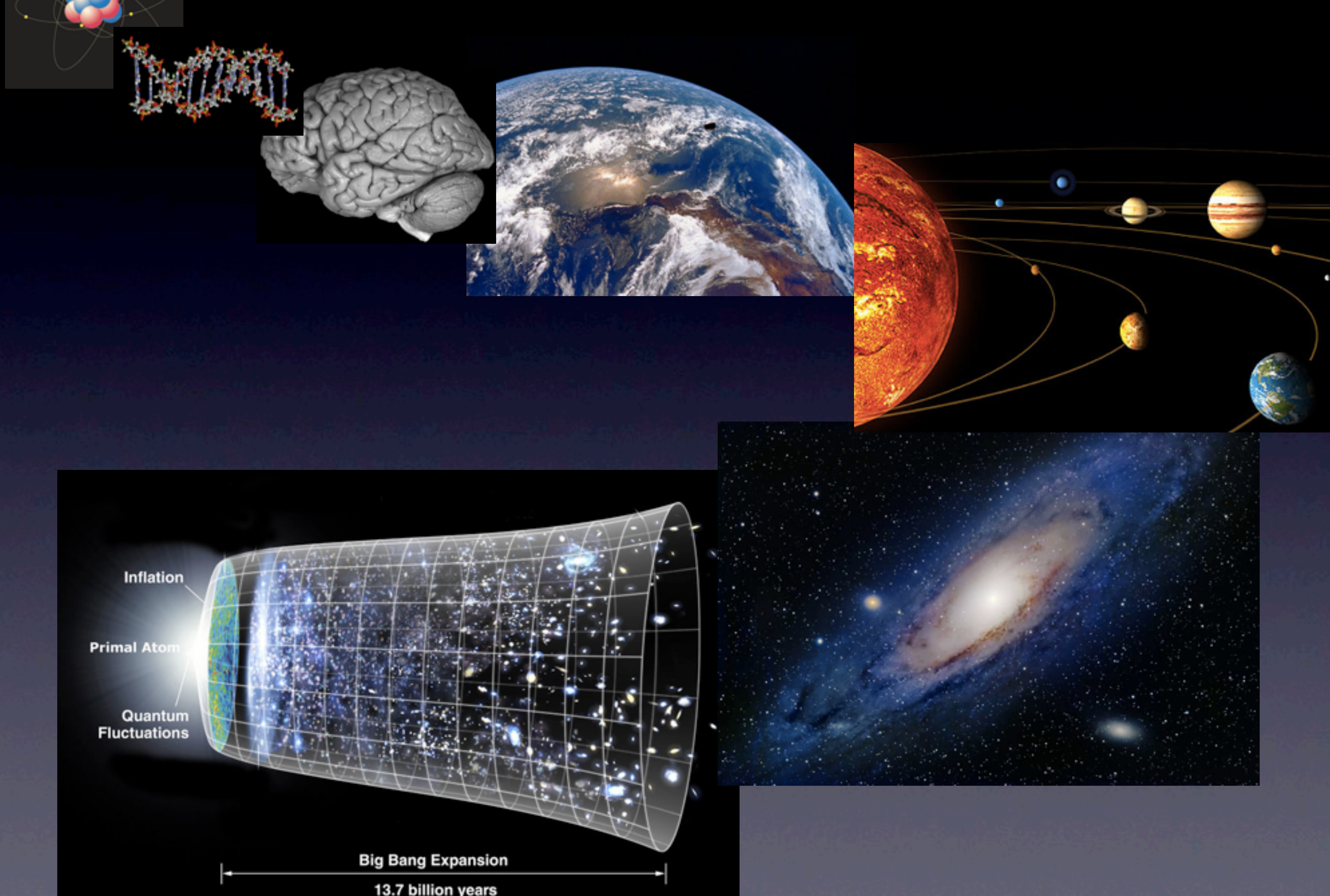
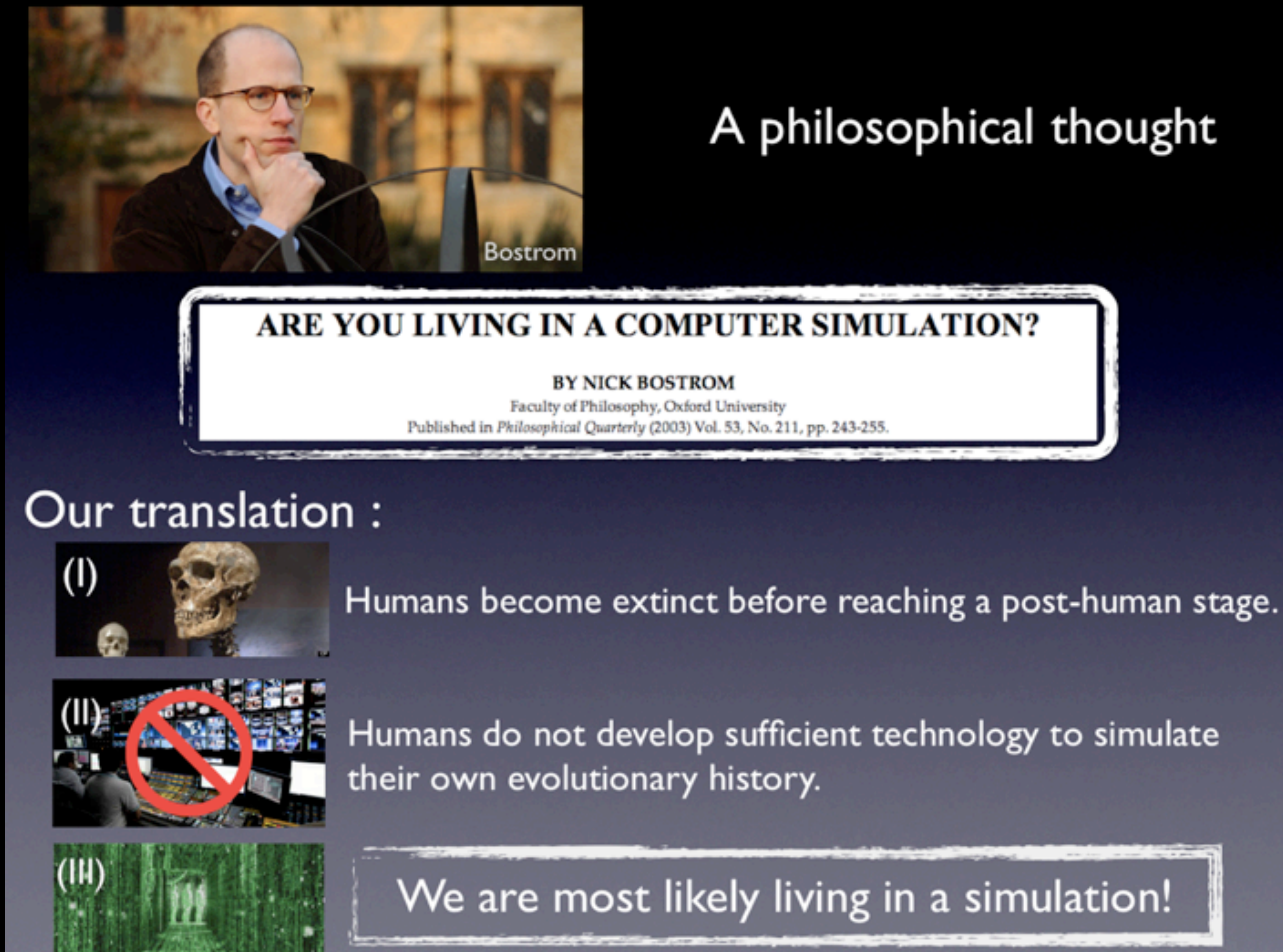
There are compelling philosophical reasons to consider the possibility that our universe is a numerical simulation. Presently, there is no indication that our universe is a simulation, or is fundamentally digital, but as physicists, we wish to explore signatures that could be imprinted on our universe by such a scenario. Theories can never be proven, but they can be constrained or disproved. The first step toward constraining or disproving a theory is to make predictions from it and establish its consequences. Our work is an attempt to identify signatures that are consistent with the universe being a numerical simulation; focusing mainly on the impact of constrained computational resources. These signatures would be most prominent in *early* or *beta*-simulations, but would likely become unobservable in advanced simulations of our universe.

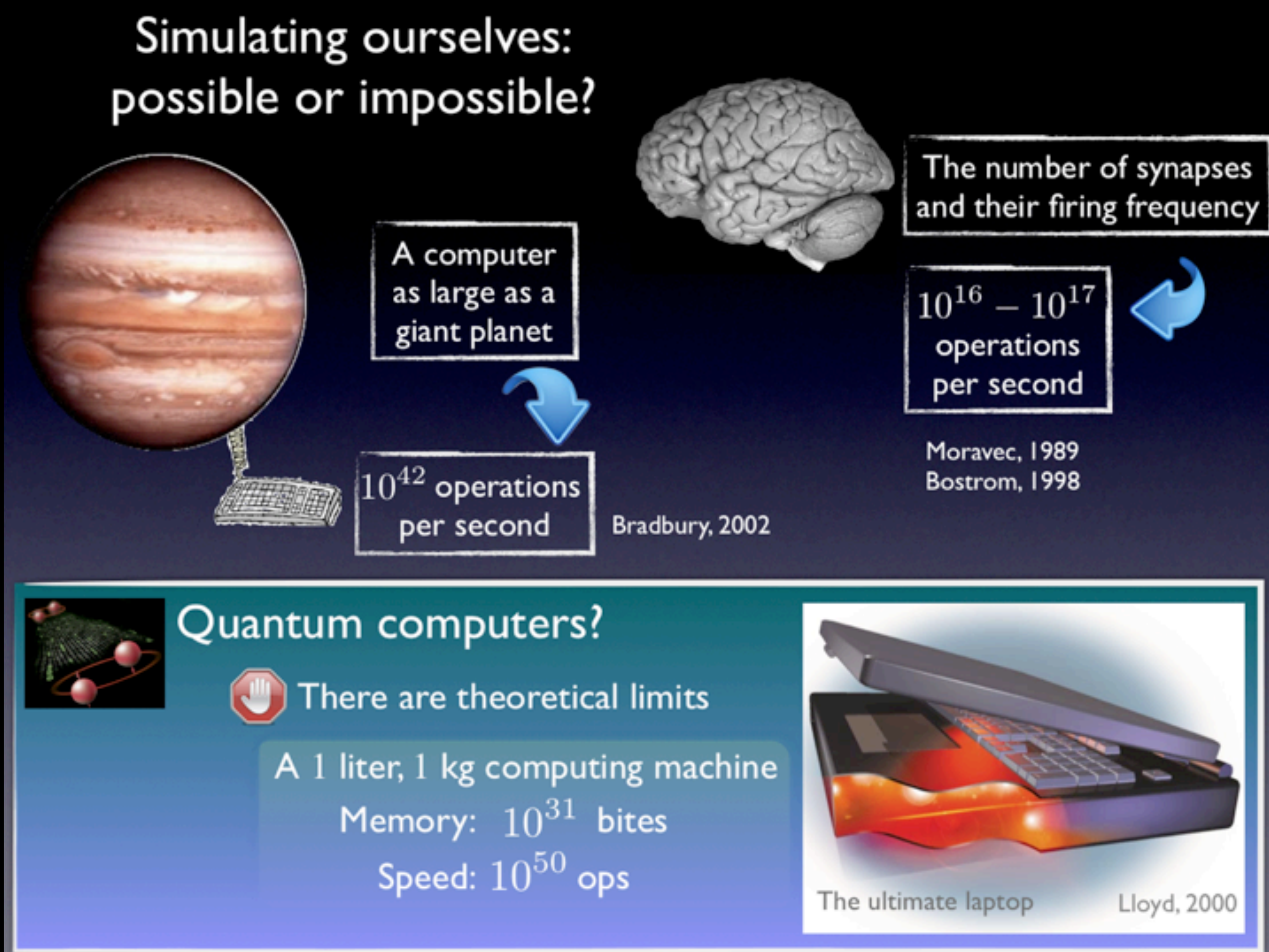
A world of complexities



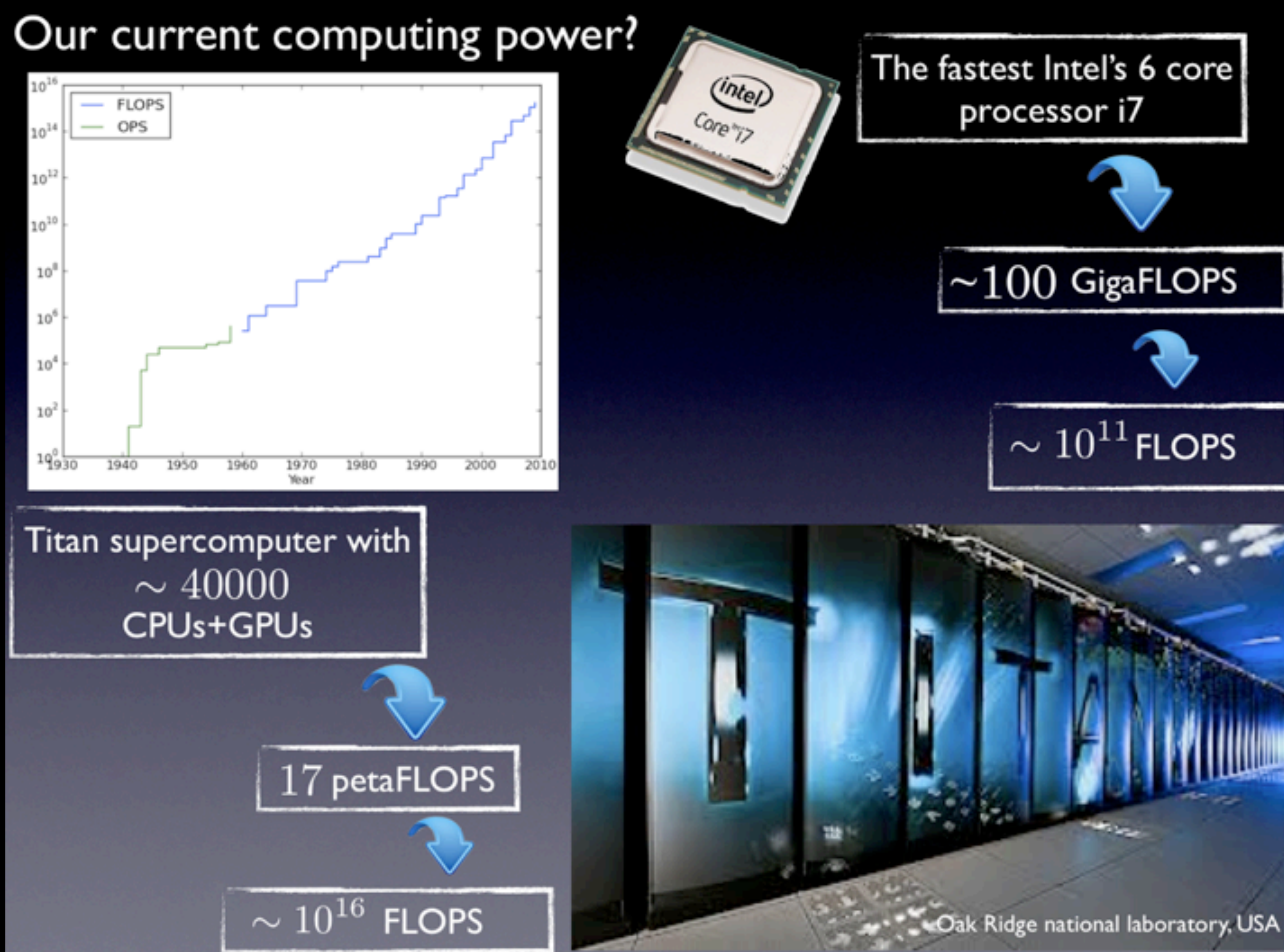
What could be the signatures for our universe being a numerical simulation, and under what conditions could we hope to detect them? This requires an introduction to the science of simulating the fundamental forces of nature. Presently, only the strong nuclear force and electromagnetism can be reliably simulated. To begin with, let us remind ourselves of the complexities of our universe. Any numerical simulation has to be extremely sophisticated and rich to result in the wide range of complex phenomena, starting from sub-atomic length scales all the way through to cosmological length scales. A simulation of our universe should recover, in form, 13.7 billion years of history starting from the big bang, and continuing into the indefinite future.



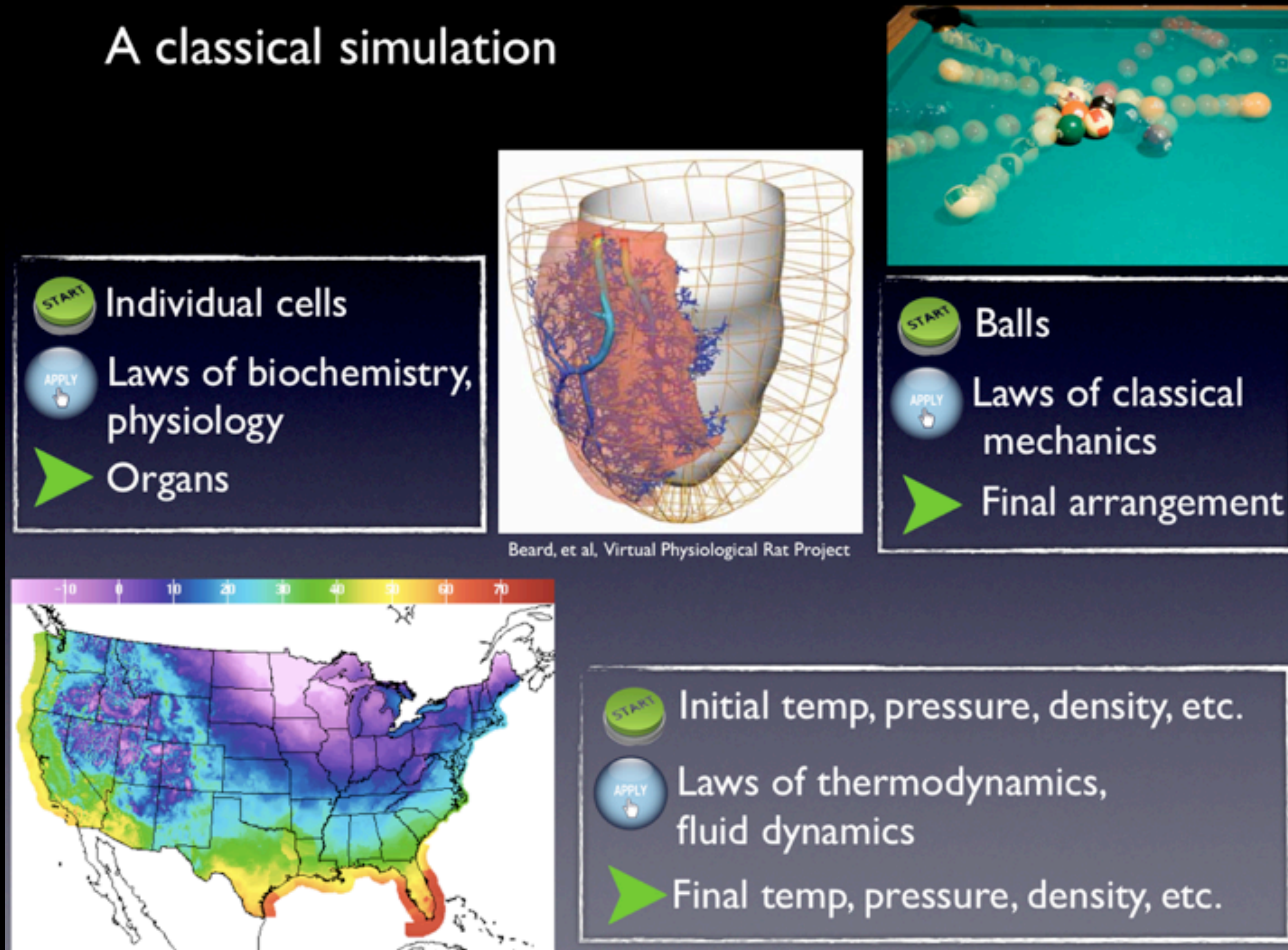
The idea of our universe being a computer simulation has been the subject of many philosophical speculations and explorations over the years, but recently the British philosopher Nick Bostrom provided one of the most compelling arguments for why one should take such a possibility more seriously. If one assumes that we do not annihilate ourselves and that we eventually become capable of simulating our own history, or part of it, then it is likely that we do not belong to the original race of humans but rather to people simulated by the advanced descendants of an original human race.



One can simply be optimistic and assume that humans don't go extinct anytime soon. But how likely is it that we become able to simulate ourselves and our universe? An estimate of what it takes to simulate ``fundamental'' objects, like the brain is shown at the left. Although such estimates do not account for a first-principles simulation of the brain, it already provides a reasonable idea of the number of logical operations the brain performs per second from a biological point of view. If humans become able to build a classical computer the size of Jupiter, they could simulate billions of billions of brains (in principle)! Even a small-size quantum computer (``laptop'') could easily perform such a simulation, although there are still theoretical limits to its computational power (Seth Lloyd, 2000).

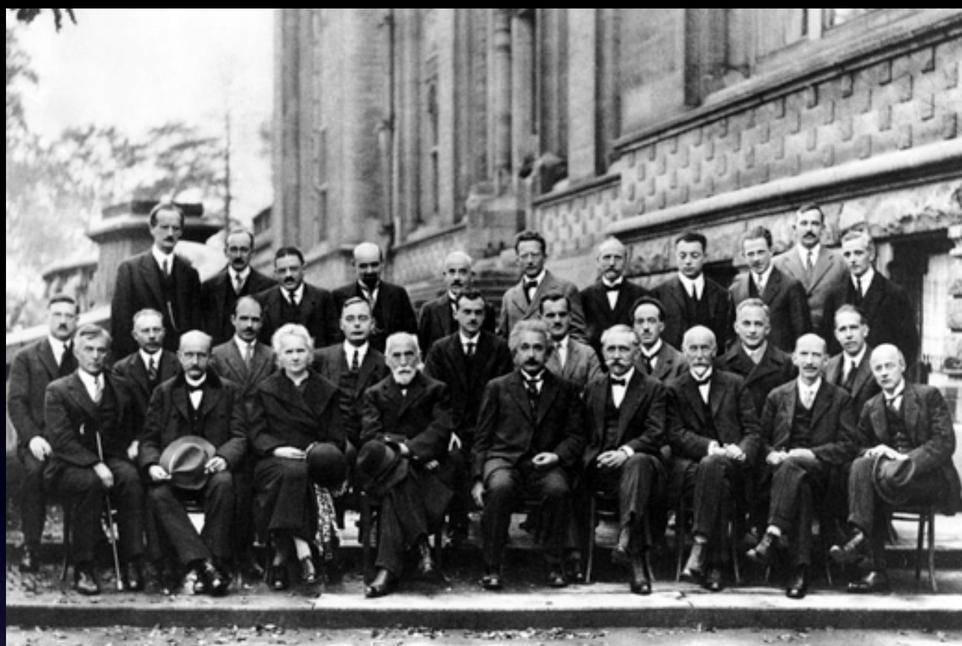


But where do we stand today in terms of computational resources? Obviously even the fastest PC processors available in the market are far from being able to simulate fairly basic objects in nature, but with the aid of powerful supercomputers, of ever increasing capability and capacity, this goal is likely to be achieved in the not-so-distant future. The currently fastest supercomputer in the world, Titan at Oak Ridge National Laboratory, can perform on the order of 10^{16} floating point operations per second (flops). As is clear from the graph at the left, in the last 50 years computers have become almost 10 billion times faster. If the observed trend continues, we will deploy computers that perform at least 10^{26} flops within the next 50 years. So is the simulation of the human brain possible? Most likely yes!



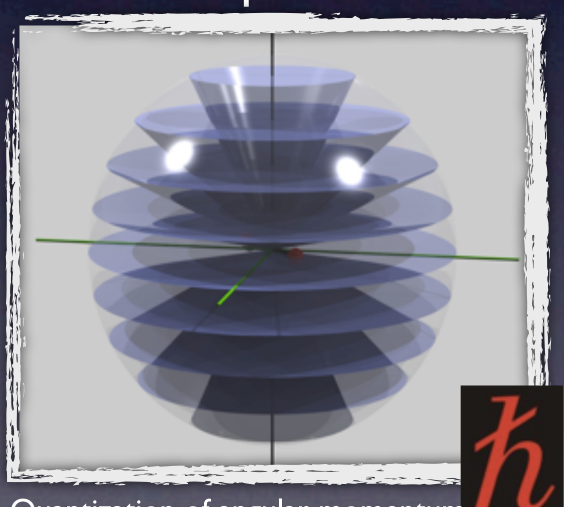
It is important to understand what a simulation means in this context. First note that any simulation aims for a prediction of the final state of a system given its building blocks and the fundamental laws according to which the system evolves. For example, a simple computer program can simulate the final configuration of billiard balls on a table, given their initial position and velocity, using the laws of mechanics. More sophisticated simulations will require vastly more computational resources. For instance, simulations of the brain may start from individual cells and apply the detailed laws of biochemistry to predict functionality. Similarly, numerical simulations are powerful tools in climatology, oceanography, astrophysics and many other areas of science and engineering. These simulations are all based in classical physics.

Quantum mechanics



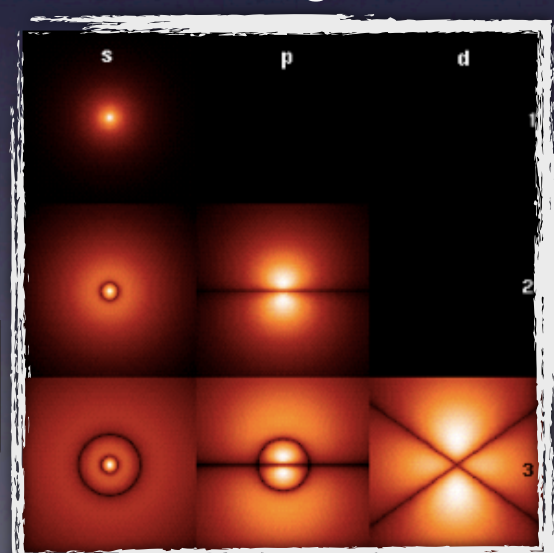
The founders of Quantum Mechanics
Solvay conference, 1927

What is quantized?



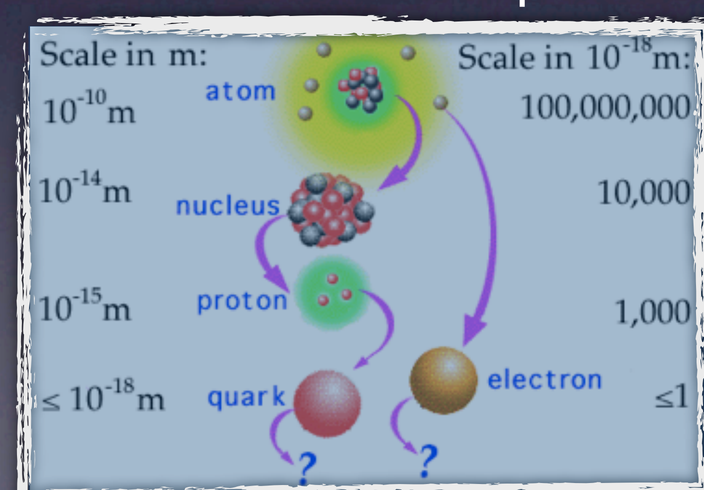
Quantization of angular momentum

Some striking features?

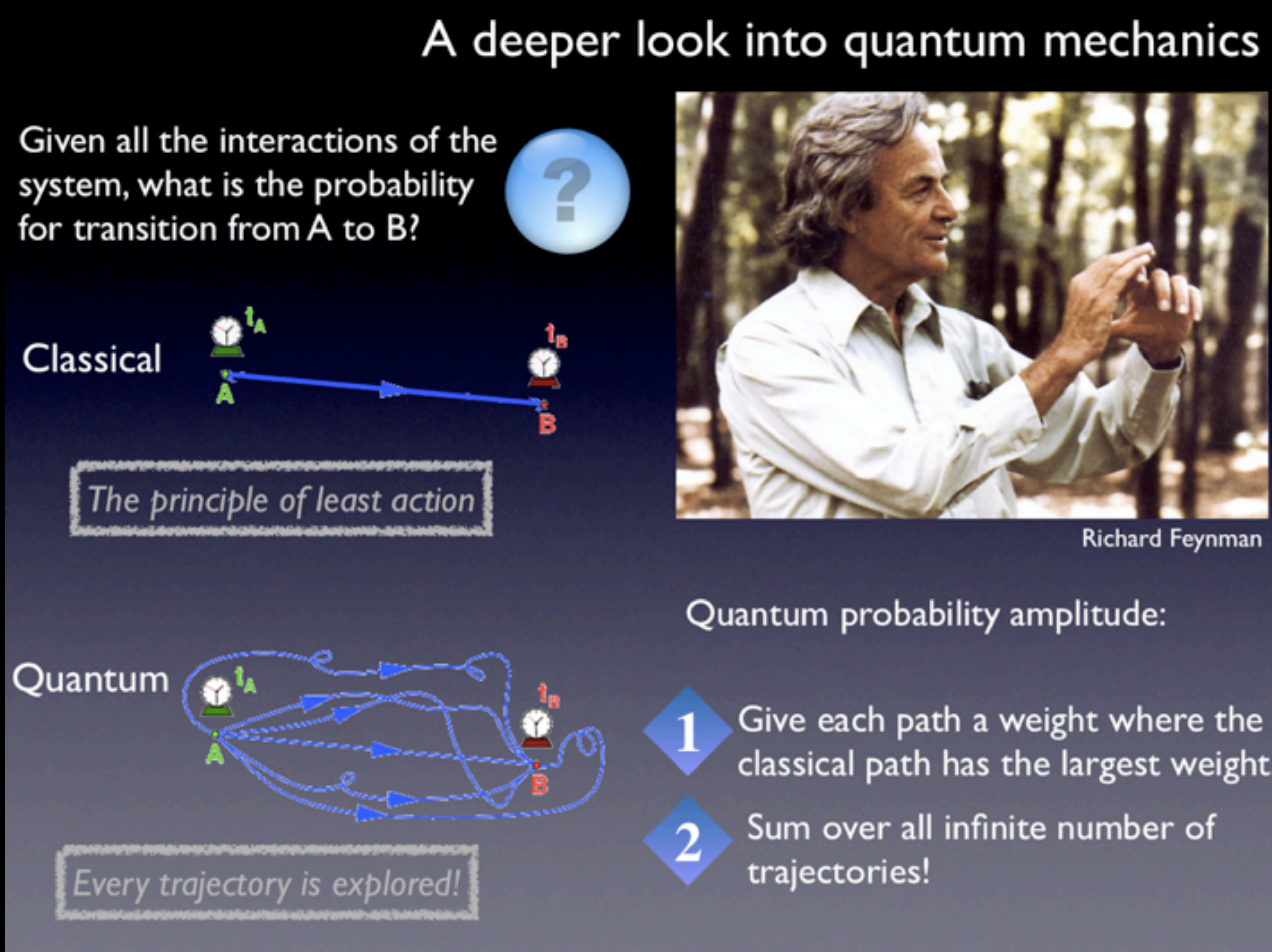


The first few orbitals in the Hydrogen atom

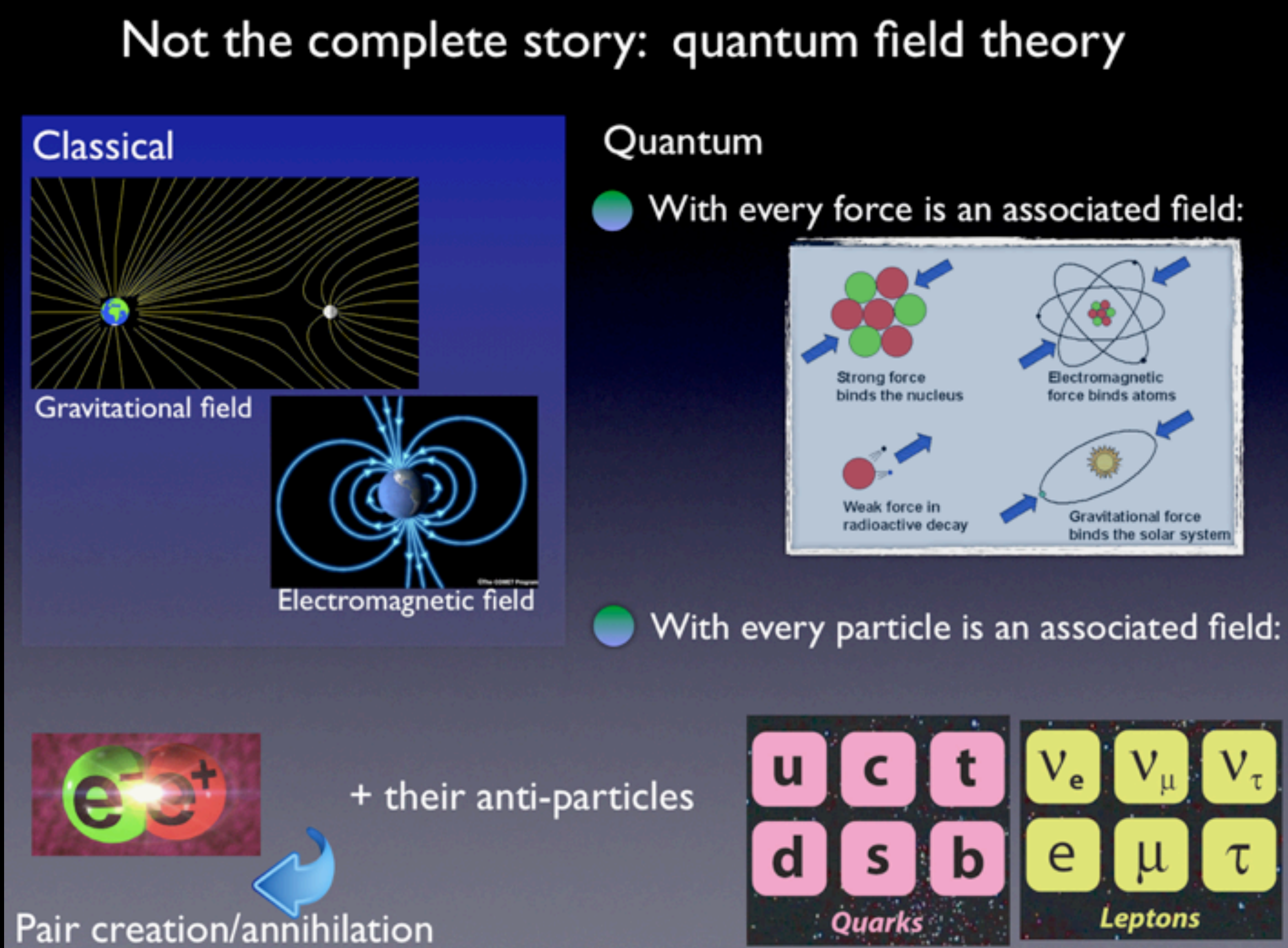
Where is it most important?



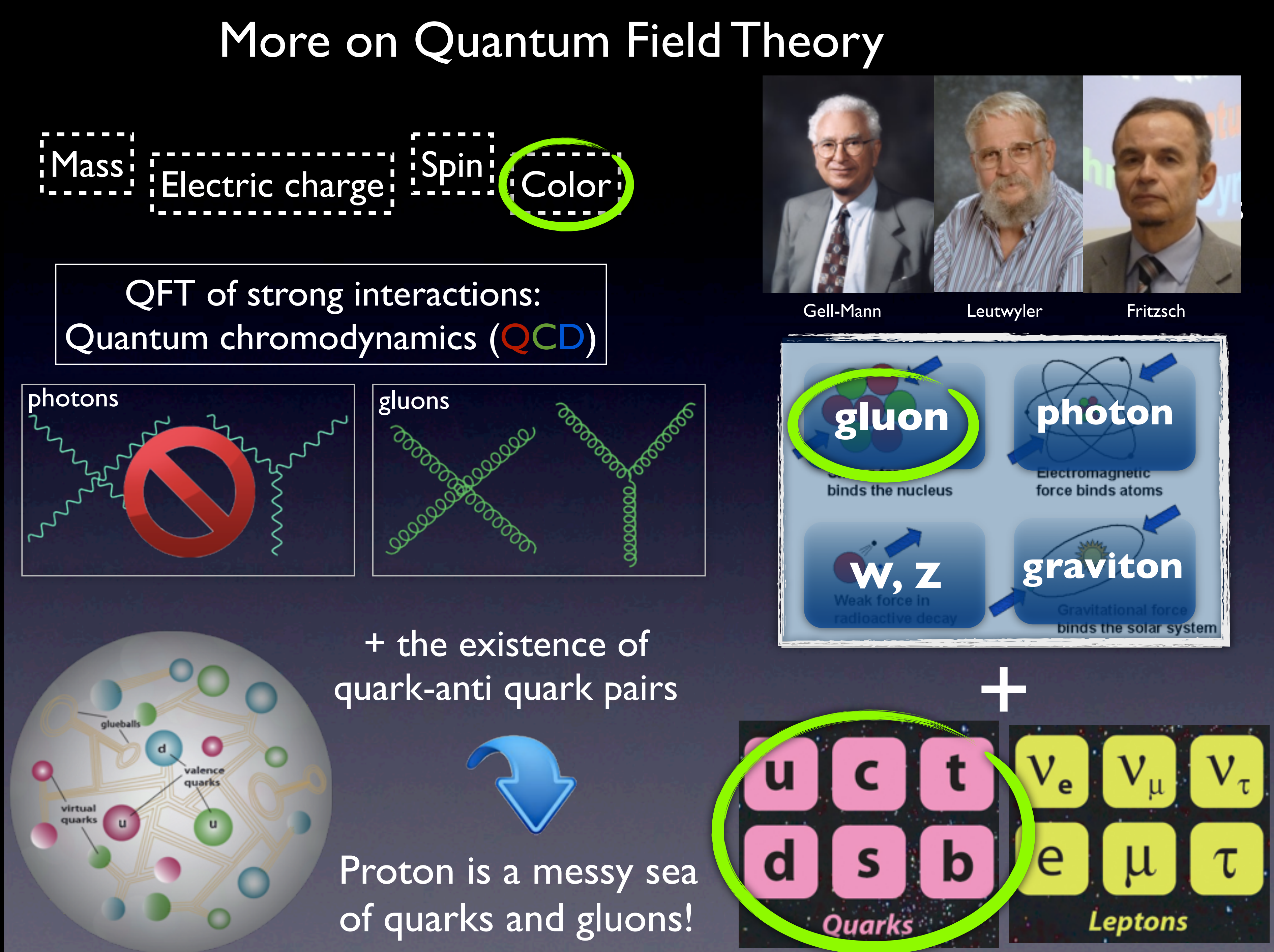
A complete simulation of the universe requires starting from the fundamental building blocks of nature, applying the fundamental laws of physics and letting the system evolve. As the quantum mechanical features of subatomic systems are unavoidable, a fundamental simulation must be based on the laws of quantum mechanics. These laws were discovered by physicists in the twentieth century. The basic idea of the theory of quantum mechanics is that many physical quantities, such as the energy and the angular momentum of the particles, are quantized in units of Planck's constant. Another striking feature of the quantum mechanical world is that a particle is not a completely localized object, but has a probability of being found at any given point in spacetime.



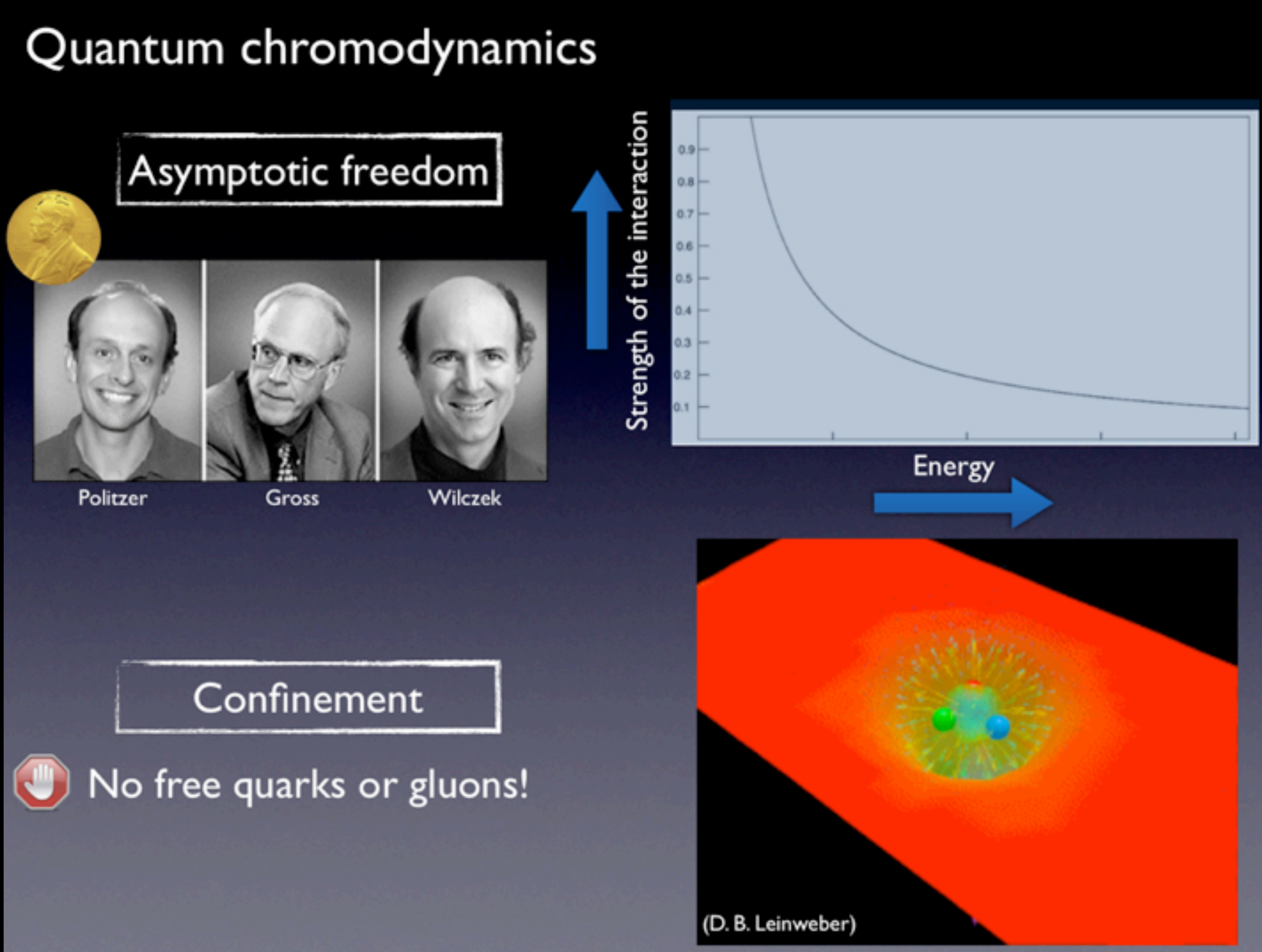
Suppose a physical system starts evolving from some initial configuration A. What is the probability for the system to end up at configuration B at a later time? Classically, there is only one trajectory for this evolution, dictated by *the principle of least action*. However, in a quantum mechanical system, every trajectory is explored by the system during its evolution. To find the quantum probability amplitude for this transition, the infinite number of possible trajectories is summed over with an appropriate weight such that the classical path is an extremum. This fundamental difference between the classical and quantum mechanical world is explicit in *the path integral* description of quantum mechanics developed by Richard Feynman during the 20th century.



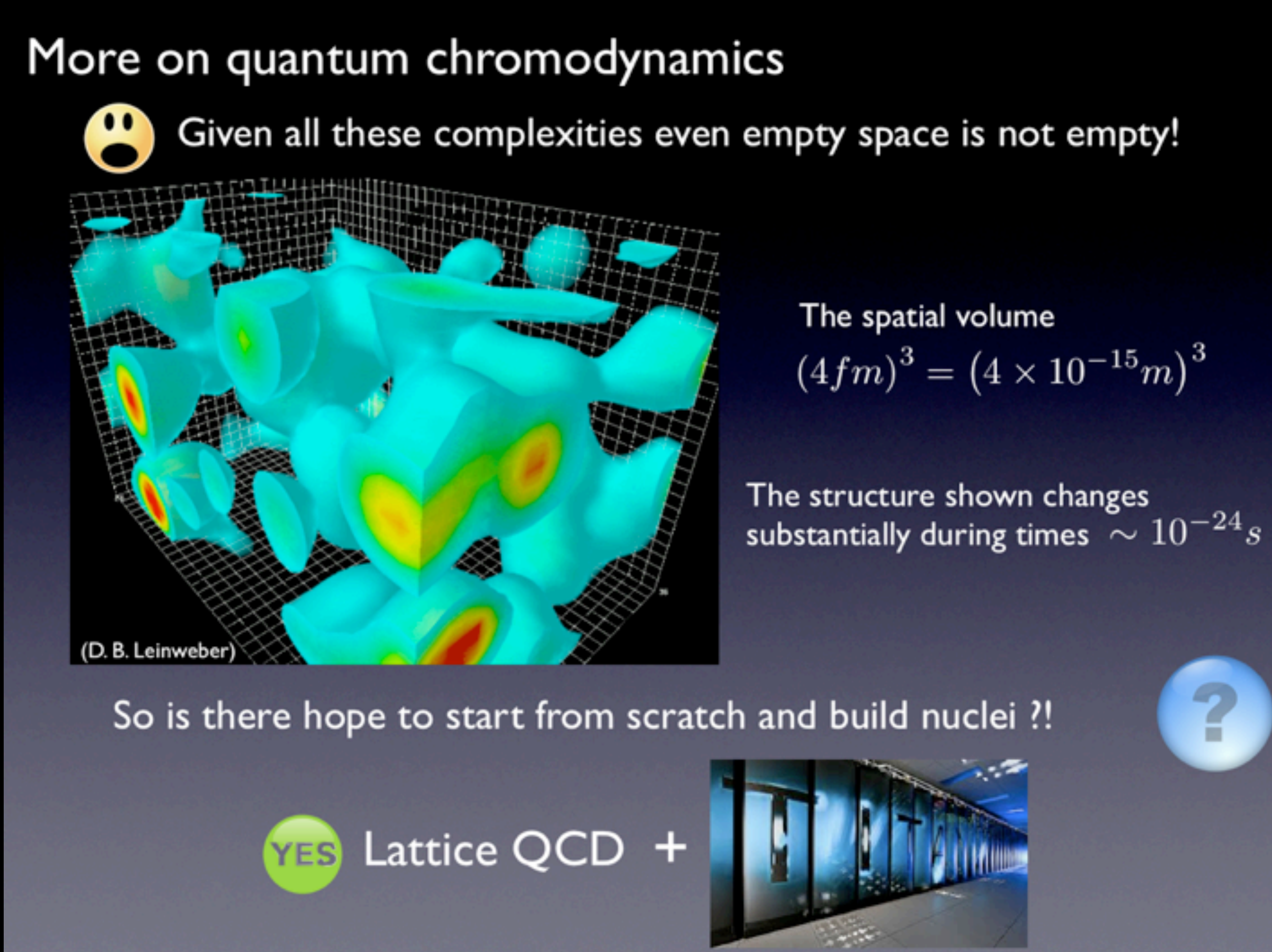
A deeper step to understanding the subatomic world is to describe the particles and forces with fields; the theory of which called quantum field theory (QFT). We all have a good intuition for the gravitational and electromagnetic forces in classical physics. In QFT, there are also fields associated with the other two fundamental forces of nature; the strong force and the weak force. The less intuitive feature of this theory is that with every fundamental particle of nature is also an associated field. For each quark or lepton there is a corresponding anti-particle, and QFT explains the creation and annihilation of particle-anti particle pairs. In addition to the matter particles, there are particles associated with the excitations of the force fields, which mediate the interactions.



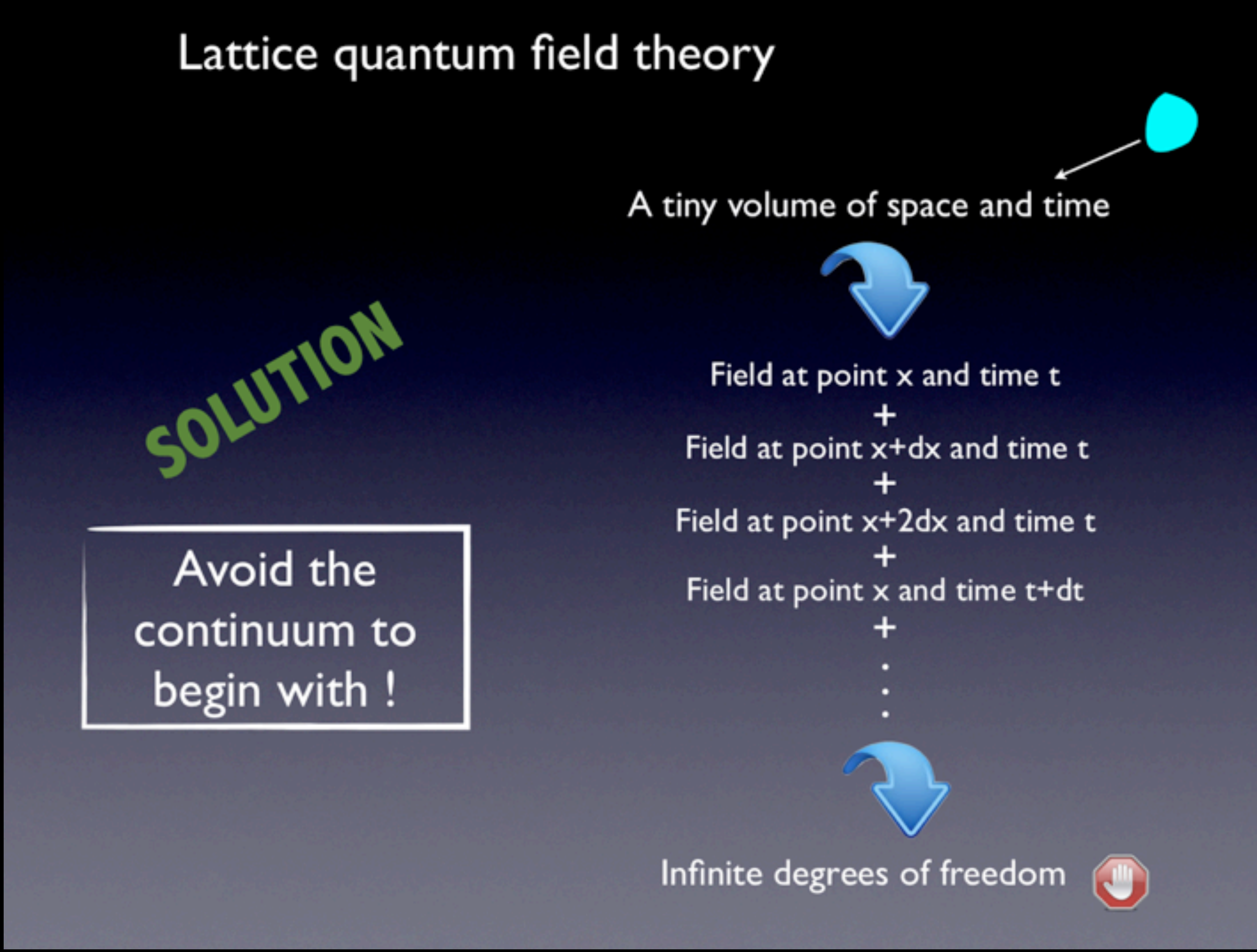
The strong forces are responsible for the existence of galaxies and stars, and ultimately the existence of humans. While very complicated, physicists are able to simulate the strong interactions between the quarks and gluons using supercomputers to postdict the masses and interactions of the nucleons, and to predict new phenomena that cannot be accessed in the laboratory. At the fundamental level, only those particles that are endowed with ``color'' can be affected by the strong force. Quantum chromodynamics (QCD) is the QFT of the strong interactions. Due to complicated self-interactions between gluons, as well as the possibility of quark-anti quark production/annihilation, even a seemingly simple object, such as the proton, is a highly non-trivial sea of quarks and gluons.



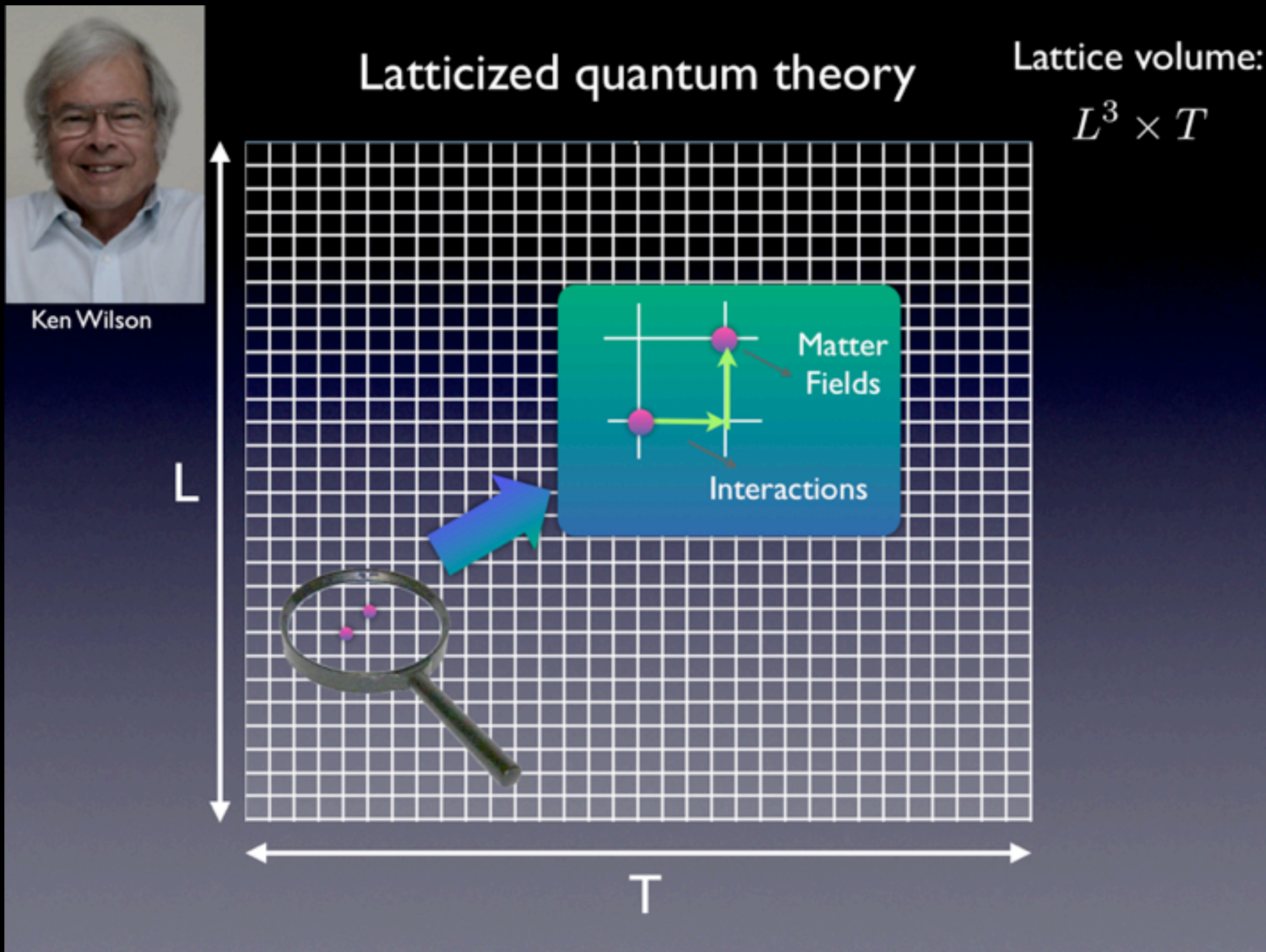
There are two important features of the strong interaction that distinguish it from the other forces. First, the strong interaction turns out not to be strong at small distances (or high momentum-transfers), and thus the theory is called asymptotically free. At large distances, of the order of nucleon's size or larger, the force becomes extremely strong. The other feature of quantum chromodynamics is confinement. No free quarks or gluons have been observed. If one attempts to break the bonds between them, they eventually favor binding with other quarks or antiquarks that fluctuate out of the vacuum to form new colorless bound states.



The consequences of the complex features of QCD are striking. For example, it turns out that even empty space is not empty! The picture (left) is a snap-shot of the vacuum state in a tiny volume of space calculated with the numerical technique of *lattice QCD*. Quark-anti-quark pairs continually ``pop out'' of the vacuum, and the interactions of gluons among themselves, as well as with quarks and anti quarks, make the evolution of the system highly complex. In a real simulation of nature, not only should the vacuum be accurately simulated from first principles, but one must simulate even more complicated systems, such as nuclei. Can this ever happen? As we will see, the answer is yes, and in fact, with the aid of lattice QCD and big supercomputers, this program has already started!



Simulating any quantum field theory requires evaluating the value of the fields corresponding to matter and forces at each point of space at any given time. Even in a tiny region of spacetime there are an infinite number of points, rendering it impossible to perform a simulation with finite computational resources. To avoid this infinity of the continuum, simulations are performed with a discretized spacetime.



With a discretized spacetime, it is impossible to launch a simulation of an infinite volume. So the volume of the simulated spacetime is truncated in both its spatial and temporal extent. Quantum field theories on a latticized spacetime are called lattice field theories, and most of the initial development in this area was accomplished by Ken Wilson. The matter fields are placed on the sites of the lattice, while interactions among them are described by the *links* between fields as shown in the picture (left). Most lattice field theory calculations are performed in a cubic volume of spacetime. In a lattice field theory calculation of the strong interactions, the volume of space needs to be much larger than the largest length scale of the process, while the lattice spacing, b, must be much smaller than the smallest length scale of the process in order to compare with nature.

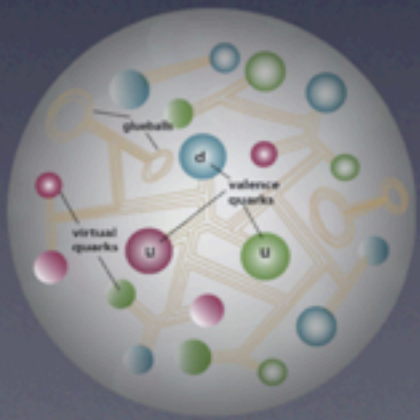
Lattice QCD calculations

Pick the quantity you want to calculate

Average it over in~~fin~~ite number of trajectories

Monte Carlo sampling

Take the $b \to 0$ and $L \to \infty$ limits at the end!

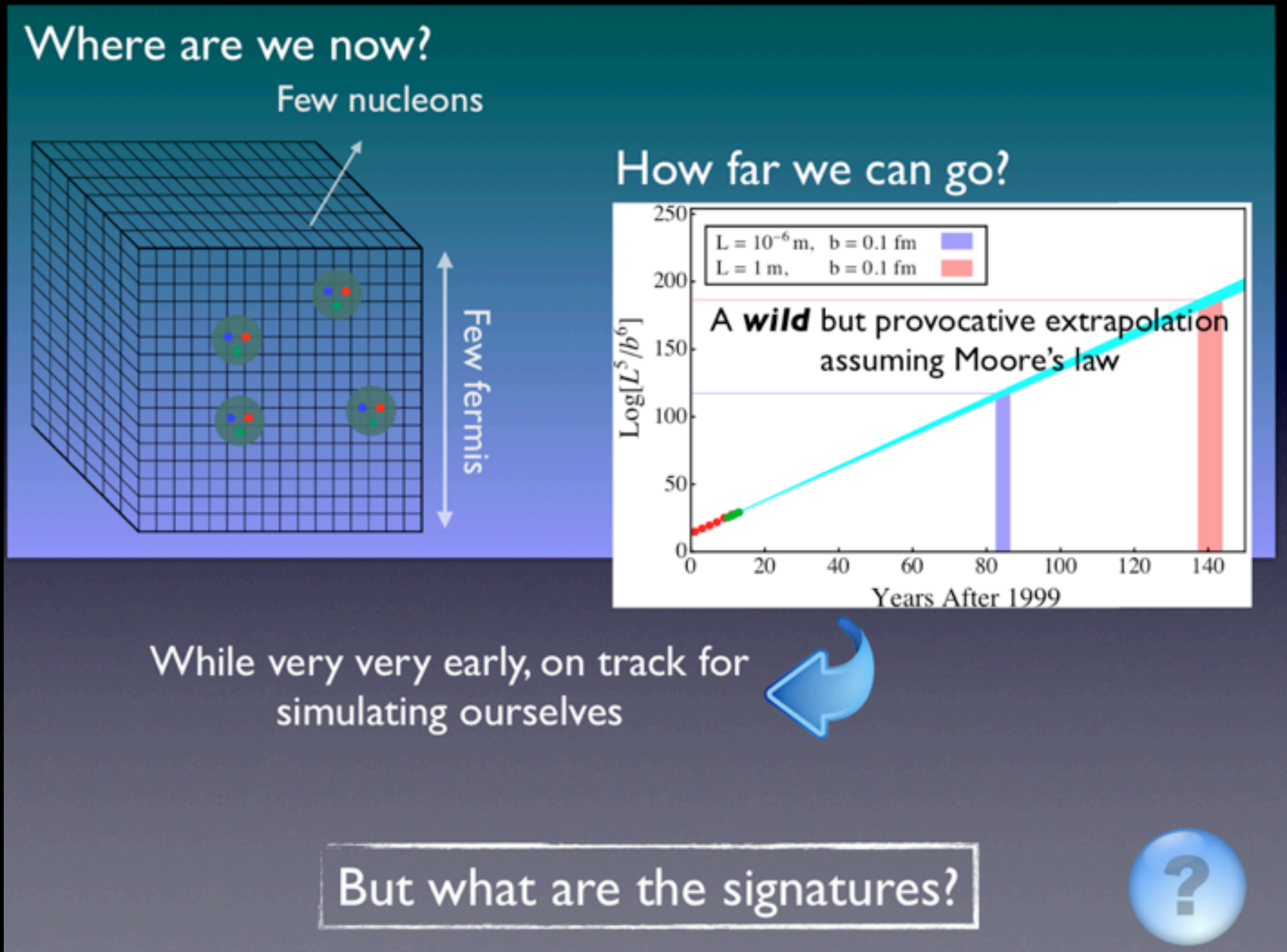


Many non-trivial results!

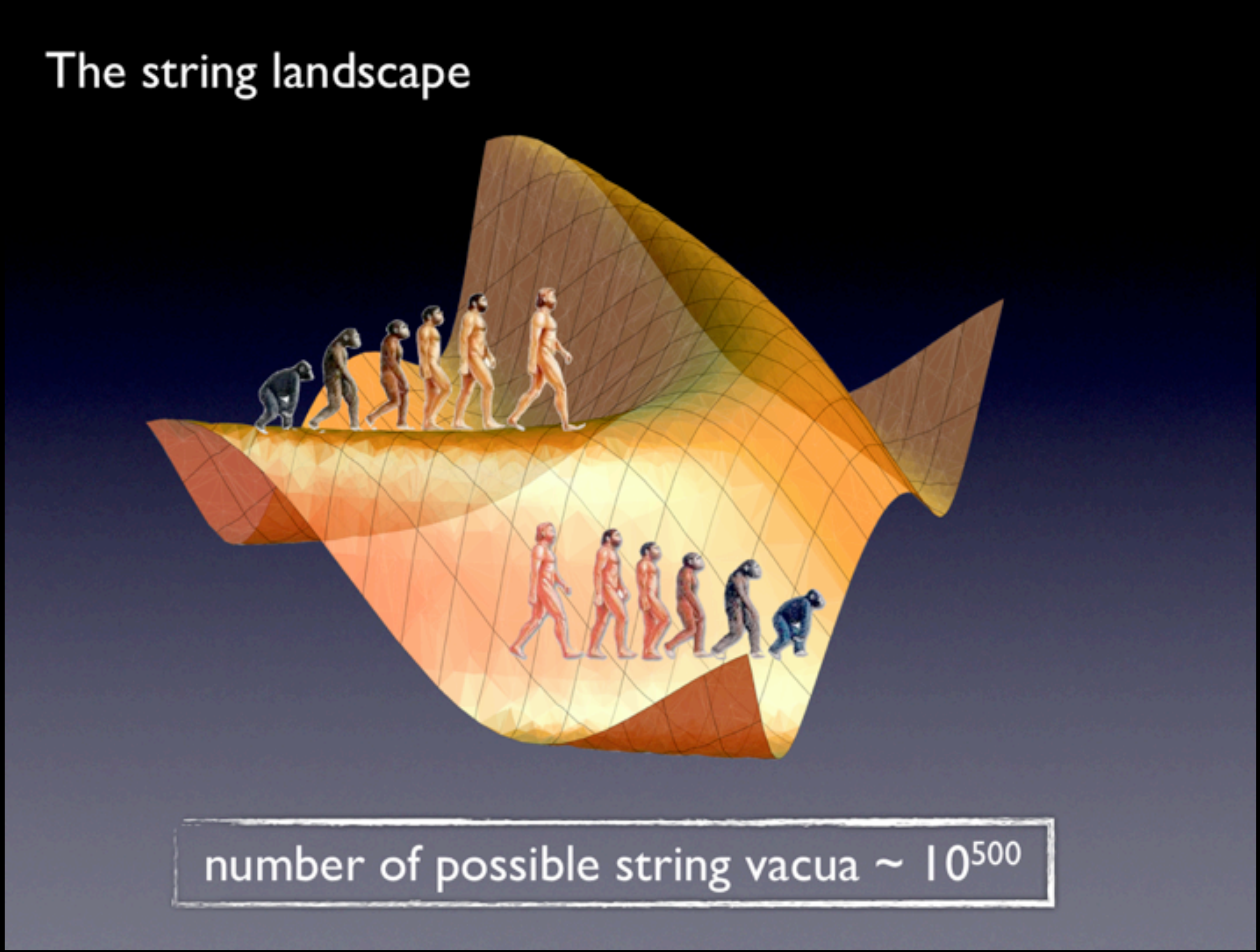
e. g.

What is the mass of proton? Simple!

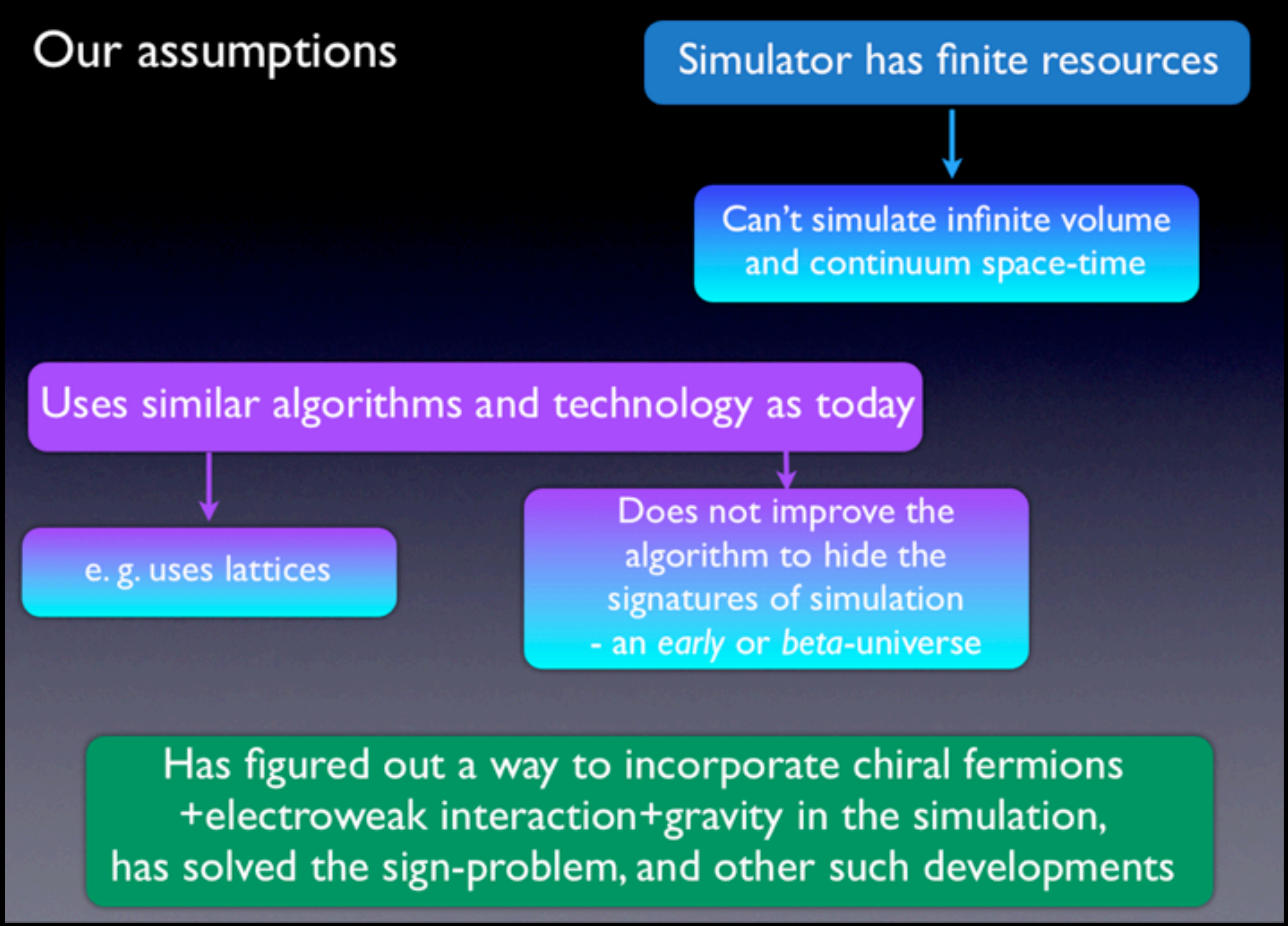
Setting up the theory of QCD in a finite volume with a finite number of spacetime points allows for systematic calculations on a computing machine. In doing so, it is important to keep in mind that in such quantum mechanical systems, the value of a physical quantity is a weighted average over its value on each of the infinite number of evolution trajectories. With finite computer resources one cannot compute an infinite number of anythings, and the method of *Monte Carlo* importance sampling is used to pick a finite number of the most important trajectories. Finally, theoretical tools and/or multiple numerical calculations allow for an extrapolation to infinite volume and to the continuum. With this technology many important results have already been obtained for strongly-interacting systems.



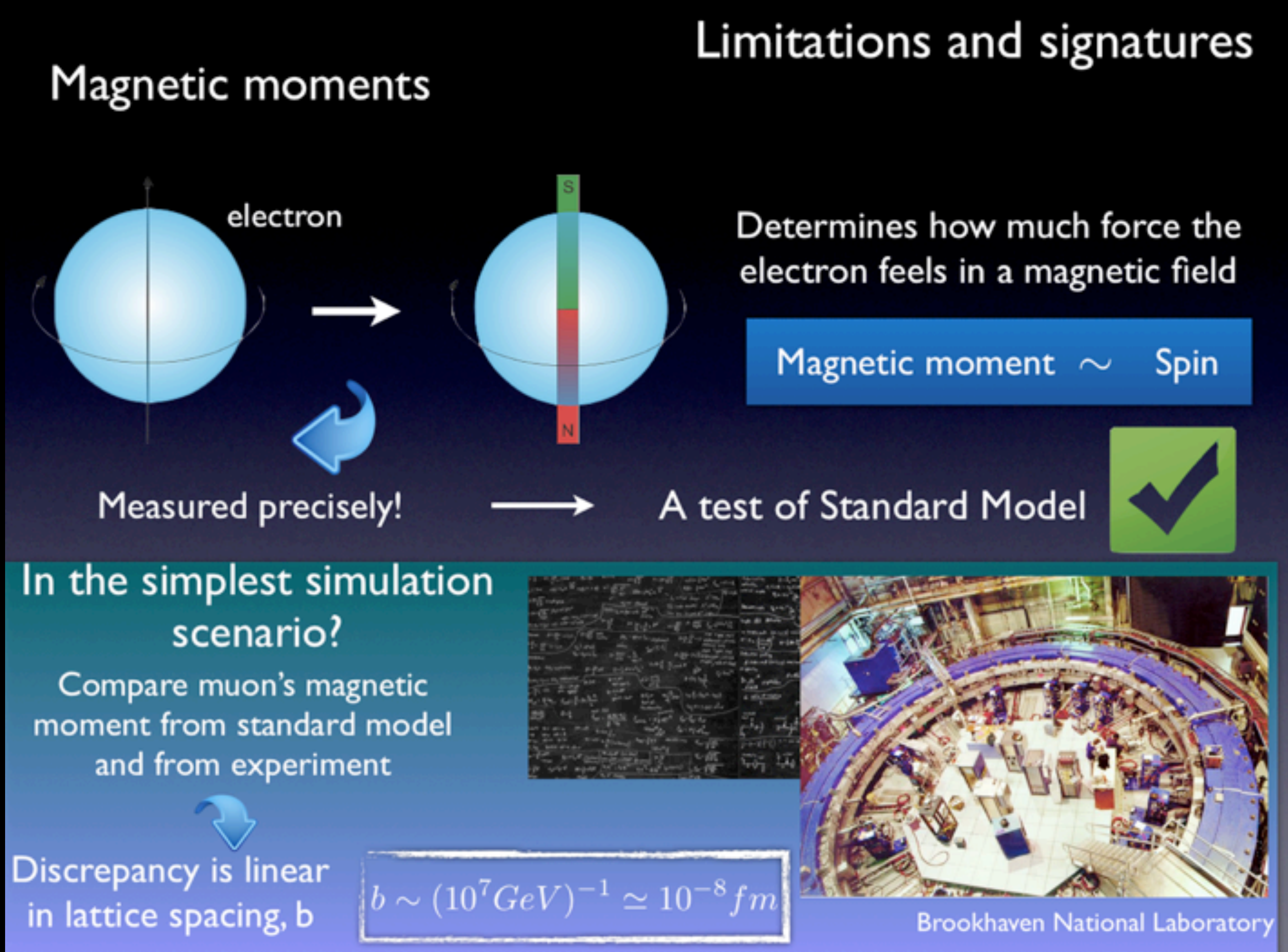
Currently we have been able to simulate small nuclei in cubic volumes that are a few fermis across. Taking the progress in this direction over the last decade, we have done a *wild* extrapolation of the capabilities in simulating the strong interaction into the future. Assuming continued Moore's Law growth of resources, in less than one century one can hope to achieve truly fundamental simulations in volumes as big as a large molecule, and soon after, simulations in volumes as large as the human body. Although this estimate can be affected by many known and unknown technical difficulties along the way, it already moves us along the path toward simulating ourselves and our universe.



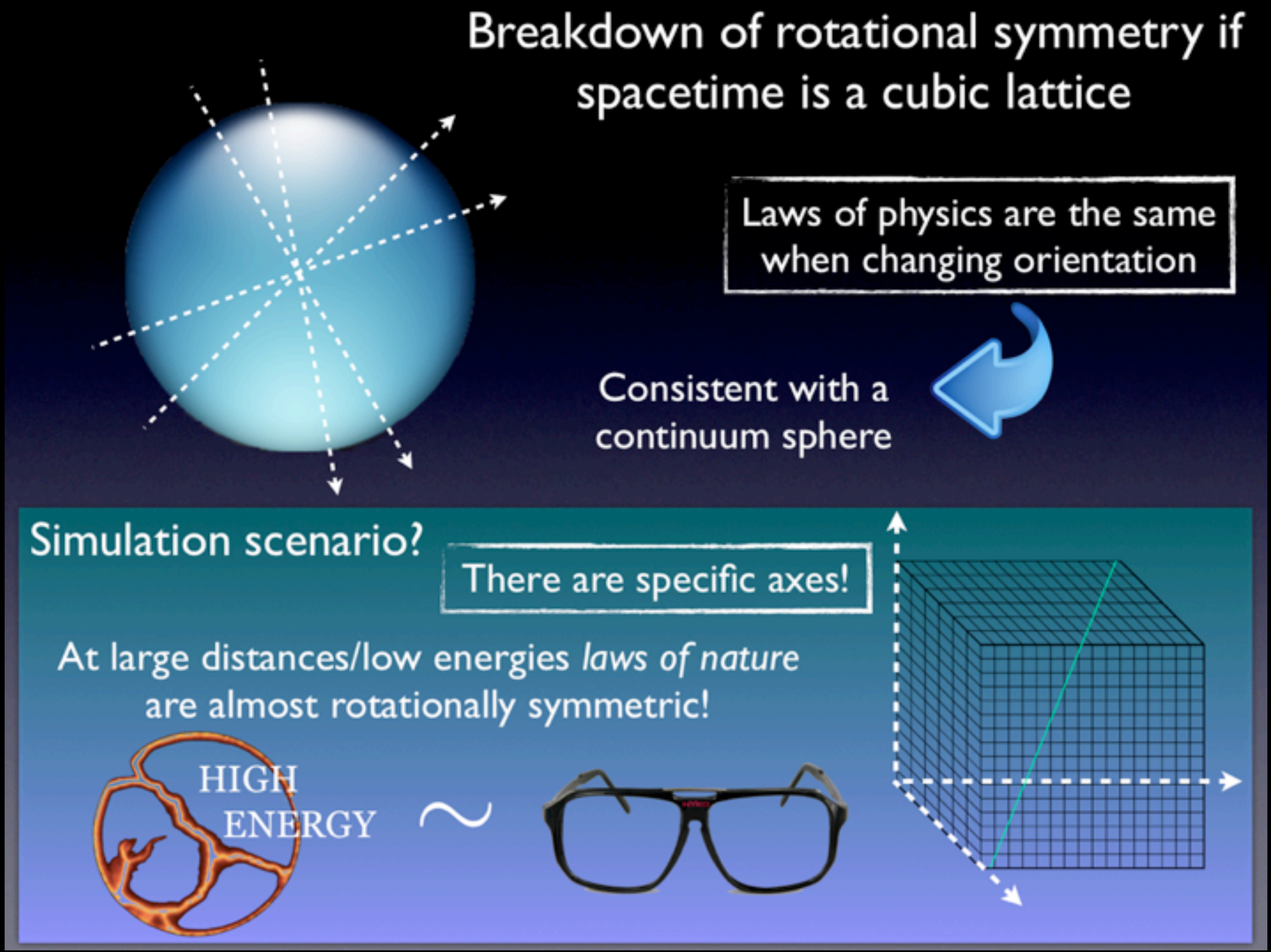
Why would future scientists want to simulate a universe? An interesting answer to this question is provided by string theory, which in its modern incarnation posits the existence of many possible universes (googol to the fifth power!) which differ in the values of the input parameters to the fundamental equations; e.g. the values of the cosmological constant and the quark and lepton masses. The universe that we inhabit is one which happens to have parameters which allow for the emergence of carbon based lifeforms. Given unlimited computational resources, the exploration of this “string landscape” through universe simulation could be the most profound of all tasks that a sentient being could undertake.



As physicists, we should identify the signatures of the simulation scenario and determine where to look for them in nature. At present, we are able to do this only if we make certain assumptions about the underlying simulation of the universe. These assumptions are shown in the figure (left). The most important assumption is that the simulation is performed with finite computational resources, which insures that *the simulator* must avoid a continuum spacetime. This simply implies that any imprint of a non-zero lattice spacing of the universe would be consistent with a finite-resource simulation. However, clearly this in itself cannot prove that our universe is a simulation.



The magnetic moments of particles will be modified by a finite lattice spacing. A spinning particle feels a force in a magnetic field that is proportional to its magnetic moment. This quantity has been measured very precisely for both the electron and the muon, and its value for electron is consistent with the prediction of the standard model of particles physics. However, there is a slight discrepancy between the experimentally measured value of muon magnetic moment and the theoretical prediction. In the simplest simulation scenario, one can attribute this discrepancy to a non-vanishing lattice spacing of the universe simulation and place an upper bound on the lattice spacing, as is given in the figure (left). Note that this upper bound is a hundred million times smaller than the proton radius.



A consequence of a simulation performed with an underlying cubic lattice is the breakdown of rotational symmetry. There are tight constraints on the degree of violation of rotational symmetry in the laws of physics, consistent with a continuum spacetime. In the simulation scenario we should not expect rotational invariance to hold as the lattice introduces preferred axes in the spacetime. At low energies, corresponding to distances much larger than the lattice spacing, the underlying granularity of spacetime is hidden and the laws of nature remain approximately invariant under rotations. However, this is not the case at short distances, and very high energy probes could uncover such granularity or pixelation.

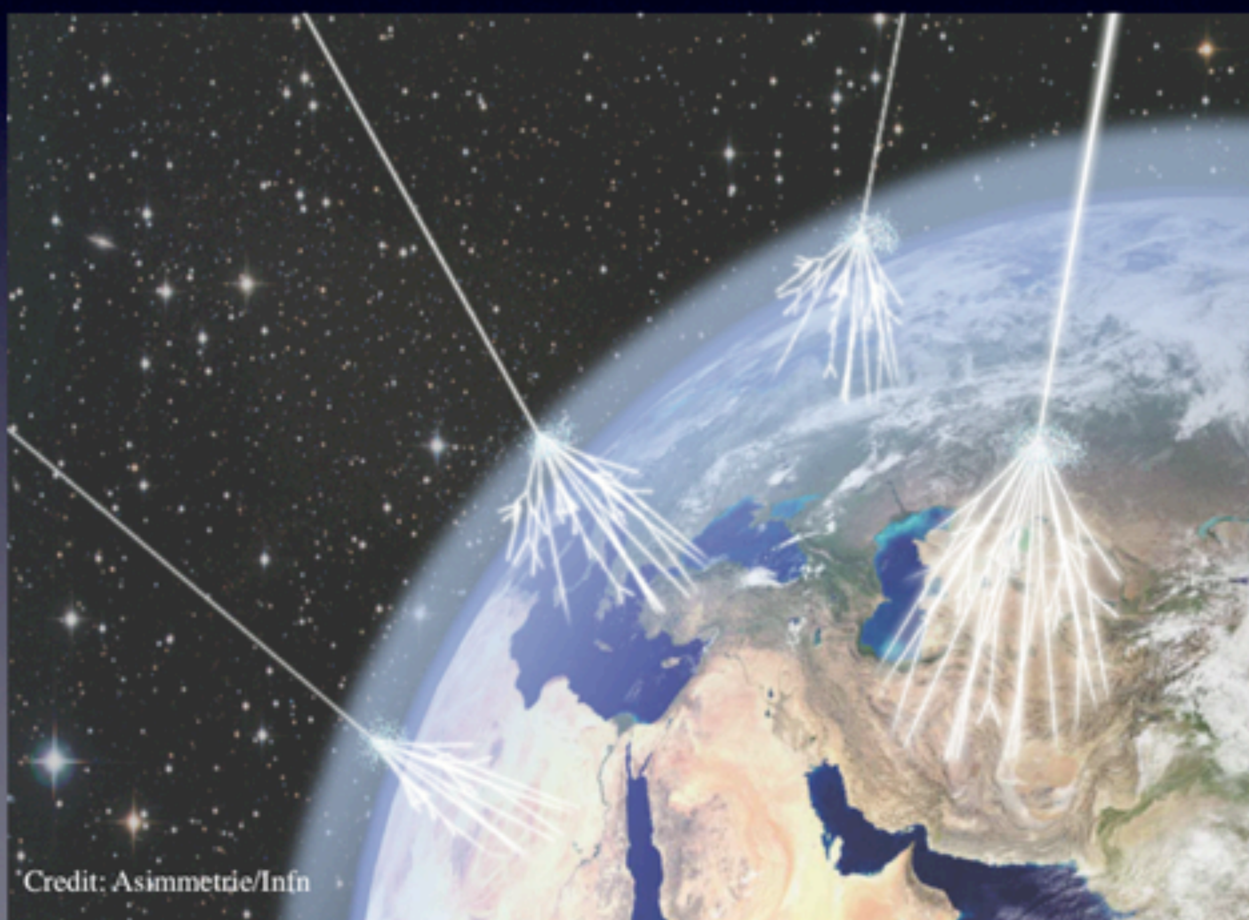
Ultra-high energy cosmic rays (UHECR)

What are they?

Mostly protons, sometimes electrons or heavier nuclei

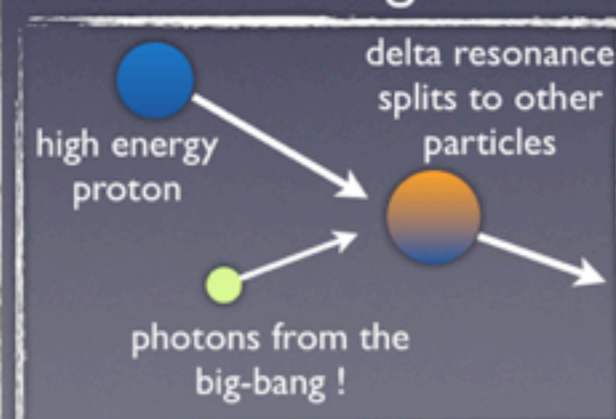
How energetic they are?

$$E_{max} \sim 10^7 TeV \simeq 10j$$

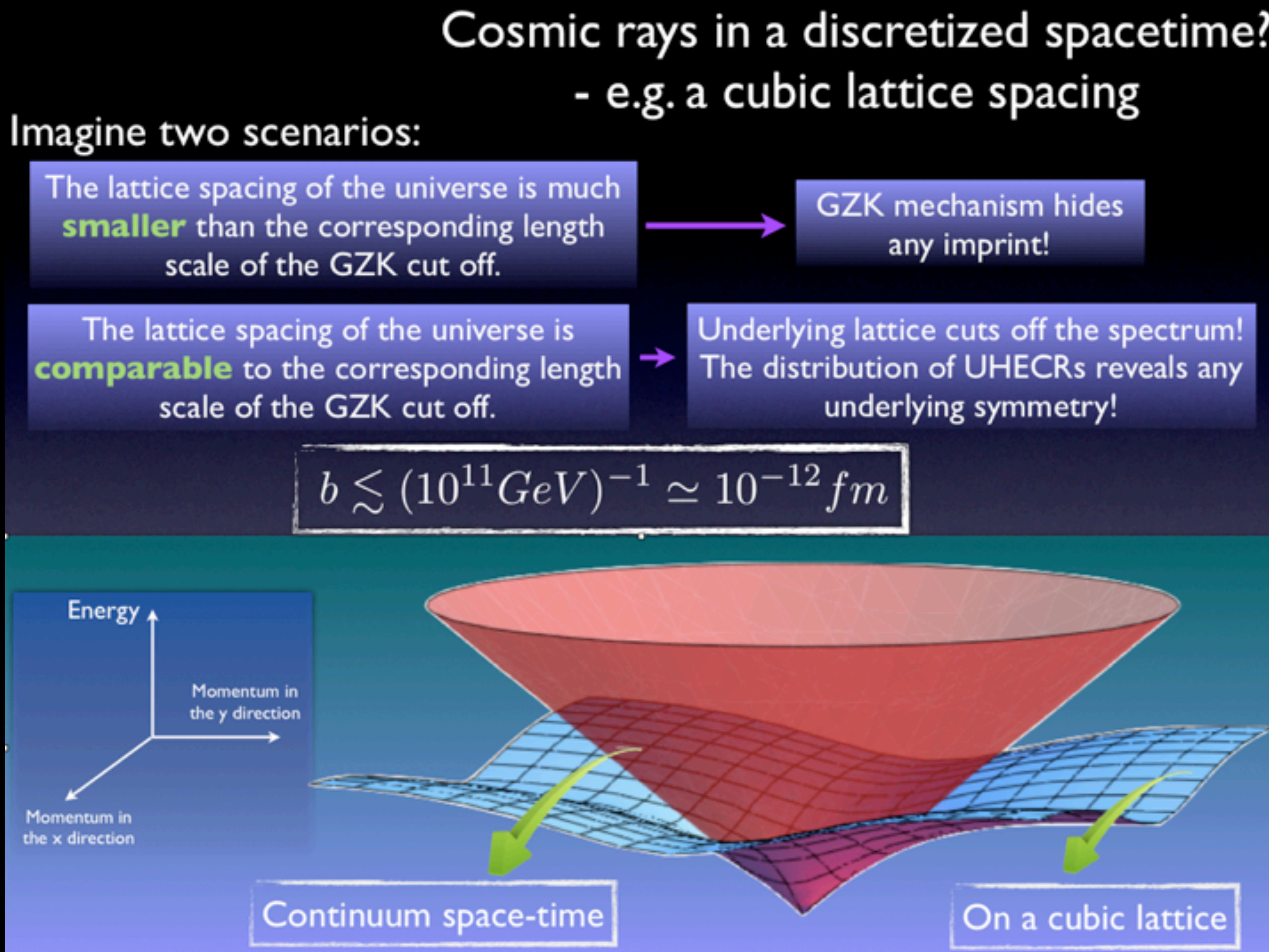


Greisen-Zatsepin-Kuzmin (GZK) cut off

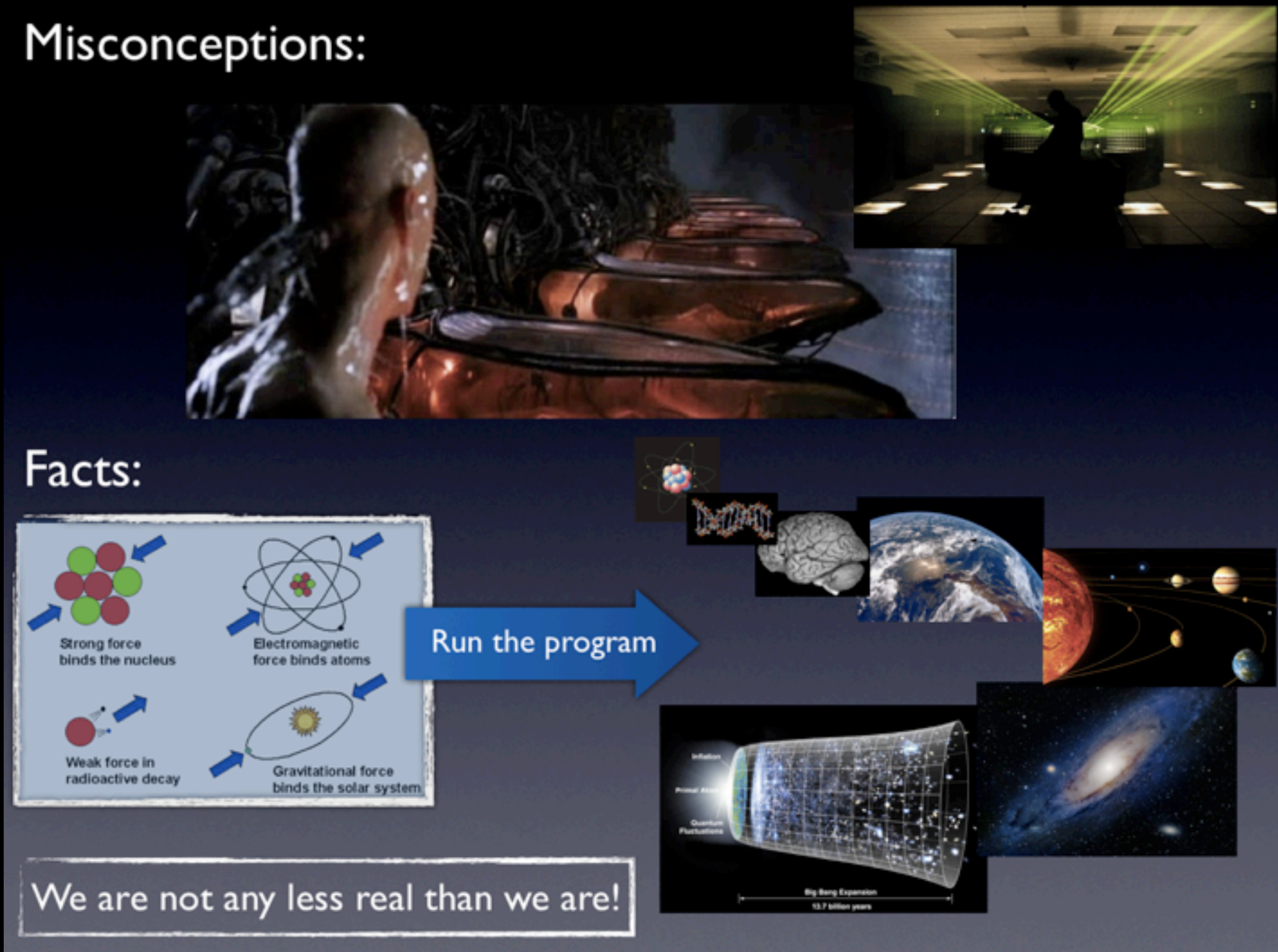
Why is there a cut-off on their energies?



What are the highest energy particles we can observe in our laboratories/observatories? It turns out that the ultra-high energy cosmic rays that frequently hit the earth's atmosphere are sometimes millions of times more energetic than the highest energy particles scientists have produced in particle accelerators! These high energy cosmic rays, which are mostly protons, have not been observed with energies above a certain value. Three physicists, Greisen, Zatsepin and Kuzmin (GZK), suggested that this observed cut-off is due to the inelastic scattering of protons beyond a certain energy with photons in the cosmic microwave background. These scattering processes provide an energy-loss mechanism for the high-energy protons.



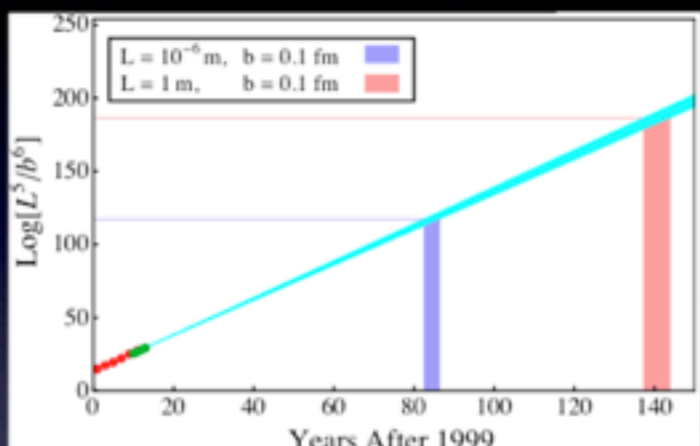
What information can ultra-high energy cosmic rays (UHECR's) provide about a spacetime that is built upon an underlying lattice? Two scenarios are presented in the figure (left) for a cubic lattice. Since the spectrum of the particles in a cubic lattice depends on the direction of propagation, the highest energy particles will travel along the diagonal of the underlying cube. If the lattice spacing is large enough to cut off the spectrum at a scale comparable to the GZK cutoff, the observed distribution of the UHECR's will reflect the underlying cubic symmetry of the simulation (or more generally, the symmetry group underlying spacetime). However as the UHECR's are rare, collecting a conclusive set of data might take some time. Even a fabric with no symmetry will leave an imprint on the UHECR's.



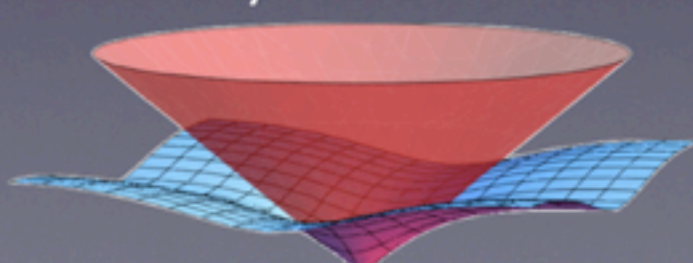
Getting back now to the original idea of the simulated universe, let us attempt to eliminate misconceptions that may arise. The simulation scenario presented in this work by no means implies an illusion of reality (e.g. The Matrix), or the existence of ``machine's users'' (e.g. God(s)) who are directly influencing our lives and our perception of reality, in any way. Once one starts from the building blocks of the universe, sets the values of the input parameters of the simulation, and applies the fundamental laws of nature, with sufficient computational resources, a universe such as ours should naturally emerge.

Summary

- Various well-motivated arguments suggest the possibility of a simulation scenario.



- By putting the laws of physics in a computing machine, one may be able to eventually perform truly fundamental simulations of nature. Lattice QCD has started down this path.
- If we can eventually simulate versions of our universe, we must consider the possibility that we ourselves, and the world around us, are a numerical simulation.
- Looking for evidence under certain assumptions about the simulation, i.e. model-building
- Our best chance is the ultra high energy cosmic rays and their distribution.



- What are other signatures if any?

It is, in fact, possible that our universe is one large-scale numerical simulation. At present there is no evidence to conflict with such a scenario, but no evidence to support it either. Our work is an effort to identify observables that would show deviations from their continuum spacetime values due to an underlying discretized spacetime. A multitude of quantities have to be explored and shown to be consistent with this scenario in order for it to be promoted from an unlikely philisophical suggestion to an everyday working theory with predictive capabilities.

Unless we are now living in a simulation, our descendants will almost certainly never run an ancestor-simulation.

Nick Bostrom