Million millions of atoms

Look at a dot on your paper

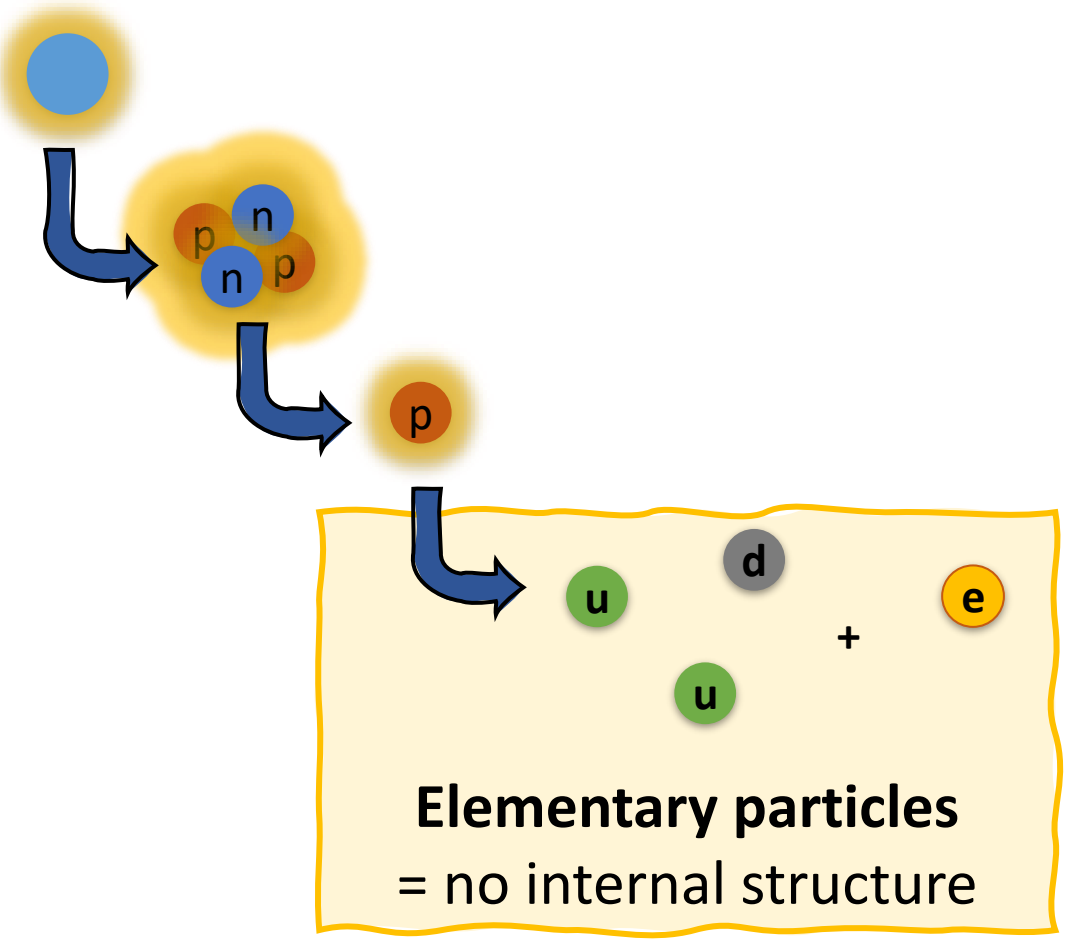
To "see" these particles, magnify the ● on your paper to …

atom
Football field

nucleus
The size of the Earth

protons & neutrons
Beyond where satellites are

3 quarks that made a proton
To the moon!!!



Fundamental particles are "building blocks" of nature

white lie

noun [C]
UK /ˌwaɪt ˈlaɪ US /ˌwaɪt ˈlaɪ/

: a lie that is told in order to be polite or to stop someone from being upset by the truth

And… I kind of lied to you

Fields are nature’s fundamental building blocks

But how did we get here?

Introduction to particle physics or: “How Did We Get Here?”

ภาวิน อิทธิสมัย
ภาควิชาฟิสิกส์ คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
โครงการอบรมฟิสิกส์อนุภาคพื้นฐาน 2565
(มหาวิทยาลัยขอนแก่น)

Image: Benjamin D. Esham (Creative Commons)

How to build a model explaining what's inside the box?

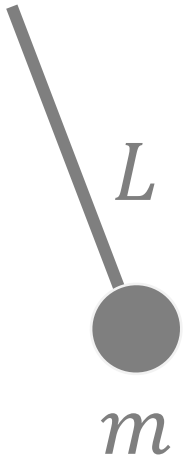
Image: Microsoft (Stock)

Richard Feynman

You guess it!

Image: Joe Munroe / Hulton Archive / Getty

Model 0
A rod length L with mass m



Experiment
shake it!

Model 0

$L \sim \text{box's height}$
$m \sim \text{box's mass}$

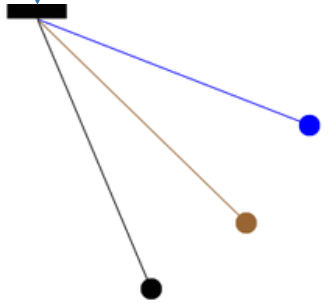
Need predictions you can test!

Model 1

It swings "like normal spring"

$$\text{Force} \propto -(\text{angle})$$

Underlying Theory = Classical Mechanics



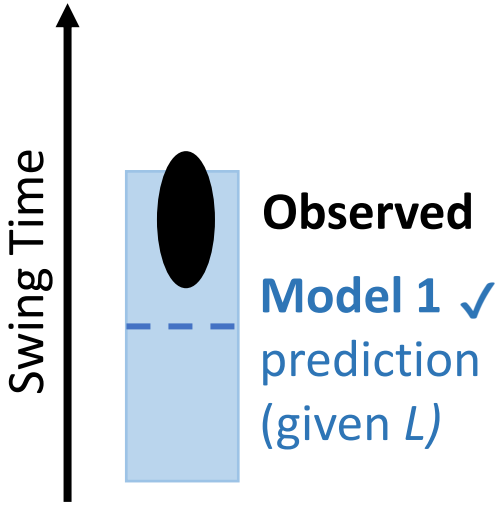
Predictions

$$\text{Swing time} = 2\pi\sqrt{\frac{L}{g}}$$

Experiment

Light flashes when something passes by

Model 1



Quantitative predictions let you probe some structure

With more precise measurements …

Old experiment

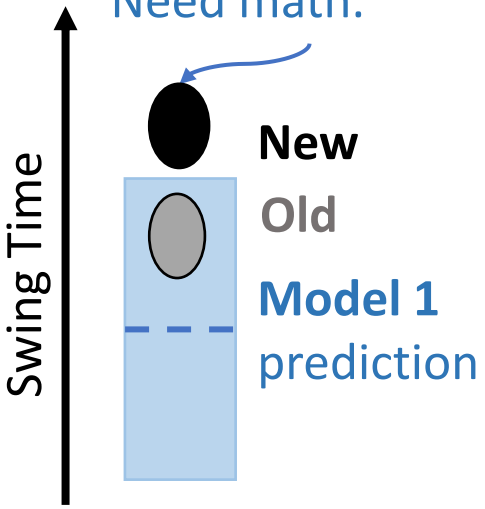
Model 1 ✓

New experiment

Model 1 ✗

Model 1

How likely for this deviation to be just a fluke? Need math.



More/better experiments set limit on models or rule them out altogether!

How to improve your model?

You guess it!

Image: Joe Munroe / Hulton Archive / Getty

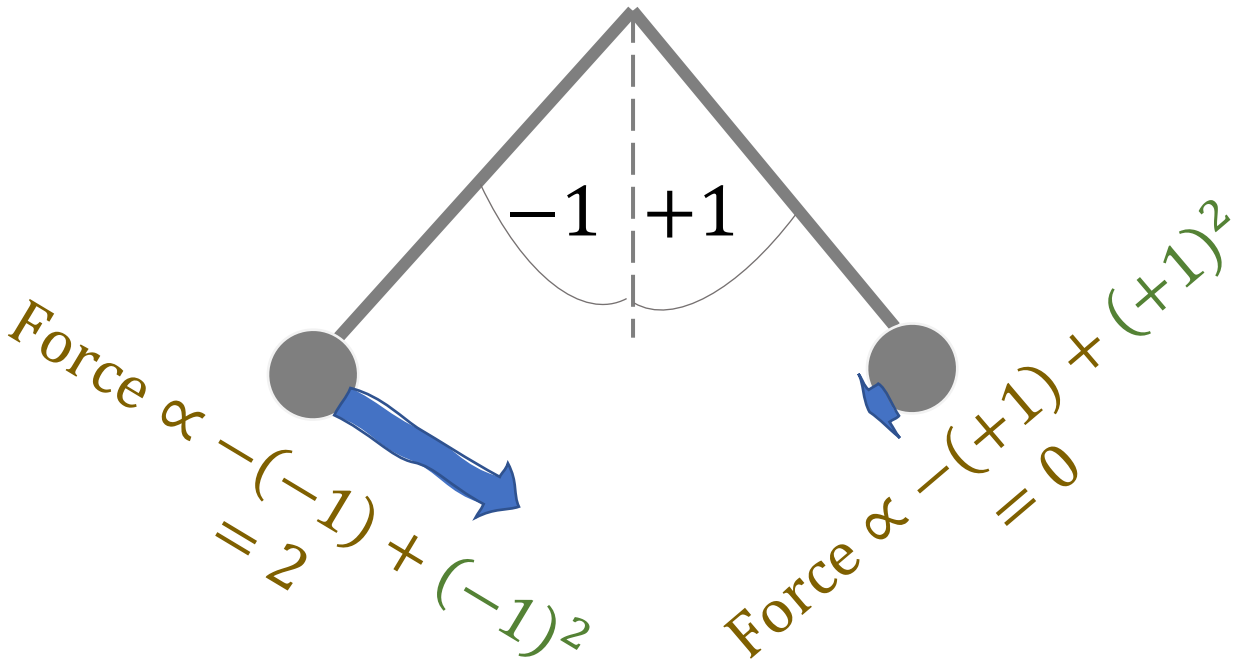
Model 2

Add funny spring effect

$\text{Force} \propto -(\text{angle}) + (\text{angle})^2$

Predicts different results when swinging left (angle) or right $(-\text{angle})$

Symmetry argument: nature should be "left-right" symmetric (not always the case!!)



Make educated guess with "symmetry"

Model 3

Add another funny spring effect

$$\text{Force} \propto -(\text{angle}) + (\text{angle})^3$$

Model 1, already did a good job

So the extra bits can't be too "important"

Model 3β

*Add "**small**" funny spring effect*

$$\text{Force} \propto -(\text{angle}) + \beta(\text{angle})^3$$

Need more experiment to determine that **small** β

Add "perturbations" to a known model

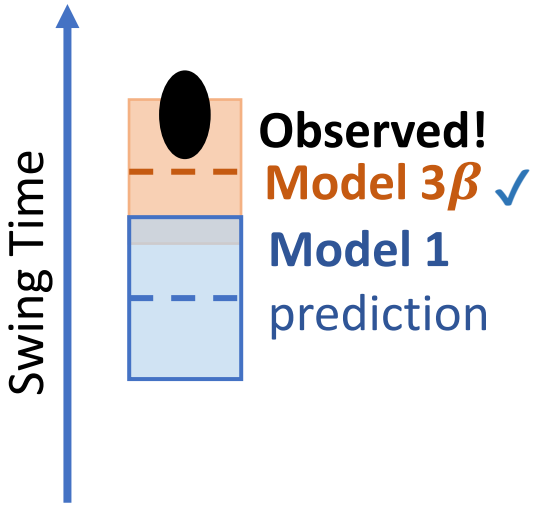
Model 3β

*Add "**small**" funny spring effect*

$$\text{Force} \propto -(\text{angle}) + \beta(\text{angle})^3$$

$$\text{Swing time} = 2\pi\sqrt{\frac{L}{g}} + 2\pi\sqrt{\frac{L}{g}}\frac{3}{8}\beta(\text{Amplitude})^2$$

Model 2



Implies a spring with some Length and Amplitude with a mysterious parameter $\beta \approx 1/6$ found from other experiments

Better model/experiments can probe more structures

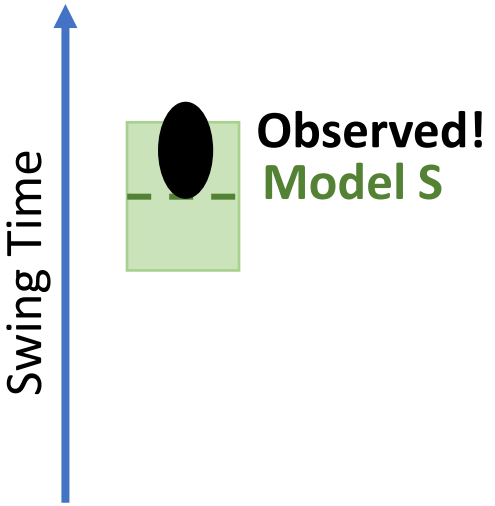
Model S

A gift from Trigonometry

$F \propto -\sin(\text{angle})$

Predicted automatically

$$\text{Swing time} = 2\pi\sqrt{\frac{L}{g}}\left(1 + \frac{1}{16}(\text{Amplitude})^2 + \frac{11}{3072}(\text{Amplitude})^4 + \cdots\right)$$



Model S: A pendulum with length L and amplitude A

Sometimes theorists build models “top-down”

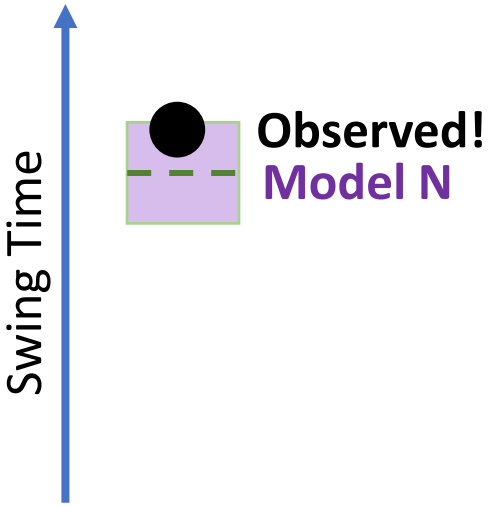
Model N

Contribution from New Physics (Wind, Heat, …?)

$F \propto -\sin(\text{angle}) + \textbf{New stuff?}$

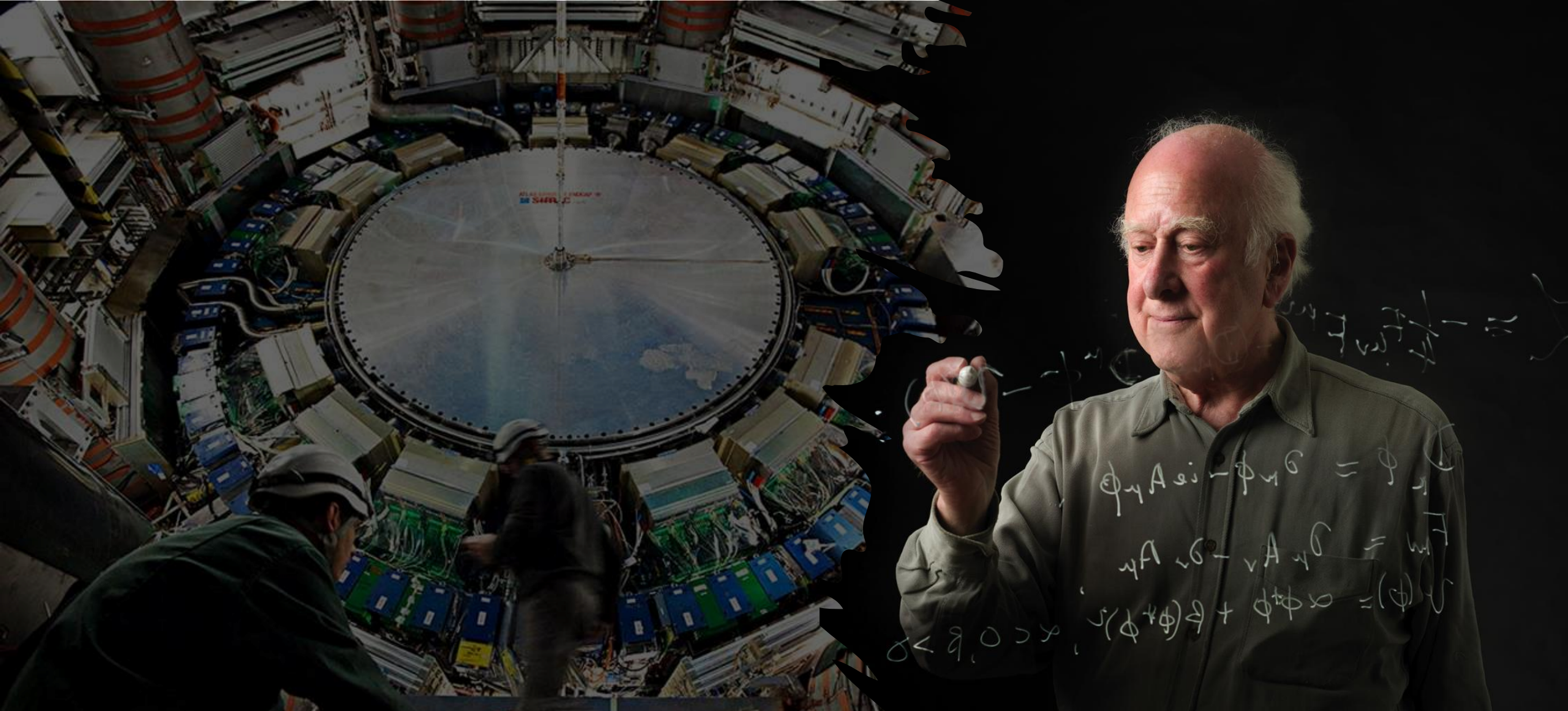
$$\text{Swing time} = 2\pi\sqrt{\frac{L}{g}}\left(1 + \frac{1}{16}(\text{Amplitude})^2 + \frac{11}{3072}(\text{Amplitude})^4 + \cdots\right)$$

$$+\boldsymbol{NP1} \qquad +\boldsymbol{NP2} \qquad +\boldsymbol{NP} \ldots$$



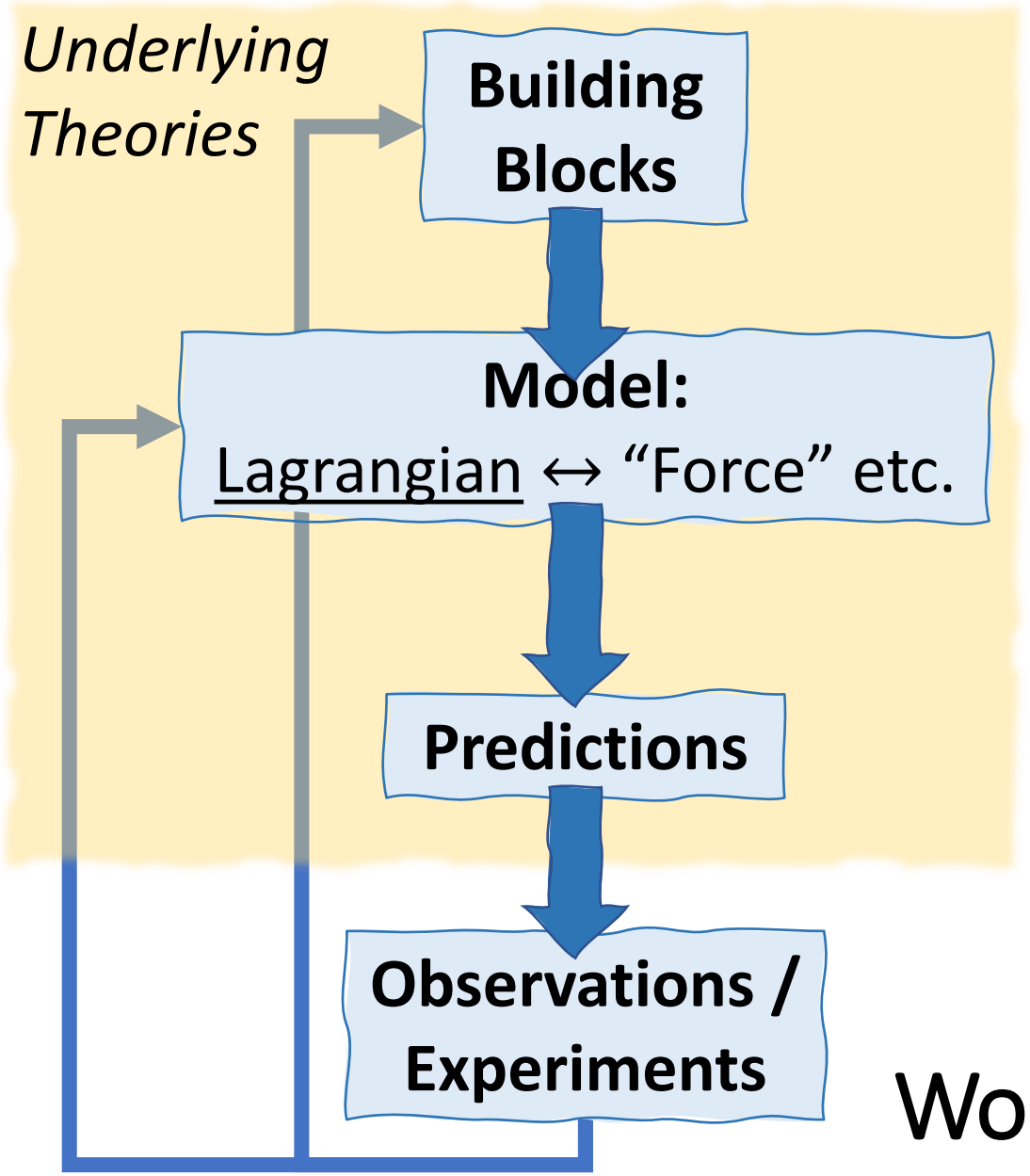
Hints for even further discoveries could come from more/better experiments.

"New Physics"?

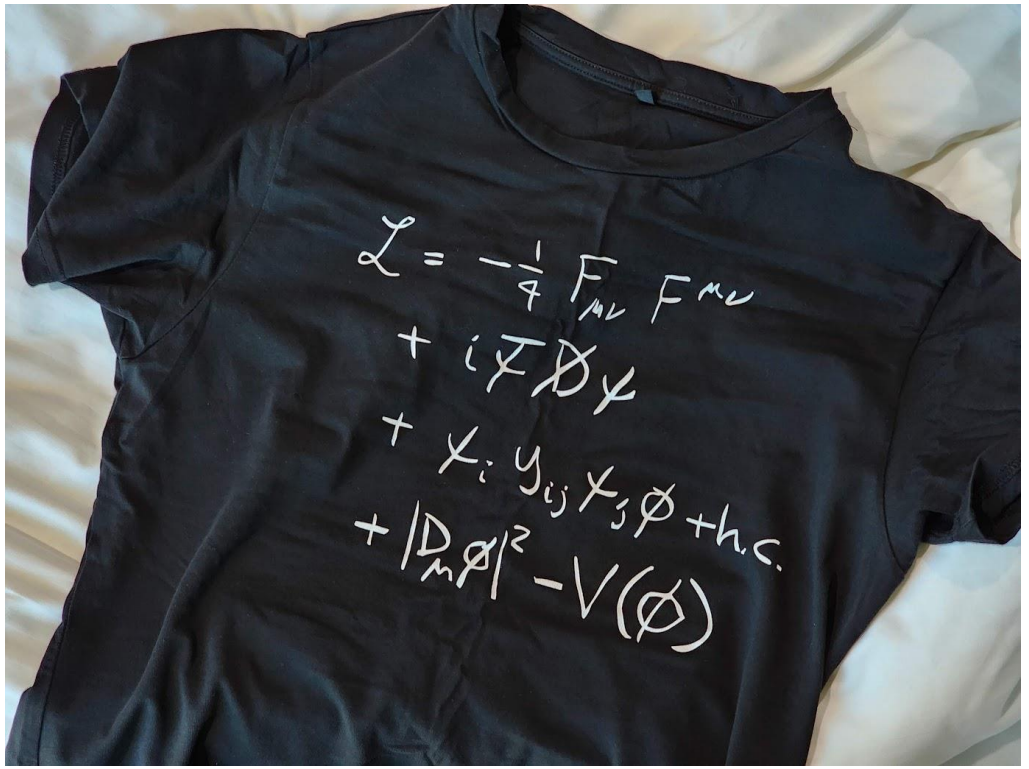


General strategy: Scientific Method!

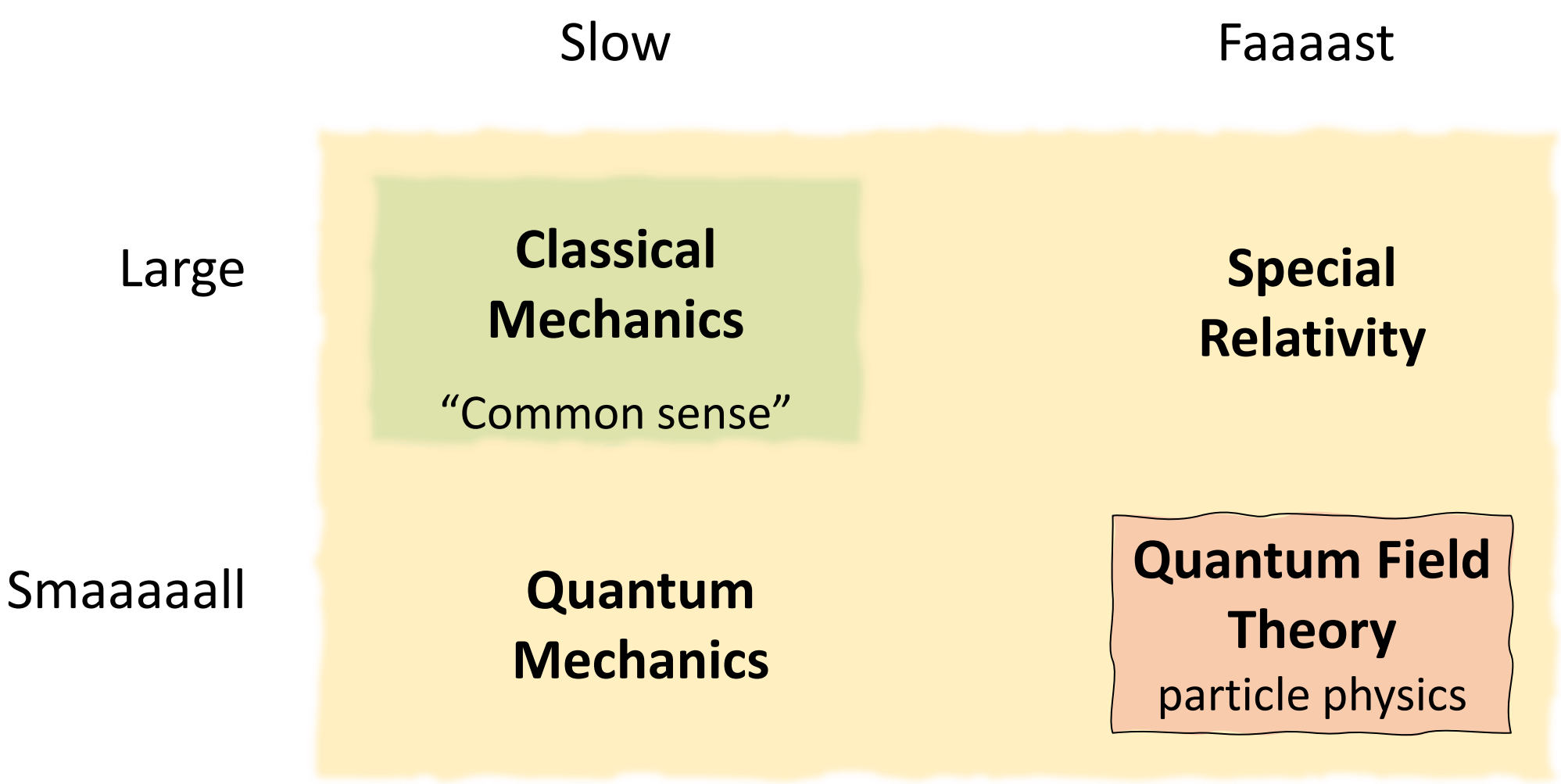
Images: Claudia Marcelloni / CERN



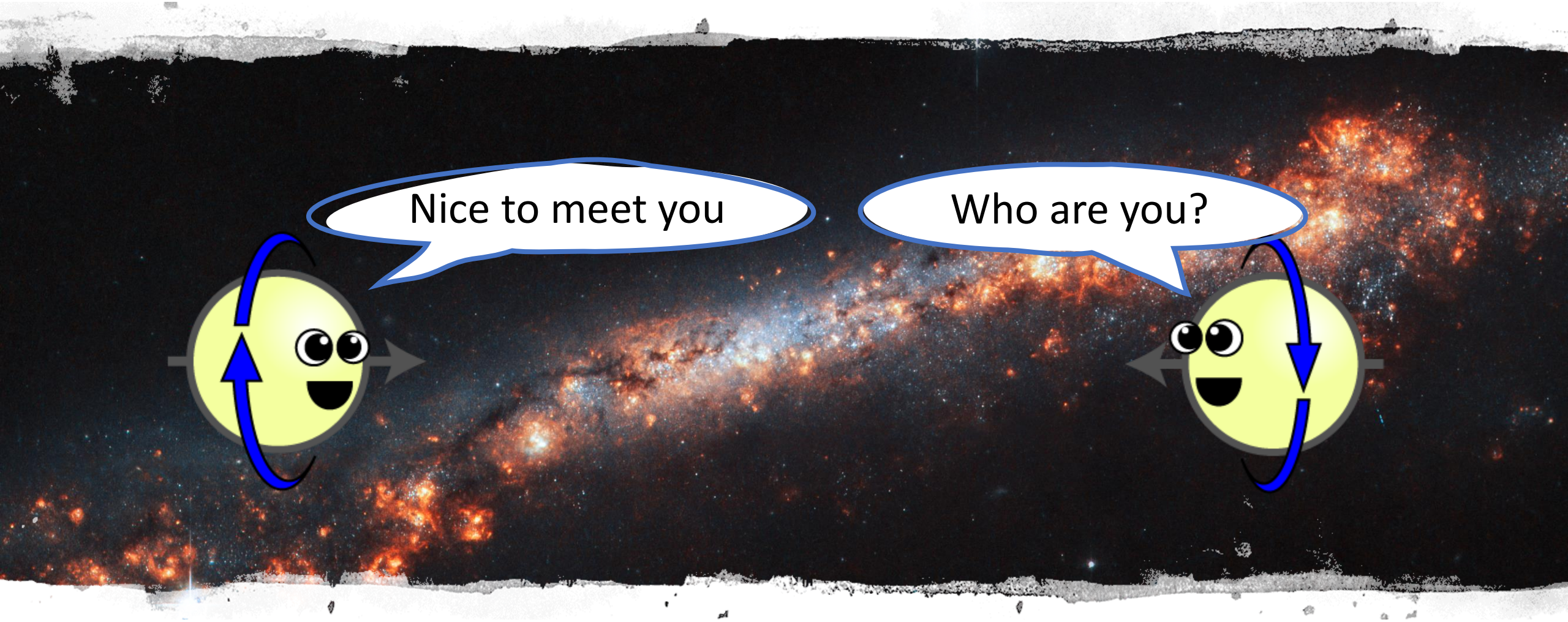
Workflow



Standard Model Lagrangian

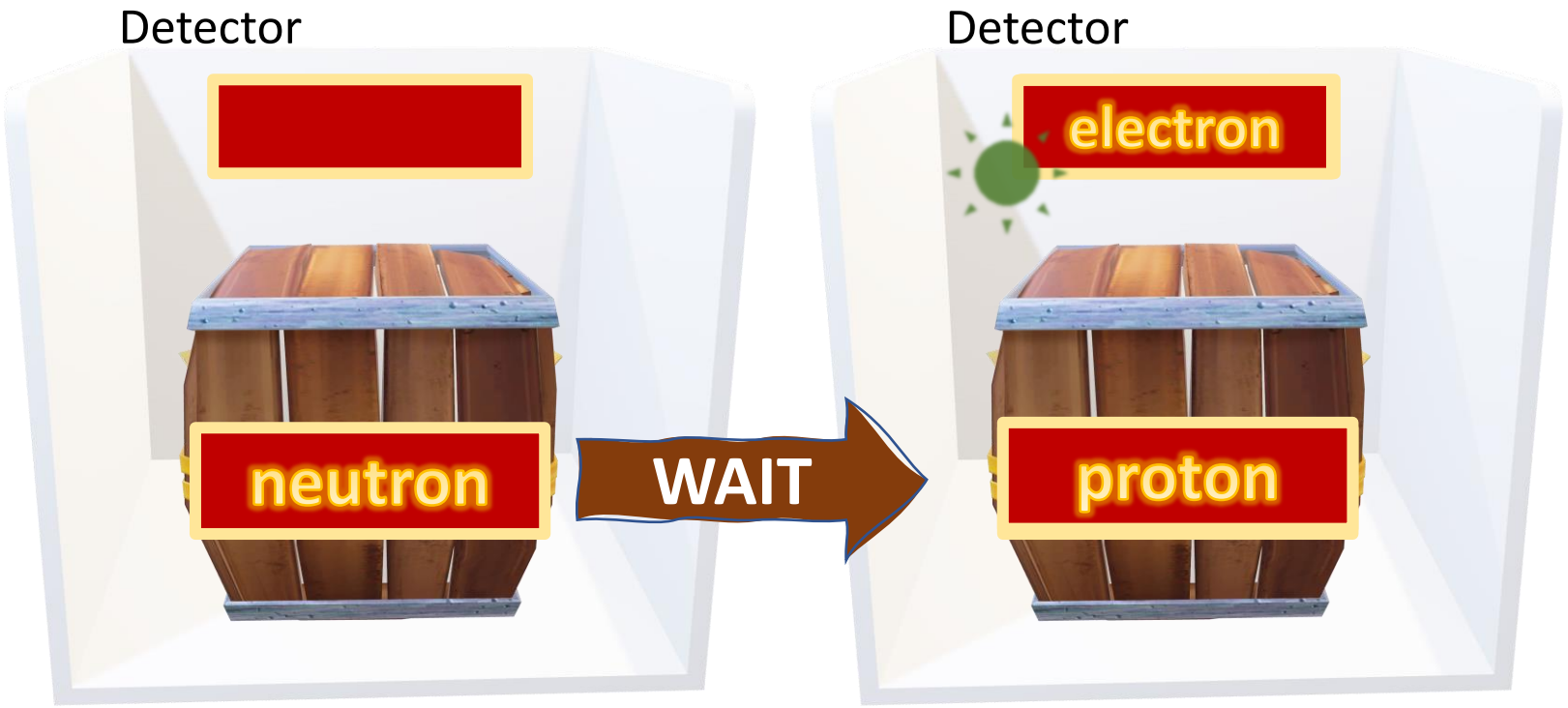


Underlying Theories:
Reality is VERY different from common sense



Clues for the building blocks?
Same electrons throughout the universe?

Image: Flip Tanedo / NASA



Wrong …

Experiment?

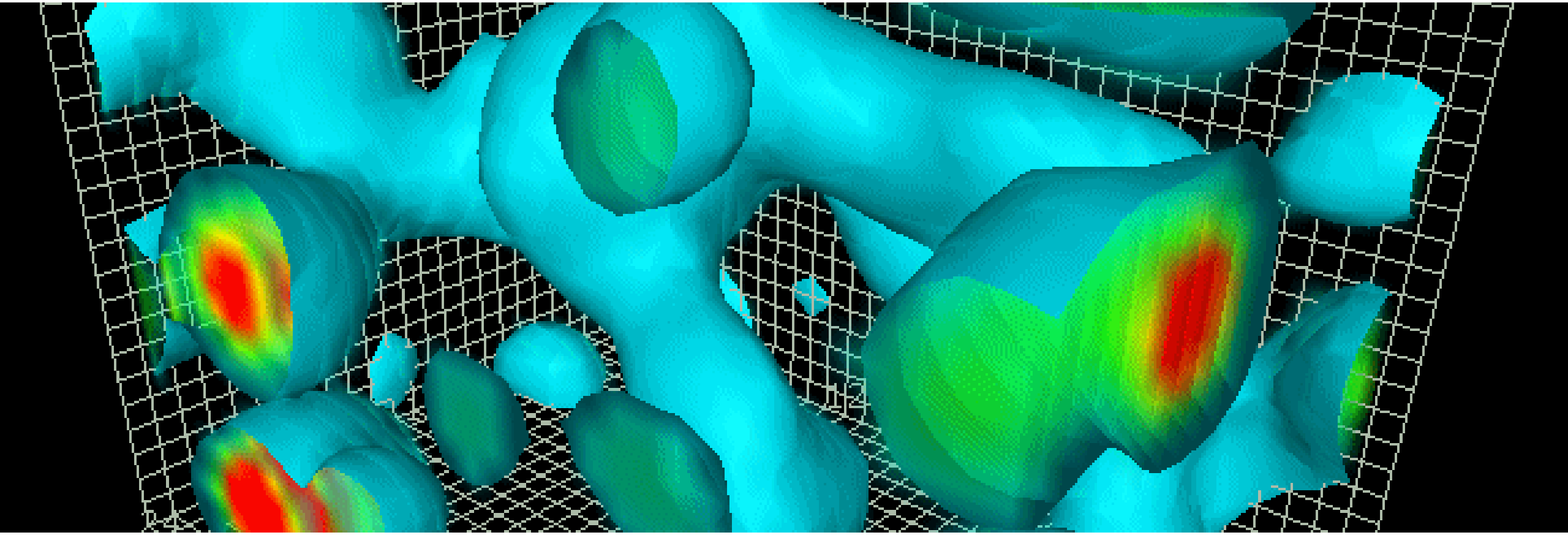
Model?

Underlying Theory?

Building blocks?

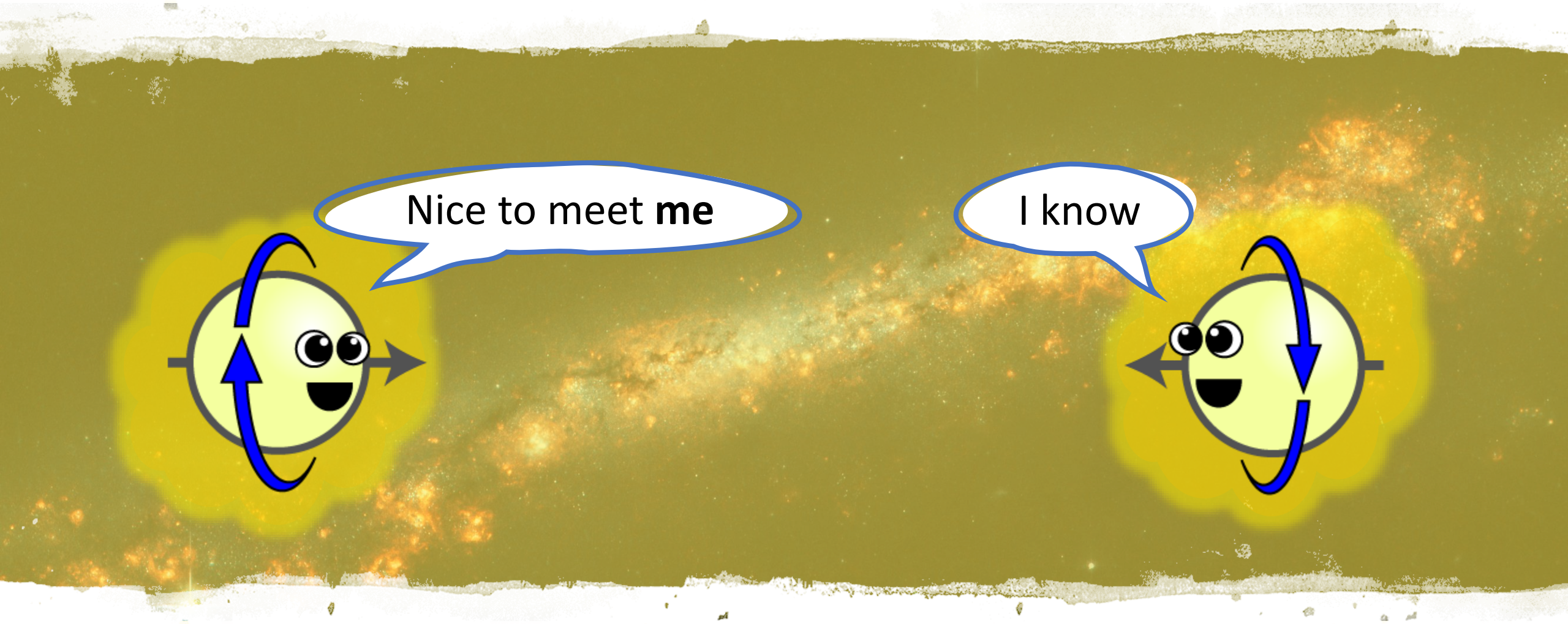
Particle + Quantum Mechanics cannot explain "mutations" of fundamental building blocks

There are no particles. Fields are everywhere.



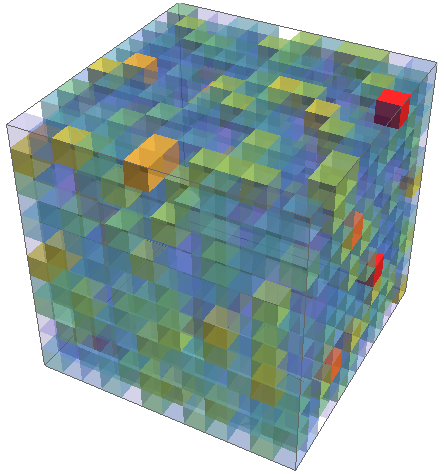
Quantum Physics: fields can’t be perfectly still.
Enough energy at a point = Lots of vibrations = “particles”.

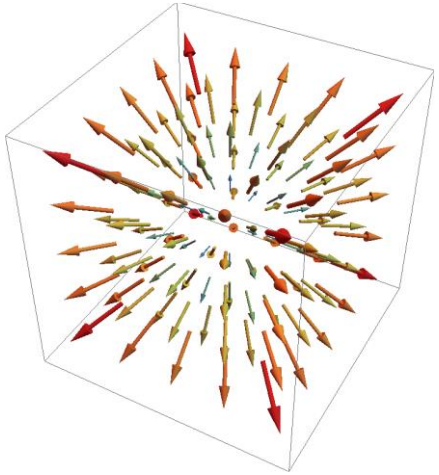
Animation: Derek B. Leinweber

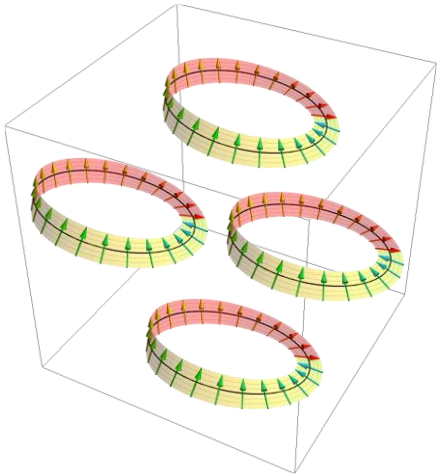


Things we observe as particles are local excitations of fields

Image: Flip Tanedo / NASA



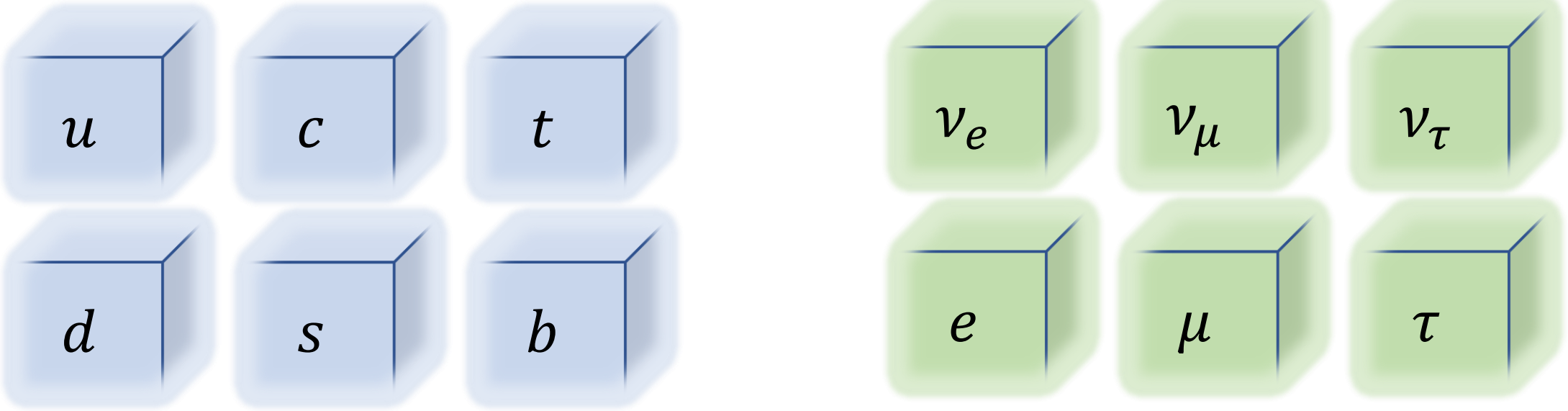




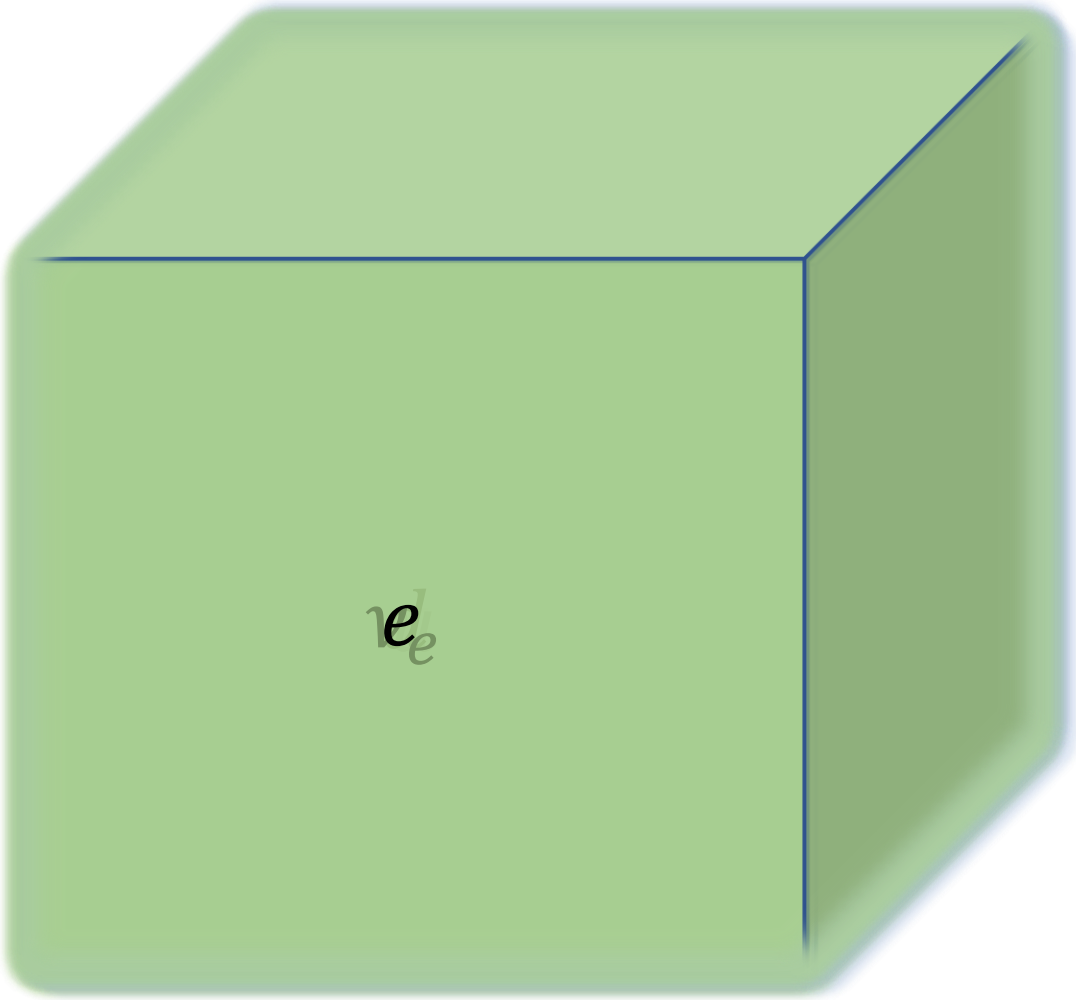
	Scalar field	**Vector field**	**Spinor field**
Excitations live at the same place?	✓	✓	✗
Care about directions?	✗	✓	✓

Building blocks: nature tells us what fields to use

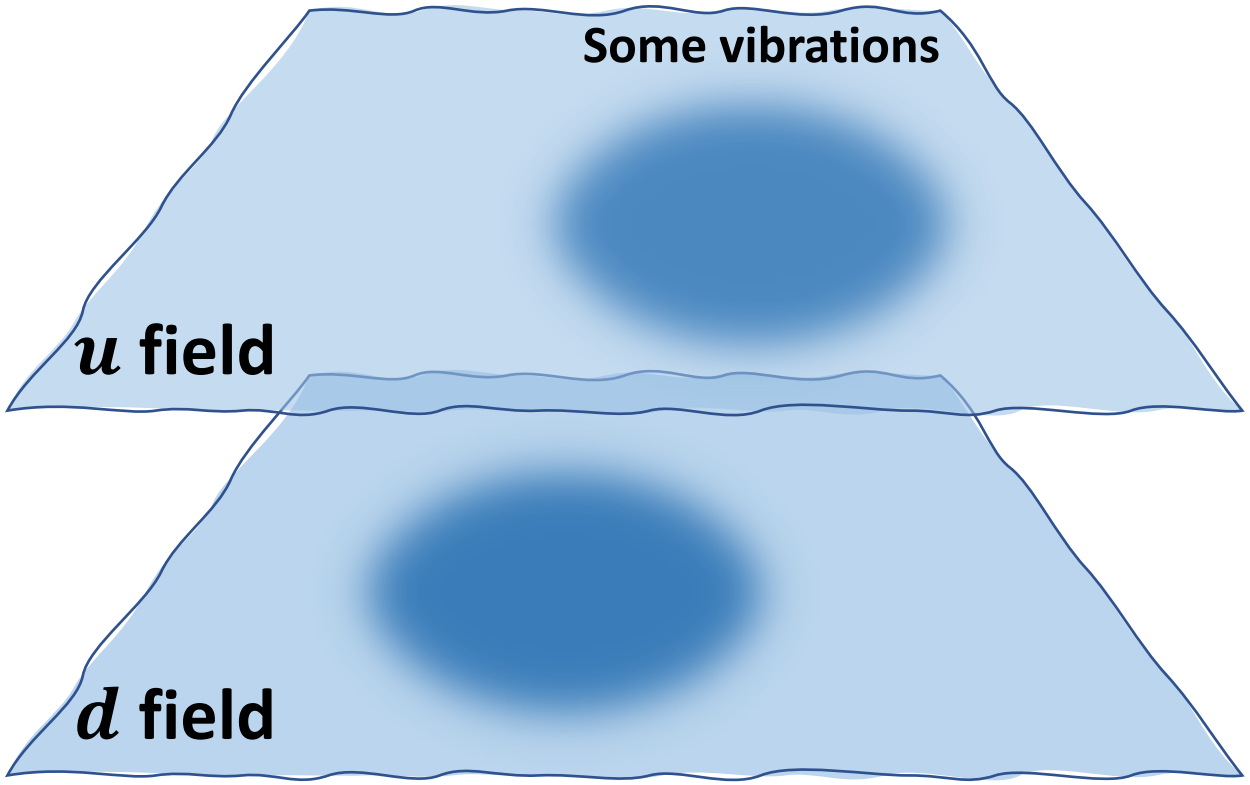
Image: Mathematica, Wikimedia Commons (spinors)



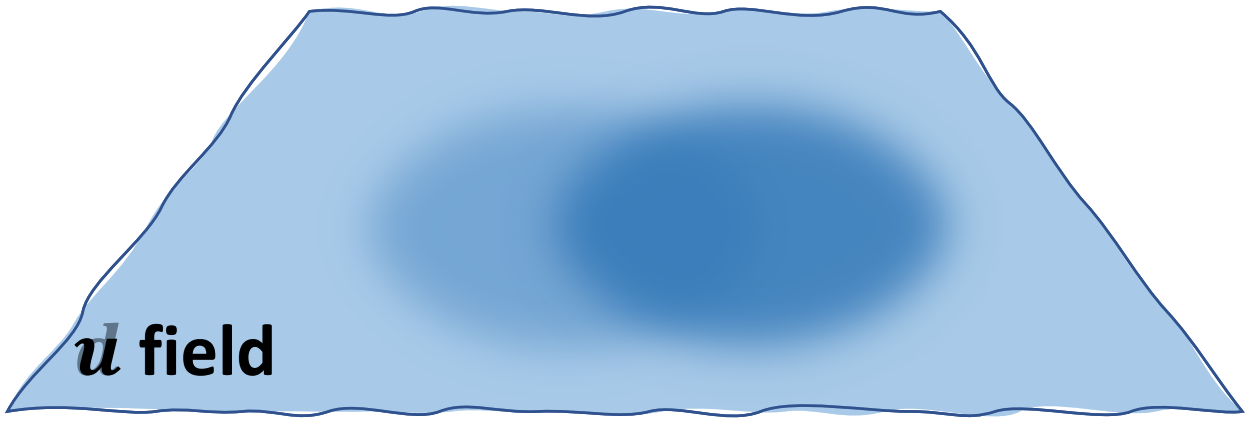
Matter fields fill the universe



Matter fields fill the universe



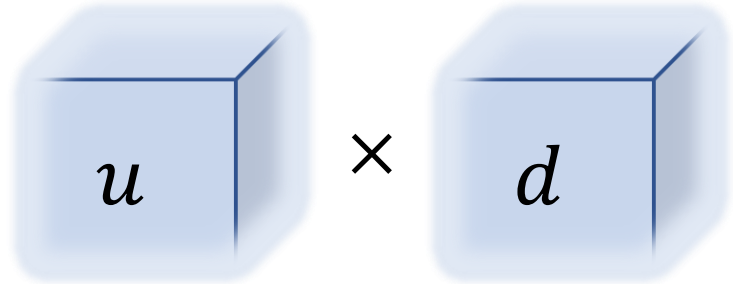
Need a model with interacting fields!

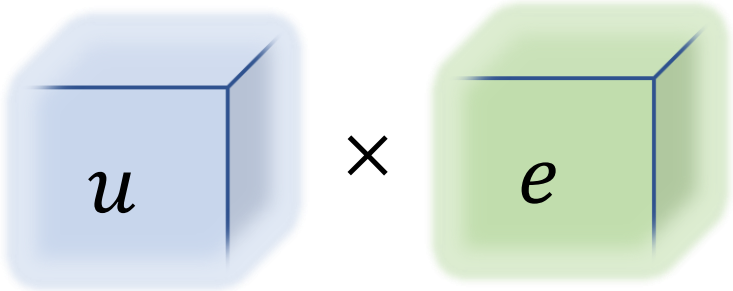


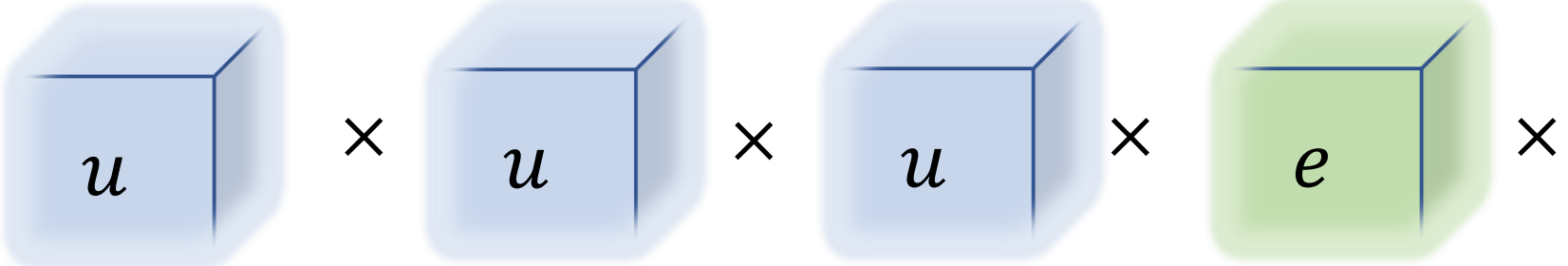
Interactions happen when fields “talk” to each other.

Need a model for interacting fields!

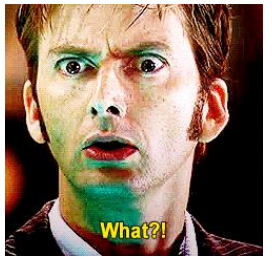
“Interaction terms” in equations





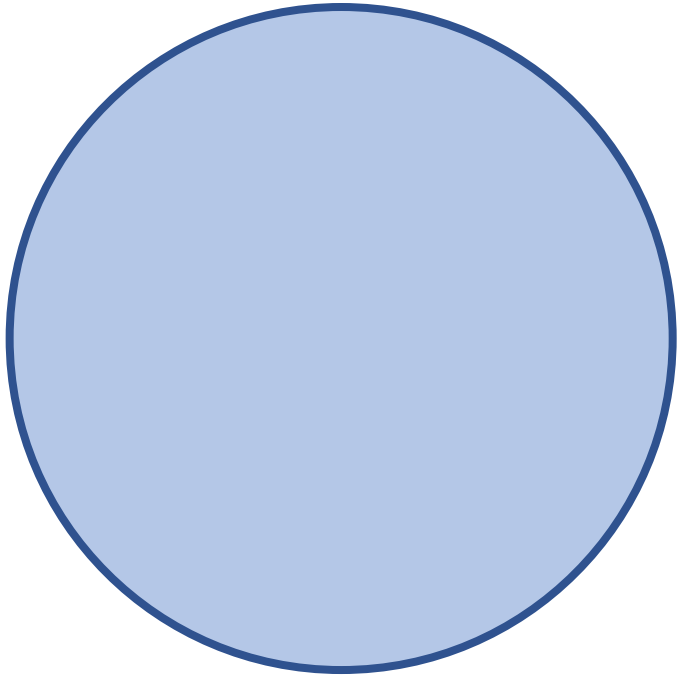


Rules must be ok with Quantum Mechanics, Special Relativity… and NATURE!!

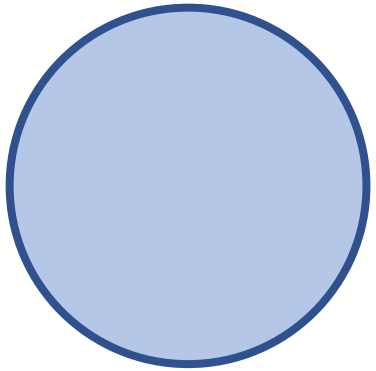


Model: how to make fields interact

Image: Dr. Who

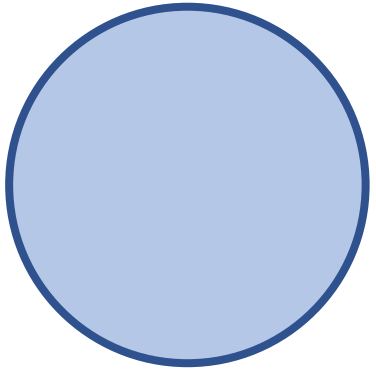


Symmetry: sameness under a certain change



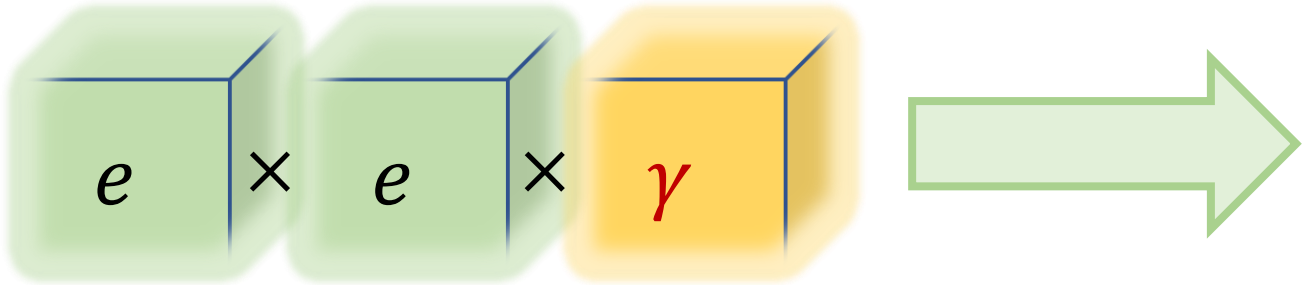
Remains the same under any rotation on its plane.

What remains the same under any rotation on its plane?



Reversed logic: nice little trick that goes a long way

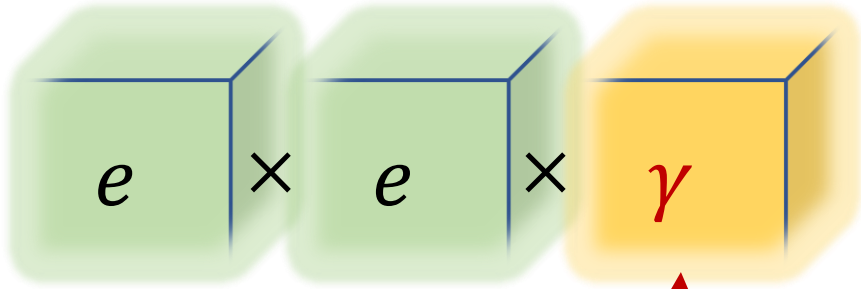
Classical electromagnetic theory (known)



Remains the same under "some change" in **matter field** (electron).

Modern Physics Trick: Assume a symmetry and ask what happens

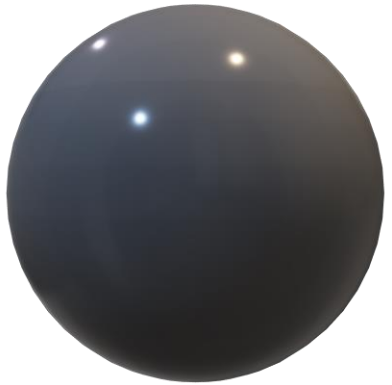
What **matter-only model** remains the same under "that change" in **matter field**?



Photon is ***Predicted*** from symmetry

Reversing the logic predicts "force" fields!

What remains the same under any rotation on any plane?



A sphere!

What **matter model** remains the same under **"the blah blah blah change"** in **matter field**?

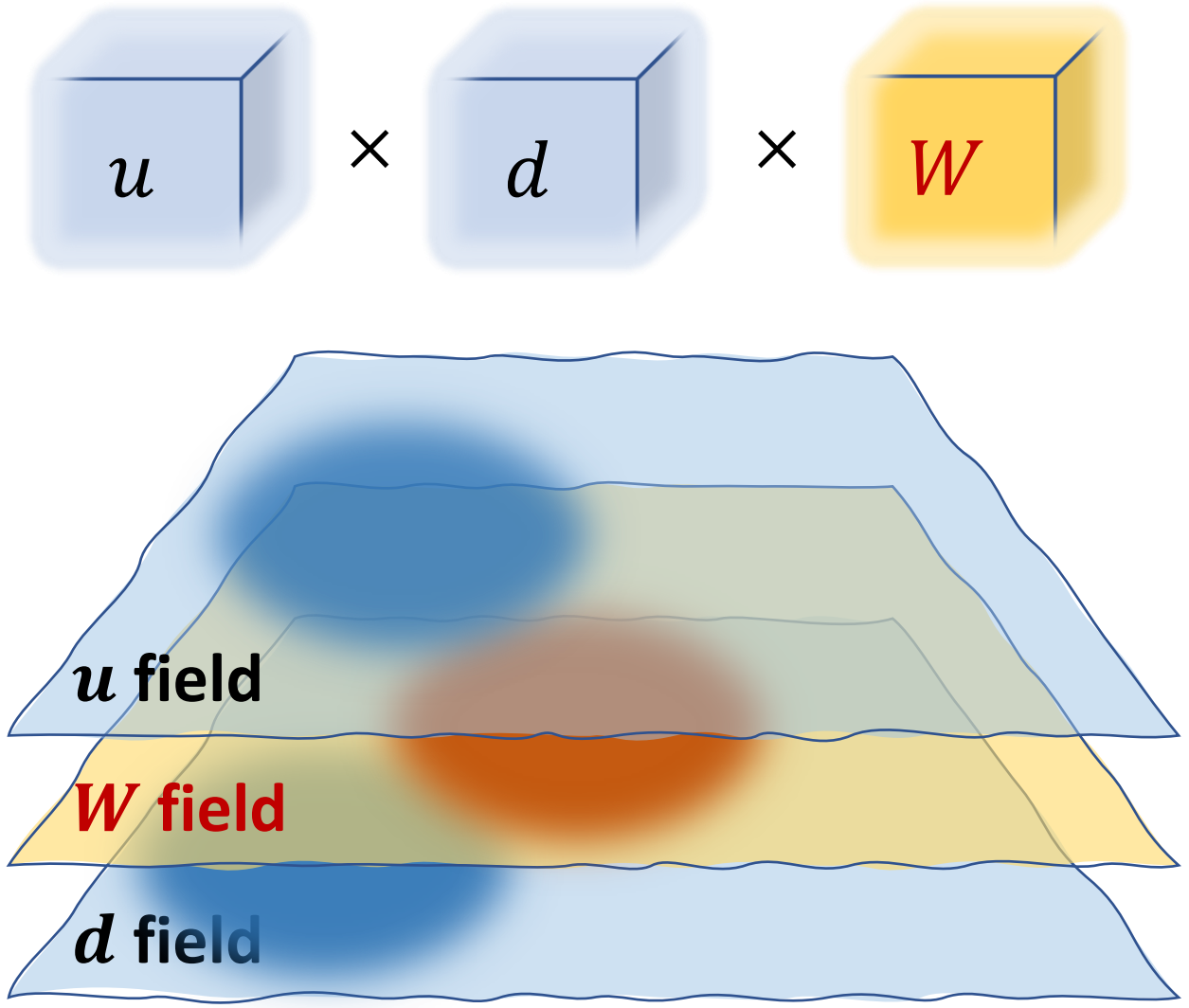
Tons of predictions for force fields!

Need help from Math Department (Group Theory)

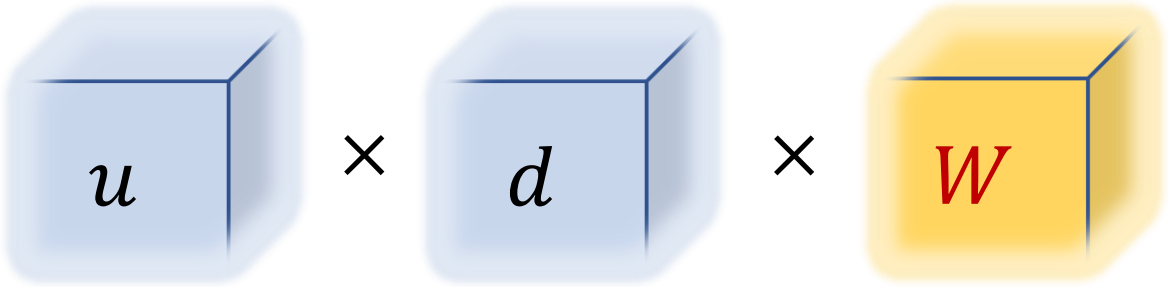
Nature doesn’t care about <u>our model</u>

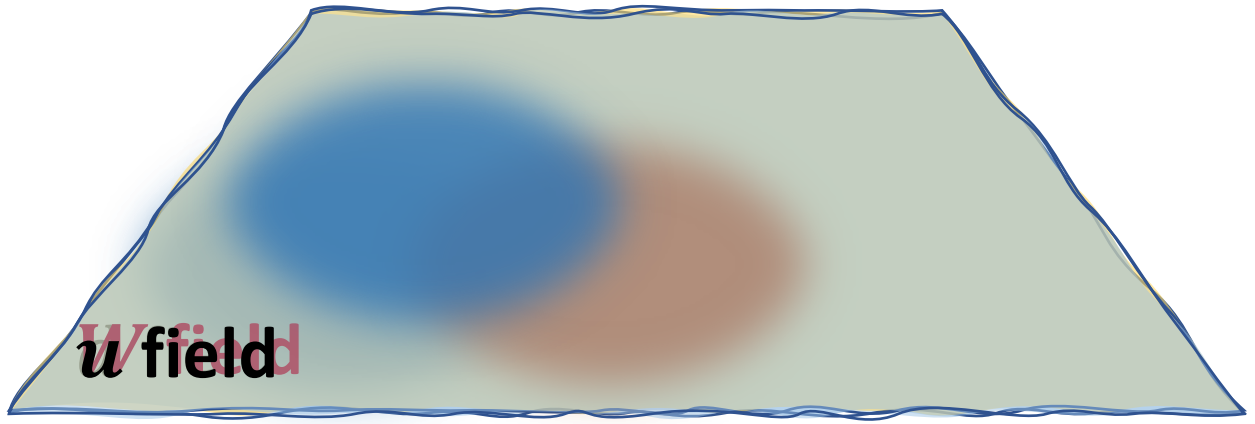
*“**If it disagrees with experiment, it’s wrong.** In that simple statement is the key to science. It doesn’t make any difference how beautiful your guess is, it doesn’t matter how smart you are who made the guess, or what his name is… If it disagrees with experiment, it’s wrong. That’s all there is to it.”*
-- Richard P. Feynman

Image: Caltech Archives

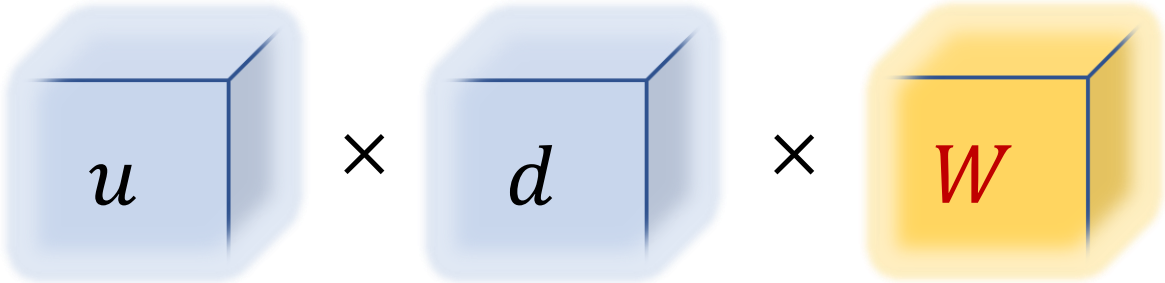


Field interaction predicted by symmetry!



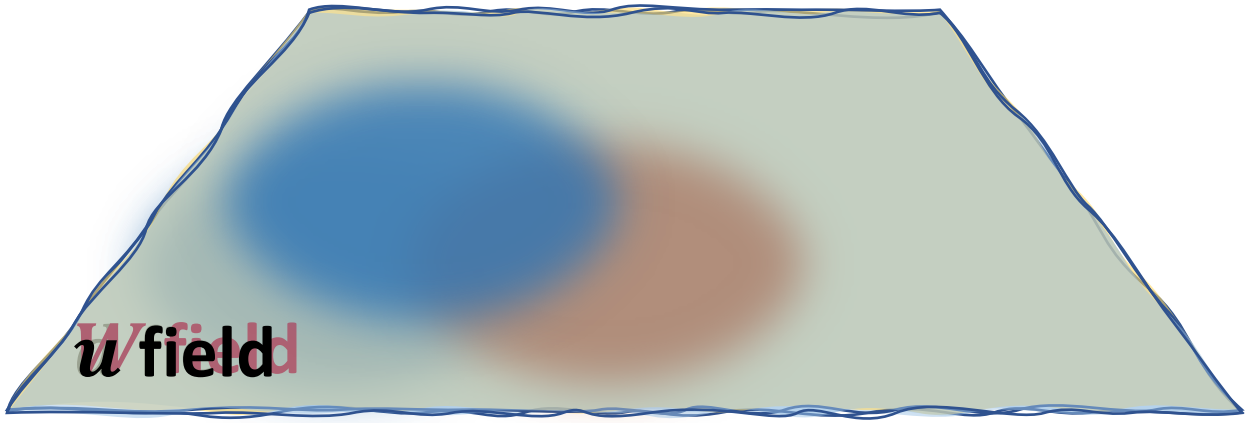


Field interaction predicted by symmetry!



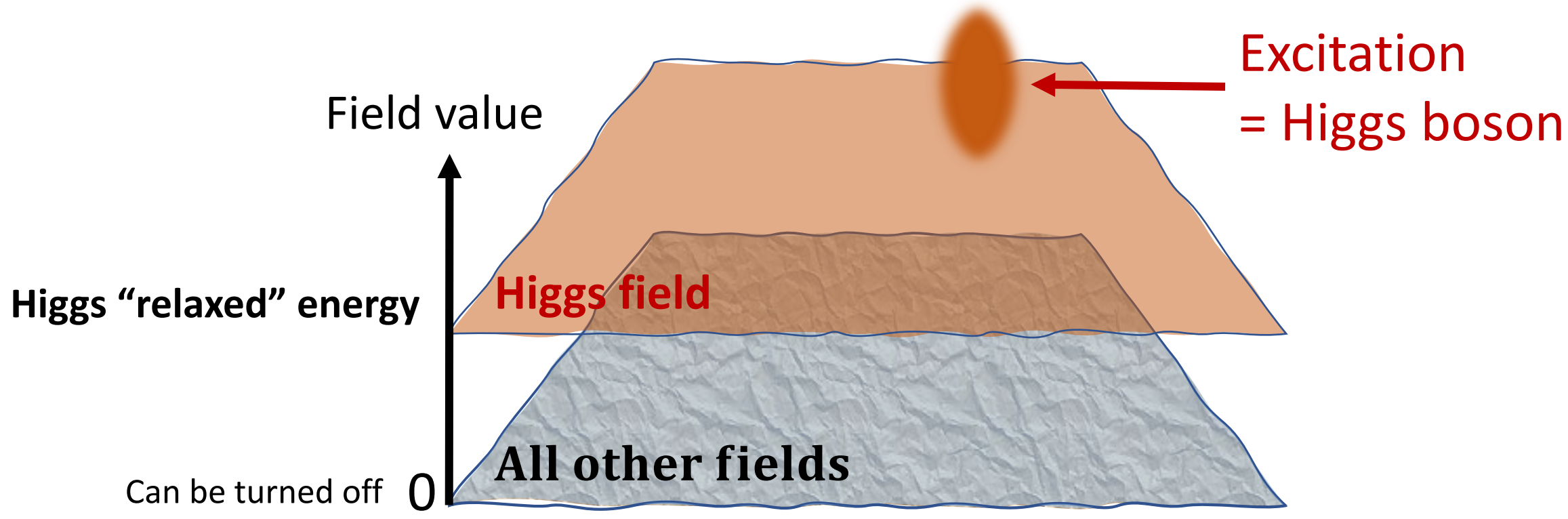
Sameness under **“the blah blah blah change”**

allows excitations of all fields at no cost!

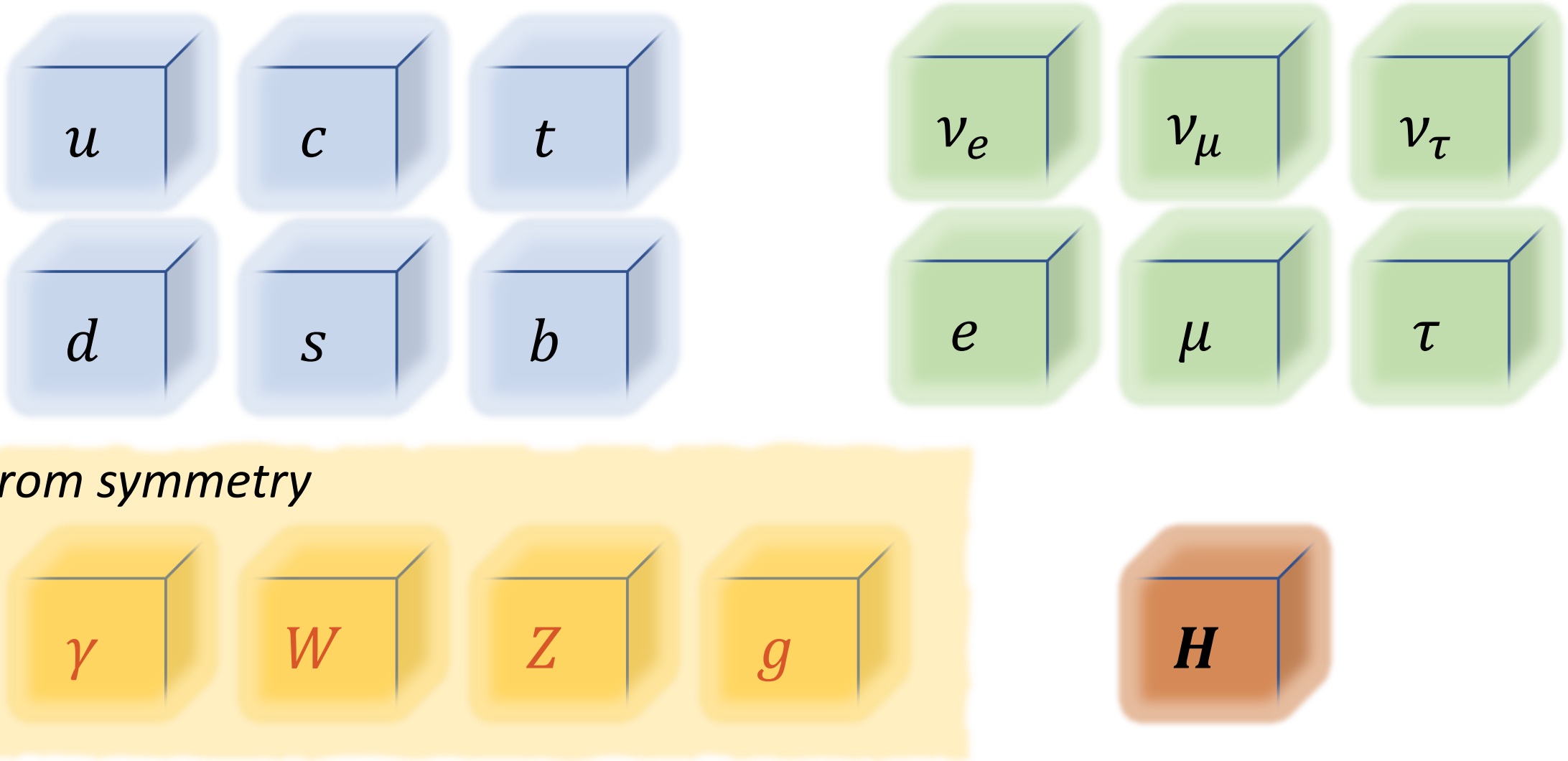


One massive problem is everybody is massless!

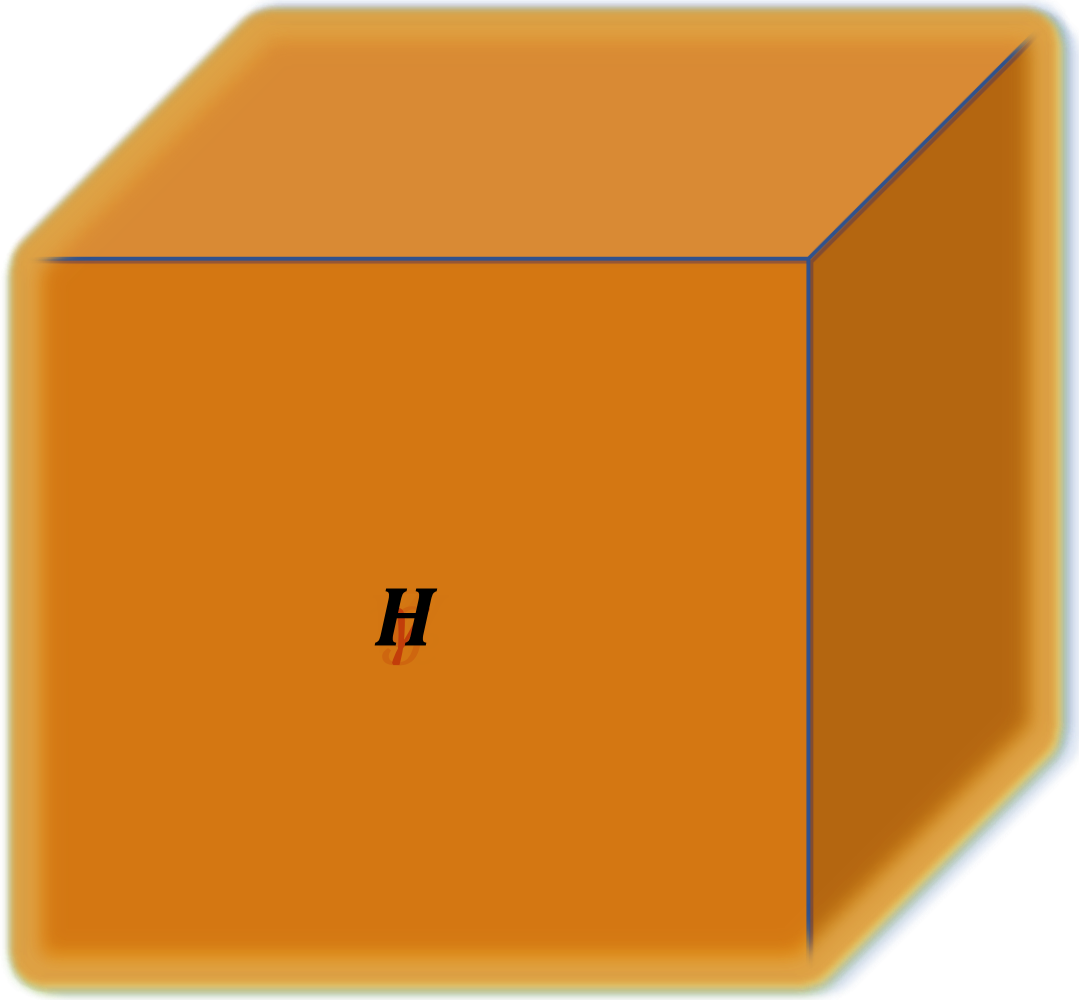
Need Higgs field that cannot be “turned off” & interact with almost everyone = massive fields



The Higgs Field to rescue



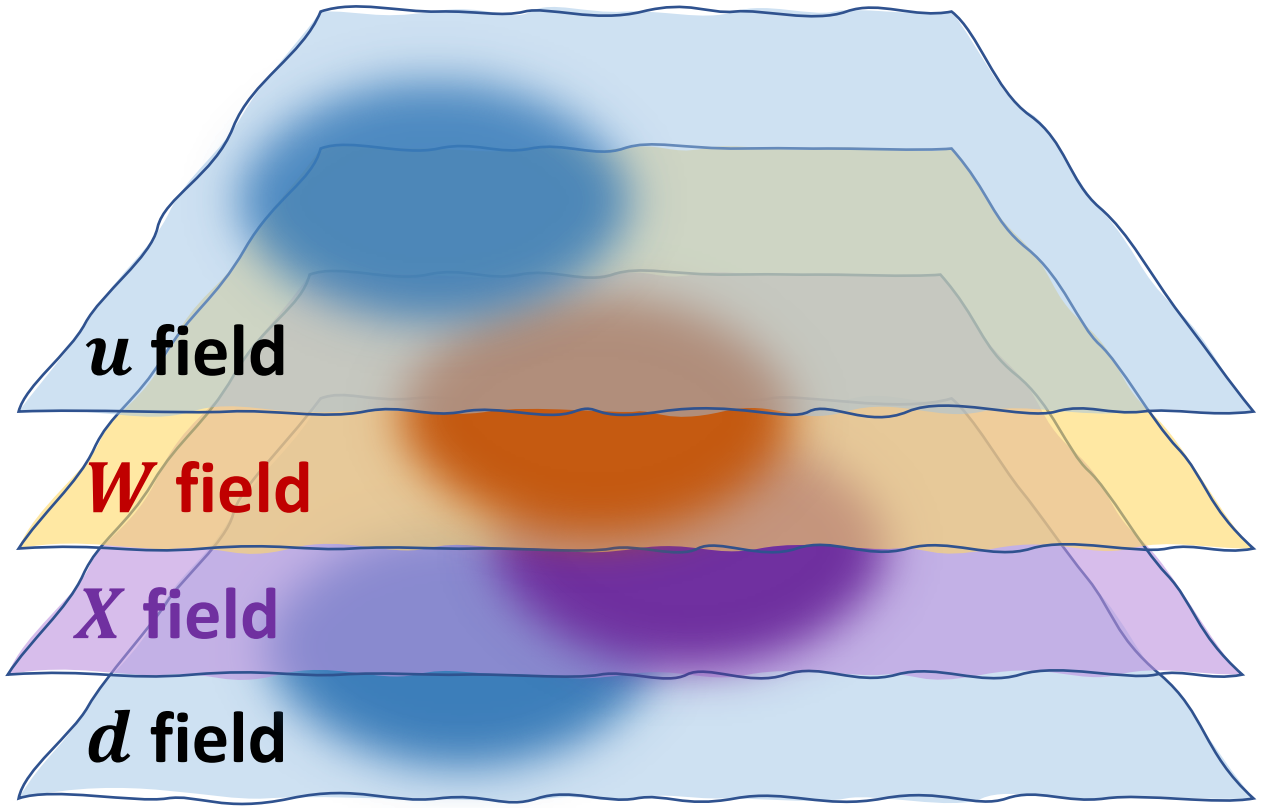
The Standard Model of Particle Physics



The Standard Model of Particle Physics

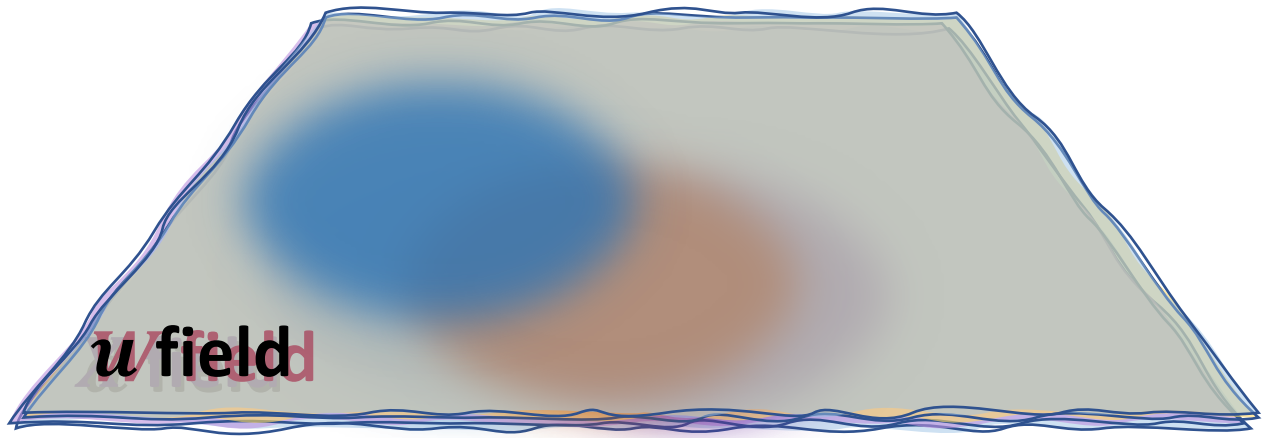
We know the Standard Model is “not enough” …

$\ldots + u \times d \times W \ldots + u \times d \times X + \cdots$



Standard Model + New Physics = More fields?

$\ldots + \boxed{u} \times \boxed{d} \times \boxed{W} \ldots + \boxed{u} \times \boxed{d} \times \boxed{X} + \cdots$



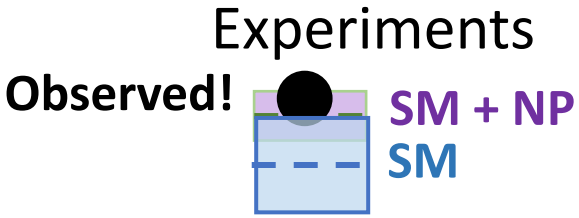
Standard Model + New Physics

SM + New Physics

SM with Contribution from New Physics?

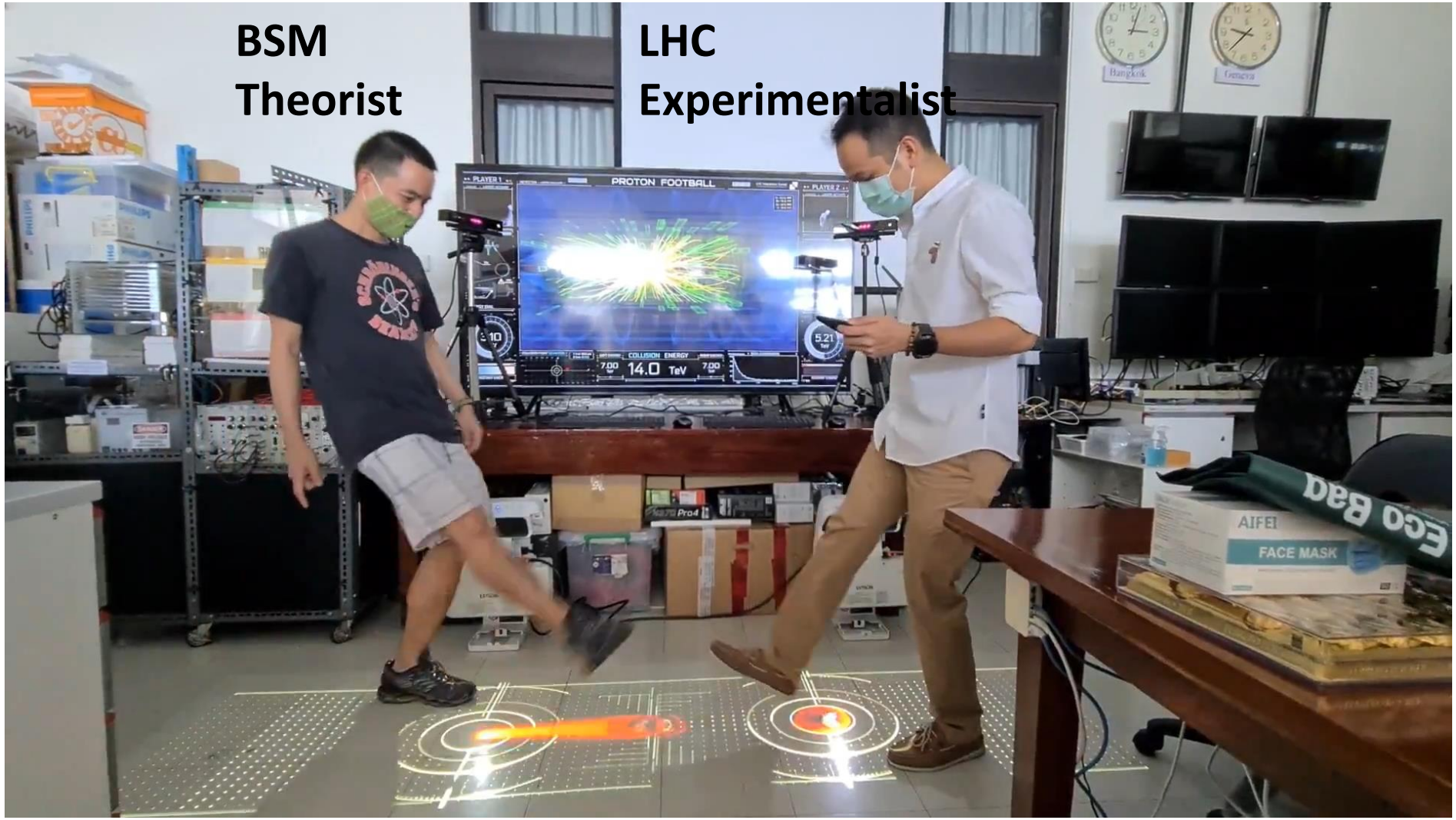
Prediction = $SM(\text{simple}) + SM(\text{complicated}) + SM\ (\text{complicated}^2) + \ldots$

$+\boldsymbol{NP1}$ $+\boldsymbol{NP2}$ $+\cdots$



Hints for even further discoveries could come from more/better experiments.

"New Physics"?



Advances in experiments and theories are crucial for understandings of the fundamental building blocks of nature.

Nature doesn't care about <u>our model</u>

- *"**If it disagrees with experiment, it's wrong.** In that simple statement is the key to science. It doesn't make any difference how beautiful your guess is, it doesn't matter how smart you are who made the guess, or what his name is… If it disagrees with experiment, it's wrong. That's all there is to it."*
-- Richard P. Feynman

Image: Caltech Archives