It’s a very small world

“Quantum field theory in nontrivial classical field backgrounds”

Yusuke Yamada

Micro world vs macroscopic universe

Macroscopic physics (classical physics)

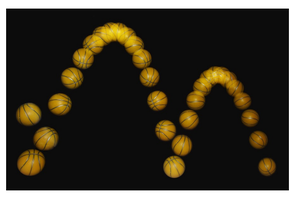
- **is deterministic:**

Given all information about the position and the velocity of objects at a given time, we can (in principle) predict the dynamics of objects at any time, either future or past

- **is more intuitive**

We can imagine how a ball will move when you throw it, however rough sketch it is

from dynamics of a ball



(from Wikipedia “parabola”)

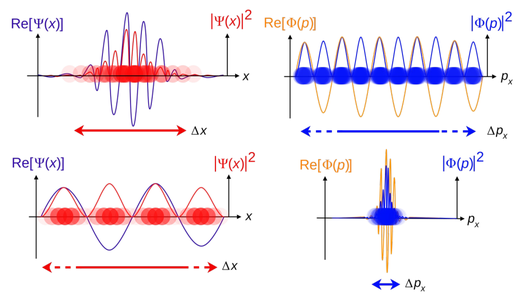
to large scale structure of the universe

Computer simulation of the LSS
(from Wikipedia “observable universe”)

Microscopic physics (Quantum physics)

- **is “probabilistic”:**

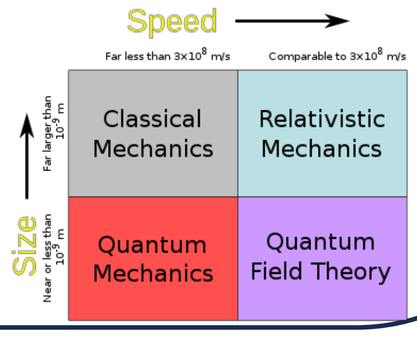
We cannot get both position and velocity (momentum) at the same observation.
→ All we can know is the probability distribution of position and momentum



Red(left) and Blue(right) are probability distribution
If a position probability is more peaky,
momentum information has no peaks and vice versa

- **is more fundamental**

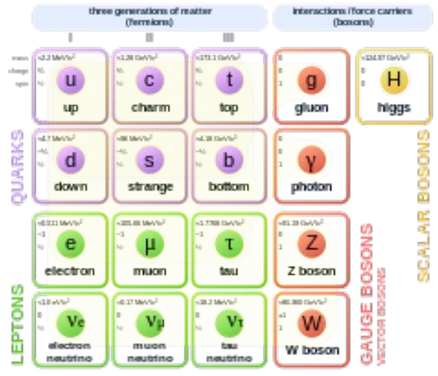
all objects we know
→ made of chemical elements
→ made of atoms
→ made of (elementary) particles (electrons), proton, neutron



classification of various physics theories (from Wikipedia “classical mechanics”)

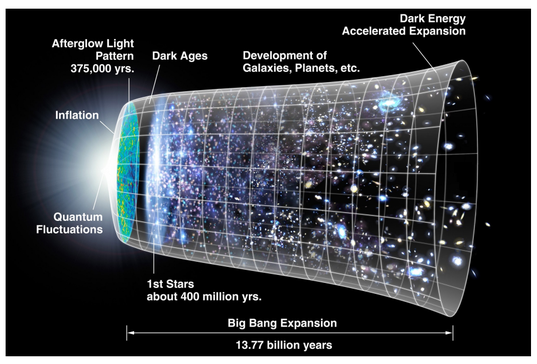
What is (un)known about micro world?

The standard model of particle physics



We know almost all particles in “our world”

Big-Bang universe



(from Wikipedia “Big Bang”)

Universe is now expanding
→ in the past, universe was very tiny.

Such hypothesis is very consistent with astrophysical & cosmological observations

Mysteries of the standard model of particle physics and cosmology

- **Particle masses**

particle masses are hierarchical
heaviest/lightest $\geq 10^5$

- **Absence of gravity**

microscopic theory of gravity is quite problematic.
Only promising theory is “string theory”.

- **Beginning of the universe?**

quantum gravity theory is necessary to discuss how the universe started.
String theory does not reach it yet

- **Dark energy? Dark matter?**

From observations, we know that the most of energy (~95%) in our universe is from *dark energy* and *dark matter,* which we cannot “see”

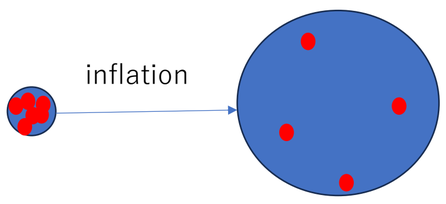
- **Why 3D?**

we do not know why the dimensions of space should be “3”. String theory tells that there should be 6D extra spaces! But how can it be consistent with what we see?

Microscopic universe

How were “matters” created from “nothing”?

cosmic microwave background observation supports “cosmic inflation”:
accelerating expansion of the very early universe before Big-Bang stage



Inflation dilutes everything→ very cold universe

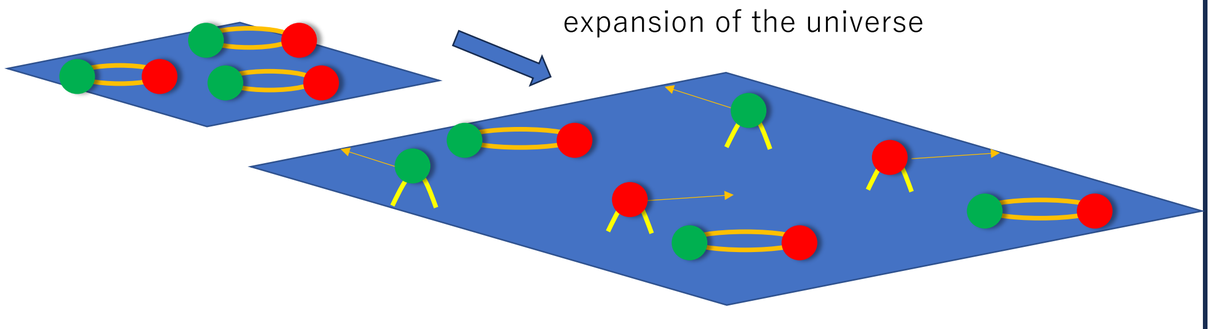
but universe should become hot to create light elements such as hydrogen, helium…

How was the universe “heated” after inflation?

“Nothing” is not really nothing in Quantum theory

How to realize hot universe filled with particles?

Nothing but expansion of the universe may be needed:



quantum mechanically, “vacuum” is filled with virtual particle and anti-particle pairs
→ energy of the expansion may materialize particle and anti-particles to be real ones
→ particles can be created from nothing!!

Quantum theory in the expanding universe shows unexpected behavior
e.g. enhanced particle production processes without energy conservation

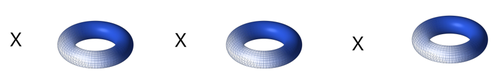
H. Taya , **YY** [JHEP 02 (2023) 048]

Microscopic extra dimensions

We don’t know the # of dimensions in our universe!

string theory suggests macroscopic 3 dimensions with very tiny compact 6 dimensions
If too small, we cannot see the extra dimensions, so no inconsistency

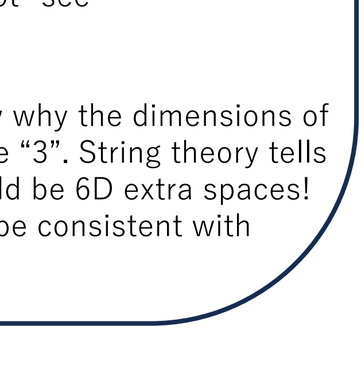
$3\mathrm{D}\ {}_{+2\mathrm{D}\ +2\mathrm{D}\ +2\mathrm{D}}\ \approx \mathbf{3D}$



Flavors and shape of “donuts”

The “shape of torus” affects the properties of particles such as mass (flavor structure) in the effective 3D universe!
→ **the choice of the donuts really matters**!

Which one does realize correct particle spectrum?



https://cerncourier.com/a/who-ordered-all-of-that/

How can the shape of donuts be determined?

torus shape is dynamical
in the theory of general relativity:

Change of the particle mass → particle creation from “vacuum”

From Einstein‘s relation $E = mc^2$, particle mass is energy
Lower energy is more stable→ produced particle should be light
→ torus shape that realizes light particles is dynamically chosen

S. Kikuchi, K. Nasu, T. Kobayashi, **YY** [JHEP08(2023) 081]