

# The exotic world of quarks!

*a stroll through modern day nuclear physics*

**Raúl Briceño**

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[https://www.jlab.org/div\\_dept/theory/staff/Briceño.html](https://www.jlab.org/div_dept/theory/staff/Briceño.html)

The logo for Jefferson Lab, featuring the text "Jefferson Lab" in a bold, black, sans-serif font. A red swoosh underline is positioned above the text, starting from the left and curving under the word "Jefferson". A small red sphere is located at the end of the swoosh on the left side.

**Jefferson Lab**



Richmond, April. 2015

# Disclaimer

*JLab is a world class research facility with hundreds of participating scientists from all over the world. I am just one of the many.*

*This talk is not a reflection on the lab's priorities, goals or mission statement.*

*This talk is my personal take on some of the fascinating ideas being explored in the lab and elsewhere in the world.*

*Enjoy*

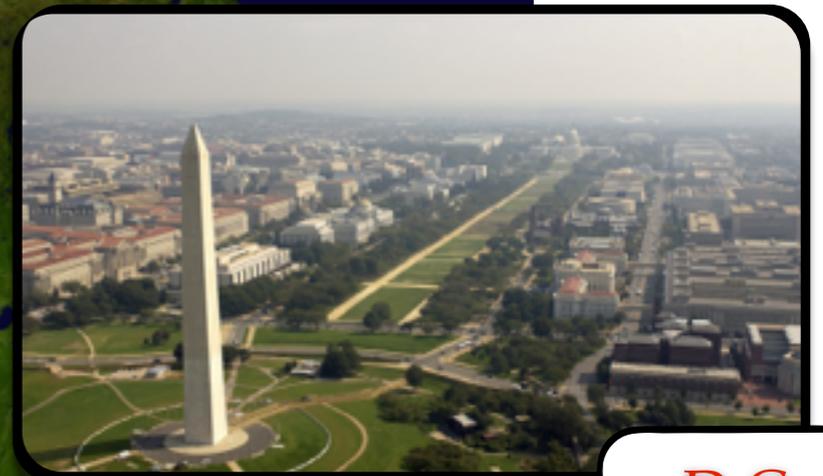


# Who am I?



Caracas, Venezuela

# Who am I?

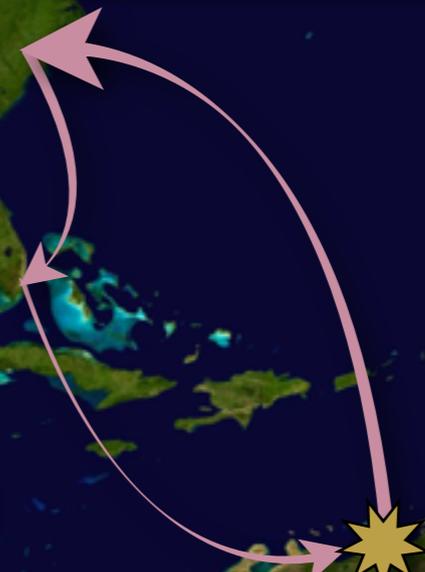


D.C.



Miami

Caracas, Venezuela



# Who am I?



New College of Florida  
Sarasota, FL

Caracas, Venezuela

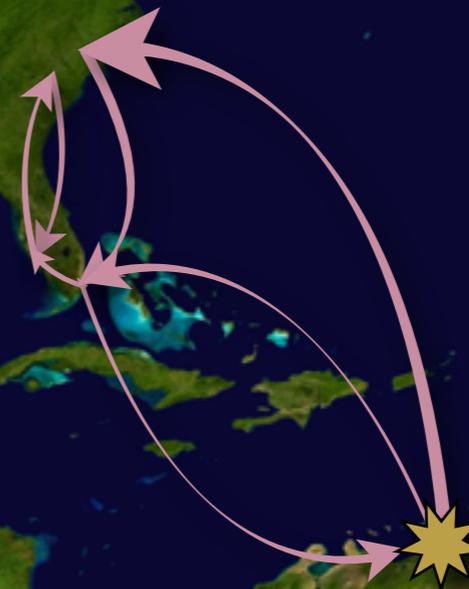


# Who am I?



JLab

Caracas, Venezuela



# Who am I?



Seattle

Caracas, Venezuela

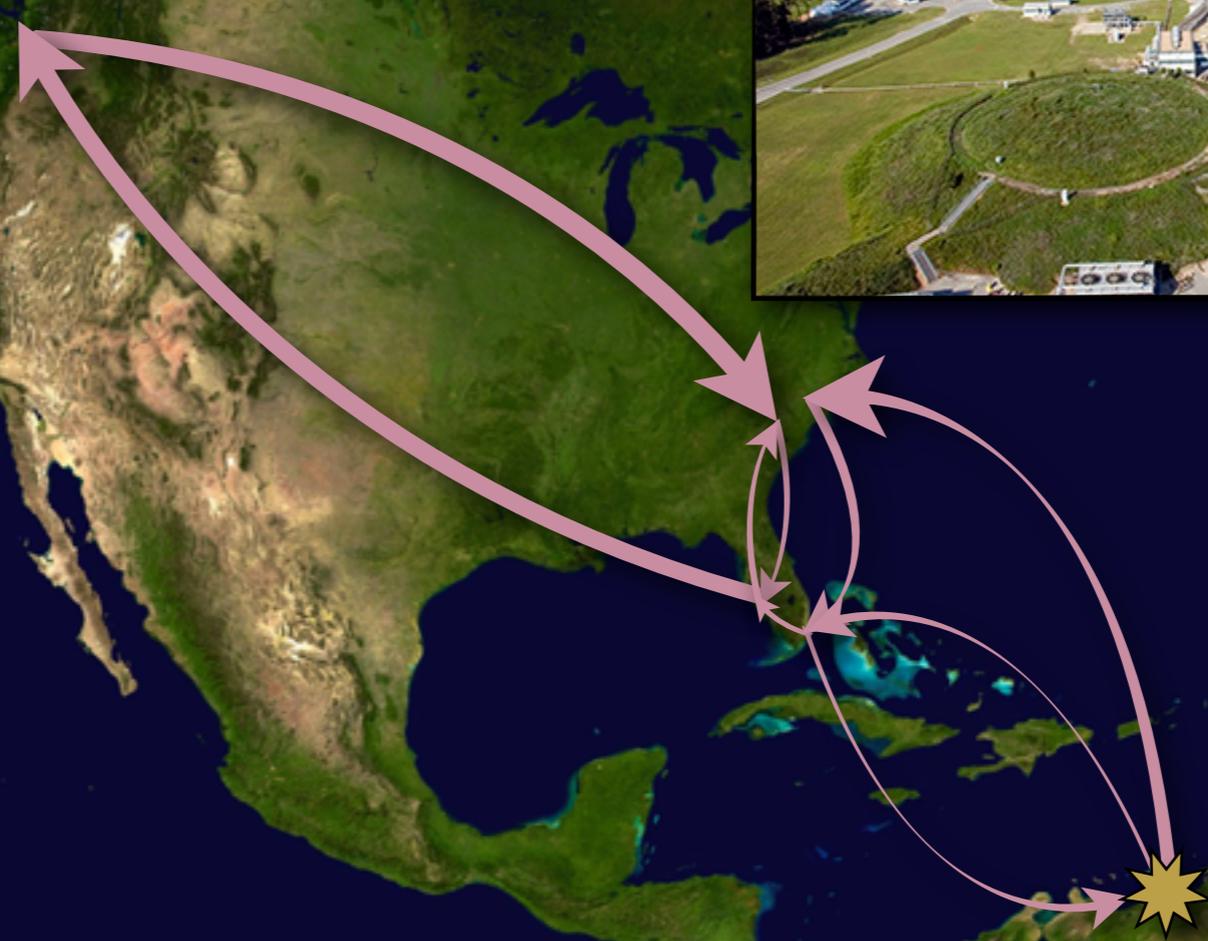


# Who am I?



JLab

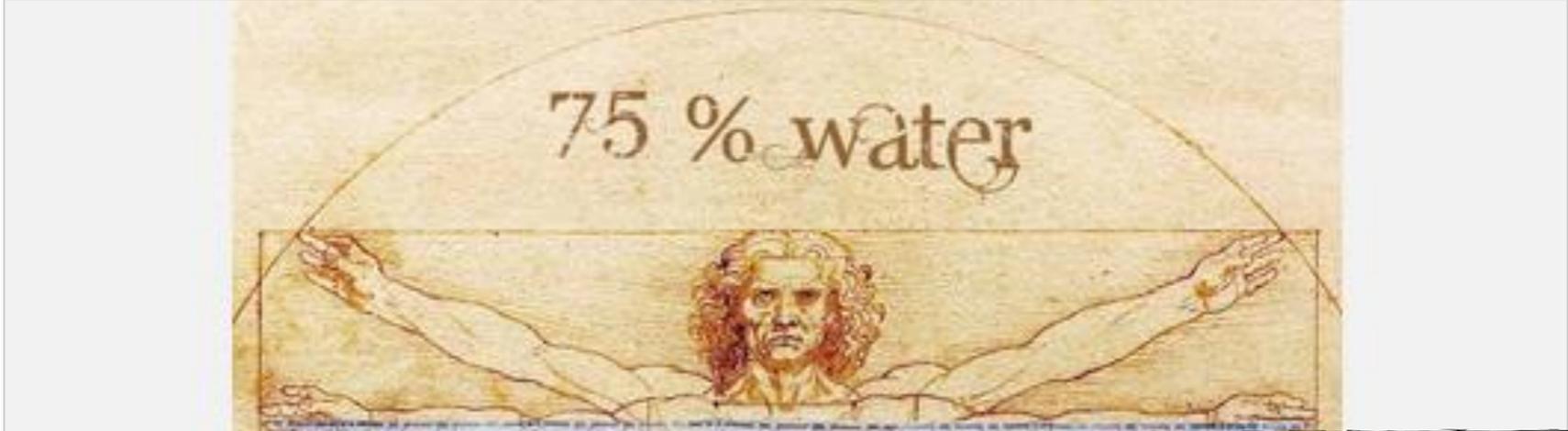
Caracas, Venezuela



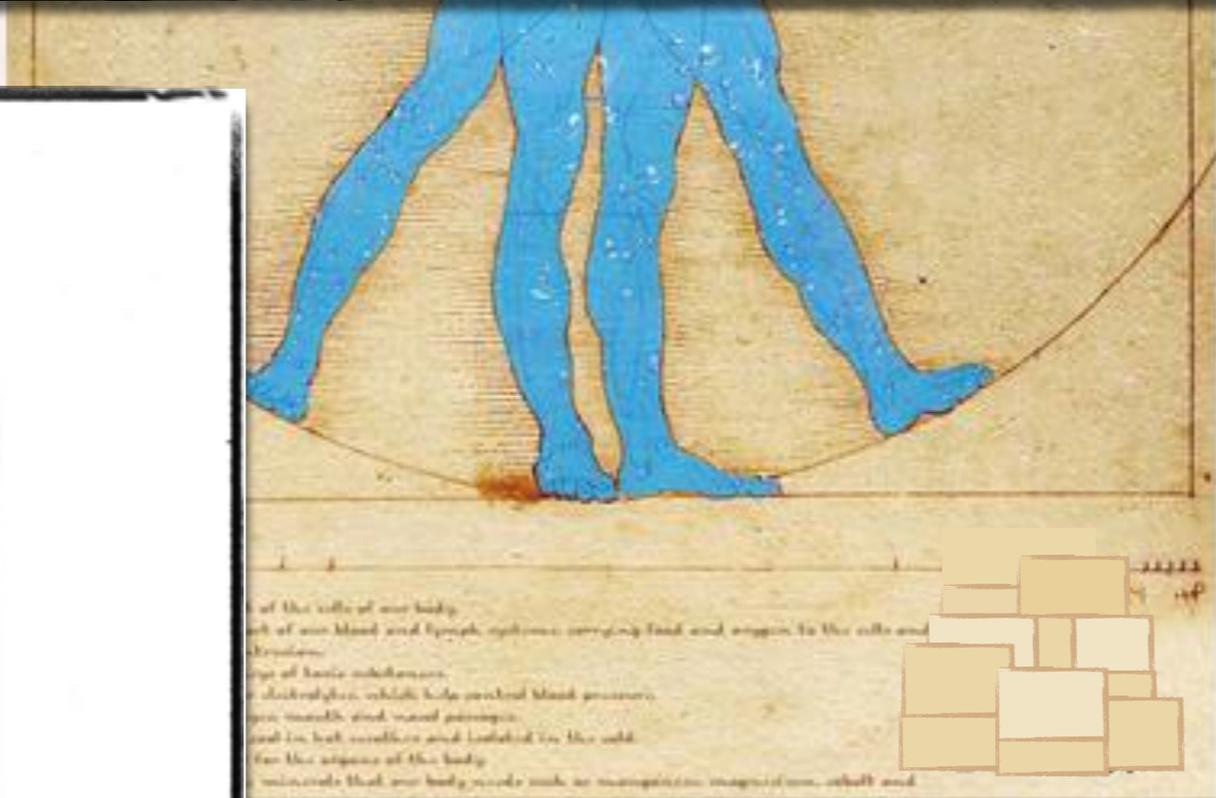
OK, Let's

Dive in





You are actually 95% Glue!



what does this mean?

is this true?

how do we know this?

You are actually 95% Glue!



what does JLab have to do with this?

what do I have to do with this?

**Nuclear?**

JLab is a nuclear physics lab  
I am a theoretical nuclear physicist



# The nucleus

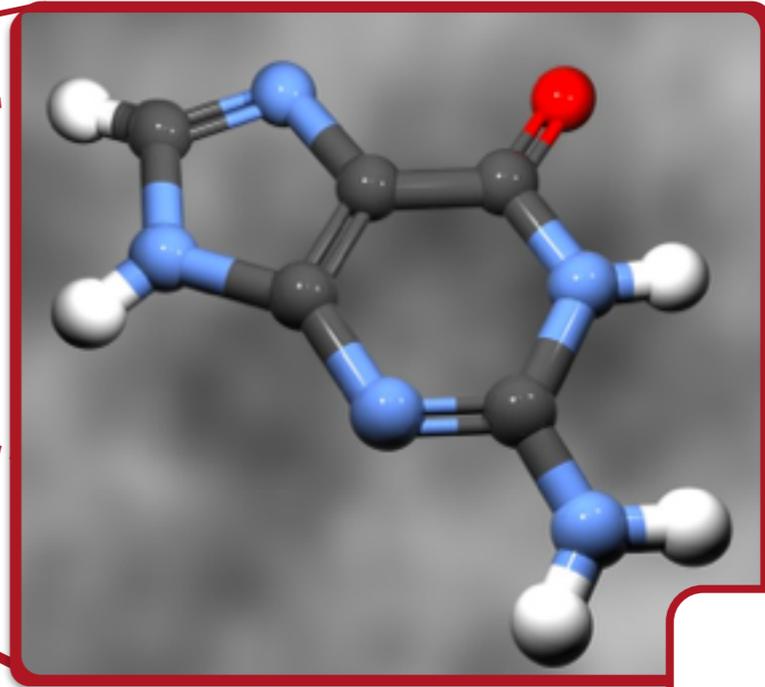


*DNA*

# The nucleus



*DNA*

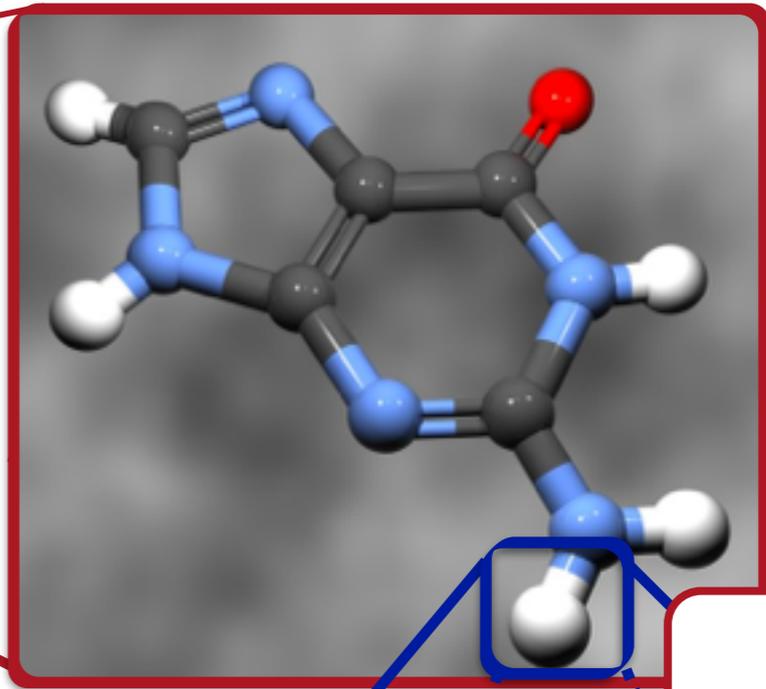


*Guanine  
molecule*

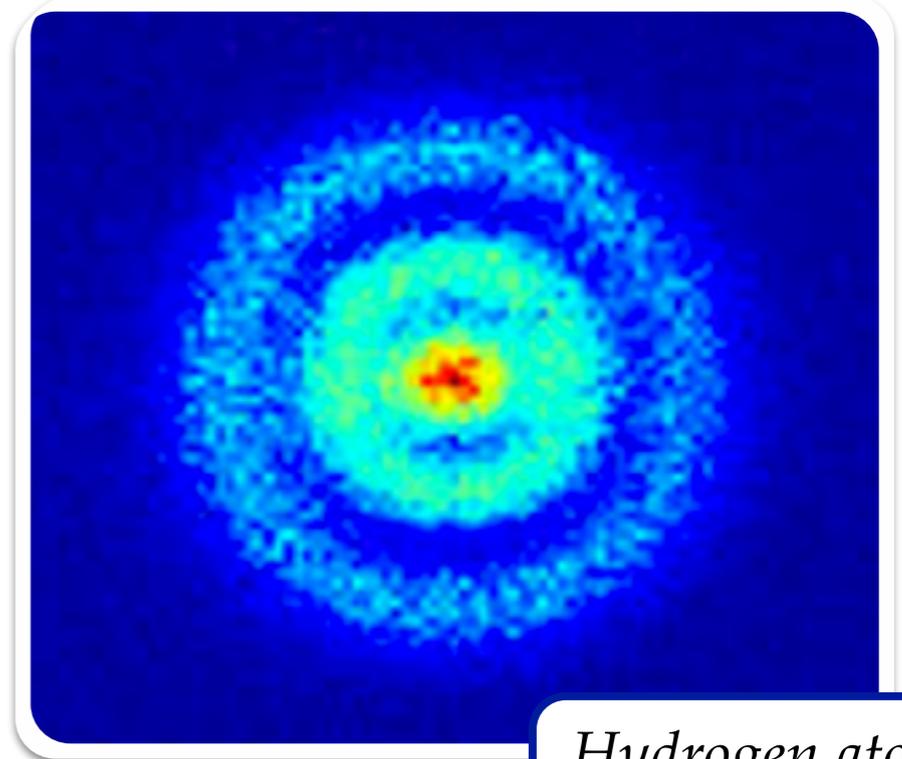
# The nucleus



*DNA*



*Guanine molecule*

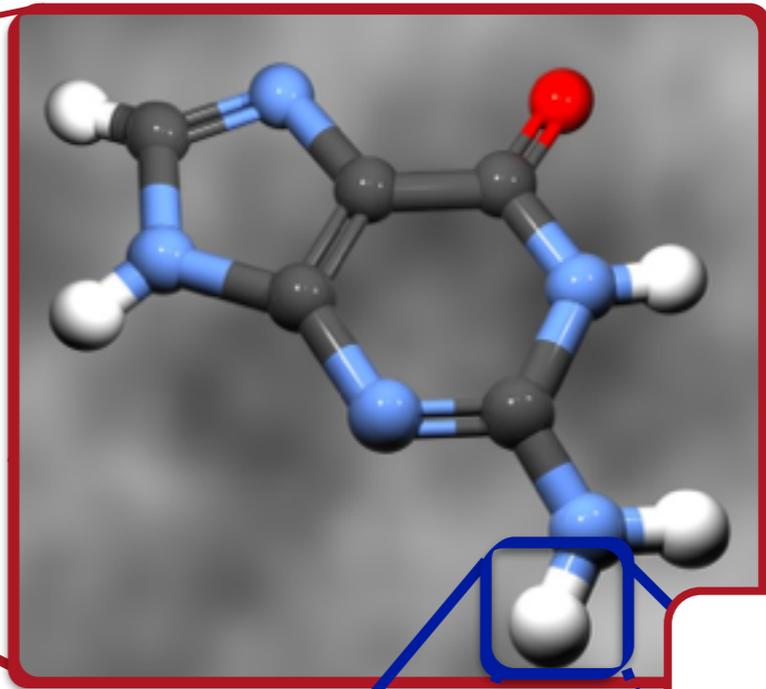


*Hydrogen atom*

# The nucleus

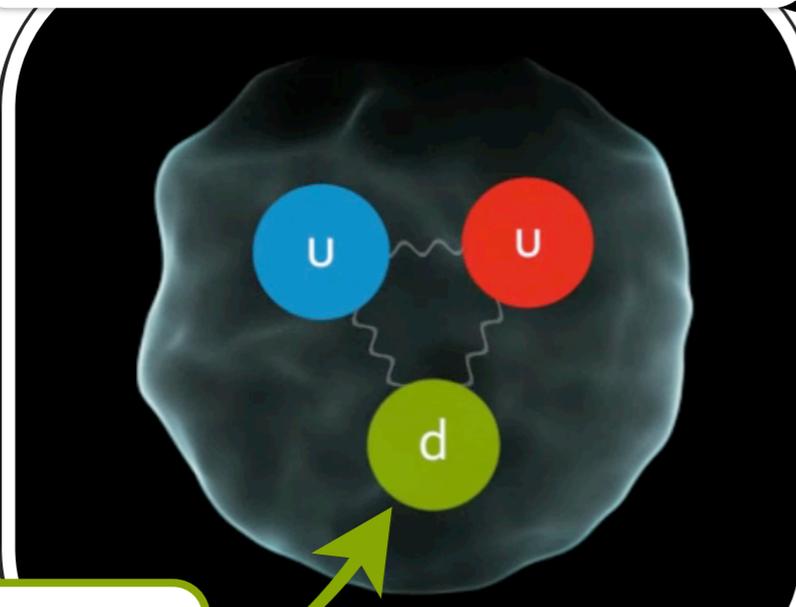


DNA



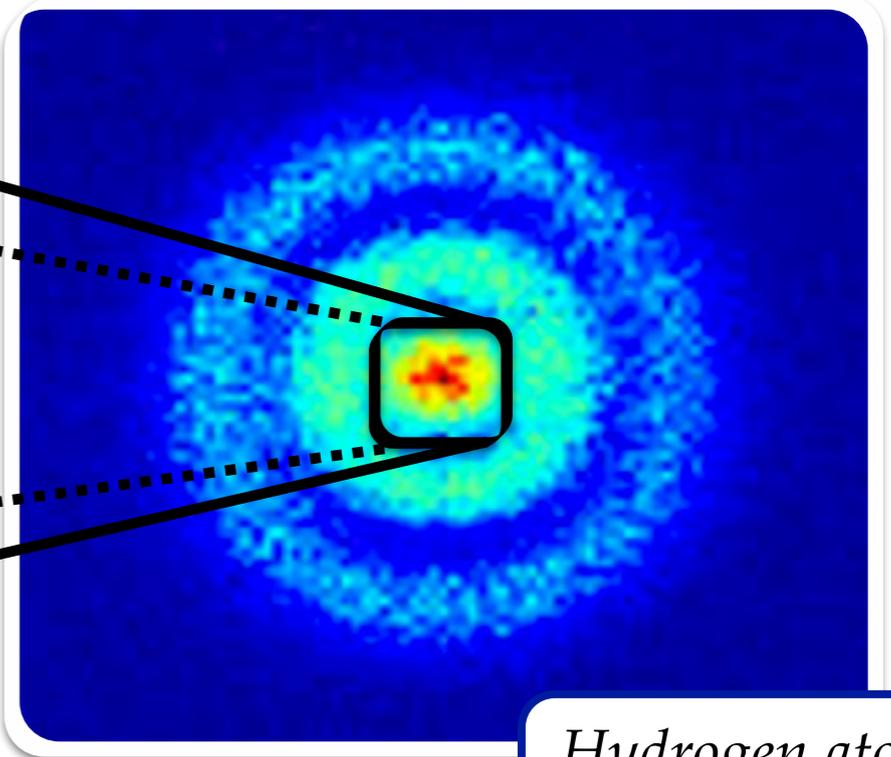
Guanine molecule

*proton, carries 99.95% of hydrogen's mass*



quarks

*proton: the lightest nucleus*



Hydrogen atom

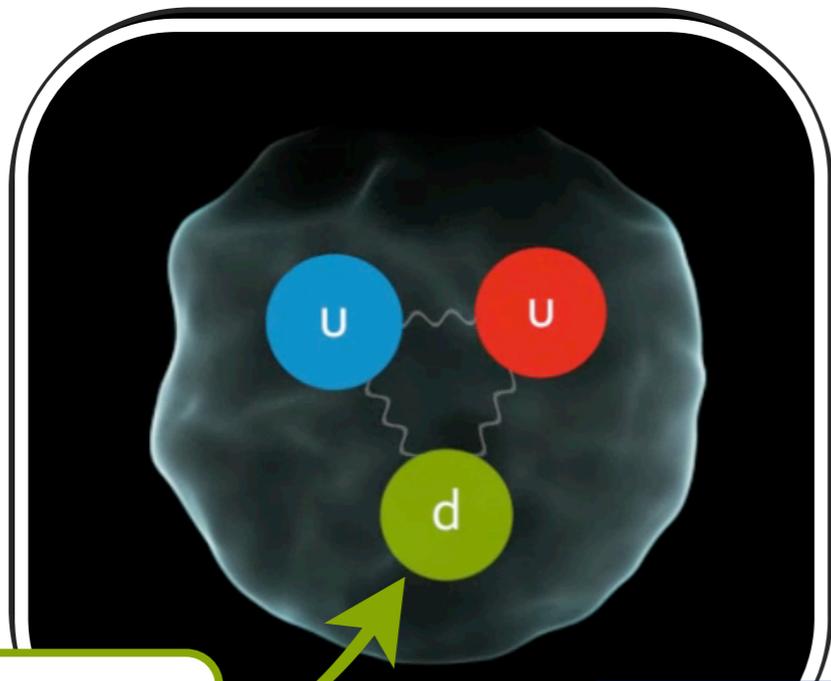
# The nucleus

in general, nuclei are composed of **protons** and **neutrons**

example:  $^{12}\text{C}$ , the basis of life, is made of 6 protons and 6 neutrons

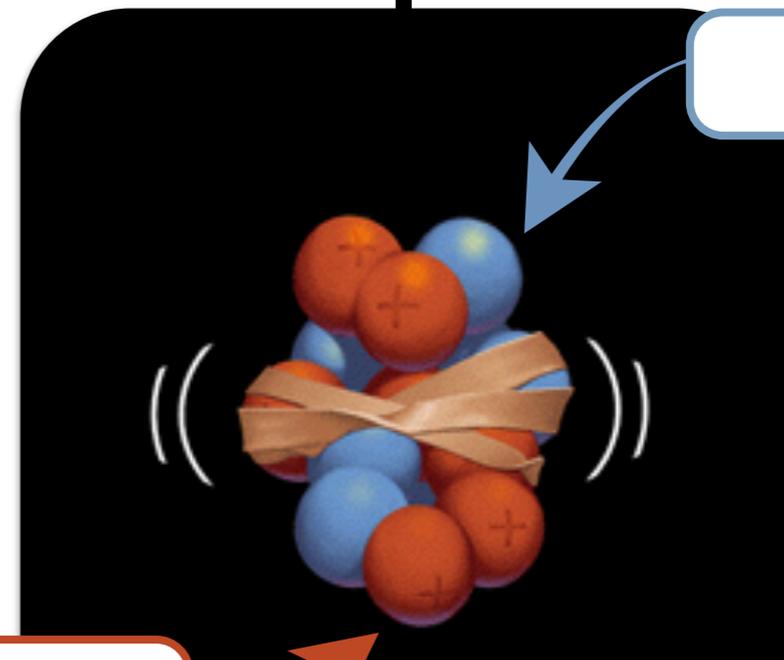
these interact and are bound together by the strong nuclear force

nuclear physics = physics of the strong nuclear force



*quarks*

*proton: the lightest nucleus*

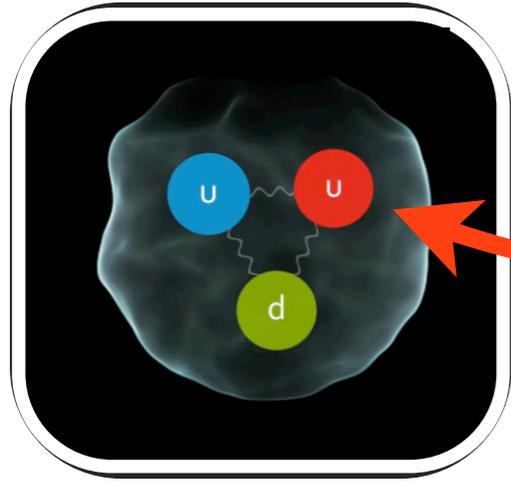


*neutrons*

*protons*

*nuclei*

# A sense of scale



*radius of a quark = 0 (?)*

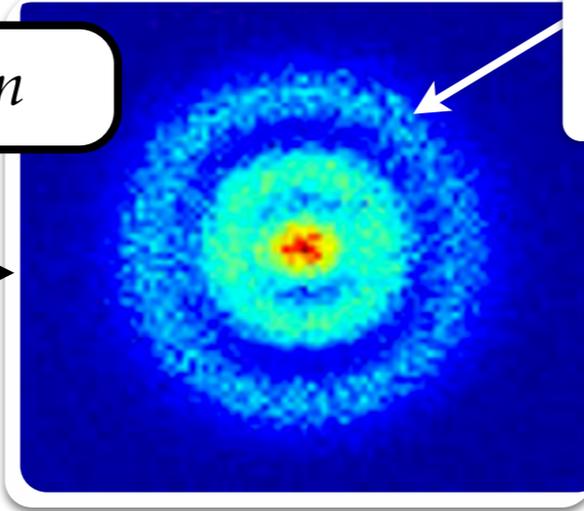
*the proton: radius  $10^{-15}$  m = 1fm*  
 $10^{-15}=0.0000000000000001$

# A sense of scale



x 100,000

hydrogen



*the electron cloud: responsible for electricity, chemistry, ...*

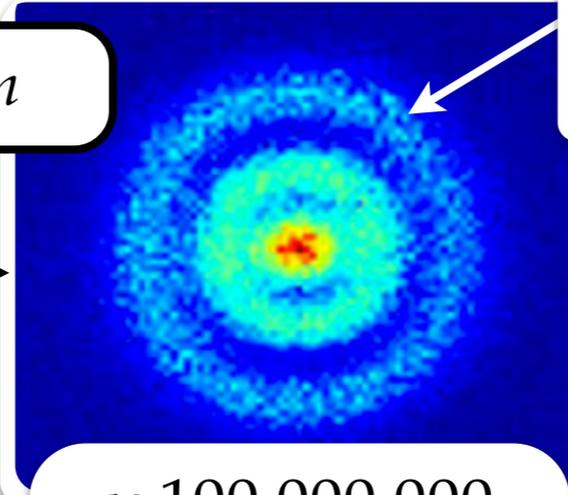
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x 100,000

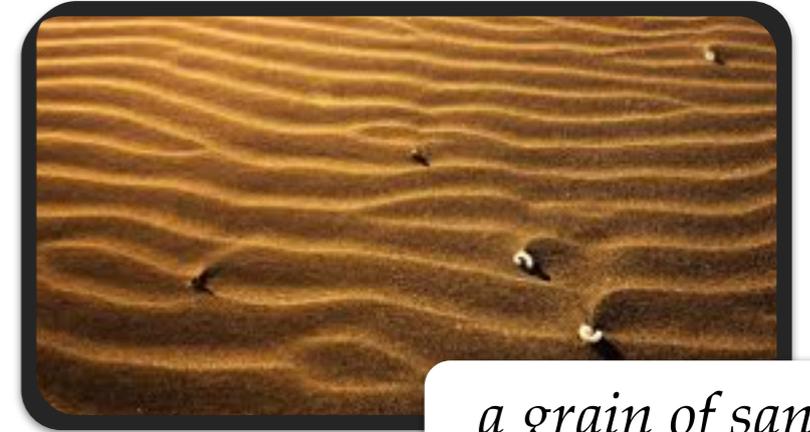
hydrogen



*the electron cloud: responsible for electricity, chemistry, ...*

x 100,000,000

100 million



*a grain of sand*

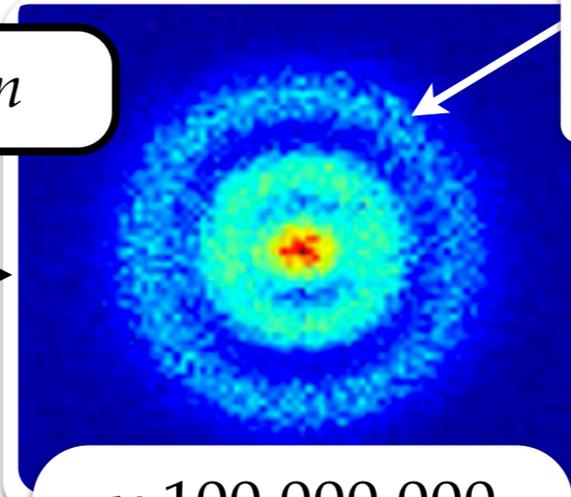
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# A sense of scale



hydrogen

x 100,000



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*the proton: radius  $10^{-15}$  m = 1fm*  
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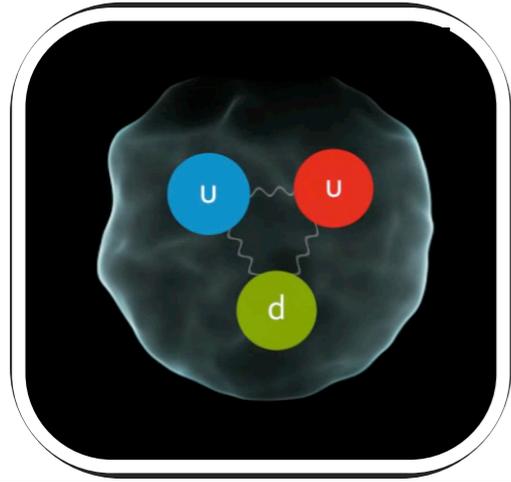
x 100,000,000

100 million



*Mt. Rainier*

# Quantum mechanics in a nutshell

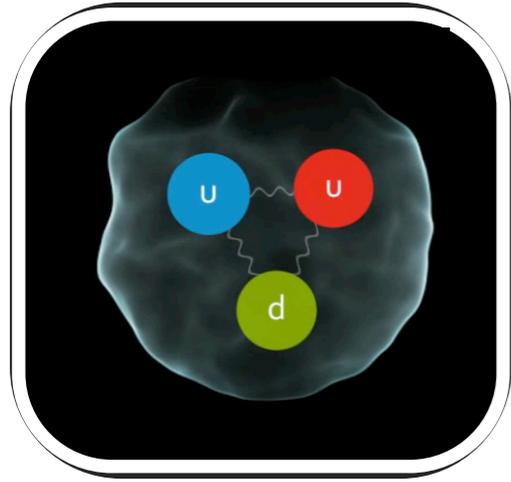


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today we are interested in thinking about the small world where these particles *"live in"*

we should not expect the rules of the everyday world to apply to subatomic particles!

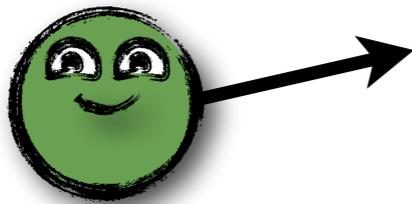
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example #1: we never really know where they are and where they are going



"I think I saw the particle here moving in that direction"

time=0 sec

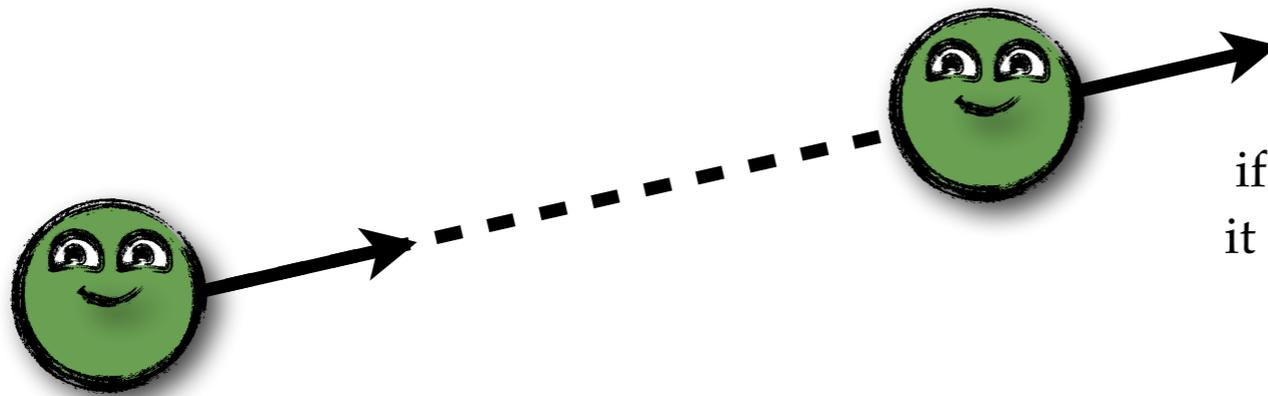
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if the particle were a baseball, it would be here at time = 1sec

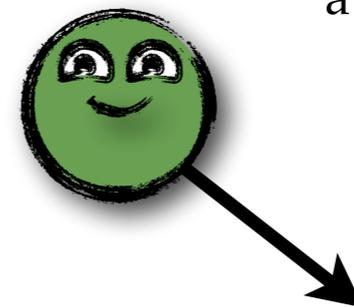
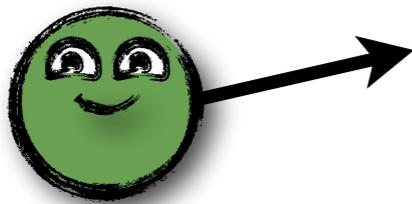
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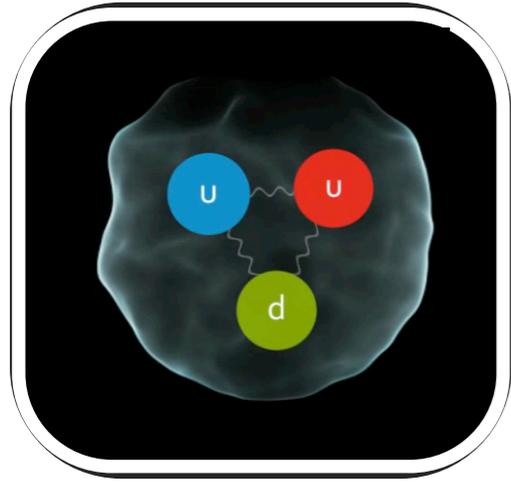
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example #1: we never really know where they are and where they are going



a atomic/subatomic particle  
could end up here  
at time = 1sec

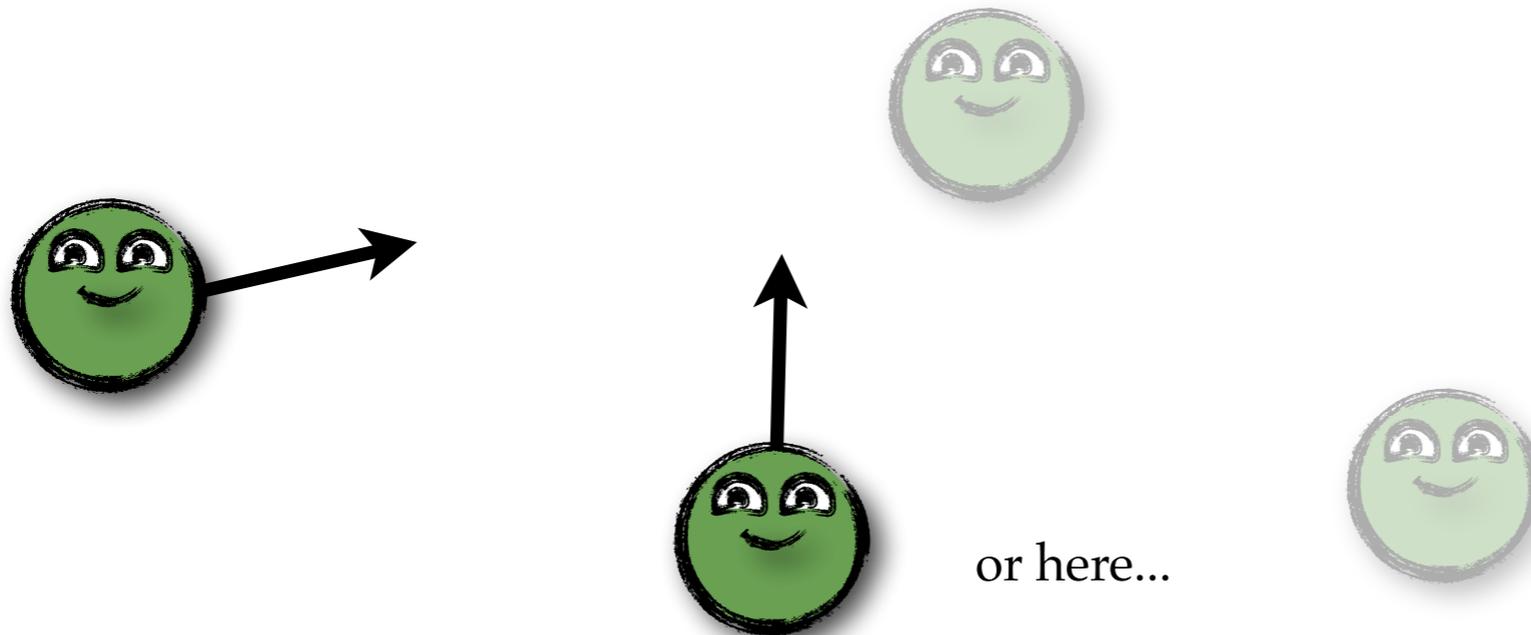
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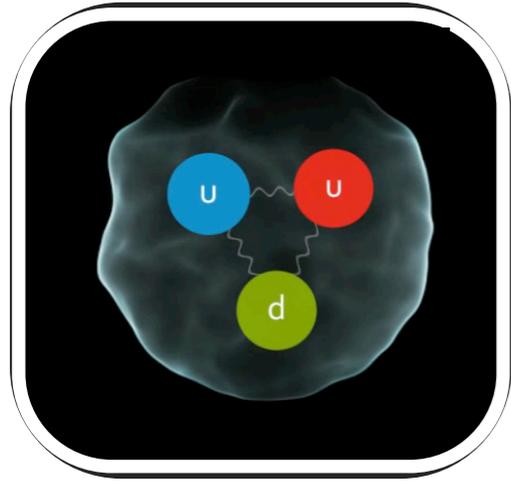
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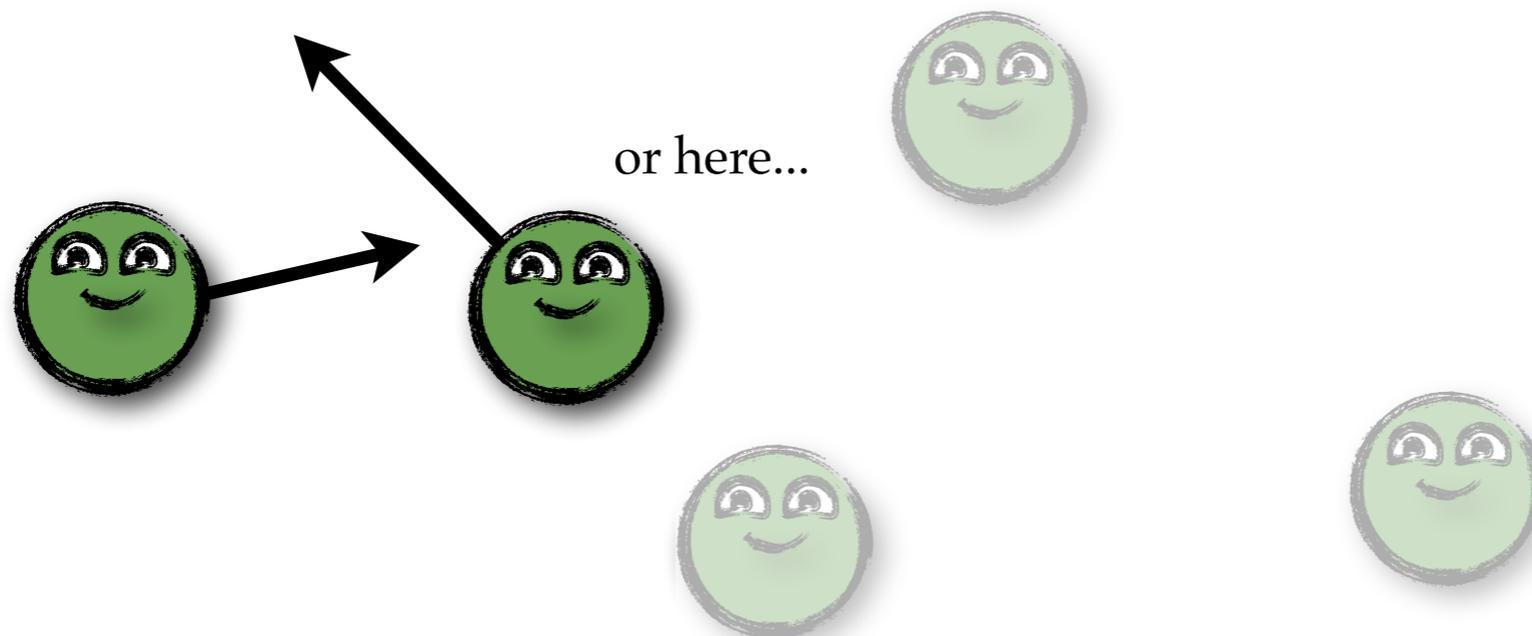
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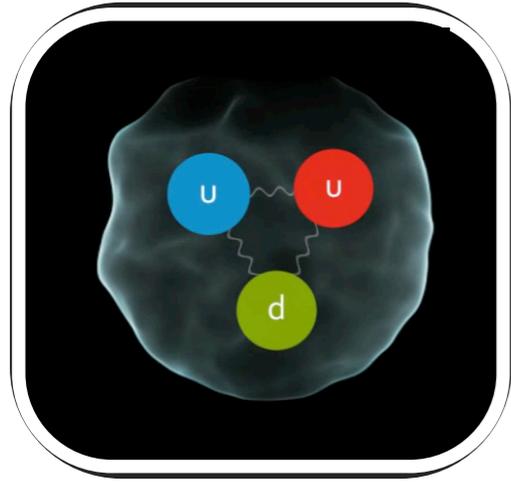
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# Quantum mechanics in a nutshell



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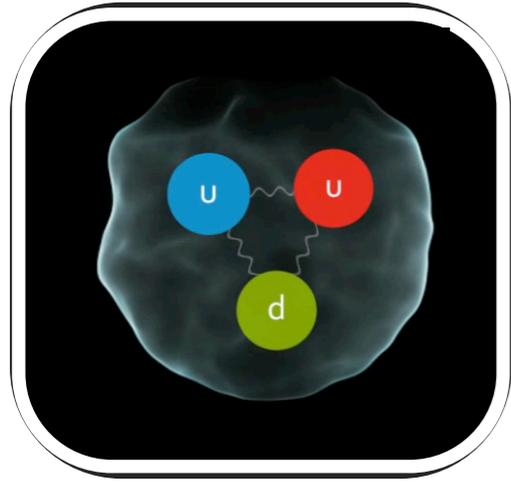
**example #1:** we never really know where they are and where they are going

The uncertainty principle of quantum mechanics

*"the universe is made of an infinite number of games of chance happening in every instance of time"*



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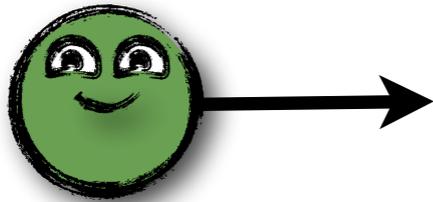
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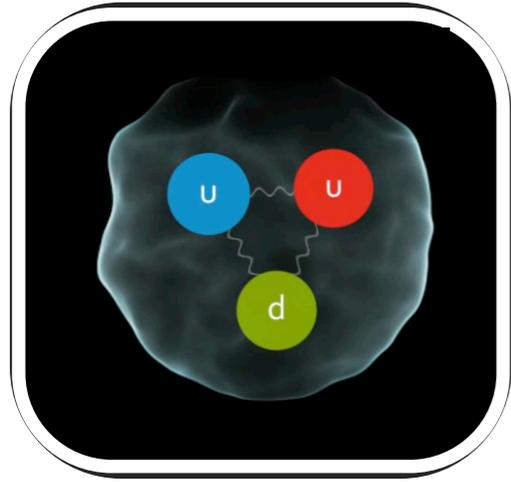
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example #2: particles can instantaneously transformed into other particles



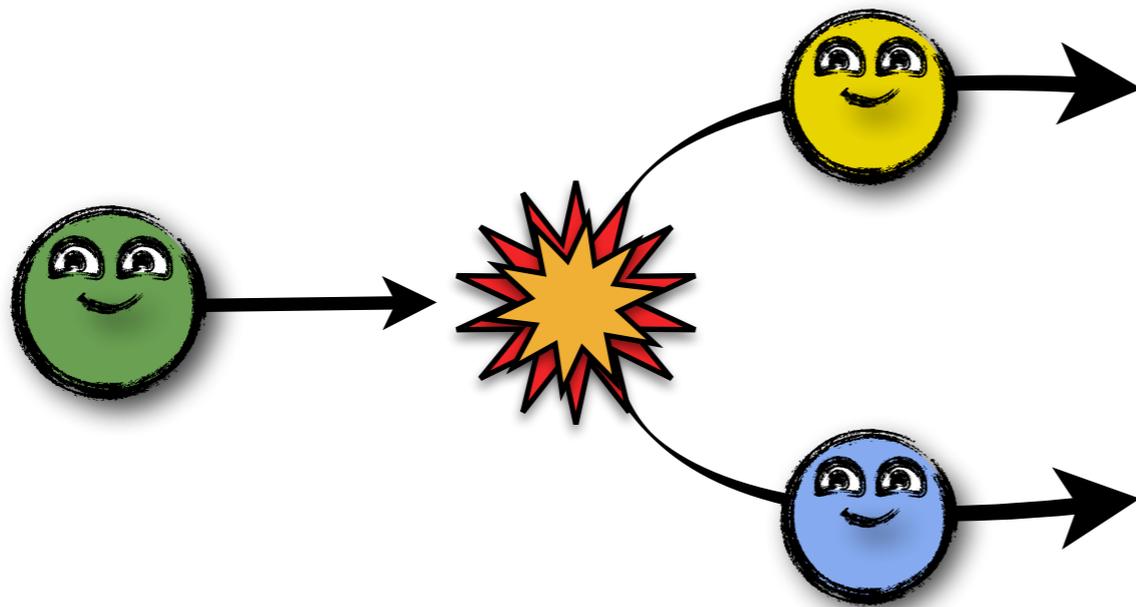
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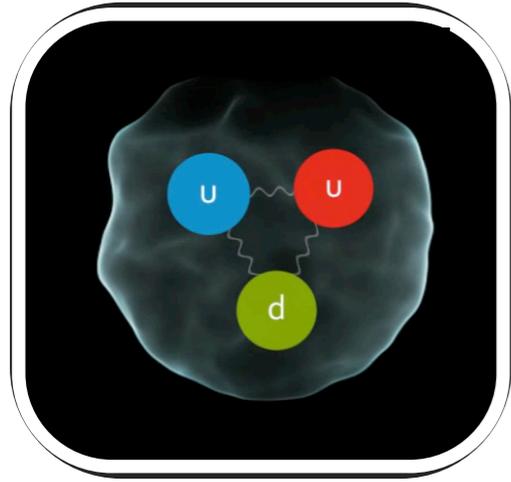
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$$E=mc^2$$

this is allowed by  
Einstein's theory of relativity

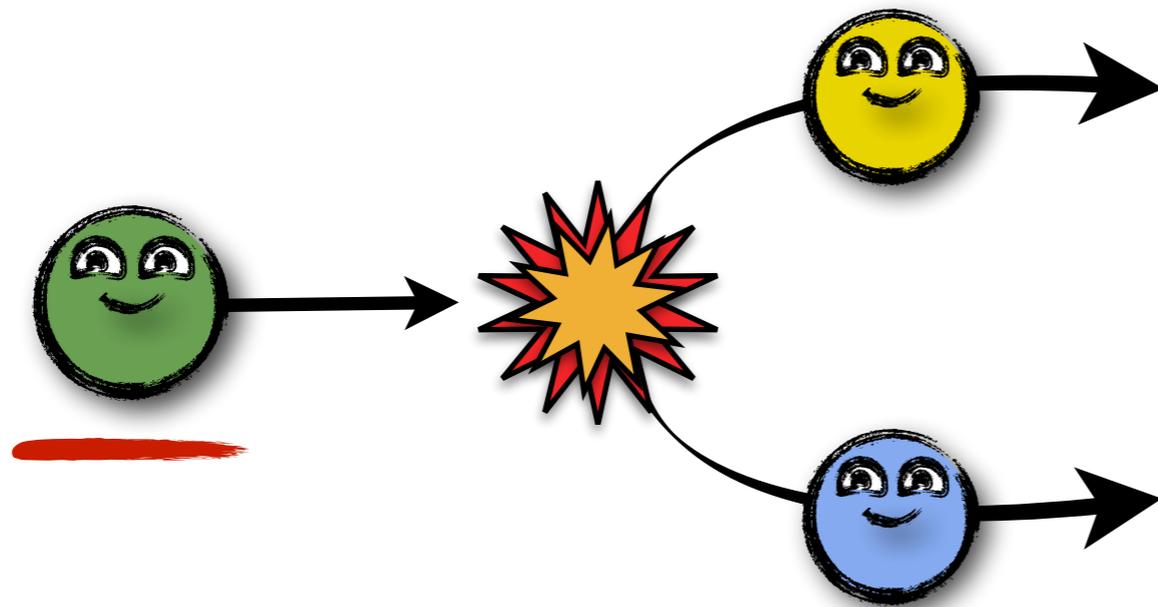
# Quantum mechanics in a nutshell



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$$E = mc^2$$

Mass of the initial particle

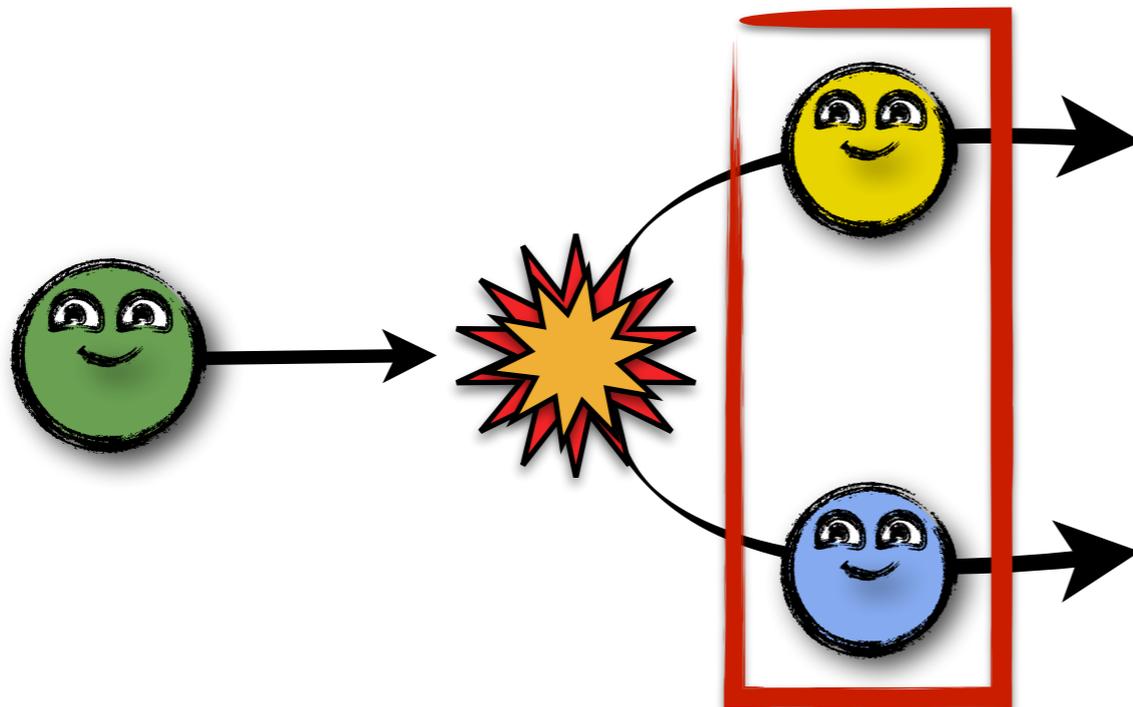
# Quantum mechanics in a nutshell



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example #2: particles can instantaneously transformed into other particles



$$E=mc^2$$

the total energy of the final two particles

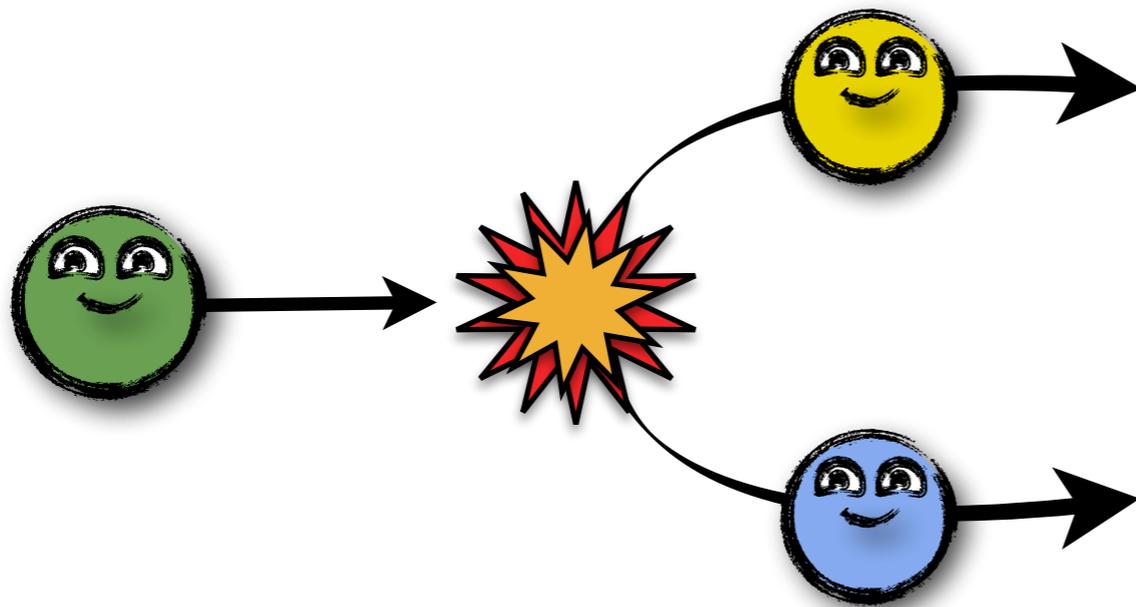
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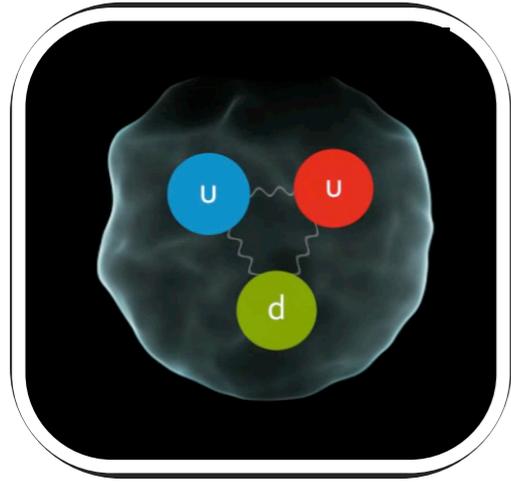


$$E=mc^2$$

speed of light:

300 million meters per second  
(in order words, a big number!)

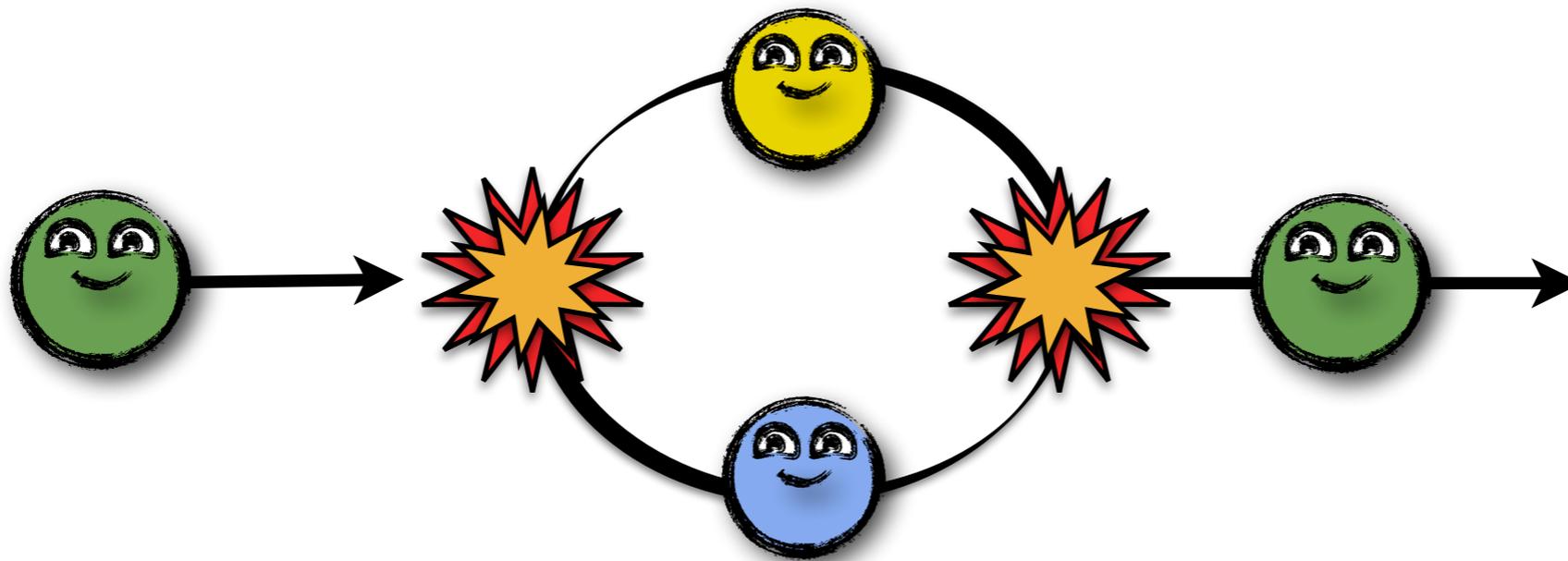
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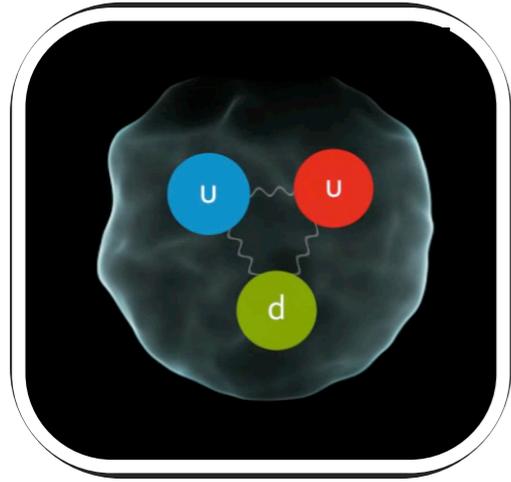
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example #2: particles can instantaneously transformed into other particles



this could be a momentary transition...

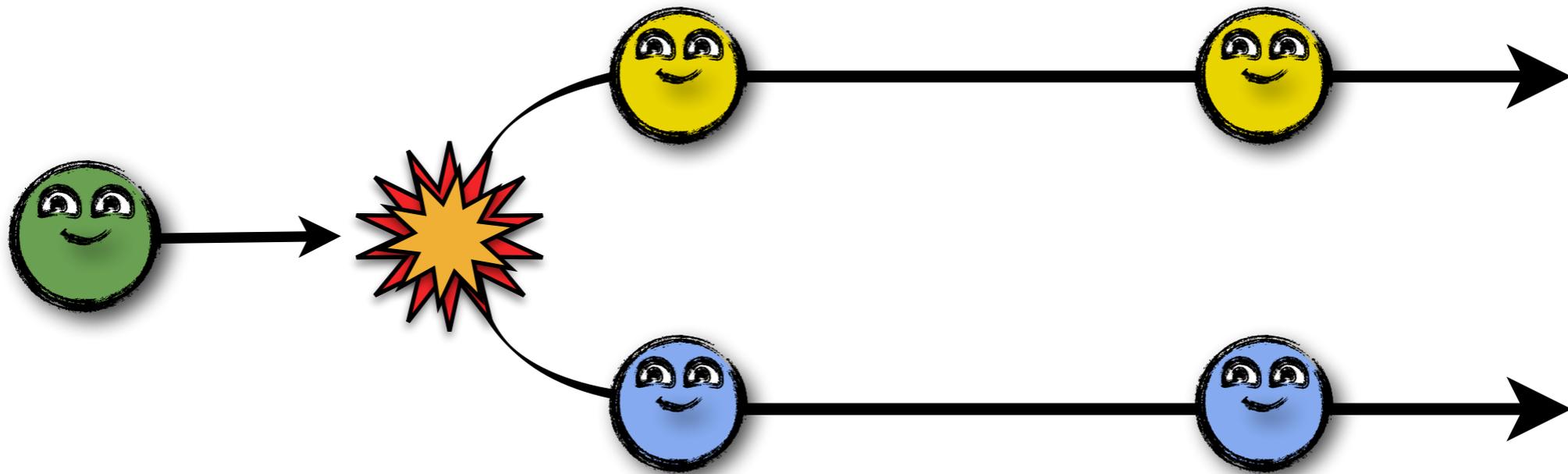
# Quantum mechanics in a nutshell



today we are interested in thinking about the small world where these particles *"live in"*

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example #2: particles can instantaneously transformed into other particles



or it could be a permanent one...

# Quantum mechanics in a nutshell



example #2: parti

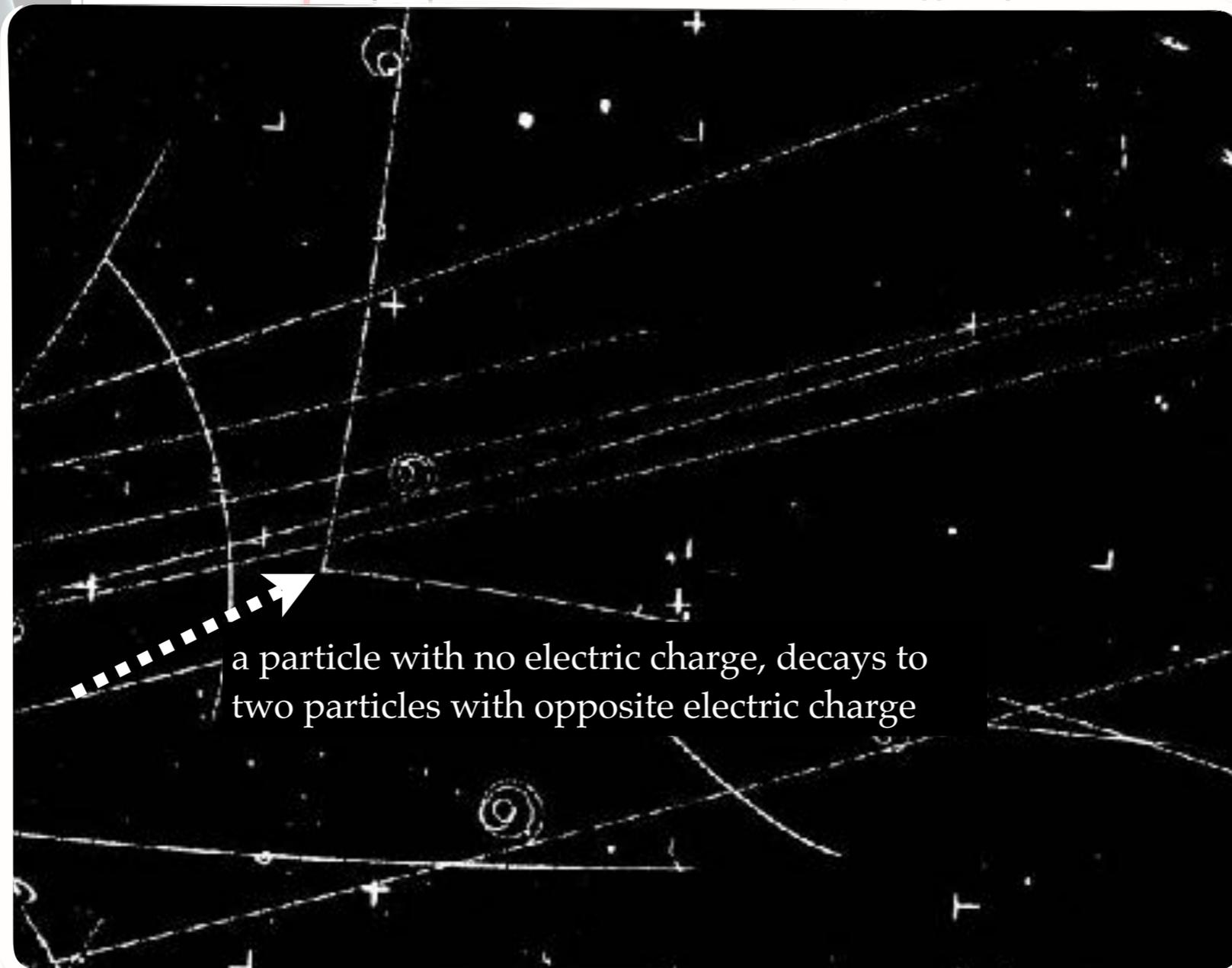


or it could be a permanent one...

# Quantum mechanics in a nutshell



example #2: parti

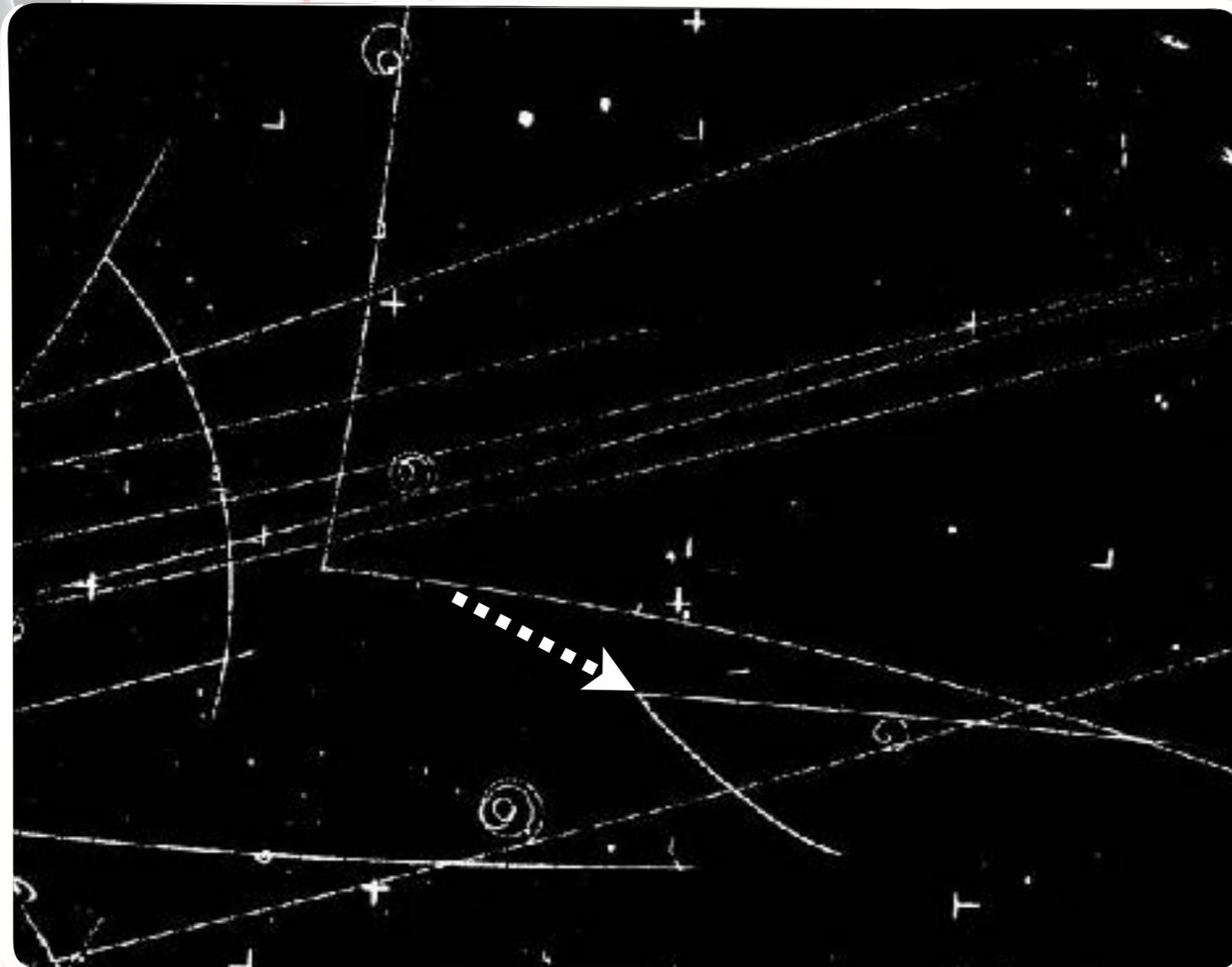


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# Quantum mechanics in a nutshell



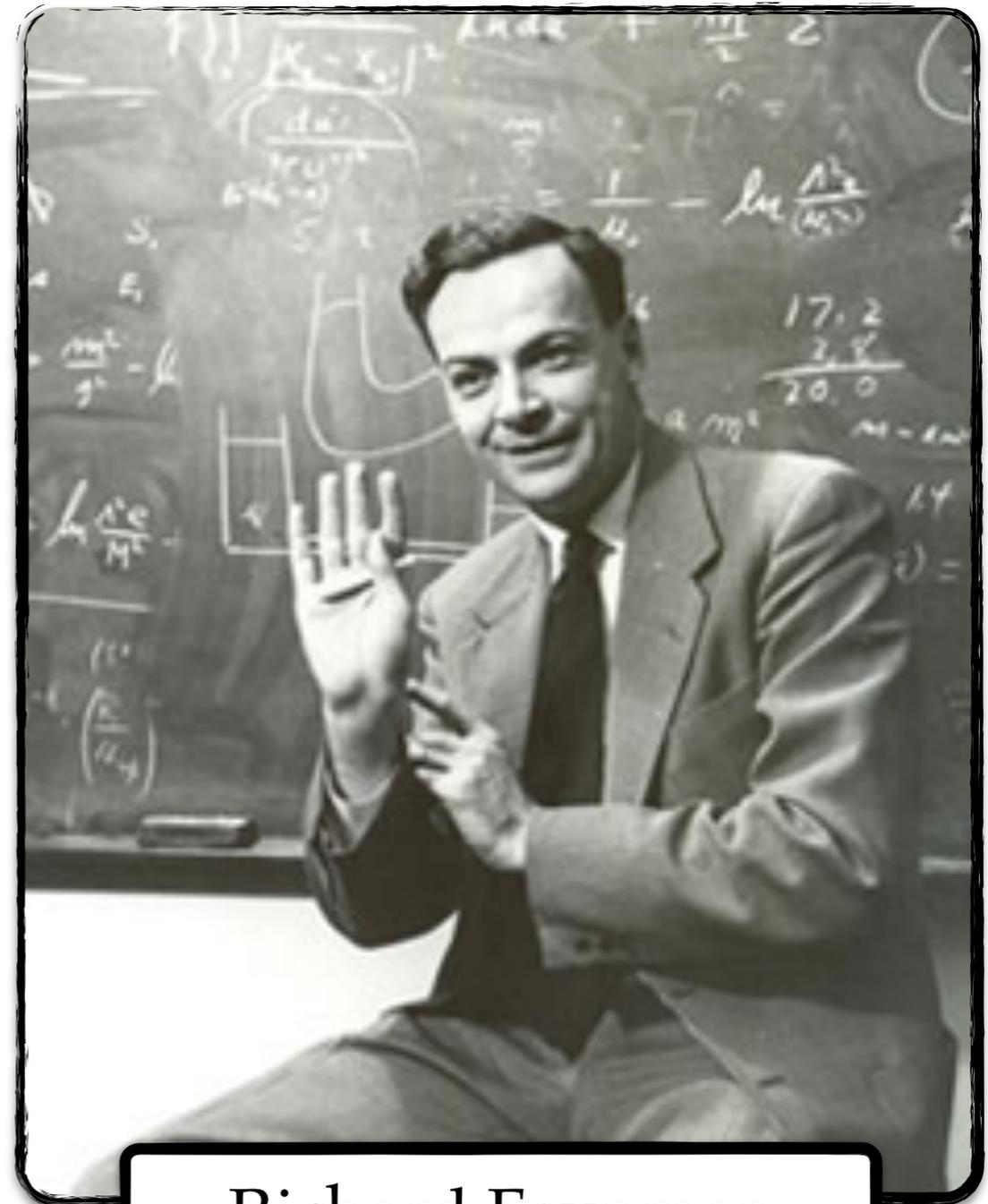
example #2: parti



or it could be a permanent one...

# Particle accelerators

Step #0: write down theory, and make a prediction!



Richard Feynman

# Particle accelerators

Step # 0: write down theory, and make a prediction!

Step # 1: accelerate particles to speeds close to the speed of light!



# Particle accelerators

Step # 0: write down theory, and make a prediction!

Step # 1: accelerate particles to speeds close to the speed of light!

Step # 2: smash them against each other

this can create a smattering of particles



# Particle accelerators

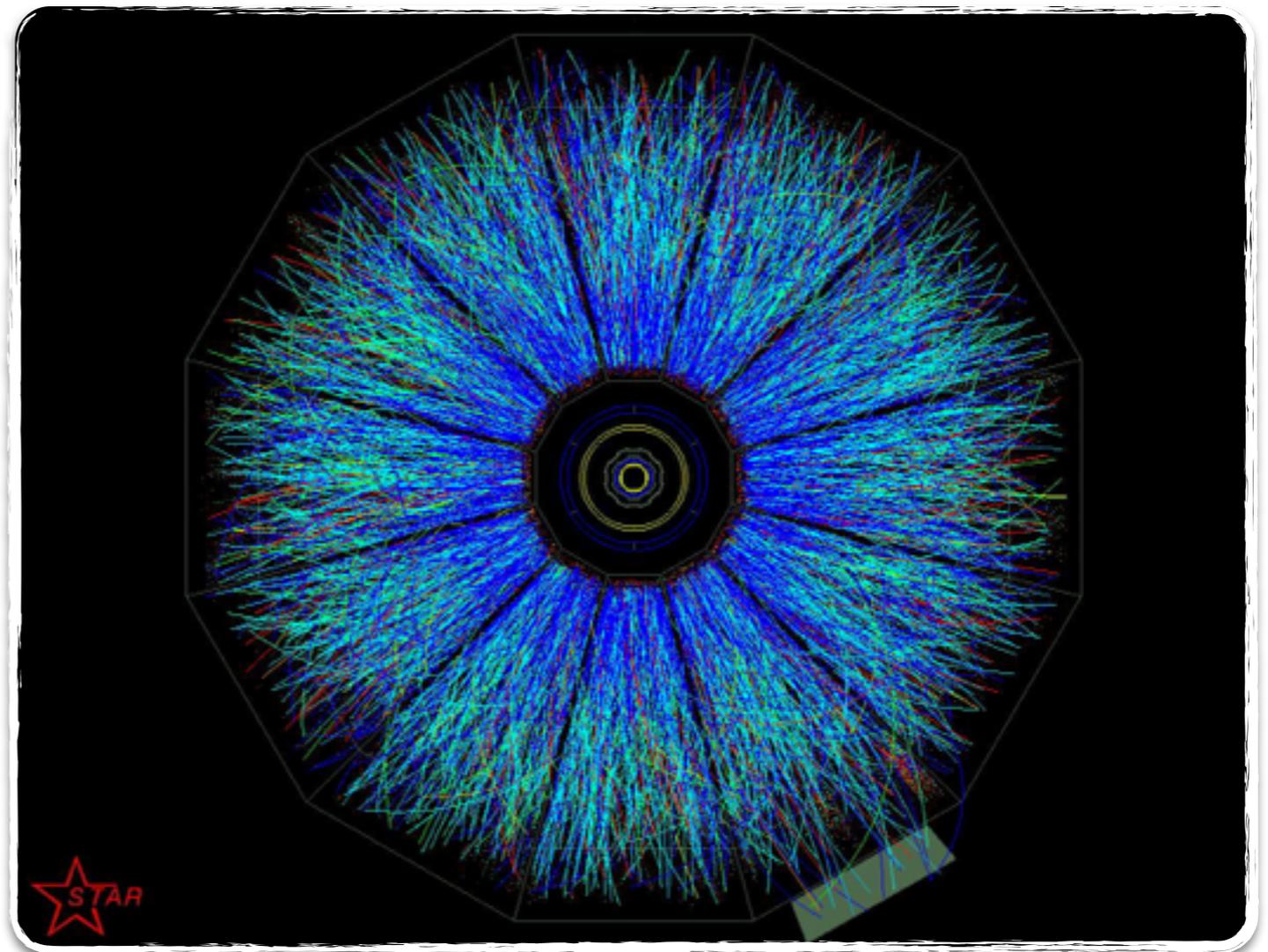
Step # 0: write down theory, and make a prediction!

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this can create a smattering of particles

Step # 3: detect the debris



# Particle accelerators

Step # 0: write down theory, and make a prediction!

Step # 1: accelerate particles to speeds close to the speed of light!

Step # 2: smash them against each other

this can create a smattering of particles

Step # 3: detect the debris

Step # 4: compare the outcome with theory

without theory, there's no meaning to experiments!

without experiments we do not know which theory is right!

# Particle accelerators

Step # 0: write down theory, and make a prediction!

Step # 1: accelerate particles to speeds close to the speed of light!

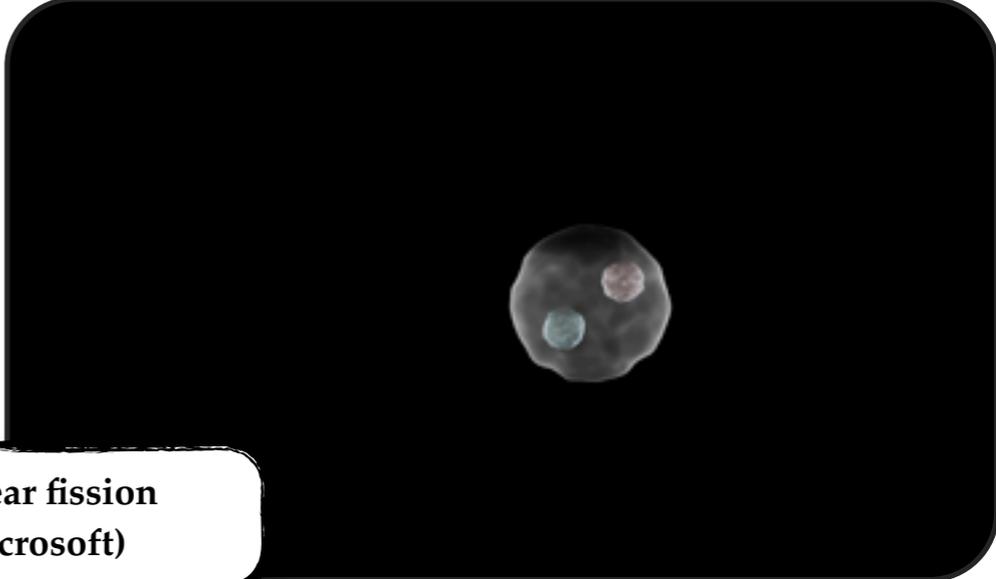
Step # 2: smash them against each other

this can create a smattering of particles

Step # 3: detect the debris

Step # 4: compare the outcome with theory

Step # 5: deduce what happened in the “*crash*” from the debris (*run the movie backwards*)

An artistic rendering of nuclear fission. A central nucleus, depicted as a cluster of red and blue spheres, is shown in the process of splitting into two smaller nuclei. The background is dark, and the fission process is highlighted with a glowing effect.

artistic rendition of nuclear fission  
by Jose Rodriguez (Microsoft)

# Virginia's biggest particle accelerator

electrons are accelerated to speeds close to the speed of light

this is done in an underground beam



# Virginia's biggest particle accelerator

electrons or photons are piped  
underground

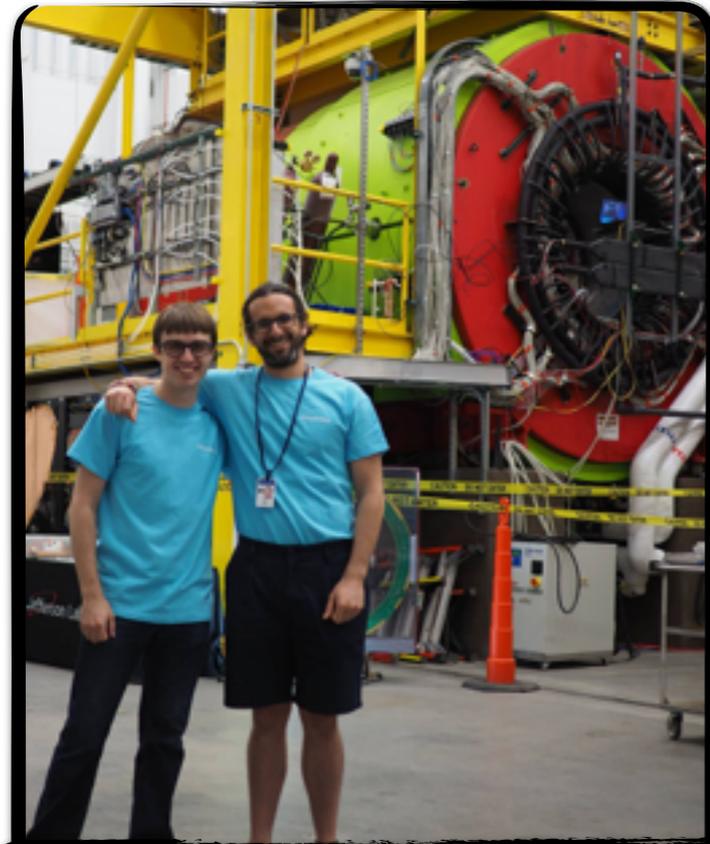


# Virginia's biggest particle accelerator

these are smashed against a target. the debris is detected in particle detector



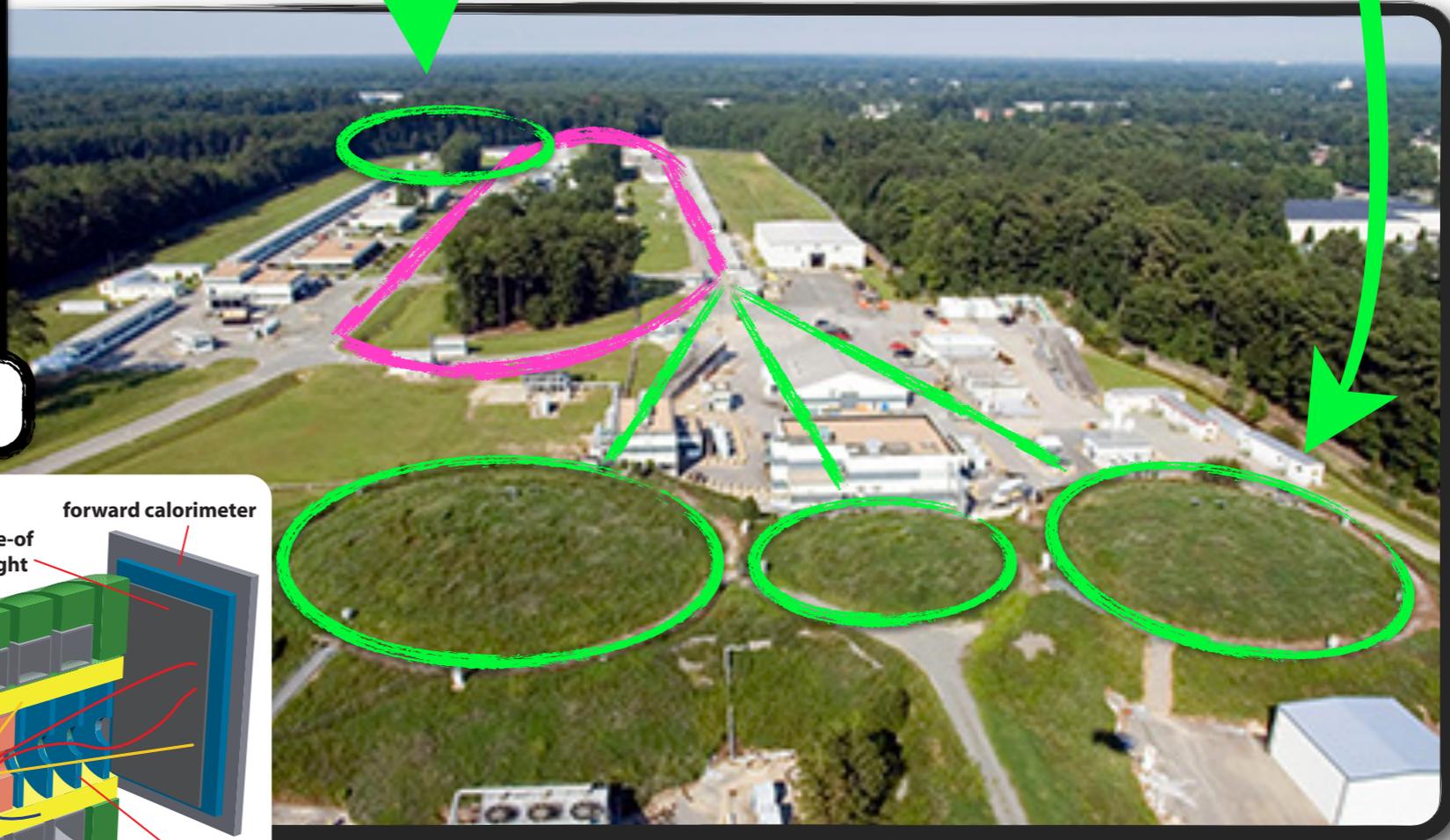
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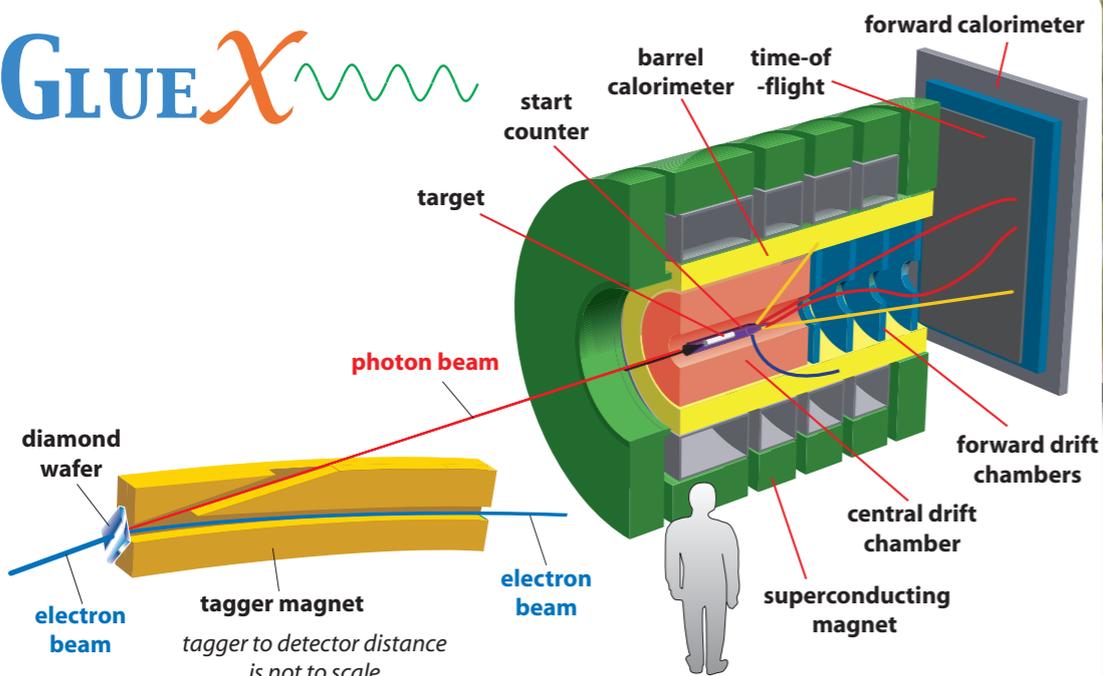
with David Wilson (ODU/JLab)

the new GlueX experiment

these are smashed against a target. the debris is detected in particle detector



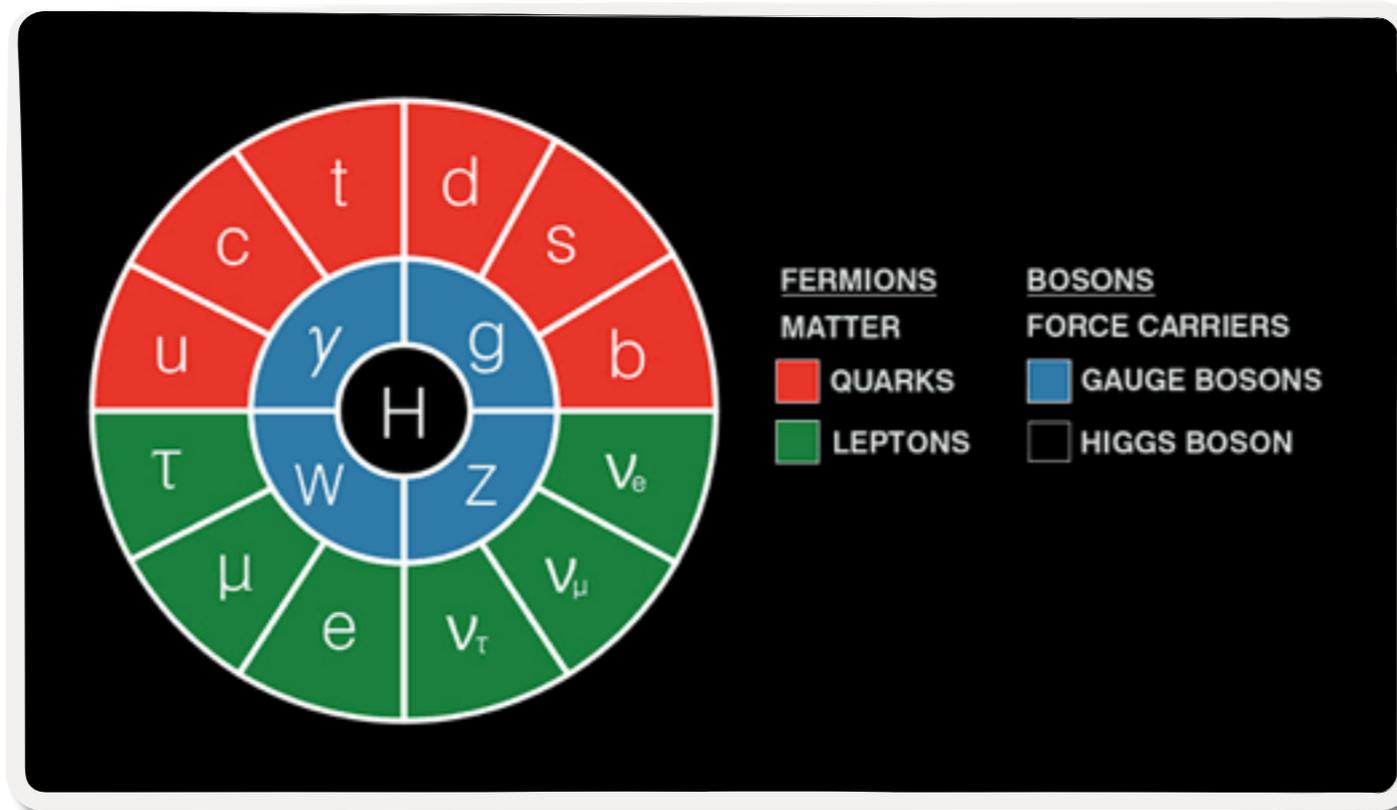
GLUE X



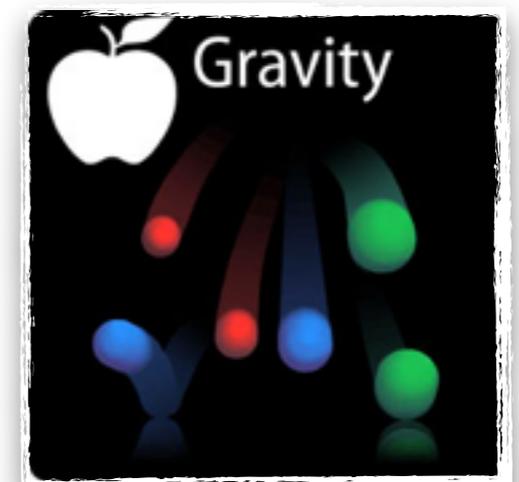
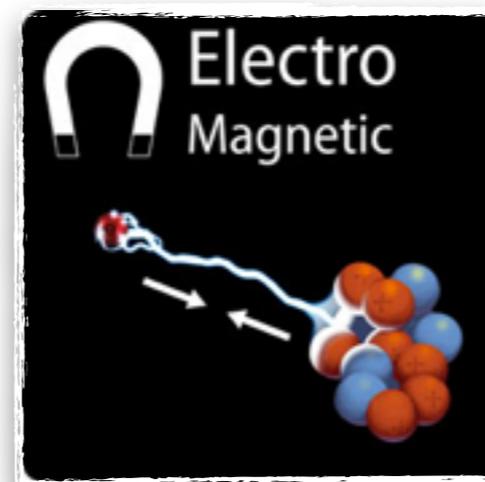
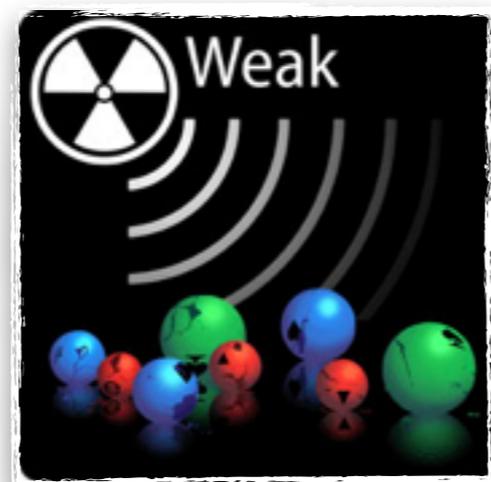
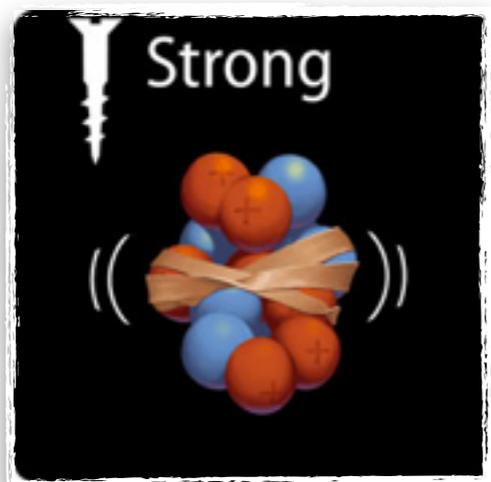
you too can visit lab and its various experiments!

# The standard model of particle physics

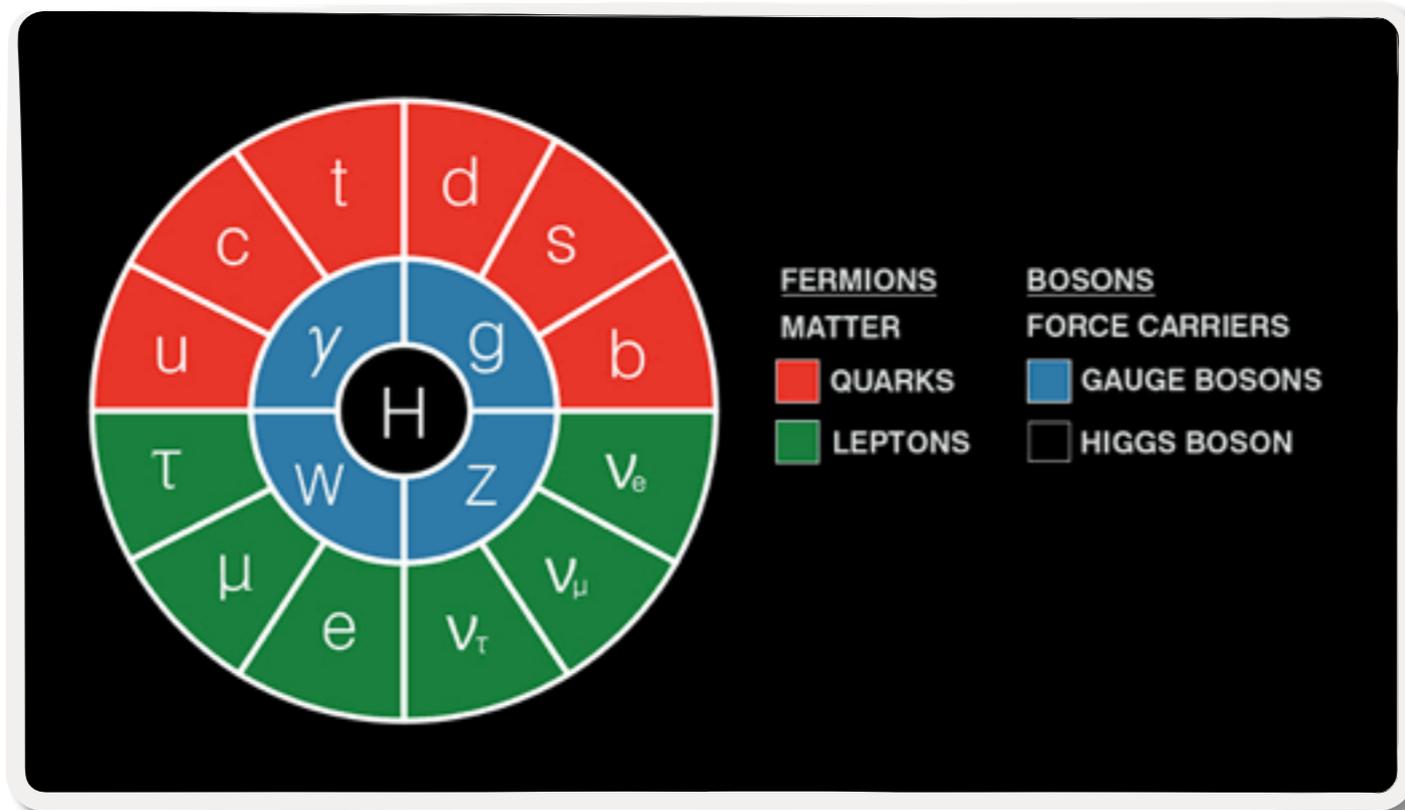
This procedure has resulted in the standard model of particle physics



It accurately describes three of the four known forces of nature:



# The standard model of particle physics

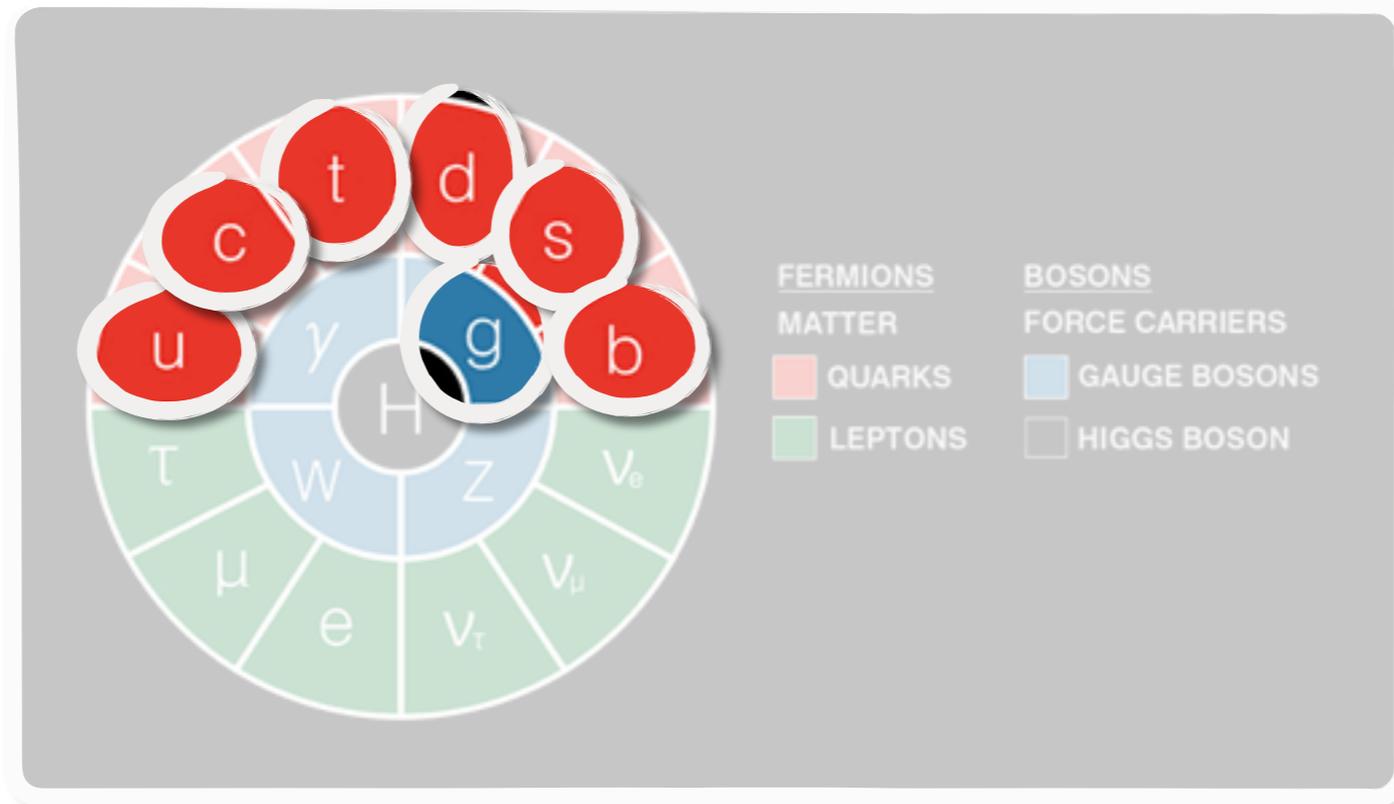


In principle, this describes our whole universe!

Ok, not quite! There are still big open questions: *what are dark energy and dark matter?, How does gravity get incorporated onto the standard model?,...*

but at least it should describe the stuff we see everyday!

# The standard model of particle physics



*not really color or flavor!*

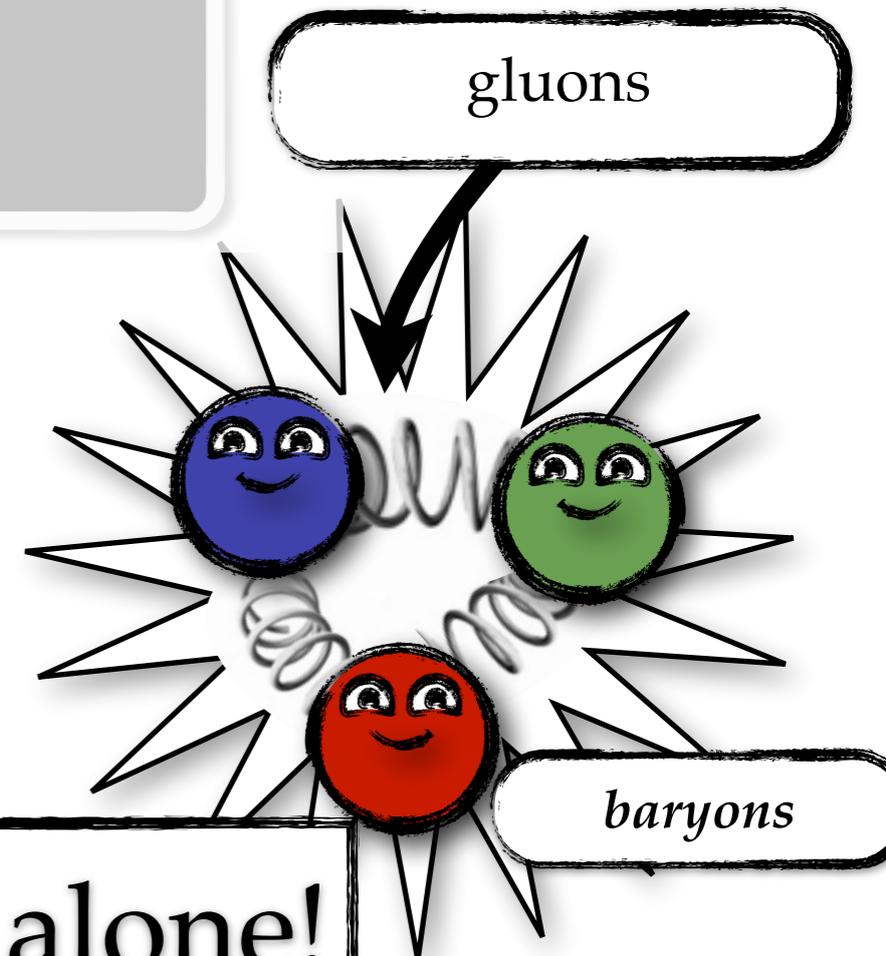
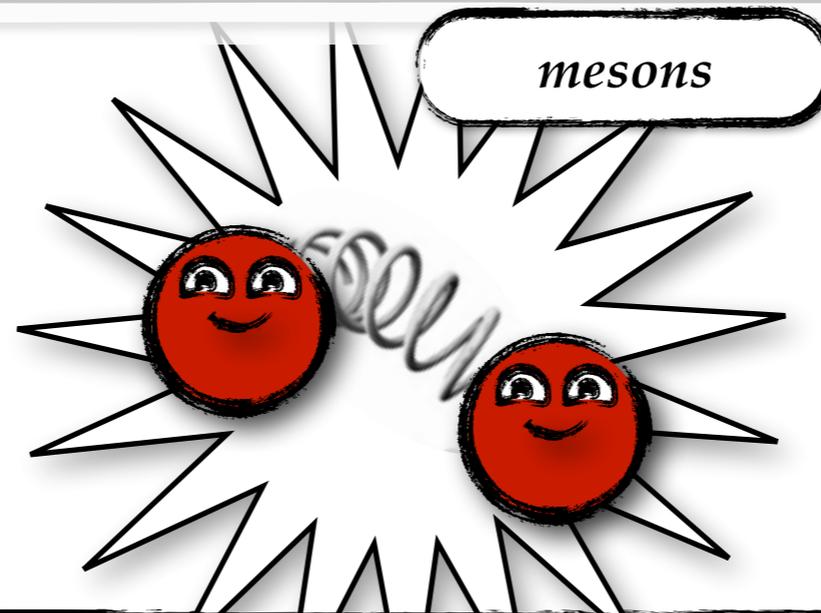
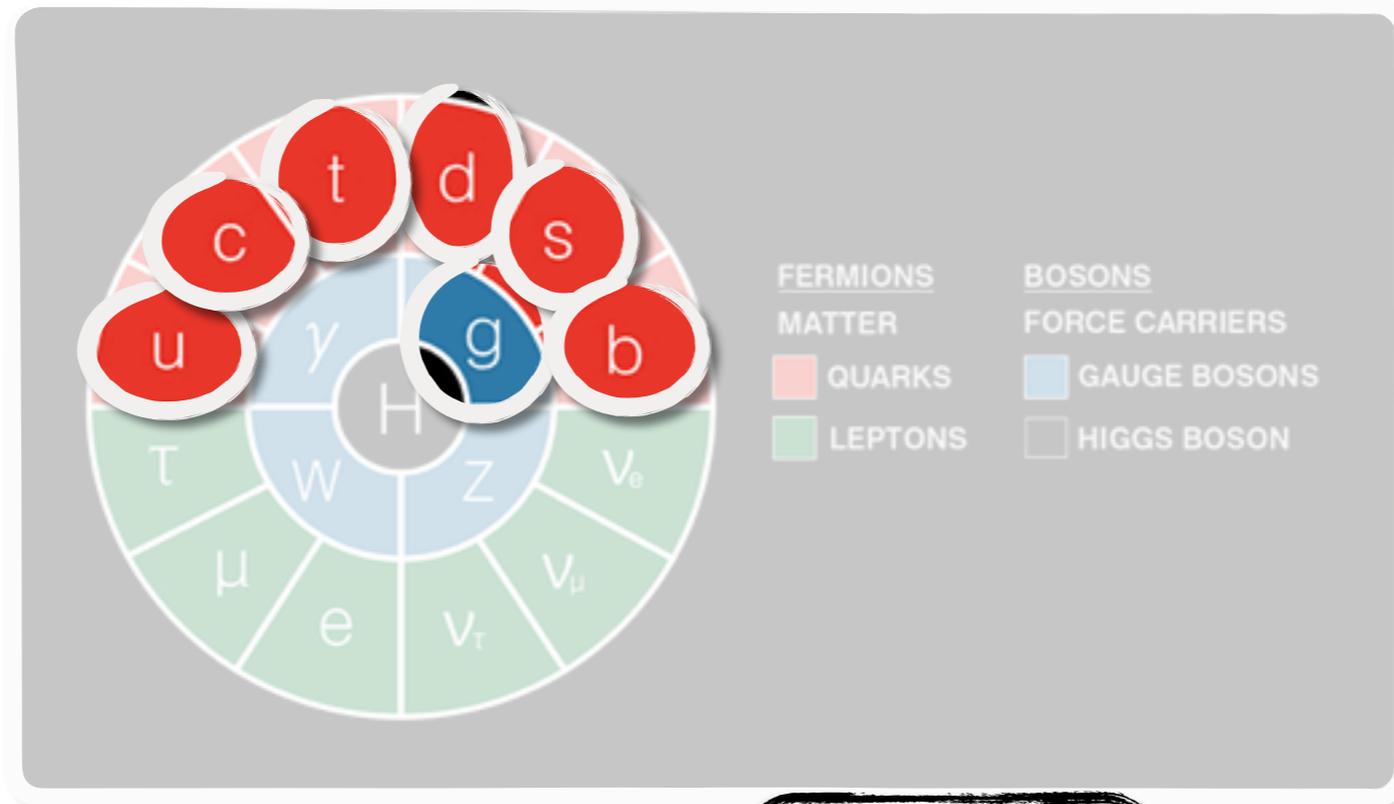
the 60s: *quarks* carry “color” (red, blue or green)  
they come in six different “flavors” :  
(*up, down, strange, charm, bottom/beauty, top/truth*)

the 70s: **gluons** also carry color  
bind quarks together  
*dress* quarks



**GROOVY 70s**

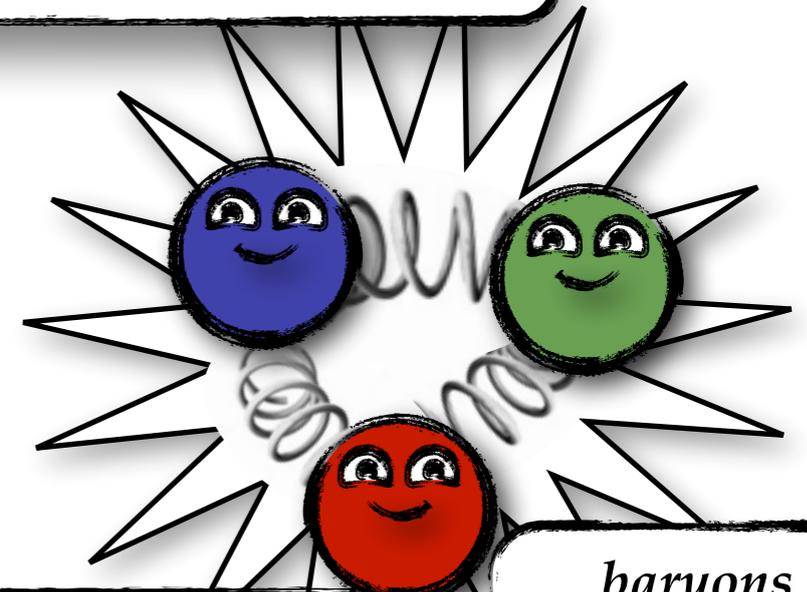
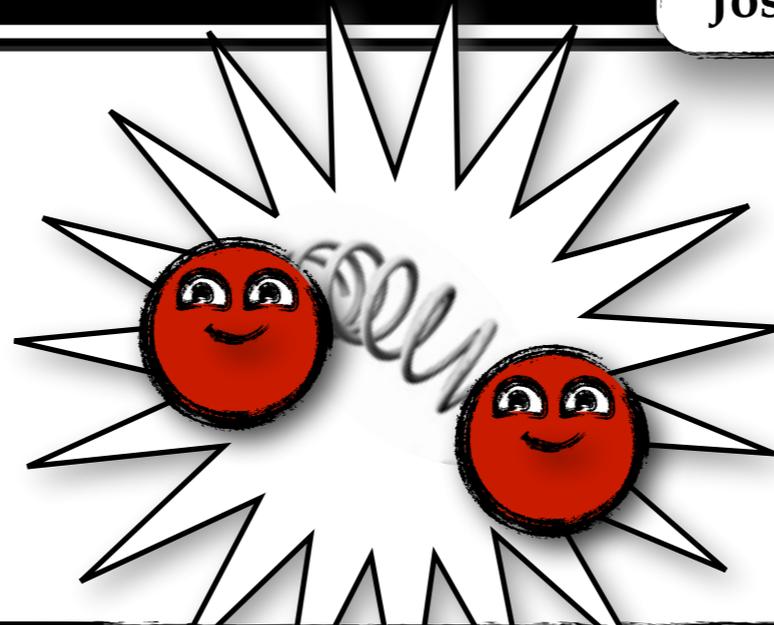
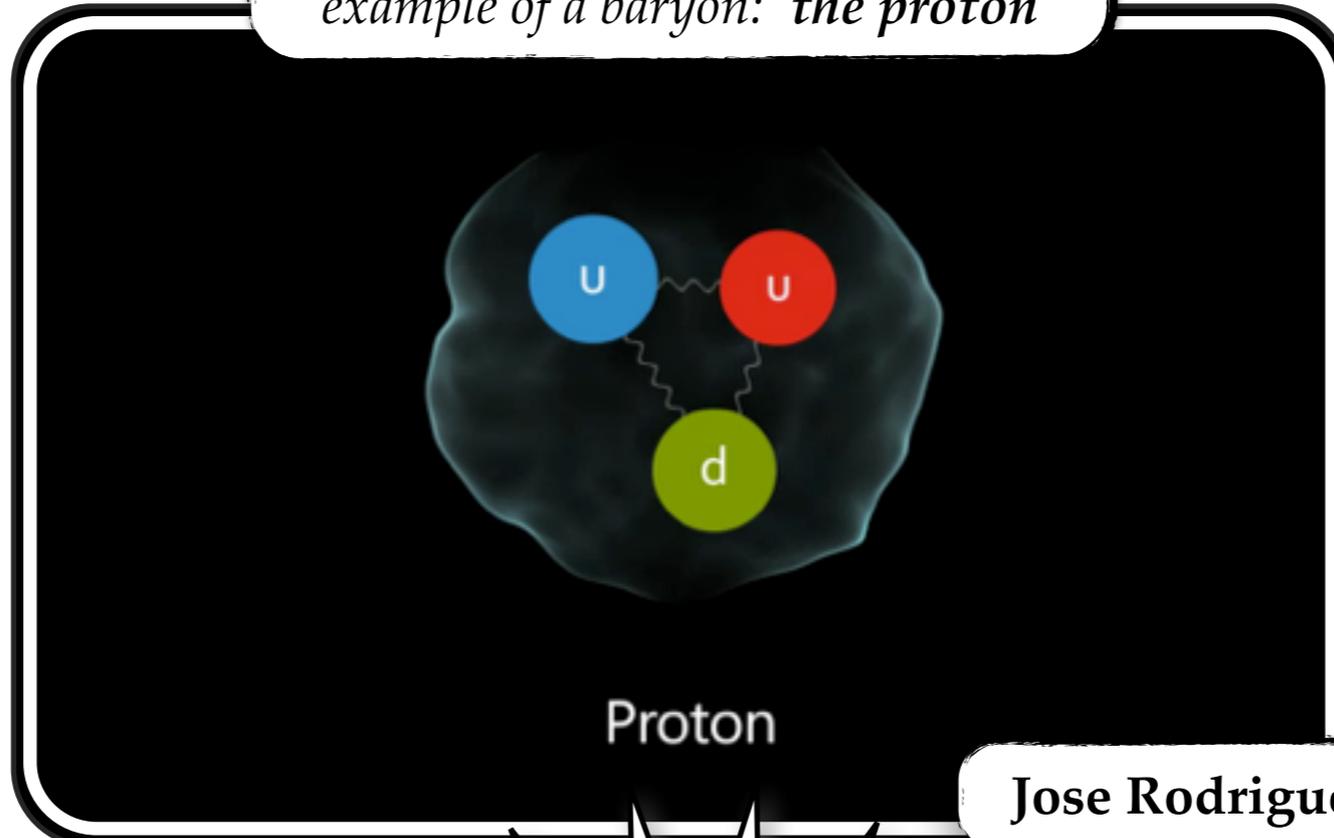
# The standard model of particle physics



quark can't stand being alone!

# The standard model of particle physics

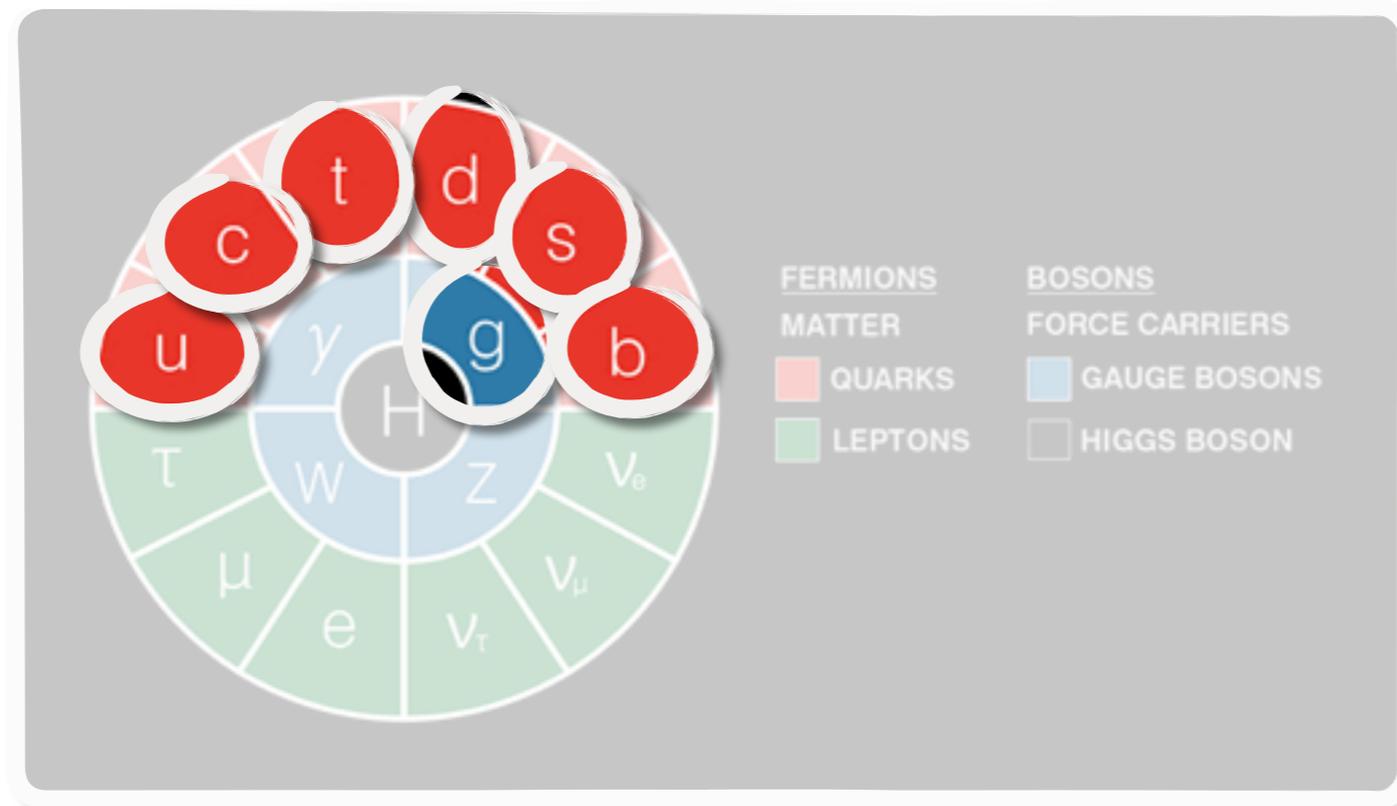
*example of a baryon: the proton*



*baryons*

quark can't stand being alone!

# The standard model of particle physics



$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (GG)$$

quantum chromodynamics

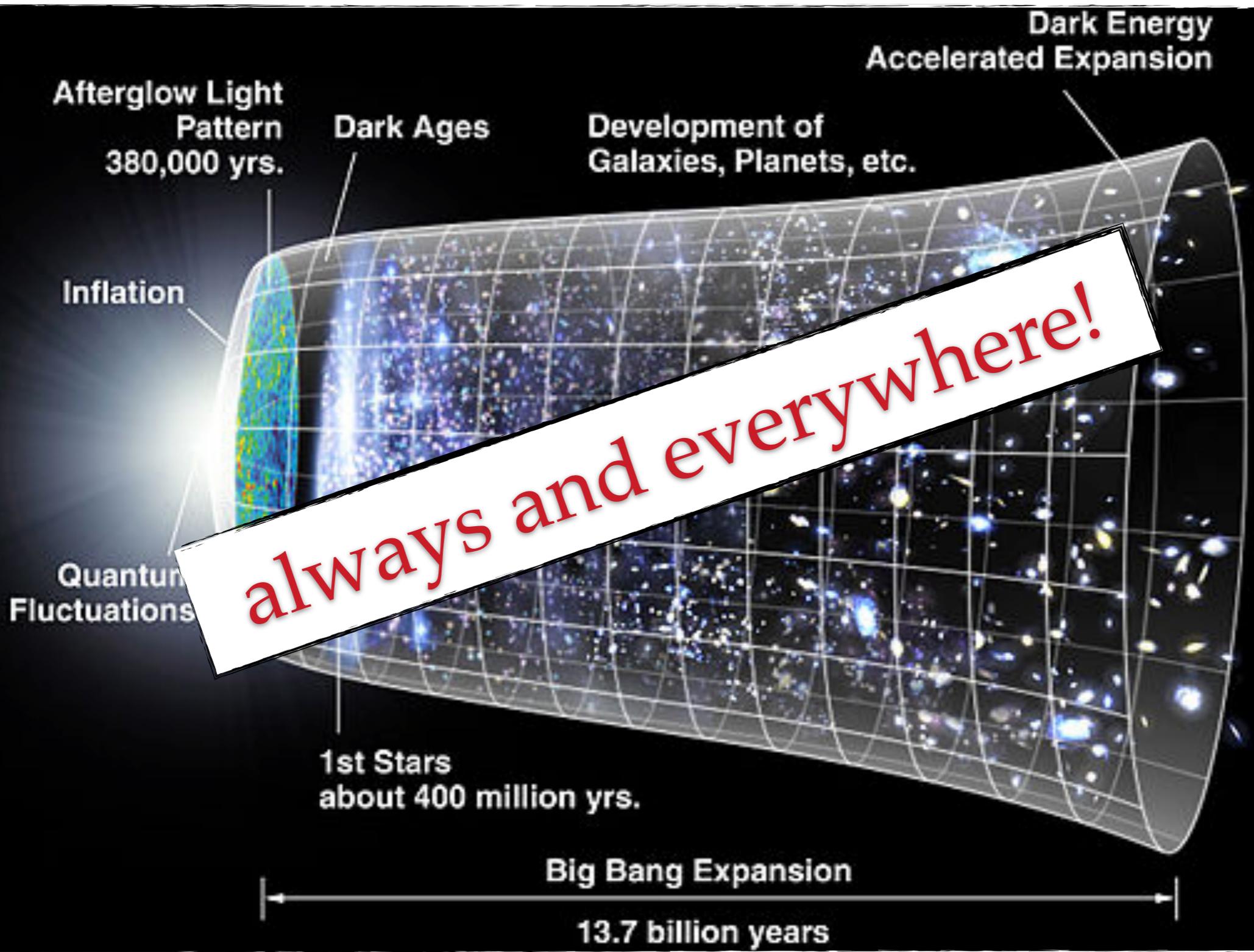
# The standard model of particle physics

when, where does/  
did QCD matter?

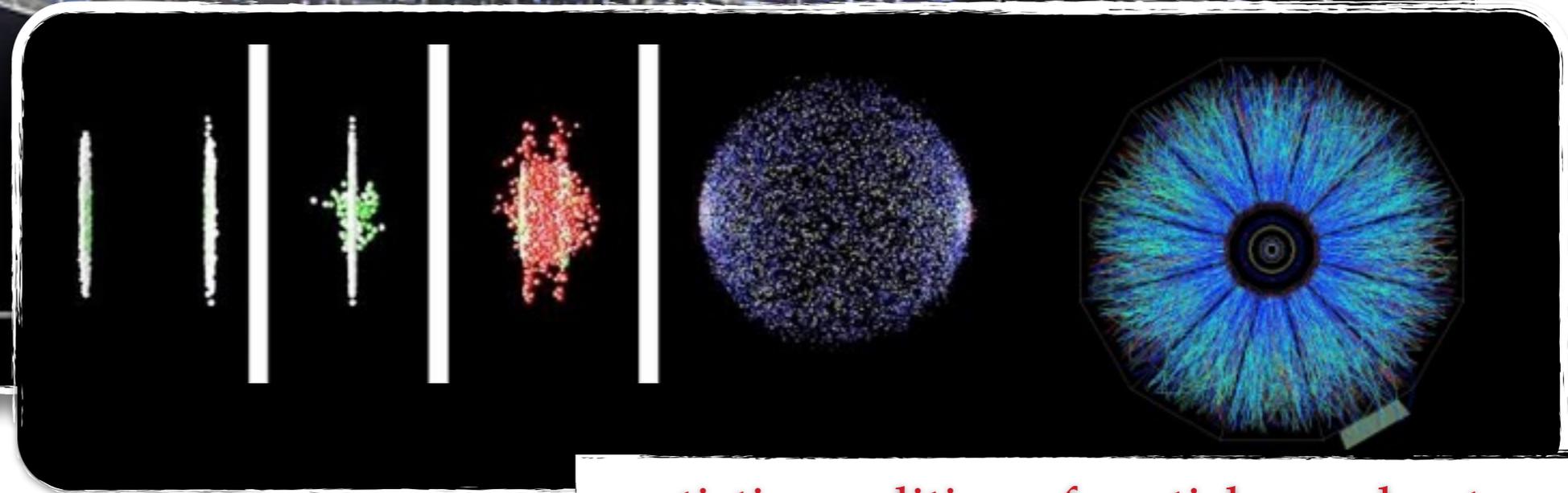
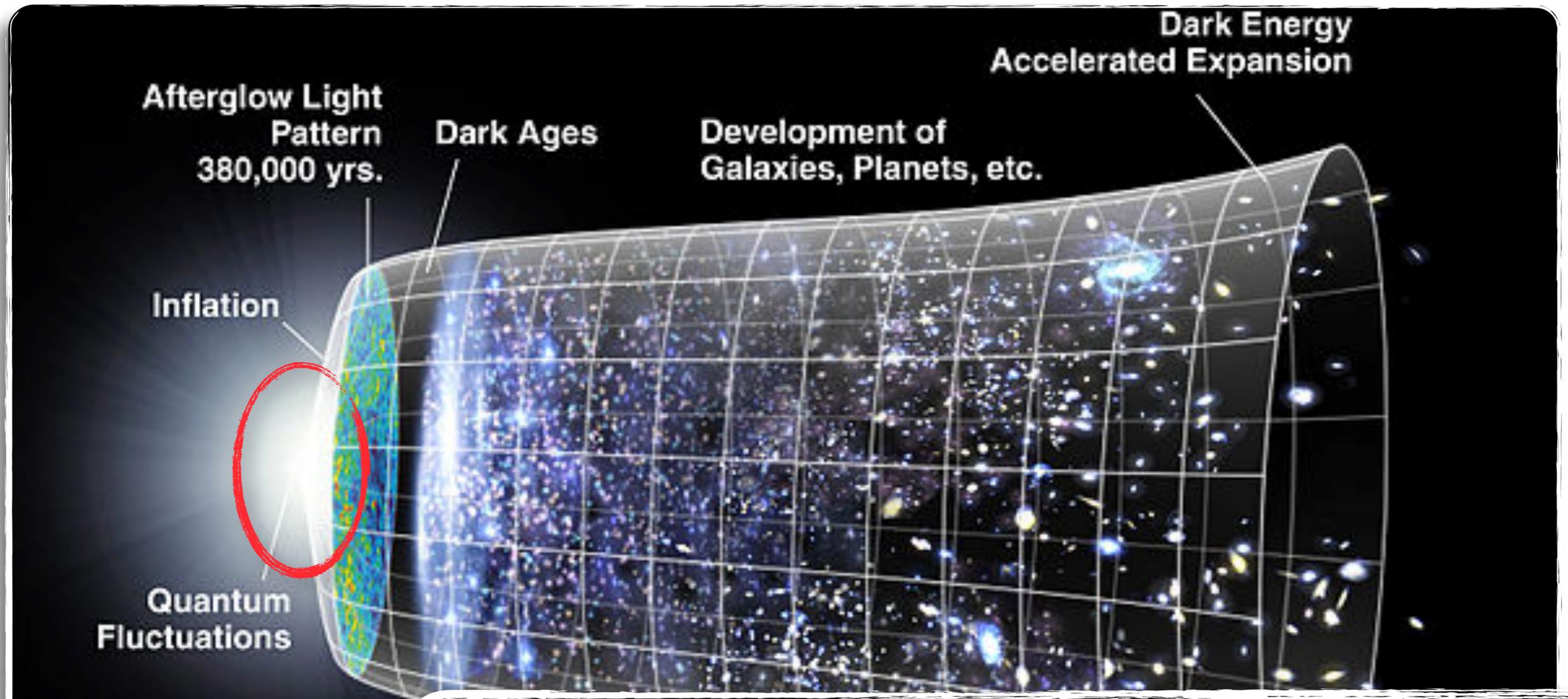


$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (G G)$$

Quantum Chromodynamics (QCD)

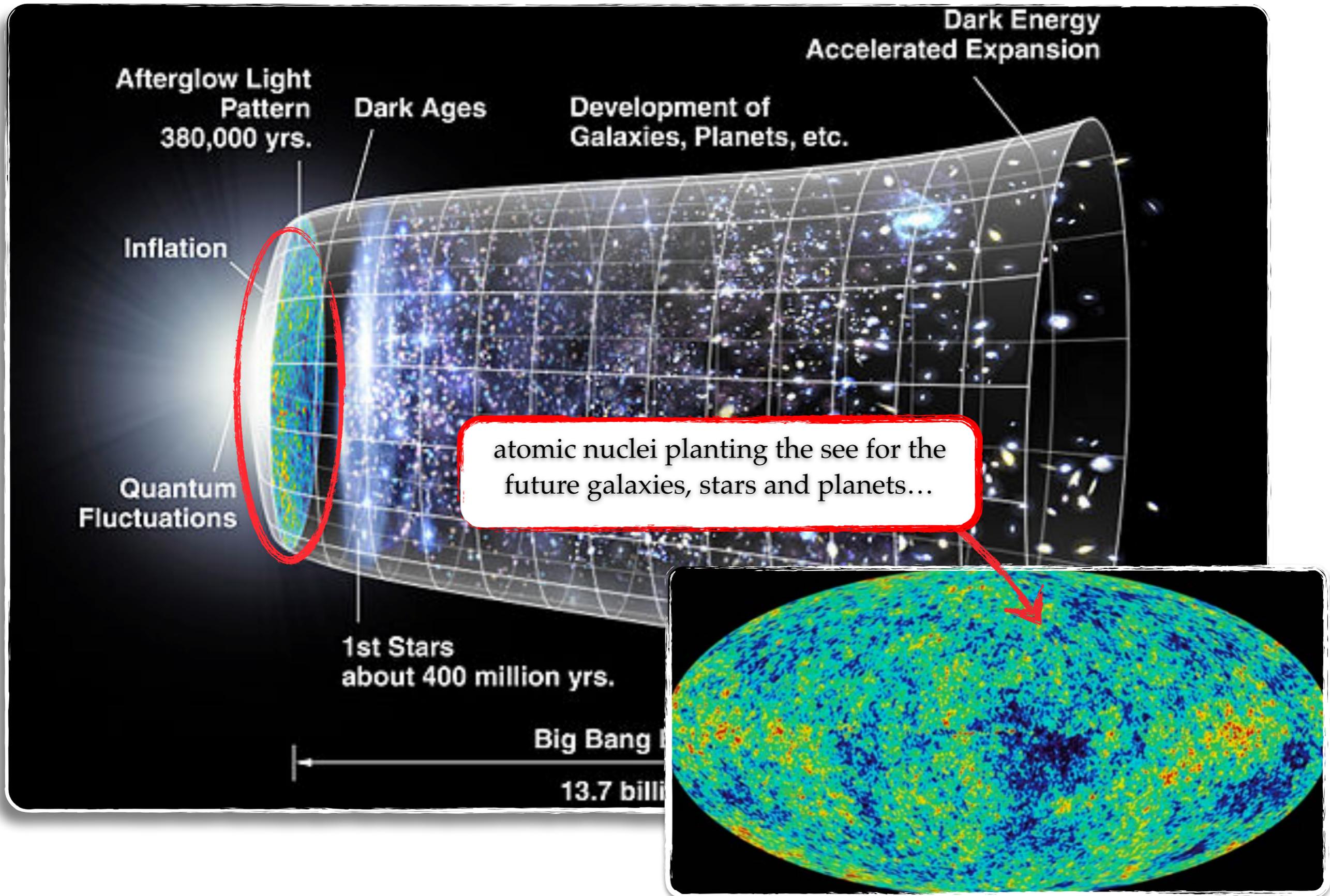


# The Big Bang!

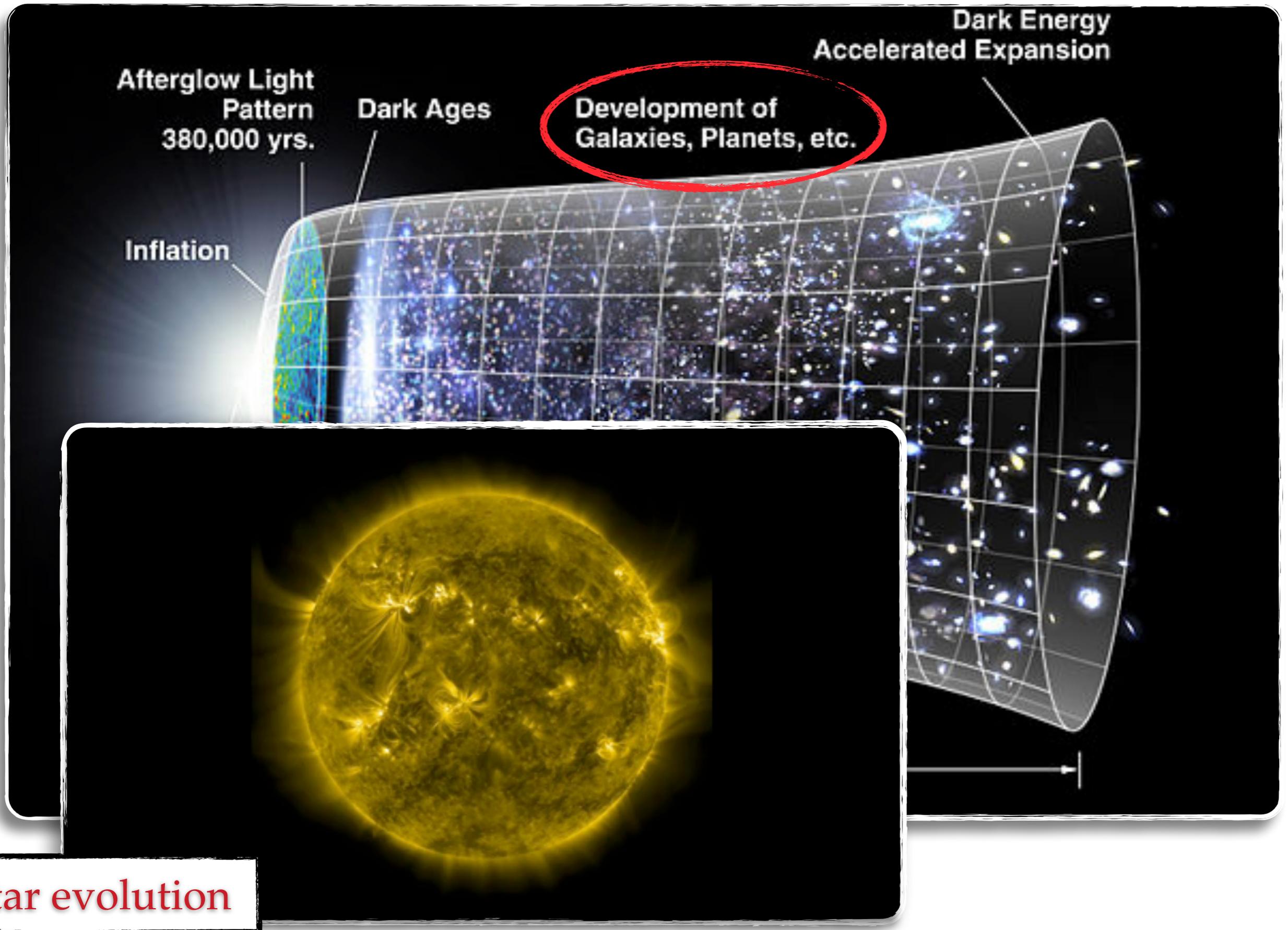


artistic rendition of particle accelerator

# The cosmic microwave background



# The cosmic microwave background

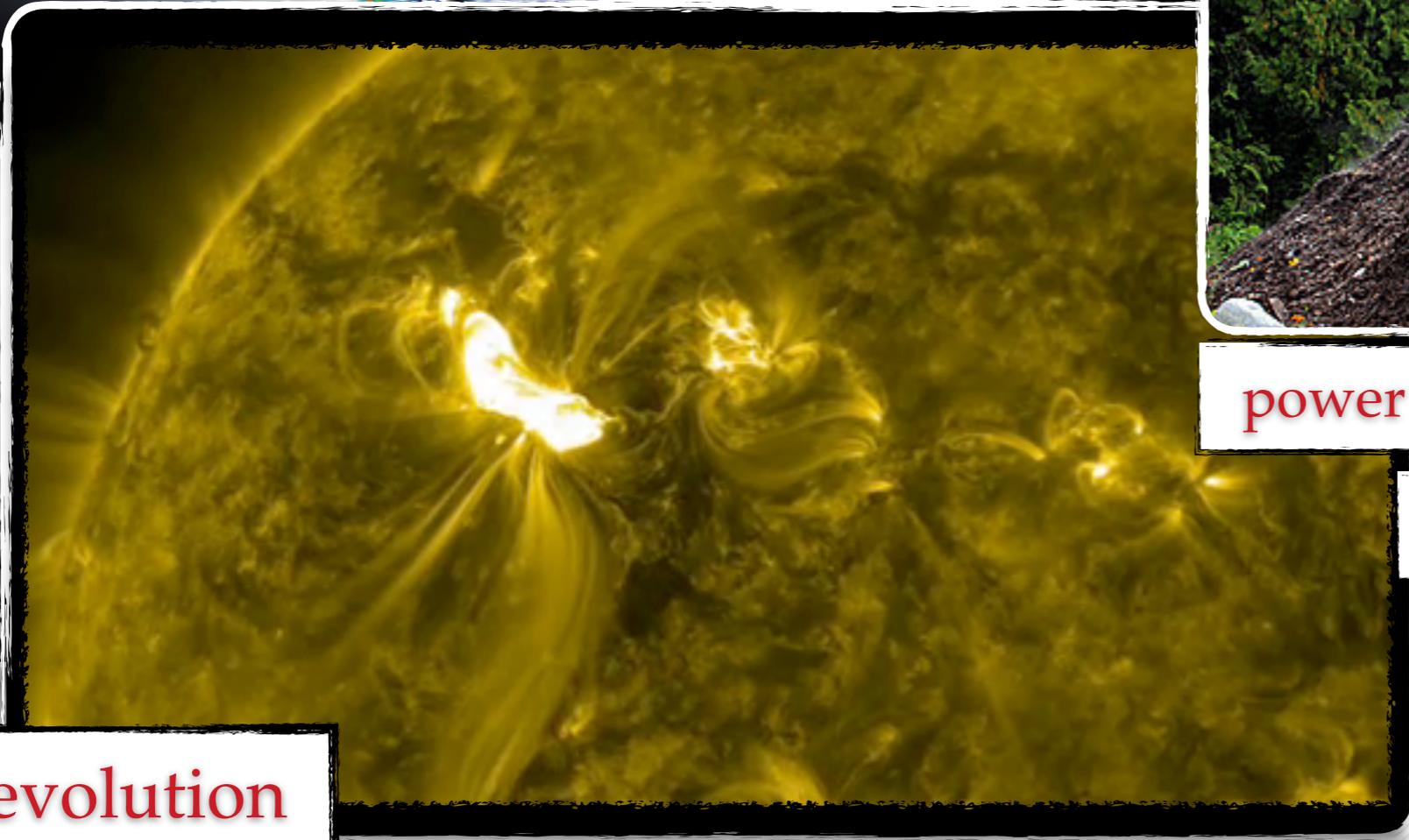


# The cosmic microwave background



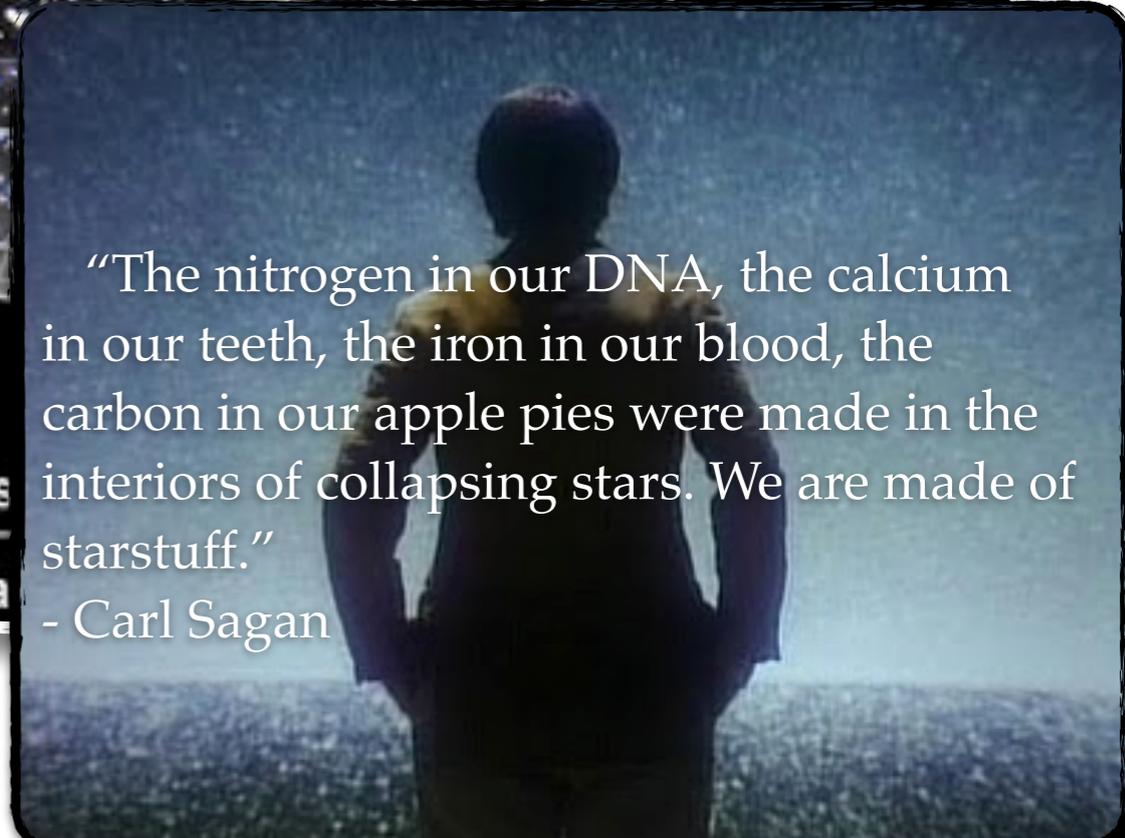
power density of a compost heap

essential for life!

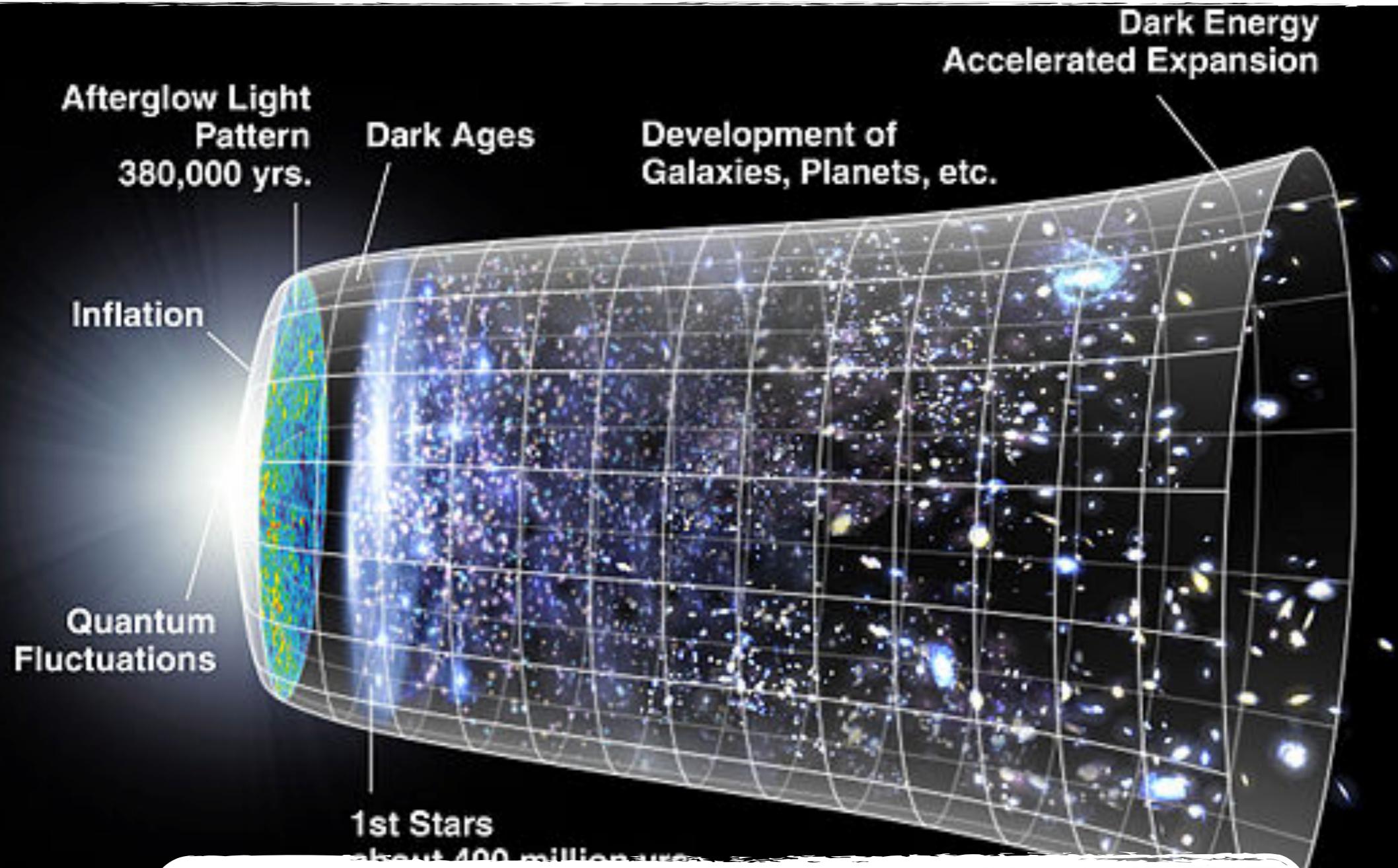


star evolution

# The cosmic microwave background



# The cosmic microwave background



$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (G G)$$

*one "tiny" equation should describe all of these nuclear phenomena*

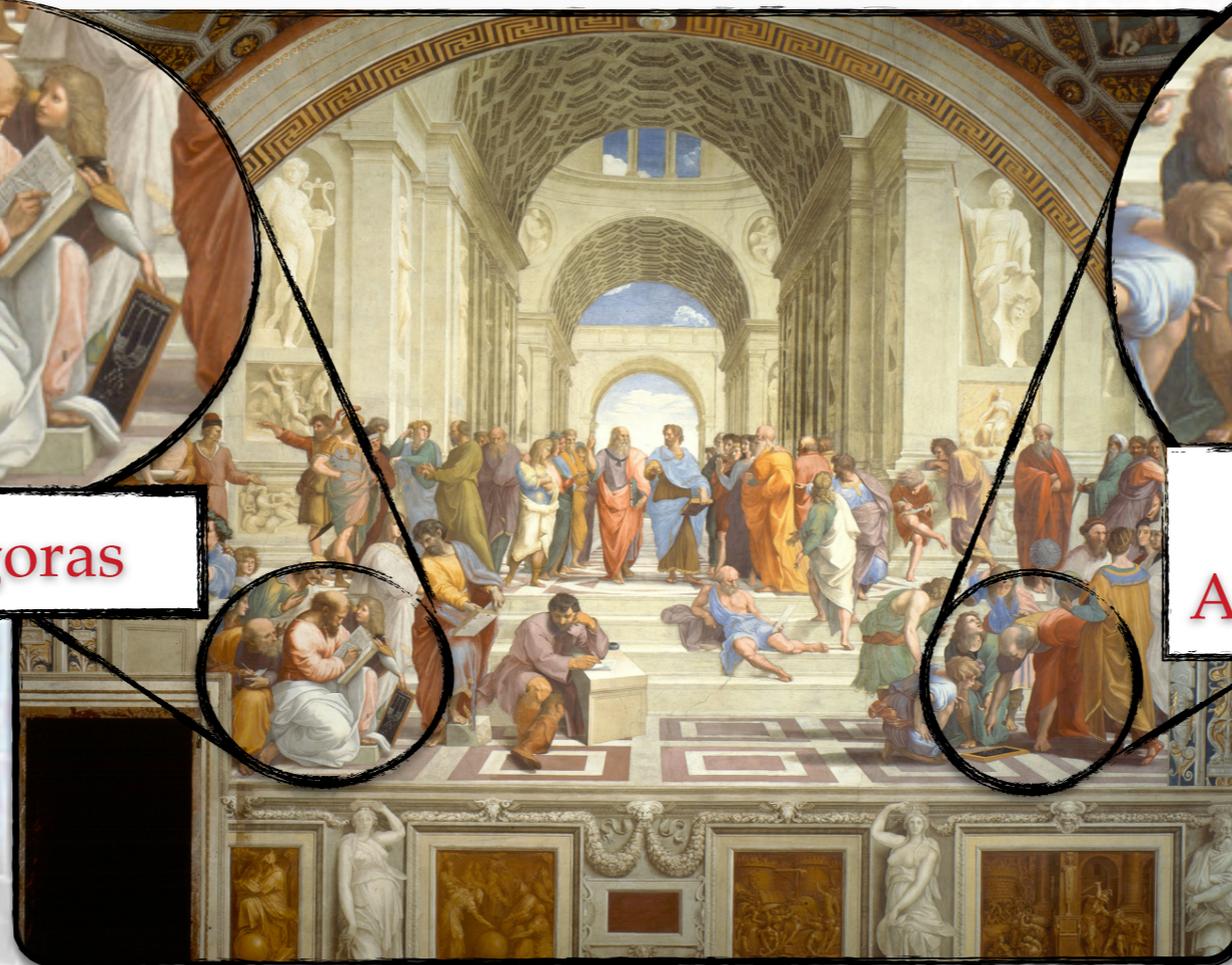
# A rich and long history of math



Pythagoras



Euclid or Archimedes (?)



Quantum  
Fluctuations

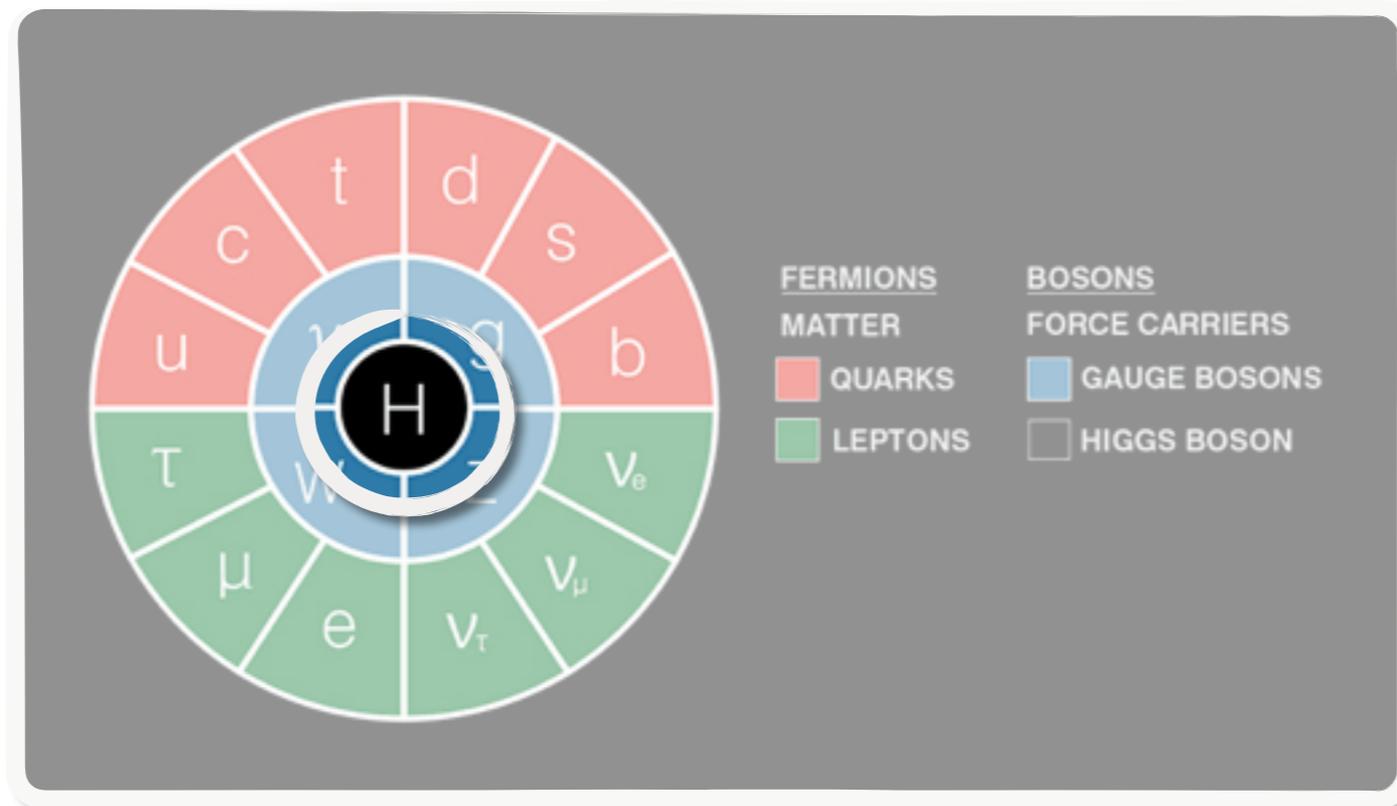
*standard mathematical tools developed over  
the millennia fail to solve this equation*

*looking for a nobel prize?*

*more on modern day solutions in a minute*

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (GG)$$

# The standard model of particle physics



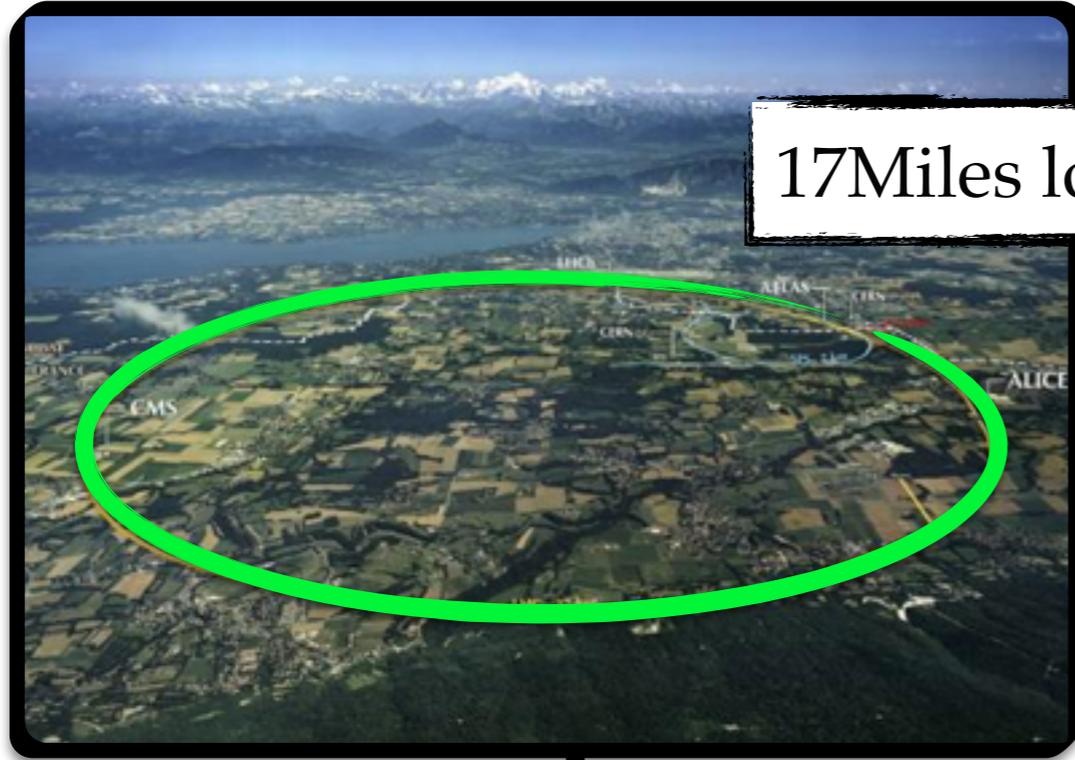
Until 2013, all of these particles had been observed experimentally, except for the Higgs boson [predicted by Englert and Higgs]

**the Higgs is responsible for giving particles like quarks and electrons mass. while the photon and the gluon remain massless!**

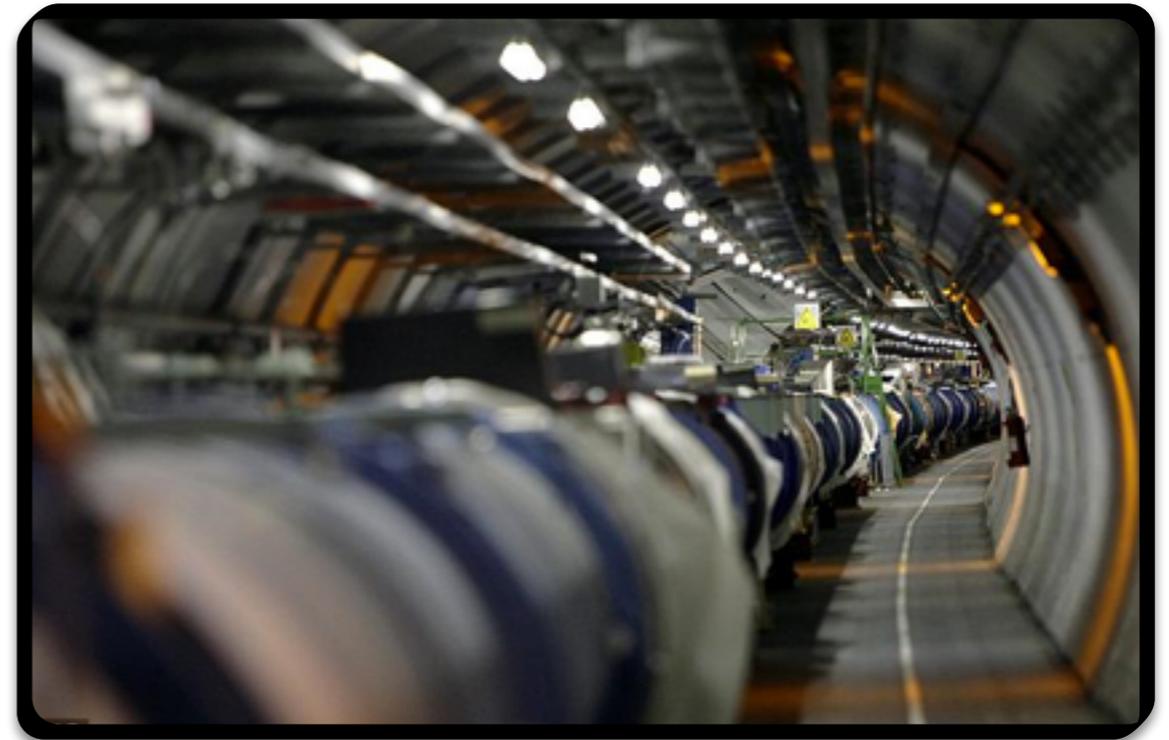


*Francois Englert and Peter Higgs*

# CERN and the LHC



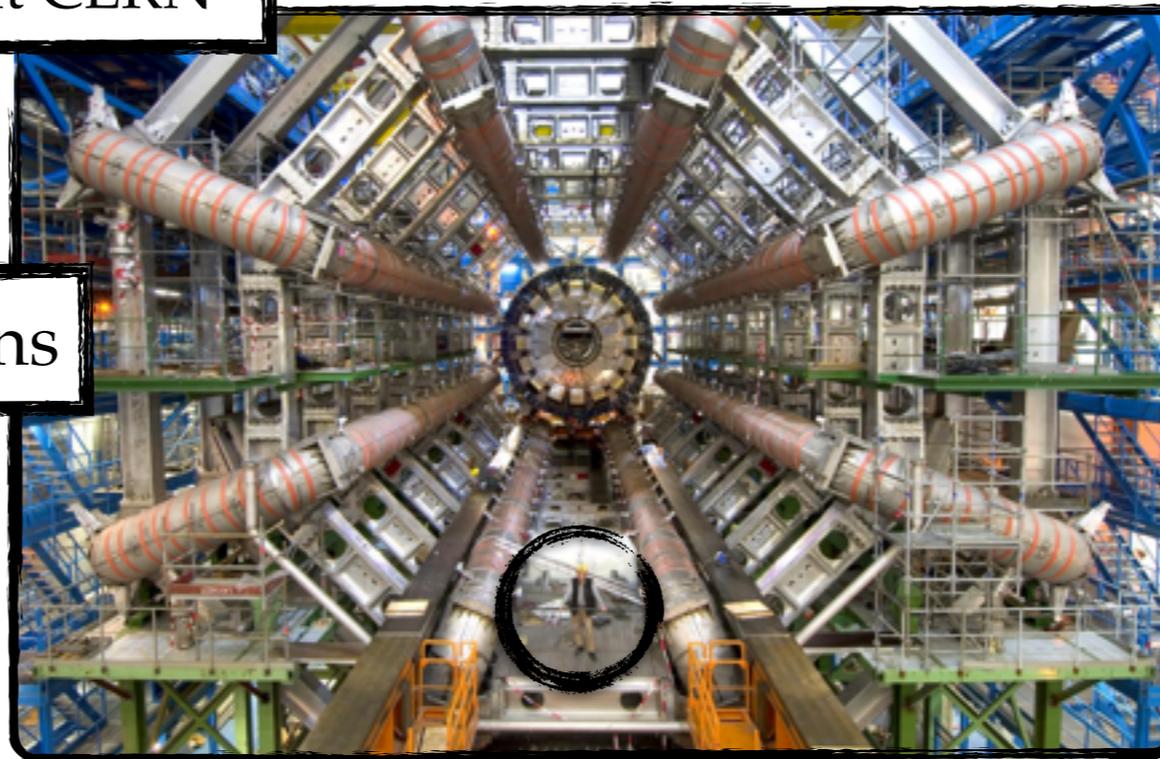
17Miles long



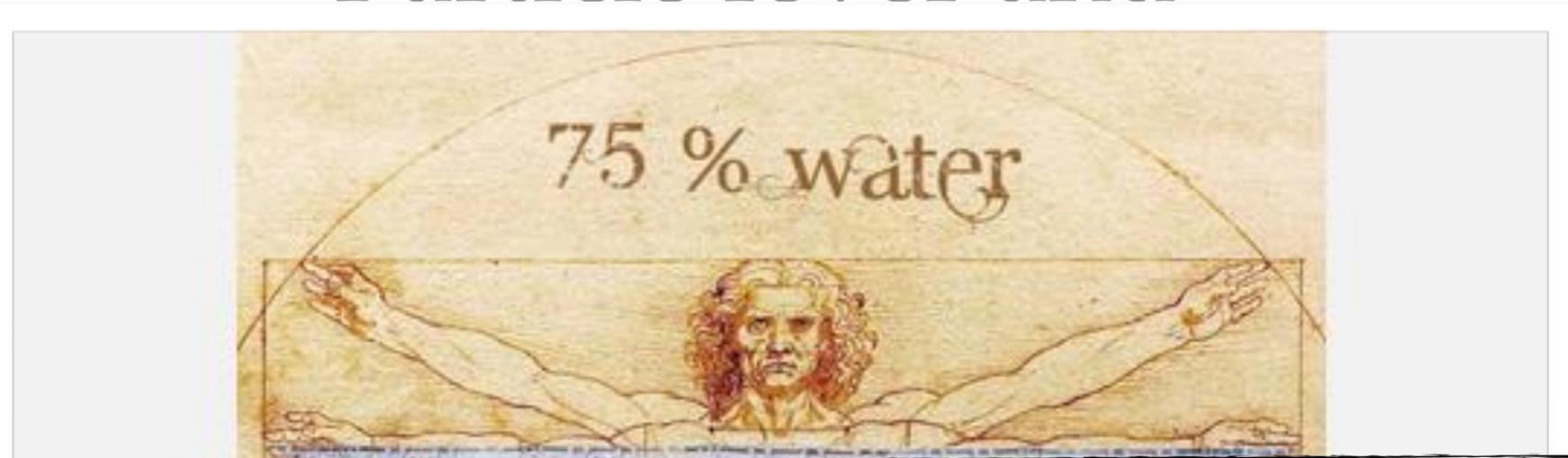
the Large Hadron Collider (LHC) at CERN

the world's largest

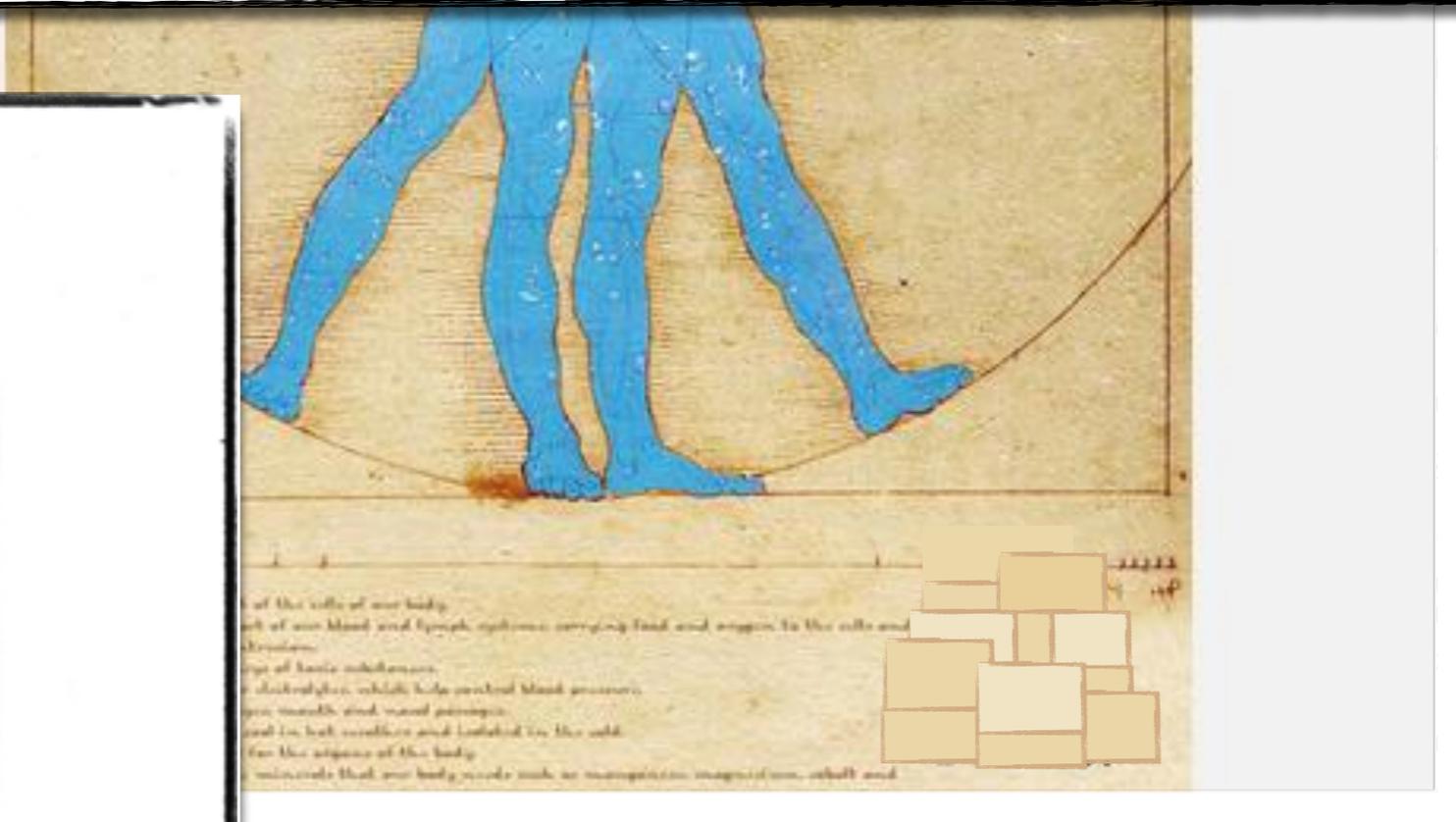
CERN accelerates protons



# Particle fever and



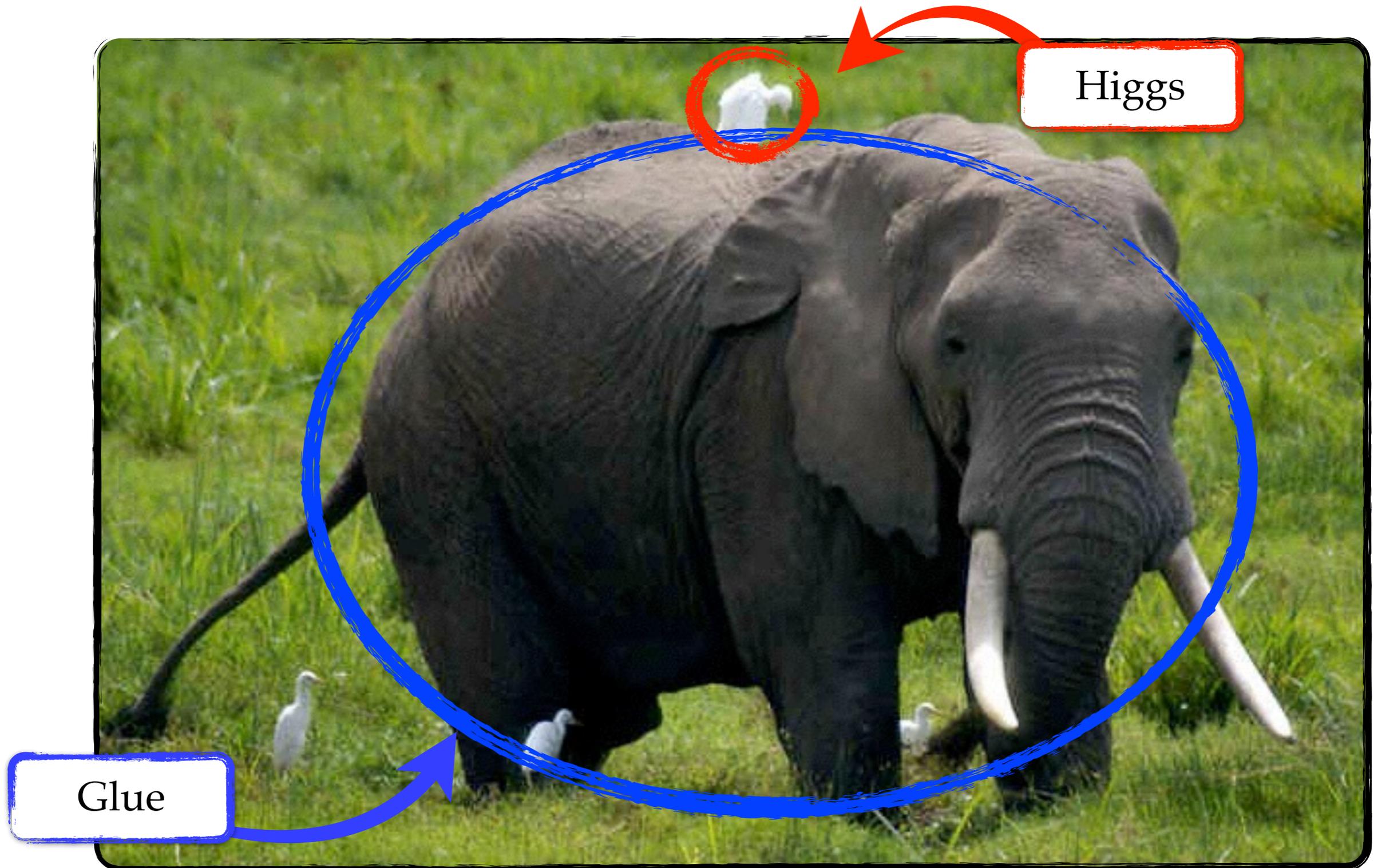
You are actually 95% Glue!



but

of your mass  
ns!

# The big picture



# A rich and long history of math



Pythagoras



Euclid or Archimedes (?)

Quantum  
Fluctuations

*standard mathematical tools developed over the millennia fail to solve this equation*

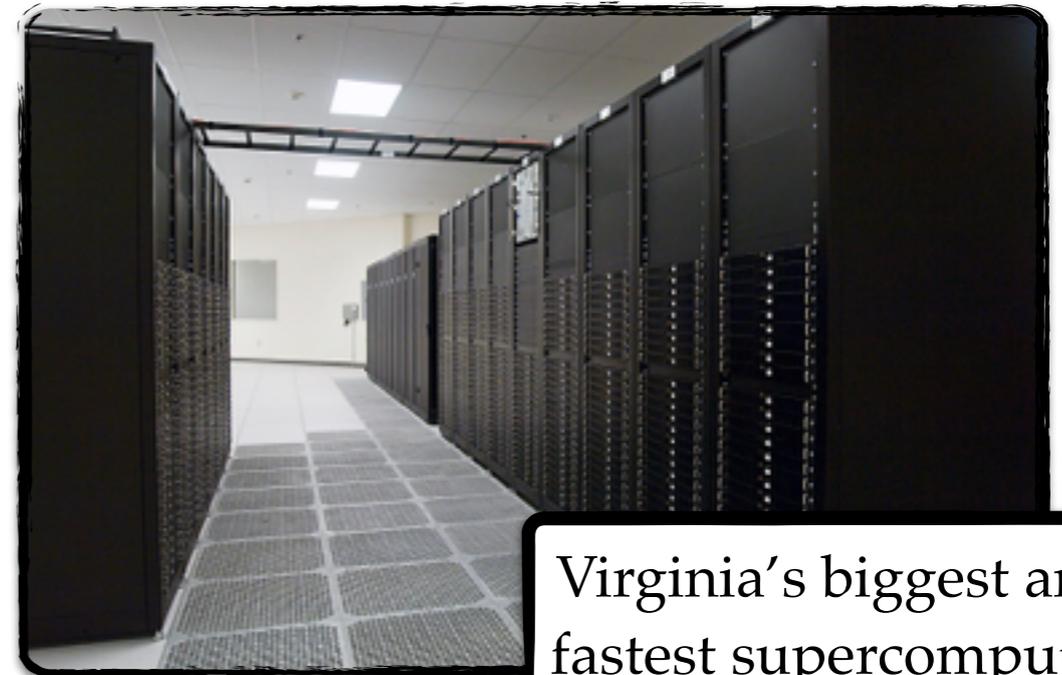
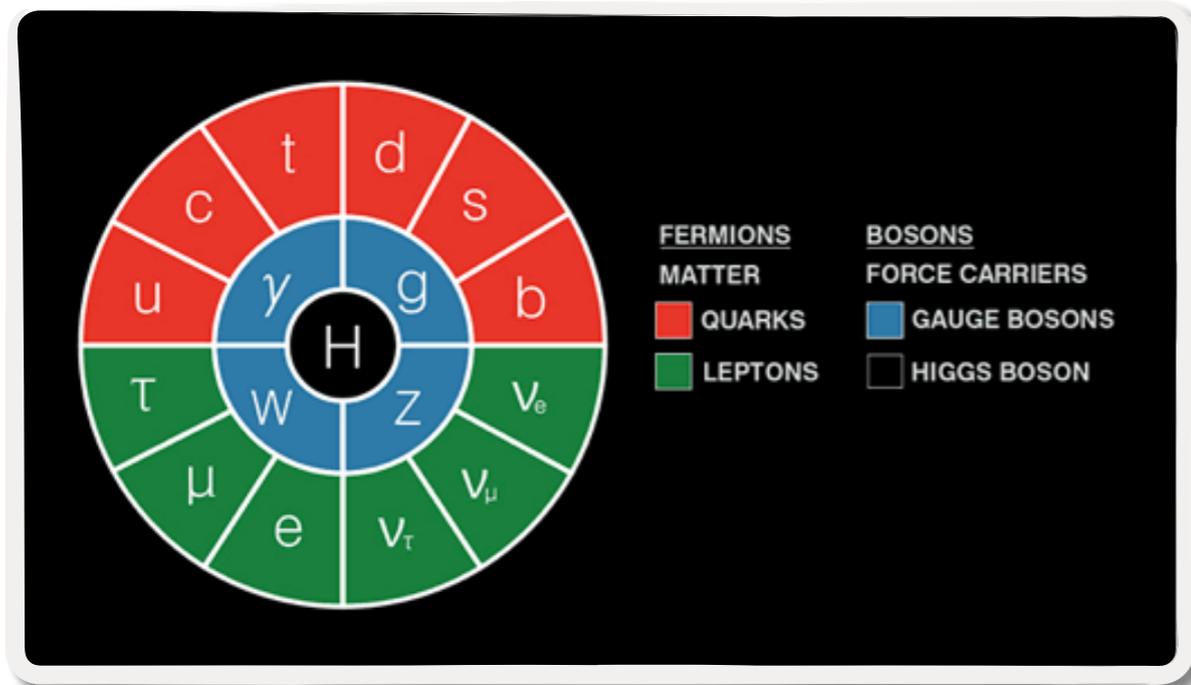
*looking for a nobel prize?*

*more on modern day solutions in a minute*

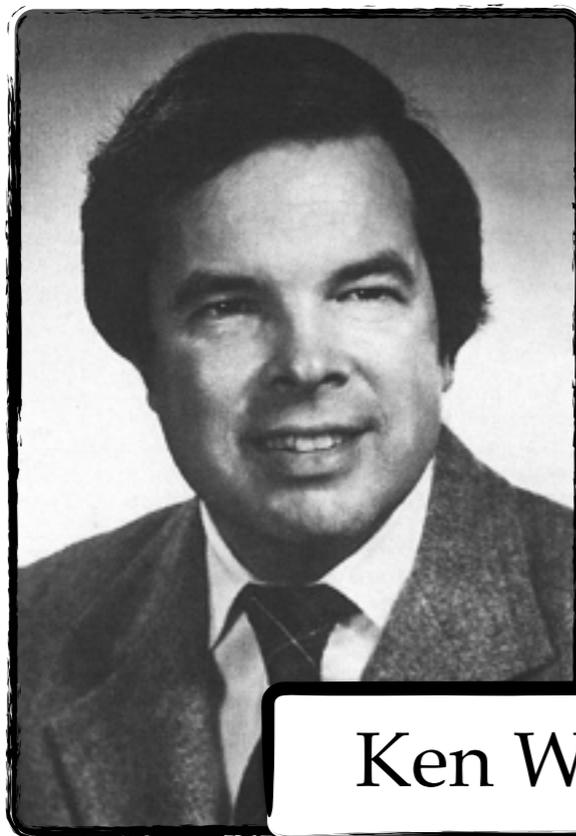
$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (GG)$$

# Present-day theoretical nuclear physics

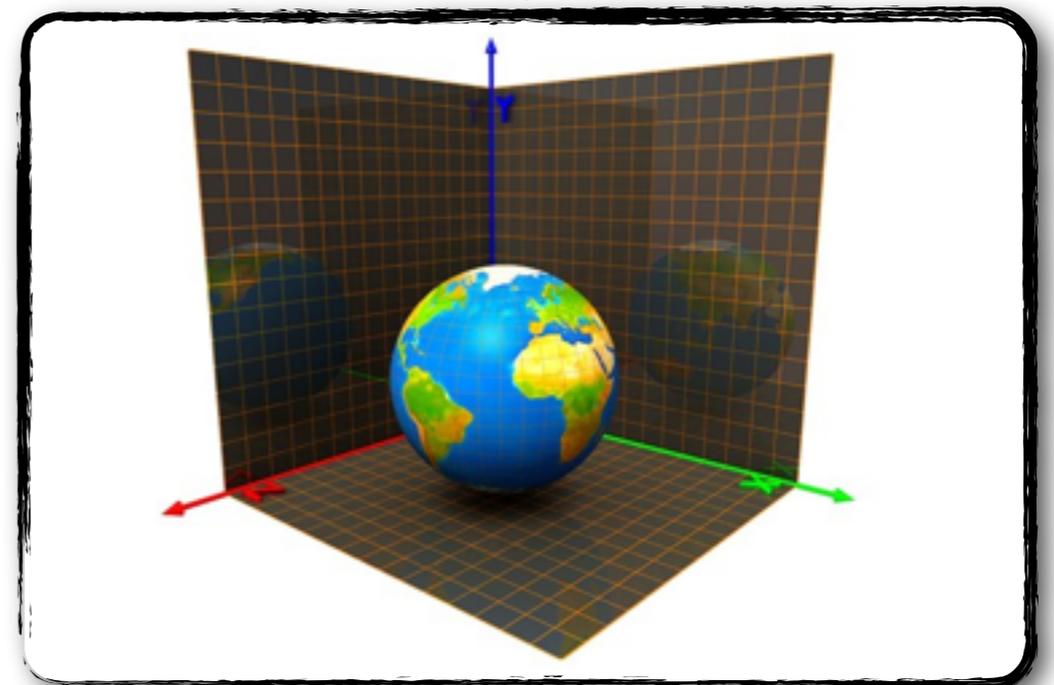
*put the fundamental equations into a computer and let nature emerge*



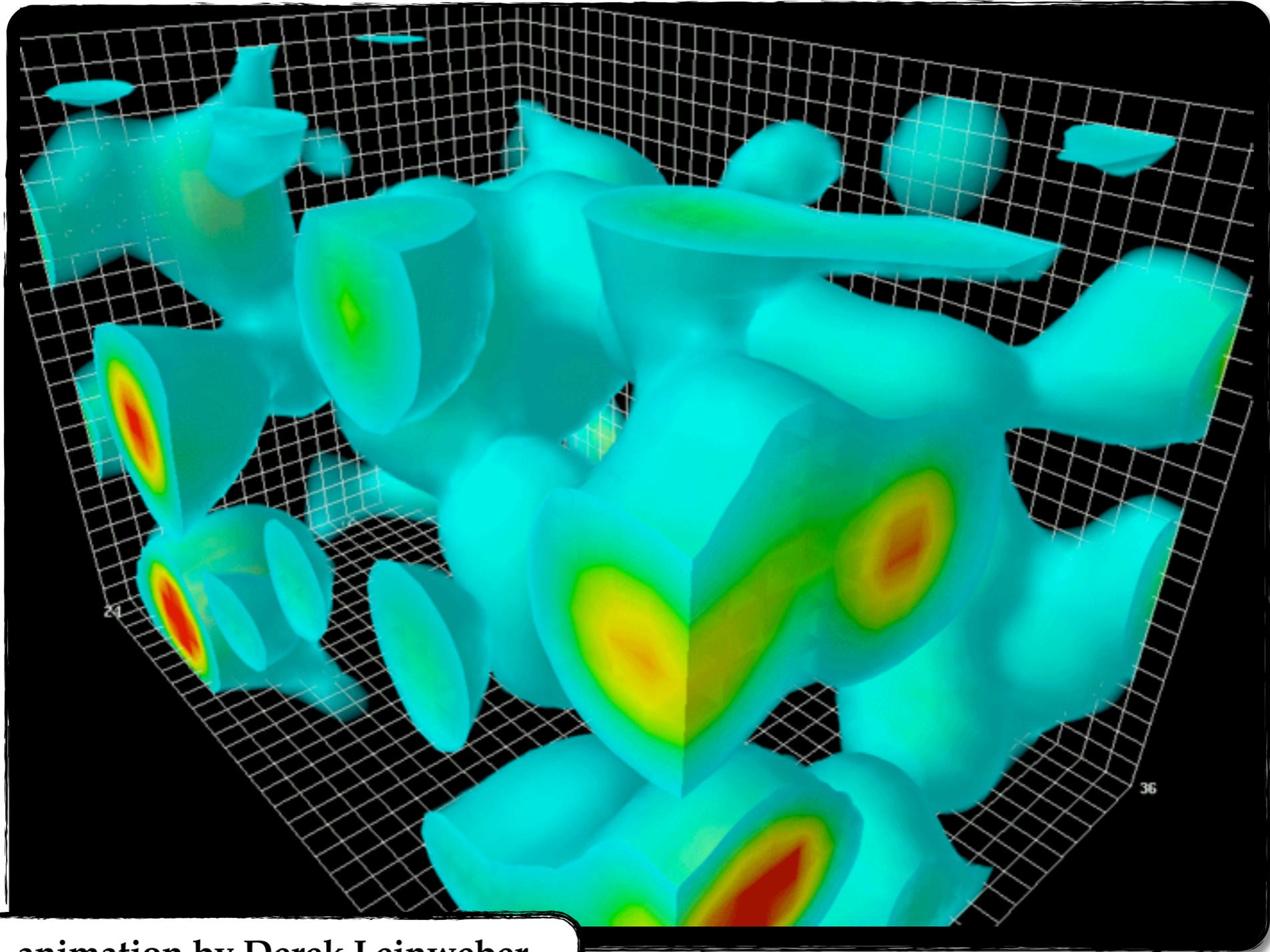
Virginia's biggest and fastest supercomputer



Ken Wilson



# Quantum Fluctuations

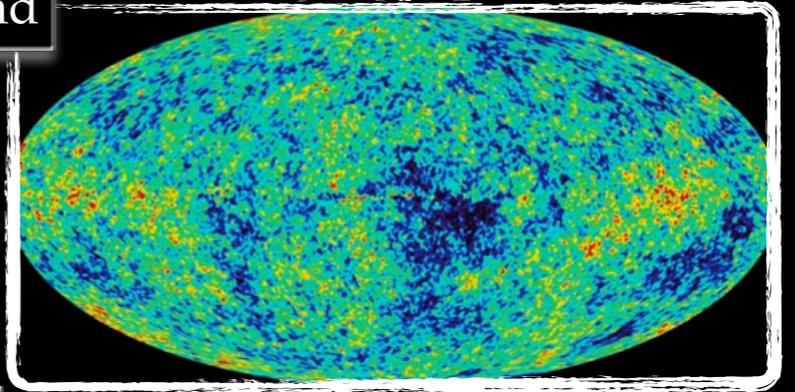


animation by Derek Leinweber

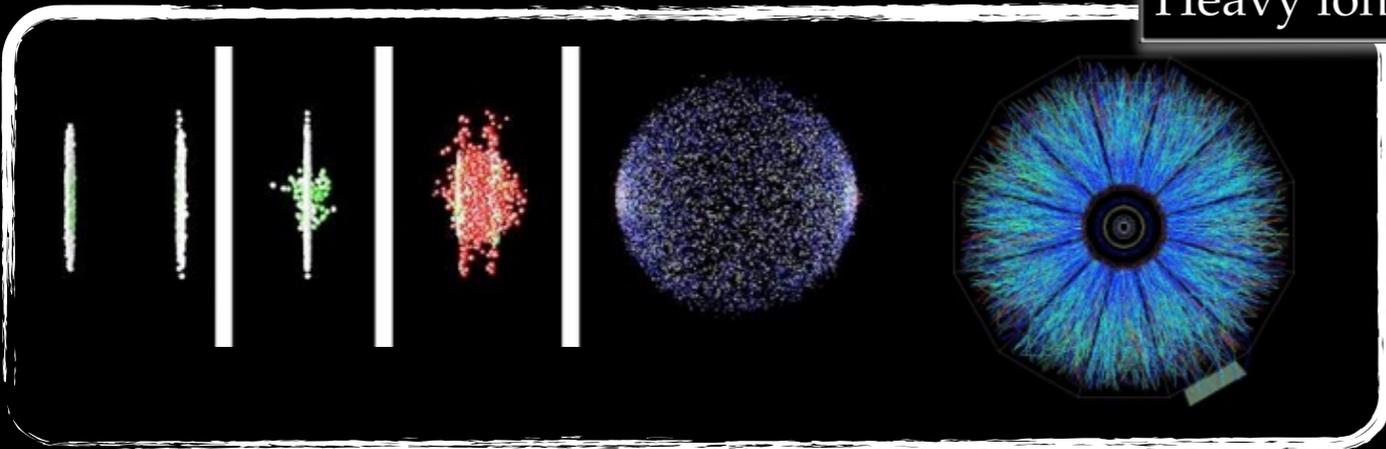
Volume =  $(2.4 \times 2.4 \times 3.6) \text{ fm}^3$   
 $1 \text{ fm} = 10^{-15} \text{ m}$ ,  $10^{-15} = 0.0000000000000001$

# Nuclear physics

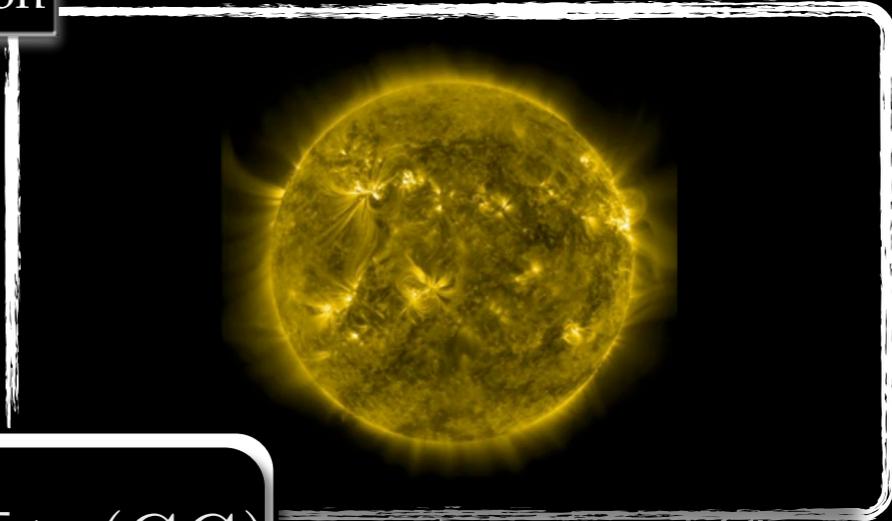
Cosmic microwave background



Heavy ion collisions



Stellar evolution

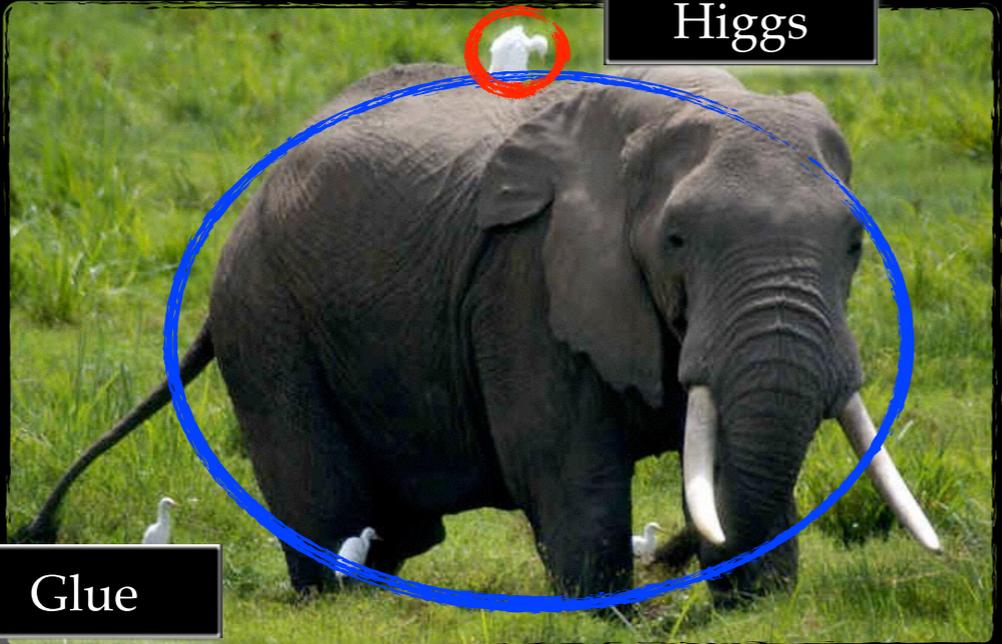


$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (GG)$$



Supernova

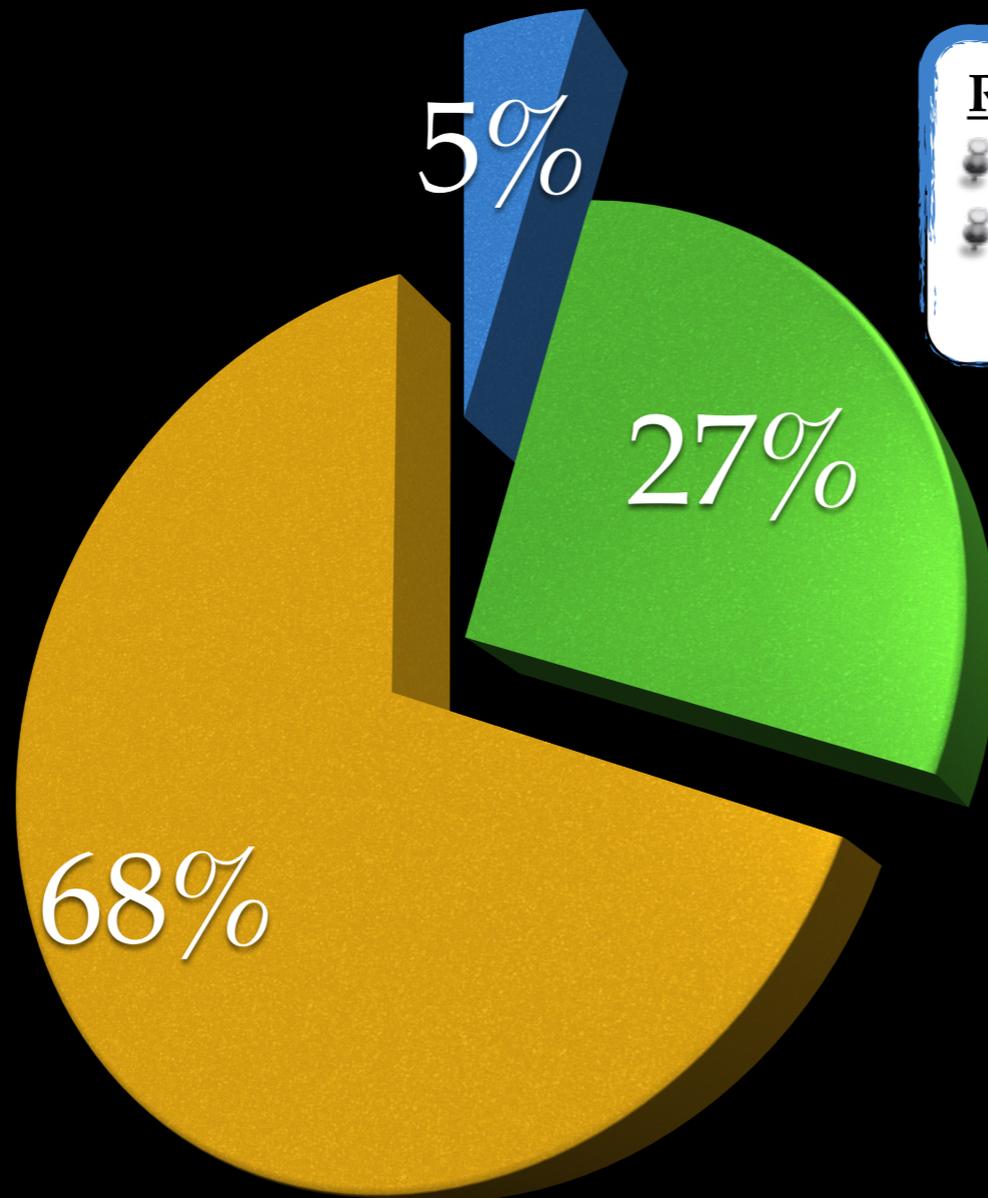
A bottom-up approach to understanding nature



Higgs

Glue

# The future of physics / the matter content of the universe



## Regular matter [5% of the universe]:

- *we have an almost complete theory*
- *more work needed to connect theory to all observed phenomena*

## Dark matter [27% of the universe]:

- *we know it is there*
- *theories are at early stages*

## Dark Energy [68% of the universe]:

- *we know it is there*
- *theories are at early stages*

exciting work

under  
**construction**

---



please come back later...

or just come visit us at the lab!







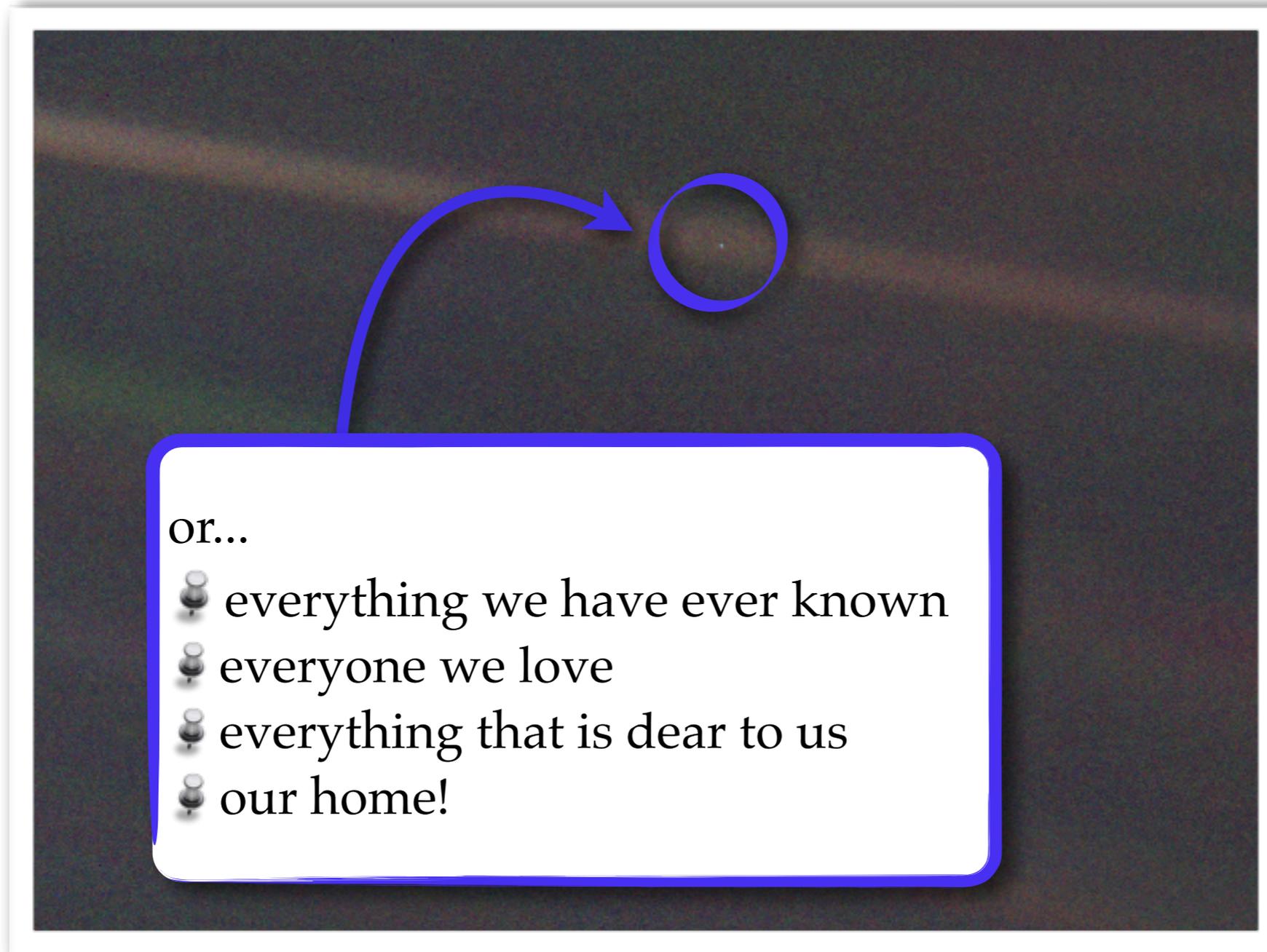
- pp-fusion
- jeopardy question with music
- “it is the same power density as the sun’s inner core”
- “what is the power density of a compost heap?”
- “what is the power density of a cellphone?”
- “what is the power density of a toaster?”
- “what is the power density of a super computer?”
- the sun is a very slowly burning object and this is necessary for us to live, evolve from cells to humans in a period of 2.1 billion years

# Take home message



- An artist's rendition of our particle beam?
- A granular image of particles trapped in a atomic vacuum chamber?
- ...?

# Take home message

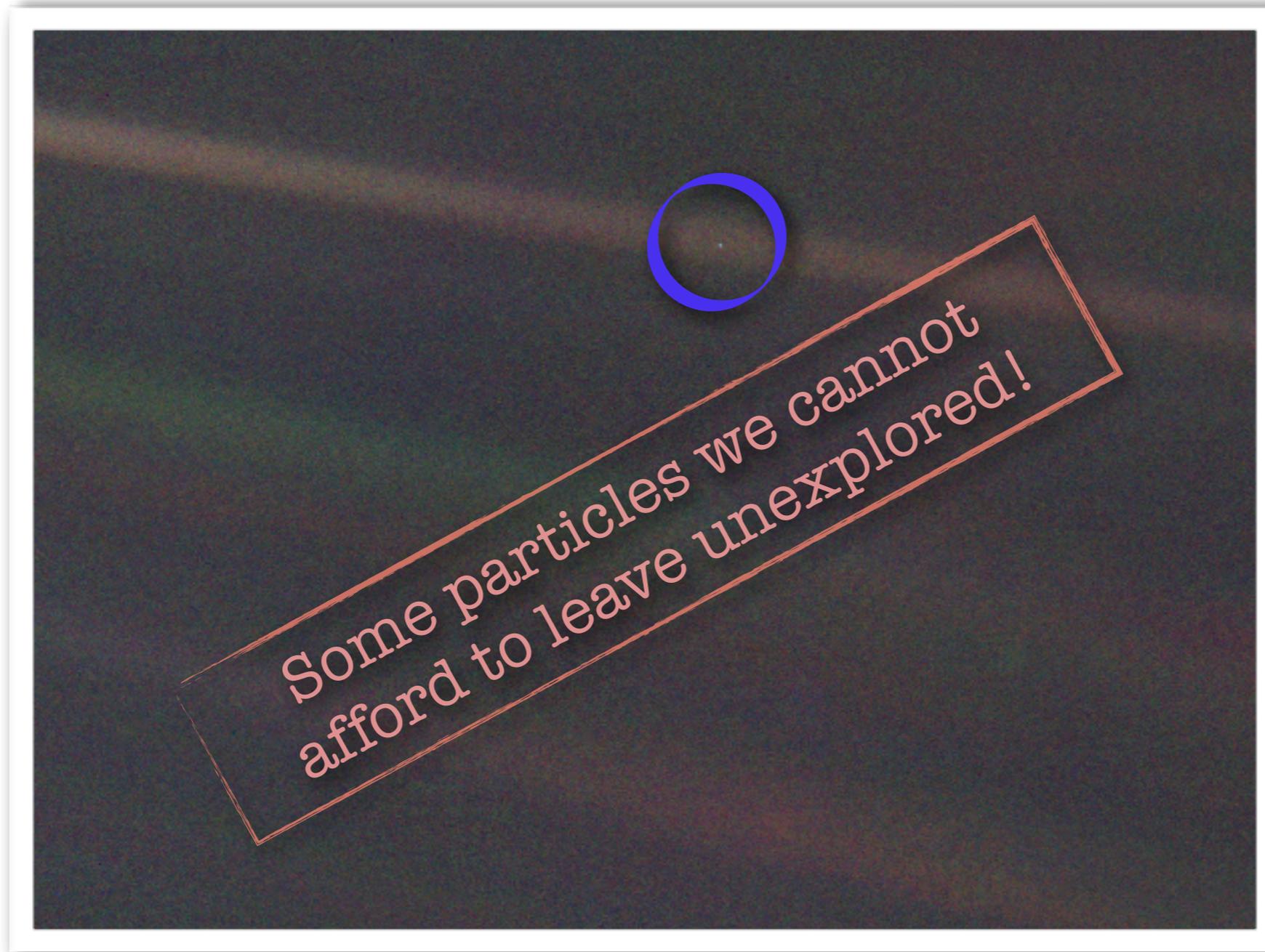


Or...

- everything we have ever known
- everyone we love
- everything that is dear to us
- our home!

- An artist's rendition of our particle beam?
- A granular image of particles trapped in a atomic vacuum chamber?
- ...?

# Take home message



There is more than meets the eye!