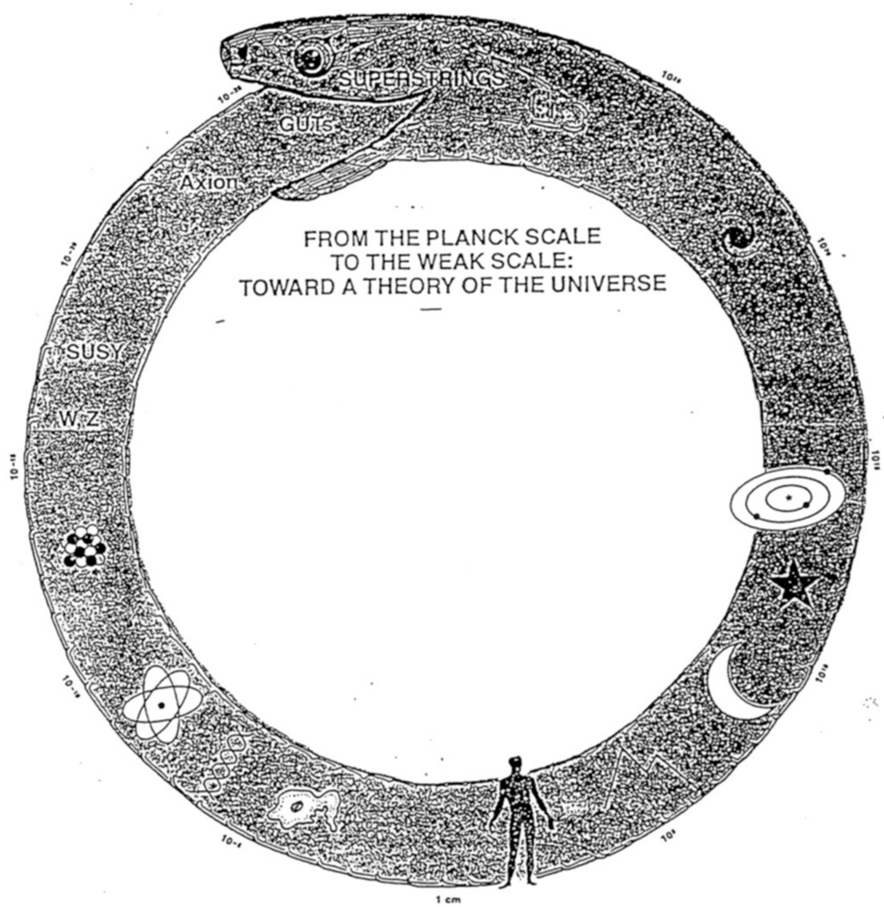
Frontiers of the small and large

- There are, of course, many major and interesting problems in modern physics. Any selection is necessarily biased. Here we will focus mainly on issues in particle physics and in cosmology.
- You can see my bias: these are the fields that extrapolate furthest from the human scale. Thus, they are farthest removed from daily human experience.
- Perhaps they are where we may have the most to learn, where the laws of physics might be most surprising (eg, quantum mechanics, and GR).
- Following the principles of reductionism and holism, they aspire to the realm of "fundamental".



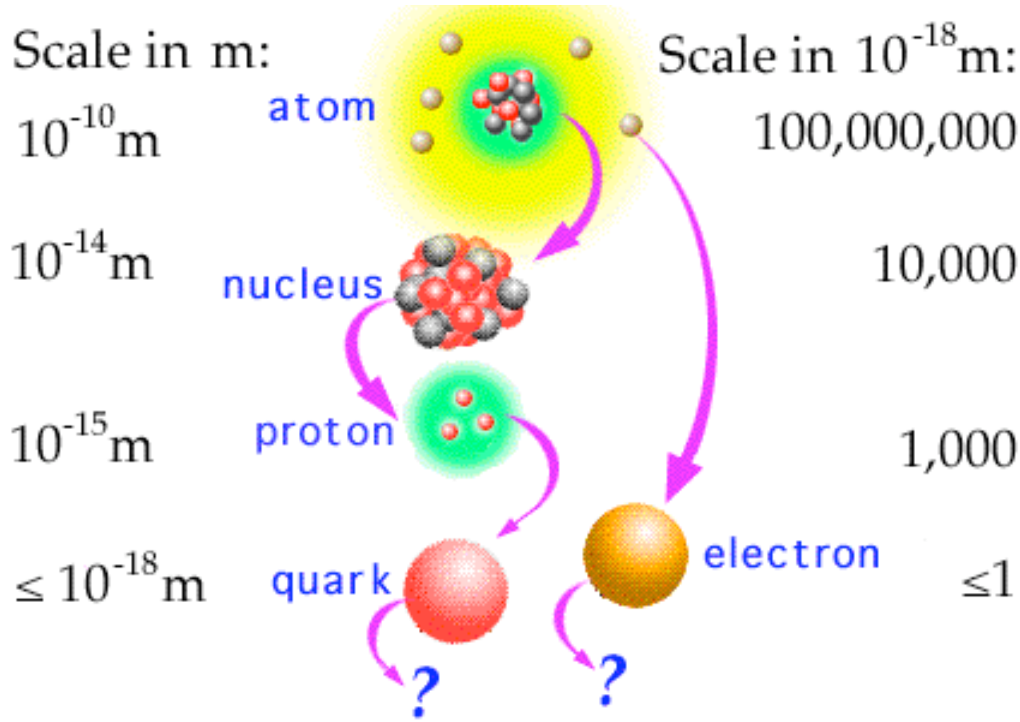
The Oroborus of Physics

Why put such a huge amount of time, money and effort into the LHC?

- That's the question this course will address.
  - the Standard Model
  - the origin of mass
  - beyond the SM: SUSY, dark matter, CP violation, unification, extra dimensions, …
- But first, step back for a little philosophy…

Philosophy

- Physics is the study of
  matter, energy, space and time,
  at a predictive level
- The structure of matter is built of ever-smaller stuff – substructure – the layers of the onion
- This “reductionistic” world view is, of course, suspect; but it has been spectacularly successful in the last century.
- the layers of substructure can be studied in the laboratory, to the limits of our ability to sense and measure; this has been the history of particle physics.

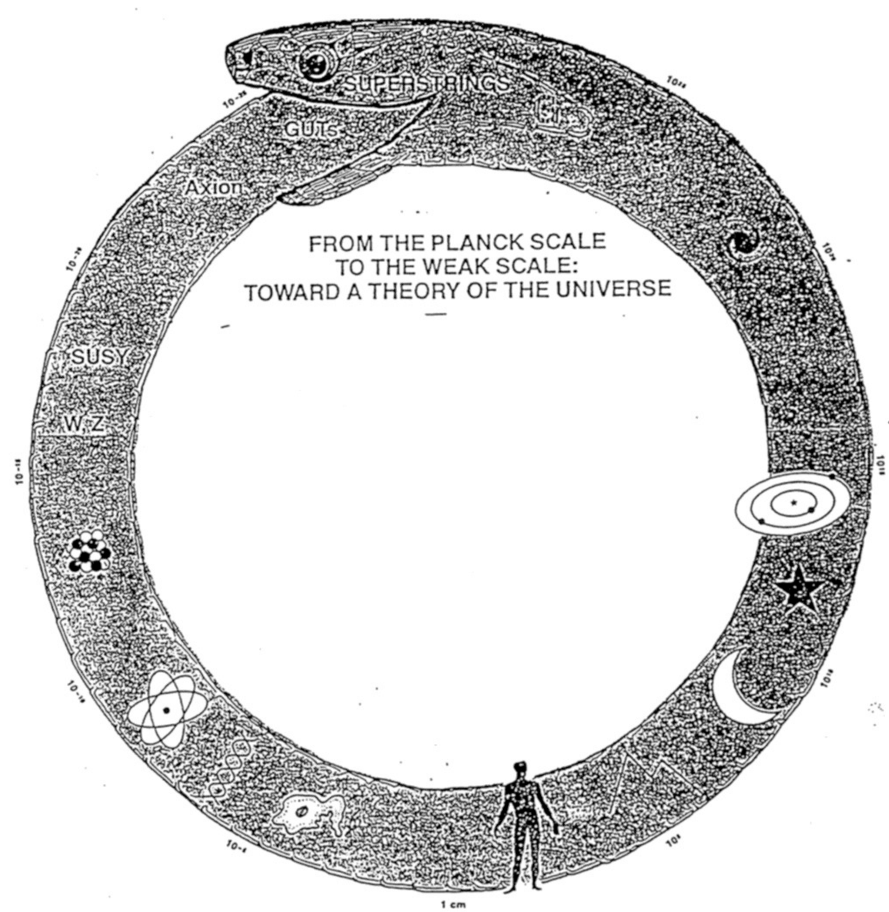


• Taken to its limit, a layer whose substructure cannot be detected (how can we know?) is “elementary”, with properties and “geometry” (pointlike, strings?) which can be completely described (complete in the sense of quantum mechanics).

• Then we say (repeat after me) “In principle, every thing in the universe can be described in terms of its elementary constituents.”

In principle

- Of course, that's a big "In principle". But so far, it's been incredibly successful.
- Both small (solids → molecules → atoms → nuclei → quarks) and big physical systems (stars, galaxies, cosmology) can be well described.
- These systems aren't too complex (unlike you and me).
- The physics of complex systems will be a big field in the 21st century!
- But of course, we can't be sure that everything in between is completely explainable, "in principle", by science…
- "The most incomprehensible thing about nature is that it is comprehensible"
  - A. Einstein



The oroborus of physics

The Mathematical basis of fundamental physics

- Physics is mathematical, and rigorously so. Progress in our understanding is so enormous because of the incredible interplay between detailed experiments and detailed mathematical theory. Nowhere has this been more satisfying than in particle physics and cosmology, where mathematics enables the extrapolation of our understanding to distance scales far removed from direct experience.
- By now, you know how much time you spend learning the math. Sometimes it feels like all the math gets in the way of the physics, but by now you know that it's the only real way to get to the physics.
- We will not be spending much time learning mathematical physics.
- Unfortunately, some of the deepest problems in modern physics are deep into the interplay between experiment/observation and mathematical theory.
- You simply can't understand, for example, the deep problems associated with the Higgs mechanism, without knowing quantum field theory, gauge symmetry, the Standard Model, spontaneous symmetry breaking, grand unification, renormalization…

Dreams of a final theory

- Some believe that the laws of physics will ultimately be found to be the only possible set of laws that are mathematically consistent (maybe also requiring a weak anthropic principle that there be sufficient opportunity for complexity to support observers such as ourselves). Are the laws of physics inevitable (if only in a probabilistic sense) or is this only one of many possible worlds?

The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms.

Fundamental vs emergent

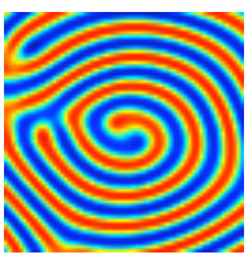
- The paradigm of 20th c. physics has been the success of "reductionism". Figure out the behavior of the simplest parts of a system, and, "in principle", you can understand everything. What you are learning is "fundamental".
- For example, the goal of particle physics is nothing less than finding the "Lagrangian of the universe", from which, "in principle", all phenomena can be derived. Discovering a new term in the Lagrangian, or a new quantum number, is a fundamental discovery.
- We will tour the Lagrangian of the Standard Model, later.
- Of course, this is NOT the whole story. We understand little about the complex phenomena that abounds at the human scale: life, the mind, etc.

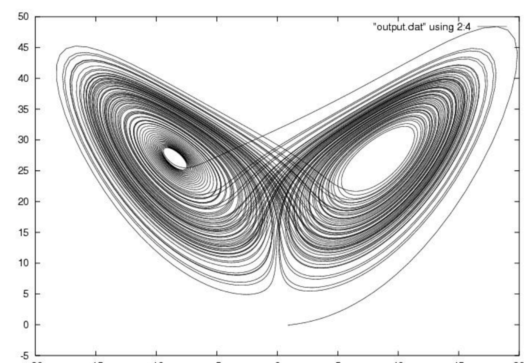
Fundamental vs emergent

- Critics argue that reductionism misses the essential aspects of a whole system, and only a "holistic" approach can give you a clear picture of the nature of a physical system.
- The problem is that the explicitly holistic approach addresses questions that might be "too big", and as a result, science has made precious little progress in deepening our understanding of physical systems with a "holistic" approach.
- It might be said that modern science is (or has become) inherently reductionistic (in addition to being explicitly materialistic, empirical, and objective.
- We also know that many complex phenomena are "emergent": not simply derived from L.
- It is almost impossible to predict such phenomena even when all the fundamental physics of it is understood (eg, pattern formation, the "game of life", self-organized and adaptive systems, self-referential systems ("this statement is wrong"), etc.).
- On the other hand, it may be that some/many "emergent" properties of complex systems are independent of the microphysics of the system or the underlying fundamental theory.
- Condensed matter systems often exhibit complex, emergent phenomena: strongly-coupled systems, superconductivity, phase transitions, criticality, …

Fundamental vs emergent

- Even within particle physics, there is a broad range of “emergent” phenomena that we can’t, or at least don’t know how to, predict, including the spectra of hadrons, the structure of the proton, etc.
- The physics of chaos, Lorenz’ “butterfly effect”, bifurcations, pattern formation, self-organized criticality, etc, are first steps towards a new science of emergent phenomena in complex systems.
- The physics of complexity is likely to bloom and result in major discoveries in the 21st century.
- The problem is, I don’t know much about it, and there will be none of it in this course (except for our discussion of the emergent property “mass”).
- Question: Is Nature simple or complex?





Length scales and energy scales

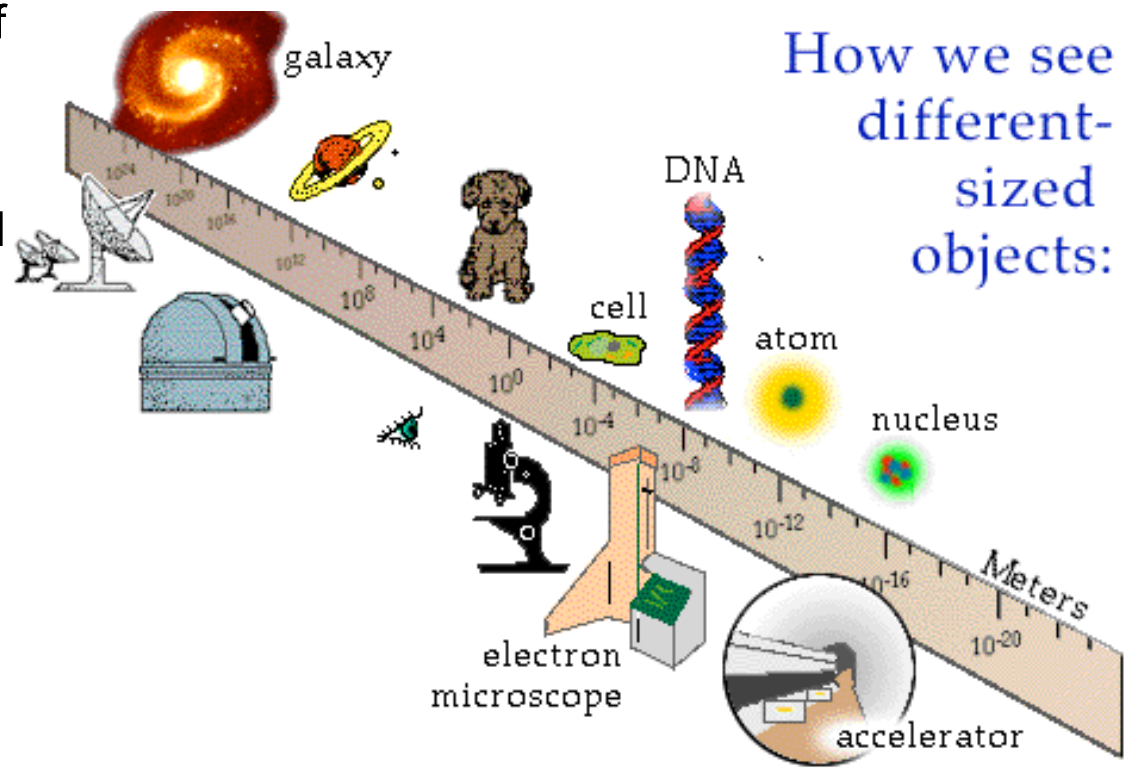
- Physics is about matter, energy, space and time.
- These are all eminently measurable, quantifiable things.
- By now, you are aware of the huge range of these measurable quantities that have been explored in modern physics.

- Distance scales have been explored from the substructure of hadrons from 10^{-16} m to the distance to last scattering 10^{26} m

- The lifetimes of the shortest-lived particles ~ 10^{-26} s, the shortest measurable times 10^{-16} s, the age of the universe ~10^{18} s.

- Cosmic radiation has been observed with energies from 10^{-6} eV to 10^{20} eV

- From the electron mass 9×10^{-31} kg to the baryonic mass of the universe ~10^{51} kg



Length scales and energy scales

- Depending upon the physics you are doing, all these quantities can be related to one another!
  - atomic physics: Planck's constant h relates energy to time. With $\hbar = 1$, time and energy are the same.
  - relativity: c relates time and space, or energy and mass. With c=1, time and space are the same.
  - particle physics: with $\hbar = c = 1$, everything is measured in eV
  - gravitation: G_N relates mass, energy, and distance.
    In GR, everything is geometry, all physical quantities are measured with the same units (distance).
    But by convention, distance is measured in units of solar masses.
- Characteristic length (energy, etc) scales arise naturally in dimensional analysis. Equations in mathematical physics can usually be reduced to expressions involving dimension-ful quantities (defining a characteristic scale), factors of order one (like π), and dimensionless transcendental functions, integrals, etc.
- Important goal for this course: become intimate with the length, time, energy, mass scales associated with the problems we will study on the frontiers.
- What sets the scale for atomic physics? nuclear physics? Hadronic scale? Electroweak scale? GUT scale? At what scale does gravity alone dominate the dynamics of the universe?

Decoupling of Length scales

- Physical phenomena at different length scales do not affect each other and are said to decouple. Why?
- The decoupling of different length scales makes it possible to have a self-consistent theory that only describes the relevant length scales for a given problem.
  - You don’t need to know atomic physics to understand the basic properties of condensed matter (solids, liquids gases). Boltzmann's statistical mechanics only makes use of the fact that atoms exist, and needs to know almost nothing about their micro-properties.
  - You don’t need to know nuclear physics to understand the structure of the atom. This is very good, because if we *did* need to know both to understand either, we’d still be struggling to do so.
  - You don’t need to know particle physics to understand the basic structure of the nucleus, although the understanding of the nature of the strong nuclear force came only from studies and experiments in particle physics (the force between the nucleons is a residual, van-der-Waals type remnant of the much stronger force between quarks, QCD).
  - you don’t need to know about atoms to understand the large-scale structure of the cosmos; this is governed dominantly by gravity, which cares only about mass, not the microscopic structure of mass. In fact, most of the mass in the universe appears to be something other than atoms, and we don’t know what!

Decoupling of Length scales

- Going from micro-physics on up to the macro-laws: Scientific reductionism says that the physical laws on the shortest length scales can be used to derive the effective description at larger length scales.
- The idea that one can derive descriptions of physics at different length scales from one another can be quantified with the renormalization group.
- The RG allows us to extrapolate the “fundamental” couplings between particles, from long-distance (low-energy) to short-distance (high energy).
- This extrapolation fails when new physics, new interactions, which were not important or relevant at long distance, suddenly come into play at shorter distances. If we know that physics, we can take it into consideration in the extrapolation. If we don’t, we can’t extrapolate, and our theory is fundamentally incomplete and even mathematically inconsistent.
- This is the problem with the Standard Model, especially regarding the Higgs. The “hierarchy problem” tells us that the Standard Model is incomplete and that new physics is… just around the corner, at energy scales within reach of the next generation of accelerator experiments.

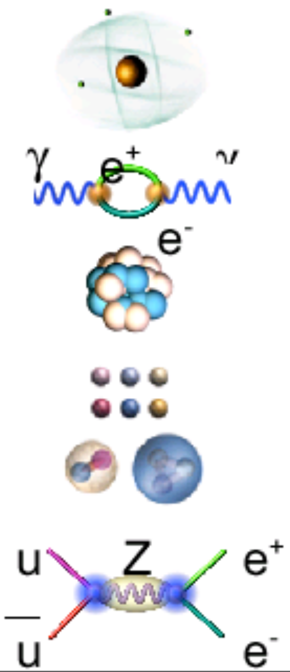
What does decoupling tell us about the nature of the physical world?

Laws of Nature

- Although this course focuses on the edges of our knowledge and the frontiers of discovery, it's important to remember what physics does *best*: establish *Laws of Nature* that we know with a certainty that goes beyond most anything else in the human experience.
- The Standard Model is now well established as a Law of Nature (not just a good idea). This might be the greatest achievement of the last quarter of the 20th century.
- This confidence comes from subjecting the SM to a broad, deep, thorough series of tests based on *precision* measurements of many inter-related phenomena.
  - The predictions of the SM have been tested to "beyond leading order" in perturbation theory.
- We still call it a "model" because
  - it contains many ad hoc ingredients whose origin / purpose / meaning is not known, but which clearly point to deeper truths.
  - it contains ~ 29 free parameters; there shouldn't be any!
  - it contains specific mathematical inconsistencies (associated with the Higgs)
  - it cannot consistently describe gravity.
- All of these problems strongly suggest a deeper theory into which the SM is embedded, and which it emerges from as an effective theory at low energies. We'll look at some of the candidates for that deeper theory (GUTs, supersymmetry, superstrings).
- I think it's fair to say that cosmology is at the state that the SM was in, in the early 80's: it looks right, but the holes in our understanding are rather big, and the theory has not yet been challenged by a broad range of precision tests. We will look at some of those tests: the future of precision observational cosmology is rich!

Make
everything
as simple
as possible,
but no
simpler.

Short history and new frontiers



	$\lambda = h/p$		$T \approx t^{-1/2}$		
	10^{-10} m	≤ 10 eV	>300000 Y	1900....	Quantum Mechanics Atomic Physics
				1940-50	Quantum Electro Dynamics
	10^{-15} m	MeV - GeV	≈ 3 min	1950-65	Nuclei, Hadrons Symmetries, Field theories
	10^{-16} m	>> GeV	≈ 10^{-6} sec	1965-75	Quarks. Gauge theories
	10^{-18} m	≈ 100 GeV	≈ 10^{-10} sec	1970-83 SPS	ElectroWeak Unification, QCD
				1990 LEP	3 families
				1994 Tevatron	Top quark
Origin of masses The next step...	10^{-19} m	≈ 10^{3} GeV	≈ 10^{-12} sec	2009 LHC	Higgs ? Supersymmetry ?
Proton Decay ?	10^{-32} m	≈ 10^{16} GeV	≈ 10^{-32} sec	Underground Labs	GRAND Unified Theories ?
The Origin of the Universe	10^{-35} m	≈ 10^{19} GeV (Planck scale)	≈ 10^{-43} sec	??	Quantum Gravity? Superstrings ?

6 Leptons	ν_e e	ν_μ μ	ν_τ τ
6 Quarks	u d	c s	t b
3 "Colors" each quark	R	G	B

CP violation in B meson mixing / decay

Dark Matter!

Dark Energy!

Neutrinos mix and have mass!!

Short history and new frontiers