \rho_\Lambda < 500\ \mathrm{u/m^3}$
  - Smaller values generally work better
- Looks like we got lucky by about a factor of about 10^{120}
  - Like winning the lottery every day for three weeks
- Had the number been zero, it would be reasonable to imagine that it came about because of something *forcing* it to be zero
  - Much as inflation explains why the universe is nearly flat
- But there *may* be logical reasons why it is so small*
- Many ideas have been proposed; most are, at present, untestable

*Eric D. Carlson and W. Daniel Garretson, "Could there be Something Rather than Nothing?", *Phys. Lett.* **B315**, 232 (1993).

The Neutron-Proton Mass Difference

- The proton and neutron are very close in mass
- Suppose the neutron masses had been a little different?

$$m_n = 939.57\ \text{MeV}/c^2$$

$$m_p = 938.27\ \text{MeV}/c^2$$

$$m_e = 0.51\ \text{MeV}\ /\ c^2$$

- If the neutron mass were 0.79 MeV lower, then we would have $m_p + m_e > m_n$
- Hydrogen atoms would be unstable

$$p^+ + e^- \rightarrow n^0 + \nu$$

- After recombination, all the protons would disappear
- Stars, planets, etc., as we know them would not exist

- If the neutron mass were 1.44 MeV higher, then deuterium would be unstable

$$^2H \rightarrow p^+ + p^+ + e^- + \overline{\nu}$$

- Deuterium would not form in stars
- Nuclear fusion would not proceed

- Once again, it looks like we got lucky
- About 1 part in 1000 lucky

What Causes the Neutron-Proton Mass Difference?

- We now know protons and neutrons are actually made of quarks
- About 98% of the mass/energy of these particles comes from strong interactions
  - The same for protons and neutrons
- The remaining 2% comes from a combination of
- Up quark (~5 MeV) and down quark (~10 MeV) mass
- Electrostatic interactions
  - Favors the neutral neutron by about 4 MeV
- So, in round numbers, our neutron and proton masses are about

$$m_n = 939.57 \text{ MeV}/c^2$$

$$m_p = 938.27 \text{ MeV}/c^2$$

$$m_e = 0.51 \text{ MeV} / c^2$$

$$p^+ = [uud]$$

$$n^0 = [udd]$$

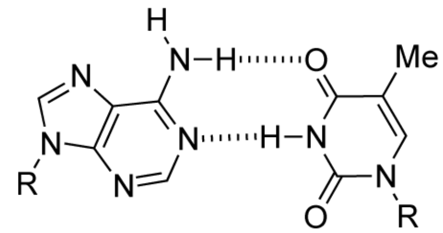
$$m_n c^2 \approx (918-4)\text{MeV} + 2m_d + m_u$$

$$m_p c^2 = (918+0) \text{ MeV} + m_d + 2m_u$$

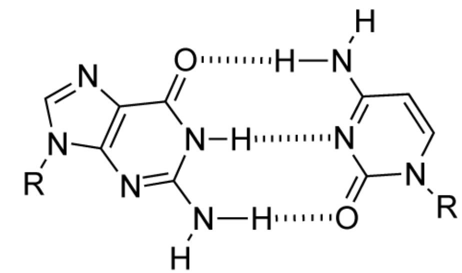
- Hence the real question is why down minus up is between 4 and 6 MeV
  - And now it doesn't look so ridiculously lucky

The Importance of Carbon to Life

- Many elements are critical to life as we know it
- All life depends *critically* on H, C, N, O, S, P
  - And probably others



A·T base pair



G·C base pair

- Hydrogen was produced in the big bang
- Carbon is produced in stars
- All other elements are made out of carbon
- Almost all complex chemicals contain carbon as a backbone element
  - Probably because of its four covalent bonds
- Not only is carbon critical to life on Earth, it is probably critical to almost any conceivable chemistry-based life

The Triple-α Reaction is Hard

- Carbon is produced by the Triple-α interaction
- Step 1 produces unstable ^{8}Be
- Step 2 produces ^{12}C

$$^{4}\text{He} + {}^{4}\text{He} + \text{ 91.8 keV} \rightarrow {}^{8}\text{Be}$$

$$^{4}\text{He} + {}^{8}\text{Be} \rightarrow {}^{12}\text{C} + \gamma\left(7.367 \text{ MeV}\right)$$

- The first step would be very difficult to do, except we are at high temperatures
  - $T \sim 2\times10^{8}$ K corresponds to $k_B T = 17.2$ keV
- Only the tininess of the energy required makes this conceivable
  - Normal nuclear interactions would involve several MeV of energy

- The second step *should* be heavily suppressed, because making the photon makes it difficult
- Based on the fact that ^{12}C was produced in stars, Fred Hoyle predicted there must be an intermediate excited state with the correct energy
- It was shortly thereafter discovered

$$E\left({}^{12}\text{C}^{*}\right) - E\left({}^{12}\text{C}\right) = 7.65 \text{ MeV}$$

- This double coincidence allows carbon to be formed
- And hence life to exist

How Coincidental Is It?

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} + 91.8\ \mathrm{keV} \rightarrow {}^{8}\mathrm{Be}$$

$$^{4}\mathrm{He} + {}^{8}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \gamma\left(7.367\ \mathrm{MeV}\right)$$

$$E\left({}^{12}\mathrm{C}^{*}\right) - E\left({}^{12}\mathrm{C}\right) = 7.65\ \mathrm{MeV}$$

- Is it such a big coincidence that ^{8}Be is barely unstable?
- Not surprising that it’s kind of close – after all ^{8}Be is mostly just a bound state of two ^{4}He
- Is it such a big coincidence that there is a resonance near the right energy for ^{12}C?
- This is hard to figure out, so we don’t really know how to calculate the resonance energy
- But there are *several* other resonances, so we have several chances for a coincidence
- And the match is only 5% or so
    - Only a little lucky

Cosmic Philosophy

Is the Universe Fine Tuned for Intelligence?

- We have several apparent coincidences:

- Omega started ridiculously close to 1
  - Can be explained by inflation or other theories
- The density of empty space is very low
  - Not well explained, but there are some potential explanations
- The neutron/proton mass difference is right in the correct range
  - When you understand quarks, this is less coincidental than it appears
- The triple-alpha reaction seems to have two coincidences that make it work
  - Unclear how much of a coincidence this is

- There are others I don't know as much about …
- Some of them we can already partly explain in terms of known physics
- Others we have potential explanations, but we don't know if they are right

What Remains to be Explained?

Things we've resolved:

- Why the universe has the fraction of hydrogen/helium, etc. we see
- The nature of the cosmological background radiation
- How all the structure in the universe formed from initial perturbations

Things we've got good guesses on:

- Where the dark matter came from
- Why $\Omega = 1$
- Why the universe is nearly uniform
- The likely causes of initial perturbations
- Why there's more matter than anti-matter in the universe

Things we don't really know:

- Where the universe came from
- Why the vacuum energy density is so low
- Why the various particle physics parameters are what they are

The Best of All Possible Worlds?

- If some of the parameters were very different than they are, then **life as we know it** would be impossible

- But for *some* of the parameters, some other type of intelligence might be possible

- For example, if parameters were different, maybe we could make ^{12}C in primordial nucleosynthesis
  - Don't need to make it in stars

- The real question is, if we change these parameters a lot, would intelligence still form?

- Answering this would require redoing all of physics (and chemistry, and biology) *from scratch*

- We are not currently capable of doing it

- Bottom line – for *many* of the parameters, we can't tell if they are fine tuned for life

Are These Variables Truly Variable?

- If there is truly *one* simple theory with no or few adjustable parameters, then it may be that the "coincidences" are inevitable
- As if math is fine tuned for life
- Until we have such a theory, we really can't say how coincidental these things are

The Anthropic Principle

- Science involves repeatable experiments
  - Other sciences, even history, can in principle be subject to verifiable predictions
- In the case of the universe as a whole, we only get *one* experiment to see if it produced intelligent life
  - We already know the answer
- And if it *didn't* produce life, we wouldn't even be asking the question

- Some philosophers suggest we should follow the *anthropic principle:*
  - "The anthropic principle is a philosophical consideration that observations of the Universe must be compatible with the conscious and sapient life that observes it."

Multiple Universes

- What do we mean by multiple Universes?
  - The *Universe* is the totality of existence that we are aware of or can be aware of us
  - If there are places that are real, but we can't see them, they are other Universes

Reasons to believe in multiple universes with different physical constants

- Chaotic/eternal inflation
  - Different portions of the universe may look very different

- Spontaneous appearance of multiple universe
  - If our universe came from nothing, why not others?

- Many Worlds Interpretation of quantum mechanics
  - If correct, then everything happens

Multiple Universes and the Anthropic Principle

- According to inflation, the universe is *much* bigger than the portion we can see
  - The number of stars could be much bigger then the known 10^{27} stars
- If life is super-rare, it doesn't matter, it's still inevitable

- In some pictures of inflation, there are a large or infinite number of "bubble universes" that escape from inflation
- The apparent laws of physics could be very different in each of them
- Recall that in string theory, for example, the number of possibilities could be huge
  - 10^{100} to 10^{1000} might be typical possibilities

- So intelligence might actually be very rare
- But only in those universes where there are intelligences do we wonder why the universe is fine-tuned for intelligence

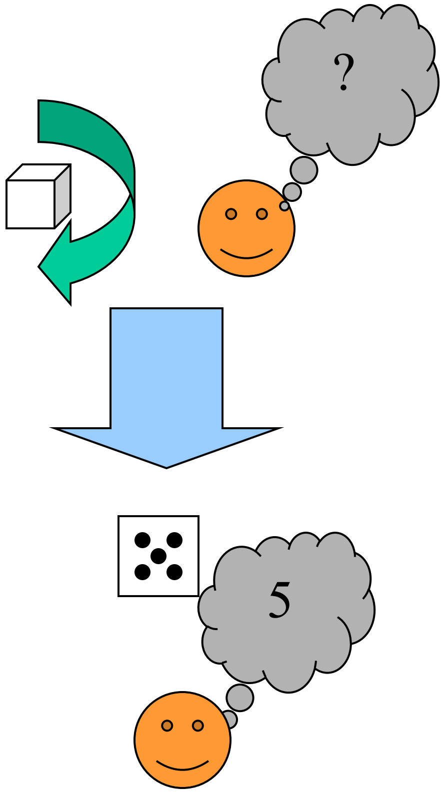
- In this view, there is no surprise
  - Only universes where intelligence is possible are worthy of consideration

Spontaneous Creation of the Universe

- It is possible that the universe we see was created from nothing
  - Indeed, this seems likely
- If it happened once, it could happen again
  - The universes would not in any sense be connected, so they don't even have a time ordering
- No particular reason that the different universes would have the same physical constants

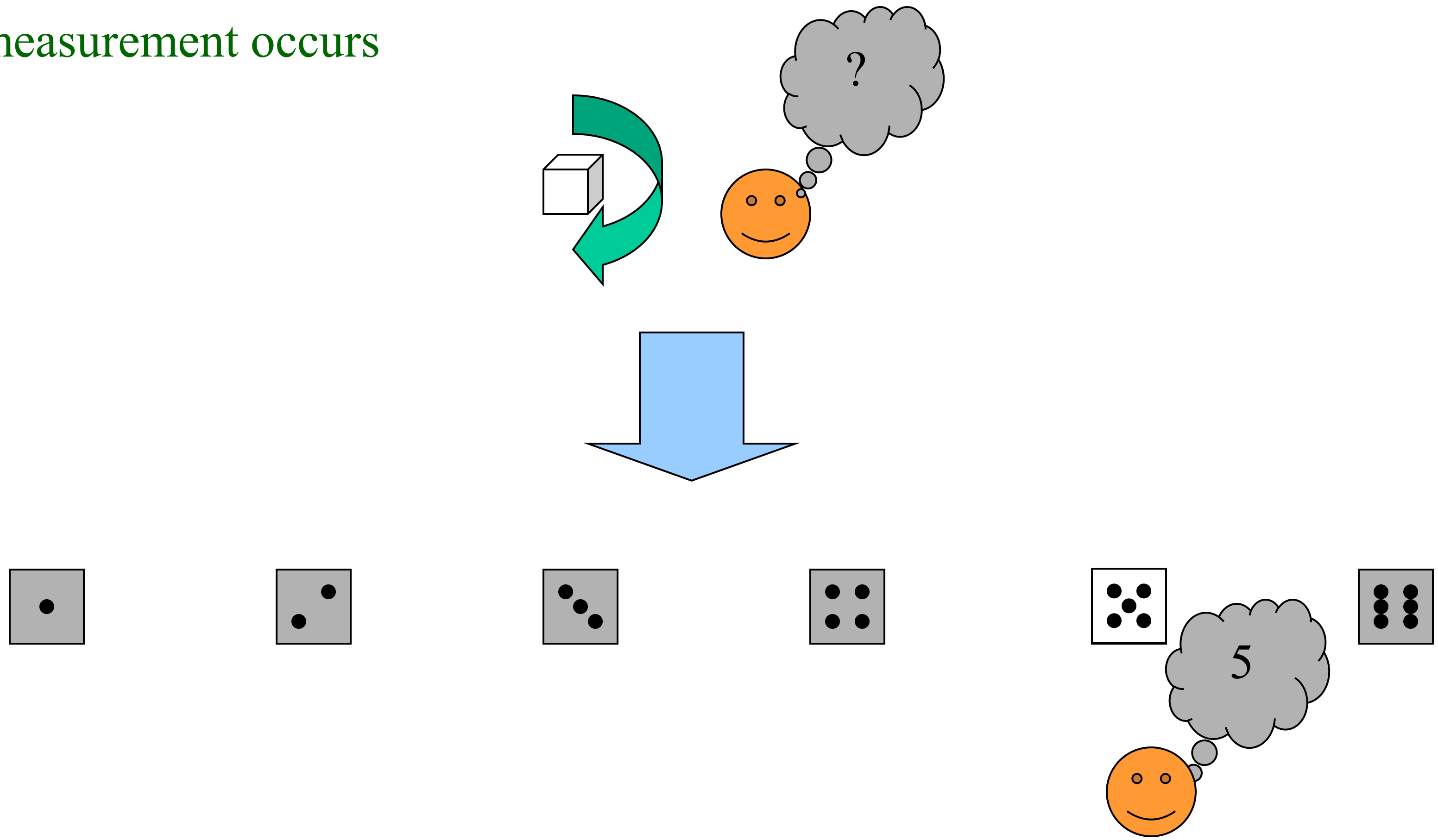
Quantum Mechanics and Probability

- In the everyday world, we think of probability as expressing our ignorance



Copenhagen Interpretation of Q. M.

- Some processes are inherently quantum uncertain
- All possibilities actually occur
- Until a measurement occurs

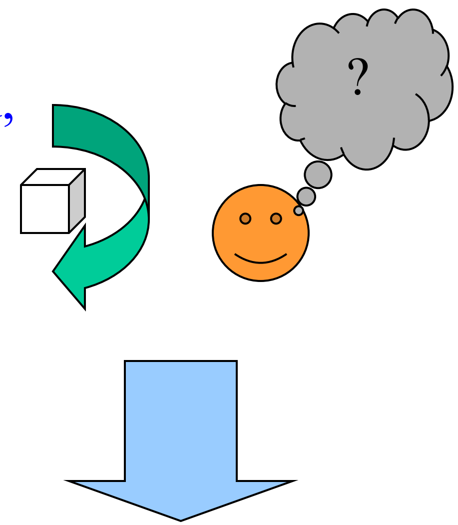


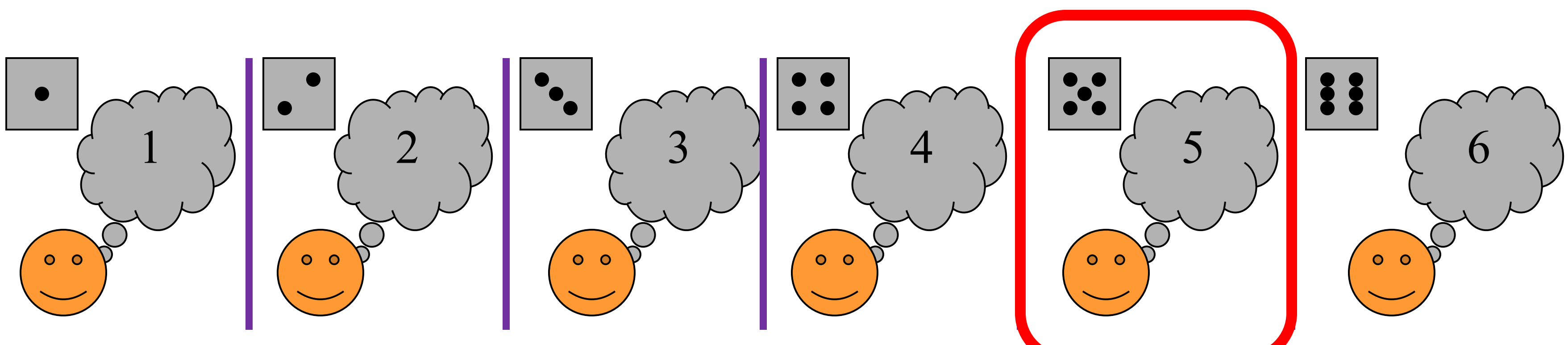
Many Worlds Interpretation of Q. M.

- All possibilities actually occur
- Even after a measurement occurs

- In many cases, the different possibilities become so disconnected, they effectively become separated universes

- We are only cognizant of one



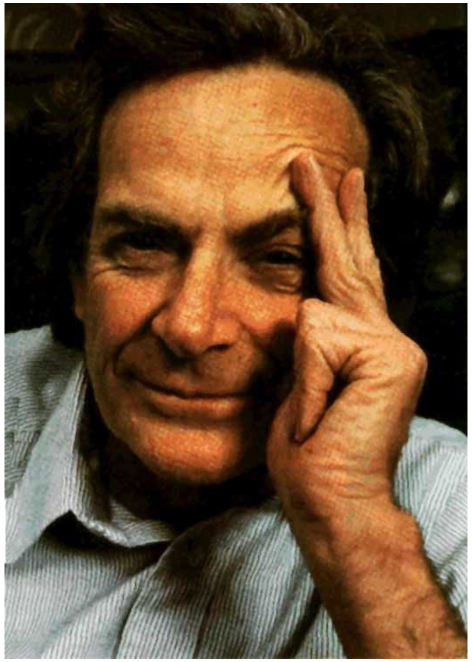


Do People Take This Seriously?

- Many famous physicists, and a lot of obscure ones, believe in the Many Worlds Interpretation

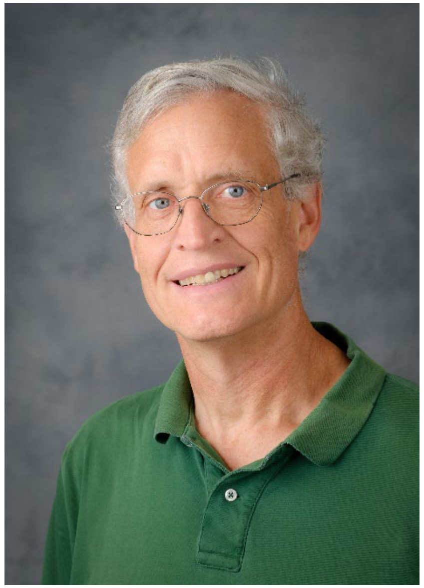
Stephen Hawking

Murray Gell-Mann



Richard Feynman

Steven Weinberg



World Expert on 11/11/11