Welcome to Fermilab!

Why Quantum?

Roni Harnik,

Fermilab Theoretical Physics Div.

Fermilab

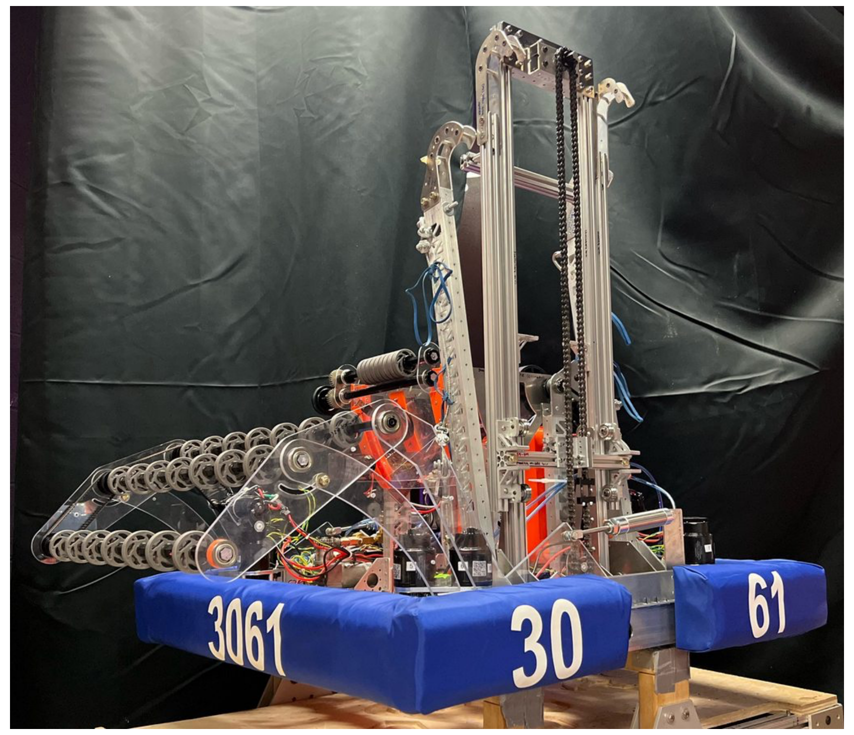
Welcome to Fermilab's QCIPU! The 3rd annual, 1st in person!

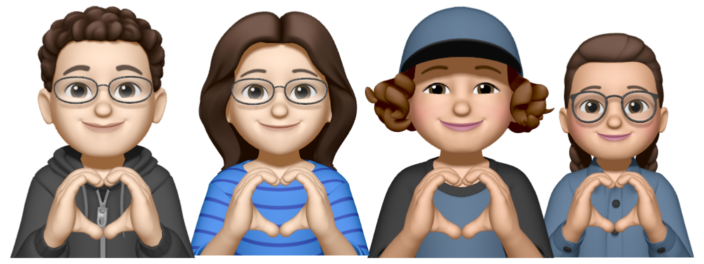
Outline:

- I'm Roni.
- Flash Survey on who y'all are.
- What is Fermilab all about?
- Why is Fermilab interested in Quantum and QIS?
  - What can quantum do for us?
  - What can we do for quantum?

Intro

- I'm Roni. I work in the Fermilab Quantum theory Department (and at SQMS).
- Originally from Israel. Did my undergrad there.
- Grad school was in the US.
- After 10 years in the bay area, I moved out here.



- I like traveling (with my family),  , hiking …
- … and being a mentor on my kids' high school robotics team. Go Huskies!!

Intro

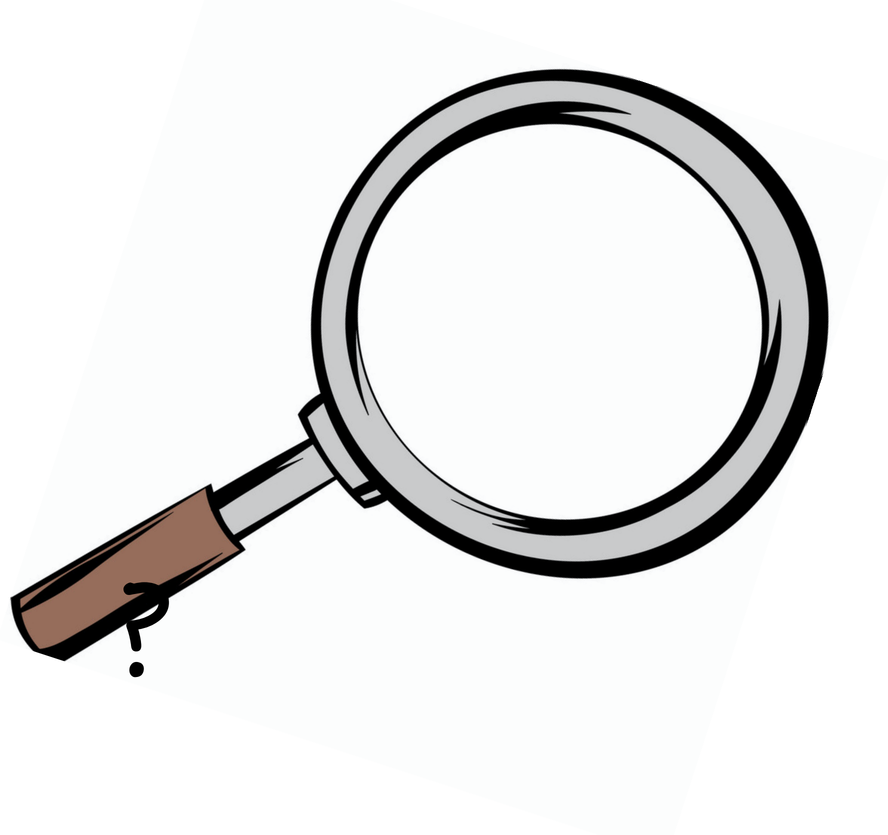
- There will be introductions, but, show of hands:
  - Who is a rising Senior? Junior? Sophomore?···
  - Who took a class in quantum mechanics? Not required.
  - Who is studying in the east coast? west coast? the south? midwest?
  - ···

PARTICLE PHYSICS

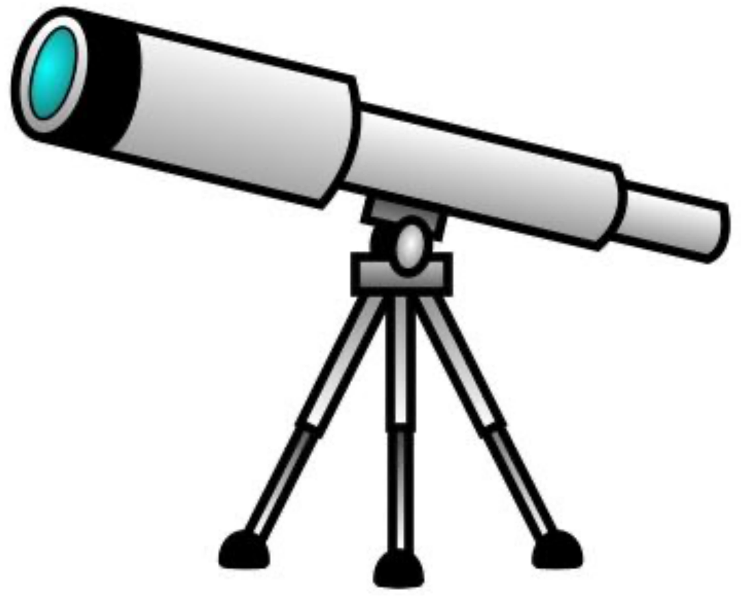
We are Curious!!!

What is everything made of?
What are the basic degrees of freedom?
What rules do they follow?

What does the Universe contain?
What is its history?

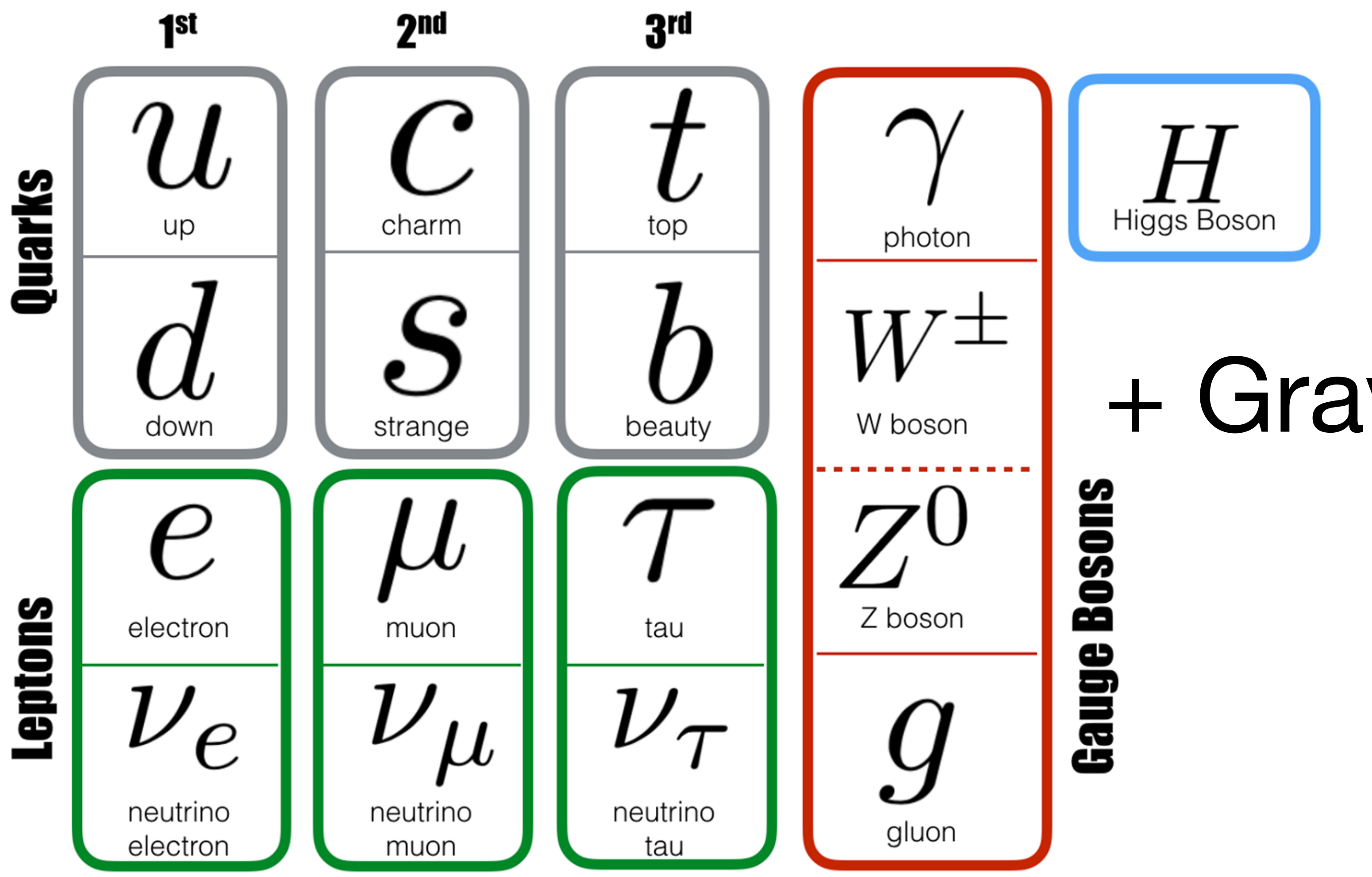


Look small

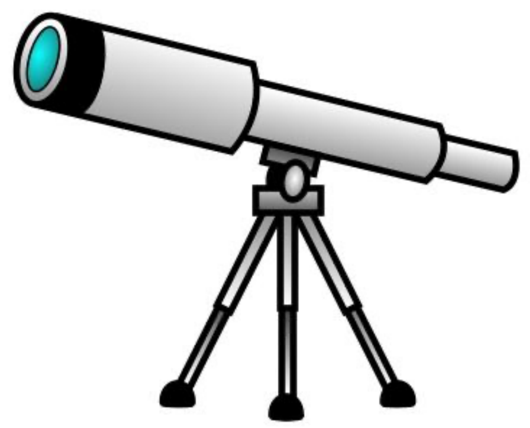


Look big

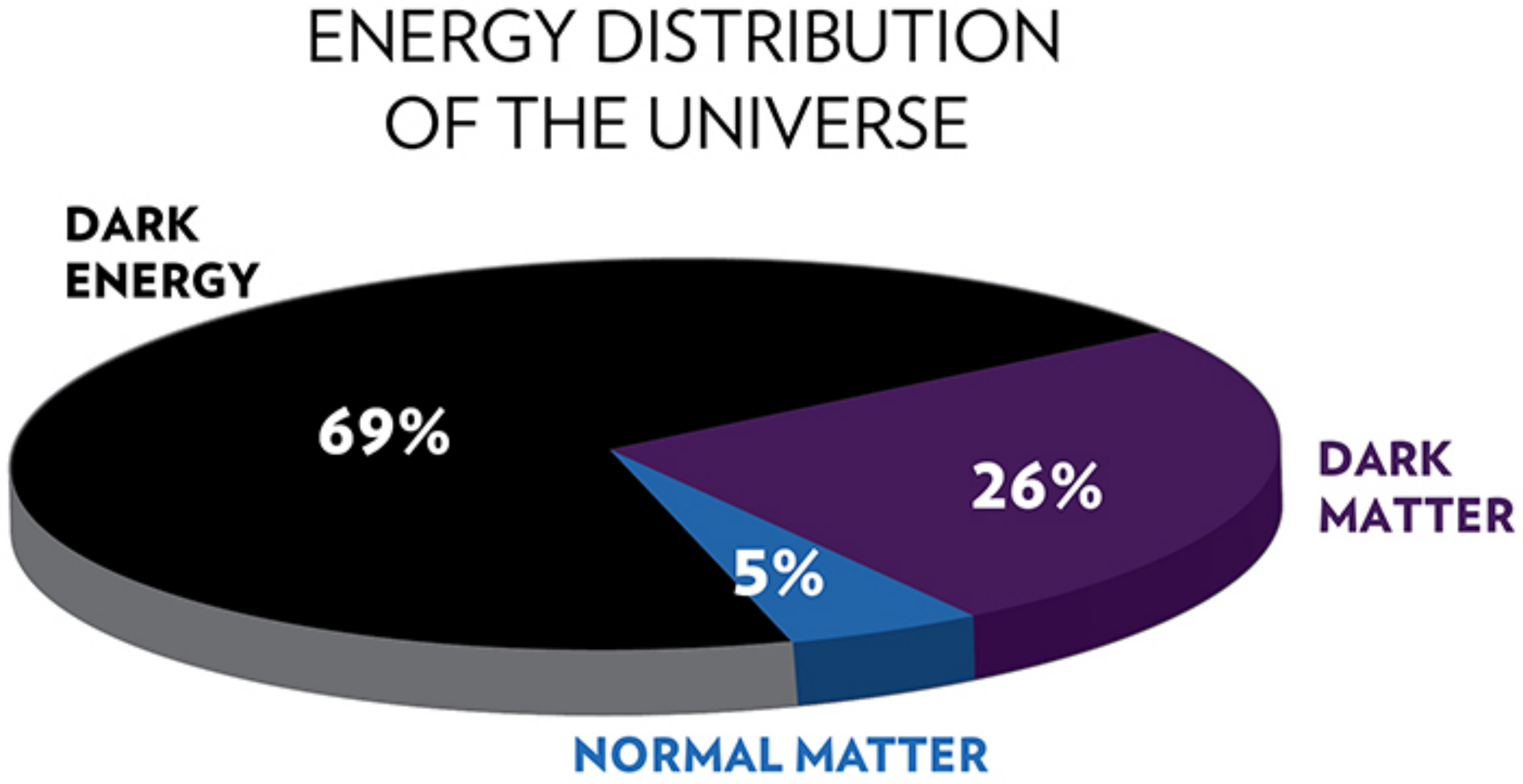
The Standard Model
(of particle physics)

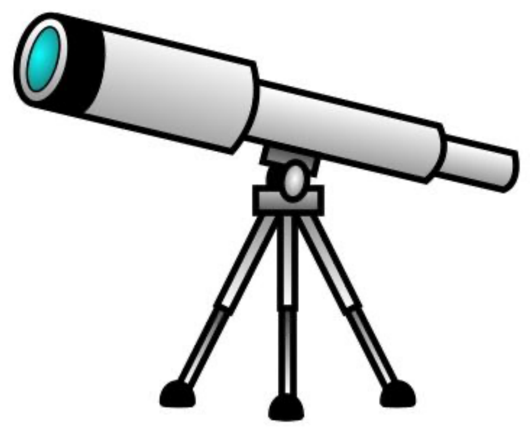


+ Gravity



The Standard Model
(of cosmology)





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The Standard Model
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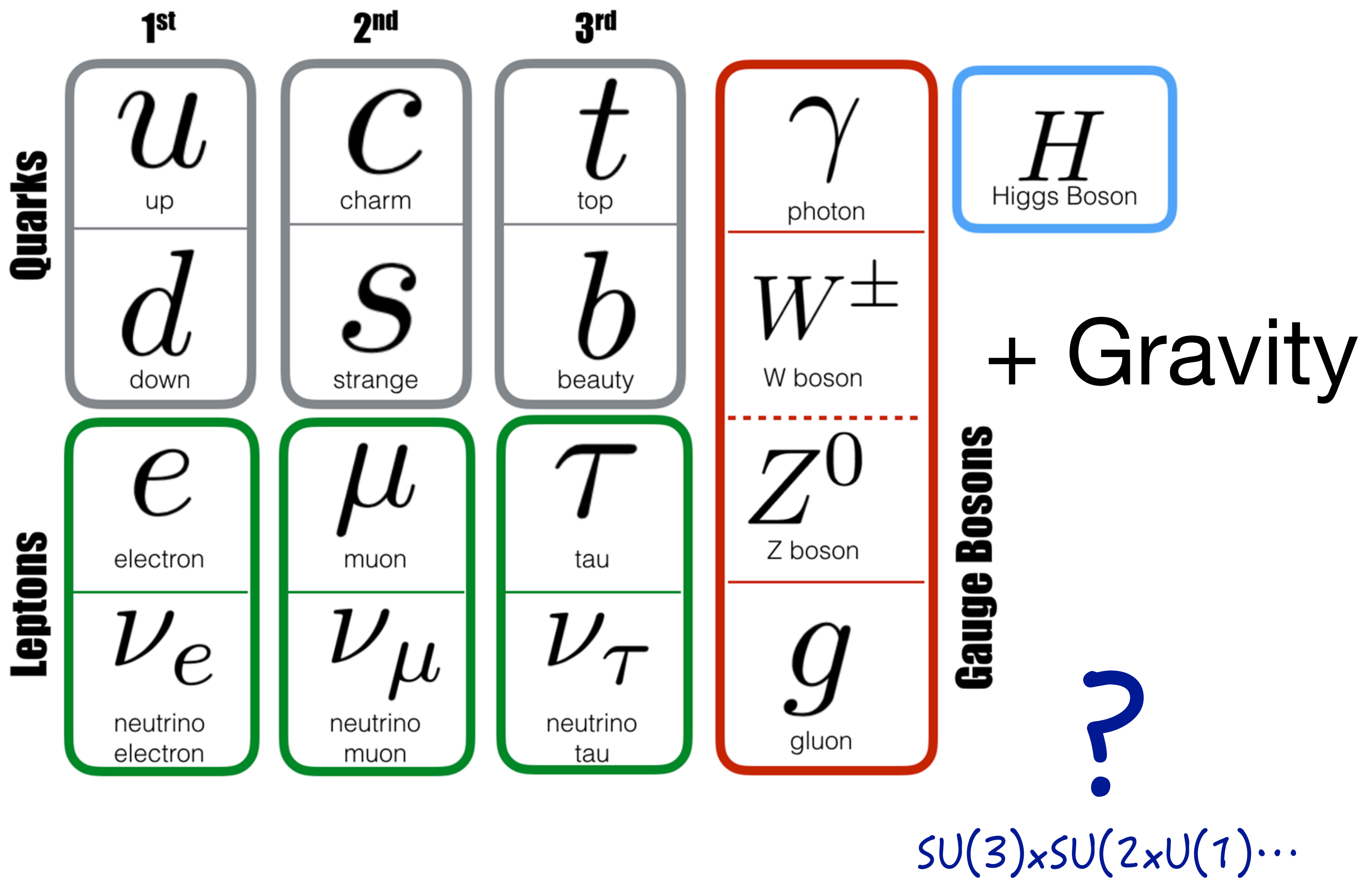
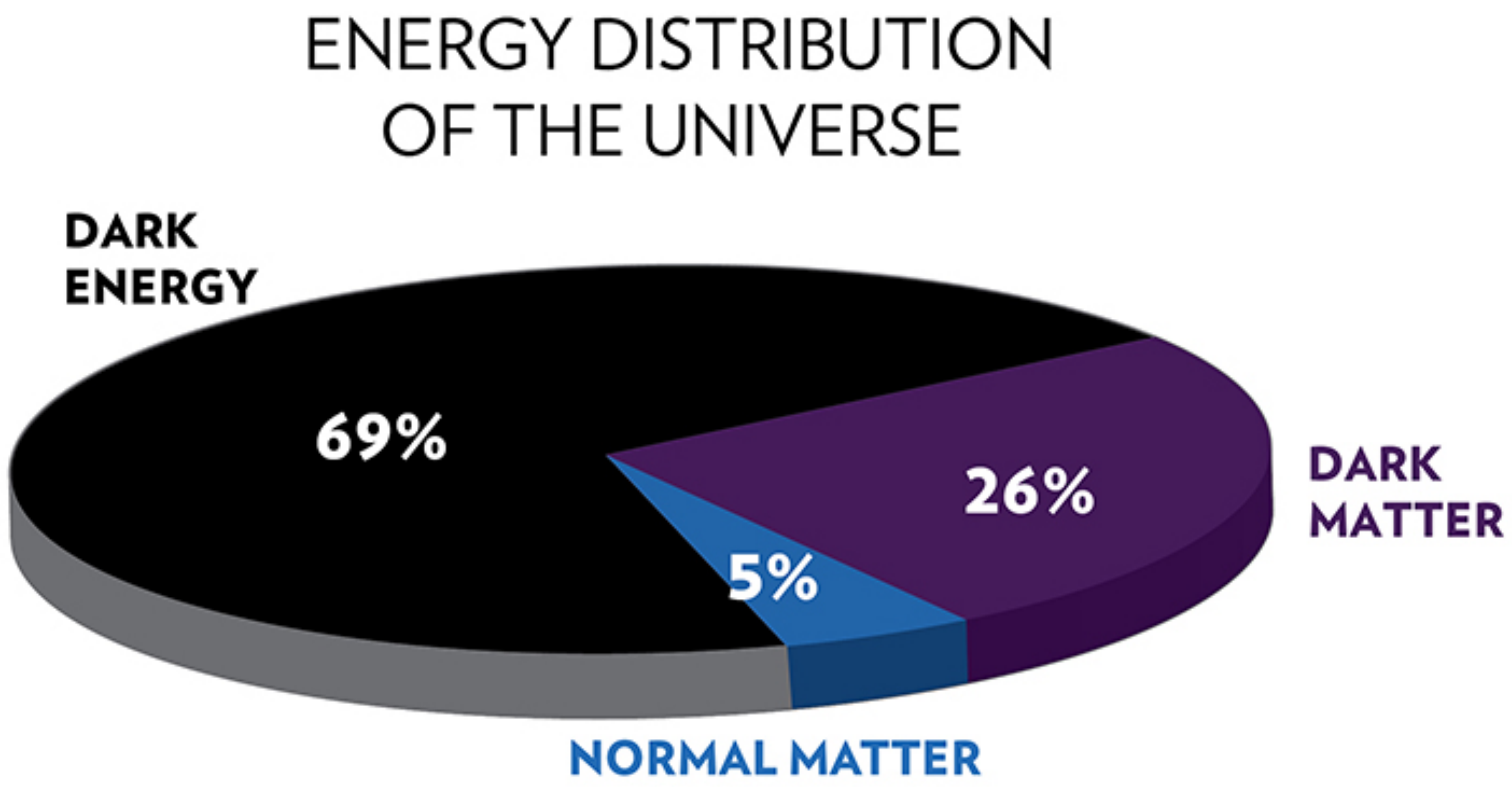
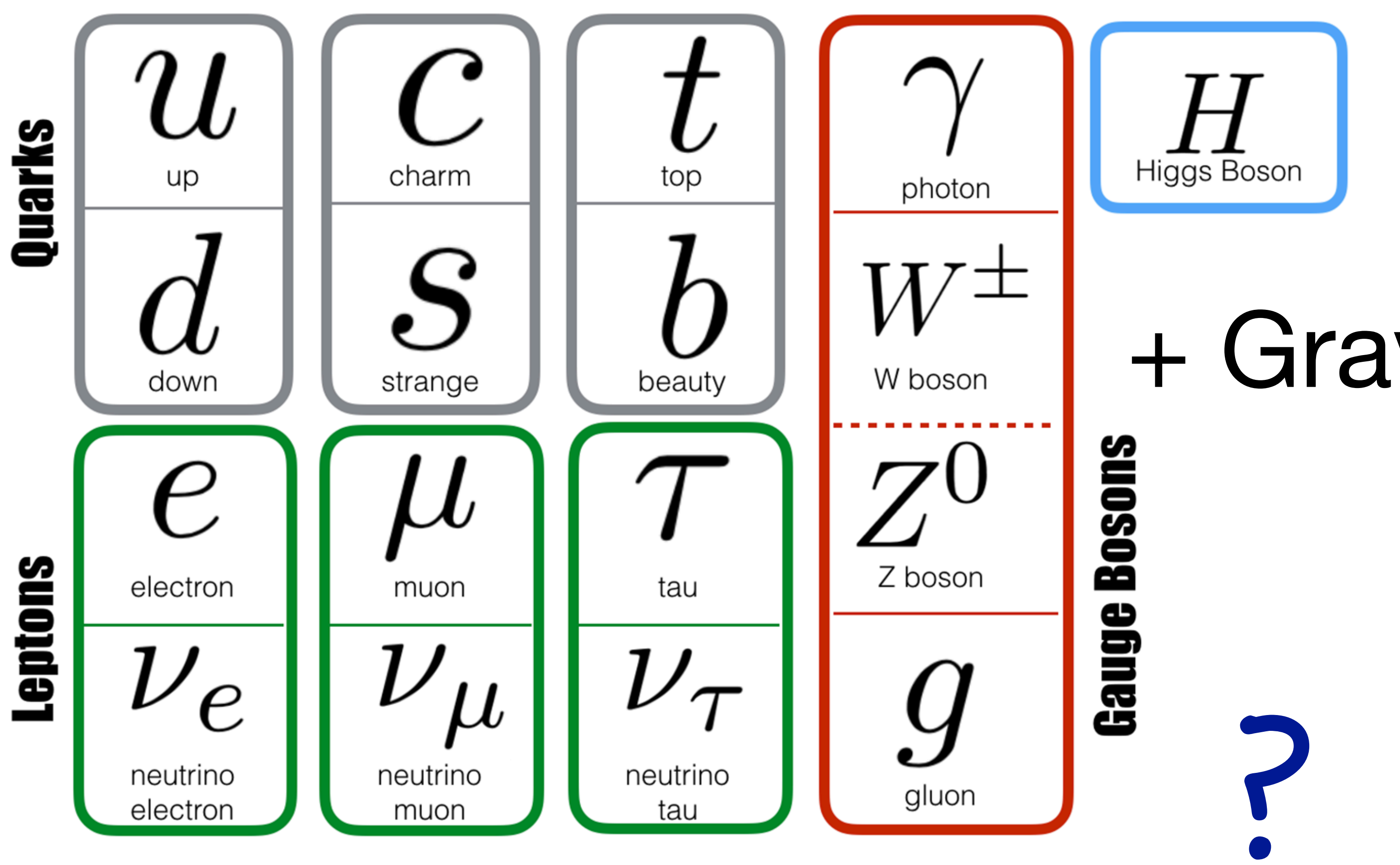




The Standard Model (of particle physics)

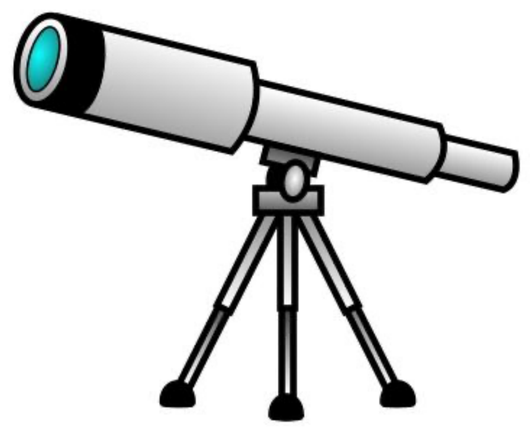
? flavor…



+ Gravity

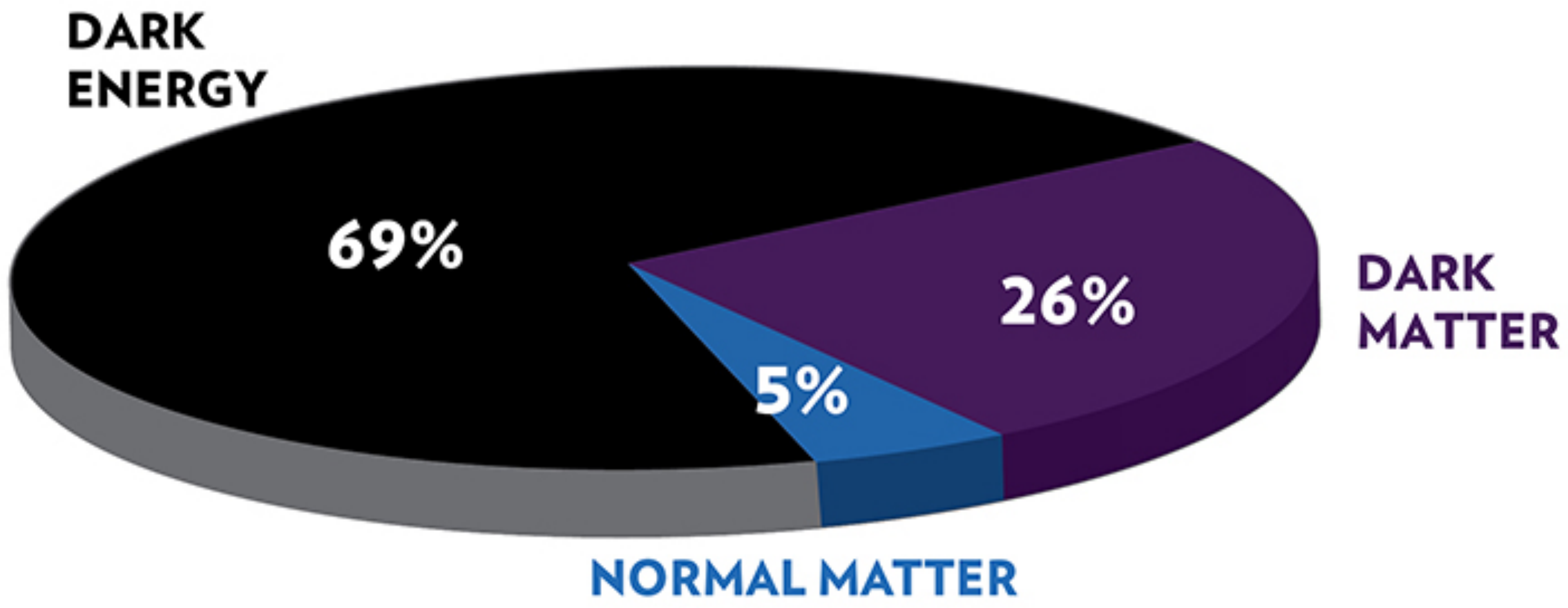
?

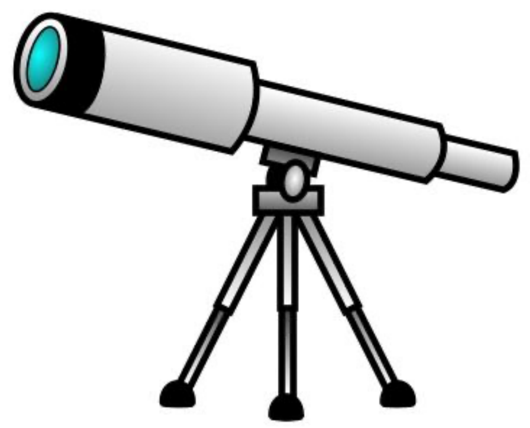
SU(3)xSU(2xU(1)…



The Standard Model (of cosmology)

ENERGY DISTRIBUTION OF THE UNIVERSE





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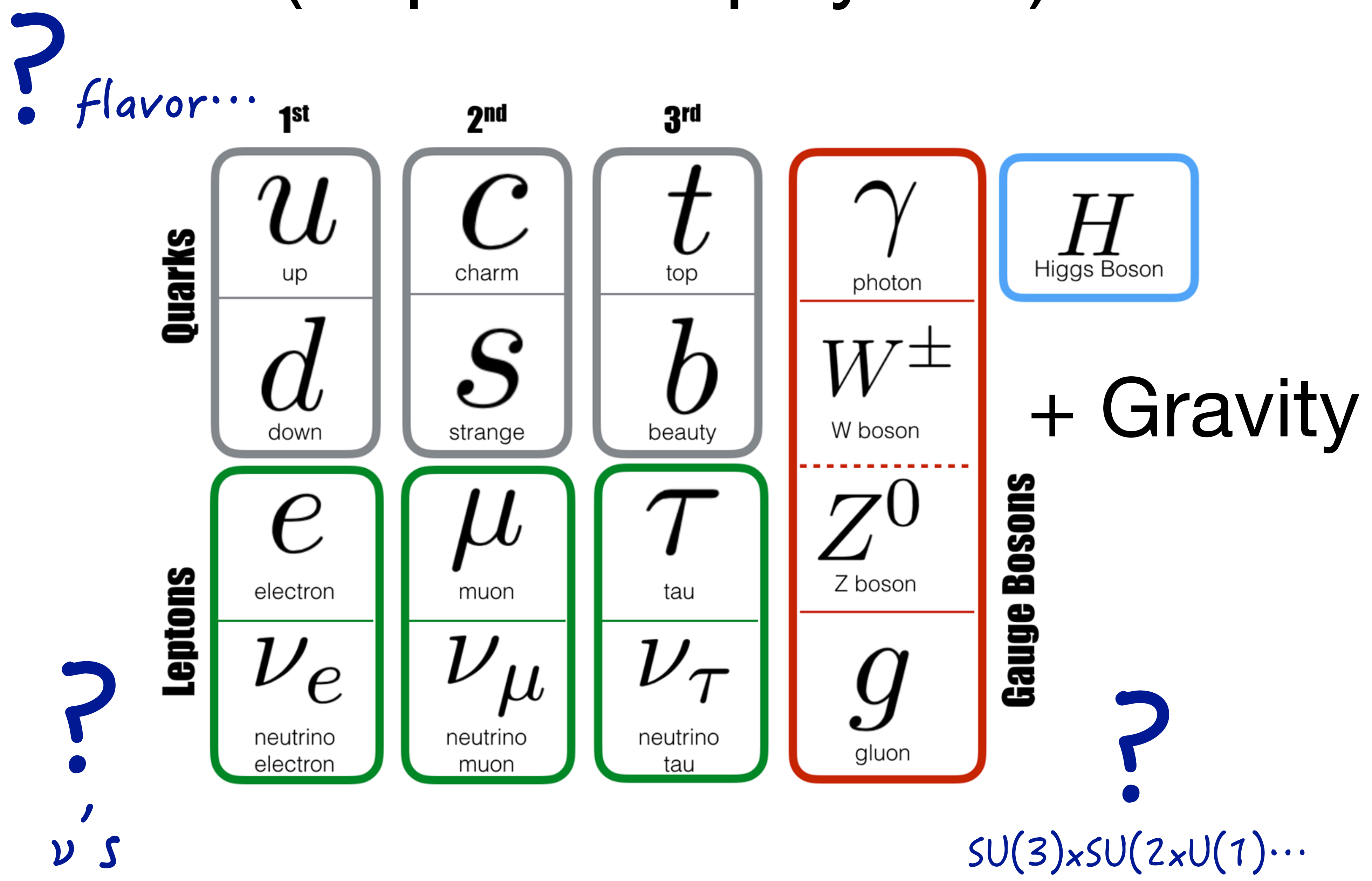

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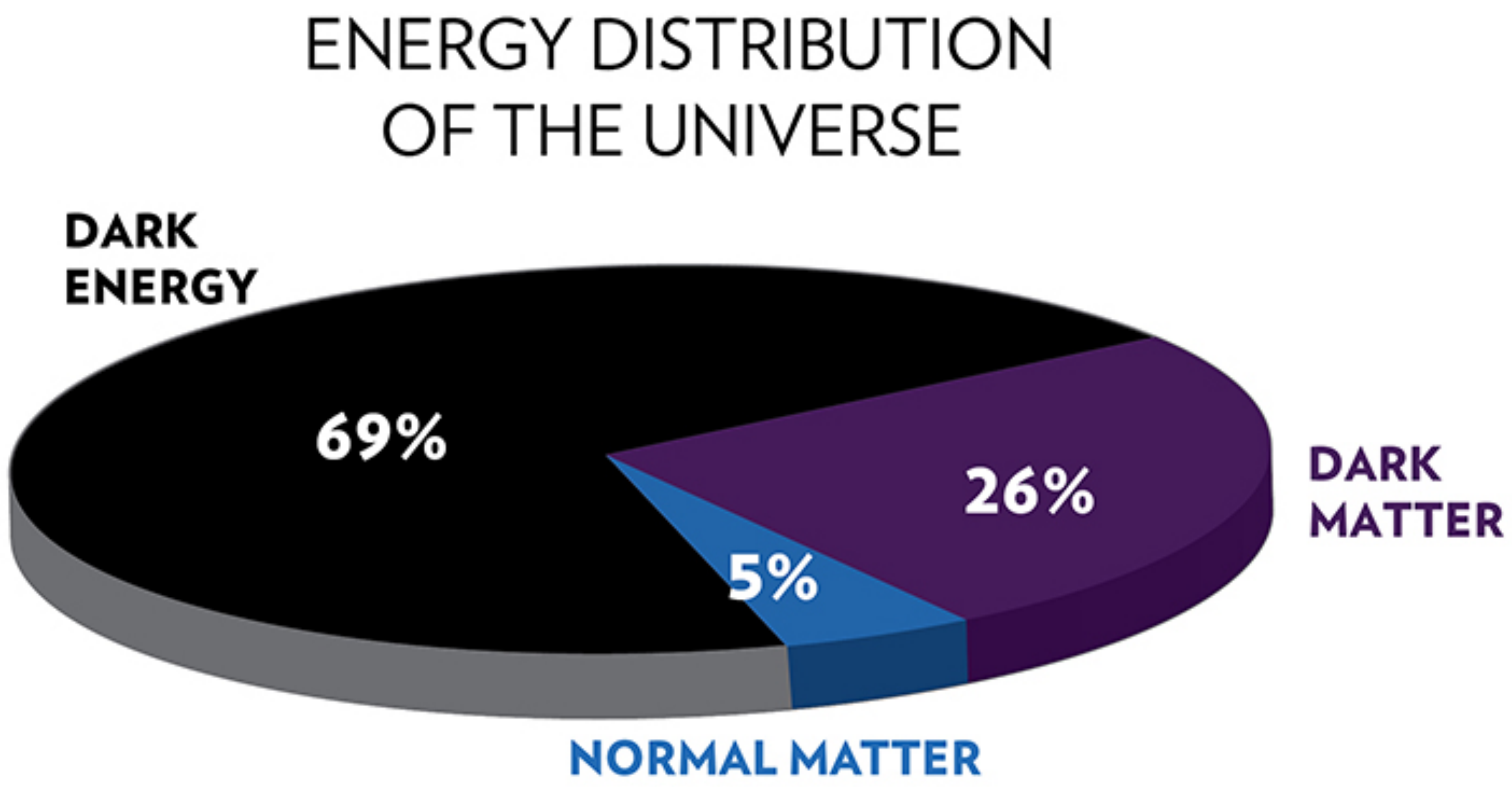

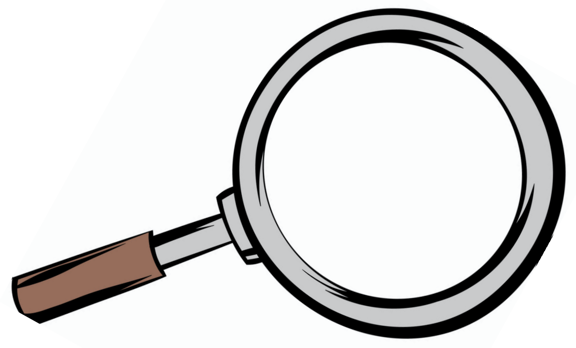

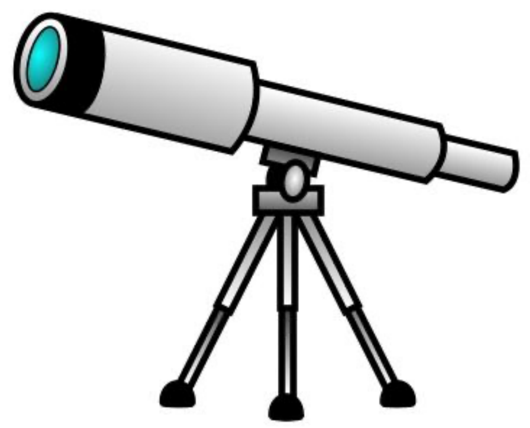

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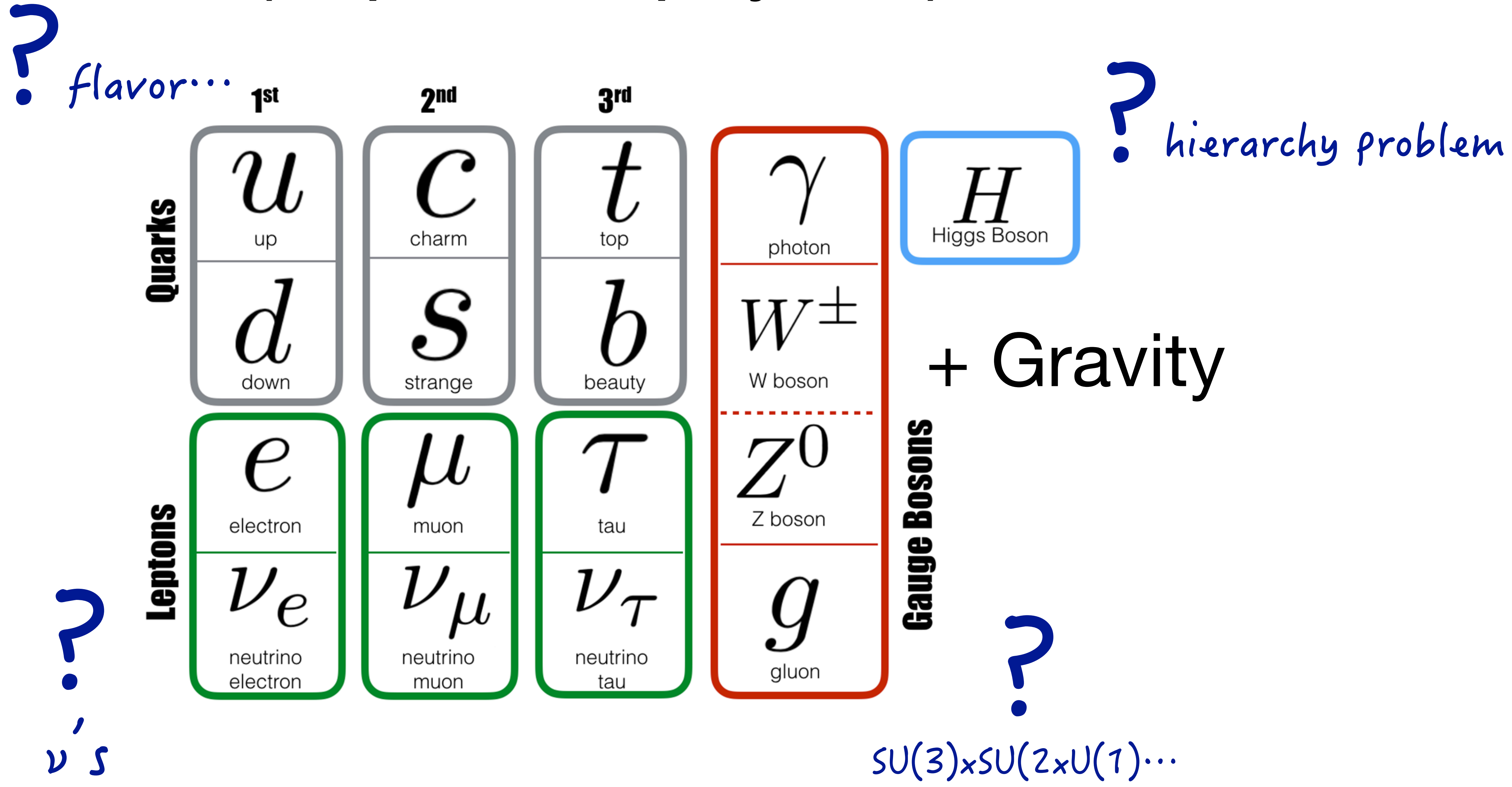

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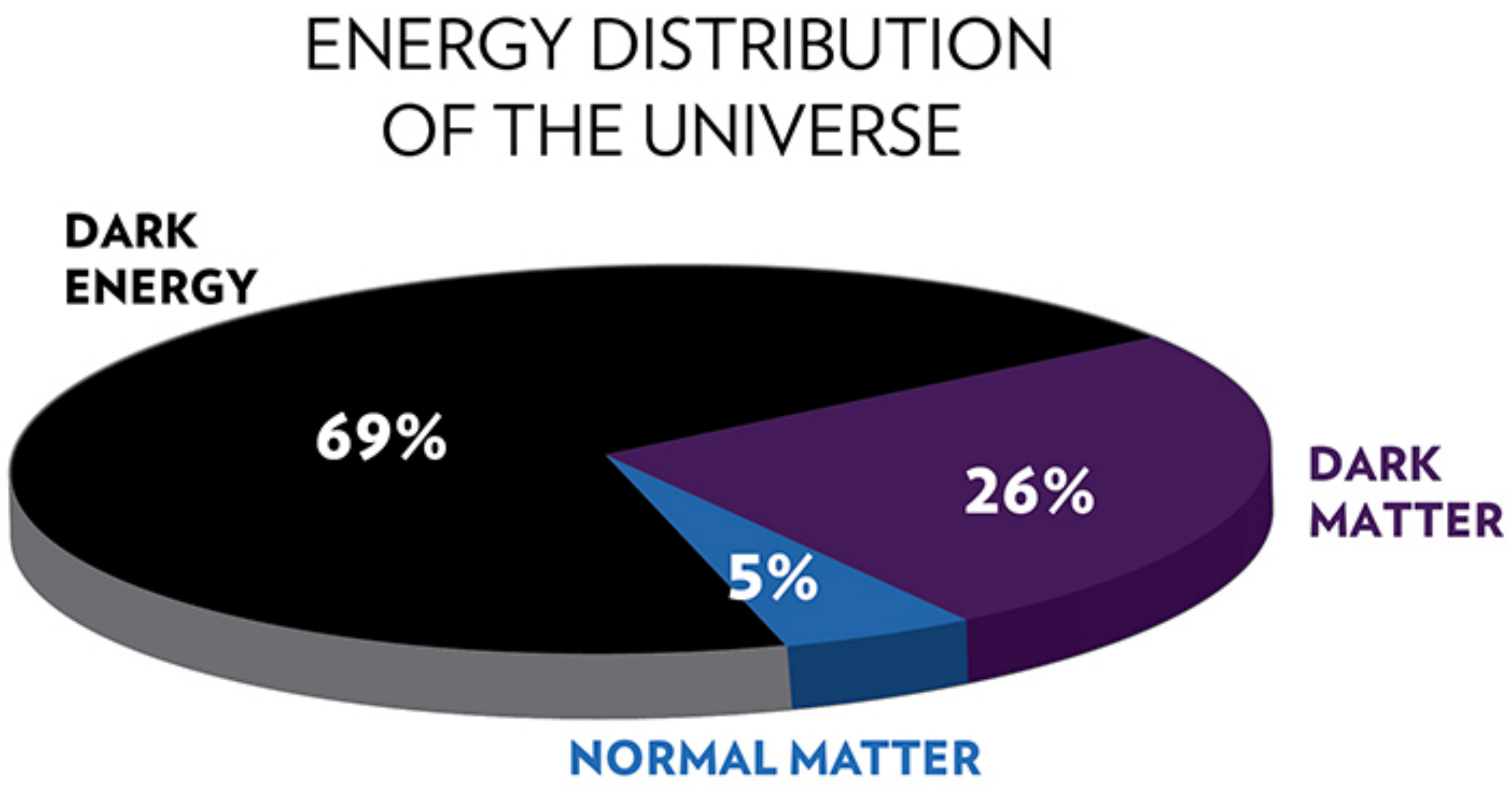

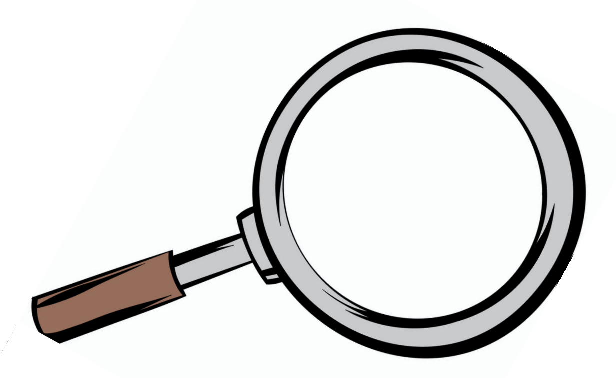

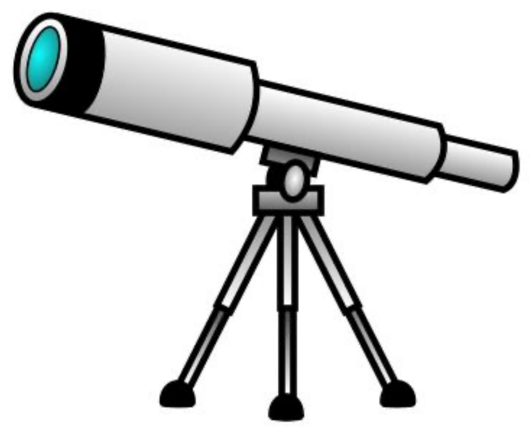

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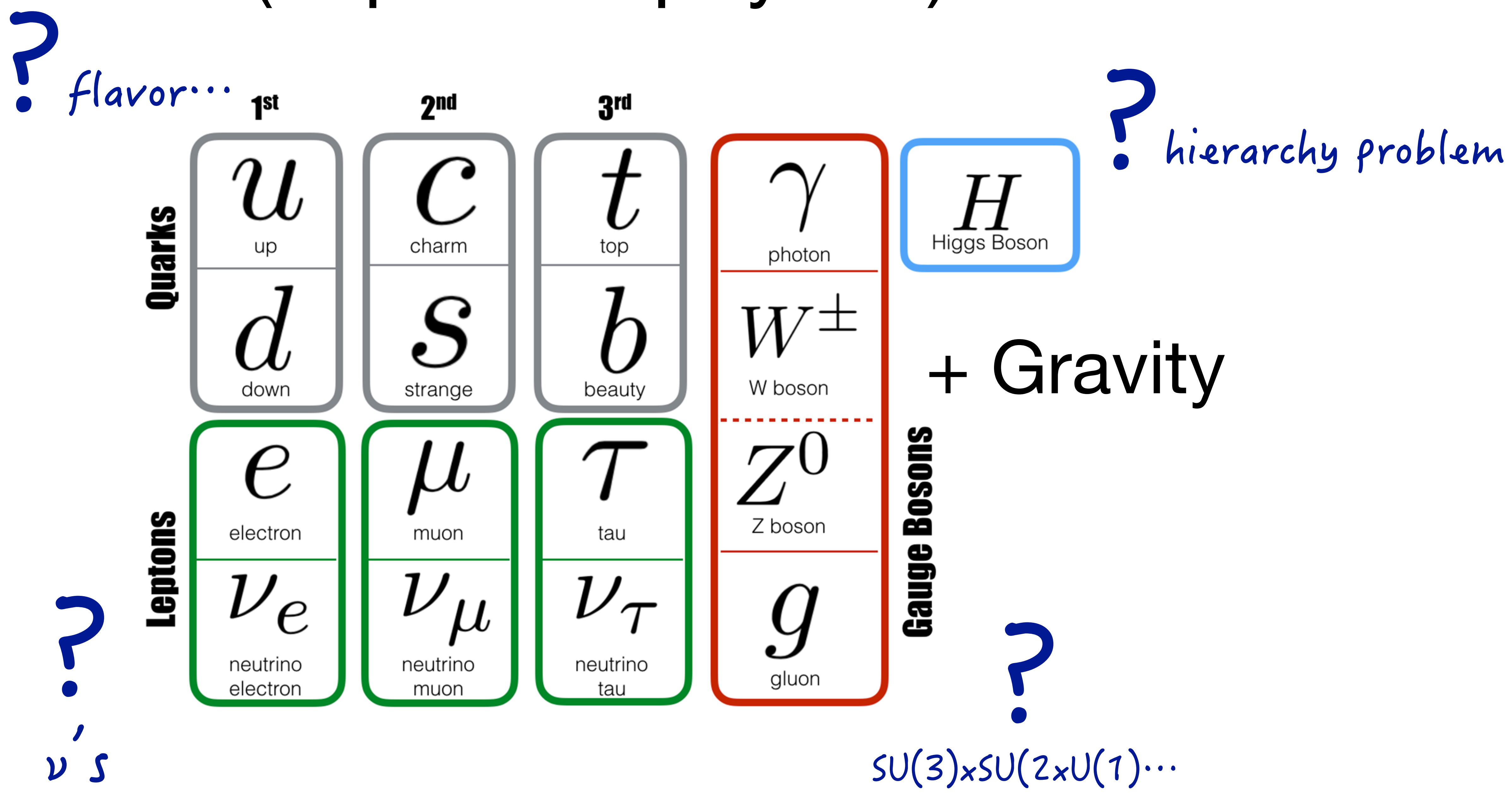

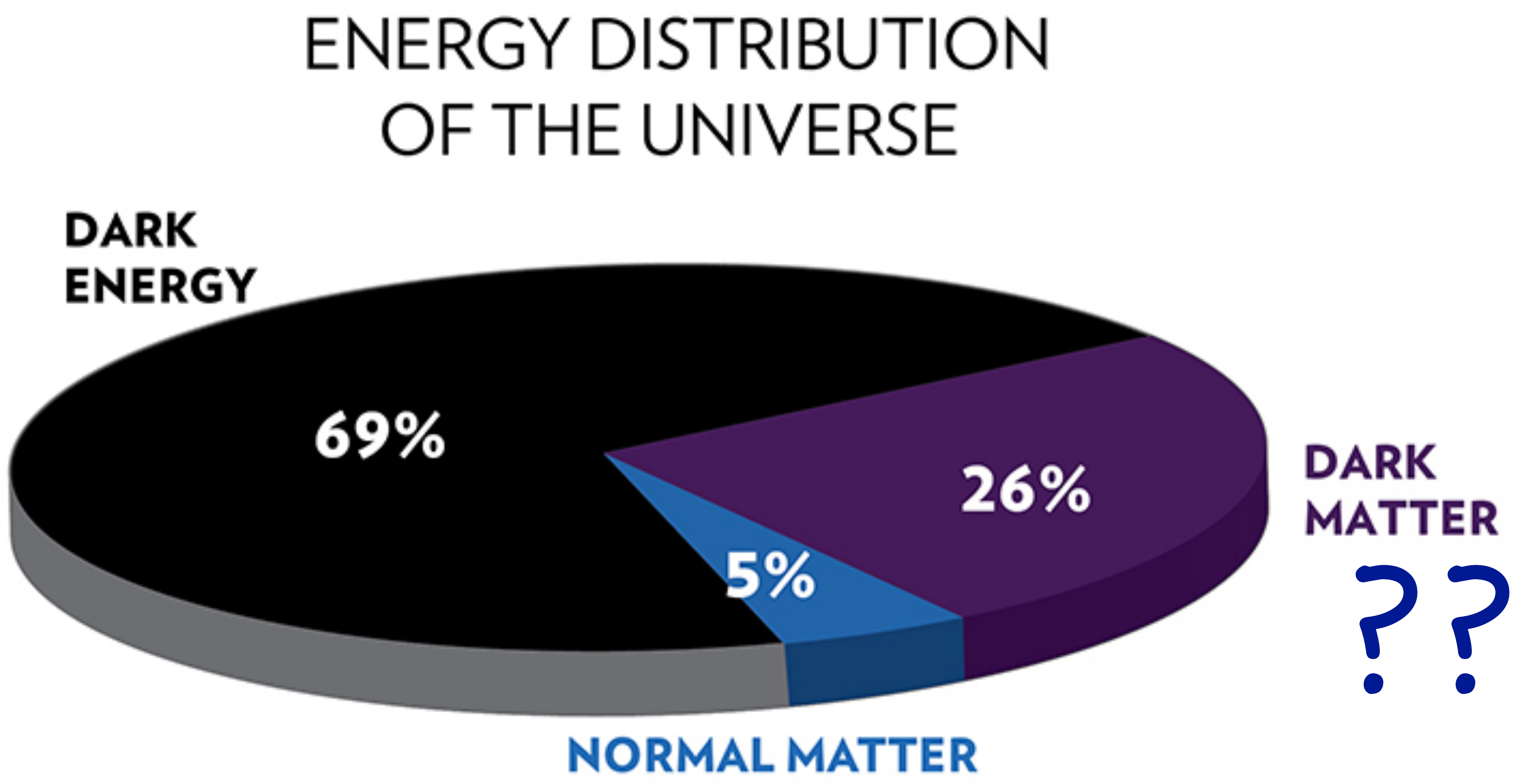

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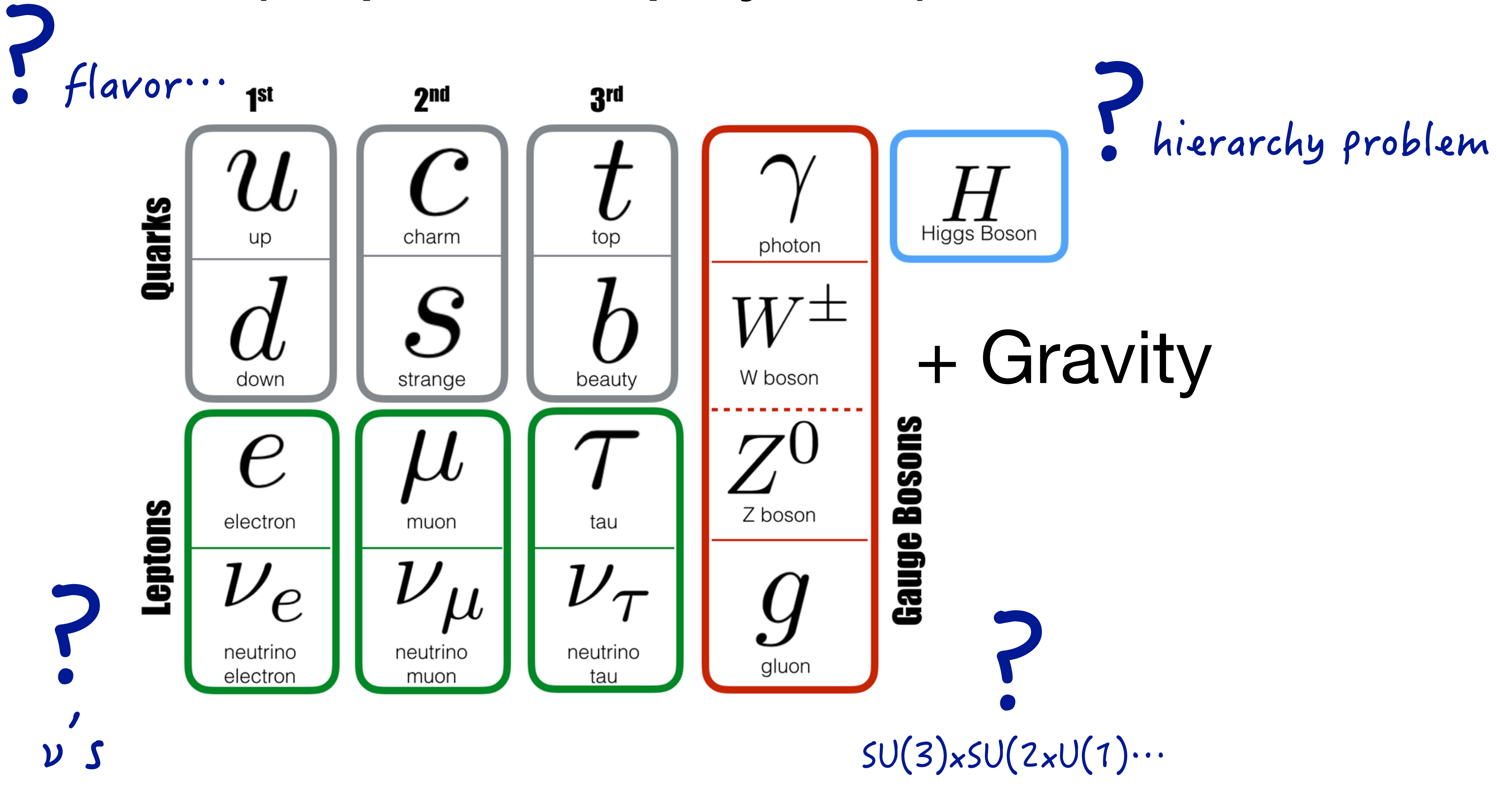

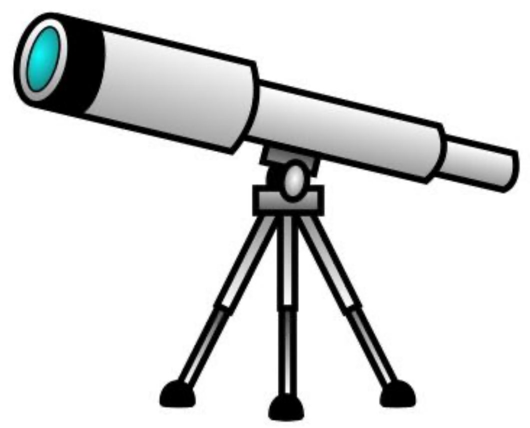

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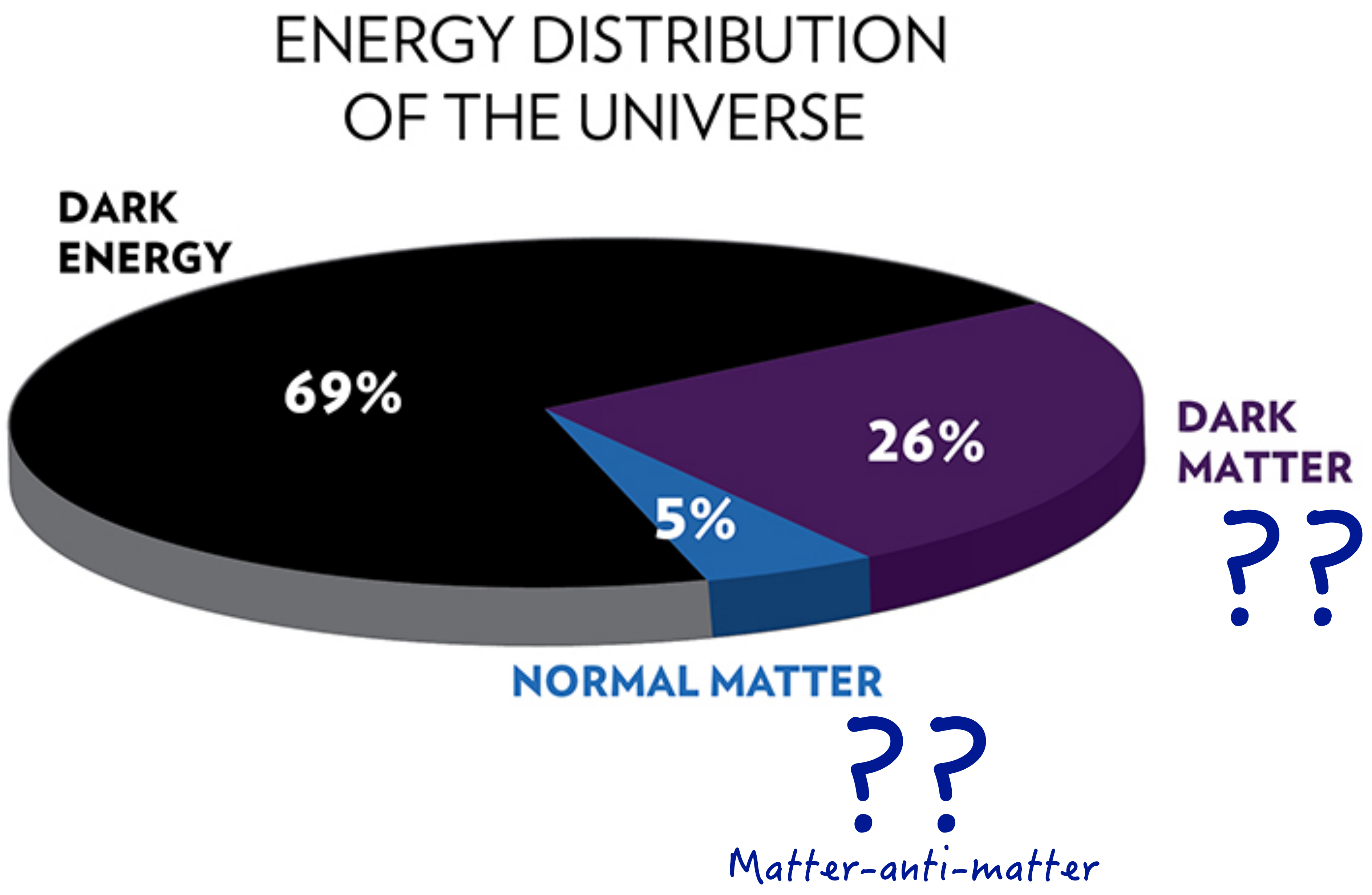
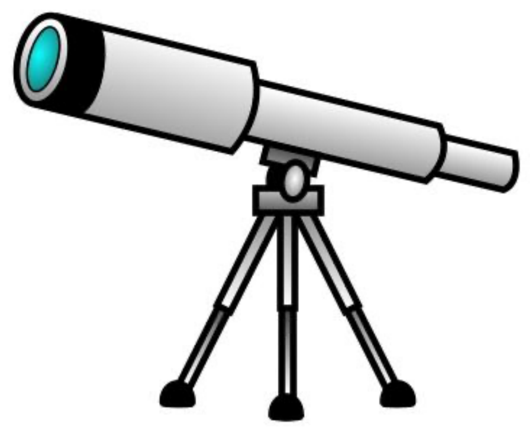
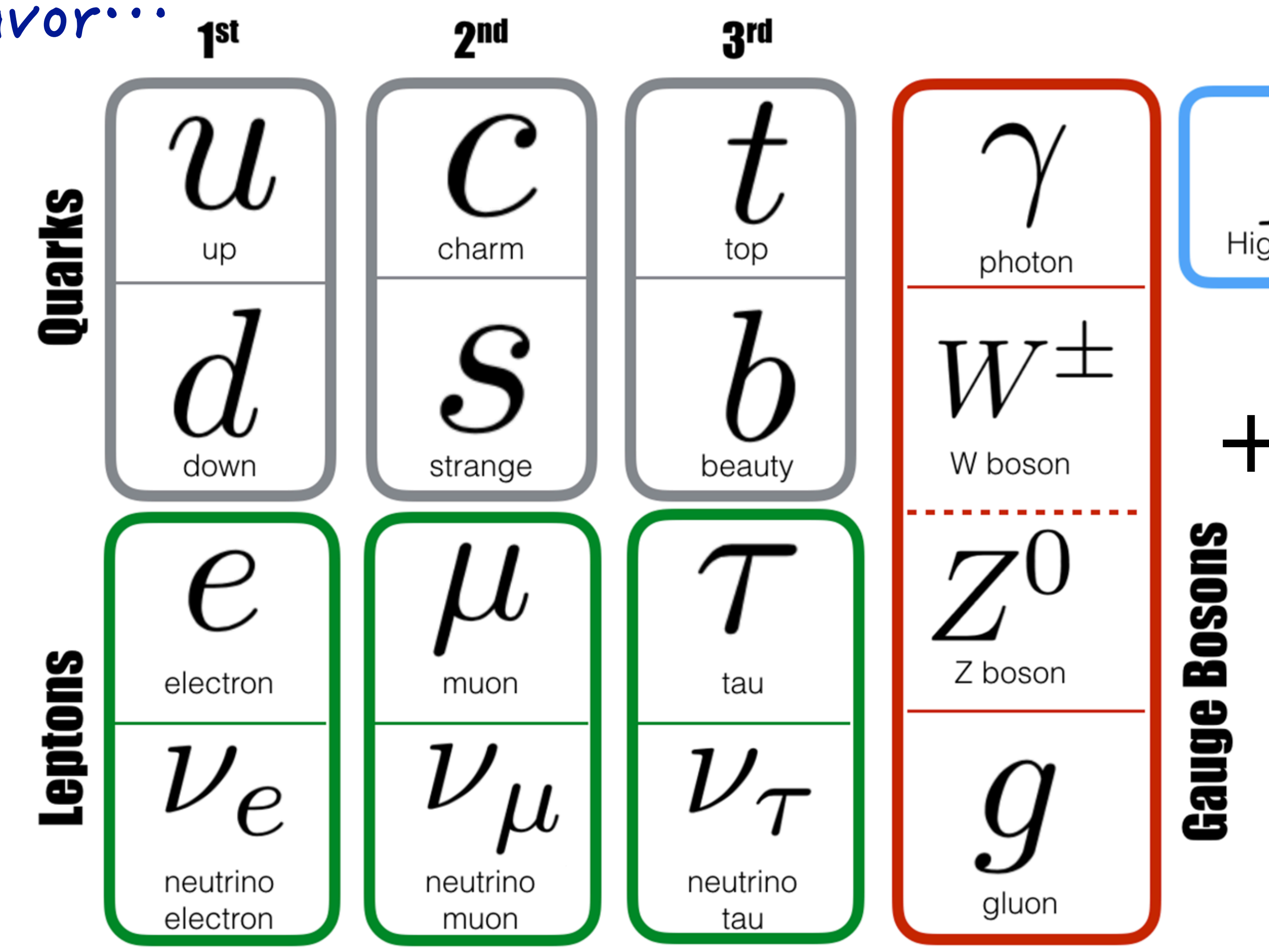




The Standard Model (of particle physics)

The Standard Model (of cosmology)

? flavor...

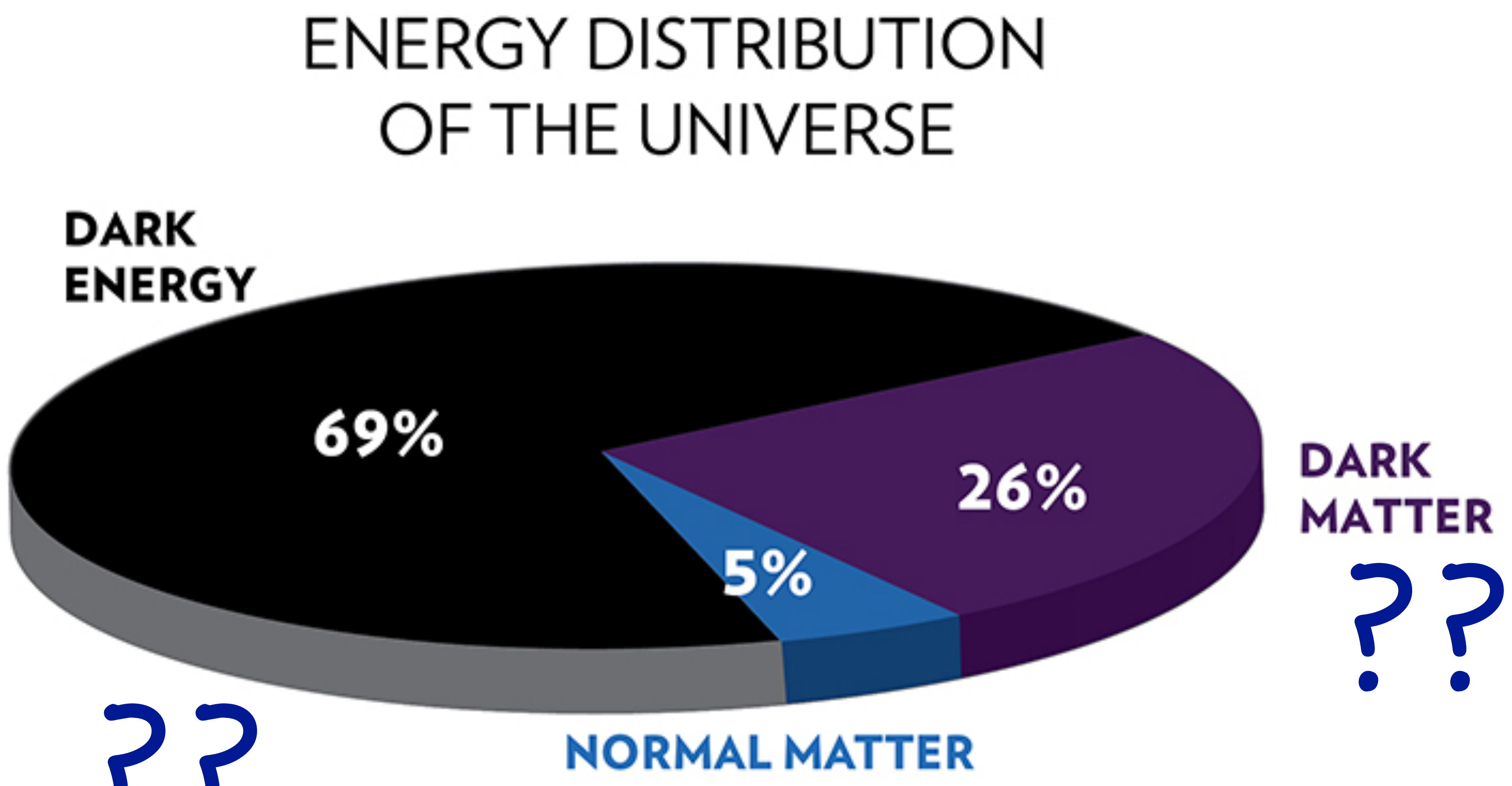


? hierarchy problem

+ Gravity

? ν's

? SU(3)xSU(2xU(1)...



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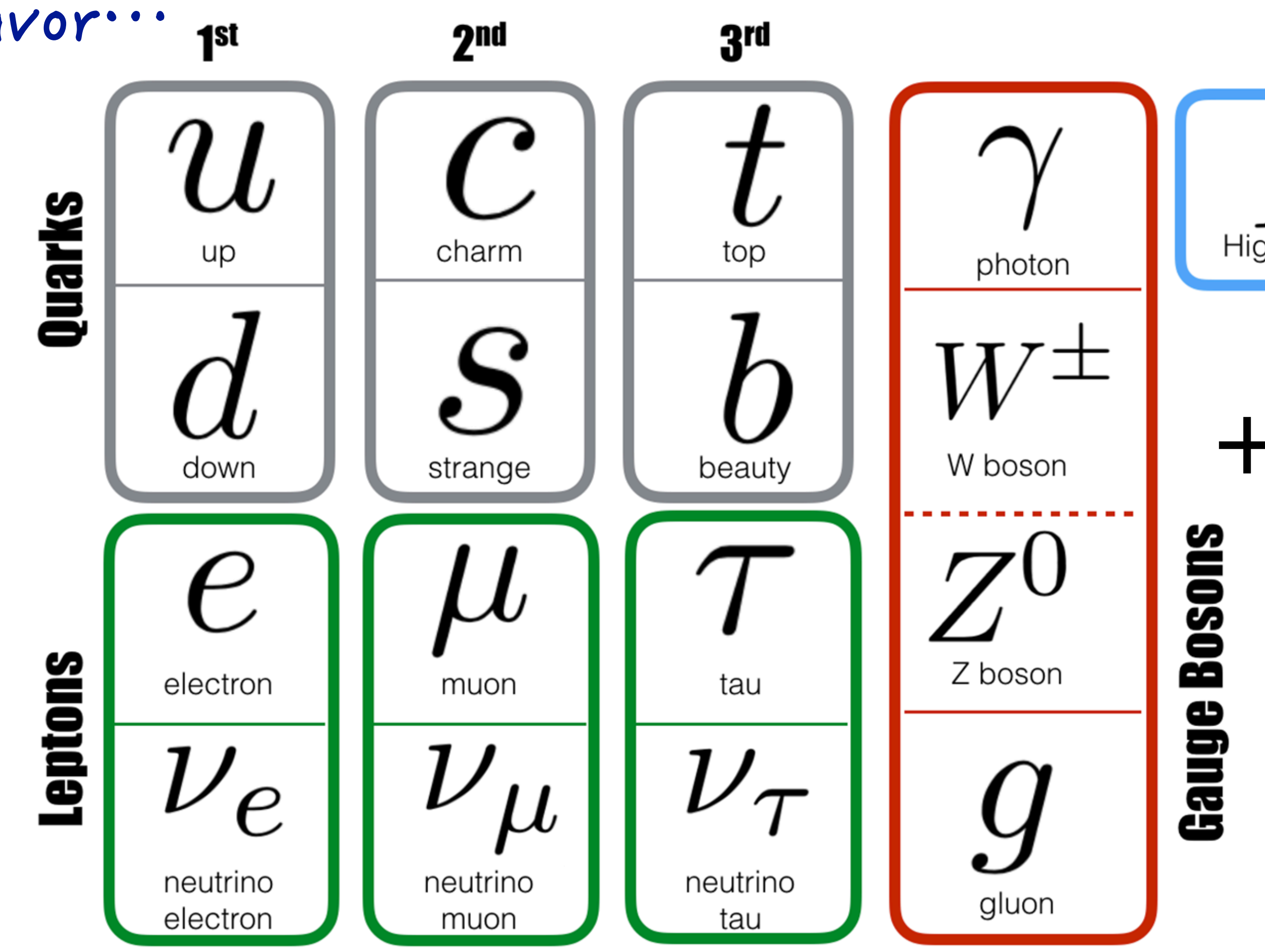
Matter-anti-matter

The Standard Model (of particle physics)

? flavor…



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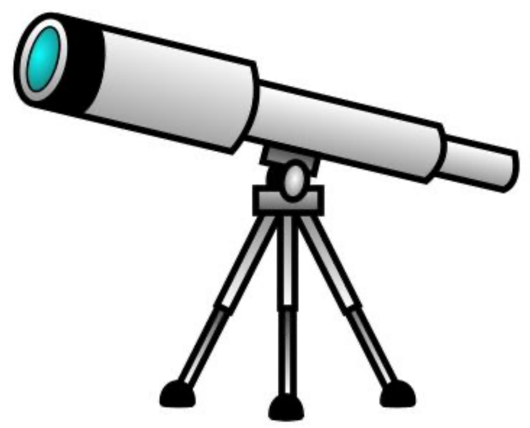
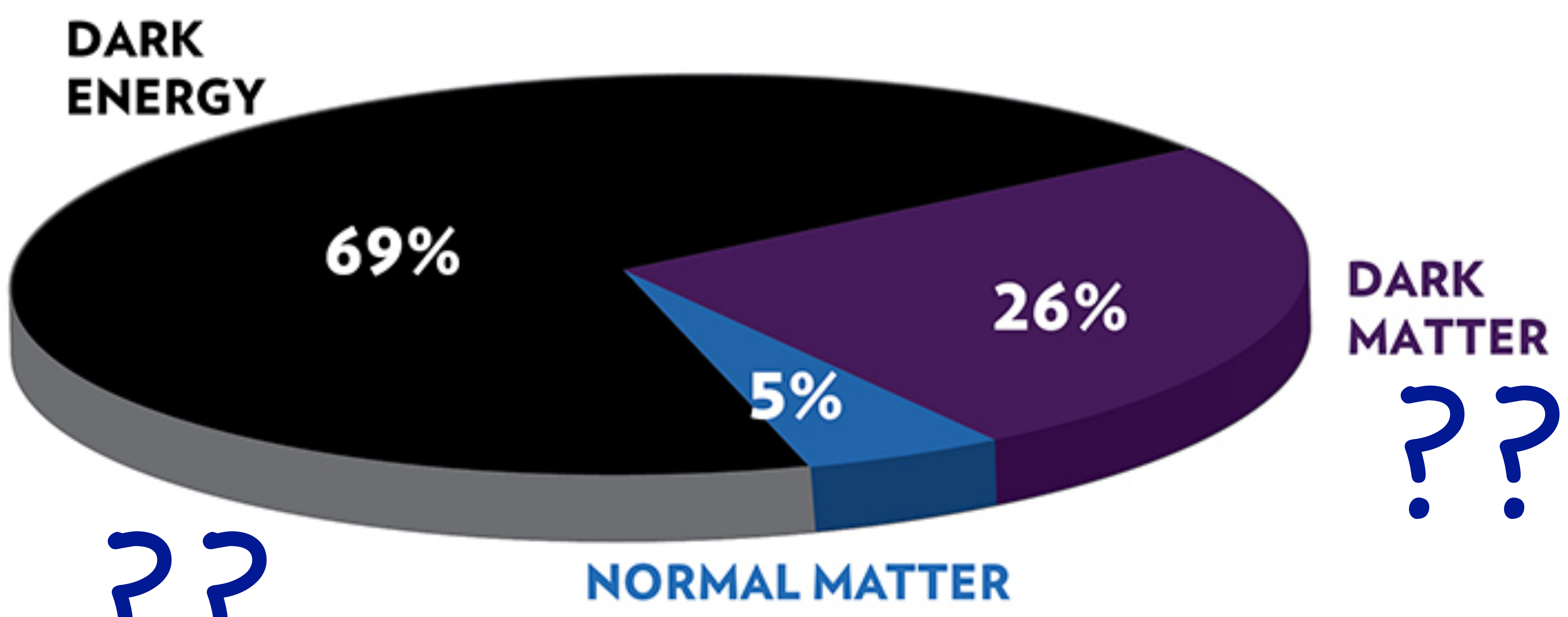


The Standard Model (of cosmology)



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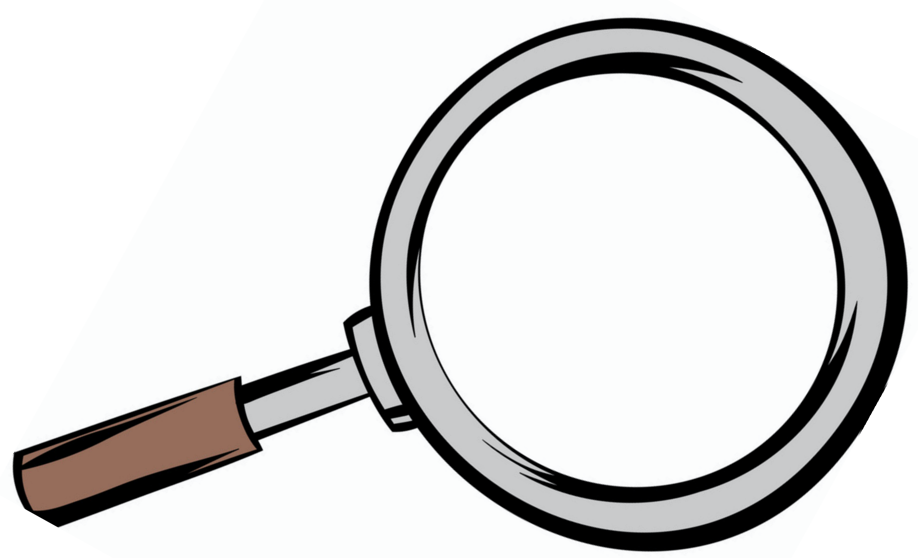
Matter-anti-matter

Is there anything else? Could that be the dark matter?

Can we learn more about cosmic history?



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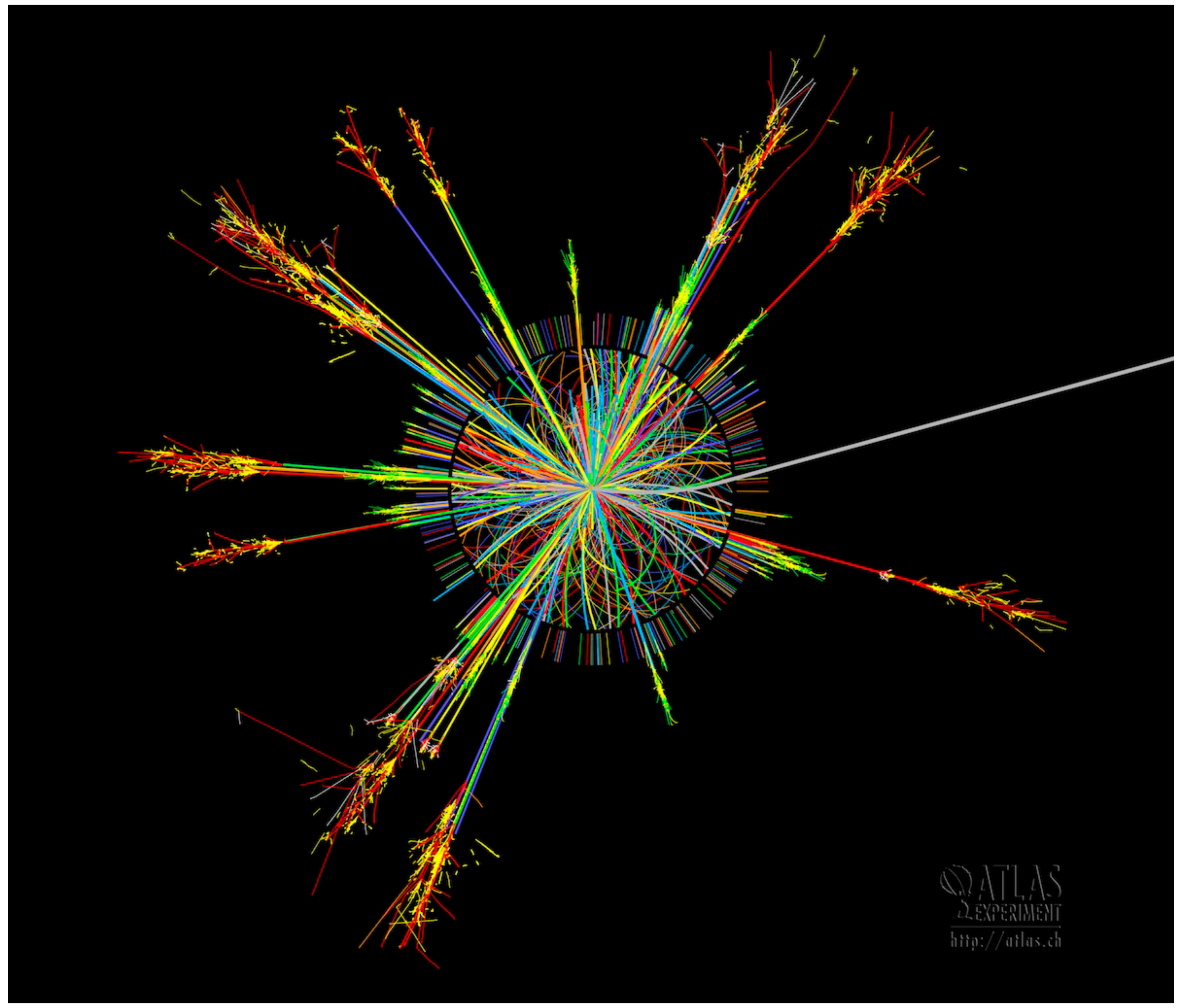
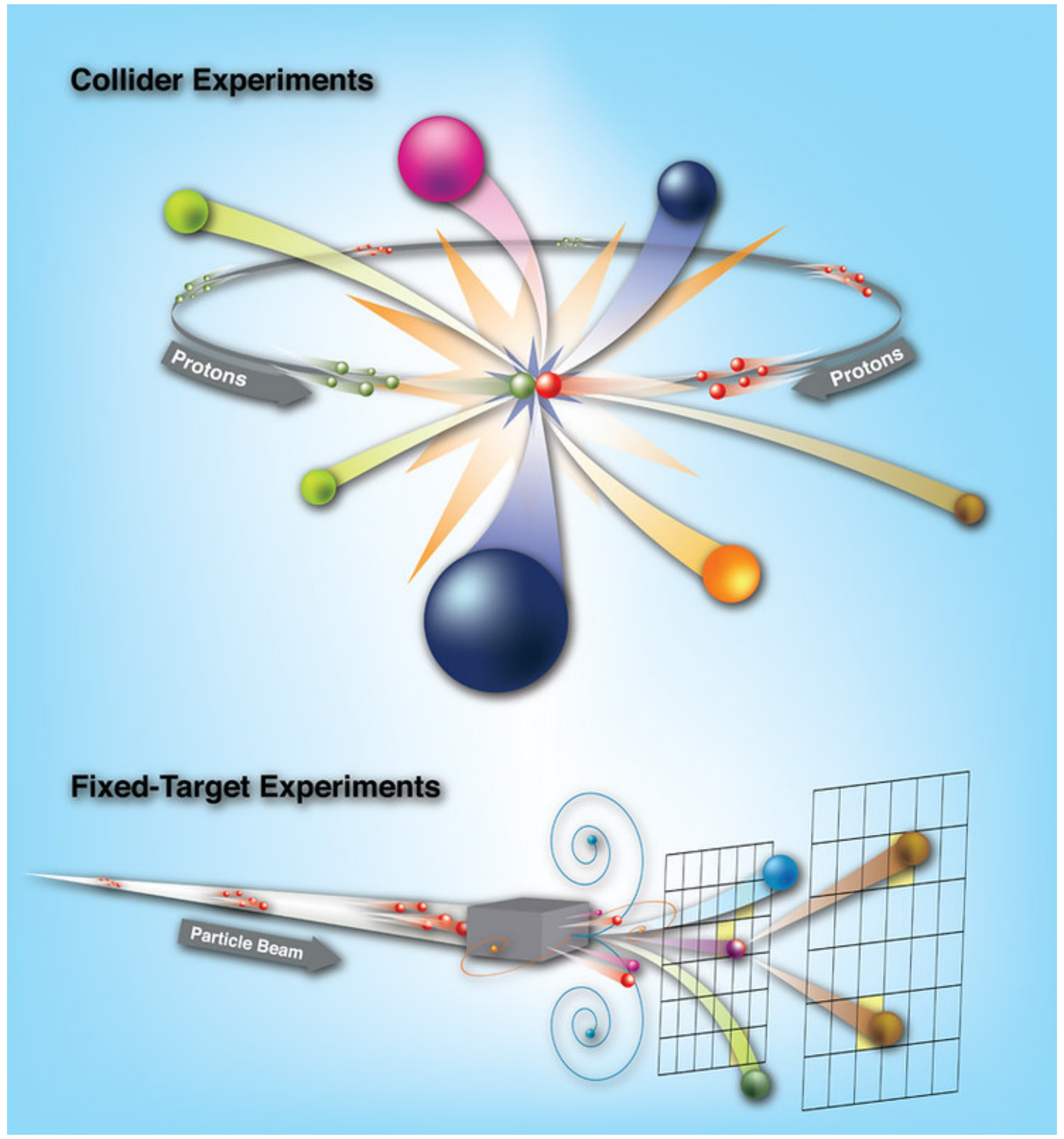
Accelarators, colliders,
detectors, neutrino experiments,
cosmic rays...

Colliders & Fixed target

- A naive way to figure out what stuff is made of - smash it at something!!

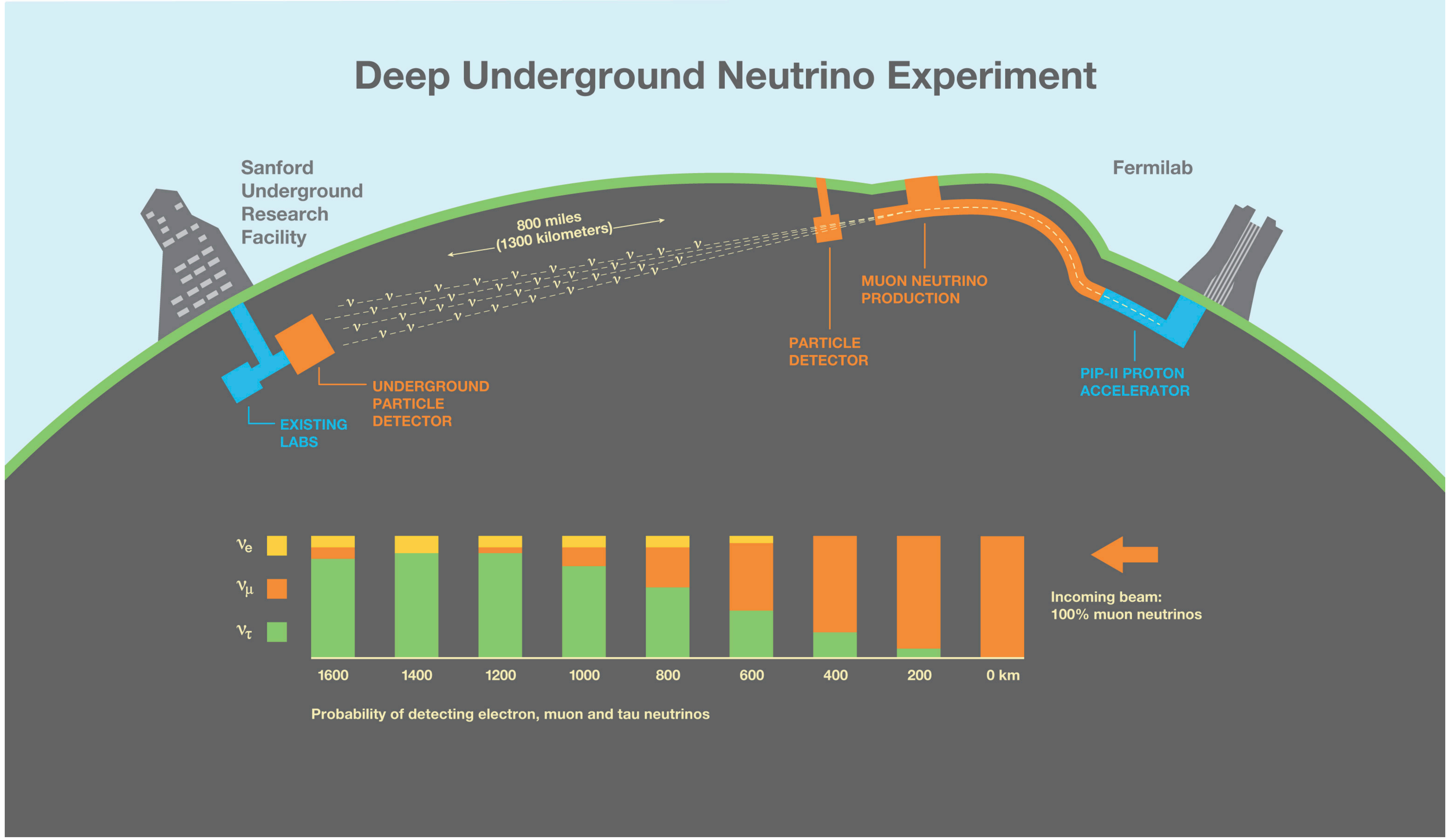


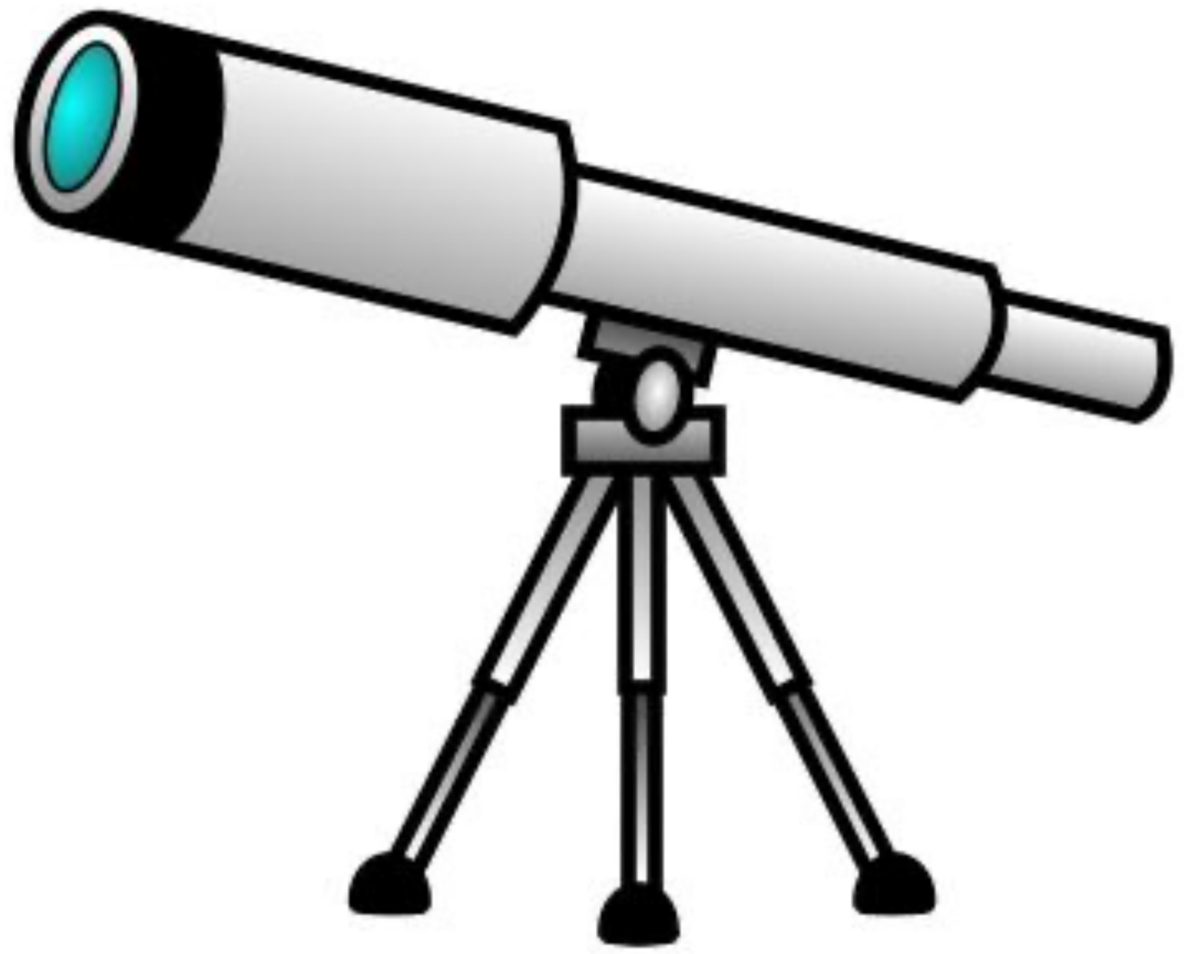


LHC, Tevatron, …

Neutrino

- Neutrinos go through everything!





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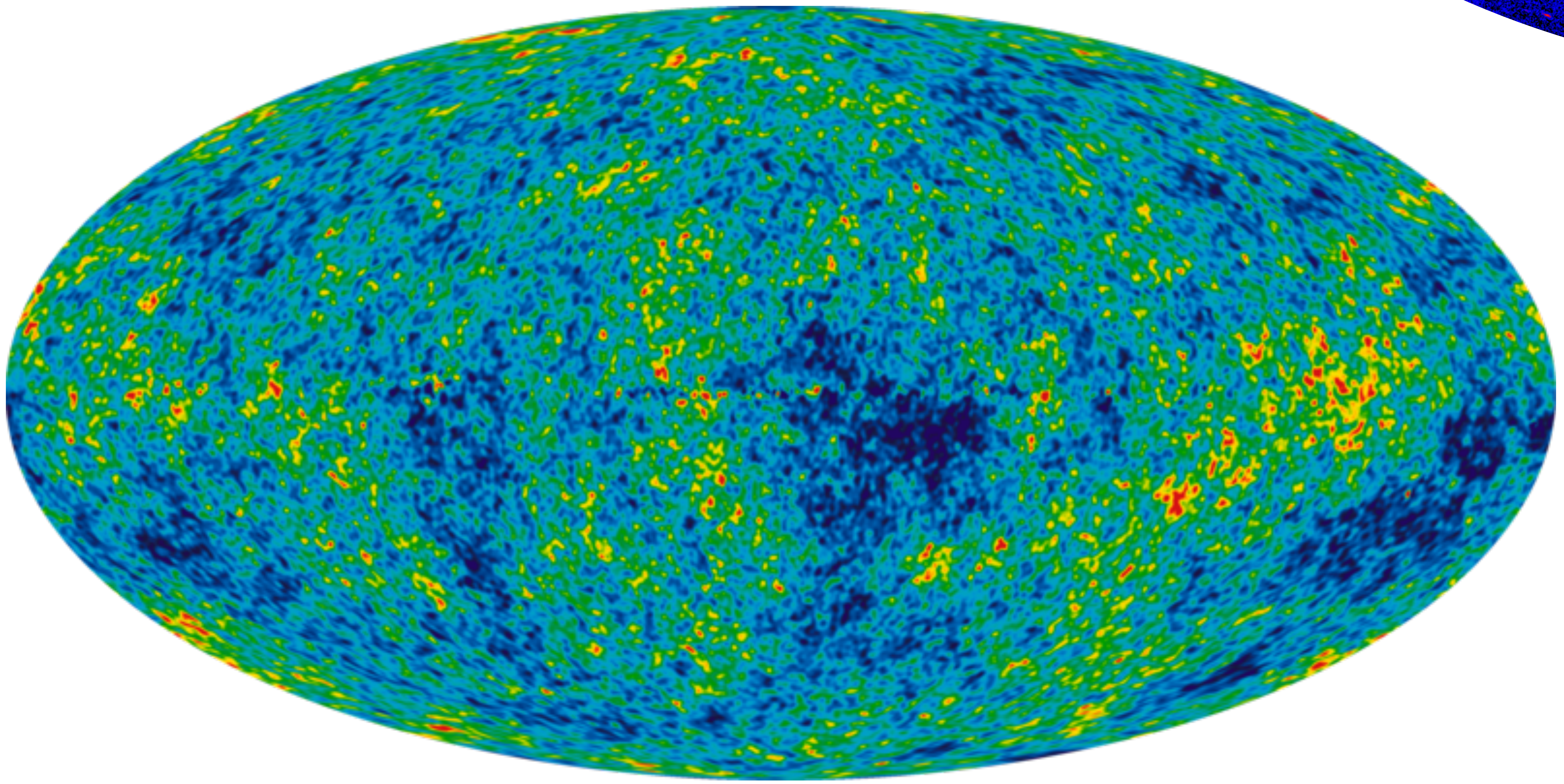
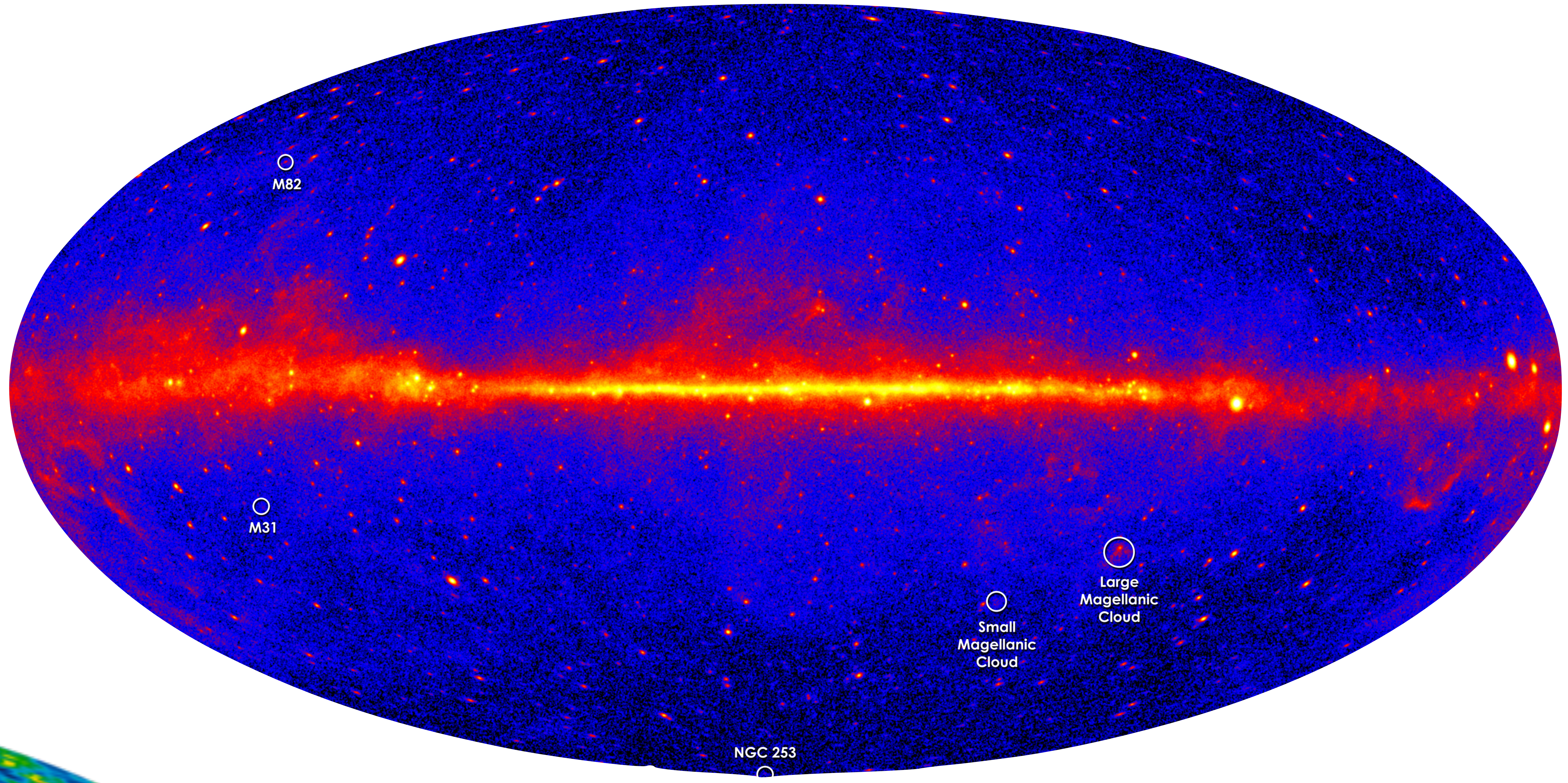
Telescopes, observatories, CMB, x-ray, gamma-ray, radio, direct detection experiments…

Cosmic Observation

- Telecopes, broadly defined:

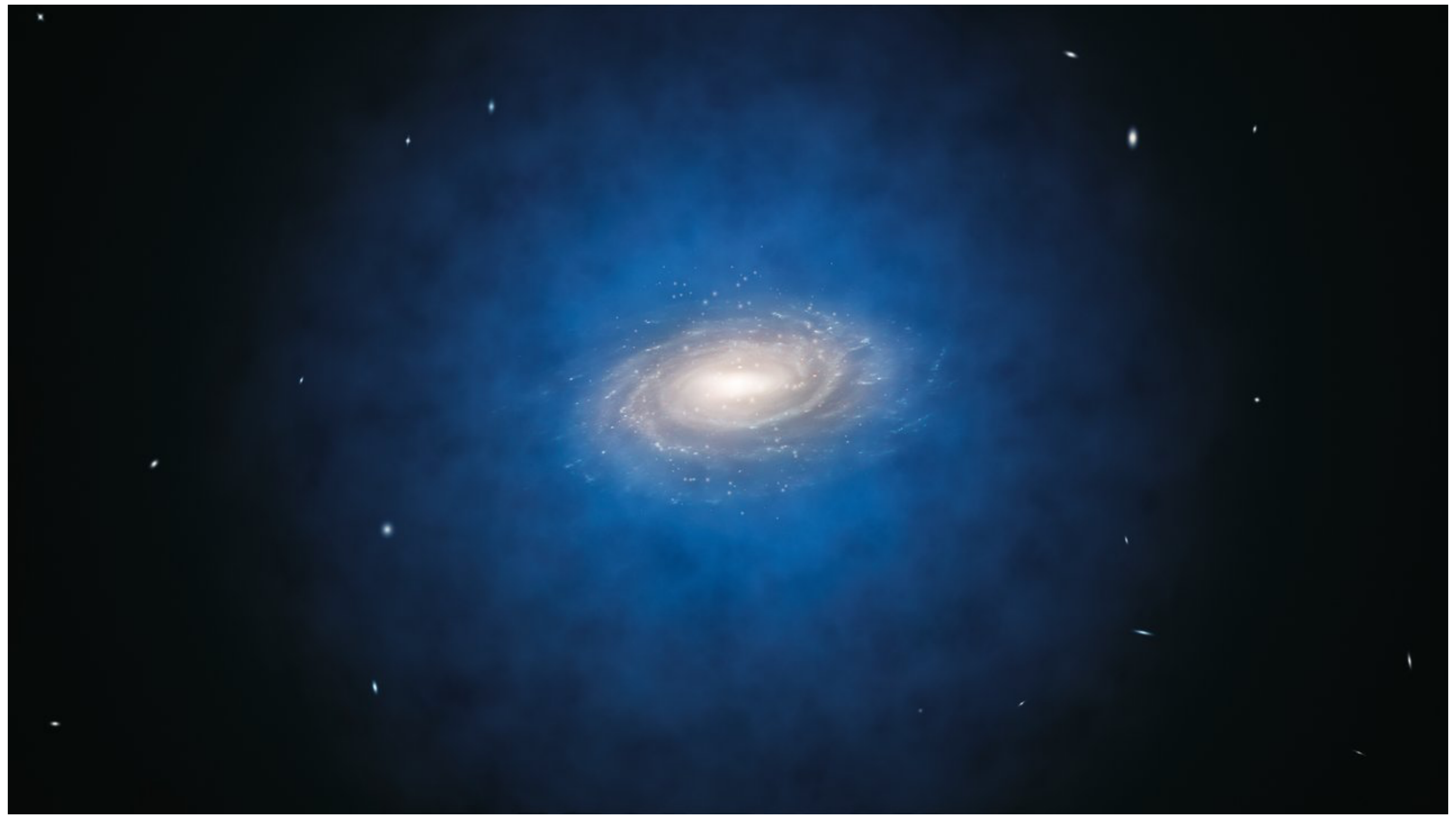
CMB (microwave)

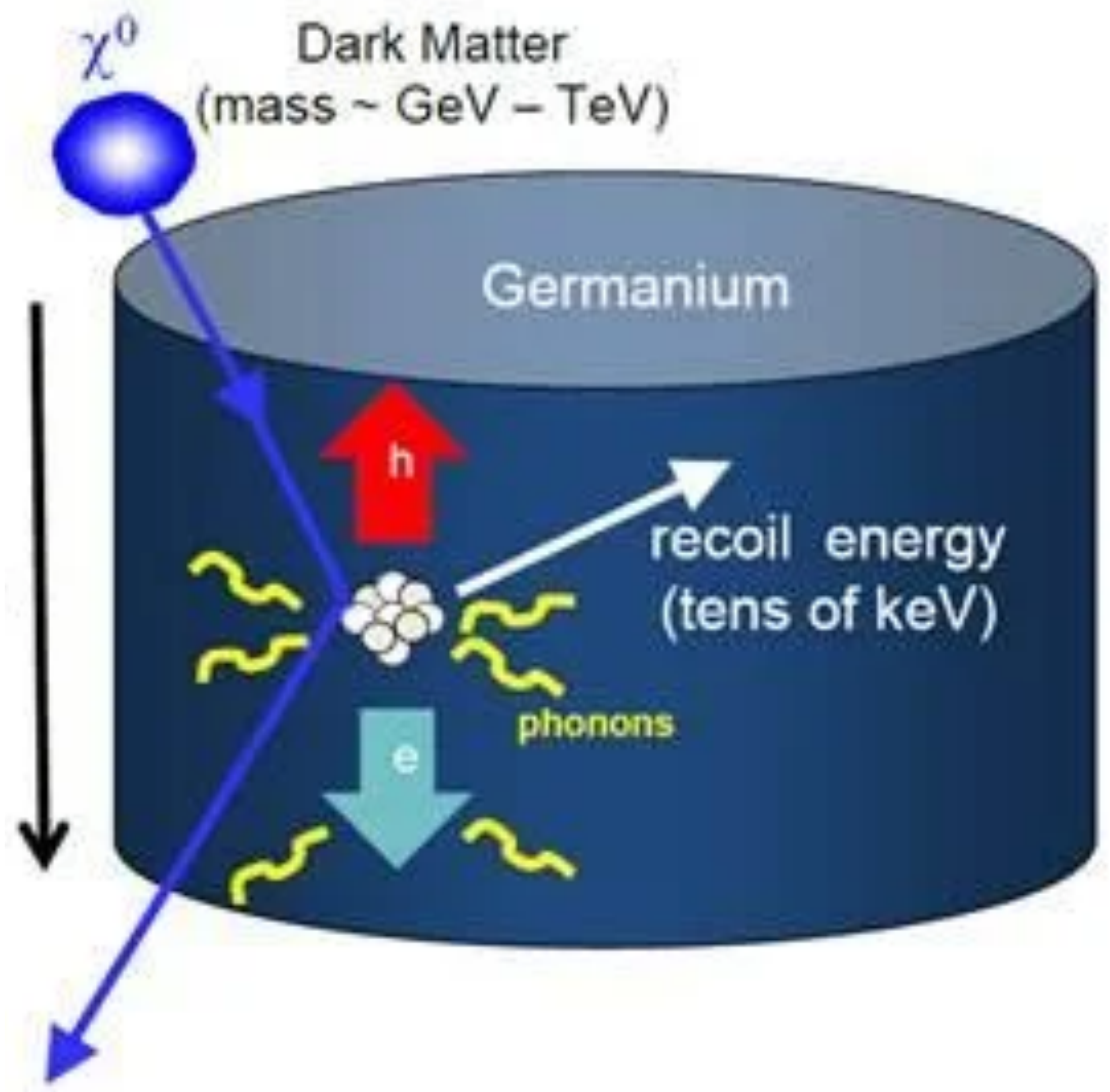


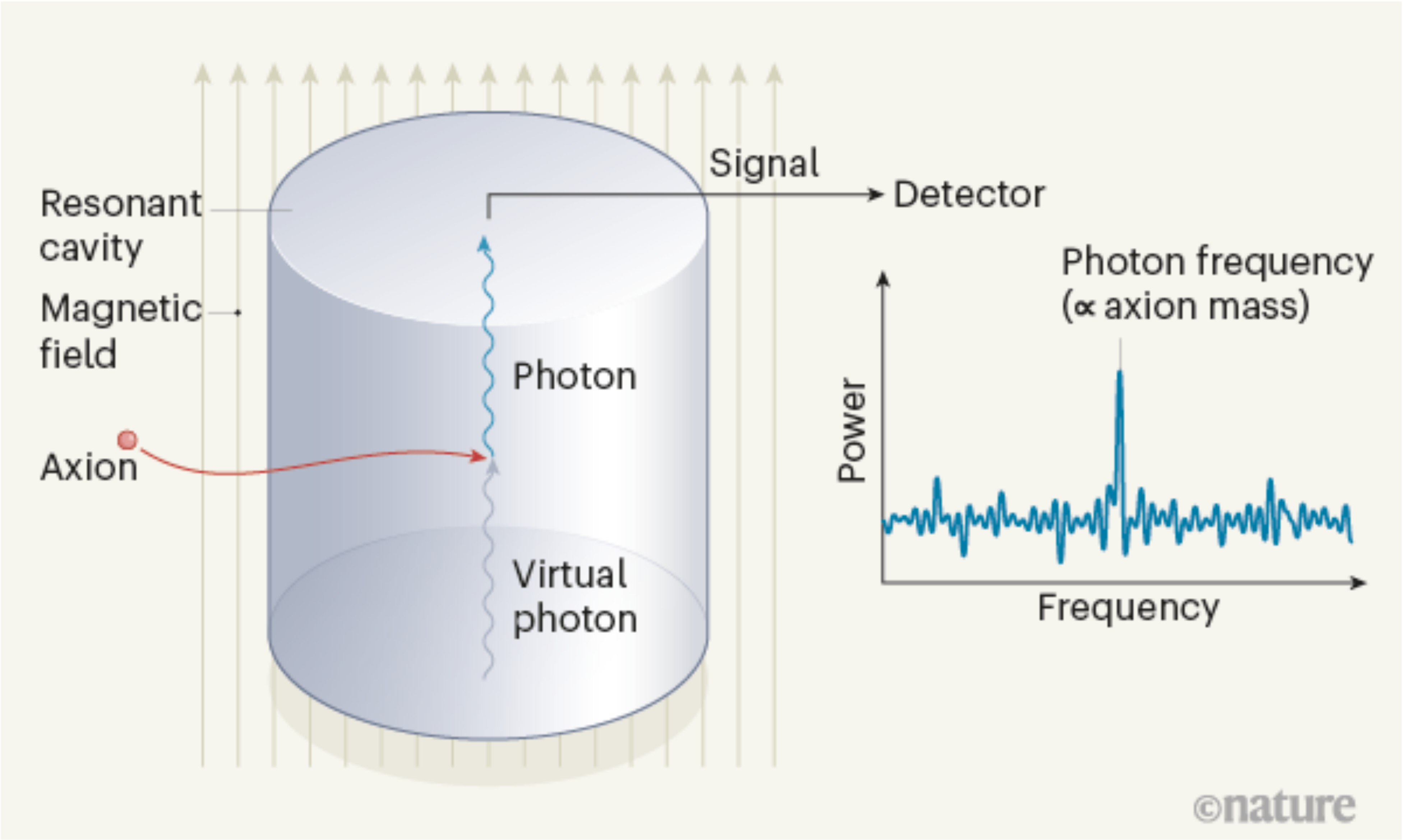


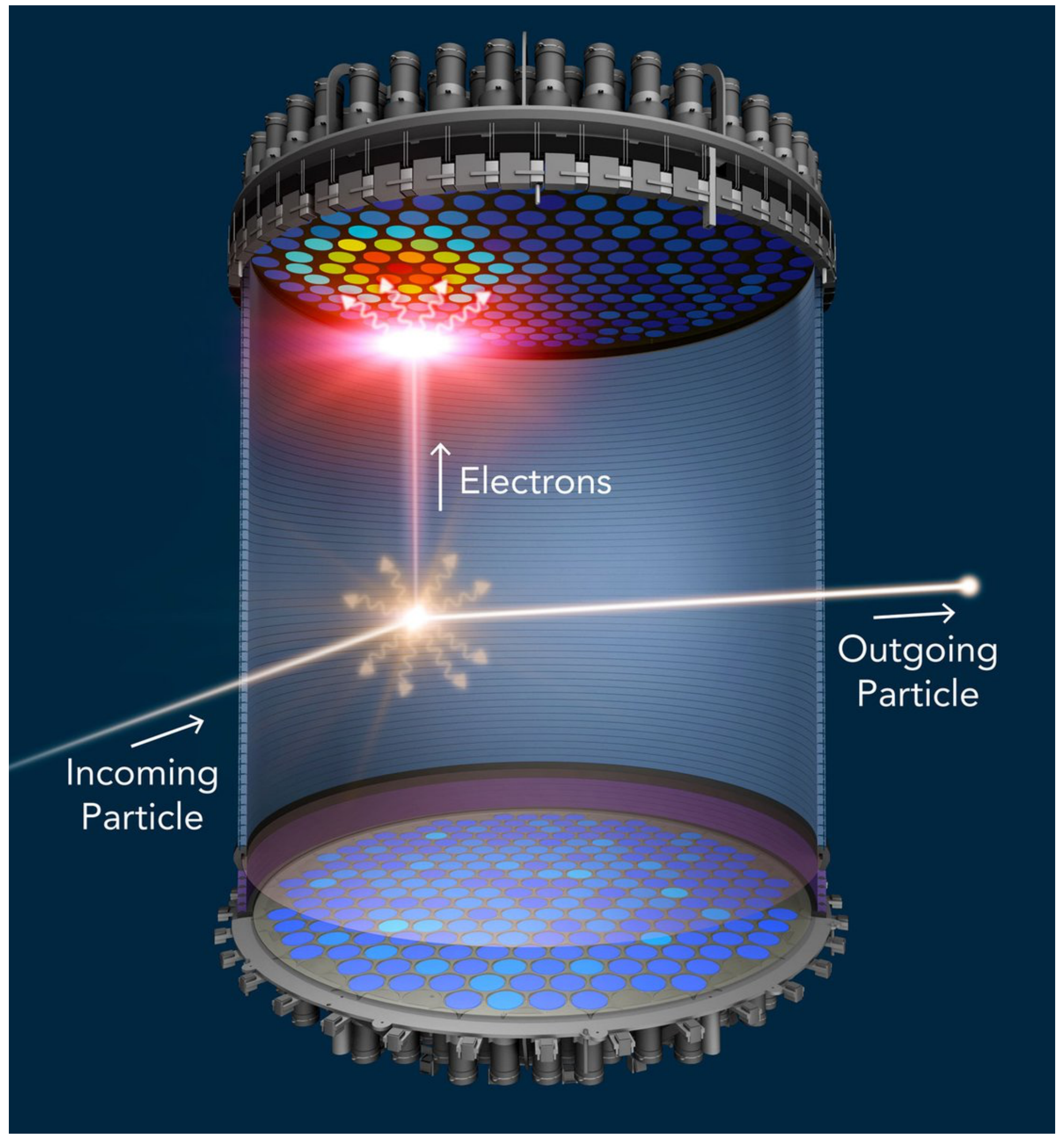
Gamma-ray

Dark Matter

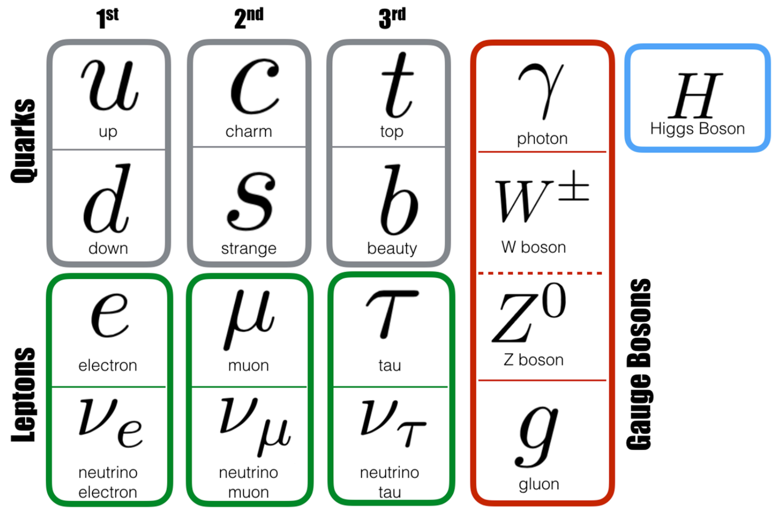


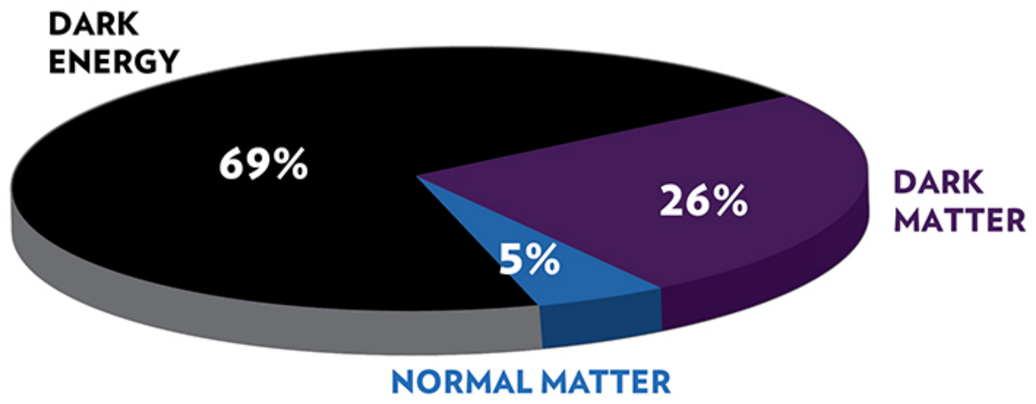

χ^0
Dark Matter
(mass ~ GeV – TeV)
Germanium
h
recoil energy
(tens of keV)
phonons
e


Resonant cavity
Magnetic field
Axion
Signal
Detector
Photon
Virtual photon
Photon frequency
(∝ axion mass)
Power
Frequency
©nature


Electrons
Outgoing Particle
Incoming Particle

PARTICLE PHYSICS





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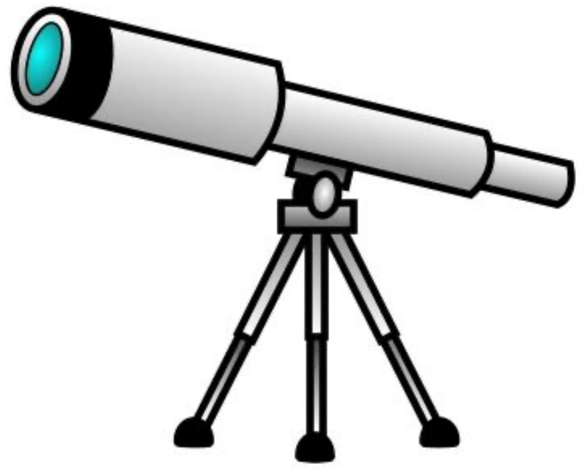

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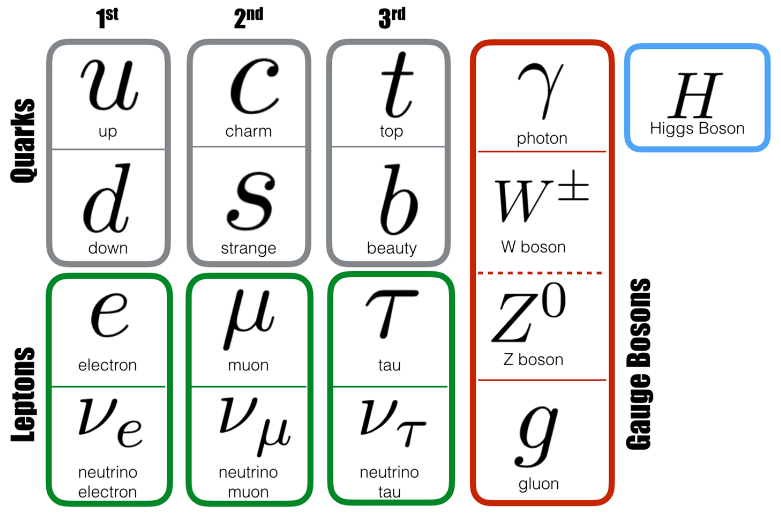
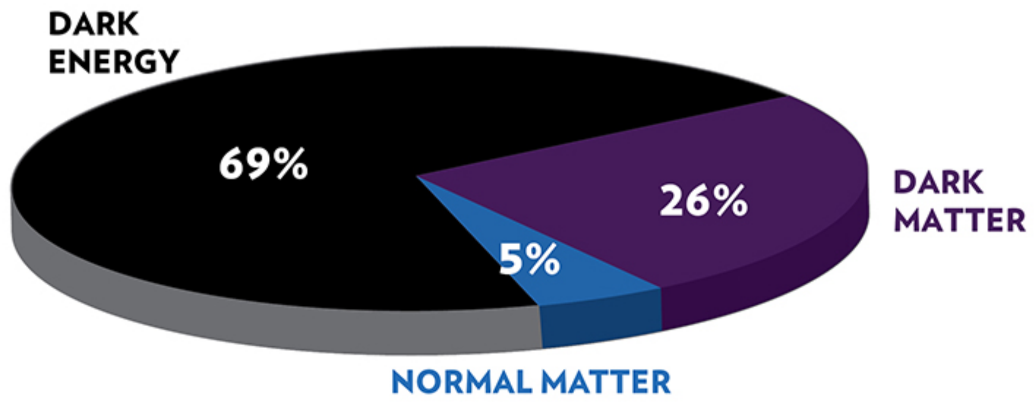
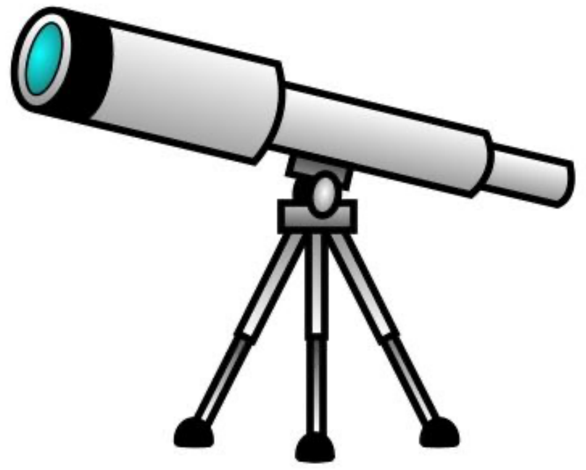
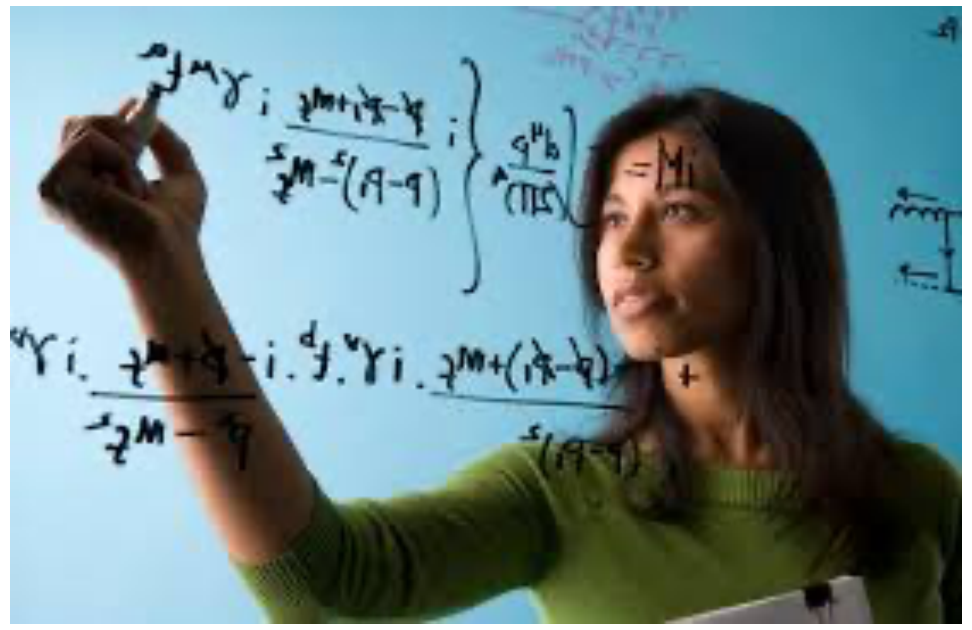




 +  + 

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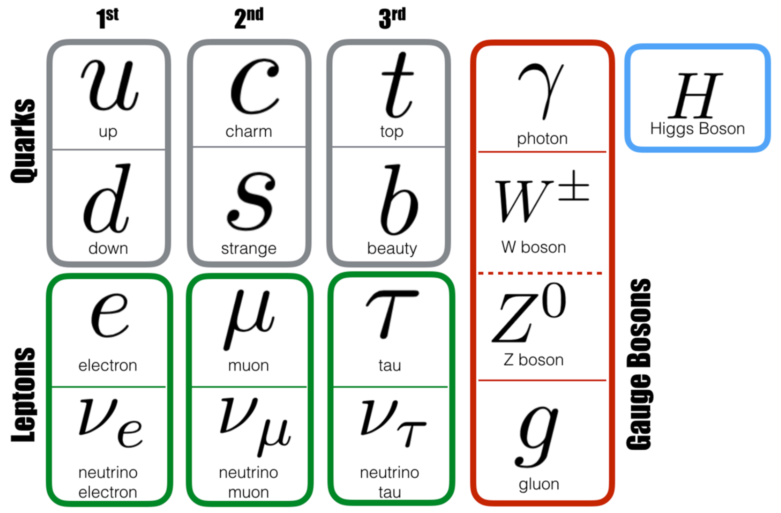
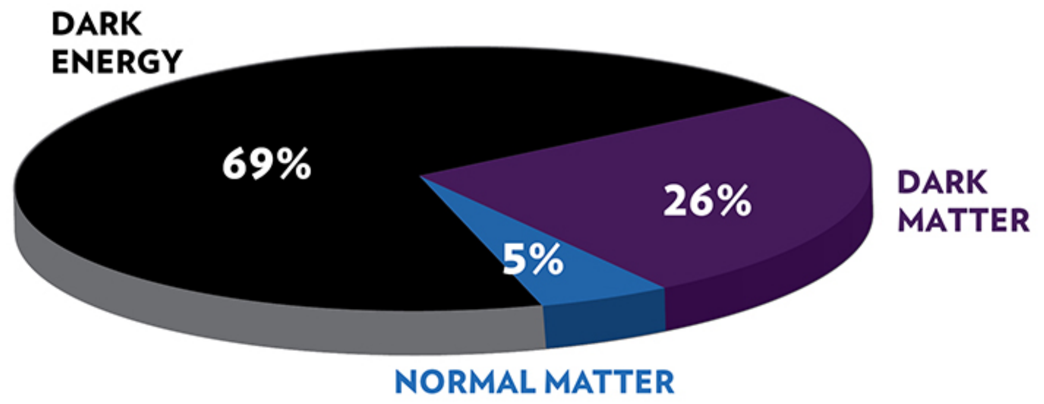
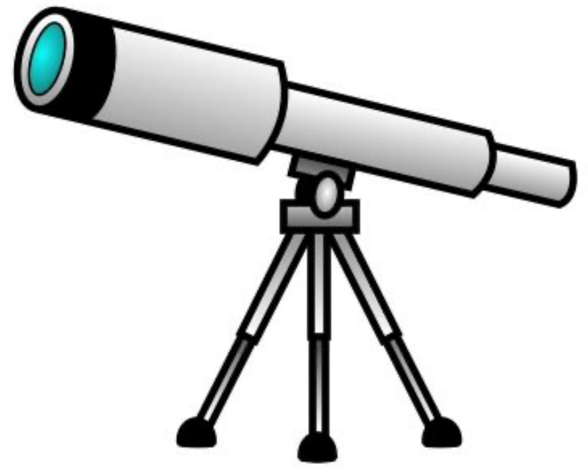
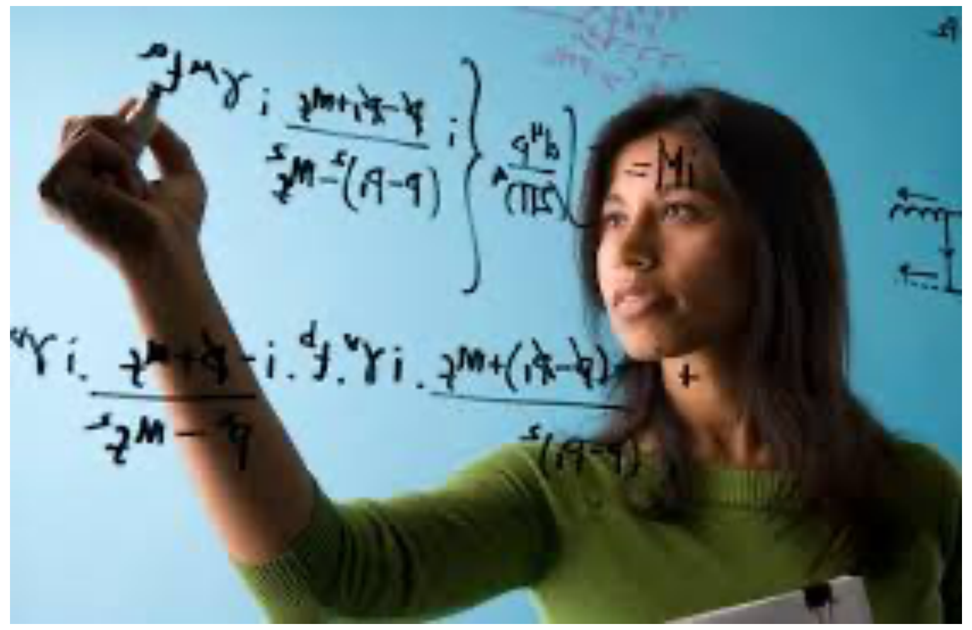
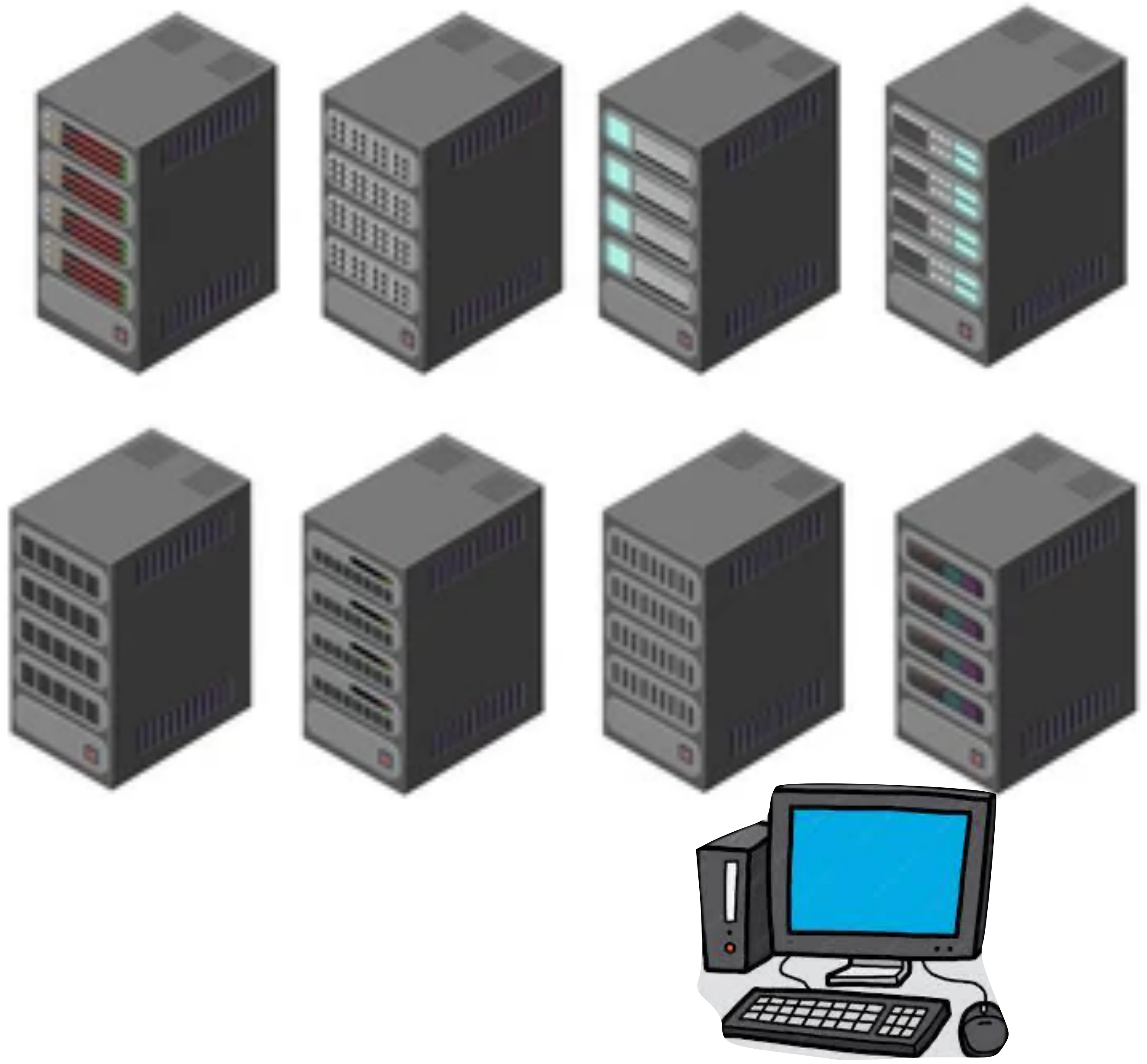




 +  +  + 

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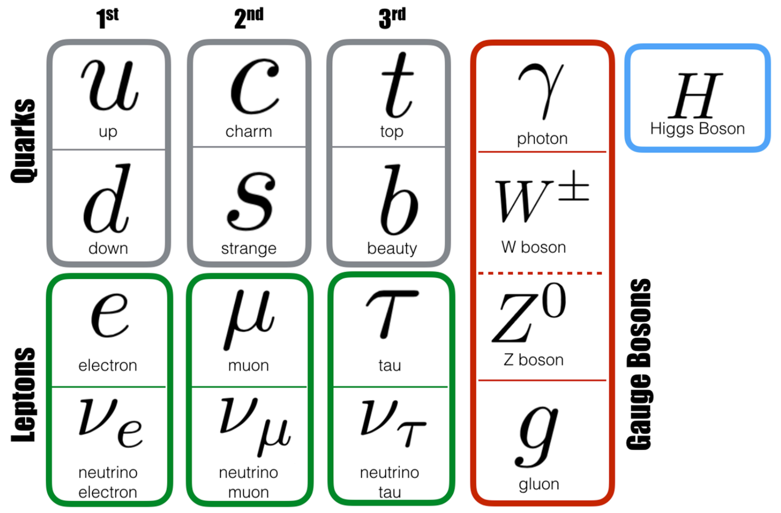
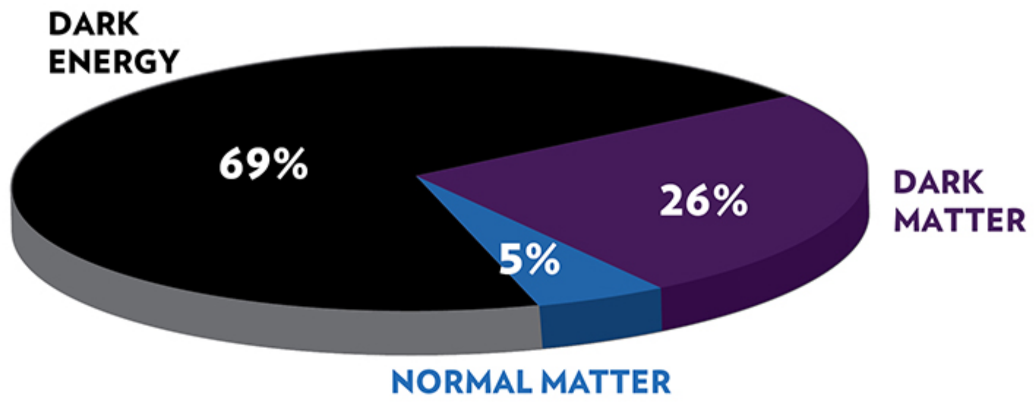
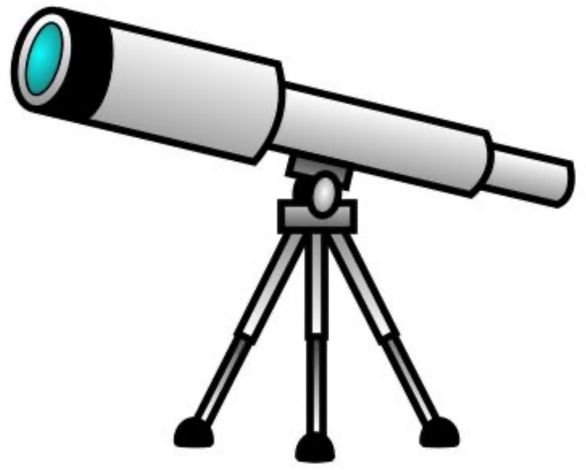
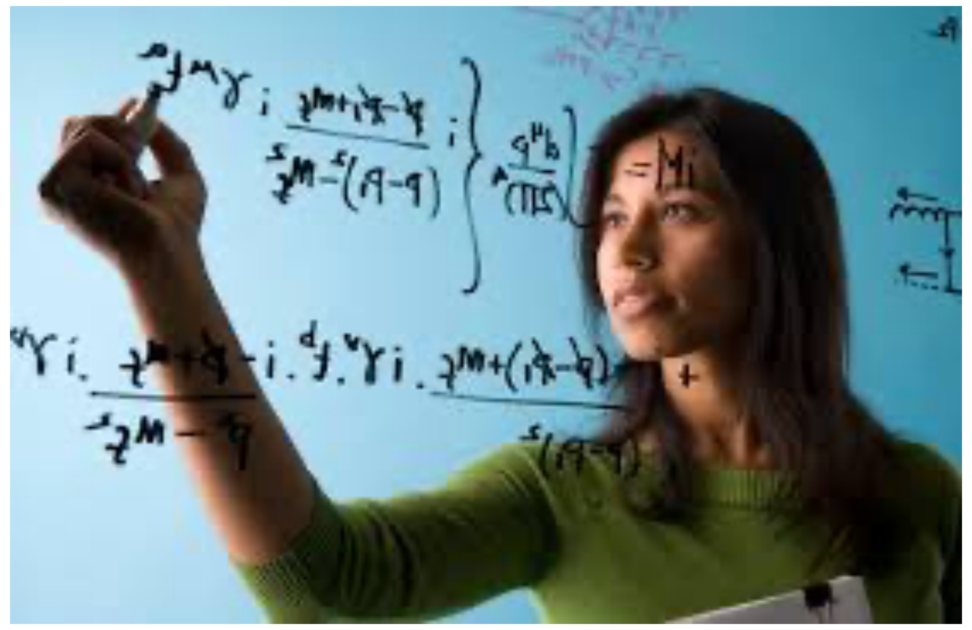
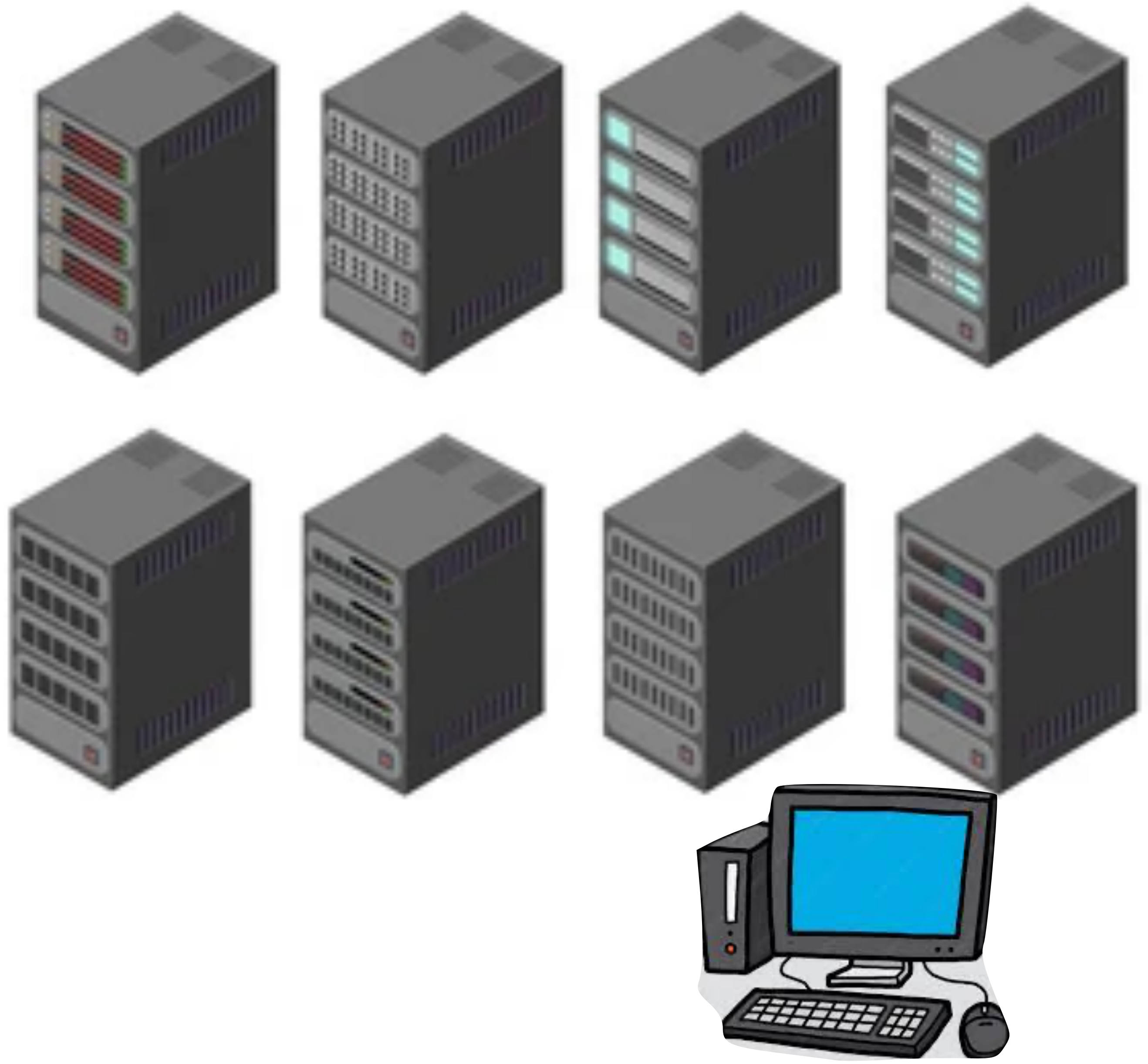




 +  +  + 

Particle physicists are pushing on the computing edge!

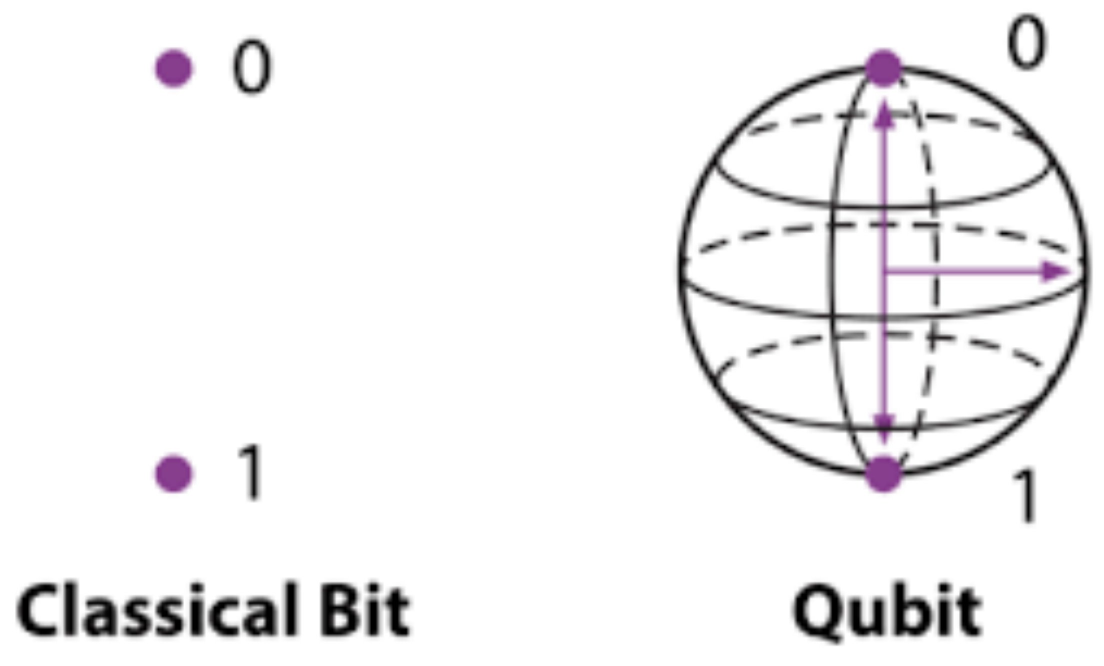
Why Quantum?

If you gave us a quantum computer,
what would we compute?

Can we detect something new with a
quantum device?

Qubits

- A bit is a building block of information. A binary unit. 0 or 1.
- A qubit is a quantum system that can be in either of two states, or in any superposition!
- Can be:
  - Superconducting circuits
  - Atoms
  - Ions
  - ...

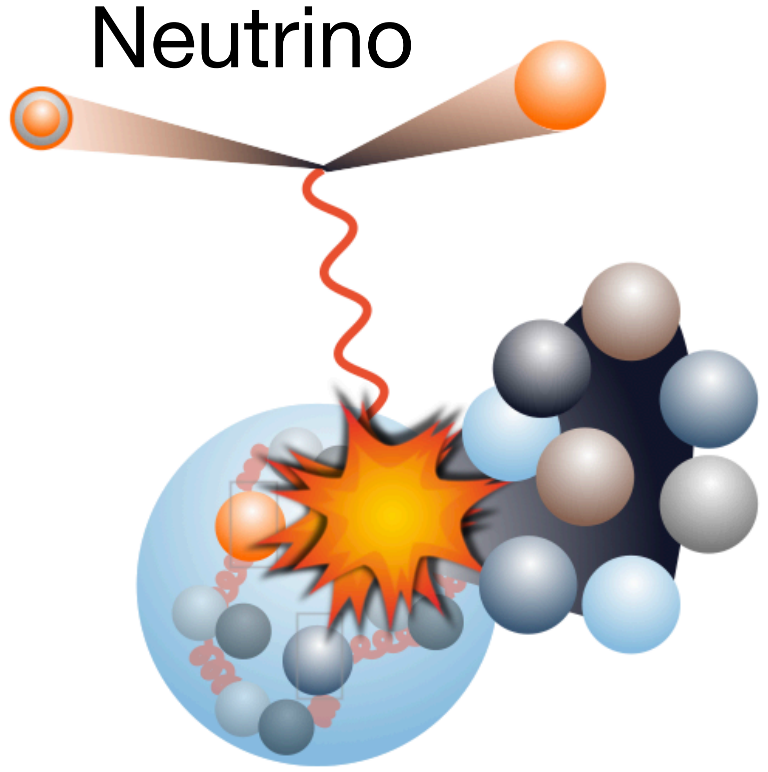


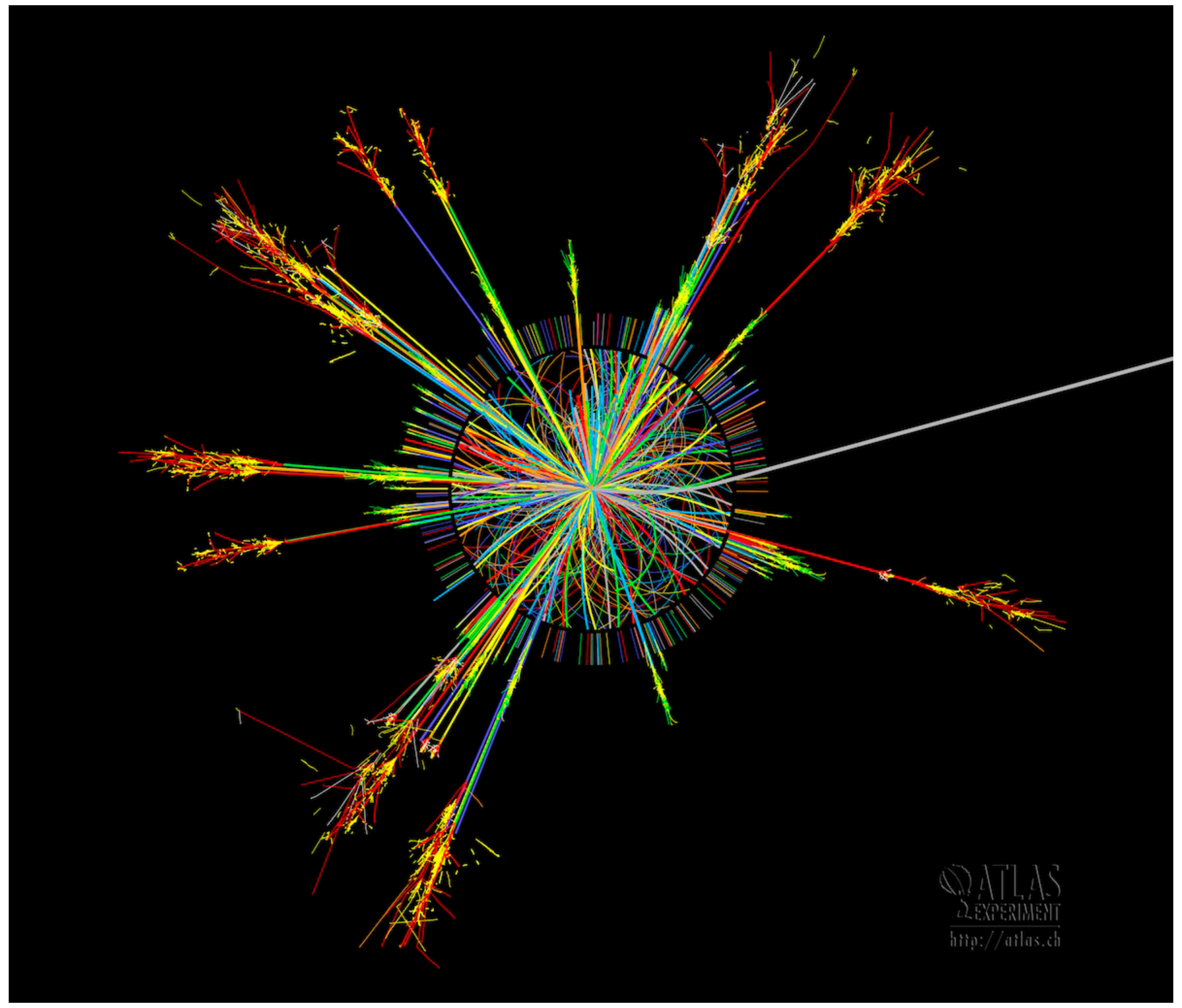
Going for bits to qubits changes the rules of the game!

(You will learn about Shor/Grover algorithms)

Quantum Simulation

- We would like to simulate particle physics processes.
- Perturbation theory does not always work!





- **Feynman:** "Nature isn't classical, dammit! and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Quantum Simulation

- But why should we make it quantum mechanical?
- Here is a reason: Simulating a quantum system evolving in time is numerically hard!

A “sign problem”

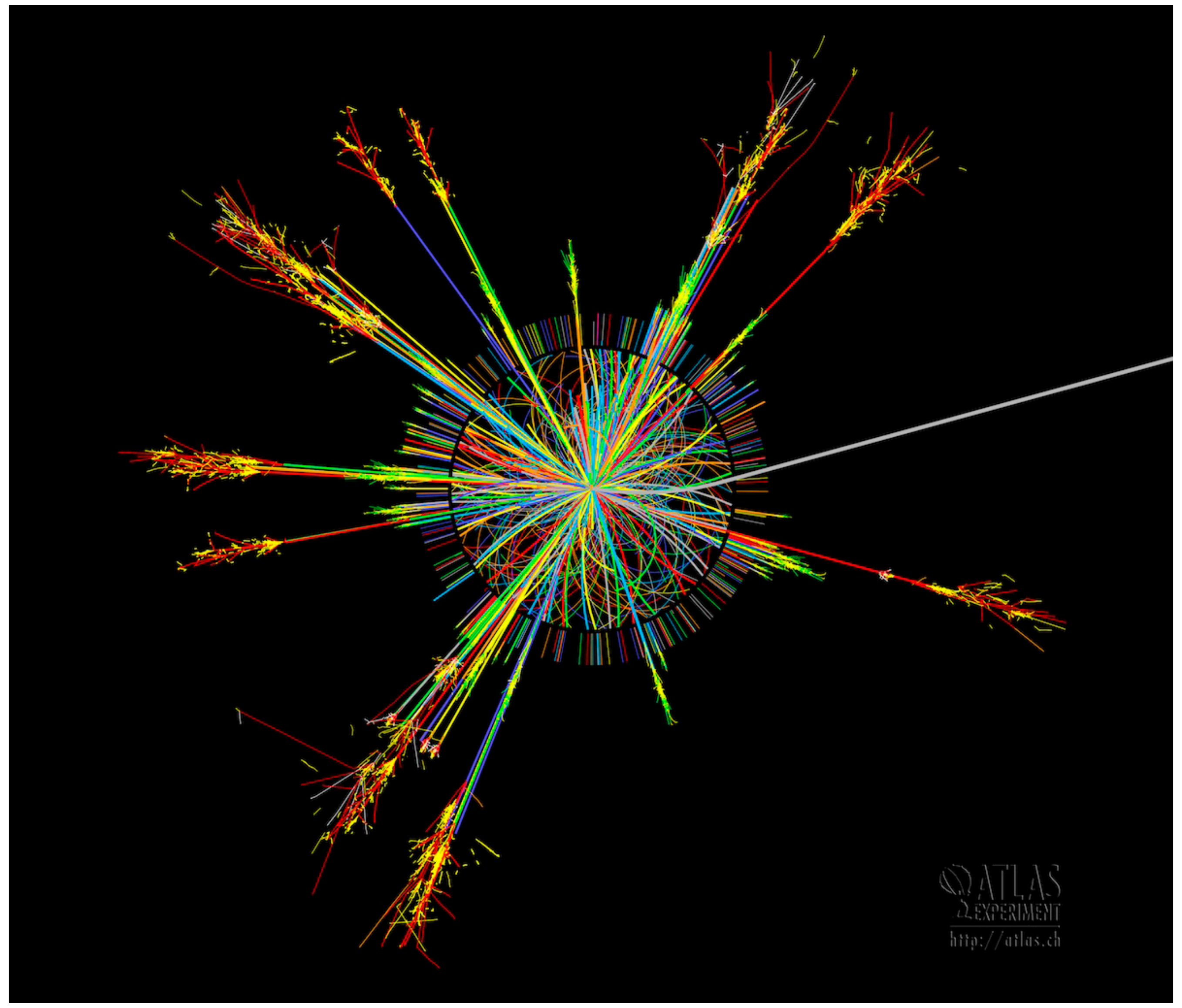
$$\psi(t) = e^{iEt/\hbar}\psi(0)$$

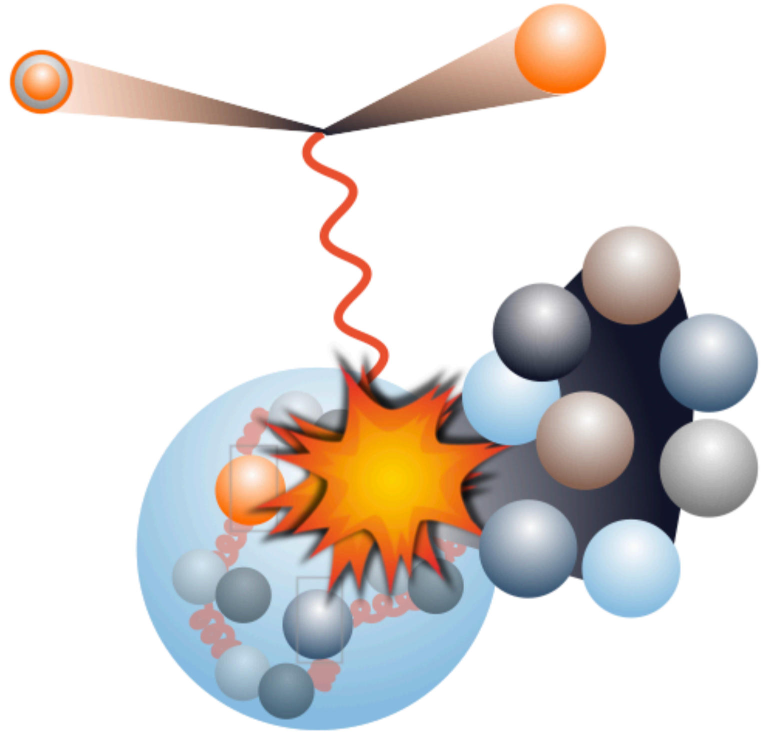
Rapid oscillation!

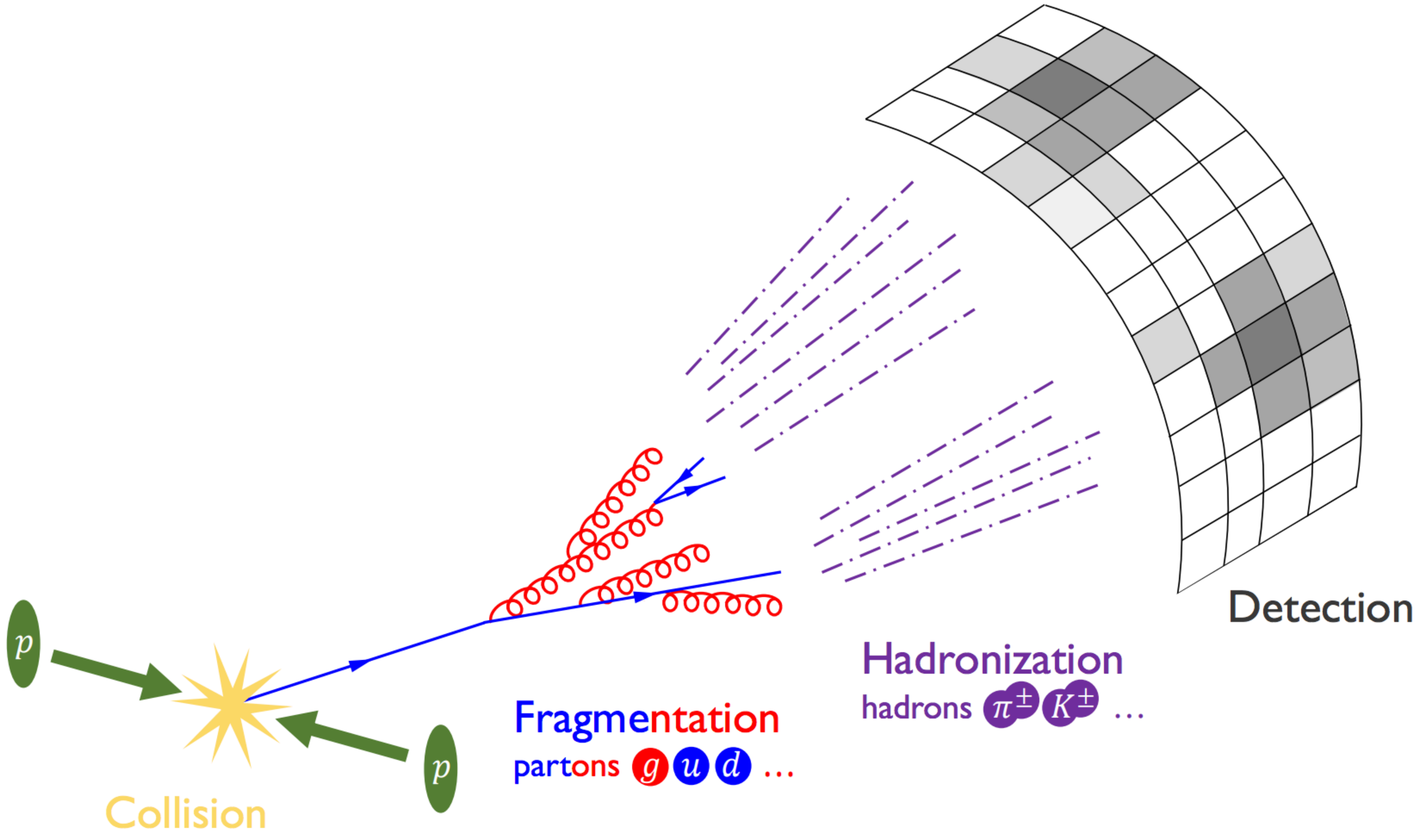
A quantum system will keep track of this inherently

Quantum Simulation

- What would we simulate?
- For example, some day, Hadronization
- Neutrino interacting with a nucleus.
- Processes in the early Universe







Quantum Sensors

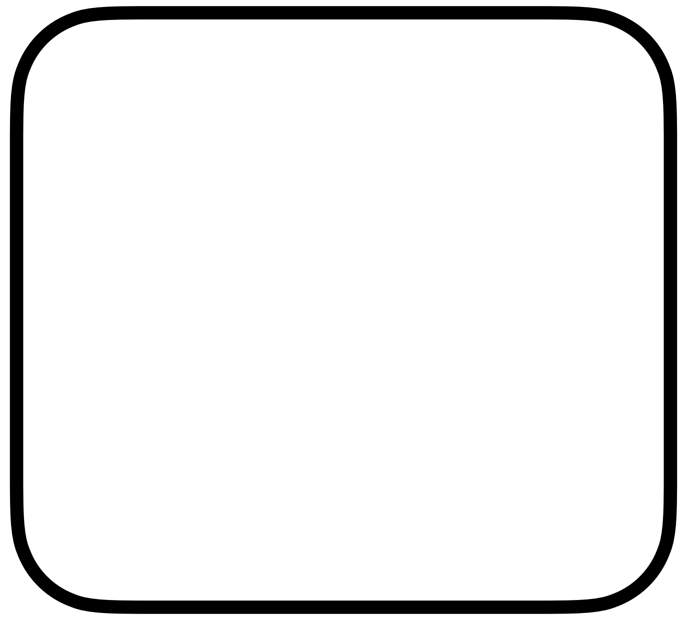
- **Feynman:** "Nature isn't classical, dammit! and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."
- Why is it so hard?
- Because a quantum state is VERY sensitive to environmental disturbance.

It makes for a great sensor of small effects.

e.g. **Dark matter? Gravity waves?**

Counting Photons

- Example of a quantum computer concept: a box for photons.
- Assume we can control and count the number of photons!



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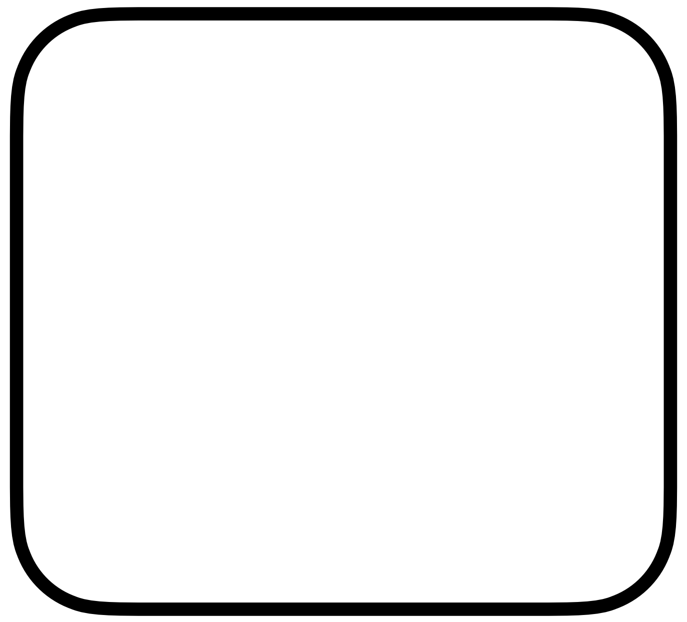

0 photons

1 photon

Superposition of
0 and 1 photon

…

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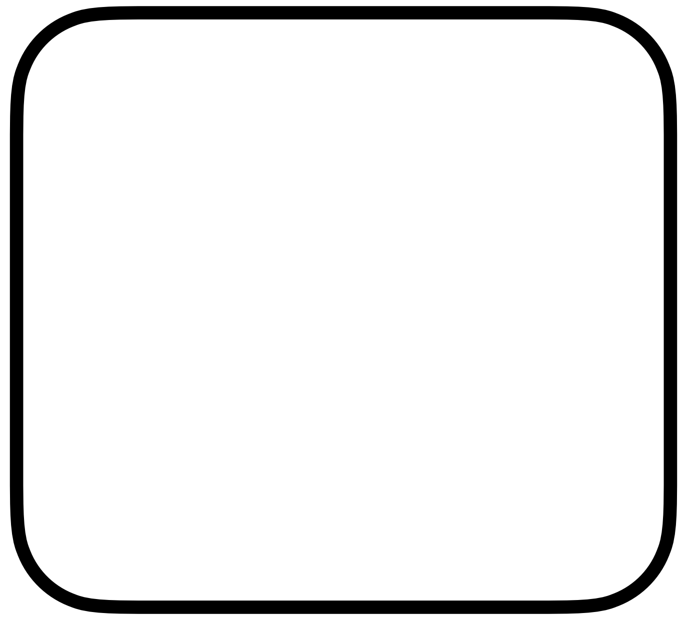

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This is a qubit!
We can use it to do quantum computation!

Counting Photons

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0 photons

1 photon

Superposition of
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…

This is a dark matter detector!
We look for DM that converts
to a photon!
(axions, dark photons, etc)

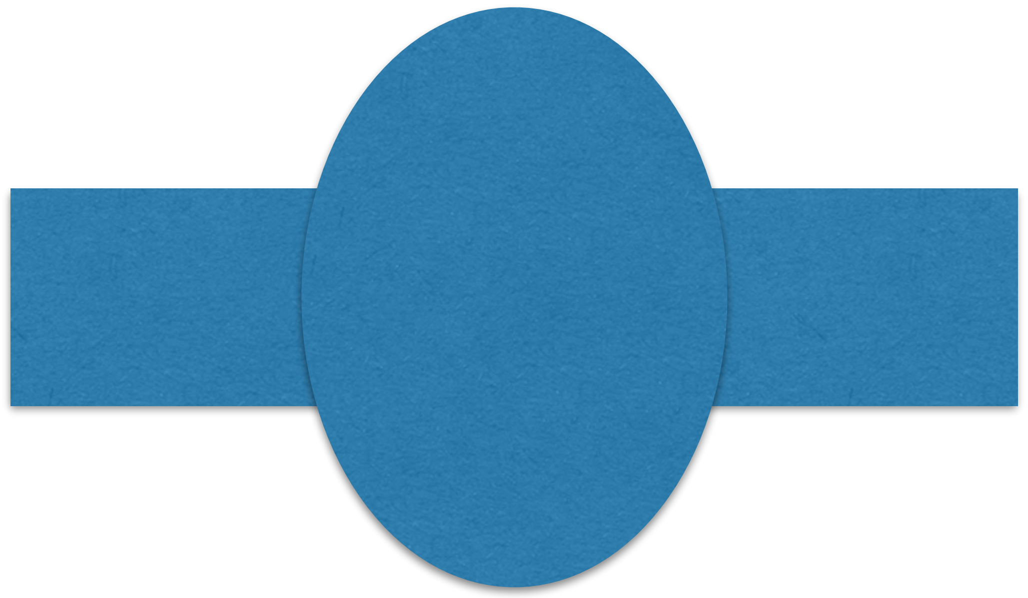
This is a qubit!
We can use it to do quantum
computation!

Looking for new particles with cavities

- ❑ Two high quality cavities with with **exactly** same frequency

A "light-shining-through-wall" experiment. [Dark SRF]

- ❑ Or, a dark matter search:



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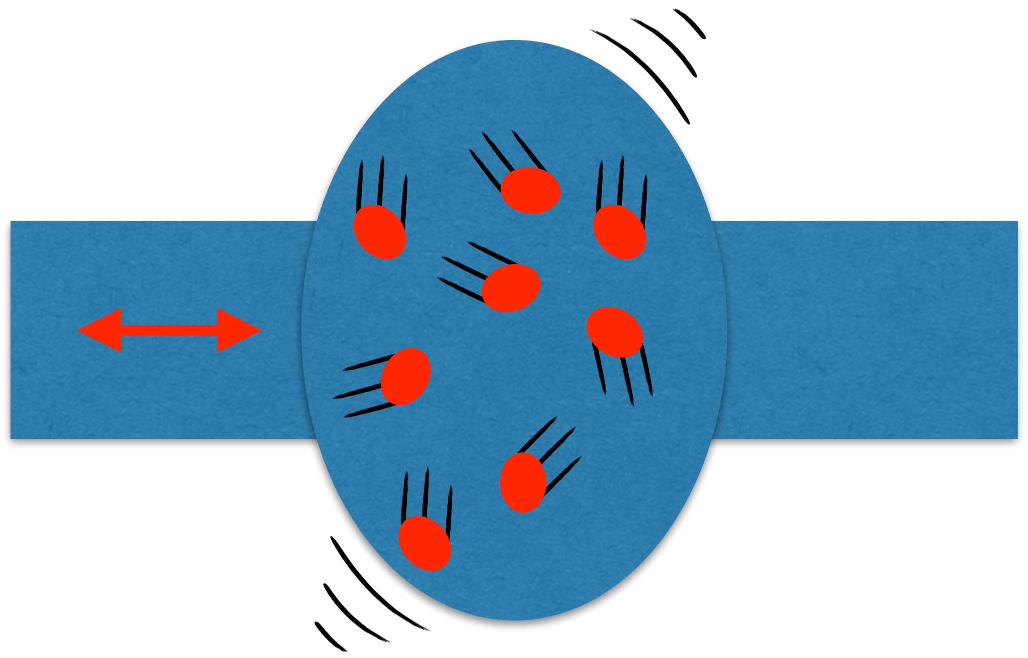

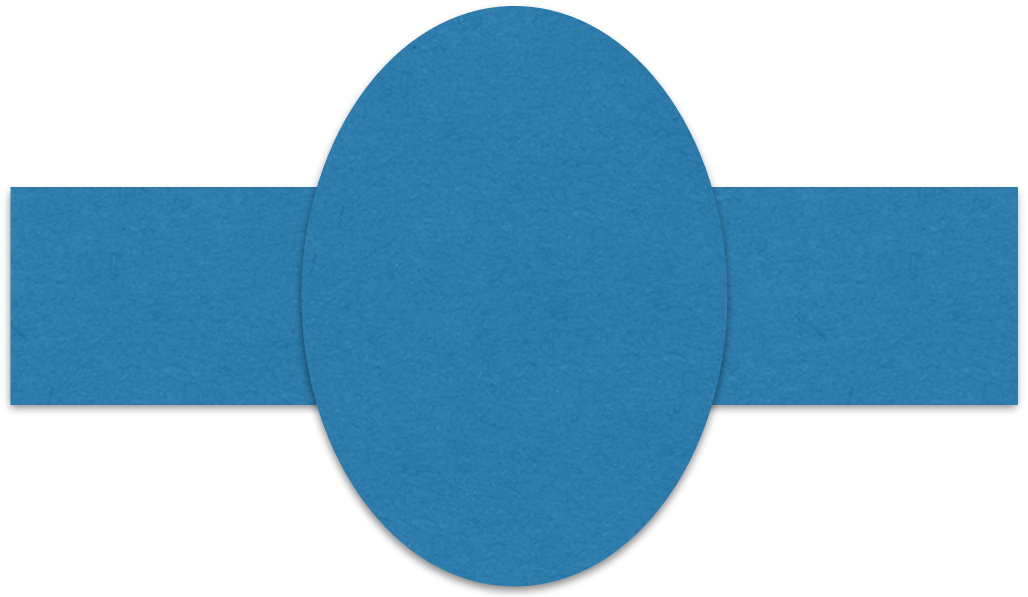

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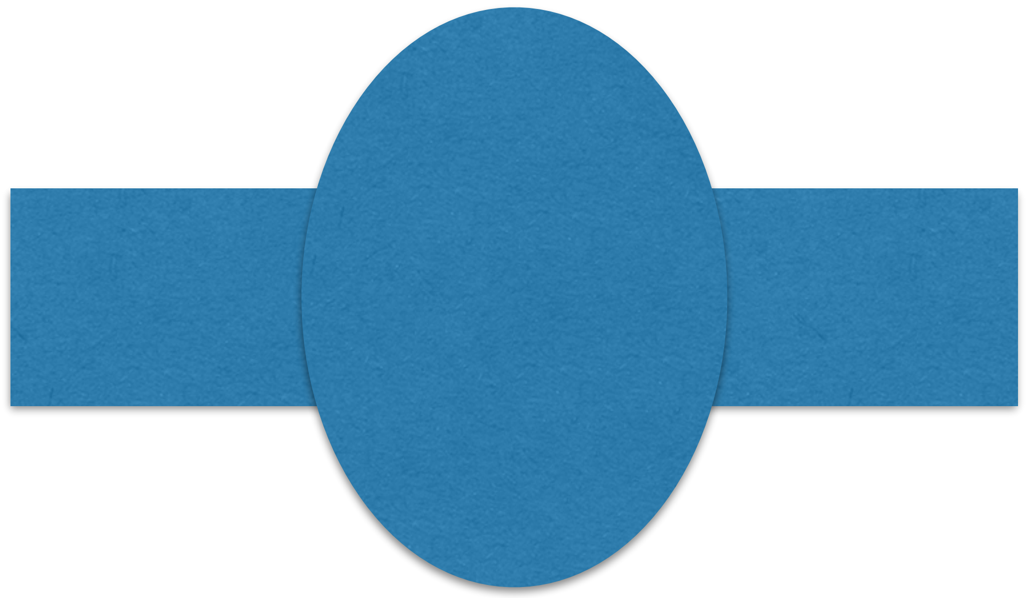

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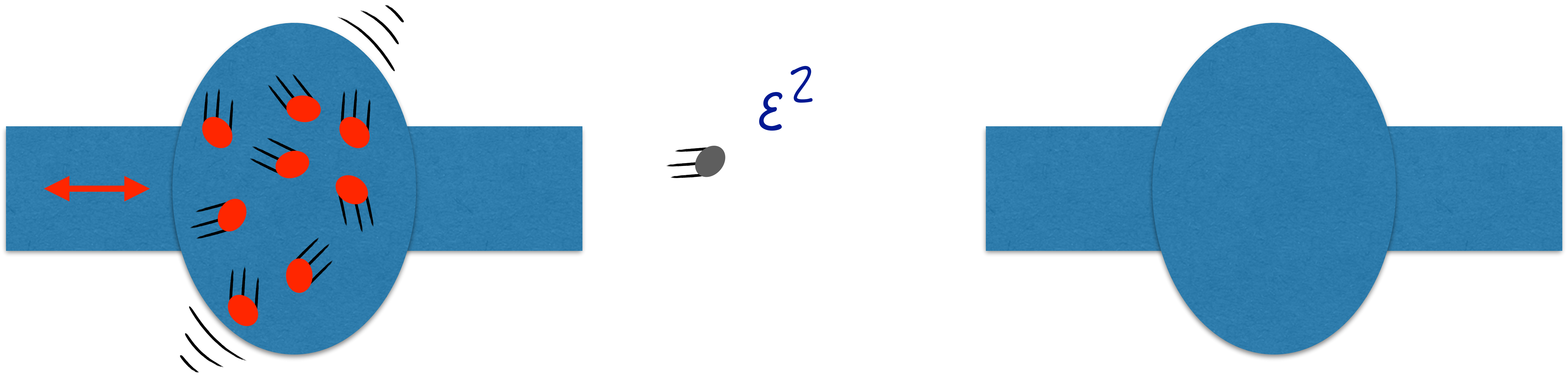

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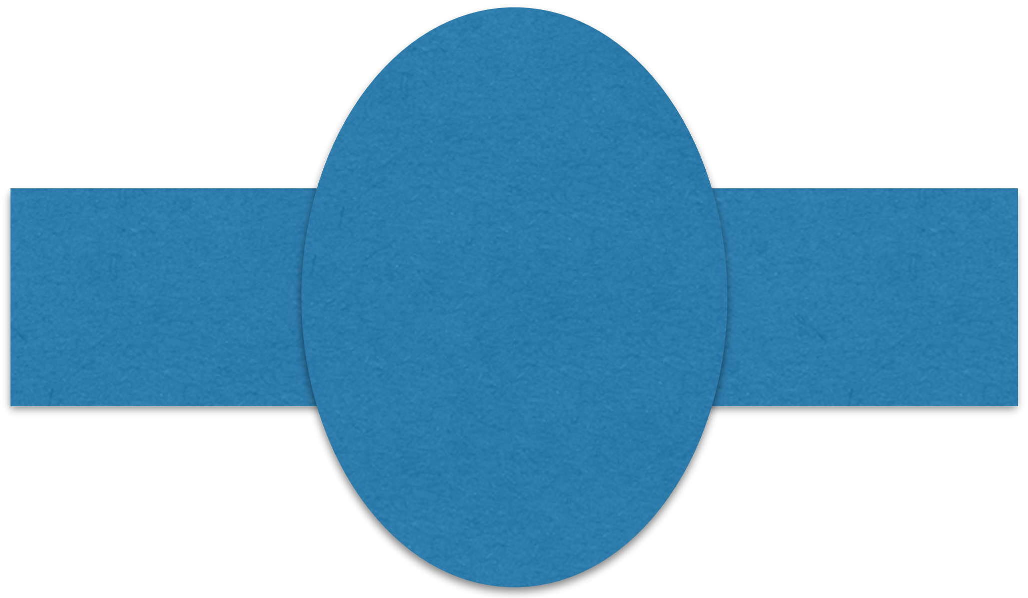

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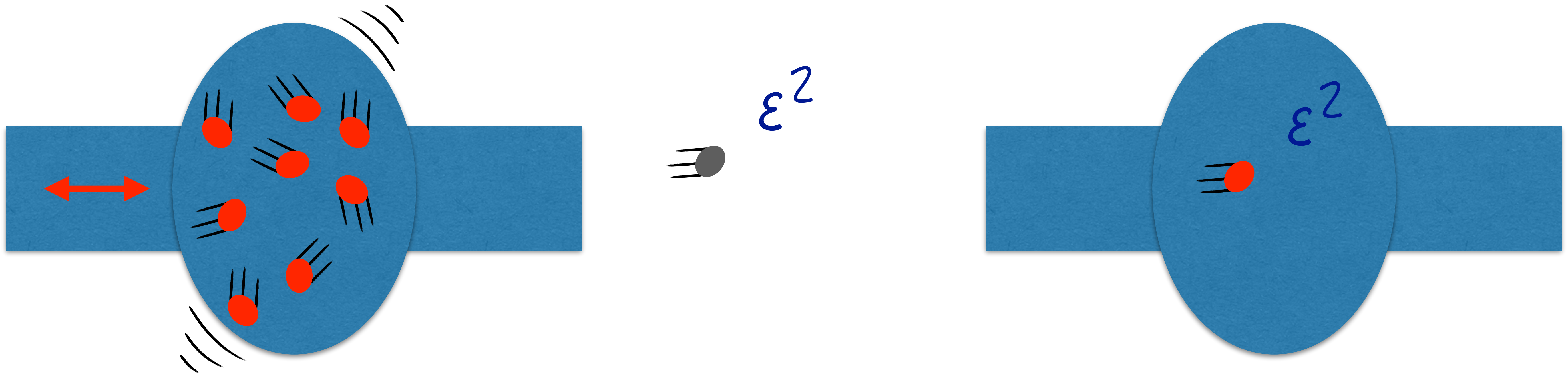

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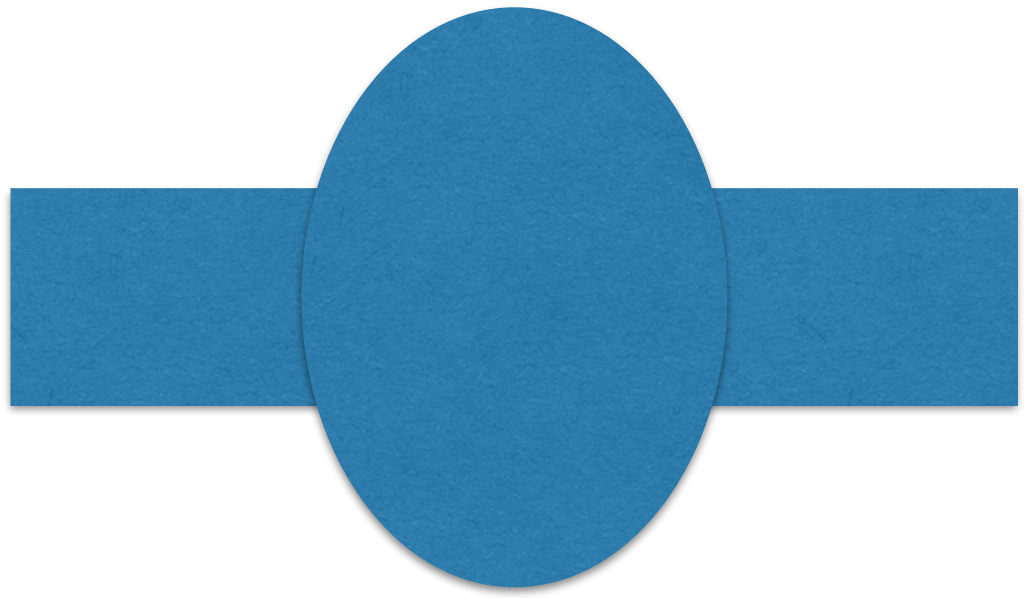

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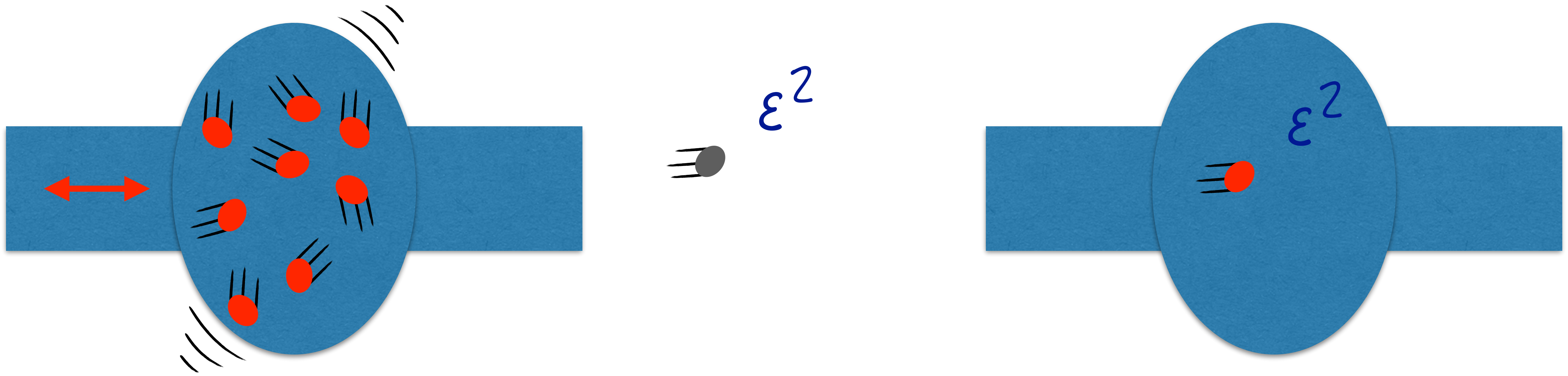

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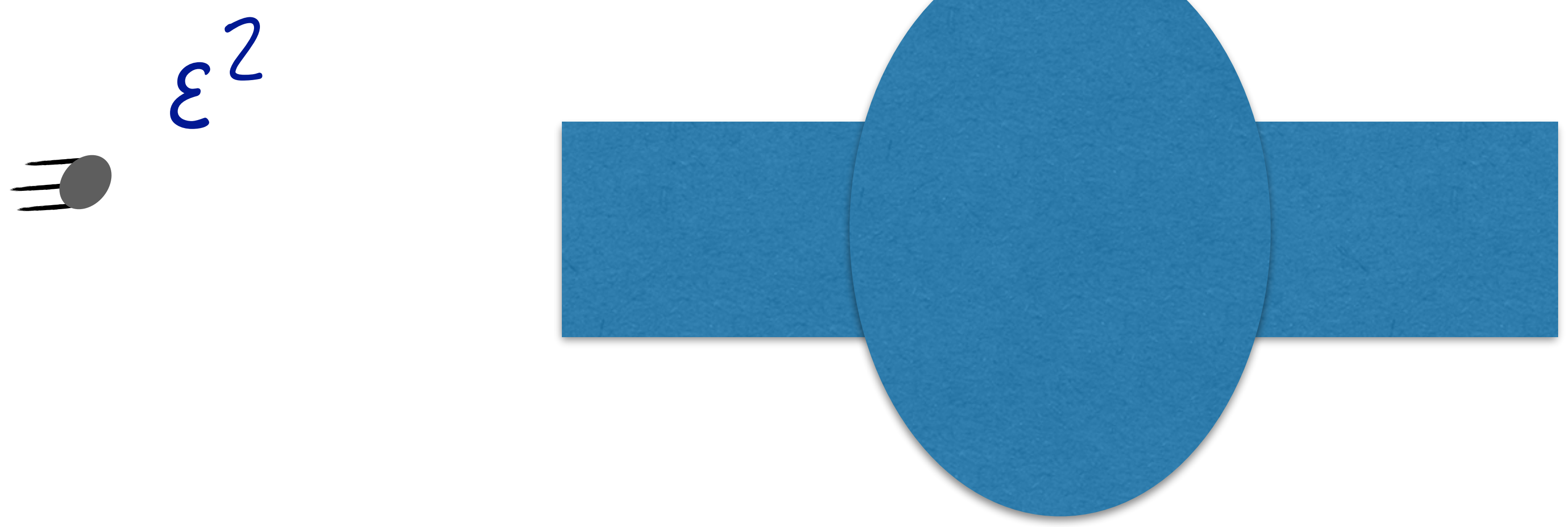

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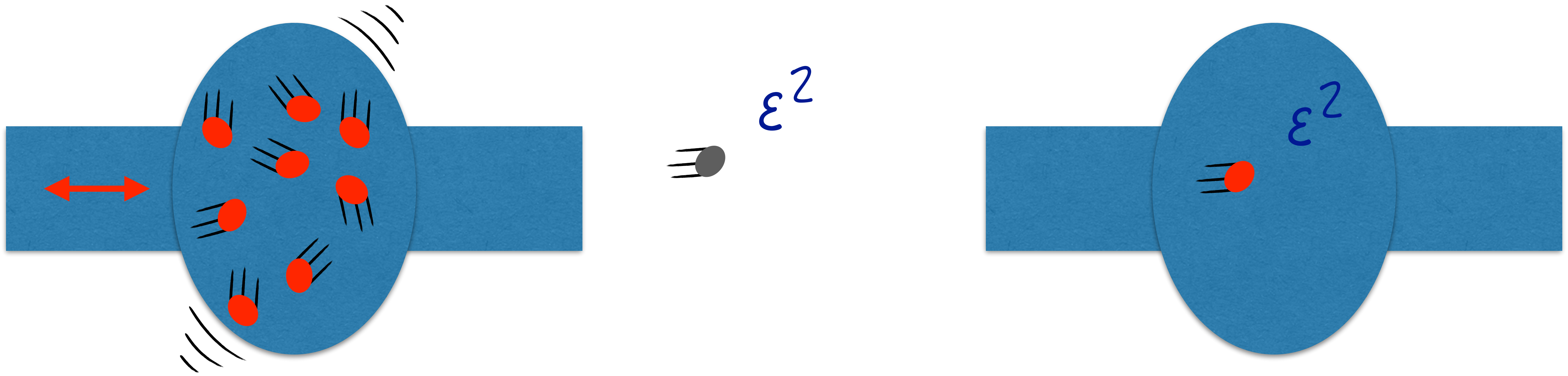

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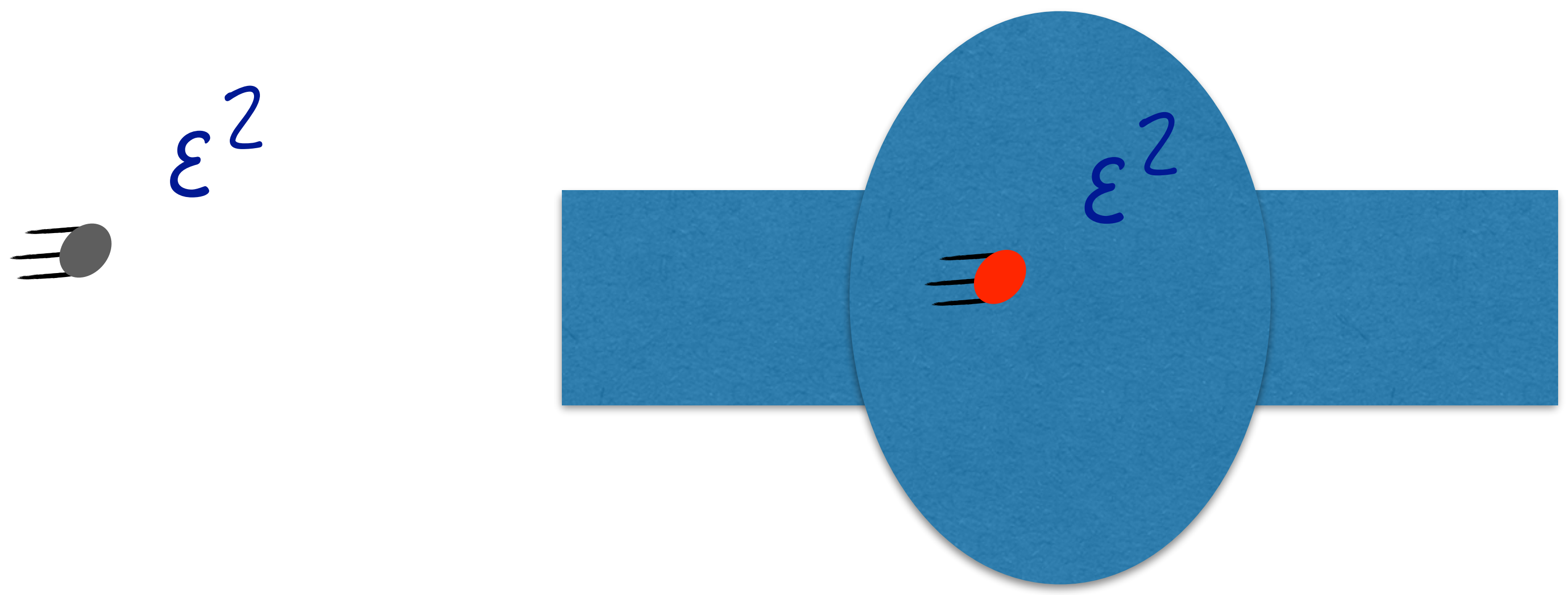
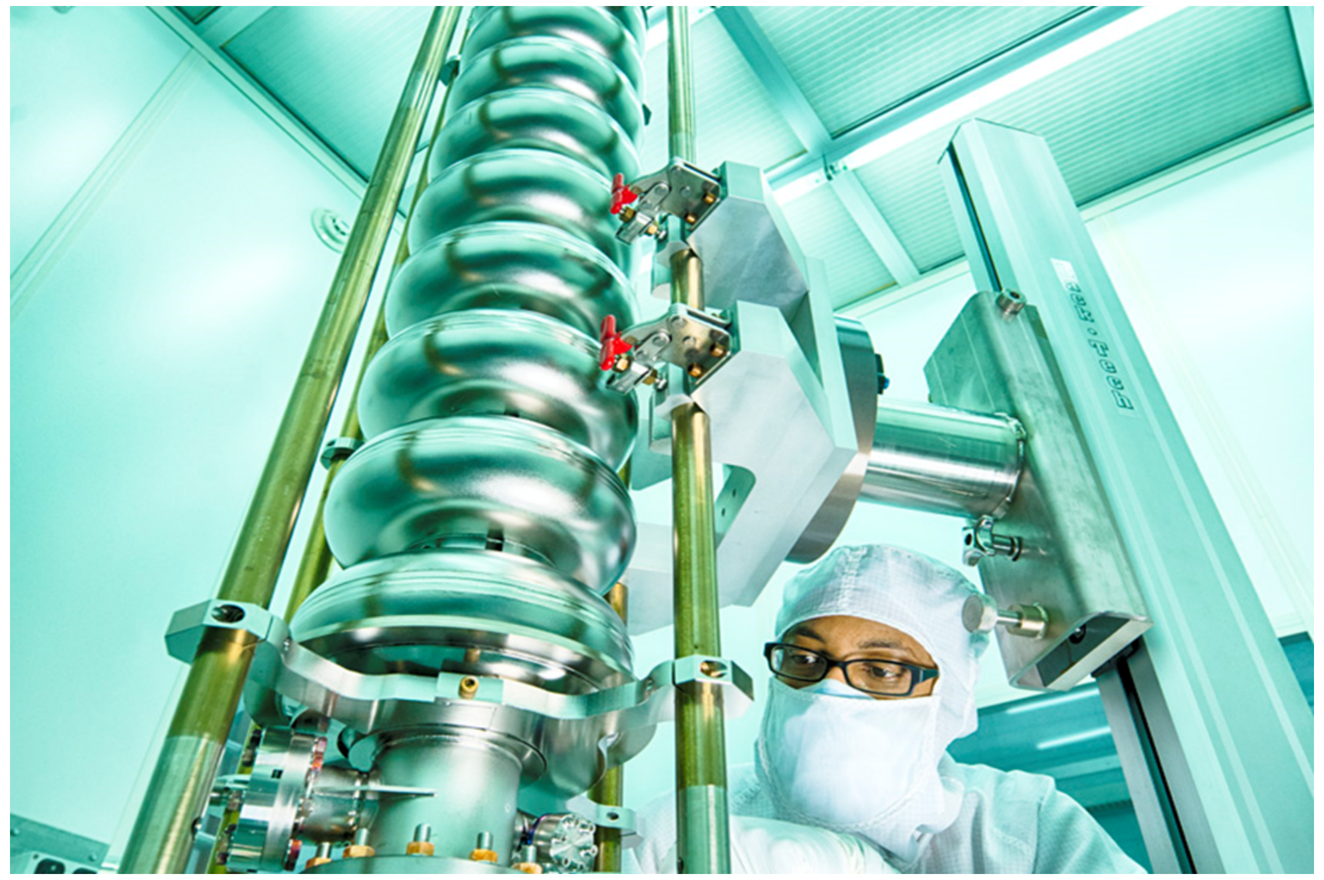


Cavities

- "Boxes for photons" are called cavities.
- Cavities are very useful, have been for decades, to build particle accelerators!
- Fermilab is a world leader in superconducting cavities
- In fact, cavities are more than qubits!



SQMS
SUPERCONDUCTING QUANTUM
MATERIALS & SYSTEMS CENTER

Cavities

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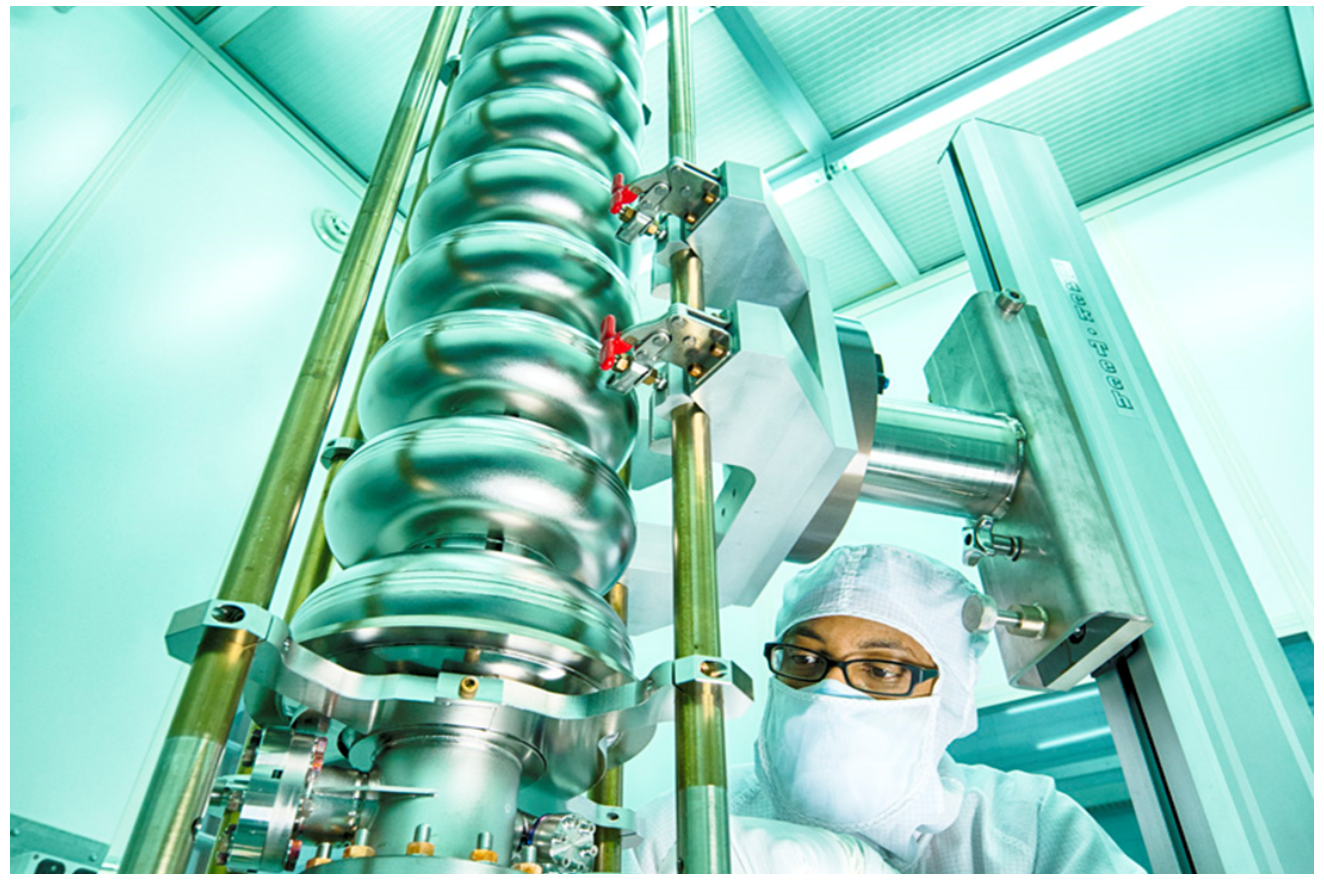
0, 1, 2, 3, 4,… photons. And suppositions!

qudits!

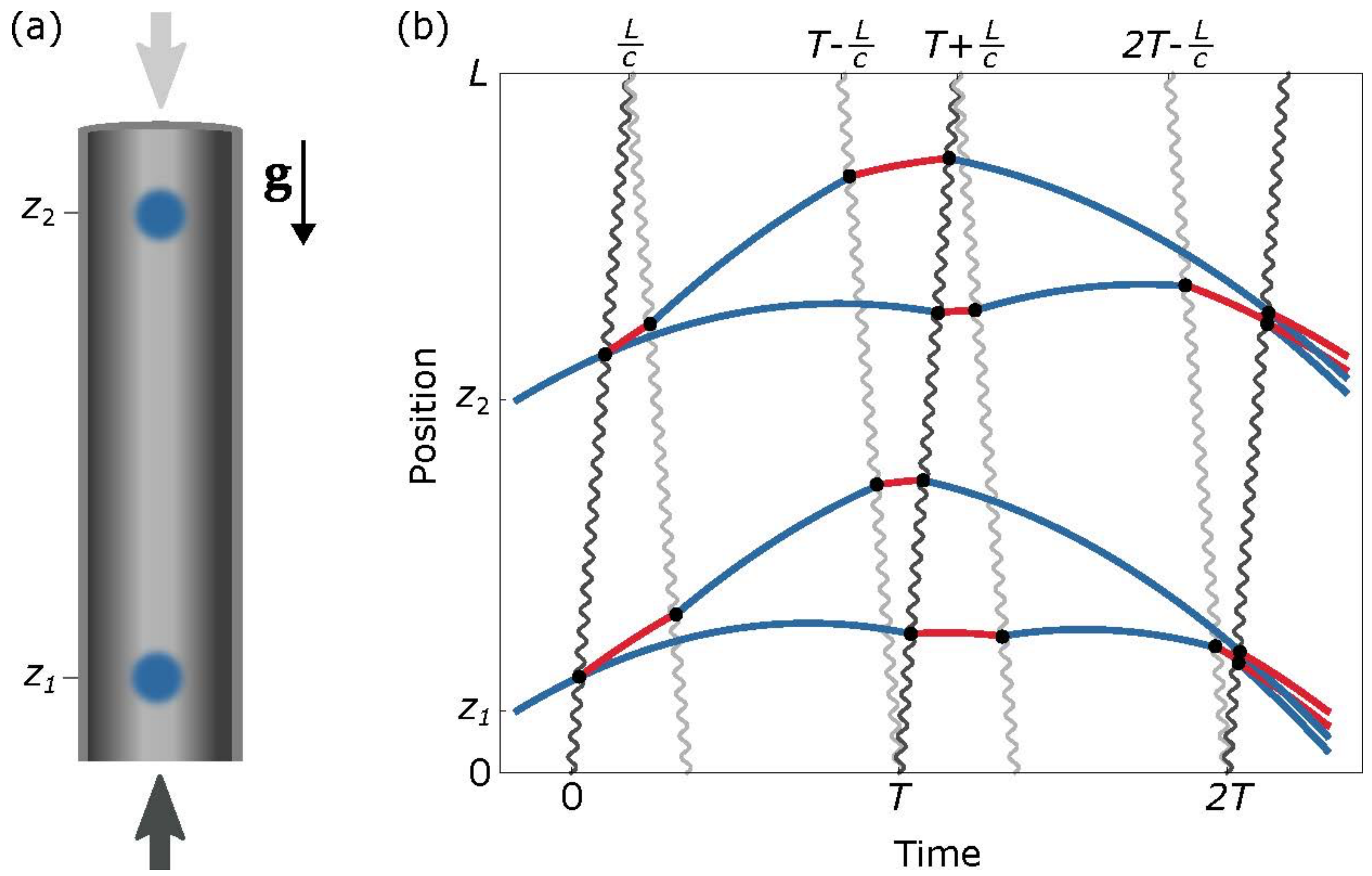


SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Atom Interferometers

- Superposition allowed for more cool stuff.
- E.g. atomic clocks: am atom in a superposition of quantum states can keep time!

$$|\psi_1\rangle + e^{i\Delta Et/\hbar}|\psi_2\rangle$$



MAGIS 100, under construction, will look for gravity waves!

(The distance between clocks oscillating…)

In summary

- Fermilab is about figuring out the Universe!
    - What's stuff made of?
    - How did it come about?
- Quantum computing and sensing can play a big role in answering our questions!
- Its a fascinating field.
- Enjoy it!